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Regional projections of North Indian climate for adaptation studies

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ABSTRACT

Adaptation is increasingly important for regions around the world where large changes in climate could have an impact on populations and industry. The Brahmaputra–Ganges catchments have a large population, a main industry of agriculture and a growing hydro-power industry, making the region susceptible to changes in the Indian Summer Monsoon, annually the main water source. The HighNoon project has completed four regional climate model simulations for India and the Himalaya at high resolution (25 km) from 1960 to 2100 to provide an ensemble of simulations for the region. In this paper we have assessed the ensemble for these catchments, comparing the simulations with observations, to give credence that the simulations provide a realistic representation of atmospheric processes and therefore future climate. We have illustrated how these simulations could be used to provide information on potential future climate impacts and therefore aid decision-making using climatology and threshold analysis. The ensemble analysis shows an increase in temperature between the baseline (1970–2000) and the 2050s (2040–2070) of between 2 and 4 °C and an increase in the number of days with maximum temperatures above 28 °C and 35 °C. There is less certainty for precipitation and runoff which show considerable variability, even in this relatively small ensemble, spanning zero. The HighNoon ensemble is the most complete data for the region providing useful information on a wide range of variables for the regional climate of the Brahmaputra–Ganges region, however there are processes not yet included in the models that could have an impact on the simulations of future climate. We have discussed these processes and show that the range from the HighNoon ensemble is similar in magnitude to potential changes in projections where these processes are included. Therefore strategies for adaptation must be robust and flexible allowing for advances in the science and natural environmental changes.

1. Introduction

Carbon dioxide emissions from anthropogenic sources are now widely considered very likely to have contributed to observed changes in climate (Meehl et al., 2007). The Intergovernmental Panel on Climate Change (IPCC AR4, 2007) also highlight in its fourth assessment report (AR4) that inertia in the climate system, the atmospheric lifetime of carbon dioxide and feedbacks within the climate system mean that previous emissions will continue to have an impact into the future. We are therefore already committed to some level of climate change at least to the middle of the 21st century which means that adaptation to a changing climate will be a necessity around the world in the next few decades, increasing in priority for more vulnerable populations. Often the change in climate is discussed in terms of global mean temperature, for example Betts et al. (2011) focuses on the potential for breaching the threshold of 4 °C in global mean temperature. However, regionally, a global mean temperature change can translate to a much bigger or smaller regional or local temperature change; therefore for adaptation purposes, analysis of climate change for individual regions is important.

The EU funded HighNoon project focuses on how water resources may change in the future for the region of South Asia, specifically Northern India; the region comprises the Indian Himalayas and its foothills, home to an estimated 500 million people. The economy is predominantly rural, highly dependant on climate sensitive sectors such as the agricultural and horticultural industry and characterised by a large demand for water resources. In India agricultural use comprises 80 or 90% of human water extraction with almost 60% of this from groundwater. This large demand is part of an increasing trend with groundwater withdrawals increasing by 113-fold between 1950 and 1985 (Douglas et al., 2006).

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Products using a combination of models with satellite observations (during the period 2002 to 2008) from GRACE (NASA Gravity Recovery and Climate Experiment Satellites) have shown that this trend has continued suggesting a mean depletion in groundwater of 4.0 ± 1.0 cm yr^{-1} (Rodell et al., 2009). This increased demand and use of previously unavailable water resource has resulted in a rapid rate of economic development and has helped alleviate poverty in the region. However as a result, groundwater stores have declined at a rate of 20 cm per year in as many as 15 Indian states. In most of these states the resource from ground water is projected to dry out as soon as 2025 (Douglas et al., 2006, 2009). On the other hand, most Himalayan glaciers, the largest ice pack outside the poles, have been retreating over the past decades (Bolch et al., 2011). The relative contribution of snow and glacier melt to river flows decreases with increasing distance from the mountains and may vary from 10% or less annually (Immerzeel et al., 2010) to 12–38% during the months of March, April and May (MAM), outside the Indian summer monsoon (ISM defined as extending from June to September, JJAS, Goswami and Xavier, 2005) when other sources of water are scarce. This contribution is likely to decrease with increasing glacier wasting (Immerzeel et al., 2010; Siderius et al., 2013). Irrigation and drinking water supplies are thus likely to decrease and become seasonal if water deficits are not compensated for by increased precipitation.

The ISM has been a critical source of water for this region in terms of ground water recharge, river basin and river flow (Rodell et al., 2009) with the HighNoon region (defined by 25°N79°E −32°N88°E and illustrated in Fig. 1, centre) receiving up to 70% of its annual precipitation during this period based on APHRODITE data from 1979 to 2007 (Yatagai et al., 2009). The ISM could become even more important in the future as other sources of water for agriculture and domestic use could become more scarce and inter-sectoral competition for water may increase. Future changes in precipitation amounts and timing could therefore be of critical importance to the region.

Apart from the changes in the ISM other fundamental climatic changes impacting Northern India could be many and varied, some examples are given here:

- Increases in temperature could mean certain crops may no longer be viable at lower elevations, while rendering mountain areas at higher elevations suitable for horti-agricultural purposes. Kumar et al. (2011b) highlights the potential losses in wheat production with rising temperatures (4–5 million tonnes with every 1 °C increase in temperature throughout the growing period with current land use). However, in the case of irrigated rice, the negative impacts of increasing temperature may be adequately compensated by high CO_2 concentrations (Kumar et al., 2011b).
- Sea level rise could lead to salt water intrusion into highly productive deltas rendering large areas of agricultural land no longer tenable potentially causing population displacement (Dasgupta et al., 2007);
- Altered patterns of snow and glacial melt changing the availability of water for spring and summer irrigation or possibly causing sporadic flooding (Dasgupta et al., 2007).
- Changes in weather extremes, leading among others to cloud bursts or flash floods could also put additional stresses on critical infrastructure such as roads, rail and energy supply networks. Such networks are already under stress from population growth, increased urbanisation, resource use, and regionally imbalanced economic growth. This could critically impair economic growth by disrupting connectivity or damaging basic service installations such as water supply and drainage (Naswa and Garg (2011).

Acting to adapt to altered availability of resources and potential changes in extreme weather is therefore an urgent need for this region, especially if the economic growth it has experienced in recent years is to be sustained. In order to adapt a population needs to make informed decisions both in terms of policy and as individuals. In recent years through the publication of the IPCC reports, climate models have become more accessible as tools to aid decisions for adaptation, for example, through methods such as climatology assessments and threshold analysis.

Climatology assessments are important in developing a general understanding of regional climate change using standard climate parameters such as temperature and precipitation. They are often used for presenting key generic messages including uncertainties for policy makers, for example in the IPCC AR4. Threshold analysis, on the other hand, is suited to more specific adaptation applications, such as the rail and power distribution network (Thornton et al., 2011; McColl et al., 2012) making climate information directly useable by, and relevant for, specific industries.

Many industries (see Table 1), for example agriculture, are influenced directly by weather and climate on a wide range of timescales (e.g. precipitation, temperature and CO_2 concentrations) and indirectly (e.g. by changes in the occurrence of pests and diseases, or changing market forces). Adaptation in the agricultural industry tends to be influenced by knowledge of the local climate and individual experience (Gornall et al., 2010). Changes to the local climate could threaten established farming methods; however adaptation to climate change could provide the mechanism through which these methods could be improved. Hydroelectric power is another important industry in India with the Brahmaputra catchment and Ganges highlighted by the World Development Bank as key areas with potential for development (Ramanathan and Abeygunawardena, 2007). The benefits and problems from such developments need to be evaluated using understanding of the likely future changes to precipitation and runoff in order to ensure that facilities are developed in a robust and resilient way.

The use of scientific information in policy making is often complicated due to the uncertainties inherent in the climate system, which in reality can never be entirely eliminated (Webster, 2003), and

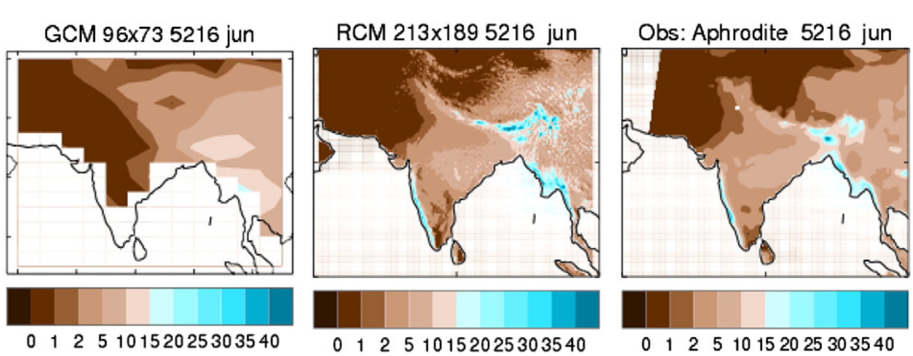

Fig. 1. Precipitation climatology for India with the sea masked out to show grid box coverage over land for India, in the global model (left) and the regional model (centre). Climatology of APHRODITE observations are also shown (right).

Table 1
Summary of sectors and the information needed from climate models (†Gornall et al., 2010, §Dutt et al., 1992; Sirohi and Michaelowa, 2007, ‡Naswa and Garg, 2011, ΩBOM: http://www.bom.gov.au/info/thermal_stress/).

Sector	Climate variables	Timescales known to be important for sector	Examples of important thresholds
Agriculture	Temperature	Annual — important for established farming practises Seasonal — high growing season temperatures can affect crop productivity by bringing forward harvest times. Even high temperatures for only a short period can have severe detrimental effects to some crops if they occur at crucial times e.g. flowering in rice†.	Max temperature during rice flowering affecting crop yield > 35 °C Upper limit of max temperature for milk production is 27 °C§
	Precipitation	Seasonal — low rainfall during the growing season can have a detrimental impact on productivity (e.g. Ganges), conversely high rainfall can lead to flooding in some areas (e.g. Brahmaputra basin). Excess water from prolonged periods of rain can lead to soil water logging, anaerobicity and reduced plant growth†.	
	Runoff	Seasonal — changes to seasonal flows could affect the availability of water for irrigation and domestic use particularly when flows are very low or even cease flowing completely during the dry season†.	
Hydro-power	Temperature	Seasonal — rising temperatures could impact energy demand, particularly during warmer periods of the year, this could mean a greater demand for energy for cooling. This could translate into a high demand during periods with low flow and therefore reduced supply‡.	
	Precipitation and runoff	Annual — changing patterns in precipitation and runoff could mean hydro-power is more or less viable‡. Seasonal — changes in seasonal cycles of precipitation and glacial melt could result in large changes in river flows with some rivers completely drying up in the low flow months and others very high during peak flows, thus having implications for hydropower‡.	Minimum flows needed to sustain a healthy river ecosystem are different for each river.
Health and housing	Temperature	Seasonal — rising temperatures could affect the population directly through heat stress or indirectly through changes to the spread of pests and diseases‡†.	Heat stress threshold: daily maximum temperature > 28 °C although the effect of high temperatures can be reduced or exacerbated by different levels of humidityΩ.

those due to scientific understanding, which has seen rapid development in recent years. One of the overarching issues is uncertainty in the size and, for some regions, direction of future projected changes in water-related quantities. For example, the IPCC AR4 climate models do not agree on the sign of annual/seasonal precipitation changes for some key regions, including South Asia — particularly for December January February (DJF). In other regions and seasons there may be greater consensus on the sign of future changes, but a wide range of magnitudes may be projected across the models. These uncertainties are potentially challenging for assessing the scale and nature of adaptation options required.

In this paper we describe the latest high-resolution (25 km) ensemble of regional climate model (RCM) simulations run for the HighNoon project for India and the Himalayas. These simulations covering the whole of India (See Fig. 1, centre) are described and evaluated in detail in Pankaj et al. (in preparation). We briefly verify model performance in simulating the current climate of the specific region of the Ganges and Brahmaputra catchments (Section 2). This is then extended to assess the use of the ensemble to provide information on climate change impacts on adaptation timescales (i.e. to the middle of the 21st century; IPCC AR4, 2007), providing information for adaptation decisions for these catchments using the methods described above (climatology assessment and threshold analysis, Section 3.1). We also discuss the main sources of uncertainty and the potential limitations of these model simulations (Section 4).

2. HighNoon simulations

2.1. Experiment design

The HighNoon regional climate model simulations provide data at a 25 km resolution for the HighNoon domain (See [Fig. 1, centre) for the period the 1960 to 2100 using the SRES A1B scenario (Nakićenović et al., 2000). Two global models that represent the monsoon well for the current climate; The Third Version of the Met Office Hadley Centre Climate Model (HadCM3; Pope et al., 2000; Gordon et al., 2000 — A version of the Met Office Unified Model, MetUM) and ECHAM5 (3rd realisation, Roeckner et al., 2003) provide the boundary conditions for the two regional climate models; REMO (Jacob, 2001, 2009) and HadRM3 (Jones et al., 2004). This is illustrated by the flow chart shown in Fig. 2, which shows the inputs, the main processes and outputs of a typical RCM. The configuration of HadRM3 includes representation of land surface sub-grid scale heterogeneity provided by version 2.2 of the Met Office Surface Exchange Scheme (MOSES 2, Essery et al., 2003). The combination of two RCMs each driven by two GCMs provides an ensemble of four high resolution model simulations for the HighNoon domain (see Fig. 1).

The influence of horizontal resolution on the simulations is illustrated in Fig. 1 which shows three plots of June precipitation climatologies; a global-scale HadCM3 simulation (left), a regional-scale 25 km resolution HadRM3 simulation (centre), the latter driven with HadCM3 data at the boundaries and APHRODITE observations (right). Fig. 1 (left) shows clearly visible grid cells with limited detail around the coastlines, over orography or the Indo-Gangetic plains. In contrast, the 25 km RCM is more detailed with the coastlines and other features represented in more detail. Comparing the observed June APHRODITE climatology (Fig. 1, right) with the RCM illustrates the improvements in the representation of current climate by using high resolution RCM simulations.

2.2. Assessment of HighNoon simulations

Future climate projections may be treated with more credibility if a given model can realistically simulate the physical and dynamical processes of the current climate since it may adequately capture the fundamental processes and therefore project a plausible future climate (Liang et al., 2008). In this section the outputs from the HighNoon ensemble

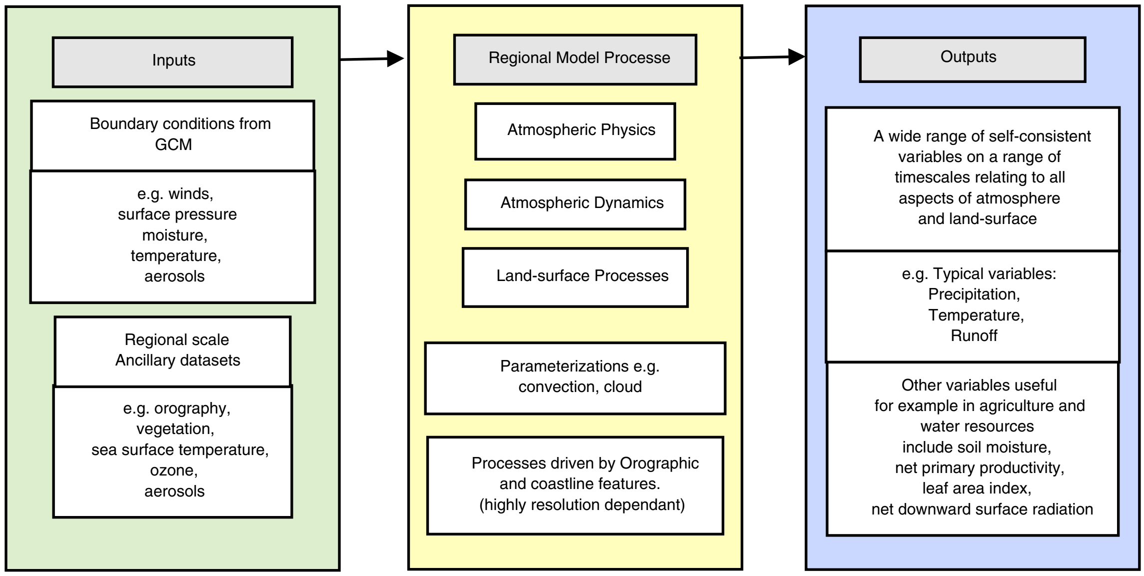

Fig. 2. Flow chart showing the inputs, main processes and example outputs for a regional climate model.

are compared with observations to verify that the simulations capture the main features of the current climate of the Ganges Brahmaputra region in order to provide confidence in the analysis of the future period of 2040–2070 presented in Section 3.

Fig. 3 shows the annual cycle of 30-year climatologies, for the Ganges and Brahmaputra catchment (highlighted by the black outline in Fig. 4) using the baseline period 1970–2000 of temperature (top row) and precipitation (bottom row) for both global (left column) and the regional 25 km data (right column). The shaded region represents 2-standard deviations in the 30-year means of a 150-year control global HadCM3 run. Natural climate variability is commonly represented by ±2 standard deviations of a long control climate model simulation (Collins et al., 2006;

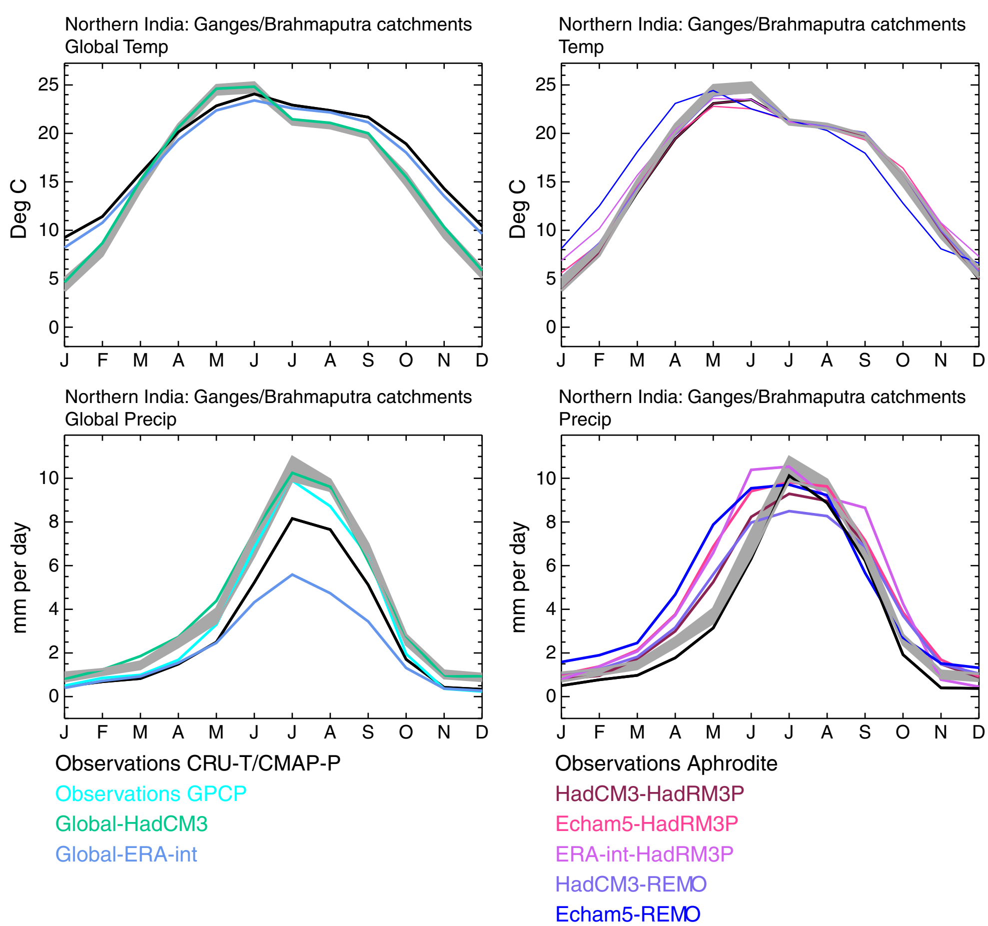

Fig. 3. Annual cycle of temperature (1st row) and precipitation (2nd row) 30-year climatologies for global resolution data (left) and 25 km resolution data (right) with the 2 standard deviation envelope for 30-year global HadCM3 control run (shaded).

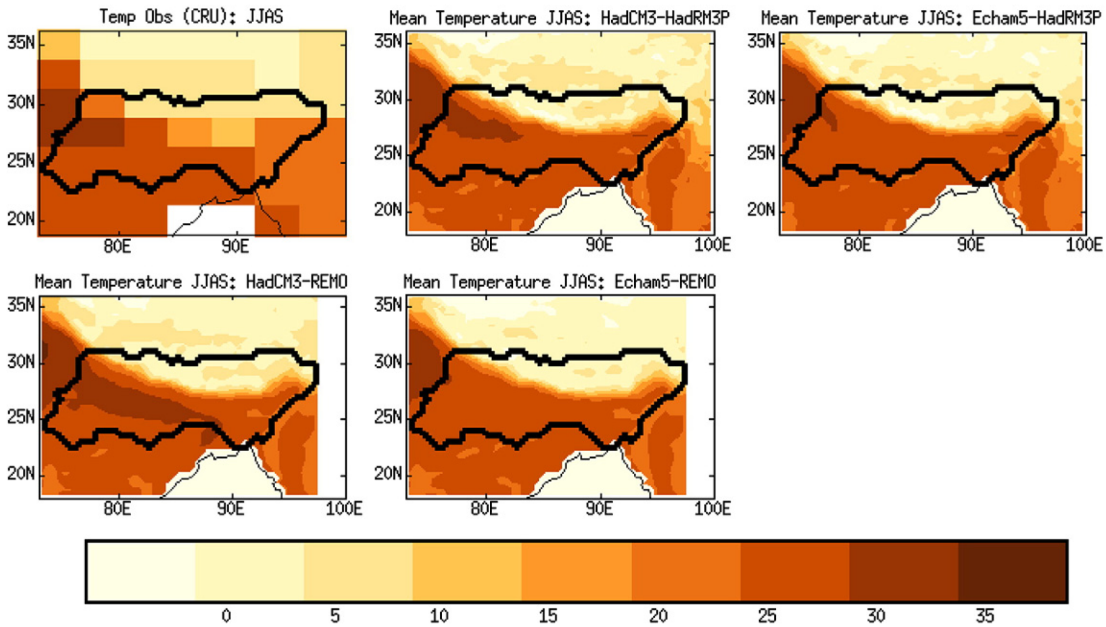

Fig. 4. 30-year JJAS temperature climatology for observations (CRU — 1st row, left) and each HighNoon model run for Ganges/Brahmaputra catchment. Left to right along each row HadCM3–HadRM3, ECHAM5–HadRM3, HadCM3–REMO and ECHAM5–REMO.

Cowling et al. 2009). Hence changes outside this range may be considered as a signal outside the "noise" of natural climate variability. Excluding changes within ± 2 standard deviations of the control simulation is approximately equivalent to a signal:noise ratio of 2 (Hawkins and Sutton, 2011). The global models show a larger annual cycle of temperature than that shown in the global observation dataset (CRU temperatures: Mitchell and Jones, 2005). The ensemble of regional model simulations has an improved range although one model (ECHAM5-REMO) shows a shift in phase of the annual cycle — earlier by one month; this could be associated with the way that the REMO land-surface soil properties are specified see Section 4.3.3 for discussion of the REMO soil properties used in the HighNoon ensemble.

The annual cycle of precipitation (Fig. 3, bottom row) shows that there is more variability in simulations of precipitation than temperature, with HadCM3 having a strong annual cycle and ERA-Interim (Simmons et al., 2007, 2010) a weak cycle compared to observations (CMAP Precipitation, Xie and Arkin, 1997). The global models (Fig. 3, bottom left) diverge during JJAS tending to underestimate the rainfall during this period compared to observations. The regional models (Fig. 3, bottom right) generally compare well against the APHRODITE observations, but have longer wet seasons such that they overestimate the observed precipitation between January and June. This difference between the model and observations should not be over-interpreted as the large spread in the precipitation observations mean it is difficult to robustly attach error bars to the observations for this region, particularly given the relative scarcity of observations in the mountains (this is also illustrated in Fig. 6a).

The spatial pattern of the observed and model temperature and precipitation climatologies are shown in Figs. 4 and 5 respectively for the wet season (JJAS). The temperature observations shown in Fig. 4 (top row, left) are CRU observations and are therefore of lower resolution than the regional models. This considered, the model climatologies all show a reasonable approximation to the observed climatology; a more in depth analysis of the models for the whole HighNoon domain is completed in Pankaj et al. (in preparation). Fig. 5 shows three observed precipitation climatologies (first row), of these APHRODITE (Fig. 5, first row, centre) is the highest resolution and shows the region of highest rainfall along the Himalayan foothills, although observations are sparse in this region. The regional model climatologies show the region of maximum rainfall to be slightly further north. In other seasons there is a general over estimation in the models of the precipitation in the east of the catchments, particularly in the pre-monsoon season (MAM — not shown).

Fig. 6 shows a comparison of the observed; GPCP (Adler et al., 2003), CRU, GPCC (Beck et al., 2005; Rudolf et al., 2003; Rudolf and Schneider, 2005; Rudolf et al., 2005), and APHRODITE JJAS precipitation, averaged across the HighNoon domain, with two regional simulations which use ERA-Interim global re-analysis data to provide boundary conditions. Fig. 6a shows a decreasing trend in the observations (except APHRODITE), and for the ERA-Interim forced models; HadRM3 shows a trend of increasing precipitation while REMO shows no trend but strong decadal variability. There is some agreement across the observational datasets on seasonal precipitation extremes; the models show a range of interannual variability (IAV) in agreement with the APHRODITE data. The correlation of the IAV from APHRODITE and the RCMs, shown in Fig. 6b, is 0.42 for REMO and 0.38 for HadRM3. Such low correlations may be related to the weak annual cycle in the ERA-Interim precipitation, (Fig. 3) the model representation of convection (Pal et al., 2007), and the model ability to recycle precipitation through evaporation (Giorgi and Bi, 2000).

Though the number of models in the HighNoon ensemble is limited and therefore spread in the HighNoon ensemble is relatively small, in general, the models do represent the current climate in terms of the seasonality of temperature and precipitation, and therefore provide useful information about the Brahmaputra and Ganges region. This is reflected in the analysis presented in Pankaj et al. (in preparation) which analyses the RCM ensemble (using ERA-Interim boundary conditions) for the whole of India. The model simulations capture the major rainfall regimes over India compared to observations (Indian Meteorological Department, IMD). The temperature patterns are also well simulated though they showed a schematic cold bias for country as a whole, also reported in IPCC 2007.

3. Climate projections in adaptation studies

The assessment of the ensemble members (Section 2.2) demonstrates that the models in the HighNoon ensemble simulate the important processes of the current climate and therefore should

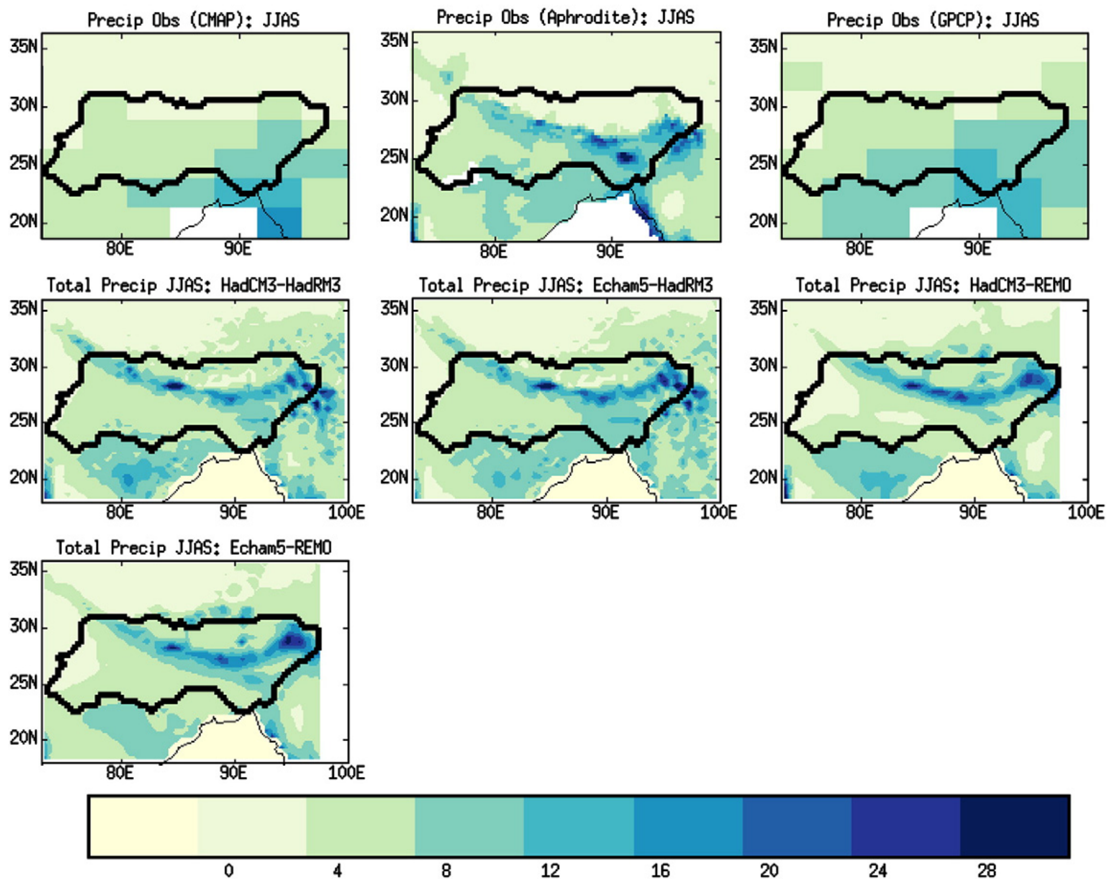

Fig. 5. 30-year JJAS precipitation climatology for observations (CMAP, APHRODITE, GPCP — 1st row, left to right) and each HighNoon model run for Ganges/Brahmaputra catchment. Left to right along each row HadCM3–HadRM3, ECHAM5–HadRM3, HadCM3–REMO and ECHAM5–REMO.

simulate a realistic future climate for the Ganges and Brahmaputra regions (Liang et al., 2008). The climate projections provide information on a range of timescales, however at very short timescales the natural variability masks the climate signal and therefore we use 30-year means to analyse future changes in climate.

In this section we explore how the output from RCMs can be used directly in studies of adaptation focussing on the 30-year period centred on the 2050s (2040–2070) as this timescale is appropriate to inform adaptation policies (IPCC AR4, 2007). This is mainly due to the inertia in the climate system which means that some change in climate is inevitable, and will be evident by the 2050s given the emissions already in the atmosphere (IPCC AR4, 2007).

3.1. Using the climate projections

The analysis of the HighNoon RCM ensembles presented here suggests two possible approaches for general analysis; the first considers the 30-year seasonal means and the differences between the projection of the future period (here the 2040–2070) and the estimate of the current climate provided by the period 1970–2000 (Section 3.1.1 applies this method to the HighNoon ensemble); this is a more generic method which is independent of the end user or the application. The second approach uses known thresholds at which a climate variable is known to have an impact, for example, if the temperature exceeds 35 °C during the critical flowering period of a rice crop it can cause infertility of the plant (Yoshida, 1981) and therefore detrimentally impact the crop yield (Section 3.1.2 applies this method to the members of the HighNoon ensemble). This requires some knowledge of the end user as this information is more specific; however thresholds of standard parameters such as temperature and precipitation could have multiple applications.

3.1.1. Climatology analysis

The HighNoon ensemble analysis focuses on the Ganges and Brahmaputra catchments for two 30-year periods; the baseline (1970–2000) and future (2040–2070) and three variables; temperature, precipitation and runoff. Fig. 7 (left column) shows the annual cycle for the temperature, precipitation and runoff across the four member HighNoon ensemble for these two periods. The magnitude of the differences between the two periods is shown in Fig. 7 (right column). Fig. 7 (top row) shows that there is a near constant increase in the regional mean temperature across the four ensemble members by the 2050s, in the annual mean of between 2.5 and 3 °C. These values compare with the projections of the 23 member AR4 ensemble which shows an annual mean temperature rise of 2 ± 1 °C (Kumar et al., 2011a). Thus, the RCM ensemble under-samples the uncertainty, with projections at the higher range indicated by the AR4 global models. Across the annual cycle, the RCMs show temperature changes of between 2 and 4 °C, with suggestions that the mean dry season temperature (DJF) could increase more than the mean JJAS temperature.

The spatial distributions of the temperature changes (not shown) are similar across the catchment although during DJF and SON the temperature rise is greatest in the mountainous regions of the catchment. An increase in temperature at higher elevations could have impacts on the glacial melt and the risk of glacial lake related floods, possibly making runoff from glacial melt and snowmelt occur earlier in the year. Increases in temperature could also mean that regions previously too cold for crops become more temperate therefore increasing the viability of land at higher elevations for horti-agricultural activities. At lower elevations where temperatures are already at the physiological maxima for crops, the impact of even a small increase in temperature could be detrimental to crop yields (Gornall et al., 2010). In order to adapt to increasing temperatures,

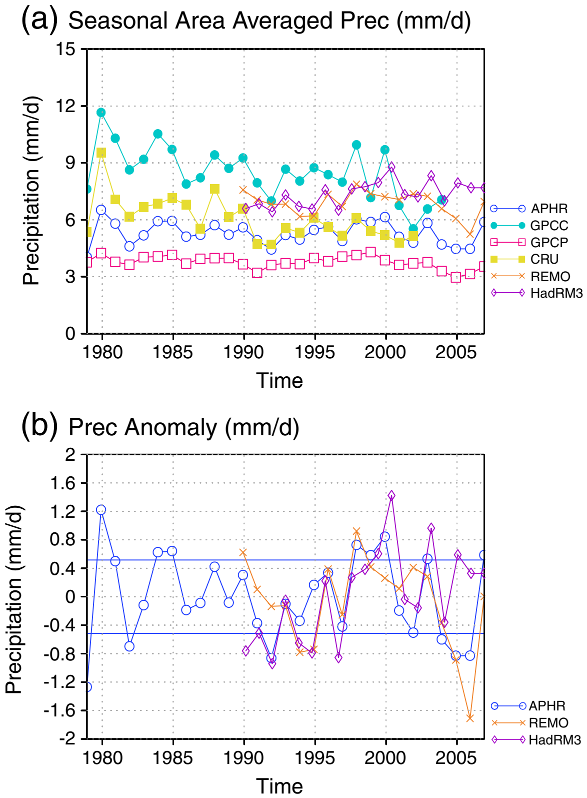

Fig. 6. (a) Interannual Variability in seasonal (JJAS) averaged precipitation (mm/day) over HighNoon region with various observational fields (GPCP, GPCC, CRU and APHRODITE (APHR)) and (b) Seasonal (JJAS) precipitation (mm/day) anomaly in APHRODITE and regional models (HadRM3 and REMO) driven by ERA-Interim boundary conditions.

a shift in the growing season to avoid the highest temperatures might be necessary which could itself have an additional impact on the regional climate by altering irrigation demands (see Section 4.3.2).

There is considerable uncertainty within the ensemble with regard to changes in wet season precipitation illustrated in Fig. 7 (middle row). Precipitation also has a much more variable spatial distribution. These are highlighted in Fig. 8, which shows the difference between 2040–2070 and 1970–2000 climatologies of total precipitation for JJAS for the Ganges Brahmaputra catchment (highlighted with the black outline) for the HighNoon ensemble. March, April and May (MAM, not shown) also showed distinct spatial differences, in particular, there was an increase in all four ensemble members to the east of the catchment and a reduction in the west.

The annual cycle in runoff is shown for those members of the HighNoon ensemble for which data were available, Fig. 7 (bottom row). In general the two HadRM3 simulations show an increase in the runoff through most of the year, with the REMO run driven by ECHAM5 showing a slight reduction during certain months of the year (e.g. April, August November and December). The spatial distribution is not uniform across the catchment; this is illustrated in the difference (2040–2070 minus 1970–2000) plots of runoff shown Fig. 9.

In both precipitation and runoff the ensemble members span zero and therefore even given the similarities between these models, there are considerable differences in their projections of future climate. This highlights that projections of rainfall and runoff are more variable and therefore less certain than those for temperature, where all the models in this analysis agree on sign if not magnitude. This is highlighted in the summary given in Table 2. The uncertainty in precipitation is supported in the AR4 model ensemble which indicates a small, 5%, increase in monsoon season rainfall (by 2050), but with an uncertainty of 20% (Kumar et al., 2011a). The variability in runoff and precipitation both in terms of sign of change and spatial pattern means that adaptation strategies should be both robust and flexible (e.g. Hay, 2007; Hertzler, 2007). In addition advances in modelling to include important aspects of the local environment such as aerosols and their transport, irrigation and land use change may alter the projections presented here (see Sections 4.3.1 and 4.3.2). Adaptation strategies such as improving the efficiency of water storage and infrastructure are positive changes in any climate. For example, in 2006 Singapore aimed to meet 15% of its water needs using reclaimed wastewater, a process with a low energy requirement (Tortajada, 2006), however Singapore's national water agency indicate that reclaimed water now accounts for 30% of the nations water needs (PUB, Singapore's national water agency, 2011).

3.1.2. Threshold analysis

The understanding of the vulnerability of a population, sector or industry to current weather and climate is an essential precursor to being able to adapt to potential changes to the climate in the future. Often this understanding is through critical thresholds above which there are impacts on a population or industry, for example, a total monthly rainfall value which could affect infrastructure or a temperature which is significantly warmer than the average temperature and could therefore cause health problems or crops to fail (see Table 1).

The main industry in the Brahmaputra–Ganges catchment is agriculture and in this industry there are many fundamental thresholds that are important. One example of a critical temperature for rice production is a temperature of greater than 35 °C during the crucial flowering period as this can affect the fertility of the plant (Yoshida, 1981). Fig. 10 (bottom row) shows the change in the number of days per year with the maximum temperature above 35 °C between the baseline (1970–2000) and the future (2040–2070) for two of the HighNoon ensembles. In these two ensembles, there is an increase in the number of days exceeding the 35 °C threshold across the south of the catchments for these two ensembles of 26 to 28 days on average but an increase of 70 days in the east of the region. On the basis that this region is one suitable in the current climate for multiple crops per year, an increased incidence of periods with temperatures above the 35 °C threshold could increase the likelihood of these temperatures coinciding with crops flowering. Further analysis would be necessary on temperature, water availability and other interactions for example the influence of rising CO_2 to diagnose the full regional impact on crop yield.

Another factor important to India is population health and energy demand. Anecdotally a temperature threshold of 28 °C has been used (gathered from various online sources, see web references 1; 2 and 3) to represent a threshold at which energy demand increases; due to the population using energy to operate cooling mechanisms such as air conditioning to remain comfortable. Sherwood and Huber (2010) also highlight the importance of humidity and how this exacerbates the effect of high temperatures, while the UK Heat Health watch[2] recognises the importance of cooler nights which allow a period of recovery. Fig. 10 (top row) shows the difference between the two periods: 2040–2070s and the baseline (1970–2000) in the mean number of days per year that are projected by these two ensembles to exceed 28 °C. Both ensembles indicate an increase in the south of the Ganges–Brahmaputra catchment, with a mean increase of 25 to 30 days for these two ensembles, with a maximum of 80 days in the east of the region.

This large range in the difference between the numbers of days with a maximum temperature that exceeds particular thresholds for the 2050s compared to the baseline is due to the complex terrain of the region which varies from high mountainous regions to low-lying deltas. Analysis of lower thresholds would be more appropriate for regions of high elevation where the mean temperature is lower; in addition, different temperature thresholds for both health and energy

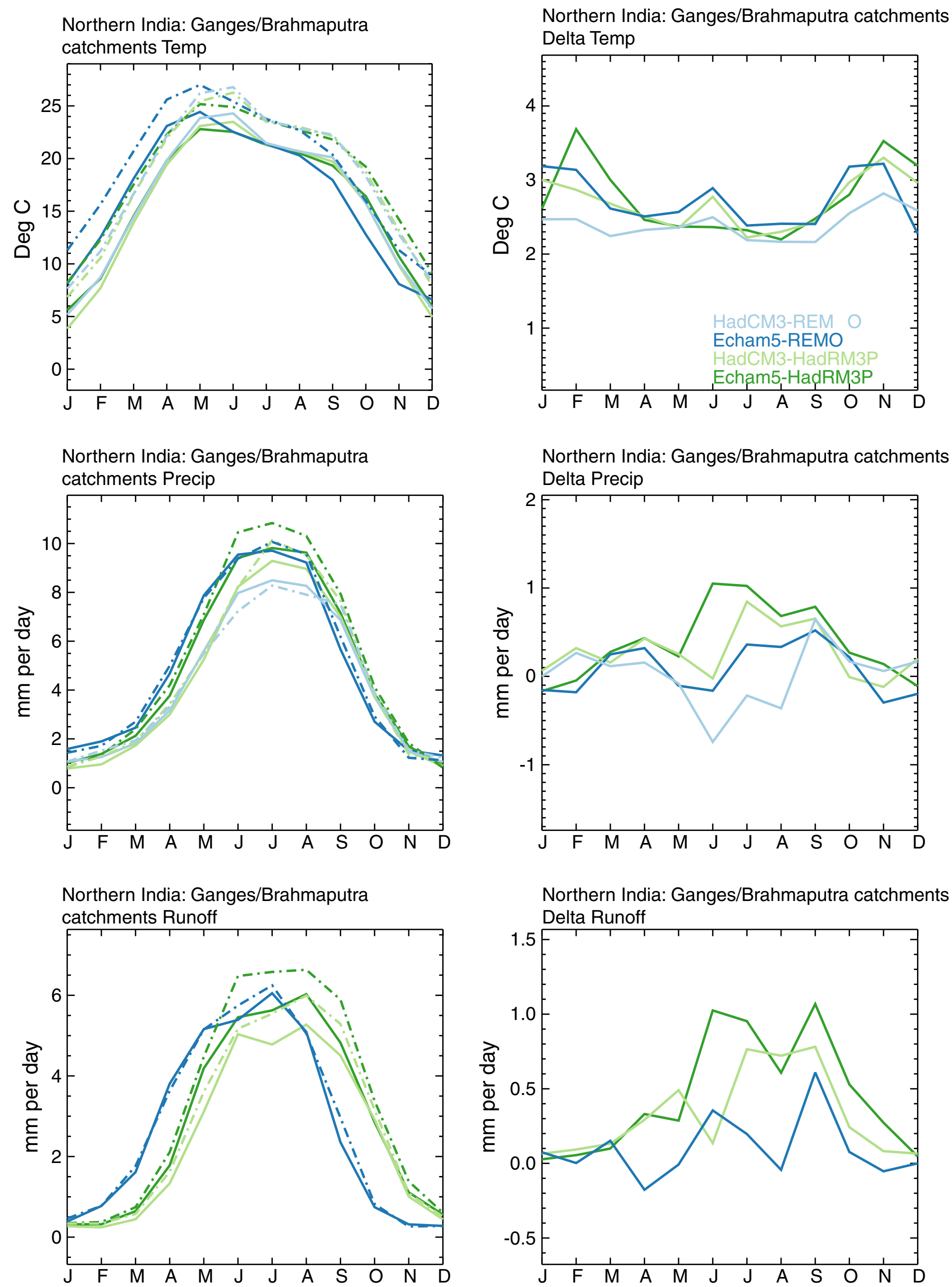

Fig. 7. Annual cycle in temperature (top row), precipitation (middle row) and runoff (bottom row) for the future period: 2040–2070 (dotted lines) and baseline: 1970–2000 (solid lines, left column) climatologies and the differences between the annual cycles for the two periods (right column) for the Ganges Brahmaputra catchment HighNoon ensemble members.

demand may apply to different locations since local infrastructure and local populations may differ in their current adaptation to heat.

4. Discussion: uncertainty and adaptation

The model simulations from the HighNoon project are the most complete set of data available for South Asia and are therefore a useful and important resource for the types of climate analyses illustrated in Section 3.1. However there are uncertainties in the models and understanding of atmospheric processes at both global and regional scales, the implications of which are not yet fully understood and yet could significantly change the regional projections if included in climate models. In this section we describe sources of potential uncertainty in climate models and specific processes that could be particularly relevant for the South Asia region. This uncertainty needs to be accounted for if adaptation related decision making is to be robust.

4.1. Sources of uncertainty

Climate models are a physical representation of a highly complex system based on mathematical equations that simplify complicated physical processes. In defining a climate the complex system is the whole Earth system, including oceans, atmospheric processes, the land surface and ecosystems and atmospheric chemistry. While parts of this system can be well represented by mathematical relationships, models cannot provide a 'perfect' representation, due to limitations in scientific understanding of the large number of different processes, dependencies and feedbacks and due to limitations in computing resources. Climate models and their projections are therefore affected by many aspects

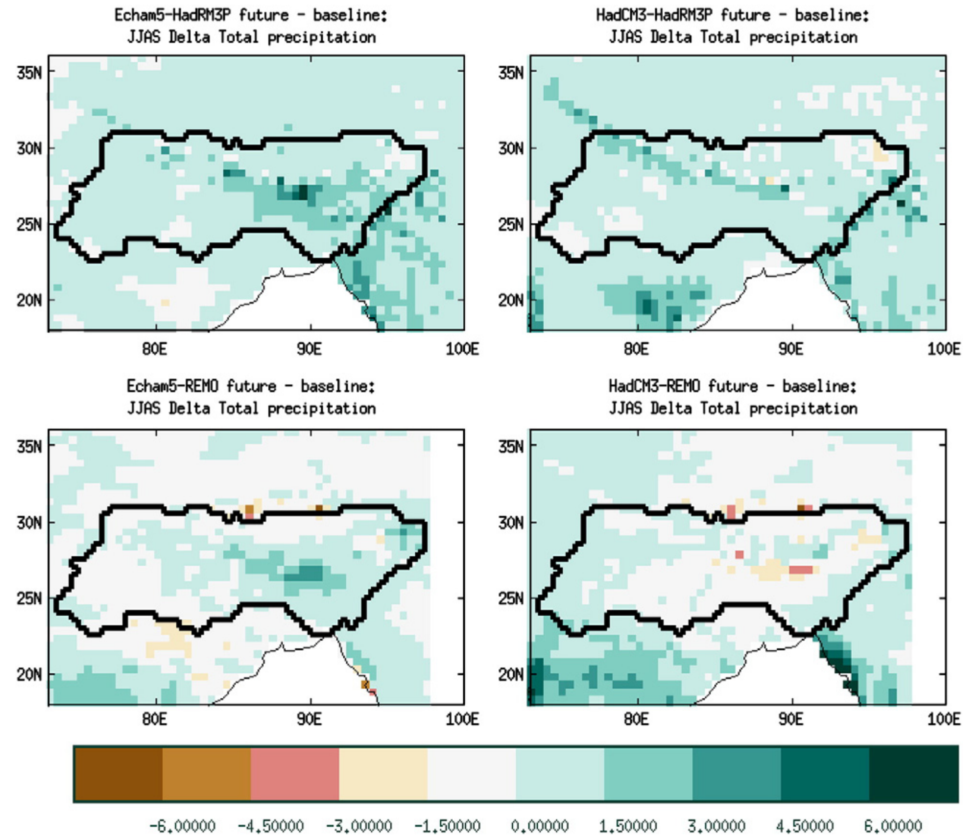

Fig. 8. Difference between 2040–2070 and 1970–2000 climatologies of total precipitation for the JJAS season for the Ganges Brahmaputra catchment (highlighted) for the four HighNoon ensemble members.

such as the choice of numerical method to solve the dynamical equations; the processes that are included and the parameterizations that are used; as well as any assumptions that are made. All of these potential differences between models mean that every climate model could produce different projections creating a spread of results; this is known as structural uncertainty (Sexton et al., 2011; Sexton and Murphy, 2011). In addition to uncertainty from the structure and composition of the model, different settings of key parameters within the parameterizations of one model can also lead to a spread in projection results; this is parametric uncertainty (Sexton et al., 2011; Sexton and Murphy, 2011). For example an uncertain physical parameter relevant to water and agriculture is the relationship between carbon dioxide concentration in the atmosphere and plant stomatal closure, in this example the uncertainty has considerable implications for water resources (Wiltshire et al., 2013).

Model and parametric uncertainties are mainly due to the limitations of the current modelling system; however there are other sources of uncertainty that are more related with the chaotic nature of the natural environment; this is referred to as natural internal variability. This type of variability in the climate system occurs from regional scales to large-scale interactions between the atmosphere and oceans such as the El Niño/La Niña-Southern Oscillation (ENSO). Natural external variability includes factors that can influence the climate but are not part of the climate system, such as volcanoes and the solar cycle. Currently, there is no way of predicting how the solar radiation reaching the Earth will change in the future; therefore this is not included in models. There is also no way of predicting when, on climate timescales, a volcano might erupt in the future nor how much ash it will emit into the atmosphere, therefore this is not modelled in any climate projections. Though both of these types of variability are missing in the climate models used in

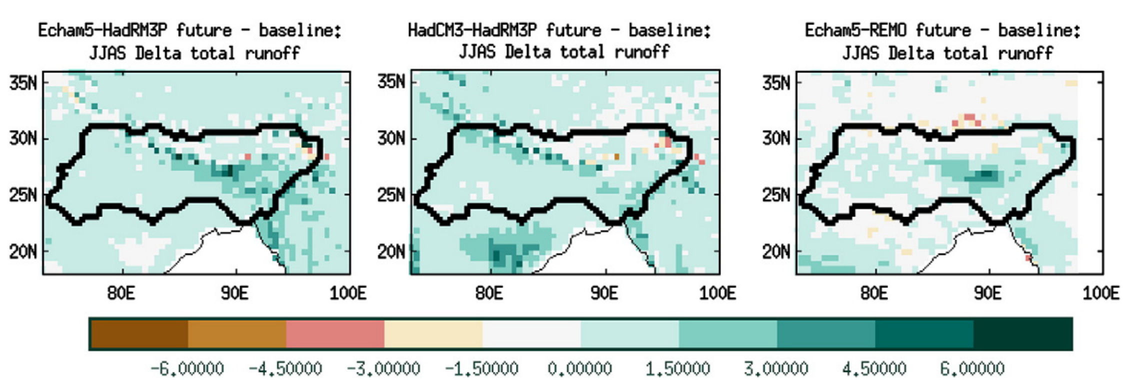

Fig. 9. Difference between 2040–2070 and 1970–2000 climatologies of total runoff for the JJAS season for the Ganges Brahmaputra catchment (highlighted) for the HighNoon ensemble members (the units of river flow given in mm/day).

Table 2
Summary of differences future − baseline for temp, precip and runoff.

Differences future − baseline across ensemble	Annual			Seasonal (JJAS)		
	Min	Mean	Max	Min	Mean	Max
Temperature (°C)	2	2.6	3.7	2	2.4	2.9
Precipitation (mm/day)	−1	0.2	1	−1	0.4	1
Runoff (mm/day)	−0.2	0.2	1	0	0.45	1

the analysis in this paper, on the 30-year timescales (used in Section 3) their effects are considered unlikely to have a large long-term impact.

The third major uncertainty in climate projections is associated with how human activities will influence and interact with the environment. This is dependent on many factors across a broad spectrum from economic and policy driven aspects to social behaviour; making it difficult to predict how the population could change or how future populations might consume resources. In the IPCC AR4, the Special Report on Emissions Scenarios (SRES) representative pathways were used to depict a range of plausible future emissions (Nakićenović et al., 2000); however none of these scenarios represent a mitigation scenario and therefore no projection of the impact of future mitigation is currently available. These scenarios often include assumptions about future changes in population, land use and other socio-economic factors.

The relative roles of these different sources of uncertainty depend on the time scales under consideration. On decadal timescales, the climate change signal is small compared to natural variability, such that uncertainty caused by initial conditions and natural forcing dominates (Hawkins and Sutton, 2009, 2011). This timescale is often consistent with the timescales of adaptation of infrastructure. Research on decadal climate predictions is just emerging (e.g., Collins et al., 2006; Smith et al., 2007; Keenlyside et al., 2008), and no regional climate predictions on decadal scales currently exist. However, decadal and seasonal prediction may significantly improve our understanding of adaptation requirements over the next few decades (Betts et al., 2009).

The HighNoon RCM ensemble is comprised of four simulations and therefore it is unlikely to capture the full range of uncertainty of a larger ensemble for example, from the IPCC AR4 (IPCC AR4, 2007). The IPCC AR4 ensemble showed a global mean annual temperature change of between 1.7 and 4.4 °C for the A1B scenario, regionally for South Asia the change was between 2 and 5 °C. Precipitation for South Asia is much more variable in the IPCC ensemble, showing changes in annual precipitation of between −15 and +20% for the A1B scenario. Though the analysis showed here does show a similar range in temperatures and large variation in precipitation, similar to the AR4 ensemble, this analysis is for a much smaller area (just the Ganges–Brahmaputra catchments) than the IPCC South Asia region so the two are not directly comparable.

In general the implications of using an ensemble of future climate projections that captures the uncertainty in the climate system sufficiently may include the following:

- *Strong agreement on sign and magnitude of changes*: more confident adaptation decisions can be made (for example, on both the need to increase water storage, and on the range of capacity required).
- *Agreement on the sign, but not magnitude of changes*: adaptation decisions will need to be more flexible (for example, a broader range of water storage capacity).
- *Disagreement on the sign of changes*: adaptation plans may need to be flexible to changes in both directions (for example, a very broad range of water storage capacity or hedging by planting mixes of different crop types).

4.2. Large scale processes

Global model simulations supply the large scale information at the boundaries of the RCMs and the correct representation of key large-

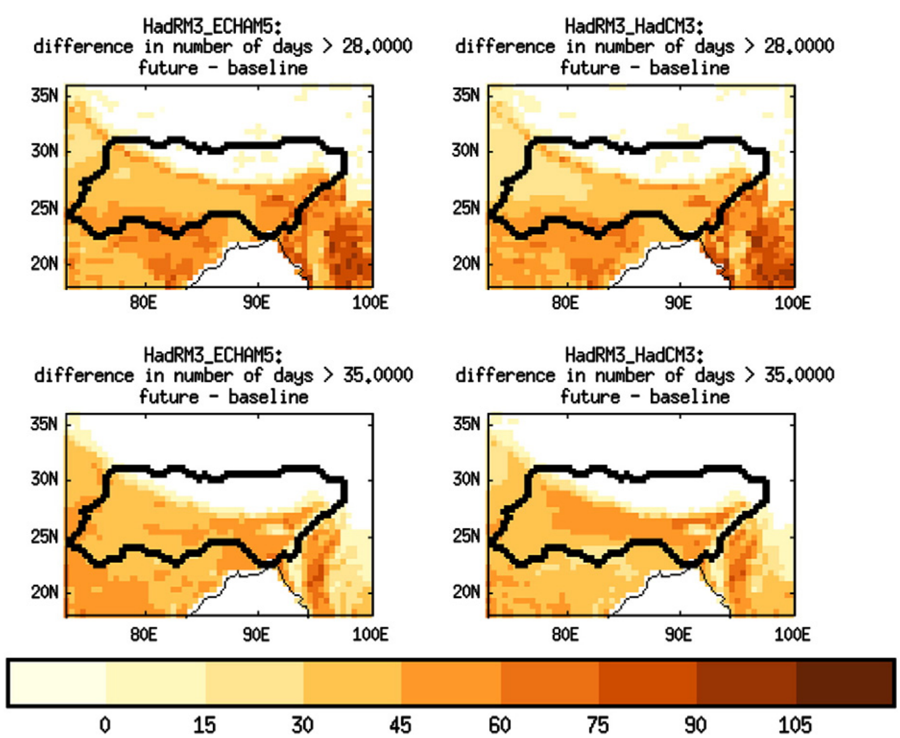

Fig. 10. The figure shows the difference between the number of days per year for the future period 2041–2070 minus the baseline (1971–2000) where the maximum daily temperatures exceed 28 °C (top row) and 35 °C (bottom row) for the two HadRM3 simulations driven at the boundaries by ECHAM5 (left) and HadCM3(right).

scale processes is therefore extremely important in constraining the RCMs (Lucas-Picher et al., 2011). An RCM is first-order sensitive to the driving lateral boundary conditions (Liang et al., 2008) and therefore reduction of the errors in the large-scale circulation will mainly be possible through development of the driving GCM. Therefore it is important to improve representation of physical processes at the global scale as these could have an impact on regional models, for example ensuring the large scale correlations between flows at remote locations; referred to as teleconnections (James, 1994) are represented properly. The El-Niño Southern Oscillation (ENSO) is a well known teleconnection pattern which is considered to contribute to the total interannual variance over much of the globe (James, 1994). This is particularly important for this region as the interaction between ENSO and the inter-annual and inter-decadal Hadley circulation has been shown to significantly affect the South Asian Monsoon (Krishnamurthy and Goswami, 2000).

The ISM is a key driver of the climate in South Asia providing the main source of water for populations in India, Bangladesh, Myanmar and Nepal. Therefore understanding the processes, global or more localised, that feedback and affect the intensity of the monsoon rains is important for representing the climate of the region.

The RCMs resolve other processes that are important for the regional climate but occur on a resolution too small for global models to resolve such as precipitation enhanced by local orography, coastlines or the effect of land use. Gaining a better understanding of these processes occurring on a regional scale should improve the model representation of the regional climate system and ultimately could affect the range of uncertainty in model projections of future climate.

4.3. Local influences on regional climate

As previously discussed, the inertia in the global climate is sensitive, partly to the long-lived nature of atmospheric carbon dioxide. Therefore even if atmospheric concentrations are stabilised the globe will continue to warm indicating a commitment to adaptation. However, on the regional scale, local influences can play a substantial role in the local climate on comparatively shorter timescales. For instance the atmospheric lifetime of black carbon is approximately 1 week. Similarly, irrigation has been shown to alter the climate of South Asia. In the remainder of this section we consider the processes that are not currently represented in the regional model simulations presented here, but could be important; such as black carbon and the occurrence of Atmospheric Brown Clouds, land use, irrigation and soil properties. In some cases these localised processes could substantially alter the climate over the next few decades significantly altering the needs of adaptation.

4.3.1. Atmospheric brown clouds and black carbon

Asia is a region that relies on coal powered energy generation and therefore emissions of black carbon are relatively high in this region, such that UNEP have identified this region as an Atmospheric Brown Clouds (ABC) hotspot. ABCs are regional scale plumes of air pollution consisting of particles (referred to as primary aerosols), black carbon and pollutant gases such as nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2), ammonia (NH_3) and other organic gases and acids. ABCs have been shown to have significant impacts on the regional climate of India especially the monsoon (Meehl et al., 2008; Wang et al., 2009); such is the concern over ABCs that a comprehensive impact assessment report on ABCs with particular focus on Asia was commissioned by the United nations Environment Programme (UNEP, 2008).

Black carbon particles are typically small in size and chemically inert and therefore remain in the atmosphere for up to a week before they are precipitated or deposited out. This relatively long lifetime in the atmosphere means that these particles can be transported considerable distances away from the emission source and therefore the effects of black carbon can extend well beyond the regions where the concentration is highest (Wang et al., 2007). Black carbon causes radiation to be absorbed higher in the atmosphere therefore preventing radiation from reaching the surface, simultaneously warming the troposphere and cooling the surface thereby making the atmosphere more stable. The combined effect of this change in distribution of energy through the troposphere and the reduced evaporation from a cooler surface suppresses convective precipitation (Ramanathan et al., 2005, 2007a, 2007b). Black carbon also absorbs radiation reflected from the surface, hence reducing the amount of radiation that is reflected back into space, thus reinforcing its positive radiative forcing effects.

Black carbon could also affect the lifetime of clouds in the atmosphere and therefore have an impact on large-scale precipitation patterns. The varied composition of ABCs is likely to mean that their effect on precipitation and radiative forcing is likely to vary considerably from region to region. This will mean some areas experiencing increases and others decreases in precipitation. The deposition of black carbon has also been shown to affect snowmelt and glacial melt by reducing its albedo (Qiu, 2010). The effects of black carbon and ABCs on the atmosphere are therefore complex and diverse making them difficult to represent fully in climate models. However given that black carbon emissions have increased by three times in South Asia between 1950 and 2000 together with an observed decrease in ISM precipitation of approximately 5–7% for the same period, ABCs are an increasingly important feature of the Asian climate. In the HighNoon simulations there is no representation of the aerosol species in ABCs or their transport; however it is possible that their impact on future projections could be large and have a significant impact on surface energy and moisture fluxes.

4.3.2. Land use and irrigation

As the population of India grows, demand for food and water could potentially drive changes in land use either to increase the amount of agricultural land or increase the productivity of the land already being farmed. Land use change has been identified as a key driver of climate change not only through absorption or emission of greenhouse gases but also by modifying the physical properties of the land surface (Betts et al., 2006). For example changing the land cover from dark forest to agriculture will mean more exposed bare soils which will affect the surface roughness and albedo as well as the fluxes of moisture and heat (Betts and Ball, 1997). The effects of changes in land use depend on the region and the conditions at a particular location.

There is growing evidence that human activities that change the land surface can have an impact on regional climate. Irrigation is an important modification to the land-surface, essential for the success of agriculture in dry climates such as the Ganges Brahmaputra region. Irrigation has important effects on the hydrological cycle at a number of different stages. Extraction of water from rivers and ground water for irrigation reduces their flow, transferring moisture to the soils and plants, thus modifying the land-surface moisture fluxes through evaporation and transpiration. The changes in vegetation distributions and the increased water vapour present in the atmosphere affect the heat and moisture fluxes at the surface, in turn this has an effect on the generation and lifetime of clouds, which affects precipitation. An example of this is given by Lohar and Pal (1995), they report a reduction in mean monthly rainfall over West Bengal (for example the March rainfall reduced from 50–80 mm between 1973 and 1982 to 20–40 mm between 1983 and 1992); a region which has experienced a rapid expansion of summer paddy crop agriculture along the coast (with an increase of more than 3-fold between 1980 and 1990). The high moisture content of paddy fields has reduced the temperature difference between the sea and land, thus reducing the strength of the sea breeze and therefore convection. Douglas et al. (2009) show that the effect of moving to irrigated croplands varies regionally but for the Ganges–Brahmaputra basins there is a reduction in the rainfall of between 20 and 60 mm for a 5-day period during the ISM. Douglas et al. (2009) demonstrated that by modifying the moisture flux over a large enough area and reducing the Convective Available Potential Energy (CAPE) the mesoscale convection patterns are modified therefore affecting the rainfall patterns across India. Douglas et al. (2006) reported regional differences in latent heat flux across India; with increases in the northern regions due to changes in land-use from drier soils to irrigated agriculture. These reductions in precipitation will have direct consequences on the regeneration of groundwater and the flow of the rivers in the region.

Saeed et al. (2009) demonstrate the impact of including an irrigation scheme in an RCM on the modelled South Asian Monsoon using the REMO RCM driven by ERA-40 data (Uppala et al., 2005). In parts of India such as the Indus and Ganges basins, which are highly irrigated regions, there is a warm bias in the model which can be as much as 5 °C. Including irrigation in the REMO model reduces the warm bias in the model which weakens the westerly winds from the Arabian Sea. This allows the advection of moist air into western India and Pakistan removing the low precipitation bias also in evidence in these regions. Irrigation also improves the evapotranspiration in these regions by routing water more effectively.

In the RCM runs for HighNoon there is no accounting for the effect of land use change or irrigation and therefore their impact on the regional climate is not captured. Though it is possible to use offline land-surface simulations to route the rivers more effectively this would not capture the feedbacks of the more efficient routing and improve the evapotranspiration on larger scales. Representing physical processes important in the vicinity of steep orography, leading to enhanced ascent of air, affecting cloud and precipitation formation and resulting in increased moisture along the upslope (Yasunari, 1976; Singh et al., 1995) are likely to improve the precipitation simulations for the region. Also, the important mountainous physical processes such as snow drift/accumulation, liquid to solid precipitation formation, and rain shadow effect need explicit driving mechanisms in the model physics (Leung and Ghan, 1995). Incorporation of such physical processes will enhance the model reliability towards adaptation issues associated with the extremes of precipitation issues such as changing agriculture patterns, population migration and health.

4.3.3. Soil properties

The important influence of soil properties on the climate, particularly the coupling between soil moisture and rainfall have been identified by a number of studies (Kendon et al., 2010; Koster et al., 2004, 2006). Koster et al. (2006) identify South Asia as a region with particularly strong coupling which results in a warm bias in models over the region; this is referred to as a hotspot. Though this regime has been identified in several models, a sensitivity study for Europe (Anders and Rockel, 2009) demonstrated that this warm bias is affected by soil type.

In order to isolate the effect of different soil properties two simulations using the 25 km REMO RCM using ERA-Interim boundary data for the HighNoon domain were performed; one using the standard soil hydrology and soil thermal characteristic (baseline) and the other using a modified soil thermal characteristic (test). Initial analysis of these simulations suggests that soil properties could be important.

REMO uses the Dümenil and Todini (1992) soil hydrology scheme which uses a bucket type soil module, where each grid box is represented by a single soil water reservoir i.e. the depth of the bucket. Therefore the water available for evaporation is defined by the rooting depth of the plants and the soil texture properties. The comparison of the current climate from the baseline simulation with CRU observation data sets indicates a warm bias in the surface temperature of as large as 8 °C in some parts of northern regions. In REMO, thermal diffusivity and capacity are parameterized as a function of soil moisture, using external constants as reference values independent of soil moisture. These reference values represent values of a medium moist soil for a mid-latitude rainy climate; however the climate over South Asia is mainly dry categorised as arid or semi-arid climate. Thus in the test simulation the soil thermal characteristic is modified to be more representative of dry soil by changing the thermal diffusivity and the conductivity (Gordon, 2002). The comparison of the test simulation with CRU observation data sets show a reduction of the warm bias observed in the baseline simulation of between 1.5 and 4 °C.

4.3.4. Summary of missing processes

The list of processes presented here, though not exhaustive, illustrates the considerable uncertainty that arises from these missing processes in the model simulations. For instance, the inclusion of irrigation can reduce the simulated temperature biases by approximately the same magnitude as the range presented by the ensemble members. Black carbon and other aerosols in the atmosphere, both in terms of their chemistry and transport, have been observed to have an increasing effect on the regional climate acting to reduce precipitation during the ISM, however these observed precipitation changes are currently within the range of uncertainty of the HighNoon ensemble.

5. Conclusions

We have completed four simulations for the HighNoon project covering India and the Himalaya using two different regional models (REMO and HadRM3) with boundary data supplied from two global models (ECHAM5 and HadCM3). Analysis of the ensemble members has shown that they represent the general processes and climate of the region although the observed patterns in rainfall and temperature are not replicated exactly. This ensemble is the most complete (1960–2100) high resolution (25 km) data set available for the region providing data across a wide range of model variables. This ensemble provides useful information on the potential future changes in temperature (e.g. increasing mean temperatures of between 2 and 4 °C) and precipitation (though precipitation is more variable with a range of ± 1 mm/day across the ensemble). Analysis of the model data using known critical thresholds can provide useful information for industry, population and infrastructure; for example the change (between 1970–2000 and 2040–2070) in the number of days with maximum temperatures exceeding 28 °C is between 25 and 30 days. In using this information it is therefore important to balance the risks versus benefits of the adaptation policy, for example what are the costs of adaptation against the costs of no action, while considering the potential cost of adaptation in response to incomplete science. In this situation there is a requirement for adaptation pathways that do not restrict the future ability to adapt and are therefore resilient to both future advances in science and natural changes in the environment. Therefore the projections discussed here should be viewed as providing scoping information rather than supporting detailed adaptation plans.

Regional climate impacts are often strongly dependent on the climate data and scenarios used and the assumptions made, suggesting the need for application of a wider set of common scenarios (including both climate and socio-economic factors), and a more in-depth assessment of assumptions and factors considered to enable a better comparison across studies. This also supports the need for a risk-based approach which considers model skill, confidence, and uncertainties in future projections more comprehensively. In light of the many sources of potential uncertainty discussed above, Hay (2007) and Hertzler (2007) suggest that the development of robust ways of applying uncertain climate information to agricultural decision making (e.g. hedging, foreclosing options, creating new options and diversification) will be critical in planning resilient future land/water management options for agriculture. Similar approaches will also be important for adaptation planning for other impacts sectors.

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