Climate: Observations, projections and impacts: Brazil

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.

Climate: Observations, projections and impacts

Brazil

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

- Over the period 1960-2010 there was warming in the northern, eastern and southern regions of Brazil for both summer (December to February) and winter (June to August).

- There has been a general increase in winter temperatures averaged over the country, making the occurrence of relatively warm winter temperatures more frequent and cold winter temperatures less frequent.

- Night-time temperatures the southern part of Brazil (the region where there is daily temperature data) show a decreasing frequency of cool nights and an increasing frequency of warm nights.

- Between 1960 and 2003 there has been a small increase in annual total precipitation over Brazil but variations are linked to natural inter-annual and decadal variability, rather than climate change.

Climate change projections

- For a business as usual emissions scenario temperature increases of up to around 3.5°C are projected over most of the country. Lower increases are projected along the east coast. The agreement between CMIP3 models is good over eastern and southern parts of the country, but poorer in the northwest.

- For annual precipitation changes, there is some agreement between the ensemble members over most of Brazil, and indicates a mixed pattern of precipitation changes. In the west annual precipitation increases of around 5% are projected, but with low agreement among the ensemble members. In some central and northern regions, and also in the southeast, decreases in annual precipitation of up to 5% are projected.

1

Climate change impact projections

Crop yields

- Most of the global- and regional-scale studies project yield losses for soybean, maize and rice, three of Brazil's major crops, as a consequence of climate change. The one study that considers sugarcane, projects a small increase.

- One national-scale study suggests that CO_2 fertilisation could more than offset the negative impact of temperature increases on bean yields, but not in other crops.

Food security

- Brazil is currently a country with very low levels of undernourishment. Global-scale studies included here generally project that Brazil will remain food secure over the next 40 years with climate change.

- However, recent work by the AVOID programme demonstrates that adaptive measures could be crucial towards maintaining food security in Brazil under climate change.

- One study concluded that the national economy of Brazil presents a moderate vulnerability to climate change impacts on fisheries. Another projects that maximum fish catch potential from 2005 to 2055 could decline by up to 8% under SRES A1B.

Water stress and drought

- Global- and regional-scale studies of future drought and water stress in Brazil are uncertain owing to the role of ENSO in affecting drought occurrence in Brazil under climate change.

- There is no consensus among studies as to the sign of change in water stress, with some suggesting little change and others large increases in stress, particularly in regions along the south-eastern coast.

- Recent simulations by the AVOID programme show that exposure to increased or decreased water stress with climate change is not simulated by the majority of GCMs.

Pluvial flooding and rainfall

- The IPCC AR4 noted projections of reduced mean precipitation parts of northern Brazil, and little in the way of research into changing precipitation extremes.

- More recent research suggests continued decreases in mean precipitation over Amazonia but potential increases over other parts of Brazil.

- There is also uncertainty regarding changes to the hydrological cycle associated with changes to the Amazon forest.

Fluvial flooding

- There is large uncertainty regarding the impact of climate change on fluvial flooding with climate change in Brazil.

- Recent simulations by the AVOID programme show a tendency for increasing flood risk with climate change, particularly later in the century.

Tropical cyclones

- Brazil is rarely impacted by tropical cyclones.

Coastal regions

- Sea level rise (SLR) could have major impacts in Brazil.

- One study places Brazil within the top 15 countries simulated to show an increased exposure from SLR relative to present in the 2070s, based upon a global assessment of 136 port cities.

- A 10% intensification of the current 1-in-100-year storm surge combined with a 1m SLR could affect around 15% of Brazil's coastal land area and 30% of the coastal population.

Table of Contents

Chapter 1 – Climate Observations

Rationale

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

Figure 1. *Location of boxes for the regional average time series (red dashed box) in Figures 3 and 6 and the attribution region (grey box) in Figures 4 and 5.*

The purpose of this chapter is to summarise the weather and climate from 1960 to present day. This begins with a general climate overview including an up to date analysis of changes in surface mean temperature. These changes may be the result of a number of factors including climate change, natural variability and changes in land use. There is then a focus on extremes of temperature, precipitation and storms selected from 2000 onwards, reported in the World Meteorological Organization (WMO) Annual Statements on the Status of the Global Climate and/or the Bulletin of the American Meteorological Society (BAMS) State of the Climate reports. This is followed by a discussion of changes in moderate extremes from 1960 onwards using an updated version of the HadEX extremes database (Alexander et al., 2006) which categorises extremes of temperature and precipitation. These are core climate variables which have received significant effort from the climate research community in terms of data acquisition and processing and for which it is possible to produce long high quality records for monitoring. No new analysis is included for storms (see the methodology

annex 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

Spanning latitudes 5°N to 32°S, Brazil is confined mostly to tropical latitudes at which the altitude of the midday sun is never far from vertical. Consequently, except in the far south, the climate is very warm throughout the year with only a small seasonal variation in temperature and daily maxima on low ground typically 30-34°C. Mean annual temperature at low-lying stations across much of the country is ~26-27°C. However much of central and southern Brazil is a high plateau over which annual mean temperature falls by ~6°C per 1000m of ascent, e.g. only 21°C at Brazilia, 1000m above mean sea level on the central plateau. Southward of ~12°S, annual mean temperature on low ground gradually falls to ~20°C near the southern border, mainly at the expense of lower winter temperatures while the mean temperature of the warmest month remains around 26°C. For example, at Port Alegre near the southern border, monthly mean temperature ranges from 25.5°C in February to 15°C in June. In this most southerly portion of Brazil frosts can occur and, rarely, snow on high ground, during invasions of cold air from the Antarctic.

Much of Brazil has high rainfall. A crucial factor in Brazil's climate is the position of the inter-tropical convergence zone (ITCZ) which oscillates southwards, then northwards across much of the country each year, lagging behind the latitude of overhead midday sun. The associated axis of convective-type rainfall lies to the north of Brazil for a time, May-October, but somewhere over Brazil for the remainder of the year. In the extensive Amazon Basin, lying almost along the equator, annual average rainfall exceeds 2000mm widely (e.g. Belem, Amazon estuary, 2893mm and Manaus, inland Amazon basin, 2286mm) and the 'dry season' from June to October still has typically 60-120mm per month. At Belem, the wettest months, February and March, each have more than 400mm on average. Further south on the Brazilian plateau, the dry season is somewhat longer and more marked. Nonetheless, Brazilia (16°S) receives an annual average rainfall of 1552mm. By contrast, the north-east of the Brazilian plateau is a relatively dry zone, averaging less than 750mm per year in places and with large variations from year to year resulting in prolonged droughts.

Along much of the coast south of the Amazon basin the annual rainfall cycle is again less marked as, away from the ITCZ, easterly winds still blow moist air onshore. For instance, Salvador (12°S and at rather similar latitude to Brazilia), receives an annual average of almost 2100mm, peaking in April/May but with every month exceeding 100mm. The dates of the wetter season vary from north to south along the coastline, depending on the combined effect of the ITCZ and onshore winds at other times. At Port Alegre, 30°S and beyond the

reach of the ITCZ, April/May is the relative dry season with all other months reaching or exceeding a 100mm average.

The main climatic hazards in Brazil are floods, drought (with associated wildfires) and occasional large temperature departures on the cold side of average, though in March 2004 the first recorded tropical cyclone to hit Brazil reached the far south-eastern coastline.

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 Brazil using the median of pairwise slopes method to fit the trend (Sen, 1968; Lanzante, 1996). The methods are fully described in the methodology annex. There is a mixed signal for temperature over Brazil as shown in Figure 2. For both summer (December to February) and winter (June to August) there is higher confidence in warming in the northern, eastern and southern regions, where the 5th to 95th percentiles of the pairwise slopes for the grid boxes are of the same sign. The signal is slightly more mixed for the winter months. There are few data over the central and western regions and here both warming and cooling is shown but with lower confidence in the trends. Regionally averaged trends (over grid boxes included in the red dashed box in Figure 1) show similar warming in summer [0.08^{o}C per decade (5th to 95th percentile of slopes: 0.03 to 0.14^{o}C per decade)] and in winter [0.08^{o}C per decade (5th to 95th percentile of slopes: 0.01 to 0.16^{o}C per decade)].

DJF

JJA

-1.00 -0.50 -0.25 -0.10 -0.05 -0.02 0.00 0.02 0.05 0.10 0.25 0.50 1.00
deg C per decade

-1.00 -0.50 -0.25 -0.10 -0.05 -0.02 0.00 0.02 0.05 0.10 0.25 0.50 1.00
deg C per decade
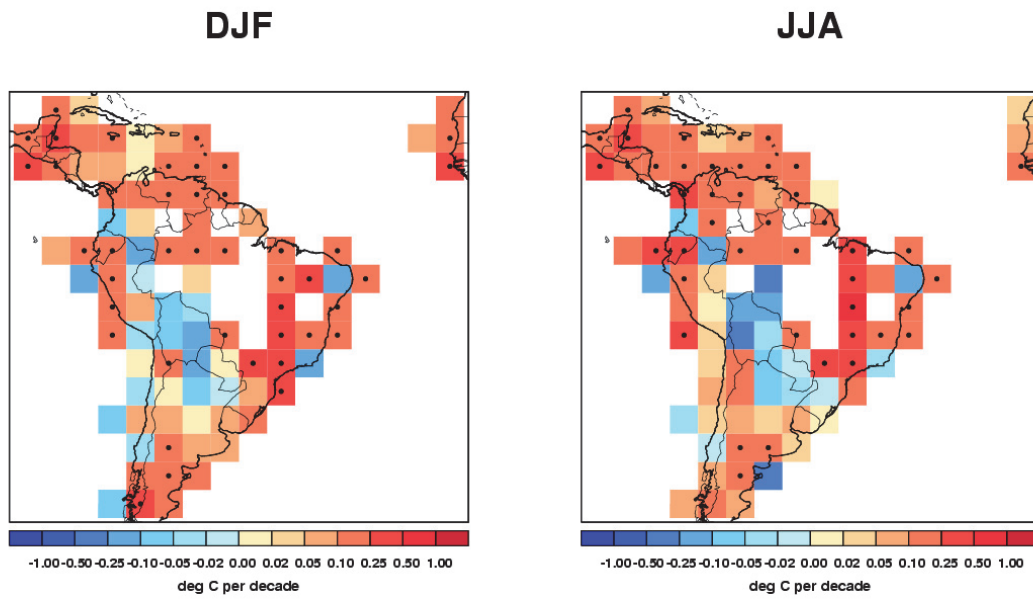
Figure 2. Decadal trends in seasonally averaged temperatures for Brazil and surrounding regions over the period 1960 to 2010. Monthly mean anomalies from CRUTEM3 (Brohan et al. 2006) are averaged over each 3 month season (December-January-February – DJF and June-July-August - JJA). Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). There is higher confidence in the sign of trends 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 respective grid-box.

Temperature extremes

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

Table 1 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. Two events, the heat waves during 2006 and the extreme cold of 2010 are highlighted as examples of extreme temperature events.

Year	Month	Event	Details	Source
2000	Jun-Jul	Cold	Numerous all-time low temperatures	WMO (2001)
2006	Jan-Mar	Heat waves	Record breaking temperatures recorded	WMO (2007)
2010	Jul	Cold	Frigid polar air affected parts of southern South America	Marengo et al. (2011)

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

Recent extreme temperature events

Heat waves, 2006

Some areas of Brazil experienced record-breaking temperatures in austral summer, for example, the 44.6°C record for Bom Jesus on 31 January (Rusticucci and Camacho, 2007). Record highs above 41°C were also detected in other cities in southern Brazil in January 2006. Associated with a period of extended drought, these were among the highest temperatures during the last 40 years (Marengo, 2007).

Extreme cold, 2010

From May to August, various cold spell episodes occurred in the southern part of South America, reaching the tropical regions of Brazil. The strongest episode was accompanied by heavy snowfall lasting nearly a week from the 11–18 July. Unusually low temperatures were observed, with -8°C recorded in the state of Santa Catarina in southern Brazil. Many people, especially young children and the elderly, died from hypothermia, pneumonia, and other respiratory diseases due to this event (Marengo et al., 2011).

Analysis of long-term features in moderate temperature extremes

HadEX extremes indices (Alexander et al., 2006) are used here for Brazil 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.

There are few daily temperature data available for Brazil and so it is only possible to look at the very south of Brazil. Between 1960 and 2003, changes in the frequency of warm nights and cool days/nights have been in concert with warming mean temperature in the very southern regions (Figure 3). However, there is no clear signal for warm days. Compared to changes in the mean temperature, changes in the frequency of daily extremes show greater consistency and have higher confidence in the majority of grid boxes for which there are data. The data presented here are annual totals, averaged across all seasons, and so direct interpretation in terms of summertime heat waves and winter cold snaps is not possible.

Night-time temperatures (daily minima) in the southern region show spatially consistent decreasing cool night frequency and increasing warm night frequency with higher confidence (Figure 3 a,b,c,d). Indeed regional averages concur with higher confidence in these signals. The data series are short, ending in 2001 for cool nights and 2000 for warm nights and so care should be taken when considering the most recent decade.

Daytime temperatures (daily maxima) in the southern region show a more mixed signal (Figure 3 e,f,g,h) than night-time temperatures. There is a spatially consistent decrease in the frequency of cool days where confidence is higher in the vast majority of grid boxes. There is no consistent signal in 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)

b)

-1.33 % per decade (-1.94 to -0.81)

-5.61 total change (%) (-8.13 to -3.42)

c) warm nights (TN90p)

d)

1.88 % per decade (1.19 to 2.79)

7.54 total change (%) (4.77 to 11.14)

18
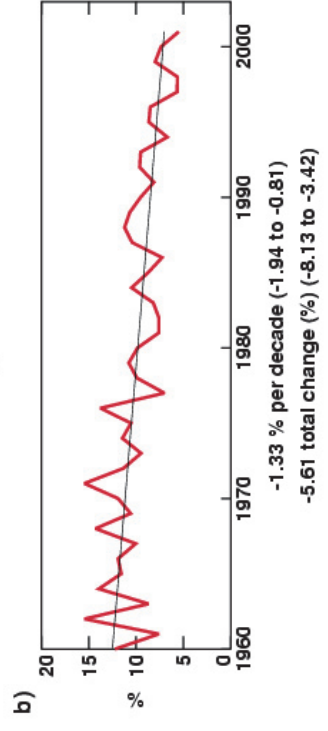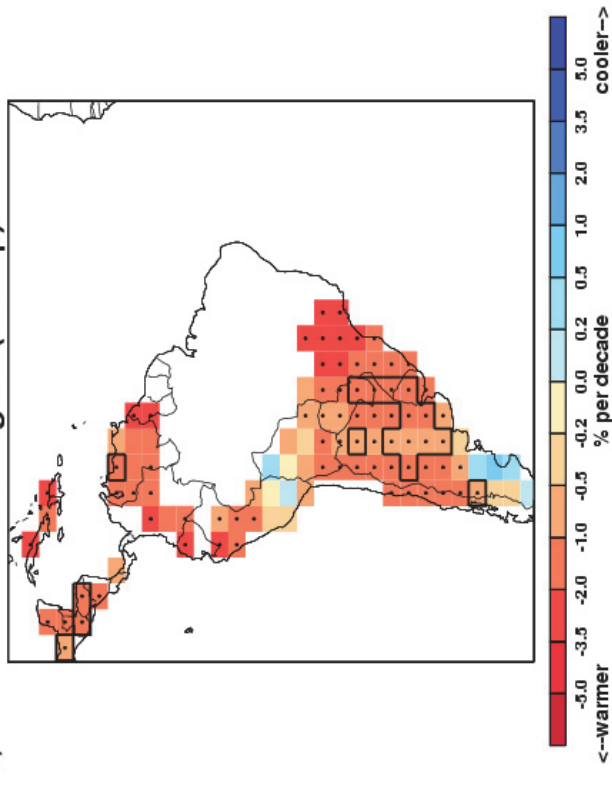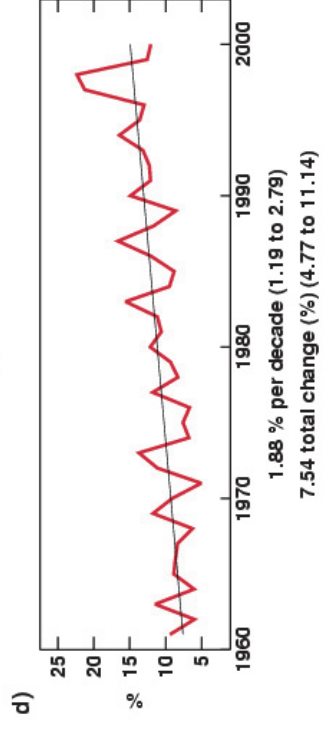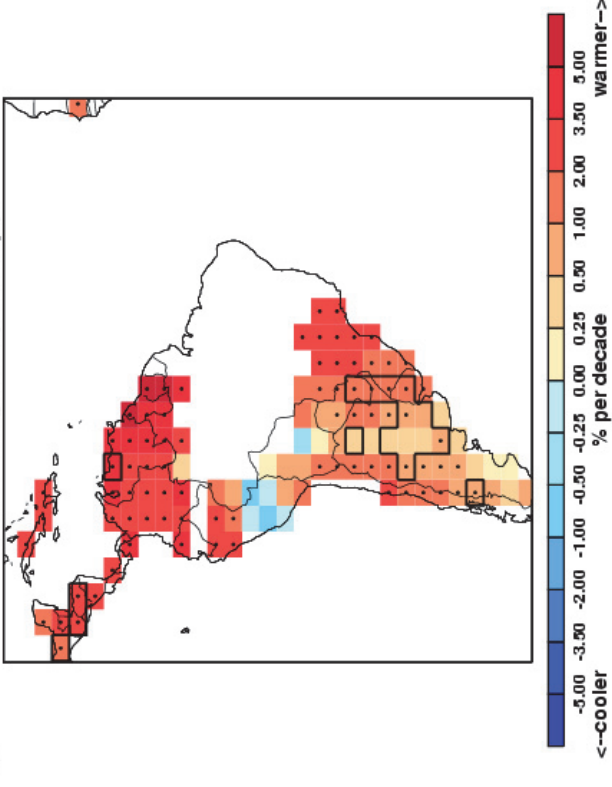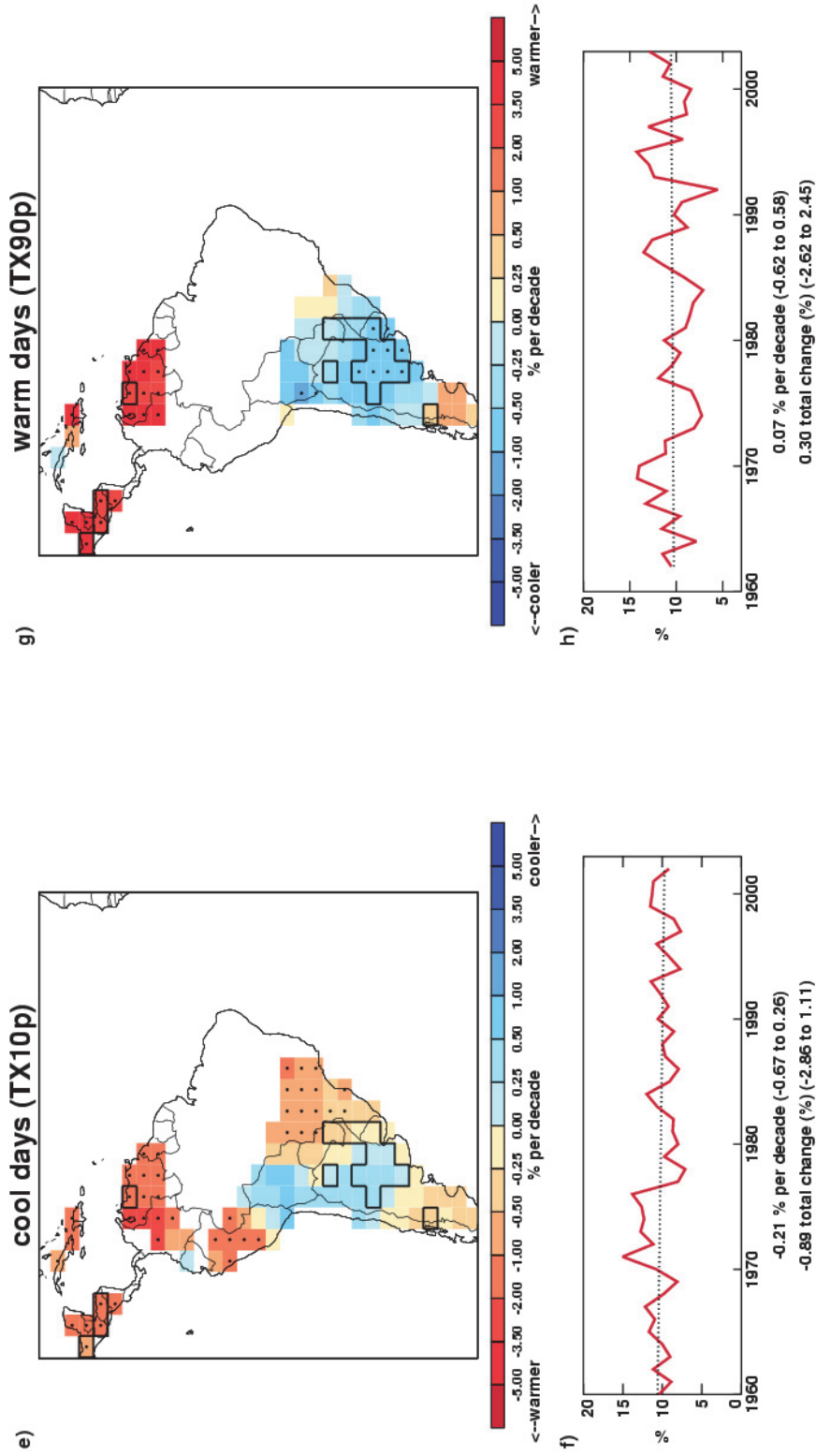
Figure 3. *Percentage change in cool nights (a,b), warm nights (c,d), cool days (e,f) and warm days (g,h) for Brazil over the period 1960 to 2003 from HadEX (Alexander et al., 2006). a, c, e, g). Grid boxes outlined in solid black contain at least 3 stations and so are likely to be more representative 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 73.125 to 31.875° W, 6.25° N to 33.75° S 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 is data. Higher confidence in the trends, as denoted above, is shown by a solid black line as opposed to a dotted one.*

19

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 2005/06

The distributions of the December-January-February (DJF) mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 4. Analyses with two models suggest that human influences on the climate have shifted the distribution to higher temperatures, though owing to natural causes such as ENSO we cannot attribute directly any change in one year or so to human activities. Considering the average over the entire region, the summer (DJF) of 2005/06 is average, as it lies in the central sector of the seasonal temperature distribution for the climate influenced by anthropogenic forcings (distributions plotted in red). It is not as extreme as the summer of 1997/98, which is the hottest sine 1900 in the CRUTEM3 dataset. In the absence of human influences (green distributions), the season lies near the warm tail of the temperature distribution and would therefore be a more uncommonly warm season. The attribution results shown here refer to temperature anomalies over the entire region and over an entire season, whereas an extreme event has a shorter duration and affects a smaller region.
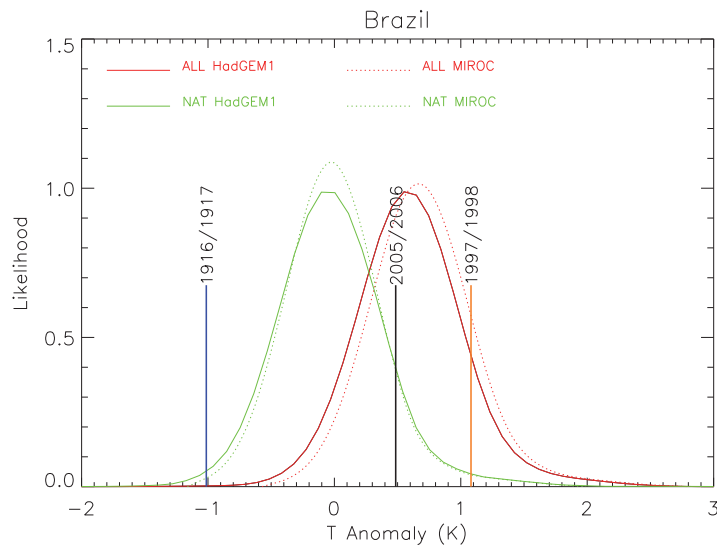
Figure 4. *Distributions of the December-January_February mean temperature anomalies (relative to 1961-1990) averaged over the Brazilian region (73-35W, 30S-5N – as shown in Figure 1) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical black line marks the observed anomaly in 2005/06 and the vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.*

Winter 2010

The distributions of the June-July-August (JJA) mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 5. Analyses with both models suggest that human influences on the climate have shifted the distributions to higher temperatures. The winter of 2010 is cold, as shown in Figure 5, as it lies near the cold tail of the seasonal temperature distribution for the climate influenced by anthropogenic forcings (distributions plotted in red). It is considerably warmer than the winter of 1917, which is the coldest since 1900 in the CRUTEM3 dataset. In the absence of human influences (green distributions), the season lies near the central sector of the temperature distribution and would therefore be an average season. The attribution results shown here refer to temperature anomalies over the entire region and over an entire season, whereas an extreme event has a shorter duration and affects a smaller region.
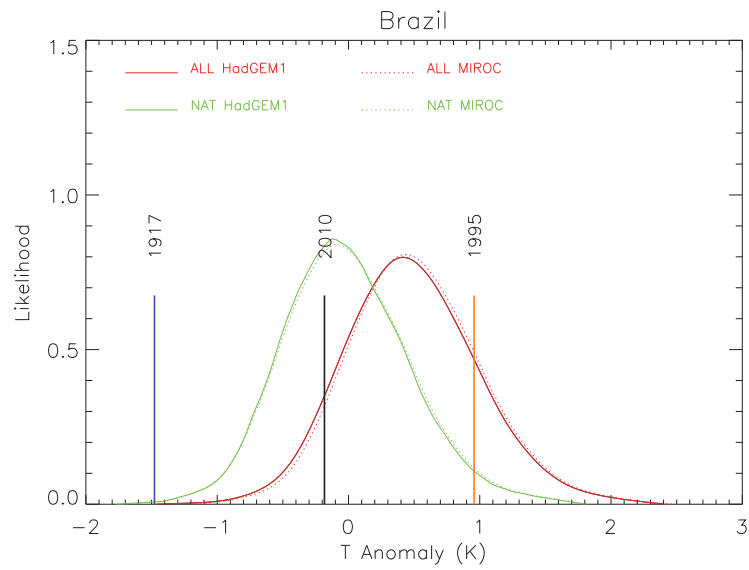
Figure 5. *Distributions of the June-July_August mean temperature anomalies (relative to 1961-1990) averaged over the Brazilian region (73-35W, 30S-5N – as shown in Figure 1) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical black line marks the observed anomaly in 2010 and the vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.*

Precipitation extremes

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

Table 2 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. Two events, the droughts during 2010 and flooding during April 2009, are highlighted below as examples of extreme precipitation events for parts of Brazil.

Year	Month	Event	Details	Source
2000	Aug-Sep	Wet	3-7 times the normal rainfall at many locations	WMO (2001)
2001	Dec-May	Drought	Drought during the normal rainy season	WMO (2002)
2002	Dec-May	Drought	Persistent drought during the rainy season	WMO (2003)
2003	Jan	Flooding	Torrential rain and flooding in Rio de Janeiro	WMO (2004)
2004	Dec-Feb	Flooding	Major flooding in January in Brazil's north east states	WMO (2005)
2005	Dec-Mar	Drought	Worst in 60 years; lowest Amazon flow in 30 years; South Brazil experienced severe agricultural impacts and water shortages.	WMO (2006)
2006		Drought	Southern Brazil experienced drought conditions with losses of about 11% in the soybean crop yield.	WMO (2007)
2007	Jan	Flooding	Heavy rain and flooding	WMO (2008)
2008	Nov	Flooding	21-24 Nov in the Santa Catarina state heavy rain and flooding affected 1.5 million people and resulted in 84 fatalities. This was the region's worst weather tragedy in history. More than 500mm of rainfall recorded, including more than 200mm in 24 hours.	WMO (2009)
2009	Apr	Flooding	Torrential downpours caused floods and mudslides.	WMO (2010)
2009	Nov	Flooding	Several intense storms severely affected south Brazil, producing daily and monthly records of rainfall.	WMO (2010)
2010	Jul-Sep	Drought	Worst drought in four decades in north and west Amazonia.	WMO (2011)
2010	Apr	Flooding	In Rio de Janiero, 279mm of rain fell in a 24-hour period (4–5 April), the heaviest rainfall event recorded in 48 years.	WMO (2011)

Table 2. *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, 2010

The Amazon rainforest was subject to widespread drought in 2010. This drought was more severe than the drought in 2005, which was considered a 'once-in-a-century' drought. The drought began

during an El Niño event in early austral summer and then intensified during the La Nina of the next dry winter and spring (Marengo et al., 2011).

The BBC News reported that the Amazon River hit its lowest water levels in half a century and more than 20 municipalities in Amazonas state declared a state of emergency as tributaries ran dry (BBC News, 2011). Rio Negro dropped to its lowest level of 13.6 m since record-keeping began in 1902 (WMO, 2011). Forest fires are generally associated with deforestation, however, despite preliminary data for 2010 indicating a fall in deforestation activities, parts of the Amazon also experienced out-of-control fires as the dry conditions amplified the impact of fires that are set in order to clear land (Nature News, 2010).

Floods, April 2009

Floods and mudslides affected over 186,000 people in north-east Brazil as this region experienced its worst deluge in over 20 years (WMO, 2011). A combination of several meteorological factors were responsible for the 2009 heavy rains. Enhanced moisture transport from the tropical North Atlantic off the coast of Venezuela-Guiana into western Amazonia, a more intense Chaco low during the summer of 2008-2009 (favouring enhanced trade winds and moisture transport) and an anomalous migration of the ITCZ during May-June 2009, are believed to have been the causes for the heavy rainfall (Marengo et al., 2011). In Addition to this, La Niña conditions developed but were weaker and began later during the 2009 flood. The warmer-than-normal sea surface temperatures in the tropical Atlantic off the coasts of Venezuela–Guiana during summer, and in the tropical South Atlantic during autumn was the most important factor responsible for the heavy rainfall in Amazonia (Marengo et al., 2011).

Analysis of long-term features in precipitation

HadEX extremes indices (Alexander et al., 2006) are used here for Brazil 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) wet and dry spells. The methods are fully described in the methodology annex.

Between 1960 and 2003 there has been a small increase in annual total precipitation; confidence is higher in this change when regionally averaged (Figure 6). Precipitation also shows decadal time scale variability (Marengo et al., 2009). The national increasing trend reflects moistening over the southernmost regions not compensated by drying in the east, for which there is less-

confidence. Similarly, there is a decrease in the continuous dry spell length and an increase in continuous wet spell length in the very south with opposing signals further north and east. Confidence in these signals is low for the vast majority of grid-boxes.
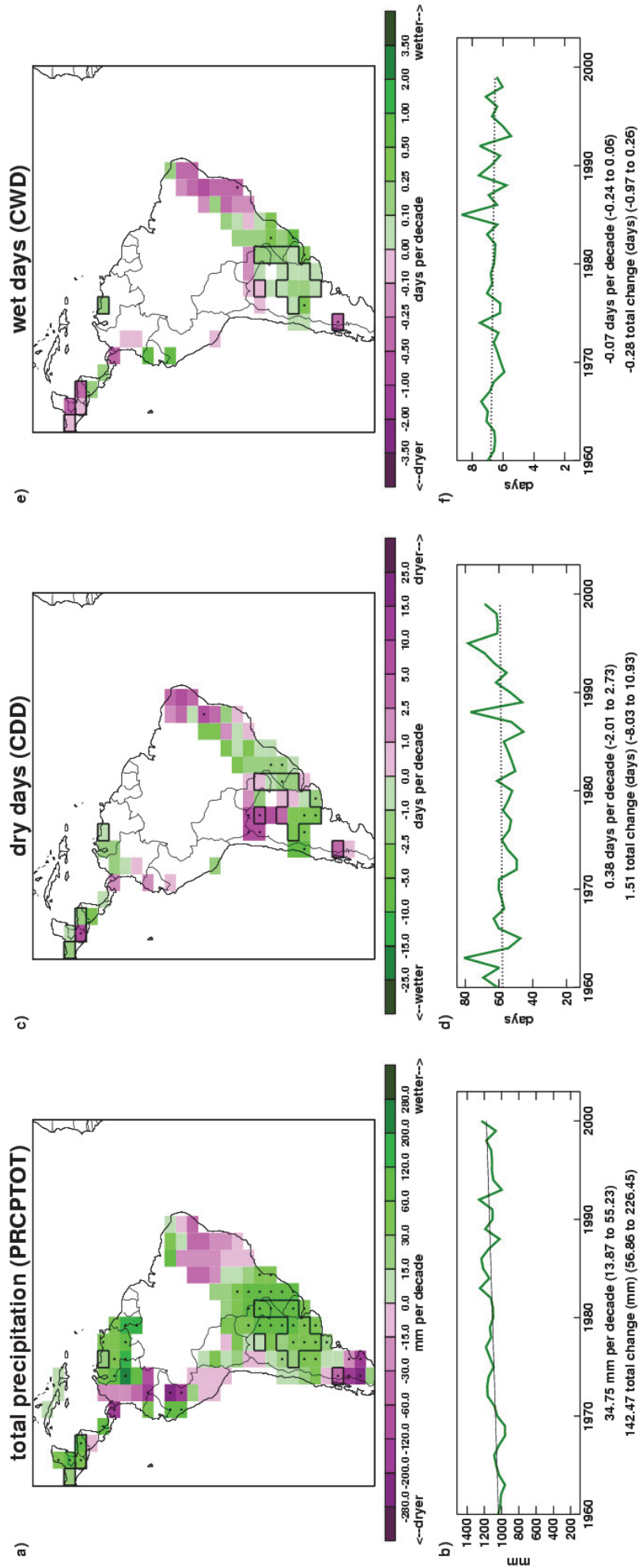
Figure 6. *Change in total annual precipitation, continuous dry spell length and continuous wet spell length for Brazil over the period 1960 to 2003 relative to 1961-1990 from HadEX (Alexander et al., 2006). a,c,e) Decadal trends as shown as in Figure 3. b,d,f) Area average annual time-series for 73.125 to 31.875° W, 6.25° N to 33.75° S as described in Figure 3.*

27

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 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. Brazil is not typically susceptible to tropical storms – these are far more likely to form and make landfall in the North Atlantic. However, Tropical Cyclone Catarina was a notable recent event that impacted Brazil.

Year	Month	Event	Details	Source
2004	Mar	Tropical Cyclone	Rare tropical cyclone in South Atlantic. Made landfall in the state of Santa Catarina, Brazil. Maximum sustained winds of 120-130 km/h. Unofficially named tropical cyclone Catarina.	WMO (2005)

Table 3. A selection of notable storm events recorded in Brazil 2000-2010 which were reported in the WMO annual Statement on the Status of the Global Climate.

Recent storm events

Tropical cyclone Catarina, March 2004

Tropical cyclone Catarina (as it was unofficially named) was the first documented tropical cyclone to develop in the South Atlantic Ocean (Levinson, 2005). The tropical cyclone developed rapidly on 27 March 2004 as a strong cyclone with hurricane-force winds. It made landfall along the southern coast of Brazil in the state of Santa Catarina and astonished the meteorological community. As it was such an unusual event, there was widespread disagreement whether the cyclone was tropical, extratropical, or a "hybrid" system (Rusticucci and Fortune, 2005).

Initially, it was observed as a low pressure disturbance that developed along a cold front over the South Atlantic Ocean, but in 2 days it acquired the typical characteristics of a tropical cyclone, with

rain and cloud bands cyclonically converging into a well-defined eye. The maximum recorded wind speed was 147 km/h and surface pressure was 993 hPa during landfall at Siderópolis, Brazil (Rusticucci and Fortune, 2005).

As the cyclone intensified over the South Atlantic Ocean, Brazilian authorities were notified and measures were taken to minimise the possible loss of human life. However, damage on the southern coast of Santa Catarina state and the northern coast of Rio Grande do Sul state was extensive, and was estimated at approximately US$ 330 million (Rusticucci and Fortune, 2005).

Summary

The main features seen in observed climate over Brazil are:

- Over the period 1960-2010 for both summer (December to February) and winter (June to August) there was warming in the northern, eastern and southern regions of Brazil.

- There has been a general increase in winter temperatures averaged over the country, making the occurrence of relatively warm winter temperatures more frequent and cold winter temperatures less frequent.

- Night-time temperatures (daily minima) in the southern part of Brazil (the region for which we have daily temperature data) show a decreasing frequency of cool nights and an increasing frequency of warm nights.

- Between 1960 and 2003 there has been a small increase in annual total precipitation over Brazil but variations are linked more to natural interannual and decadal variability.

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 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.

---

[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

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	

37

Country	Coordinates	Data source	Period	Indices	Temporal resolution	Notes
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

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

Table 5. Summary of data used for each country.

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

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

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

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

We calculate a climatology for each station (and month if appropriate) using the mean value for each index over the period 1961-1990. The values for each station are then anomalised using this climatology by subtracting this mean value from the true values, so that it is clear if the station values are higher or lower than normal. This means that we do not need to take

differences in elevation or topography into account when comparing neighbours, as we are not comparing actual values, but rather deviations from the mean value.

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

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

To present the data, the individual stations are gridded on a 3.75^{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 7).
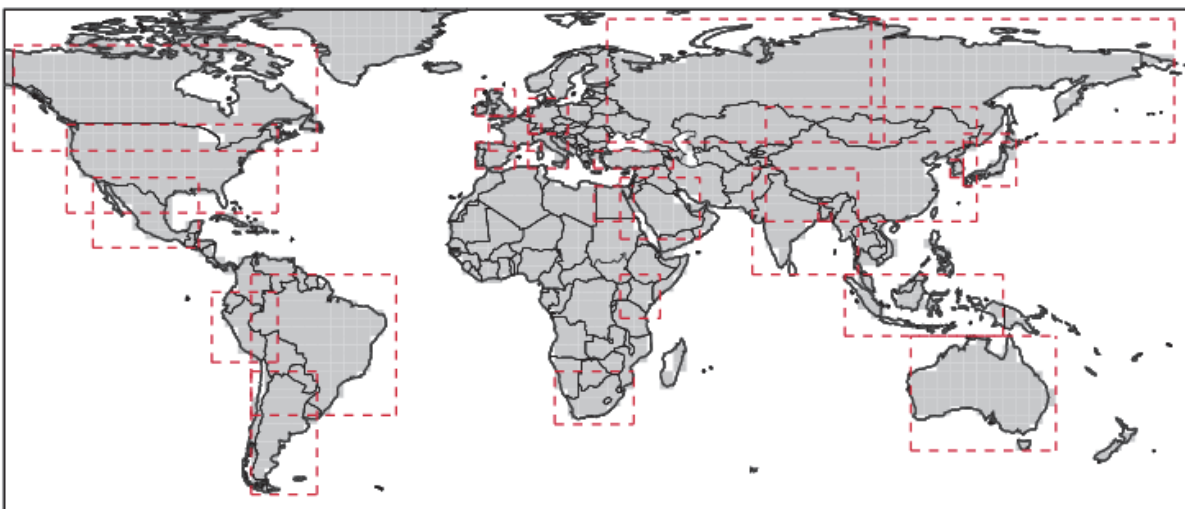

Figure 7. Land-sea mask used for gridding the station data and regional areas allocated to each country as described in Table 5.

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.
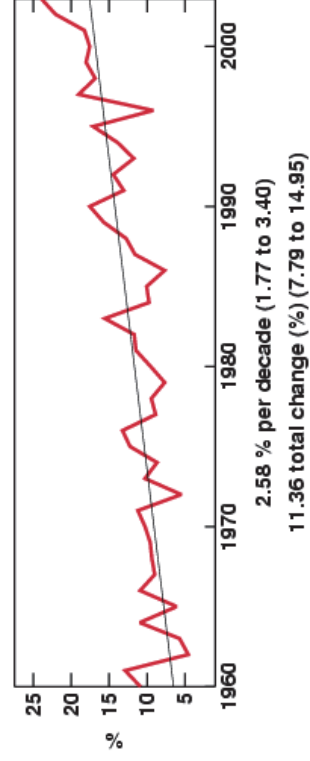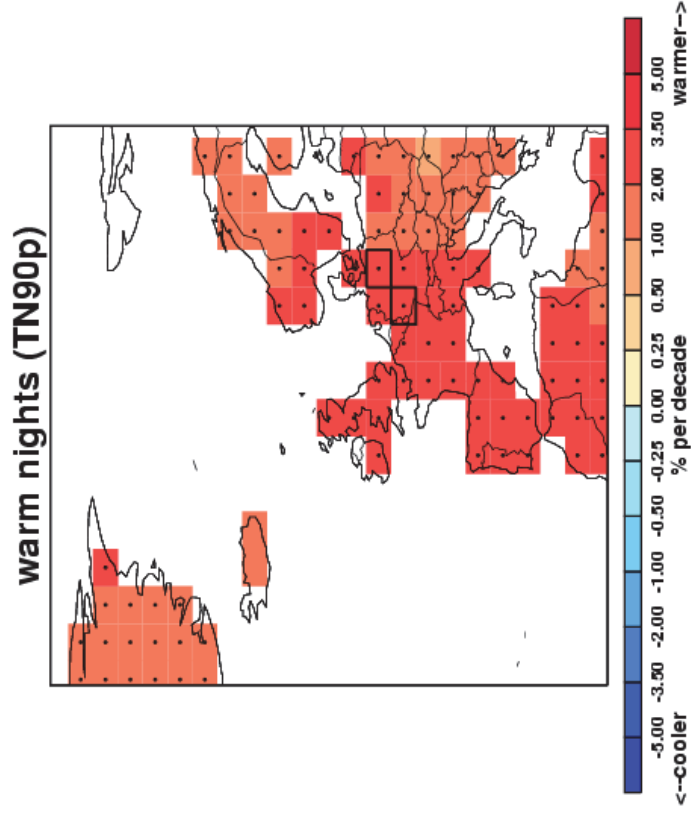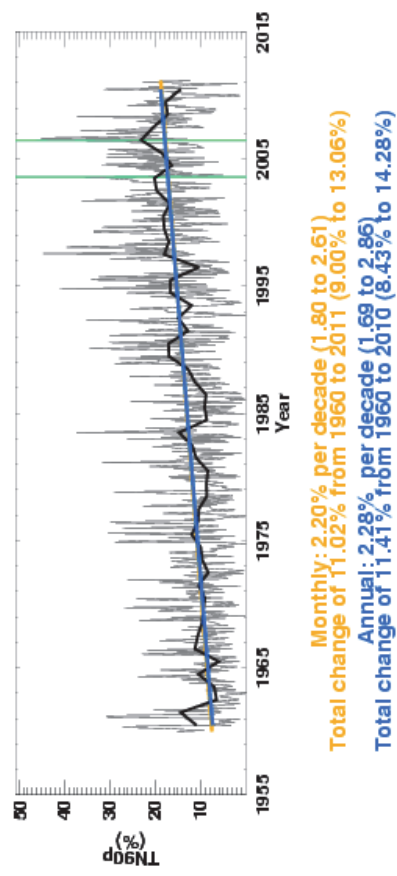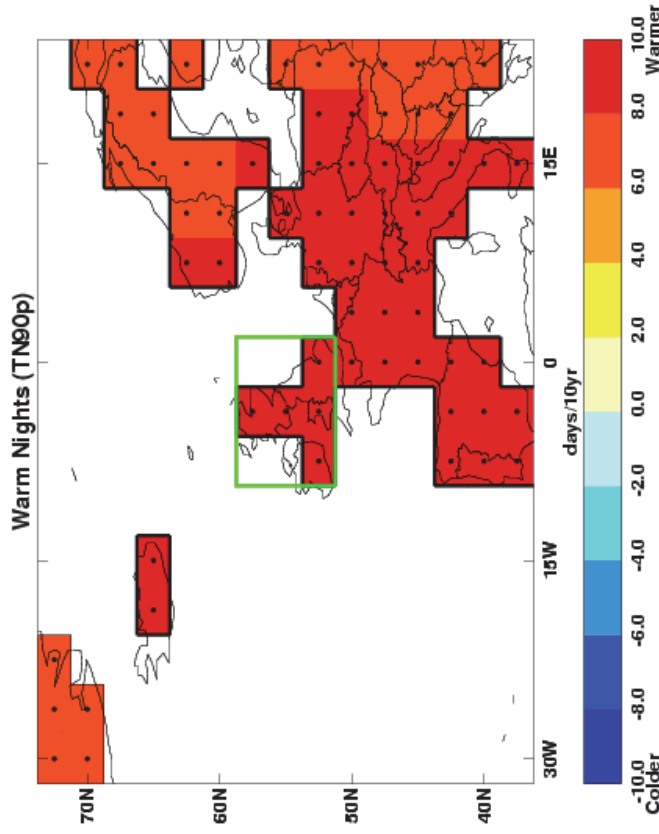
Figure 8. *Examples of the plots shown in the data section. Left: From ECA&D data between 1960-2010 for the number of warm nights, and Right: from HadEX data (1960-2003) for the total precipitation. A full explanation of the plots is given in the text below.*

44

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

There are two influences on whether a grid box contains a value or not – the land-sea mask, and the decorrelation length scale. The land-sea mask is shown in Figure 7. There are grid boxes which contain some land but are mostly sea and so are not considered. The decorrelation length scale sets the maximum distance a grid box can be from stations before no value is assigned to it. Grid boxes containing three or more stations are highlighted by a thick border. This indicates regions where the value shown is likely to be more representative of the grid box area mean as opposed to a single station location.

On the maps for the new data there is a box indicating which grid boxes have been extracted to calculate the area average for the time series. This box is the same as shown in Figure 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 9. 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.9 and Table 6) are often larger than individual countries, or include several smaller countries in a single region (for example UK, Germany and France are grouped in one region).

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

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

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

c) In the same way, additional noise from control model simulations is introduced to the distributions to represent the effect of internal variability in the annual values of the seasonal mean temperatures. The result is a pair of estimated distributions of the annual values of the seasonal mean temperature in the region with and without the

effect of human activity on the climate. The temperatures throughout the analysis are expressed as anomalies relative to period 1961-1990.
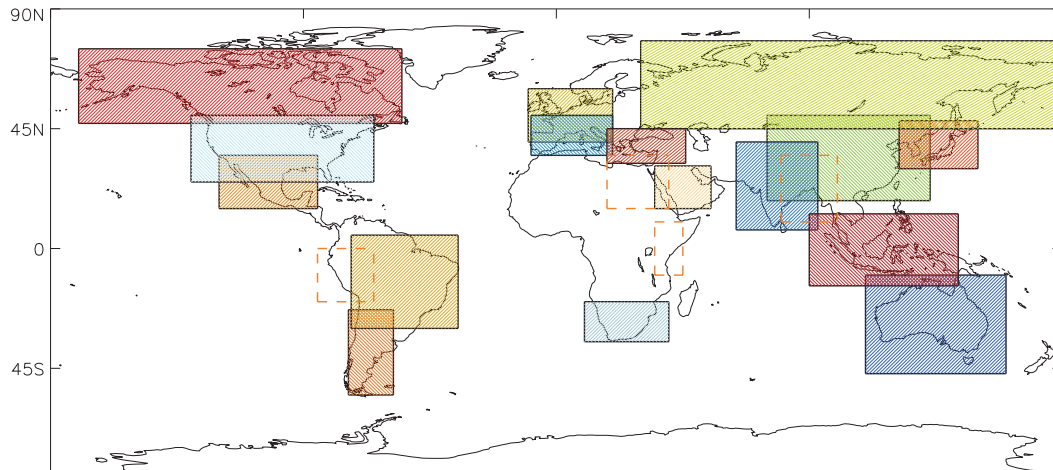
Figure 9. *The regions used in the attribution analysis. Regions marked with dashed orange boundaries correspond to non-G20 countries that were also included in the analysis.*

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.

BBC NEWS 2011 (accessed 02/09/11) Amazon drought 'severe' in 2010, raising warming fears, http://www.bbc.co.uk/news/science-environment-12356835.

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.

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.

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.

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.

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. Clim.* 16, 1197–226.

LEVINSON, D. H. 2005. Introduction in State of the Climate in 2004, *Bulletin of the American Meteorological Society* 86, S8.

MARENGO, J. 2007. Tropical South America, East of the Andes in State of the Climate in 2006, *Bulletin of the American Meteorological Society* 88, S92.

MARENGO, J. Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s*. Hydrological Processes* 23(22), 3236-3244, 2009.

MARENGO, J. A., L. M. ALVES, J. RONCHAIL, AND J. BAEZ. 2011. Tropical South America, East of the Andes i*n* State of the Climate in 2010, *Bulletin of the American Meteorological Society*, 92, S188.

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.

NATURE NEWS. 2010. Drought strikes the Amazon rainforest again, http://www.nature.com/news/2010/101029/full/news.2010.571.html.

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.

RUSTICUCCI, M. AND M. A. FORTUNE. 2005. "Fenomeno Catarine:" The South Atlantic's first hurricane? State of the Climate in 2004, *Bulletin of the American Meteorological Society*, 86, S30.

RUSTICUCCI, M. AND J. L. CAMACHO. 2007. South America in State of the Climate in 2006, *Bulletin of the American Meteorological Society* 88, S90.

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

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 in 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. 2005. Statement on Status of the Global Climate in 2004, WMO-No. 983.
http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2006. Statement on Status of the Global Climate in 2005, WMO-No. 998.
http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2007. Statement on Status of the Global Climate in 2006, WMO-No. 1016.
http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2008. Statement on Status of the Global Climate in 2007, WMO-NO. 1031.
http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2009. Statement on Status of the Global Climate in 2008, WMO-NO. 1039.
http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2010. Statement on Status of the Global Climate in 2009, WMO-NO. 1055.
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

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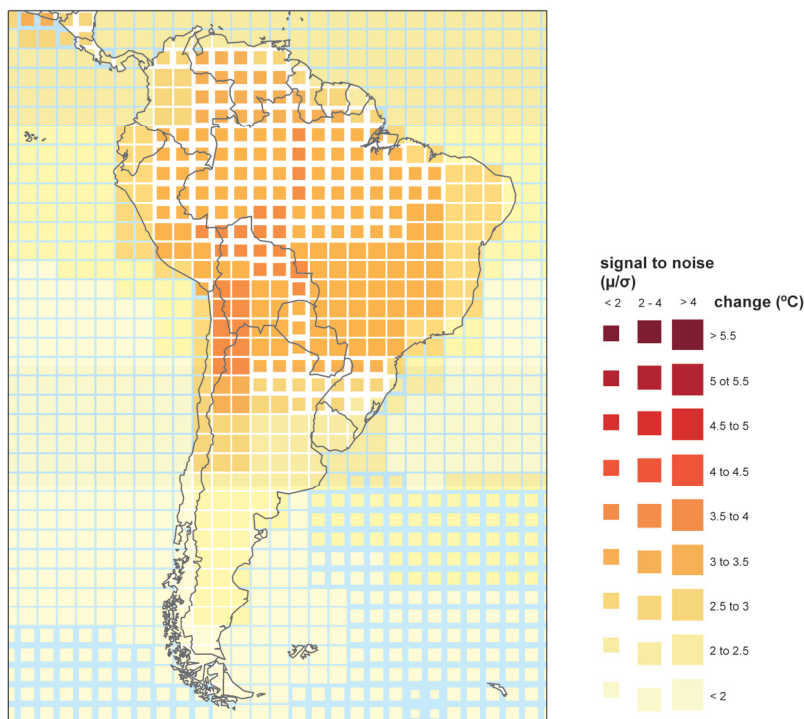
***Figure 1**. Percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the magnitude of the change.*

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 Brazil

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.

Temperature increases of up to around 3.5°C are projected over most of the country. Lower increases are projected along the east coast. The agreement between models is good over eastern and southern parts of the country, but poorer in the northwest.

Summary of precipitation change in Brazil

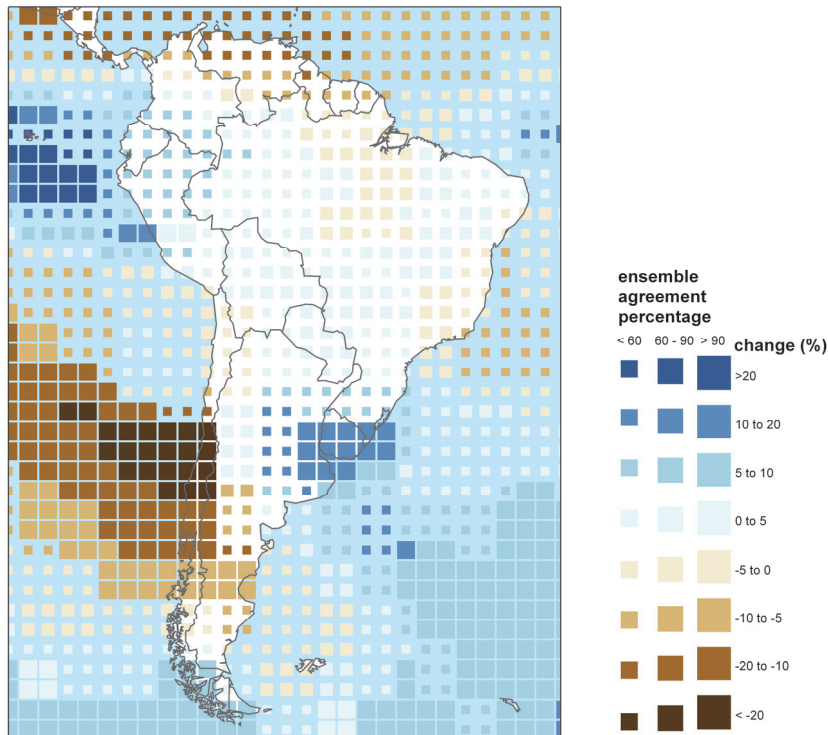Figure 2 shows the percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. Unlike for temperature, the models sometimes disagree over whether precipitation is increasing or decreasing over a region, so

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.

For precipitation changes, there is some agreement between the ensemble members over most of Brazil, and indicates a mixed pattern of annual precipitation changes. In the west annual precipitation increases of around 5% are projected, but with low agreement among the ensemble members. In some central and northern regions, and also in the southeast, decreases in annual precipitation of up to 5% are projected.

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 Brazil. 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 Brazil. 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.
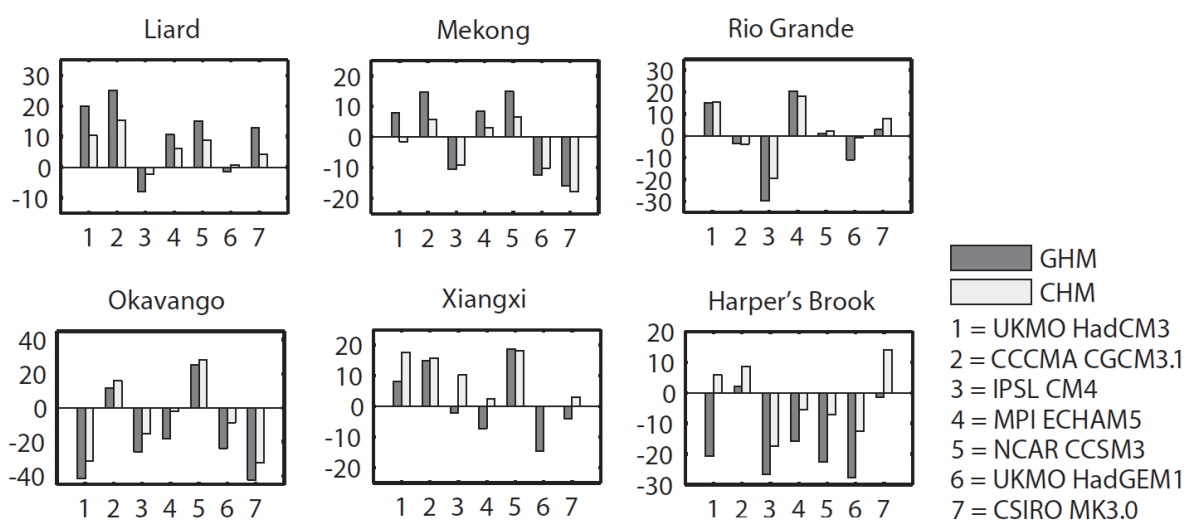

Figure 1. Change in average annual runoff relative to present (vertical axis; %), when a global hydrological model (GHM) and a catchment-scale hydrological model (CHM) are driven with climate change projections from 7 GCMs (horizontal axis), under a 2°C prescribed global-mean warming scenario, for six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

Uncertainties in the large scale climate relevant to Brazil includes changes in the El Niño-Southern Oscillation (ENSO) which could undergo rapid change with climate change. This could have a serious impact on large-scale atmospheric circulation, rainfall and seasonality in many parts of the world. Latif and Keenlyside (2009) concluded that, at this stage of understanding, it is not known how climate change might affect the tropical Pacific climate system. None of the global climate models (GCMs) they analysed showed rapid changes in behaviour. However, a threshold of abrupt change cannot be ruled out because whilst the GCMs that Latif and Keenlyside (2009) analysed (the CMIP3 multi-model dataset) are better than the previous generation of models (Reichler and Kim, 2008), these same models all show large biases in simulating the contemporary tropical Pacific, with no consensus on the sign of change in ENSO-like response.

Summary of findings for each sector

Crop yields

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

- Most of the global- and regional-scale studies included here project yield losses for Brazil's major crops as a consequence of climate change. The one study that considers sugarcane projects a small increase in future yield.

- The national-scale study considered here suggests that CO_2 fertilisation could more than offset the negative impact of temperature increases on bean yields, but not in other crops.

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

Food security

- Brazil is currently a country of very low undernourishment. Global-scale studies included here generally project that Brazil will remain food secure over the next 40 years with climate change.

- However, recent work by the AVOID programme demonstrates that adaptive measures could be crucial towards maintaining food security in Brazil under climate change.

- One study concluded that the national economy of Brazil presents a moderate vulnerability to climate change impacts on fisheries. Another projects that maximum fish catch potential from 2005 to 2055 could decline by up to 8% under SRES A1B.

Water stress and drought

- Global- and regional-scale studies included here vary in their future projections of drought and water stress in Brazil due to the application of different climate models and indicators of water stress. Important uncertainties concern the role of ENSO in affecting drought occurrence in Brazil under climate change.

- There is no consensus among studies as to the sign of change in water stress, with some suggesting little change and others large increases in stress, particularly in regions along the south-eastern coast.

- Recent simulations by the AVOID programme show that exposure to increased or decreased water stress with climate change is not simulated by the majority of GCMs.

- Recent national- and sub-national-scale research on the impact of climate change on tropical forests has focused on the Amazon, with mixed information regarding the possibility of forest dieback, timescales of change, reversibility and the influence of other forms of anthropogenic interference. There is consensus that temperature is not the only important metric for impacts here, with human activity playing an important role.

Pluvial flooding and rainfall

- The IPCC AR4 noted projections of reduced mean precipitation over Brazil, and little in the way of research into changing precipitation extremes.

- More recent research included here suggests continued decreases in mean precipitation over Amazonia with climate change but potential increases over other parts of Brazil.

- Large uncertainties remain regarding how ENSO could be affected by climate change.

- There is also uncertainty regarding changes to the hydrological cycle associated with changes to the Amazon forest.

Fluvial flooding

- There is large uncertainty regarding the impact of climate change on fluvial flooding with climate change in Brazil.

- A number of recent studies included here show that the sign of runoff change under climate change scenarios is largely dependent upon the GCM used to provide the climate change projections.

- However, recent simulations by the AVOID programme show a tendency for increasing flood risk with climate change, particularly later in the century.

Tropical cyclones

- Brazil is rarely impacted by tropical cyclones.

Coastal regions

- Sea level rise (SLR) could have major impacts in Brazil.

- One study places Brazil within the top 15 countries simulated to show an increased exposure from SLR relative to present in the 2070s, based upon a global assessment of 136 port cities.

- A 10% intensification of the current 1-in-100-year storm surge combined with a 1m SLR could affect around 15% of Brazil's coastal land area and 30% of the coastal population.

- However, an aggressive climate change mitigation scenario could avoid an exposure of around 14,000 people in Brazil, relative to un-mitigated climate change in 2070.

Crop yields

Headline

Crop yield projections for Brazil vary greatly across studies due to the application of different models, assumptions, and emissions scenarios. Generally, projections suggest yield losses for the major crops with climate change in Brazil, with the exception of sugar cane.

Results from the AVOID programme for Brazil indicate that the areas of current croplands becoming less suitable for cultivation are projected to be smaller under the mitigation scenario than the A1B scenario, and in both scenarios the area of declining suitability is larger than that of increasing suitability (which remains small over the 21st century in both scenarios).

Supporting literature

Introduction

The impacts of climate change on crop productivity are highly uncertain due to the complexity of the processes involved. Most current studies are limited in their ability to capture the uncertainty in regional climate projections, and often omit potentially important aspects such as extreme events and changes in pests and diseases. Importantly, there is a lack of clarity on how climate change impacts on drought are best quantified from an agricultural perspective, with different metrics giving very different impressions of future risk. The dependence of some regional agriculture on remote rainfall, snowmelt and glaciers adds to the complexity - these factors are rarely taken into account, and most studies focus solely on the impacts of local climate change on rain-fed agriculture. However, irrigated agricultural land produces approximately 40-45 % of the world's food (Doll and Siebert 2002), and the water for irrigation is often extracted from rivers which can depend on climatic conditions far from the point of extraction. Hence, impacts of climate change on crop productivity often need to take account of remote as well as local climate changes. Indirect impacts via sea-level rise, storms and diseases have also not been quantified. Perhaps most seriously, there is high uncertainty in the extent to which the direct effects of CO_2 rise on plant physiology will

interact with climate change in affecting productivity. Therefore, at present, the aggregate impacts of climate change on large-scale agricultural productivity cannot be reliably quantified (Gornall et al., 2010). This section summarises findings from a range of post IPCC AR4 assessments to inform and contextualise the analysis performed by AVOID programme for this project. The results from the AVOID work are discussed in the next section.

Sugar cane, soybeans and maize are among the most important food crops in Brazil according to FAO data (Table 1). Other important crops are rice, cassava, coffee and oranges.

Harvested area (ha)		Quantity (Metric ton)		Value ($1000)	
Soybeans	21200000	Sugar cane	645000000	Sugar cane	13200000
Maize	14400000	Soy beans	59800000	Soybeans	12300000
Sugar cane	8140000	Maize	58900000	Oranges	3250000
Beans, dry	3780000	Cassava	26700000	Rice, paddy	2520000
Rice, paddy	2850000	Oranges	18500000	Coffee, green	2280000
Wheat	2360000	Rice, paddy	12000000	Cotton lint	1950000
Coffee, green	2220000	Bananas	6990000	Maize	1920000

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

A number of impact model studies looking at crop yield which include results for some of the main crops in Brazil have been conducted. They apply a variety of methodological approaches, including using different climate model inputs and treatment of other factors that might affect yield, such as impact of increased CO_2 in the atmosphere on plant growth and adaption of agricultural practises to changing climate conditions. These different models, assumptions and emissions scenarios mean that there are a range of crop yield projections for Brazil.

Important knowledge gaps, which are applicable to Brazil as well as at the global-scale, include; the quantification of yield increases due to CO_2 fertilisation and yield reductions due to ozone damage (Ainsworth and McGrath, 2010, Iglesias et al., 2009), and the extent crop diseases could affect crop yields with climate change (Luck et al., 2011).

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 Brazil were also calculated. Lobell et al. (2011) divided the climate-induced yield trend by the overall yield trend for 1980–2008, to produce a simple metric of the importance of climate relative to all other factors. The ratio produced indicates the influence of climate on the productivity trend overall. So for example a value of –0.1 represents a 10% reduction in yield gain due to climate change, compared to the increase that could have been achieved without climate change, but with technology and other gains. This can also be expressed as 10 years of climate trend being equivalent to the loss of roughly 1 year of technology gains. For Brazil, negative impacts were estimated for maize yield and even more so for wheat yield, relative to what could have been achieved without the climate trends (see Table 2).

Crop	Trend
Maize	-0.2 to -0.1
Rice	0.0 to 0.1
Wheat	-0.4 to -0.3
Soybean	-0.1 to 0.0

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

Climate change studies

Global studies on changes in crop yield due to climate change covered in this report are derived mainly from applying Global Climate Model (GCM) output to crop models. The results for Brazil are presented here.

Included in this report are recent studies have applied climate projections from 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 Brazil (Arnell et al., 2010b, Arnell et al., 2010a, Iglesias and Rosenzweig, 2009, Lobell et al., 2008). The process of CO_2 fertilisation of some crops is usually included in most climate impact studies of yields. However, other

gases can influence crop yield and are not always included in impacts models. An example of this is ozone (O_3) and so a study which attempts to quantify the potential impact on crop yield of changes in ozone in the atmosphere is also included (Avnery et al., 2011). In addition to these studies, the AVOID programme analysed the patterns of climate change for 21 GCMs, to establish an index of 'climate suitability' of agricultural land. Climate suitability is not directly equivalent to crop yields, but is a means of looking at a standard metric across all the countries 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, and rain-fed and irrigated production. The study also applied a quantitative estimation of physiological CO_2 effects on crop yields and considered the affect of adaptation by assessing the country or regional potential for reaching optimal crop yield. The results from the study are presented in Table 3 and Table 4. Wheat yield was projected to be below baseline (1970-2000) levels until 2050 and was projected to increase between 2050 and 2080. Rice yield deficits were projected until 2050 but rice yield was simulated to increase from 2050 onward resulting in a rice yield gain relative to baseline level by 2080. Respectively five and four emission scenarios projected maize yield deficits by 2020 and 2050. Beyond then, maize yield was projected to increase rapidly resulting in a gain relative to baseline levels by 2080.

Scenario	Year	Wheat	Rice	Maize
A1F1	2020	-3.43	-5.43	0.23
		0.81	-1.81	1.43
2050	2080	11.06	10.06	6.83
	2020	-3.14	-5.14	-0.18
	2050	-3.98	-5.98	-0.14
A2a	2080	7.51	6.51	5.49
	2020	-4.92	-6.92	-1.33
	2050	-2.26	-4.26	0.51
A2b	2080	7.52	6.52	4.01
	2020	-3.26	-5.26	0.27
	2050	-2.74	-4.74	0.20
A2c	2080	10.13	10.47	6.36
	2020	-6.88	-8.88	-2.37
	2050	-5.85	-6.85	-1.84
B1a	2080	-4.43	-7.43	-1.11
	2020	-5.02	-7.02	-2.23
	2050	-6.19	-7.19	-1.50
B2a	2080	-1.50	-2.50	1.68
	2020	-3.21	-5.21	-1.13
	2050	-4.62	-5.62	-0.92
B2b	2080	-2.32	-3.32	1.18

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

	Wheat		Rice		Maize	
	Up	**Down**	**Up**	**Down**	**Up**	**Down**
Baseline to 2020	0	7	0	7	2	5
Baseline to 2050	0	7	0	7	3	4
Baseline to 2080	4	3	4	3	6	1
2020 to 2050	4	3	4	3	6	1
2050 to 2080	7	0	6	1	7	0

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

Lobell et al. (2008) conducted an analysis of climate risks for the major crops in 12 food-insecure regions to identify adaptation priorities. Statistical crop models were used in combination with climate projections for 2030 from 20 GCMs that have contributed to the World Climate Research Programme's Coupled Model Intercomparison Project phase 3

(CMIP3). The results from the study for Brazil are presented in Figure 2. By 2030, negative climate change impacts on crop yield were projected for soybean, cassava, maize, rice and wheat, but not sugarcane in Brazil.
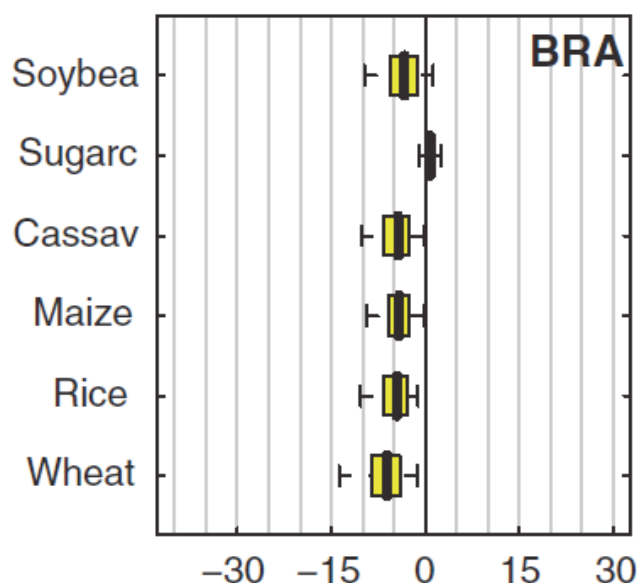

Figure 2. *Probabilistic projections of production impacts in 2030 from climate change (expressed as a percentage of 1998 to 2002 average yields) for Brazil. Red, orange, and yellow indicate a Hunger Importance Ranking of 1 to 30 (more important), 31 to 60 (important), and 61 to 94 (less important), respectively. All the results for Brazil are yellow (less important). Dashed lines extend from 5th to 95th percentile of projections, boxes extend from 25th to 75th percentile, and the middle vertical line within each box indicates the median projection. Figure is from Lobell et al. (2008).*

Arnell et al. (2010a) applied 5 GCMs to assess the effects of climate scenarios on crop productivity. Specifically, the crop simulation model GLAM-maize was used to simulate the effect of climate change on maize productivity. The model includes a simulation of the affect of CO_2 fertilisation on crop yield. For Brazil, a loss of between approximately 40% and 52% of yield by 2050 was projected under an A1B emissions scenario relative to the baseline (1961-1990) in the absence of adaptation and mitigation strategies. Implementing a climate change mitigation strategy that reduced emissions from 2016 onwards at a rate of 5%/year reduced the negative impact by approximately 15% and 27% in 2050 and 2100 respectively.

Arnell et al. (2010b) applied the same crops model used by Arnell et al. (2010a) to assess the potential impacts on water and food security avoided by a set of defined climate policies. One of the metrics of impact included was the regional change of yield. For wheat, only changes at the global-scale were reported but for soybean projected yield changes at the region or country level were published as bar charts. The results showed all models

projected a decrease in yield throughout the 21st century under the SRES A1B emission scenario. When the mitigation scenarios of 2-5% reduction in CO_2 per year were applied to two of the models the decrease in yield was reduced by between 3-13% depending on the model and the mitigation scenario, demonstrated the potential for mitigation action to reduce the impact of climate change. The detailed results for Brazil are displayed in Table 5.

	2050	2085	2100
No mitigation	-35 to -25	-53 to -37	-58 to -40
2050 IPSL	3 to 13	n/a	n/a
2050 CGCM31	3 to 13	n/a	n/a

Table 5. *Range of yield change (%) at three different times in the future as estimated by five GCMs under the SRES A1B emission scenario (Row 1; values show range across the 5 GCMs) and avoided impact on regional soybean production (expressed as % of A1B impact) by 2050 for several mitigation scenarios as simulated with two GCMs (Row 2 and 3). The mitigations scenarios included reductions in emissions from 2016 or 2030 onwards, at rates of 2-5%/year. Data is from Arnell et al. (2010b).*

Other recent studies have assessed the impact of climate change on a global-scale and include impact estimates for South America as a whole (Fischer, 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 Brazil.

Fischer (2009) projected global 'production potential' changes for 2050 using the GAEZ (Global Agro-Ecological Zones) crops model with climate change scenarios from the HadCM3 and CSIRO GCMs respectively, under SRES A2 emissions. The impact of future climate on crop yields of rain-fed cereals are presented in Table 6 (relative to yield realised under current climate) for South America.

	CO$_2$ fert.	2020s		2050s		2080s	
		CSIRO	HADCM3	CSIRO	HADCM3	CSIRO	HADCM3
Rain-fed wheat	Yes	-12	-33	-19	-54	-30	-76
	No	-14	n/a	-23	n/a	-36	n/a
Rain-fed maize	Yes	2	6	7	9	13	-1
	No	0	n/a	-1	n/a	-1	n/a
Rain-fed cereals	Yes	n/a	1	n/a	1	n/a	-1
	No	n/a	n/a	n/a	n/a	n/a	n/a
Rain-fed sorghum	Yes	8	n/a	10	n/a	15	n/a
	No	6	n/a	6	n/a	10	n/a

Table 6. *Impacts of climate change on the production potential of rain-fed cereals in current cultivated land (% change with respect to yield realised under current climate), with two GCMs and with and without CO$_2$ fertilisation ("CO$_2$ fert.") under SRES A2 emissions. Data is from Fischer (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 South America, which includes Brazil, are displayed in Table 7.

Wheat	Potato	Cassava	Soybean	Rice	Sweet	Maize	Green
0.24	0.84	6.59	-0.42	3.65	-0.58	19.39	20.79

Table 7. *Average change in yield (%), during 1990s-2090s in South 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 (O$_3$) surface exposure on crop yield losses for soybeans, maize and wheat under the SRES A2 and B1 scenarios respectively. Two metrics of ozone exposure were investigated; seasonal daytime (08:00-19:59) mean O$_3$ (M12) and accumulated O$_3$ above a threshold of 40 ppbv (AOT40). The results for Brazil are presented in Table 8.

	A2		B1	
	M12	**AOT40**	**M12**	**AOT40**
Soybeans	10-15	4-6	10-15	2-4
Maize	4-6	0-2	2-4	0-2
Wheat	6-8	30-45	4-6	20-25

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

National-scale or sub-national scale assessments

Climate change studies

A study by Costa et al. (2009) investigated maize and bean yields for the southeastern state Minas Gerais using the HadCM3 GCM and applying sensitivity experiments. The authors explicitly differentiated between non-CO_2 effects, CO_2-effects and technological advancements (through genetic improvements) on projected yield changes. The results suggested that increased temperatures lead to reductions in the potential productivity of maize and beans for the years 2050 and 2080 by up to 30%. However, for beans this negative impact was offset by the highly efficient CO_2 fertilisation effect which is expected to increase bean productivity as compared to present day conditions. For maize on the other hand the CO_2 fertilization feedback was much weaker and did not cancel out the thermal effect. The negative effects on maize yield associated with warmer climate conditions disappeared after including technological advancements as the third forcing (see Figure 3).
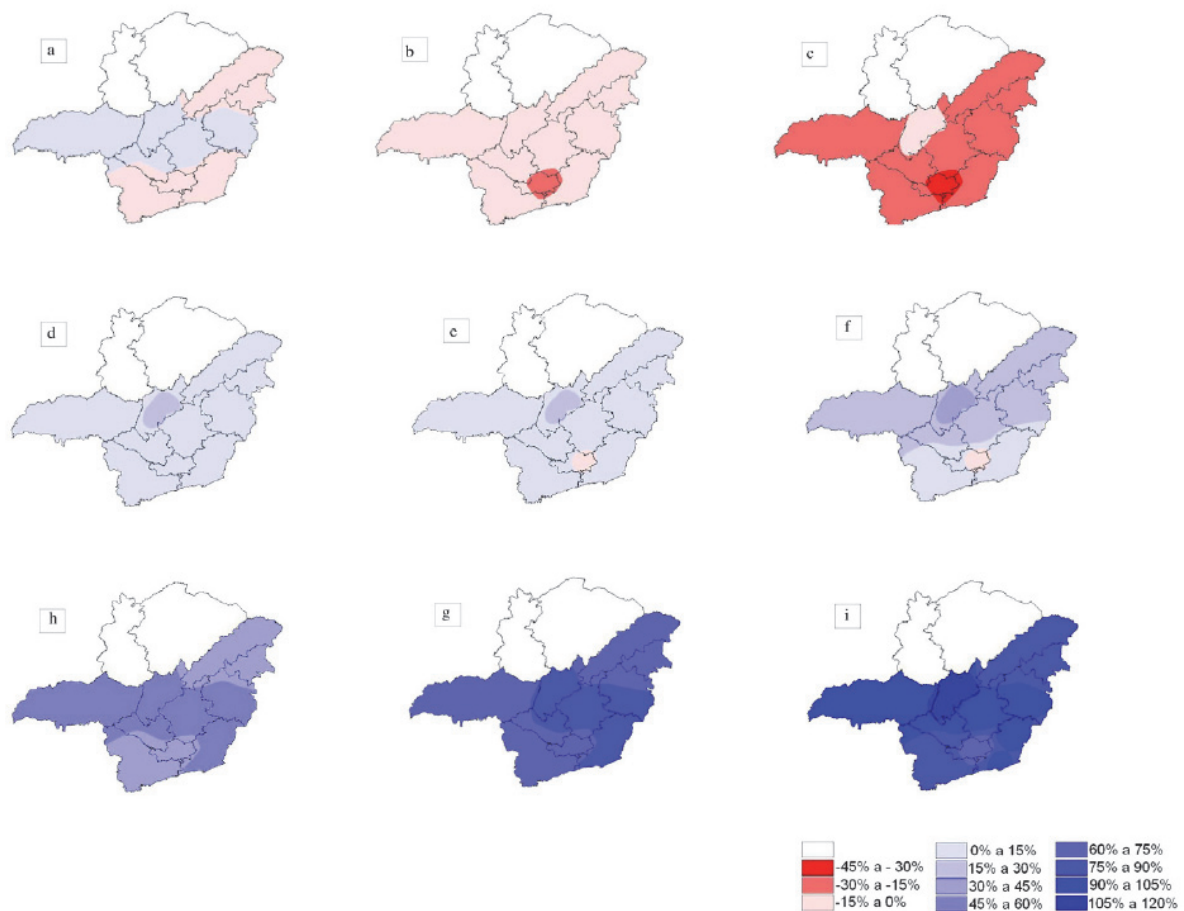
Figure 3. *Projected potential productivity for maize in Brazil, for changes in temperature alone in (a) 2020, (b) 2050 and (c) 2080; for changes in the joint effect of CO_2 fertilisation and temperature in (d) 2020, (e) 2050, (f) 2080; and the potential productivity as a result of all forcing agents (temperature, CO_2 and technological advancements) in (g) 2020, (h) 2050, (i) 2080. Figure is from Costa et al. (2009).*

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 conditions of circa 2000. The key features of the climate for the crop suitability index are temperature and the availability of water for plants. Changes in these were derived from climate model projections of future changes in temperature and precipitation, with some further calculations then being used to estimate actual and potential evapotranspiration as an indicator of water availability. It should be noted that changes in atmospheric CO_2 concentrations can decrease evapotranspiration by increasing the efficiency of water use by plants (Ramankutty et al., 2002), but that aspect of the index was not included in the analysis here. Increased CO_2 can also increase photosynthesis and improve yield to a small extent, but again these effects are not included. Exclusion of these effects may lead to an overestimate of decreases in suitability.

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

Results

Crop suitability was estimated under the pattern of climate change from 21 GCMs with two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). The application of 21 GCMs is an attempt to

quantify the uncertainty due to climate modelling, although it is acknowledged that only one crop suitability impacts model is applied. Simulations were performed for the years 2030, 2050, 2080 and 2100. The results for Brazil are presented in Figure 4.

Under all the climate projections, some existing cropland areas in Brazil become less suitable for cultivation while other existing cropland areas become more suitable. The areas of increased and decreased suitability differ considerably according to the climate model used, but some common trends can be discerned. The areas experiencing declining suitability become larger through the 21st century in both the A1B and mitigation scenario, but the increase is larger in A1B. The difference between model projections of this quantity also becomes larger over time, and also becomes larger under A1B than the mitigation scenario.

However, the range of areas projected to experience increased suitability is small at only 1-2% in most models, with only three models projecting up to 12% of current Brazilian croplands become more suitable. This is similar in both scenarios and does not change significantly over time in either scenario. This may be partly because only current croplands are considered – although over a wider area there may be differences in suitability between different scenarios and different times, this would not appear in the current analysis if such changes occurred outside current cropland areas.

In 2030, the mean and spread of projected areas of declining suitability is the same both scenarios, with the mean being 18% and the spread being 0 to 27%. Over the 21st century, the projected area of declining suitability becomes larger in both scenarios, and this increase is greater in A1B than the mitigation scenario. In both scenarios, the difference between model projections also becomes larger over time.

So, for Brazil, the areas of current croplands becoming less suitable for cultivation are projected to be smaller under the mitigation scenario than the A1B scenario, and in both scenarios the area of declining suitability is larger than that of increasing suitability (which remains small over the 21st century in both scenarios).
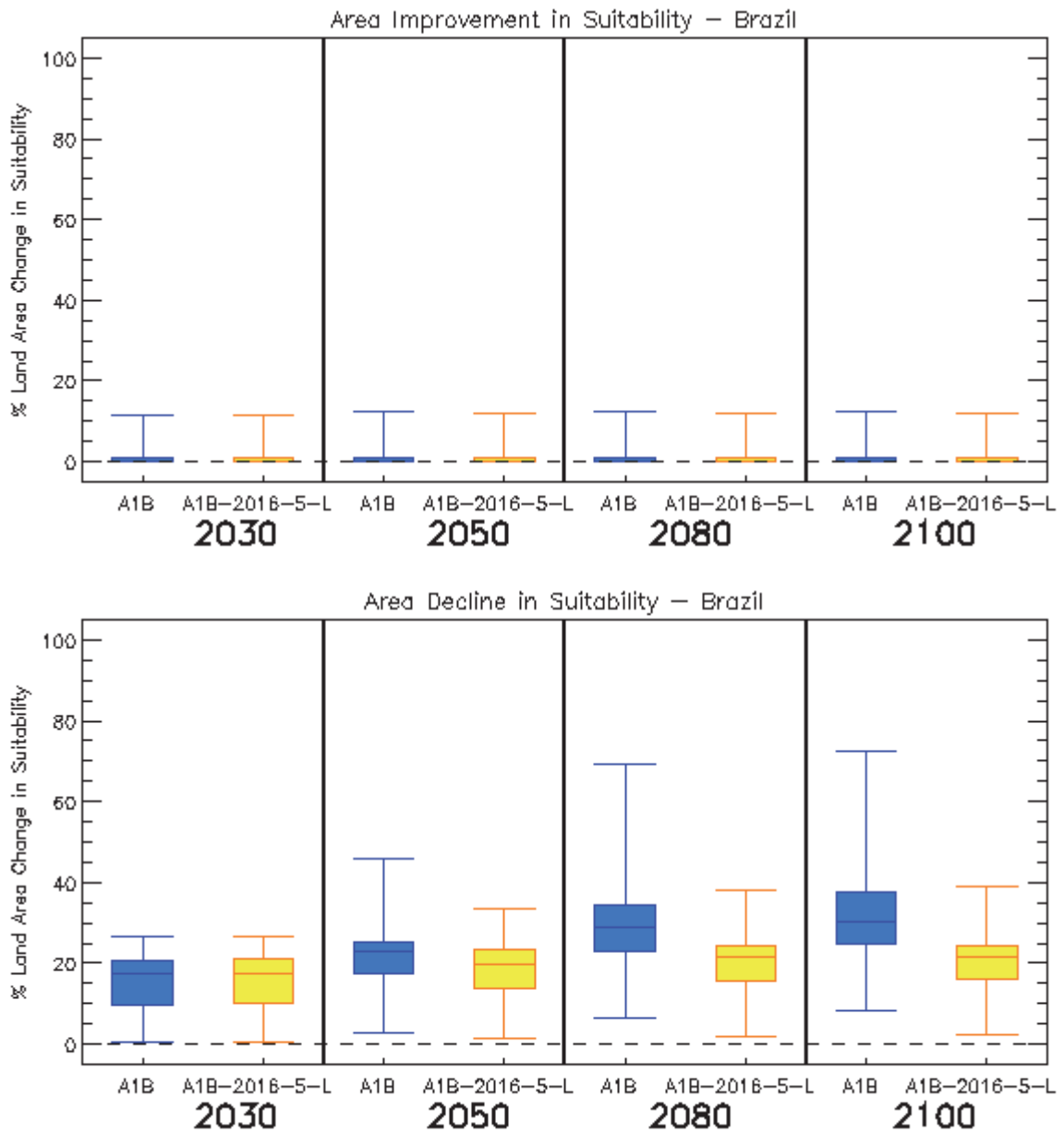
Figure 4. *Box and whisker plots for the impact of climate change on increased crop suitability (top panel) and decreased crop suitability (bottom panel) for Brazil, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Food security

Headline

The majority of studies suggest that Brazil could remain food-secure with climate change, although, recent work by the AVOID programme demonstrates that adaptive measures could be crucial towards maintaining food security in Brazil. Child undernourishment could decrease in the future and kilocalorie availability could increase, although these improvements may be mediated by climate change. One study suggests that 10-year averaged maximum fish catch potential from 2005 to 2055 could decline by around 7-8%, however.

Supporting literature

Introduction

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

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

Assessments that include a global or regional perspective

Climate change studies

Brazil is not a country of high concern in terms of food security, particularly in a global context. According to FAO statistics Brazil has a very low level of undernourishment, (between 5% and 9% of the population). Moreover, a number of global studies suggest that

Brazil may not suffer major food security issues under climate change scenarios, if considering land-based agriculture. However, the situation is less optimistic if marine based fisheries are considered.

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) conclude that Brazil is not likely to face severe food insecurity in the next 20 years

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

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

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

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

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

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

Similar to the study presented by Wu et al. (2011), there is no major treatment of modelling uncertainty; simulations were generated by only the LPJml dynamic global vegetation and water balance model Gerten et al. (2004) with population growth and climate change under the SRES A2 emission scenario. Falkenmark et al. (2009) summarise the impacts of future improvements (or lack thereof) in water productivity for each country across the globe and

show that this generates either a deficit or a surplus of water in relation to food water requirements in each country. These can be met either by trade or by horizontal expansion (by converting other terrestrial ecosystems to crop land). The study estimated that in 2050 around one third of the world's population could 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 Brazil could be a food exporting country in 2050, suggesting that food security may not be a major issue.

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. Estimates for both indicators of food security from 2010 to 2050, for Brazil, are presented in Table 9 and Table 10. Figure 5 displays the effect of climate change, calculated by comparing the 'perfect mitigation' scenario with each baseline, optimistic and pessimistic scenario. The results show that for most scenarios, the number of children malnourished in Brazil declines from 2010 to 2050 and that the average daily kilocalorie availability increases slightly. However, considering the impact of climate change alone (Figure 5), it is clear that by 2050, climate change is attributable for around up to a 7% decline in kilocalorie availability and up to a 10% increase in child malnourishment. Figure 6 and Figure 7 show how the changes projected for Brazil compare with the projections for the rest of the globe (IFPRI, 2010).

Scenario	2010	2050
Baseline CSI A1B	2881	3000
Baseline CSI B1	2885	3020
Baseline MIR A1B	2869	2946
Baseline MIR B1	2877	2984
Baseline Perfect Mitigation	2915	3155
Pessimistic CSI A1B	2879	2883
Pessimistic CSI B1	2883	2903
Pessimistic MIR A1B	2867	2828
Pessimistic MIR B1	2872	2855
Pessimistic Perfect Mitigation	2913	3034
Optimistic CSI A1B	2841	3291
Optimistic CSI B1	2844	3307
Optimistic MIR A1B	2828	3226
Optimistic MIR B1	2833	3253
Optimistic Perfect Mitigation	2874	3452

Table 9. Average daily kilocalorie availability simulated under different climate and socioeconomic scenarios, for Brazil (IFPRI, 2010).

Scenario	2010	2050
Baseline CSI A1B	3.69	2.63
Baseline CSI B1	3.68	2.61
Baseline MIR A1B	3.71	2.69
Baseline MIR B1	3.69	2.65
Baseline Perfect Mitigation	3.64	2.47
Pessimistic CSI A1B	3.69	3.22
Pessimistic CSI B1	3.69	3.19
Pessimistic MIR A1B	3.71	3.29
Pessimistic MIR B1	3.7	3.25
Pessimistic Perfect Mitigation	3.64	3.03
Optimistic CSI A1B	3.75	2
Optimistic CSI B1	3.75	1.99
Optimistic MIR A1B	3.77	2.06
Optimistic MIR B1	3.76	2.03
Optimistic Perfect Mitigation	3.7	1.87

Table 10. Number of malnourished children (aged 0-5; millions) simulated under different climate and socioeconomic scenarios, for Brazil (IFPRI, 2010).
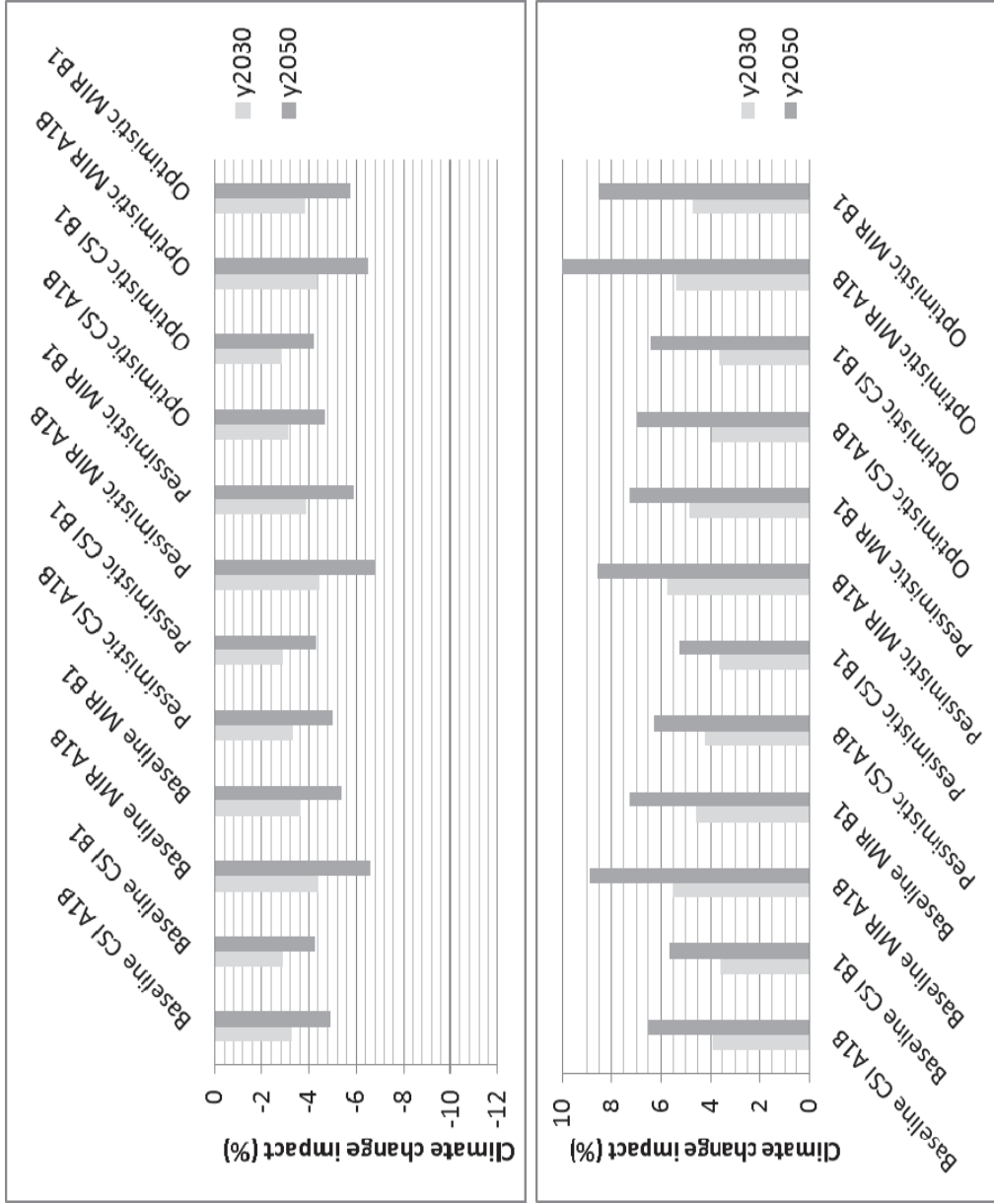
Figure 5. *The impact of climate change on average daily kilocalorie availability (top panel) and number of malnourished children (bottom) for Brazil (IFPRI, 2010)*
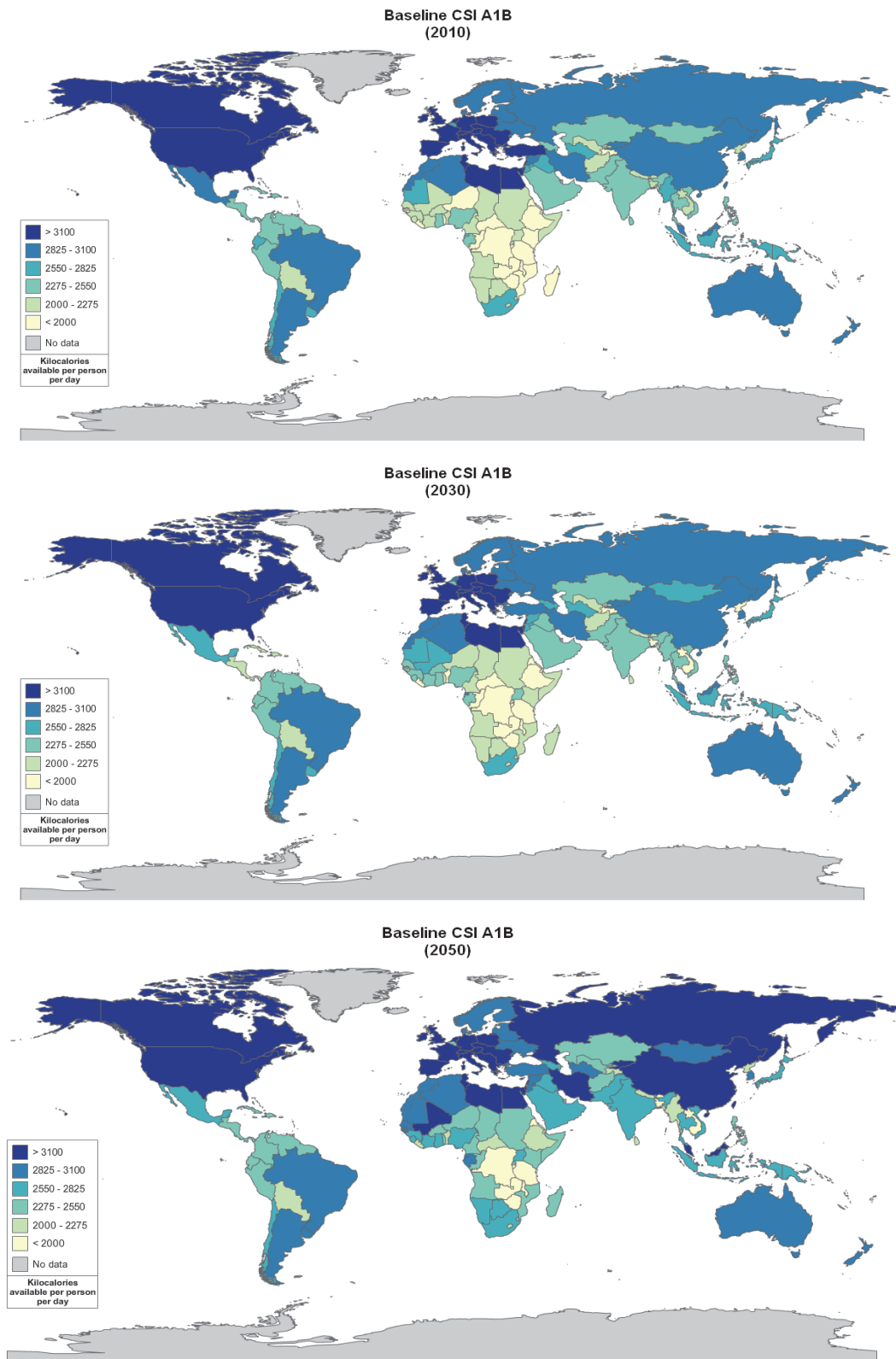
Figure 6. *Average daily kilocalorie availability simulated by the CSIRO GCM (CSI) under an A1B emissions scenario and the baseline socioeconomic scenario, for 2010 (top panel), 2030 (middle panel) and 2050 (bottom panel). The figure is from IFPRI (IFPRI, 2010). The changes show the combination of both climate change and socio-economic changes.*
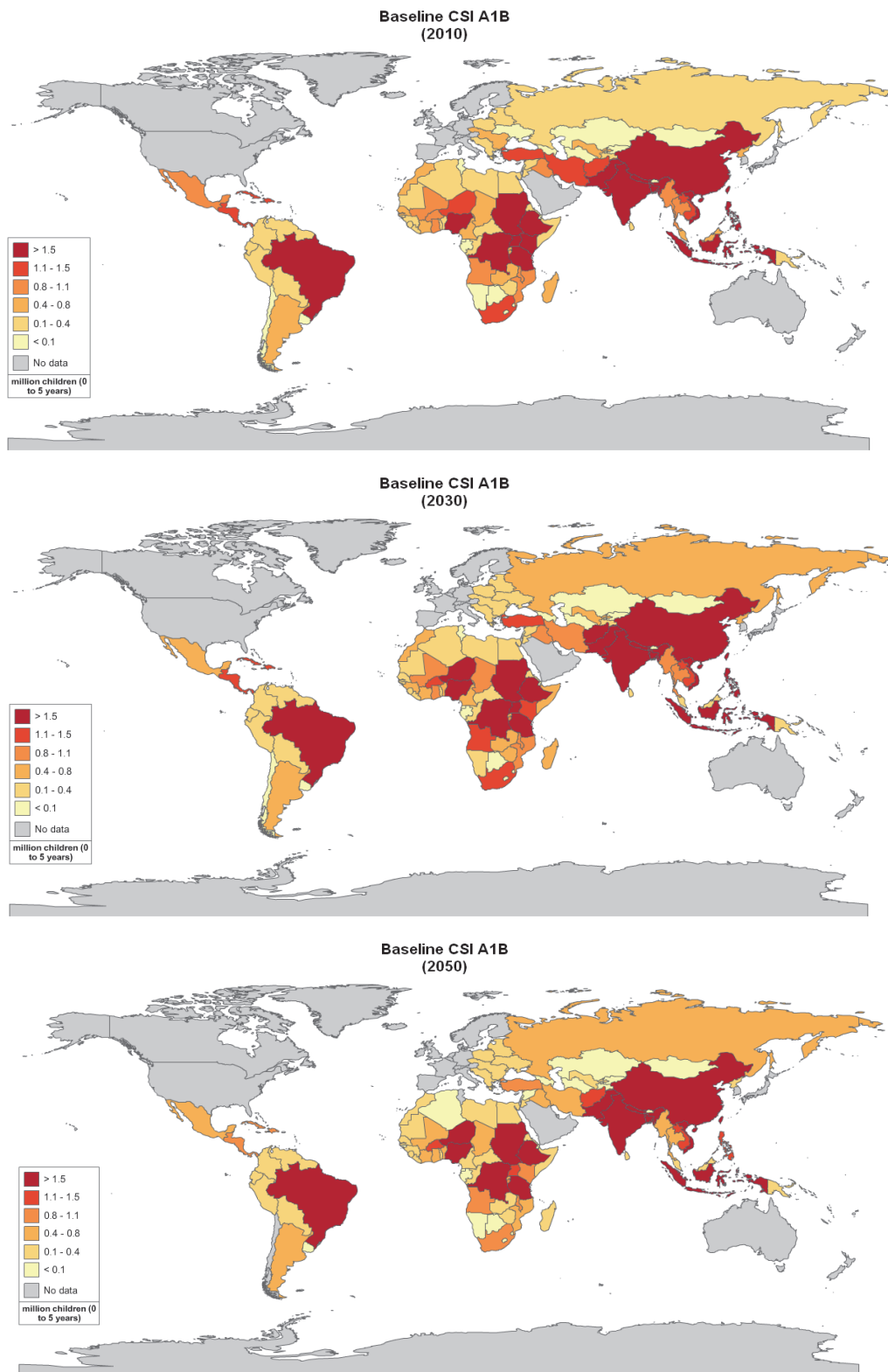
Figure 7. Number of malnourished children (aged 0-5; millions) simulated by the CSIRO GCM (CSI) under an A1B emissions scenario and the baseline socioeconomic scenario, for 2010 (top panel), 2030 (middle panel) and 2050 (bottom panel). The figure is from IFPRI (IFPRI, 2010). The changes show the combination of both climate change and socio-economic changes.

Lobell et al. (2008) explored climate risks for crops in 12 food-insecure regions, based on statistical crop models and climate projections for 2030 from 20 GCMs. The study found that, based upon a number of probabilistic projections for various crops, Brazil is unlikely to suffer food insecurity because although crop yields do decline under climate change, the crops grown in Brazil present a relatively lower "Hunger Importance Rating" (HIR) than for other regions.

The results of Arnell et al. (2010b) are in contrast to the generally optimistic estimates presented elsewhere for Brazil (Allison et al., 2009, Falkenmark et al., 2009, Lobell et al., 2008, Nelson et al., 2010). Arnell et al. (2010b) considered the impacts of global climate change and mitigation policy on food security for eleven countries. The study applied climate change patterns from the HadCM3 GCM and explored food security under two emissions scenarios; a business as usual scenario (SRES A1B) and four mitigations scenarios where emissions peak in 2030 and subsequently reduce at 2% per year to a high emissions floor (referred to as 2030-2-H) or 5% per year to a low emissions floor (2030-5-L), or where they peak in 2016 and subsequently reduce at 2% per year to a high emissions floor (referred to as 2016-2-H) or 5% per year to a low emissions floor (2016-5-L). The study also considered a series of structural adjustments that could be made in the future to adapt to food security issues, including that 1) if there is a shortfall of any per-capita food availability due to crop yield and/or population changes, then original (baseline) food amounts are made up by reducing or removing export amounts; and 2) if, after the above adjustments, there is still a shortfall, then the amount of crops going to animal feed is reduced or removed to try to make up to the original (baseline) food amounts. The model simulations presented by Arnell et al. (2010b) characterise the numbers of people *exposed to undernourishment* in the absence of increased crop production and imports, not actual numbers of undernourished people. The results are presented in Figure 8. Arnell et al. (2010b) estimated that exposure to undernourishment in Brazil increases until 2080 and then begins to decline. Although crop yields are decreased under all climate scenarios, the principle initial cause of the large increase in undernourishment is the large (28%) increase in population projected over the period 2000-2050. After this point population gradually begins to decline, beginning to offset the impact of decreasing crop yields. Undernourishment is particularly pronounced under the A1B scenario in which crop production is expected to fall by 50%. If no structural adjustments are applied, all climate scenarios considered projected over 95% of the population to be exposed to undernourishment by 2100 under the A1B scenario (mitigation

had little effect on food security relative to the A1B scenario). Structural adjustments reduce these figures to 23% under the A1B scenario.
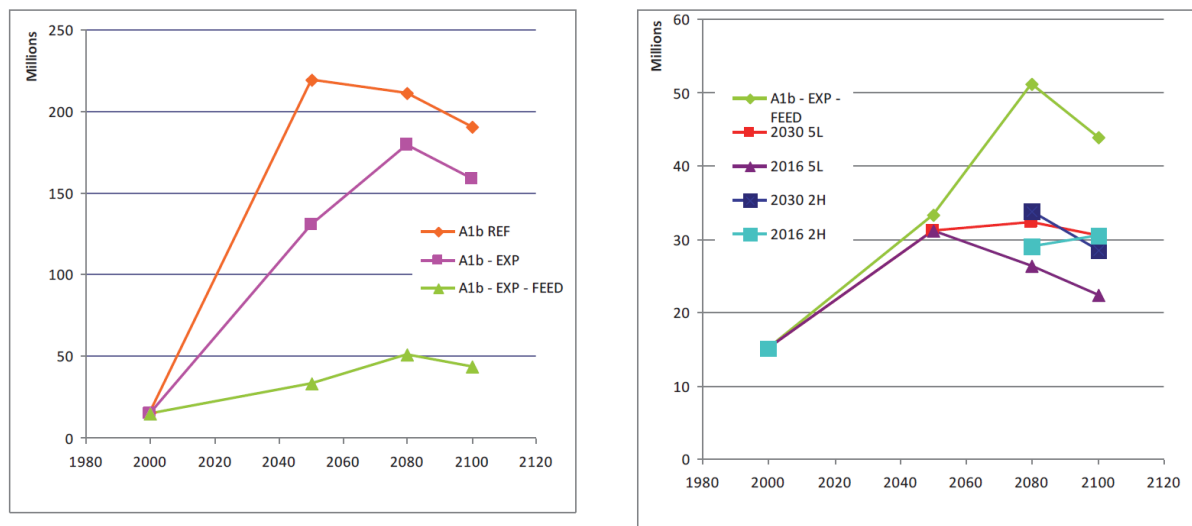

Figure 8. Total projected population exposed to undernourishment in Brazil. The left panel shows total exposure under the A1B emissions scenario ("A1b REF"), plus the A1B scenario with exports reduced or removed ("A1b–EXP") and the A1B scenario with exports removed and allocation to feed reduced or removed ("A1b–EXP–FEED"). The right panel shows the total exposure under the A1b–EXP–FEED and three mitigation scenarios. The figure is from Arnell et al. (2010b).

It is important to note that up until recently, projections of climate change impacts on global food supply have tended to focus solely on production from terrestrial biomes, with the large contribution of animal protein from marine capture fisheries often ignored. However, recent studies have addressed this knowledge gap (Allison et al. 2009, Cheung et al., 2010). In addition to the direct affects of climate change, changes in the acidity of the oceans, due to increases in CO_2 levels, could also have an impact of marine ecosystems, which could also affect fish stocks. However, this relationship is complex and not well understood, and studies today have not been able to begin to quantify the impact of ocean acidification on fish stocks. Allison et al. (2009) present a global analysis that compares the vulnerability of 132 national economies to potential climate change impacts on their capture fisheries. The study considered a country's vulnerability to be a function of the combined effect of projected climate change, the relative importance of fisheries to national economies and diets, and the national societal capacity to adapt to potential impacts and opportunities. Climate change projections from a single GCM under two emissions scenarios (SRES A1FI and B2) were used in the analysis. Allison et al. (2009) concluded that the national economy of Brazil presented a moderate vulnerability to climate change impacts on fisheries by 2050. In

contrast, countries in Central and Western Africa (e.g. Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in north-western South America, and four tropical Asian countries (Bangladesh, Cambodia, Pakistan, and Yemen) were identified as most vulnerable (see Figure 9). 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.
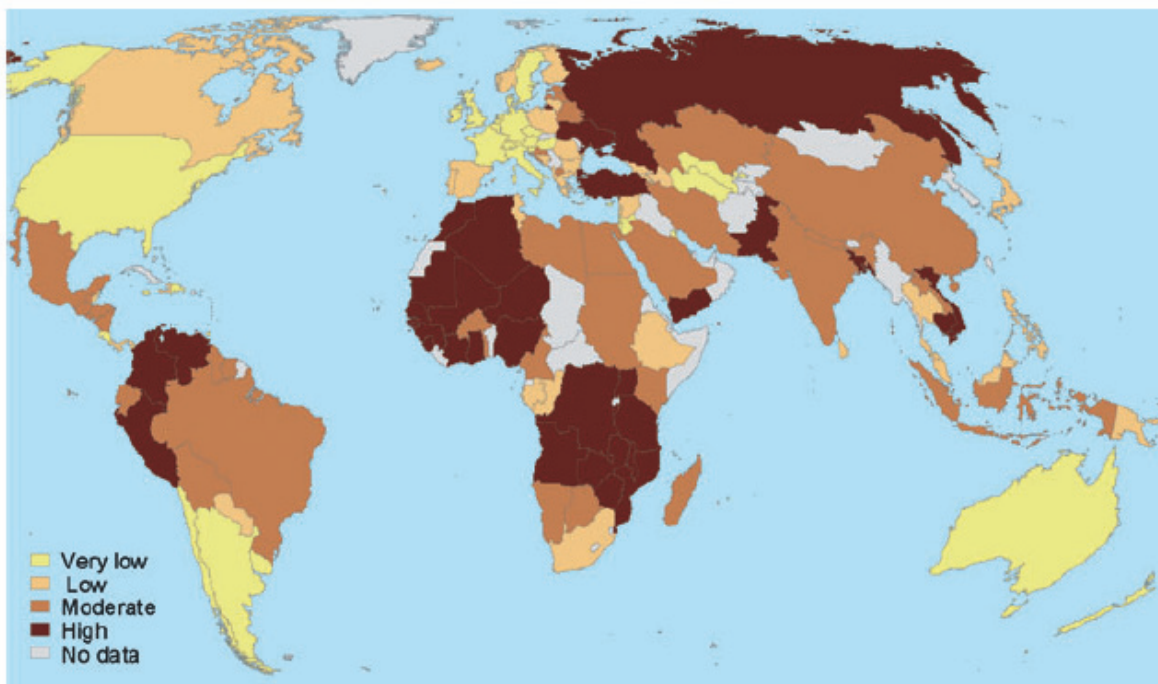

Figure 9. *Vulnerability of national economies to potential climate change impacts on fisheries under SRES B2 by 2050 (Allison et al., 2009). Colours represent quartiles with dark brown for the upper quartile (highest index value), yellow for the lowest quartile, and grey where no data were available.*

Cheung et al. (2010) also consider marine capture fisheries at the global scale for several countries. The study projected changes in global catch potential for 1066 species of exploited marine fish and invertebrates from 2005 to 2055 under climate change scenarios. Cheung et al. (2010) found that climate change may lead to large-scale redistribution of global catch potential, with an average of 30–70% increase in high-latitude regions and a decline of up to 40% in the tropics. The simulations were based 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 Brazil, the projected change in the 10-year averaged maximum catch potential from 2005 to 2055 was around a 7% reduction under A1b and an 8% reduction under the stabilisation scenario, based upon 60 exploited species included in the analysis. Figure 10 demonstrates how this compares with projected changes for other countries across the globe. The limitations of applying a single GCM have been noted previously.

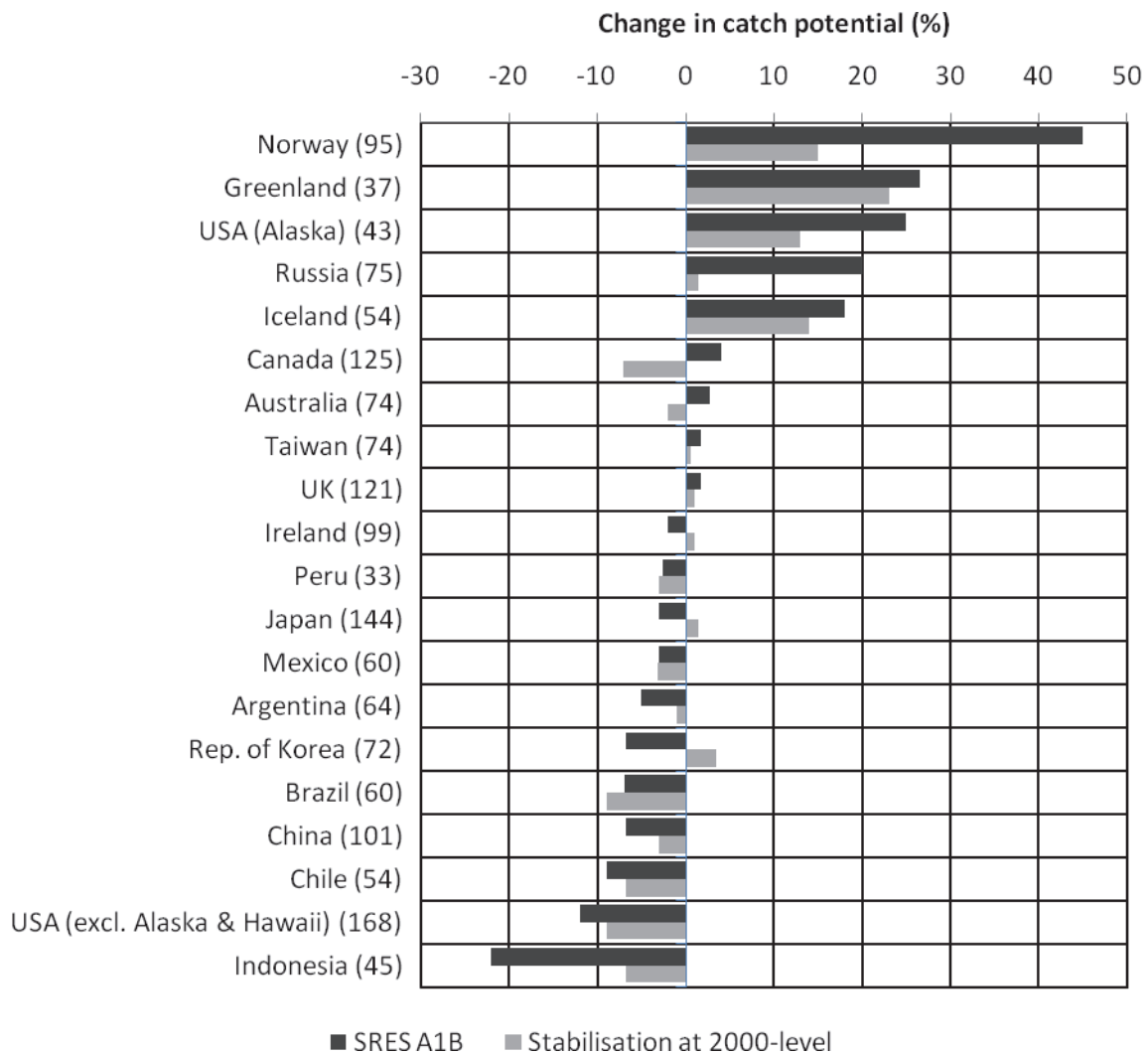
Figure 10. *Projected changes in the 10-year averaged maximum catch potential from 2005 to 2055. The numbers in parentheses represent the numbers of exploited species included in the analysis. Adapted from Cheung et al. (2010).*

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

Projections of drought and water stress for Brazil vary across studies due to the application of different climate models and indicators of water stress. Some studies suggest large increases in water stress, particularly along the south-eastern coast of Brazil, whereas other studies suggest no change in water stress. Moreover, future precipitation in Brazil could be closely associated with changes in ENSO, projections of which are highly uncertain. These uncertainties preclude a robust and definitive conclusion on the impact of climate change on water stress and drought in Brazil. Recent research on the impact of climate change on tropical forests has focused on the Amazon, with mixed information regarding the possibility of forest dieback, and a few new studies on timescales of change, reversibility and the influence of other forms of anthropogenic interference. There is consensus that temperature is not the only important metric for impacts here.

Results from the AVOID programme for Brazil show that exposure to increased or decreased water stress with climate change is not simulated with the majority of GCMs.

Supporting literature

Introduction

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

A number of impact model studies looking at water stress and drought for the present (recent past) and future (climate change scenario) have been conducted. These studies are conducted at global or national scale and include the application of global water 'availability' or 'stress' models driven by one or more climate change scenario from one or more GCM.

The approaches variously include other factors and assumptions that might affect water availability, such as the impact of changing demographics and infrastructure investment, etc. These different models (hydrological and climate), assumptions and emissions scenarios mean that there are a range of water stress projections for Brazil. 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 Brazil 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 (Vorosmarty et al., 2010).

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

Figure 11 presents the results of this analysis for Brazil. The simulated HWS threat is complex. High levels of threat to water security are found extensively in the country, especially in the east and south. Much of this is due to high population pressure generating land degradation, water abstraction and pollution. Parts of the Amazon basin also present low to moderate HWS threat.
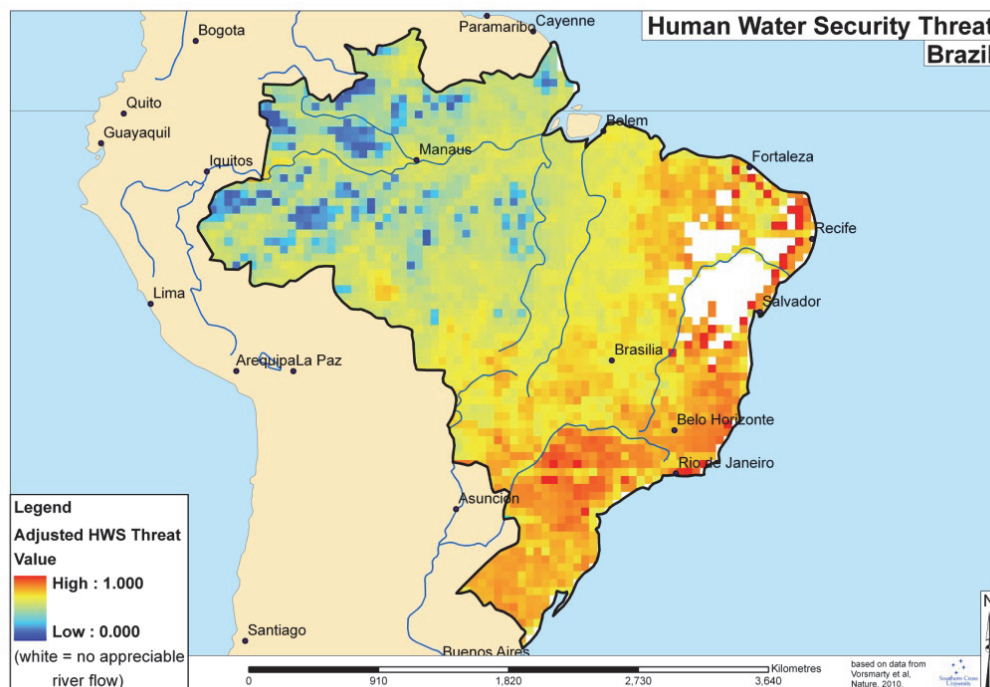

Figure 11. *Present Adjusted Human Water Security Threat (HWS) for Brazil, calculated following the method described by Vörösmarty et al. (2010).*

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 12. The results show that for the basins considered, that all of Brazil presents a low WSI value.
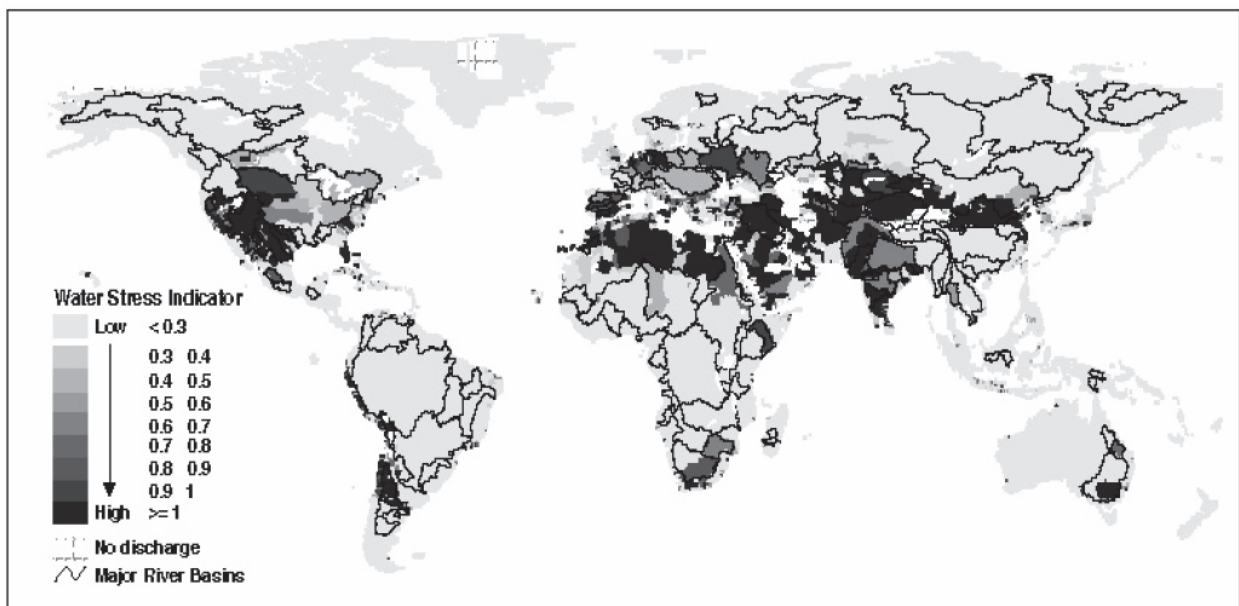

Figure 12. A map of the major river basins across the globe and the water stress indicator (WSI) for the 1961-1990 time horizon. The figure is from Smakhtin et al. (2004).

Climate change studies

The IPCC AR4 found that the CMIP3 multi-model dataset ensemble mean projection for annual precipitation, presented a decrease over large parts of northern Brazil and a decrease in summer over the Amazon basin. One version of the HadCM3 GCM showed the

largest reduction in Amazon rainfall of all the CMIP3 multi-model dataset members, a reduction of 21% under the A1B emissions scenario.

Rockstrom et al.(2009) applied the LPJml vegetation and water balance model (Gerten et al. 2004) to assess green-blue water (irrigation and infiltrated water) availability and requirements. The authors applied observed climate data from the CRU TS2.1 gridded dataset for a present-day simulation, and climate change projections from the HadCM2 GCM under the SRES A2 scenario to represent the climate change scenario for the year 2050. The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The simulations presented by Rockstrom et al.(2009) should not be considered as definitive, however, because the study only applied one climate model, which means climate modelling uncertainty was overlooked. The results from the two simulations are presented in Figure 13. 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 Brazil, Rockstrom et al. (2009) found that blue-green water availability was well above the 1,300m^3/capita/year threshold in present and under climate change. This is largely supportive of the results presented by Smakhtin et al. (2004) for Brazil.
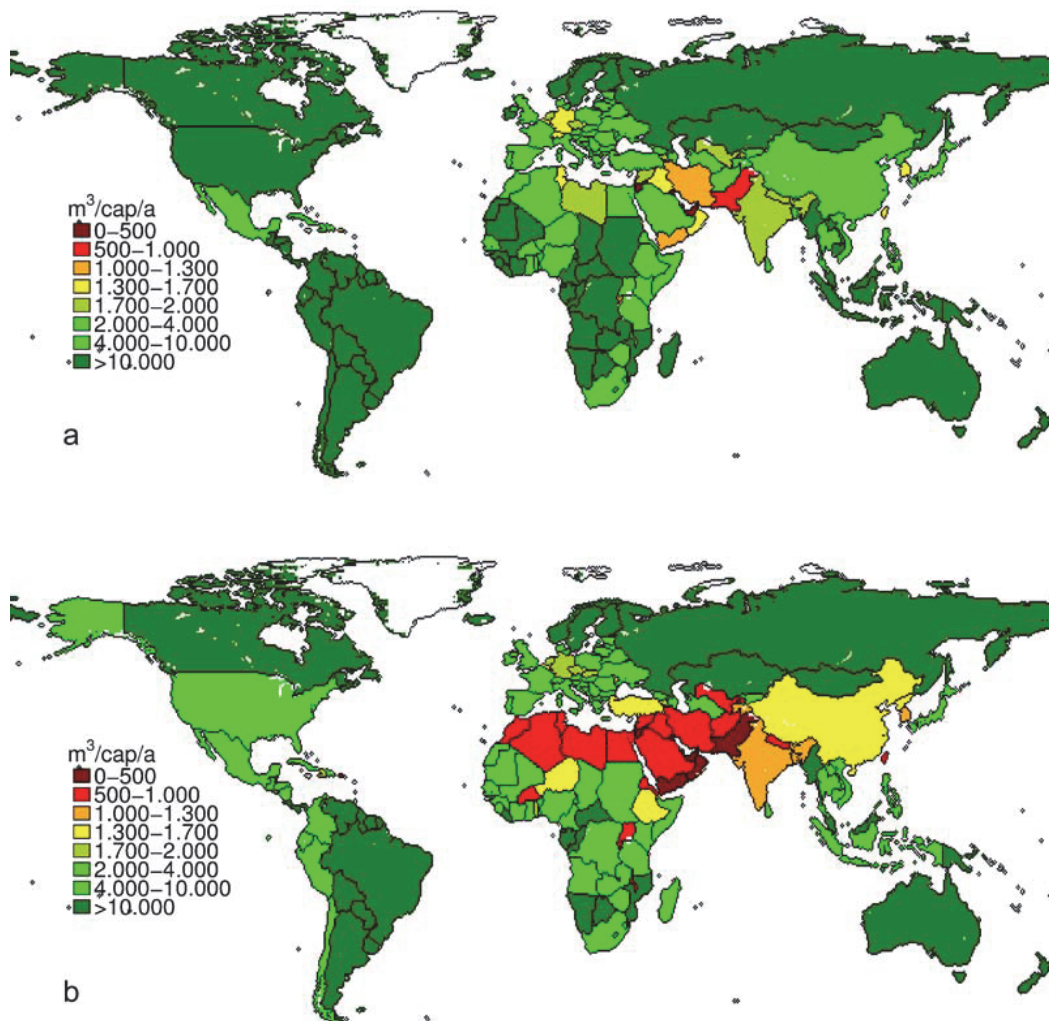
Figure 13. *Simulated blue-green water availability (m³/capita/year) for present climate (top panel) and including both demographic and climate change under the SRES A2 scenario in 2050 (bottom panel). The study assumed that if water availability was less than 1,300m³/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The figure is from Rockstrom et al. (2009).*

Doll (2009) presents updated estimates of the impact of climate change on groundwater resources by applying a new version of the WaterGAP hydrological model. The study accounted for the number of people affected by changes in groundwater resources under climate change relative to present (1961-1990). To this end, the study provides an assessment of the vulnerability of humans to decreases in available groundwater resources (GWR). This indicator was termed the "Vulnerability Index" (VI), defined as; VI = -% change GWR * Sensitivity Index (SI). The SI component was a function of three more specific sensitivity indicators that include an indicator of water scarcity (calculated from the ratio between consumptive water use to low flows), an indicator for the dependence upon groundwater supplies, and an indicator for the adaptive capacity of the human system. Doll (2009) applied climate projections from two GCMs (ECHAM4 and HadCM3) to WaterGAP,

for two scenarios (SRES A2 and B2), for the 2050s. Figure 14 presents each of these four simulations respectively. There is variation across scenarios and GCMs but there is consensus that vulnerability is moderate to high across north and north-eastern Brazil.
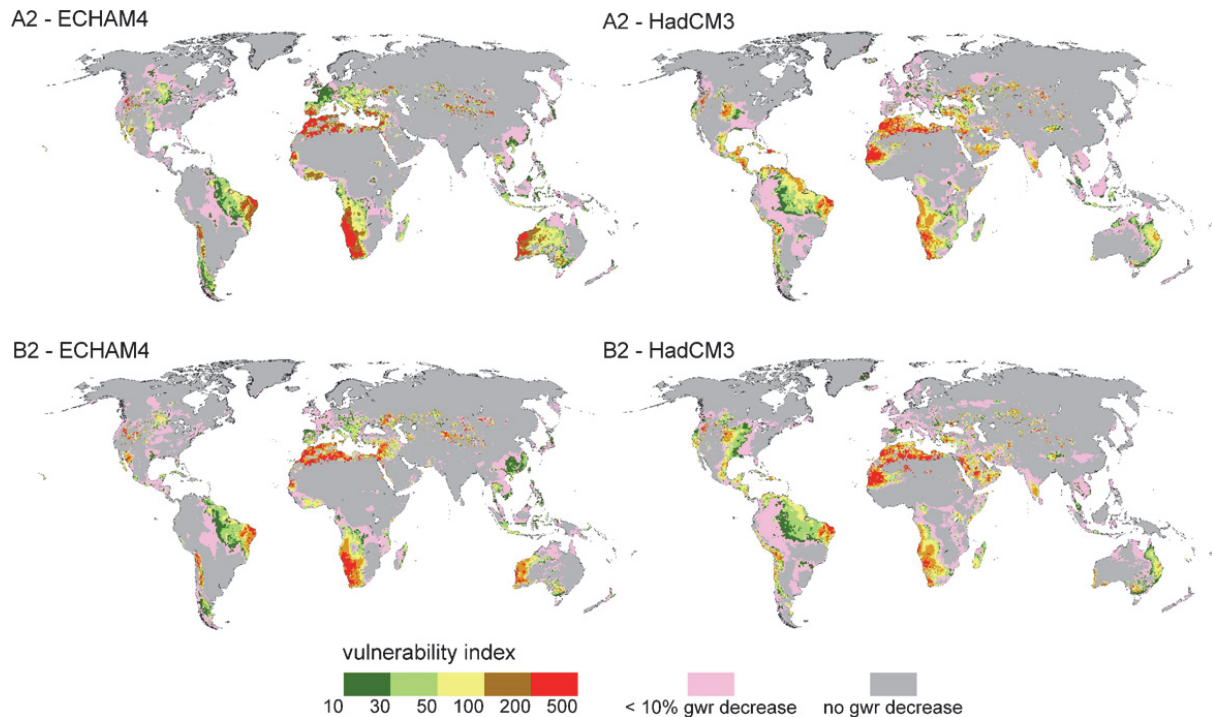

Figure 14. *Vulnerability index (VI) showing human vulnerability to climate change induced decreases of renewable groundwater resources (GWR) by the 2050s under two emissions scenarios for two GCMs. VI is only defined for areas with a GWR decrease of at least 10% relative to present (1961-1990). The figure is from Doll (2009).*

Fung et al. (2011) applied climate change scenarios for prescribed global-mean warming of 2°C and 4°C respectively, from two ensembles; 1) an ensemble of 1518 (2°C world) and 399 (4°C) members from the ClimatePrediction.net (CPDN) experiments, and 2) an ensemble of climate projections from 22 GCMs from the CMIP3 multi-model dataset. The climate projections were applied to the MacPDM global hydrological model (Gosling and Arnell, 2011) and population projections followed the UNPOP60 population scenario. Fung et al. (2011) calculated a water stress index (WSI) based upon resources per capita, similar to the method applied by Rockstrom et al.(2009). Results from the simulations are presented in Figure 15. There was consensus across models that water stress increases with climate change in much of Brazil, especially around the Amazon basin and the east coast of Brazil.

It should be noted that the estimates of drying across the globe that are presented by Fung et al. (2011) could be over-estimated slightly. This is because the MacPDM hydrological model is an offline model; i.e. it is not coupled to an ocean-atmosphere GCM. Therefore the dynamical effects of vegetation changes in response to water availability are not simulated. Recent work has highlighted that increased plant water use efficiency under higher CO_2 may ameliorate future increased drought to some extent, but not completely (Betts et al., 2007).
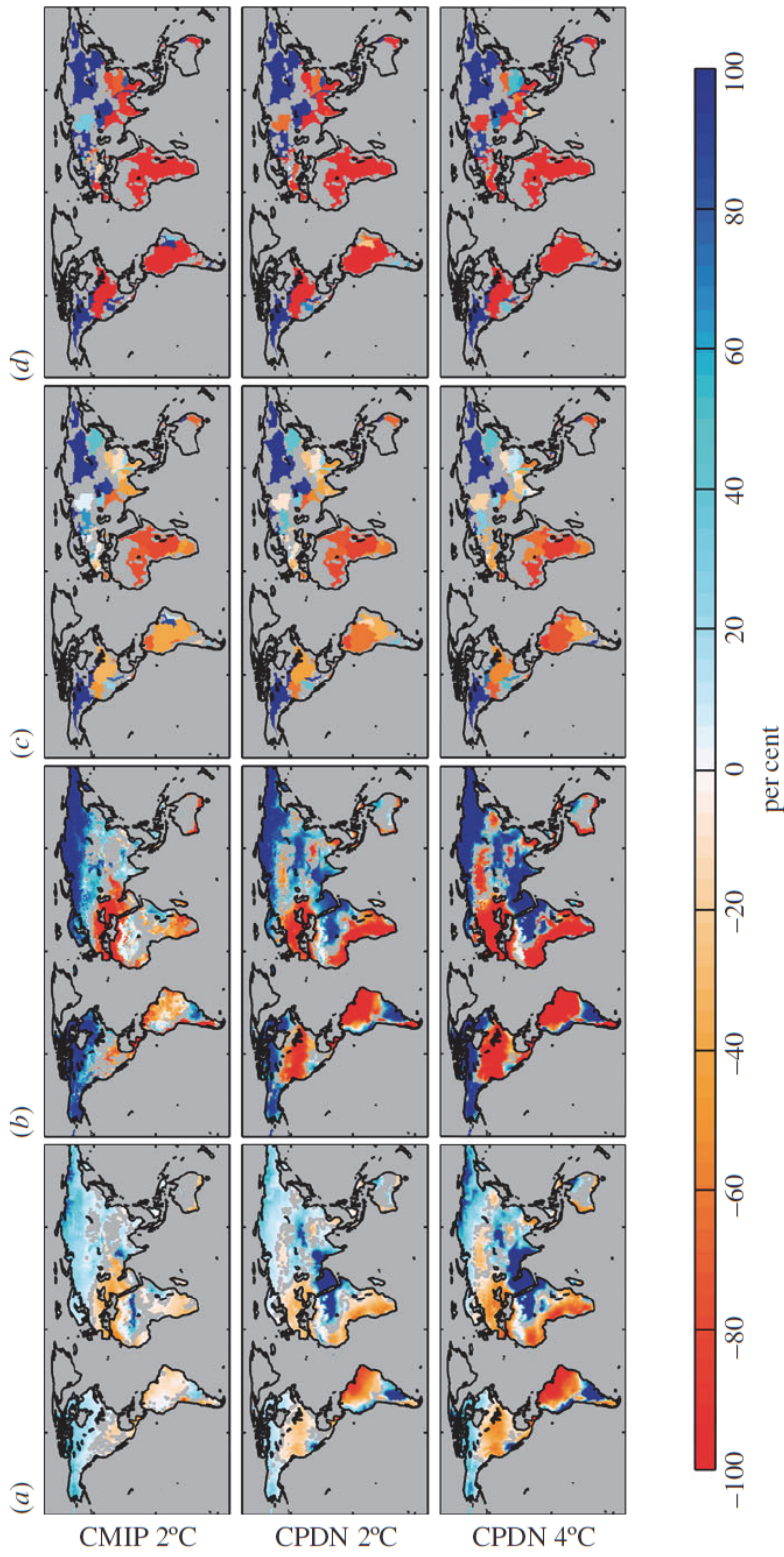
Figure 15. *For a 2°C and 4°C rise in temperature and UNPOP60 population scenario compared with the baseline period (1961-1990): (a) spatial pattern of ensemble-average changes in mean annual run-off (DMAR), (b) model consensus on direction of change in run-off, (c) ensemble-average change in water stress (DWSI) and (d) model consensus on the direction of change in water stress. For the model consensus, red and therefore negative values represent the percentage of models showing a negative change in the respective parameter and for blue, positive values, represent the percentage of models showing a positive change. For DMAR and DWSI, colour classification spans from −100% to greater than 100% (this means that high positive values of DMAR and DWSI are effectively filtered out in these plots), whereas for consensus, colour classification spans from −100% to 100%. For plots of DMAR and consensus for the direction of change in run-off, grey land areas represent where DMAR is less than natural variability. For DWSI and consensus for direction of change in water stress, only 112 major river basins are plotted (Greenland has been excluded from the analysis). The figure is from Fung et al. (2011).*

National-scale or sub-national scale assessments

Climate change studies

Costa and Pires (2009) draw attention to the potential importance of land-use change in surrounding areas on Brazil's arc of deforestation. In this study with the NCAR Community Model 3, they find that land-use change in Cerrado and Amazonia increases length of dry season in arc of deforestation.

Krol et al. (2006) showed that precipitation changes with climate change in north east Brazil differ substantially between GCMs. For example, for an annual increase of greenhouse gases by 1% per year as of 1990, projections of precipitation changes over that region (2070–2099 compared to 1961–1990) were -50% for the ECHAM4 GCM and +21% for the HADCM2 GCM. The differences in simulated precipitation were shown to have significant effects when considering future population and technological adaptation. The ECHAM4 simulations showed that a decrease in water demand must be enacted to preserve supplies. This is due to a reduction in reservoir efficiency due to reduced precipitation. This high degree of uncertainty is supported by simulations presented by Gosling et al. (2010), which showed that around 4-6 GCMs out of 21 simulated an increase in average annual runoff for Brazil, under a prescribed 2°C warming scenario, whereas the remainder simulated decreases in runoff.

Recent research on the impact of climate change on tropical forests has focused on the Amazon, with mixed information regarding the possibility of forest dieback, and a few new studies on timescales of change, reversibility and the influence of other forms of anthropogenic interference. There is consensus that temperature is not the only important metric for impacts here. Various studies address the possibility of forest dieback. Tropical forests, including old growth forests in the Amazon, are increasing the amount of carbon which they store annually as a result of climate change (Lewis et al., 2009, Phillips et al., 2009). However, recent observations of the Amazon response to the 2005 drought have demonstrated that the Amazon forest is vulnerable to possible future drying (Phillips et al., 2009).

Following on from the original Met Office Hadley Centre result of extensive dieback, simulated by the HadCM3LC model, the drying pattern over Amazon seen in HadCM3LC has been found to be plausible because it may be currently masked by aerosol forcing (Cox et al., 2008). Sitch et al. (2008) applied patterns of climate change from HadCM3LC to different vegetation model formulations. They found that loss of some Amazon forest is

robust to different vegetation model formulations. On the other hand, they found significant uncertainty in the amount of forest loss.

Lapola et al. (2009) provide further information on model uncertainty. When the authors applied patterns of climate change from GCMs other than HadCM3LC to simulate Amazon response to climate change, the response was highly dependent on assumptions about the (highly uncertain) CO_2 fertilisation effect, which in their vegetation model prevents dieback under climate change patterns from most GCMs. There is some evidence, however, to suggest that the CO_2 fertilisation effect may not persist for more than a few years (Leakey et al., 2009) and that the benefit may be significantly reduced by concurrent fertilisation of vines, which can shorten the lifespan of trees (Phillips et al., 2002).

Jones et al. (2009) investigated issues of timescales of dieback and reversibility (see Figure 16). They showed that earth system simulations to 2100 can substantially underestimate the long term committed forest loss (in simulations where forest loss occurs). Thus a threshold can be crossed before the impacts are apparent. They found that in one model (HadCM3LC), the global-mean warming temperature threshold for Amazon forest dieback was as low as 2°C. They also showed that timescales for regrowth can be very long, although there are uncertainties due to model-dependent strength of vegetation-climate coupling.
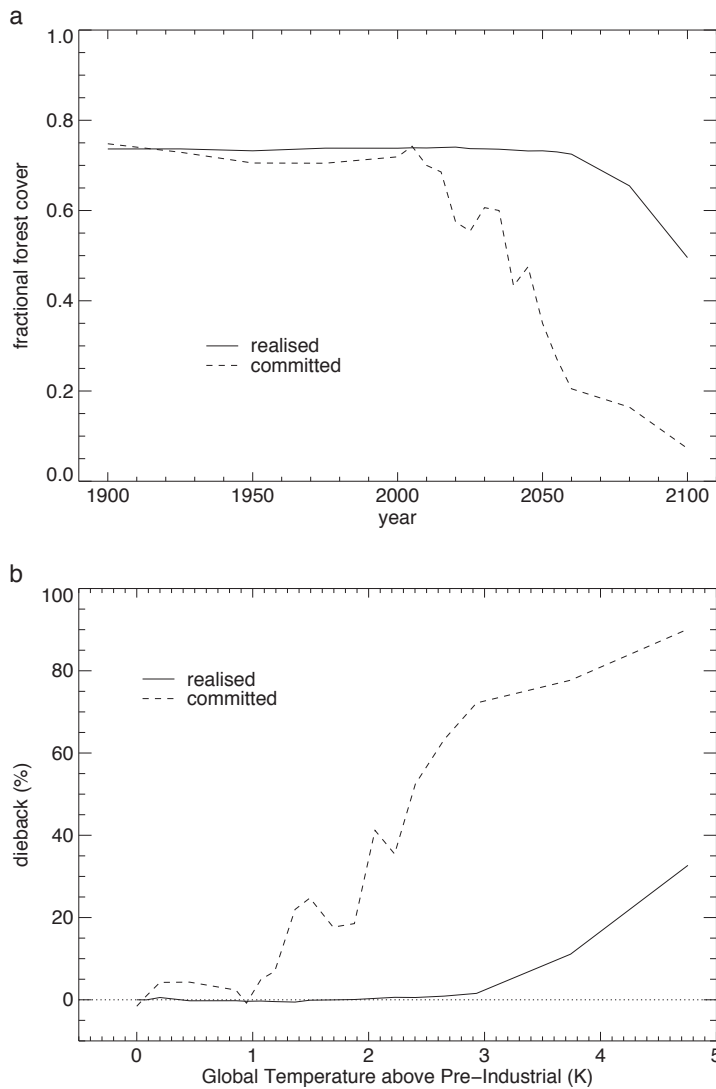
Figure 16. *(a) Fractional tree cover (represented as fractional coverage of broadleaf trees in the region 40°–70° W, 15° S–5° N) as it evolves dynamically with the HadCM3LC model under the SRES A2 emissions scenario and the committed state corresponding to each year. (b) The same information plotted as the percentage of complete die-back as a function of global mean temperature rise above pre-industrial (defined as 0 for the original, pre-industrial forest cover, and 100 for complete loss of tree cover in this region). The figure is from Jones et al. (2009).*

There is also increasing recognition that anthropogenic effects other than warming associated with greenhouse gas emissions are critical for the forest. Interactions between effects of climate change and human activity in the forest (e.g. deforestation and associated increased fire risk, currently absent from GCMs) are very important. Combined effects may be larger than the sum of individual influences. Golding and Betts (2008) and Malhi et al. (2009) showed that climate change may increase vulnerability to fire, arguing that regional management may be critical in determining the Amazon forest fate. Owing to the long-term decrease in carbon storage that results, fires could act as a positive feedback on climate

106

change (Gough et al., 2008). Lapola et al. (2009) also emphasised the critical and uncertain role of CO_2 fertilisation in forest projections.

In a report on climate change impacts for northeast Brazil, Wilby (2008) noted that there was uncertainty in rainfall projections, compounded by a lack of understanding of how the El Niño-Southern Oscillation (ENSO) could change in the future. Rainfall over the region is strongly linked to ENSO, and there is a tendency for GCMs to simulate El Nino-like patterns of SSTs, which lead to conditions favouring drought over the region. There is also uncertainty in how the Amazon forest could react to climate change (in terms of carbon cycle and vegetation), as this could have an important feedback upon the hydrological cycle.

Marengo et al. (2010) applied three RCMs (Eta CCS, RegCM3 and HadRM3P) under the SRES A2 emissions scenario to explore precipitation changes with climate change for South America. Their simulations are summarised in Figure 17. The results indicate that regions of north-east Brazil and central-eastern and southern Amazonia may experience rainfall deficiency with climate change. In a similar study, Marengo et al. (2011) showed that annual average rainfall could decrease by up to around 41% in Amazonia in the 2090s relative to 1961-1990 (see Table 11).
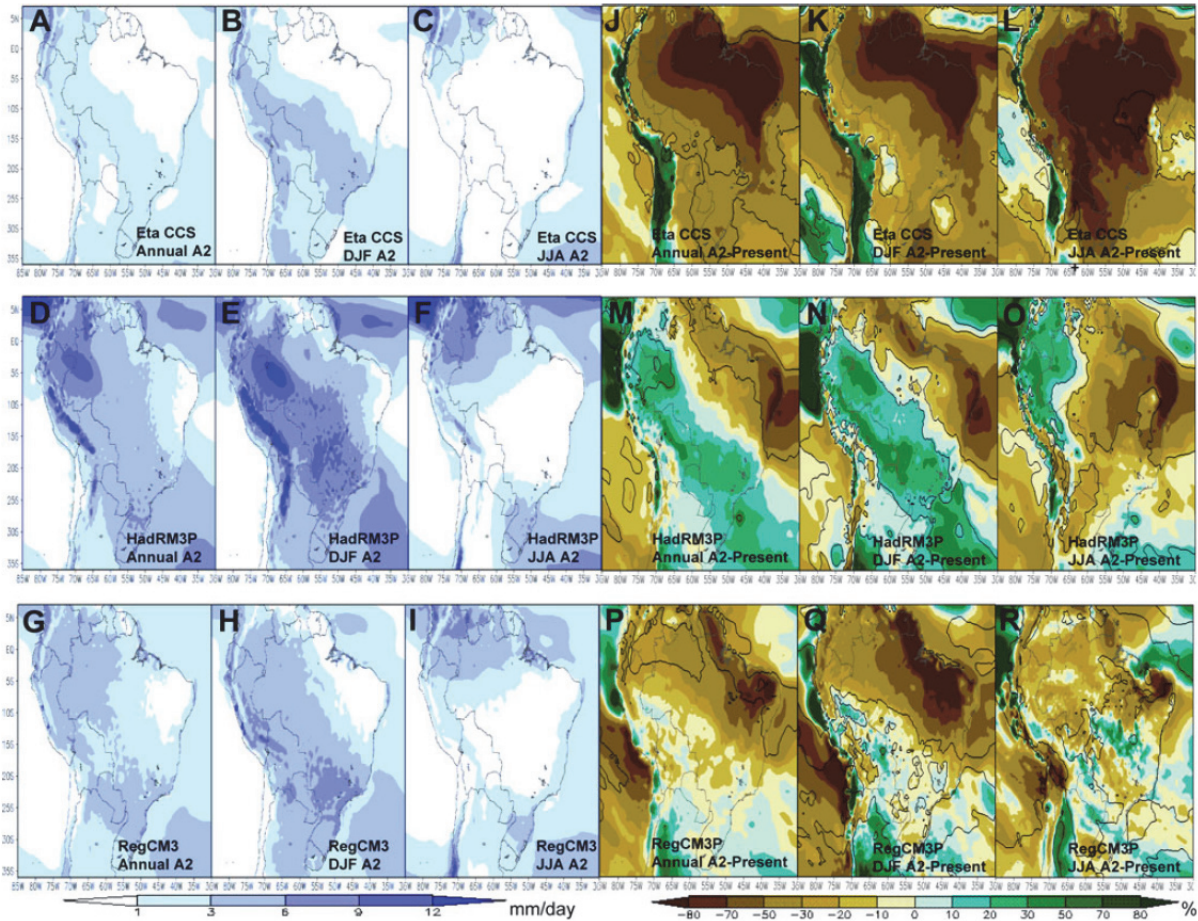
.

.

Figure 17. Projected patterns of rainfall (mm/day) and rainfall change (%) over South America for the A2 scenario, at annual, summer (December-February) and winter (June-August) time scales. A–I shows the projections for 2071–2100 from the Eta CCS, HadRM3P and the RegCM3 RCMs. J-R shows the differences between the 2071–2100 projections and the 1961–1990 model climatology (in %). Shaded areas represent regions where statistical significance at the 95% level is reached. The figure is from Marengo et al. (2010).

Scenario	Minimum % rainfall change	Maximum % rainfall change
A1FI	-22.5	-40.6
A1B	-17.0	-31.9
B1	-11.4	-22.2

Table 11. Lower and upper limits of range in projected changes in annual average rainfall in Amazonia by the 2090s with respect to the 1961-1990 baseline under three SRES emissions scenarios. Data is from Marengo et al. (2011).

Sanchez-Roman et al. (2010) applied a dynamic simulations model (WRM-PCJ) to assess water resources in two large basins located in the state of Sao Paulo. Five development scenarios were considered and the results for three water stress indices were detailed; WU (water use; %), Sustainability Index (dimensionless) and the Falkenmark Index (m3/capita/year). Scenario 1 was the business-as-usual scenario, where water consumption

and wastewater generation rates of existent consumers were maintained with no changes
and precipitation was equal to the mean value, 1,460mm/year throughout the simulation.
Scenario 2 considered a 10% reduction in precipitation due to climatic change. Scenario 3
considered a 20% reduction in precipitation due to climate change. Scenario 4 considered
the total irrigated area to stop growing in year 2020, without variations in all other variables,
including precipitation. Scenario 5 considered the conditions set in scenario 1 and an
ecological river flow equal to 19.2 m3/s. The results are summarised in Table 12, showing
that by 2030 water stress is highly plausible across large areas of this region, with the
Falkenmark Index starting to drop below or near to 1000m3/capita/year for all scenarios,
indicating chronic water shortage.

Scenario	Index	2004	2010	2020	2030	2040	2054
1	WU	74.41	83.95	96.04	97.80	110.37	131.29
	SI	0.44	0.40	0.35	0.33	0.28	0.20
	FI	1,403	1,302	1,147	1,008	884	734
2	WU	82.68	93.28	106.71	108.67	122.64	145.88
	SI	0.40	0.36	0.30	0.28	0.23	0.15
	FI	1,263	1,172	1,032	907	795	660
3	WU	93.02	104.94	120.05	122.26	137.97	164.11
	SI	0.34	0.30	0.25	0.23	0.17	0.09
	FI	1,123	1,042	917	806	707	587
4	WU	74.41	83.95	96.04	96.70	107.8	126.27
	SI	0.44	0.40	0.35	0.34	0.29	0.23
	FI	1,403	1,302	1,147	1,008	884	734
5	WU	74.41	92.44	104.53	106.29	118.86	139.78
	SI	0.44	0.34	0.29	0.27	0.22	0.15
	FI	1,403	1,302	1,147	1,008	884	734

WU Water Use (%), *SI* Sustainability Index (dimensionless), *FI* Falkenmark Index
(m3/capita/year).

Table 12. *Results of water use indexes from the five scenarios simulated using Piracicaba, Capivari*
and Jundiaí River Basins Water Resources Model (WRM-PCJ) for the state of Sao Paulo, Brazil. See
main text for description of scenarios.

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, 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.

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

The pattern of climate change from 21 GCMs was applied to MacPDM, under two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). Both scenarios assume that population changes through the 21st century following the SRES A1 scenario as implemented in IMAGE 2.3 (van Vuuren et al., 2007). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one impacts model is applied (MacPDM). Simulations were performed for the years 2030, 2050, 2080 and 2100. Following Warren et

al. (2010), changes in the population affected by increasing or decreasing water stress represent the additional percentage of population affected due to climate change, not the absolute change in the percentage of the affected population relative to present day.

Results

The results for Brazil are presented in Figure 18; they show that exposure to increased or decreased water stress with climate change is not simulated with the majority of GCMs.
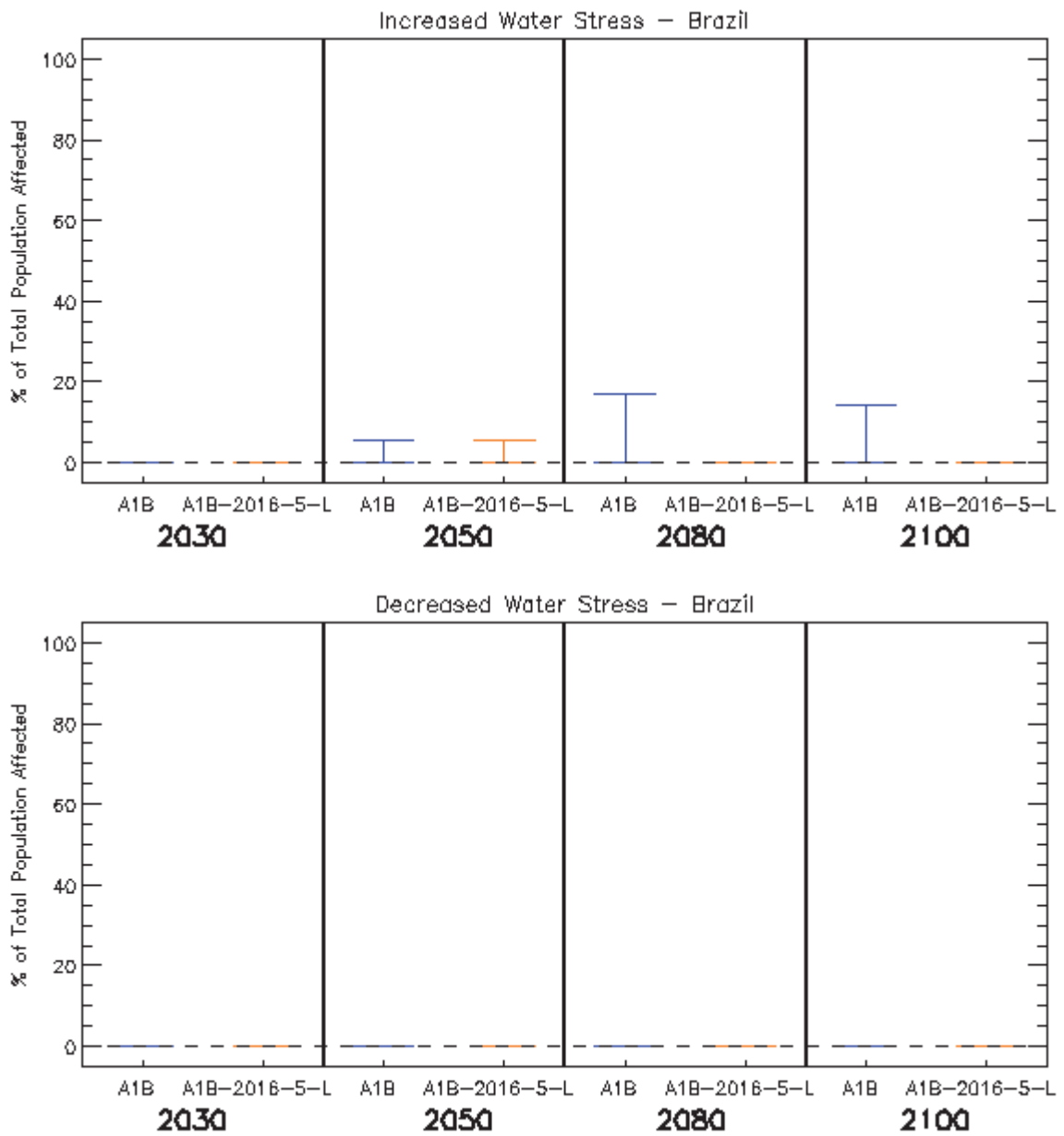
Figure 18. *Box and whisker plots for the impact of climate change on increased water stress (top panel) and decreased water stress (bottom panel) in Brazil, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (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 projections of reduced mean precipitation over parts of northern Brazil, and little in the way of research into changing precipitation extremes. Research since then suggests continued decreases in mean precipitation over Amazonia (see section on water stress and drought), but potential increases over other parts of Brazil (this section). Large uncertainties remain regarding how ENSO could be affected by climate change, and also changes to the hydrological cycle associated with changes to the Amazon forest.

Supporting literature

Introduction

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

Assessments that include a global or regional perspective

Recent past

Re and Barros (2009) found increasing trends in annual maximum rainfall at a sample of weather stations in the south of Brazil between 1959 and 2002. Marengo et al. (2010b) found an increase in the number of extreme daily rainfall events above 10mm/day during the past 40 years in southern Brazil of up to 12 days.

Climate change studies

The IPCC AR4 (2007a) stated that multi-model mean precipitation is projected to decrease over large parts of northern Brazil. The reports also noted that over the Amazon basin, monsoon precipitation is projected to increase in December-February and decrease in June-August. One version of the HadCM3 GCM showed the largest reduction in Amazon rainfall of all the CMIP3 multi-model dataset models, a reduction of 21% under A1B emissions. At the time of the IPCC AR4, there was little research available for projections in precipitation extremes over South America. Over the Amazon region, models projected extremely wet seasons in about 27% of all December-February seasons, and 18% of all March-May seasons in the period 2080-2099. Hegerl et al. (2004) analysed an ensemble of simulations from two GCMs and found that more intense wet days per year over central Amazonia, and weaker extremes over the coasts of northeast Brazil, were projected with climate change.

Marengo et al. (2009) found that in Northeast Brazil and eastern Amazonia no changes (or small increases) were seen in projected rainfall intensity. The most marked increases in extreme rainfall are projected for western Amazonia implying a higher flood risk in that region. These trends are generally greater under the A2 emissions scenario, compared to the B2 scenario. Marengo et al. (2010) find indications that regions of Northeast Brazil and central-eastern and southern Amazonia may experience rainfall deficiency in the future. More recently, a continent wide study by Kitoh et al. (2011) found that under the A1B emissions scenario, precipitation intensity could increase for all of South America. The authors also found that heavy precipitation could increase over the Amazon. The uncertainties related to future projections of ENSO behaviour were noted in the study.

National-scale or sub-national scale assessments

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

Fluvial flooding

Headline

There is large uncertainty regarding the impact of climate change on fluvial flooding in Brazil. A number of recent studies show that the sign of runoff change under climate change scenarios is largely dependent upon the GCM used to provide the climate change projections. However, simulations by the AVOID programme that applied 21 climate models, show a tendency for increasing flood risk, particularly later in the century.

Supporting literature

Introduction

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

The Amazon River is the world's largest river in terms of average discharge, and plays a key role in the global water cycle. The flood-pulse of the large rivers in the Amazon basin has been linked to El Niño-Southern Oscillation (ENSO) indices, with high and prolonged flooding associated to cold ENSO-phases (La Niña) (Schongart and Junk, 2007). Moreover, the exceptional flooding in the northern part of Amazonia in 2009 has been linked to La Niña conditions (Chen et al., 2010). Also in the Río de la Plata basin (shared between Argentina, Brazil, Bolivia, Paraguay and Uruguay) an increased frequency of floods has been linked to an intensification of the El Niño signal on precipitation (Barros et al., 2005; Depetris, 2007)

Assessments that include a global or regional perspective

Climate change studies

Although the Amazon Basin or parts thereof have been the focus of numerous hydrological modelling studies, few have investigated projected changes in peak discharges. Hirabayashi et al. (2008) applied climate change projections from a single GCM and found that by the end of this century (2071-2100) the return period of what was a 100-year flood event in the 20th century decreases to less than 30 years in most of the eastern part of the Amazon basin, but increases in some western parts. As a result, the return period of a 100-year flood in the main Amazon River itself was projected to increase to more than 200 years with the annual peak flow occurring about 1 month earlier. The projections presented by Hirabayashi et al. (2008) suggest a strong increase in flood hazard in most of the country by the end of this century, with the exception of the Atlantic Southeast coast. Elsewhere, in a global modelling study that applied climate simulations from 19 GCMs under the A1B emissions scenario for the end of the 21st century (2081-2100), Nohara et al. (2006) found a wide range of projected changes in the high-flow season discharge of the Amazon River, ranging from roughly –20% to +20% of the current observed river flow in May and June. The (weighted) ensemble mean change in this season was consequently small and likely not statistically significant given this wide spread (Nohara et al., 2006). 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.

National-scale or sub-national scale assessments

Climate change studies

Nóbrega et al. (2011) used pattern scaling of GCM scenarios to assess changes in water resources in the Rio Grande Basin in southern Brazil, one of the main tributaries of the Paraná River and an important river for water supply and hydroelectric power generation. When using results from a single climate model (HadCM3) they found a consistent trend towards an increase in discharge during the high-flow season (January-February). The 5th percentile (i.e. the discharge level that is exceeded only 5% of the time) was projected to increase by 12% under the A1B emissions scenario, and 13% under the A2 scenario. Under the B1 and B2 scenarios these increases were slightly less (+5% and +8%, respectively). When scaled according to global temperature change, the increase in the 5th-percentile flow level ranged from +8% under a 1°C prescribed global warming scenario to +53% under a prescribed 6°C global warming. However, this changed when more GCMs were included in the analysis. Using data from 6 GCMs under the A1B scenario the change in the 5th-percentile flow ranged from +12% to -20%, suggesting there is considerable structural uncertainty in the climate scenarios. A similar range of uncertainty was found in another study for the Rio Grande Basin, which applied the same scenarios and GCMs as Nóbrega et al. (2011), but a different hydrological model (Gosling et al., 2011). A reduction of the uncertainties in projected change in climate and river flow extremes is therefore highly necessary.

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 Brazil are presented in Figure 19. By the 2030s, the models project a range of changes in mean fluvial flooding risk over Brazil in both scenarios, with some models projecting decreases and others increases. However, the balance is more towards increased flood risk, with more than half of models projecting an increase. The largest decrease projected for the 2030s is a 50% decline in the average annual flood risk, and the largest increase is 100%. The mean projection across all the models is a slight increase in flood risk.

By 2100 the balance shifts 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 (more than 25%) still project a lower flood risk (down to 50%), but more project an increase. The mean projection is a 20% increase, and the upper projection is about a 200% increase. Under the A1B scenario, 75% of models project an increased flood risk, but still some project decrease in flood risk (down to about 70%). The largest projected increase is nearly 650%, with the mean projection being nearly a 100% increase in annual average flood risk compared to the present-day.

So for Brazil, the models show a tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario. Differences between the model projections are also greater later in the Century and particularly for A1B.
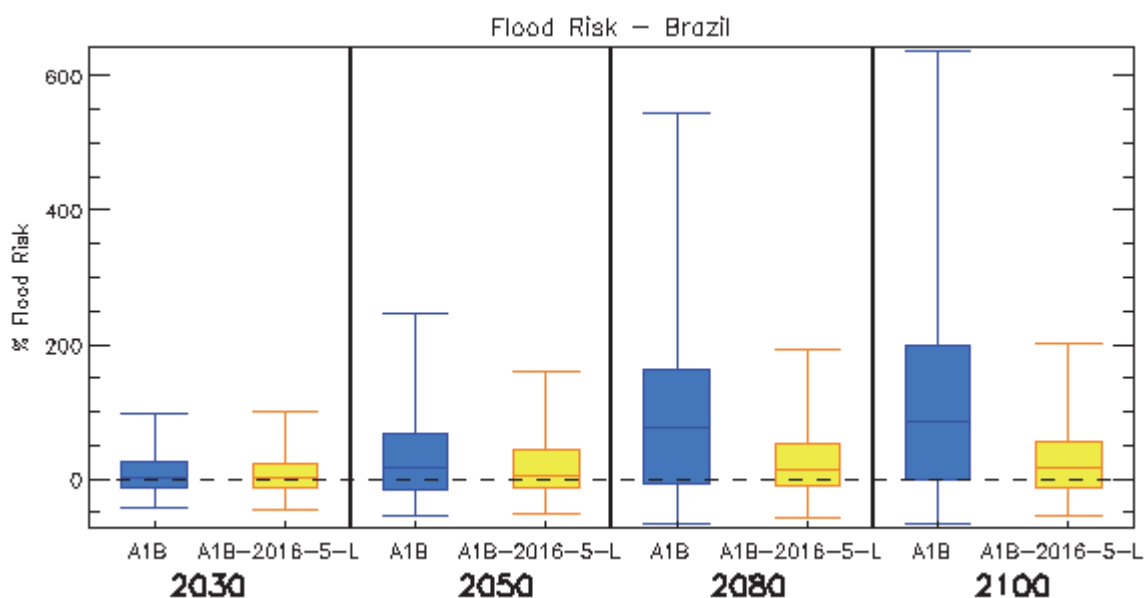

Figure 19. Box and whisker plots for the percentage change in average annual flood risk within Brazil, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).

Tropical cyclones

This country is rarely impacted by tropical cyclones.

Coastal regions

Headline

Sea level rise (SLR) could have major impacts in Brazil. One study places Brazil within the top 15 countries simulated to show an increased exposure from SLR relative to present in the 2070s, based upon a global assessment of 136 port cities. A 10% intensification of the current 1-in-100-year storm surge combined with a 1m SLR could affect around 15% of Brazil's coastal land area and 30% of the coastal population. However, aggressive climate change mitigation scenario could avoid an exposure of around 14,000 people in Brazil, relative to un-mitigated climate change in 2070.

Supporting literature

Assessments that include a global or regional perspective

Climate change studies

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 South American Atlantic Coast region that less than 100 thousand additional 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 Argentina and Uruguay). 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 South American Atlantic region suggest an approximate 5 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 and investigated the impact of a 10% intensification of the current 1-in-100-year storm surge combined with a 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 Brazil. Table 14 shows that around 15% of Brazil's coastal land area and 30% of the coastal population could be affected, which placed Brazil within the top third of countries most effected by SLR, out of the countries that Dasgupta et al. (2009) considered. Hanson et al. (2010) present estimates of the impact of

SLR on the port city fraction of coastal population in Brazil, based upon a global-scale assessment. 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. 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 13 shows the aspects of SLR that were considered for various scenarios and Table 14 displays regional port city population exposure for each scenario in the 2030s, 2050s and 2070s. The result show, similar to Dasgupta et al. (2009), that Brazil is in the top third of countries considered, which is impacted by SLR (e.g. compare the projections in Table 14 with the estimates for exposure in the absence of climate change that are presented in Table 15). Hanson et al. (2010) also demonstrated that aggressive mitigation scenario could avoid an exposure of around 14,000 people in port cities in Brazil, relative to un-mitigated climate change (see Table 16) 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 13. 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.

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 14. 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.

Rapid urbanisation projection

2030 — Water level projection

Country	Ports	FAC	FCC	FRSLC	FNC
CHINA	15	17,100	15,500	15,400	14,600
INDIA	6	11,600	10,800	10,300	9,970
US	17	8,990	8,960	8,830	8,460
JAPAN	6	5,260	4,610	4,430	4,390
INDONESIA	4	1,420	1,200	1,200	1,170
BRAZIL	10	833	833	833	802
UK	2	497	497	478	459
CANADA	2	459	433	422	405
REP. OF KOREA	3	344	344	331	441
GERMANY	1	257	257	253	248
RUSSIA	1	177	177	177	177
AUSTRALIA	5	162	162	157	157
SOUTH AFRICA	2	30	30	30	29
SAUDI ARABIA	1	24	24	24	22
FRANCE	1	15	15	15	15
ITALY	1	2	2	2	2
MEXICO	0	0	0	0	0

2050 — Water level projection

Country	Ports	FAC	FCC	FRSLC	FNC
CHINA	15	23,000	19,700	18,700	17,400
INDIA	6	16,400	14,600	13,600	12,500
US	17	11,300	11,200	10,800	9,970
JAPAN	6	6,440	5,280	5,000	4,760
INDONESIA	4	2,110	1,610	1,610	1,500
BRAZIL	10	929	929	929	879
UK	2	609	609	564	521
CANADA	2	549	512	486	457
REP. OF KOREA	3	361	361	341	318
GERMANY	1	287	287	273	269
RUSSIA	1	202	202	173	173
AUSTRALIA	5	197	197	191	181
SAUDI ARABIA	1	33	33	33	27
SOUTH AFRICA	2	28	28	28	27
FRANCE	1	19	19	19	17
ITALY	1	4	4	4	3
MEXICO	0	0	0	0	0

2070 — Water level projection

Country	Ports	FAC	FCC	FRSLC	FNC
CHINA	15	27,700	22,600	20,800	18,600
INDIA	6	20,600	17,900	15,600	13,900
US	17	12,800	12,700	12,100	10,700
JAPAN	6	7,800	5,970	5,580	5,070
INDONESIA	4	2,680	1,830	1,830	1,530
BRAZIL	10	940	940	940	864
UK	2	716	716	640	569
CANADA	2	614	585	545	489
REP. OF KOREA	3	377	377	325	303
GERMANY	1	309	309	290	280
RUSSIA	1	226	226	197	169
AUSTRALIA	5	196	196	186	175
SAUDI ARABIA	1	38	38	38	29
SOUTH AFRICA	2	30	30	30	27
FRANCE	1	23	23	23	18
ITALY	1	6	6	6	4
MEXICO	0	0	0	0	0

Table 15. 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 16. Data is for port cities and from Hanson et al. (2010) and has been rounded down to three significant figures.

Country	Ports	Population exposure 2070. Rapid urbanisation, FAC water level scenario				Exposure avoided
		Current	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 16. *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 for port cities and from Hanson et al. (2010) and has been rounded down to three significant figures.*

Hanson et al. (2011) also present estimates of the exposure of the world's large port cities (population exceeding one million inhabitants in 2005) to coastal flooding due to SLR and storm surge, now and in the 2070s. Population exposure was calculated as a function of elevation against water levels related to the 1 in 100 year storm surge. The analysis assumed a homogenous SLR of 0.5m by 2070. For tropical storms a 10% increase in extreme water levels was assumed, with no expansion in affected area; while for extra-tropical storms, a 10% increase in extreme water levels was assumed. A uniform 0.5 m decline in land levels was assumed from 2005 to the 2070s in those cities which are historically susceptible (usually port cities located in deltas). This approach provided a variable change in extreme water level from around 0.5m in cities only affected by global SLR, to as much as 1.5 m for cities affected by global SLR, increased storminess and human-induced subsidence. Population projections were based upon the UN medium variant, where global population stabilises at around 9 billion by 2050. Figure 20 shows that Brazil was within the top 15 countries simulated to show an increased exposure from SLR relative to present in the 2070s, and unsurprisingly, the results are similar to estimates published previously by Hanson et al. (2010).
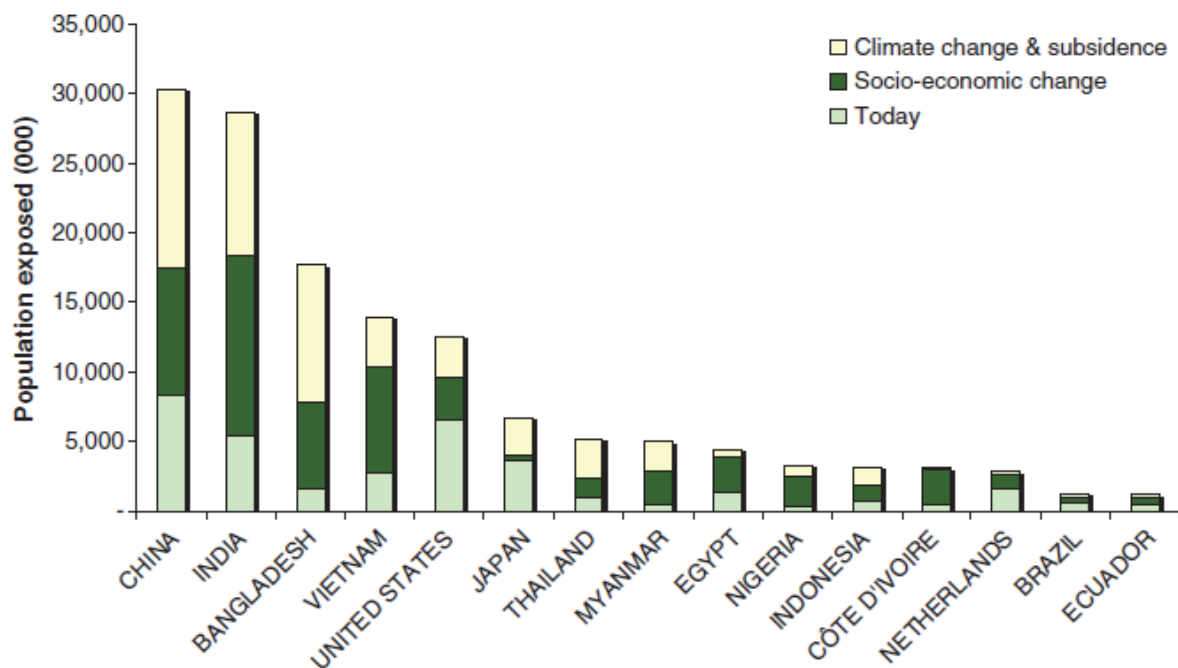

Figure 20. The top 15 countries in the 2070s for exposure to SLR, based upon a global analysis of 136 port cities (Hanson et al., 2011). The proportions associated with current exposure, climate change and subsidence, and socio-economic changes are displayed.

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 17.

	A1B		RCP	
	Low	High	Low	High
Additional people flooded (1000s)	41.00	475.85	26.26	209.07
Loss of wetlands area (% of country's total wetland)	12.56%	25.67%	5.09%	17.76%

Table 17. 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 for Brazil (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.

ALLISON, E. H., PERRY, A. L., BADJECK, M.-C., NEIL ADGER, W., BROWN, K., CONWAY, D., HALLS, A. S., PILLING, G. M., REYNOLDS, J. D., ANDREW, N. L. & DULVY, N. K. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries,* 10**,** 173-196.

ARNELL, N., OSBORNE, T., HOOKER, J., DAWSON, T., PERRYMAN, A. & WHEELER, T. 2010a. Simulation of AVOIDed impacts on crop productivity and food security. *Work stream 2, Report 17 of the AVOID programme (AV/WS2/D1/R17).*

ARNELL, N., WHEELER, T., OSBORNE, T., ROSE, G., GOSLING, S., DAWSON, T., PENN, A. & PERRYMAN, A. 2010b. The implications of climate policy for avoided impacts on water and food security. *Work stream 2, Report 6 of the AVOID programme (AV/WS2/D1/R06).* London: Department for Energy and Climate Change (DECC).

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.

BARBIERI, A. F., DOMINGUES,E., QUERIOZ, B. L., RICARDO, M., RIGOTTI, R J I., CARVALHO, J.,A.,M., and RESENDE, M. F. 2010. Climate change and population migration in Brazil's Northeast: scenarios for 2025–2050. Popul Environ 31:344–370. DOI 10.1007/s11111-010-0105-1.

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.

BARROS, V., DOYLE, M. & CAMILLONI, I. 2005. Potential impacts of climate change in the Plata basin. Regional Hydrological Impacts of Climatic Variability and Change. Seventh IAHS Scientific Assembly. Foz do Iguaçu, Brazil: IAHS Publishers.

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.

CHEN, J. L., WILSON, C. R. & TAPLEY, B. D. 2010. The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE. *Water Resources Research,* 46.

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.

CIA 2011. World Factbook. US Central Intelligence Agency.

CIFUENTES, L., BORJA-ABURTO, V. H., GOUVEIA, N., THURSTON, G. & DAVIS, D. L. 2001. Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000-2020): Santiago, Sao Paulo, Mexico City, and New York City. *Environmental health perspectives,* 109**,** 419-425.

CONFALONIERI, U., MARINHO, D. & RODRIGUEZ, R. 2009. Public health vulnerability to climate change in Brazil. *Climate Research,* 40**,** 175-186.

COSTA, L., JUSTINO, F., OLIVEIRA, L., SEDIYAMA, G., FERREIRA, W. & LEMOS, C. 2009. Potential forcing of CO_2, technology and climate changes in maize (Zea mays) and bean (Phaseolus vulgaris) yield in southeast Brazil. *Environmental Research Letters,* 4**,** 014013.

COSTA, M.,H., and PIRES, G., F., 2009. Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. *International Journal of Climatology .*DOI 10.1002/joc.2048

COX, P. M., HARRIS, P. P., HUNTINGFORD, C., BETTS, R. A., COLLINS, M., JONES, C. D., JUPP, T. E., MARENGO, J. A. & NOBRE, C. A. 2008. Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature,* 453**,** 212-U7.

DEPETRIS, P. 2007. The Parana river under extreme flooding: a hydrological and hydro-geochemical insight. Interciencia, 32, 656-662.

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

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.

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

DOLL, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters,* 4.

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].

FEARNSIDE, P. M. 2008. Deforestation in Brazilian Amazonia and Global Warming. *Annals of Arid Zone,* 47**,** 1-20.

FISCHER, G. 2009. World Food and Agriculture to 2030/50: How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability? *Expert Meeting on How to Feed the World in 2050.* Food and Agriculture Organization of the United Nations, Economic and Social Development Department.

FUNG, F., LOPEZ, A. & NEW, M. 2011. Water availability in +2°C and +4°C worlds. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 369**,** 99-116.

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

GOLDING, N. & BETTS, R. 2008. Fire risk in Amazonia due to climate change in the HadCM3 climate model: Potential interactions with deforestation. *Global Biogeochemical Cycles,* 22**,** -.

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.

GOUGH, C. M., VOGEL, C. S., SCHMID, H. P. & CURTIS, P. S. 2008. Controls on annual forest carbon storage: Lessons from the past and predictions for the future. *Bioscience,* 58**,** 609-622.

HALES, S., DE WET, N., MAINDONALD, J. & WOODWARD, A. 2002. Potential effect of population and climate changes on global distribution of dengue fever: an empirical model. *The Lancet,* 360**,** 830-834.

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.

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

HEGERL, G. C., ZWIERS, F. W., STOTT, P. A. & KHARIN, V. V. 2004. Detectability of anthropogenic changes in annual temperature and precipitation extremes. *Journal of Climate,* 17**,** 3683-3700.

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.

IFPRI. 2010. *International Food Policy Research Institute (IFPRI) Food Security CASE maps. Generated by IFPRI in collaboration with StatPlanet.* [Online]. Available: www.ifpri.org/climatechange/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.

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.

JONES, C., LOWE, J., LIDDICOAT, S. & BETTS, R. 2009. Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience,* 2**,** 484-487.

KITOH, A., KUSUNOKI, S. & NAKAEGAWA, T. 2011. Climate change projections over South America in the late 21st century with the 20 and 60 km mesh Meteorological Research Institute atmospheric general circulation model (MRI-AGCM). *Journal of Geophysical Research-Atmospheres,* 116.

KROL, M., JAEGER, A., BRONSTERT, A. & GUNTNER, A. 2006. Integrated modelling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil. *Journal of Hydrology,* 328**,** 417-431.

LAPOLA, D. M., OYAMA, M. D. & NOBRE, C. A. 2009. Exploring the range of climate biome projections for tropical South America: The role of CO_2 fertilization and seasonality. *Global Biogeochemical Cycles,* 23**,** -.

LAPOLA, D. M., SCHALDACH, R., ALCAMO, J., BONDEAU, A., KOCH, J., KOELKING, C. & PRIESS, J. A. 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America,* 107**,** 3388-3393.

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

LEAKEY, A. D. B., AINSWORTH, E. A., BERNACCHI, C. J., ROGERS, A., LONG, S. P. & ORT, D. R. 2009. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany,* 60**,** 2859-2876.

LEWIS, S. L., LOPEZ-GONZALEZ, G., SONKE, B., AFFUM-BAFFOE, K., BAKER, T. R., OJO, L. O., PHILLIPS, O. L., REITSMA, J. M., WHITE, L., COMISKEY, J. A., DJUIKOUO, M. N., EWANGO, C. E. N., FELDPAUSCH, T. R., HAMILTON, A. C., GLOOR, M., HART, T., HLADIK, A., LLOYD, J., LOVETT, J. C., MAKANA, J. R., MALHI, Y., MBAGO, F. M., NDANGALASI, H. J., PEACOCK, J., PEH, K. S. H., SHEIL, D., SUNDERLAND, T., SWAINE, M. D., TAPLIN, J., TAYLOR, D., THOMAS, S. C., VOTERE, R. & WOLL, H. 2009. Increasing carbon storage in intact African tropical forests. *Nature,* 457**,** 1003-U3.

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.

LOBELL, D. B., BURKE, M. B., TEBALDI, C., MASTRANDREA, M. D., FALCON, W. P. & NAYLOR, R. L. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science,* 319**,** 607-610.

LOBELL, D., SCHLENKER, W. and COSTA-ROBERTS, J. 2011. Climate Trends and Global Crop Production Since 1980. *Science,* 333, 616-620 [DOI:10.1126/science.1204531]

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.

MALHI, Y., ARAGAO, L. E. O. C., GALBRAITH, D., HUNTINGFORD, C., FISHER, R., ZELAZOWSKI, P., SITCH, S., MCSWEENEY, C. & MEIR, P. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America,* 106**,** 20610-20615.

MARENGO, J., BETTS, R. A., NOBRE, C. A., CHOU, S. C., TOMASELLA, J., SAMPAIO, G., ALVES, L. M., OBREGON, G., SOARES, W. R. & KAY, G. 2011. Dangerous Climate Change in Brazil - A Brazil-UK analysis of Climate Change and Deforestation impacts in the Amazon. *Centro de Ciência do Sistema Terrestre (CCST) of the Instituto Nacional de Pesquisas Espaciais (INPE), Brazil, and the Met Office Hadley Centre, UK*.

MARENGO, J. A., AMBRIZZI, T., DA ROCHA, R. P., ALVES, L. M., CUADRA, S. V., VALVERDE, M. C., TORRES, R. R., SANTOS, D. C. & FERRAZ, S. E. T. 2010. Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models. *Climate Dynamics,* 35**,** 1089-1113.

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.

NOBRE, C. A. & BORMA, L. D. 2009. 'Tipping points' for the Amazon forest. *Current Opinion in Environmental Sustainability,* 1**,** 28-36.

NÓBREGA, M., COLLISCHONN, W., TUCCI, C. & PAZ, A. 2011. Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. *Hydrology and Earth System Sciences,* 15**,** 585-595.

NOHARA, D., KITOH, A., HOSAKA, M. & OKI, T. 2006. Impact of climate change on river discharge projected by multimodel ensemble. *Journal of Hydrometeorology,* 7**,** 1076-1089.

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.

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.

PEREIRA DE LUCENA, A. F., SZKLO, A. S., SCHAEFFER, R. & DUTRA, R. M. 2010. The vulnerability of wind power to climate change in Brazil. *Renewable Energy,* 35**,** 904-912.

PETERSON, A. T. & SHAW, J. 2003. Lutzomyia vectors for cutaneous leishmaniasis in Southern Brazil: ecological niche models, predicted geographic distributions, and climate change effects. *International Journal for Parasitology,* 33**,** 919-931.

PHILLIPS, O. L., ARAGAO, L. E. O. C., LEWIS, S. L., FISHER, J. B., LLOYD, J., LOPEZ-GONZALEZ, G., MALHI, Y., MONTEAGUDO, A., PEACOCK, J., QUESADA, C. A., VAN DER HEIJDEN, G., ALMEIDA, S., AMARAL, I., ARROYO, L., AYMARD, G., BAKER, T. R., BANKI, O., BLANC, L., BONAL, D., BRANDO, P., CHAVE, J., DE OLIVEIRA, A. C. A., CARDOZO, N. D., CZIMCZIK, C. I., FELDPAUSCH, T. R., FREITAS, M. A., GLOOR, E., HIGUCHI, N., JIMENEZ, E., LLOYD, G., MEIR, P., MENDOZA, C., MOREL, A., NEILL, D. A.,

NEPSTAD, D., PATINO, S., PENUELA, M. C., PRIETO, A., RAMIREZ, F., SCHWARZ, M., SILVA, J., SILVEIRA, M., THOMAS, A. S., TER STEEGE, H., STROPP, J., VASQUEZ, R., ZELAZOWSKI, P., DAVILA, E. A., ANDELMAN, S., ANDRADE, A., CHAO, K. J., ERWIN, T., DI FIORE, A., HONORIO, E., KEELING, H., KILLEEN, T. J., LAURANCE, W. F., CRUZ, A. P., PITMAN, N. C. A., VARGAS, P. N., RAMIREZ-ANGULO, H., RUDAS, A., SALAMAO, R., SILVA, N., TERBORGH, J. & TORRES-LEZAMA, A. 2009. Drought Sensitivity of the Amazon Rainforest. *Science,* 323**,** 1344-1347.

PHILLIPS, O. L., MARTINEZ, R. V., ARROYO, L., BAKER, T. R., KILLEEN, T., LEWIS, S. L., MALHI, Y., MENDOZA, A. M., NEILL, D., VARGAS, P. N., ALEXIADES, M., CERON, C., DI FIORE, A., ERWIN, T., JARDIM, A., PALACIOS, W., SALDIAS, M. & VINCETI, B. 2002. Increasing dominance of large lianas in Amazonian forests. *Nature,* 418**,** 770-774.

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.

RE, M. & BARROS, V. R. 2009. Extreme rainfalls in SE South America. *Climatic Change,* 96**,** 119-136.

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.

ROGERS, D. J. & RANDOLPH, S. E. 2000. The Global Spread of Malaria in a Future, Warmer World. *Science,* 289**,** 1763-1766.

SANCHEZ-ROMAN, R. M., FOLEGATTI, M. V. & GONZALEZ, A. 2010. Water Resources Assessment at Piracicaba, Capivari and Jundiai River Basins: A Dynamic Systems Approach. *Water Resources Management,* 24**,** 761-773.

SCHONGART, J. & JUNK, W. J. 2007. Forecasting the flood-pulse in Central Amazonia by ENSO-indices. *Journal of Hydrology,* 335**,** 124-132.

SITCH, S., HUNTINGFORD, C., GEDNEY, N., LEVY, P. E., LOMAS, M., PIAO, S. L., BETTS, R., CIAIS, P., COX, P., FRIEDLINGSTEIN, P., JONES, C. D., PRENTICE, I. C. & WOODWARD, F. I. 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology,* 14**,** 2015-2039.

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

SUSEP. 2011. *About Brazilian Insurance Market* [Online]. Available: http://www.susep.gov.br/menuingles/about_bim.asp [Accessed July 12 2011].

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,* Published online.

VAN LIESHOUT, M., KOVATS, R., LIVERMORE, M. & MARTENS, P. 2004. Climate change and malaria: analysis of the SRES climate and socio-economic scenarios. *Global Environmental Change,* 14**,** 87-99.

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.

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

WILBY, R. L. 2008. A review of climate change scenarios for northeast Brazil: Informing climate change adaptation and water resources management policies: A Technical Brief for Tearfund.

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.

WORLD BANK 2009. Brazil, Key Actor in Global Climate Change Solutions. World Bank Press Release.

WORLD BANK 2010. Brazil Low-carbon Country Case Study. The World Bank.

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.

Acknowledgements