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Environmental Impact Statement

This work describes the modelling of climate change for the period up to 2100 over south Asia using a high-resolution regional climate model. The modelling approach takes account of model parameter uncertainty using a perturbed physics ensemble. Bangladesh is recognised as being highly vulnerable to climate change, and the model projections presented in this paper have been used to drive a diverse range of biophysical impacts models for the region and to inform scenario development in the Ecosystem Services for Poverty Alleviation (ESPA) Deltas project which is aimed at informing policy decisions.

Environmental Science Processes & Impacts

PAPER

Temperature and precipitation projections over Bangladesh and the upstream Ganges, Brahmaputra and Meghna systems

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South Asia is a region of complex atmospheric dynamics and therefore changes resulting from increasing greenhouse gas concentrations, combined with existing vulnerability to extreme weather events such as flooding, could put the region at particular risk from climate change. However, current climate projections for the region show a range of uncertainty, particularly in terms of changes in the variability and extremes of precipitation. Focusing on Bangladesh and the region encompassing parts of the Ganges, Brahmaputra and Meghna river basins, we aim to explore and quantify climate model uncertainty in climate change projections for the 21st century. We use results from a 17-member perturbed physics ensemble of projections from a global climate model which have been used to drive a higher resolution (25km) regional climate model over the south Asia region from 1971 to 2099. The range of temperature and precipitation responses across the ensemble are assessed including representation of the annual cycle, trends, and changes in precipitation extremes. The 17 ensemble members consistently simulate increasing annual mean temperatures by 2100 compared with present day, ranging between 2.7°C and 4.7°C. Additionally, all ensemble members indicate increasing annual precipitation by 2100 of between around 8% and 28%, though with interdecadal variability which results in one ensemble member showing a slight decrease in precipitation in the mid-century period. The frequency of light precipitation events is projected to decrease in the future, but with an increase in the frequency of heavy events. Three members of the climate model ensemble, representing a range of projected climate outcomes, have been selected for use in further impacts modelling for the region.

Introduction

Bangladesh is recognised as being highly vulnerable to the potential impacts of global and regional climate change due to its geographic location and in particular its low-lying topography, which is at high risk of enhanced extreme flooding. Around 80% of the country forms the floodplains of the Ganges, Brahmaputra and Meghna (GBM) rivers[1]. It is also a densely populated country which is heavily reliant on agriculture which can be severely affected by changes in precipitation variability which could lead to enhanced flooding or drought.

Bangladesh has a tropical monsoon climate, characterized by high temperatures, heavy rainfall, high humidity and strong seasonal variations. An integral part of the region's climate lies in the seasonal reversal of atmospheric circulation between the winter and summer months. On annual timescales, rainfall accumulation varies from approximately 1400 mm in western parts of the country to over 4300 mm in the east[2].

The climate in Bangladesh can be separated into four seasons: pre-monsoon (March-April-May), monsoon (June-July-August-September), post-monsoon (October-November), and winter (December-January-February). The summer monsoon is a key time for precipitation when around 70-80% of the annual total rainfall occurs[2,3]. Intense rainfall during the post-monsoon season can be related to land-falling tropical cyclones. Although the cyclone season runs from May to December in the northern Indian Ocean, the heat in the upper ocean layers during the post-monsoon can lead to more frequent occurrences[1]. In contrast, the reversal of the circulation pattern during winter brings cooler and drier conditions, with this season accounting for only 2-4% of annual precipitation totals.

Previous climate modelling studies for the region have tended to focus on the wider Indian subcontinent region[4,5,6], and there have been few studies of high-resolution models focused solely on the Bangladesh region[7,8]. Results from observational studies indicate that during the last century Bangladesh experienced an annual mean temperature increase of around 0.5°C[7], along with increasing average rainfall[9]. Climate models generally project increases in temperatures over Bangladesh by the end of the century, though with a range of uncertainty associated with the greenhouse gas emissions scenario and the climate model employed[7,8,10]. Similarly a number of studies project an increase in annual rainfall for Bangladesh in the

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future[7,8], with the intensity of heavy precipitation events projected to increase across the country[5,11].

Realistic representation of precipitation during the summer monsoon season is particularly important for producing user-relevant climate projections, since this season provides a large proportion of the region's annual rainfall. Current climate models simulate the Asian monsoon characteristics and dynamics with variable accuracy[12]. Some studies project a strengthening of the Asian summer monsoon circulation[5], whilst others project a weakening in the circulation, but with increasing precipitation also being seen in a number of these studies[13], giving an indication of the complexity of modelling the interactions between the climate processes over this region.

The Ecosystem Services for Poverty Alleviation (ESPA) Deltas project aims to provide information and tools to policy makers so that they can evaluate the effects of decisions affecting the environment on people's livelihoods in the south-western Bangladesh delta region. An important component of this project is the use of a range of biophysical models, feeding into an integrated modelling framework[14], into which the assimilation of climate variability and climate change projections are a key input. In this paper we focus upon surface temperature and precipitation as the variables most important to impacts being assessed in this project. However, in addition to these core variables, a requirement from ESPA Deltas was to provide a range of climate variables (atmospheric, land surface, and also ocean data from the driving global climate model) in order to drive a range of biophysical models[15,16,17,18].

Climate change simulations

Climate models

Global general circulation models (GCMs) are invaluable tools for assessing potential climate change resulting from increased greenhouse gas concentrations[10]. GCMs are able to simulate the interactions between the ocean, atmosphere and the land surface, and large scale processes which can influence the Asian monsoon circulation, such as the El Niño-Southern Oscillation. However, due to the high computational requirements for running century-long simulations of the global climate system, GCMs are more frequently run at a relatively coarse horizontal grid resolution, with grid boxes of a hundred or more kilometres across. This makes it difficult for the model to capture the finer-scale climate characteristics which are influenced by local conditions such as mountains or coastlines[19,20].

To overcome the limitations of the coarse resolution GCMs, we adopt an approach known as 'dynamical downscaling' whereby GCM output is used to drive a high-resolution regional climate model (RCM) which is better able to represent local topography, coast lines, land use and regional atmospheric processes. This can add significant detail to the information obtained from GCMs, in particular for regional climate impacts studies and analyses of extreme events[21]. The first stage in the process is to run the global GCM simulations that will be used to provide the boundary conditions required to run the atmosphere-only RCM. The GCM used here, HadCM3, is a version of the third climate configuration of the Met Office Unified Model[22,23,24]. It is run at an atmospheric resolution of 2.5° x 3.75° (resulting in grid boxes of approximately 300km across depending on latitude) with 19 vertical levels, whereas the ocean component has 20 vertical levels and a horizontal resolution of 1.25° x 1.25°. It should be noted that this version of HadCM3 includes flux corrections, which are not included in the version of HadCM3 used in CMIP3 and CMIP5[25]. HadCM3 is recognised as simulating the mean monsoon and inter-annual monsoon variability well compared to other GCMs[26].

The coarse resolution output from HadCM3 is used as lateral boundary conditions to drive the Met Office Hadley Centre RCM, HadRM3P[27]. This is a high-resolution limited area model which is used in the Providing Regional Climates for Impacts Studies (PRECIS) regional modelling system[20]. The resolution is 0.22° x 0.22° (approximately 25km) with 19 vertical levels and 4 soil levels. In this case, the model domain covers south Asia (with rotated pole coordinates of 260° longitude, and 70° latitude), which allows for the development of full mesoscale circulation patterns (such as drive the Asian monsoon) over the region of interest, and captures important regional dynamics[28]. A smaller sub-region was chosen in order to provide information for the region of interest in ESPA Deltas, which not only includes Bangladesh, but also the wider region encompassing the Ganges, Brahmaputra and Meghna river systems, which is important for studies of hydrology as part of the project (Figure 1).

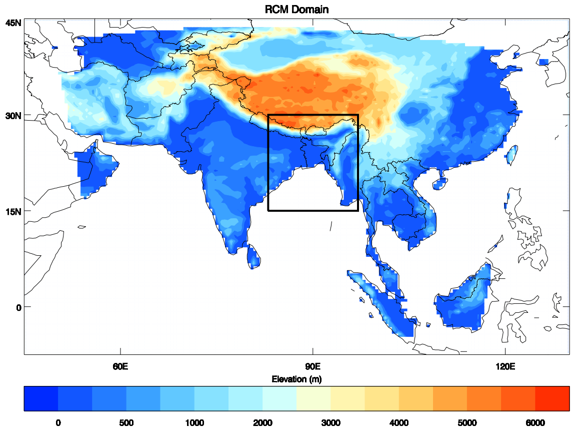

Figure 1: Regional model domain for South Asia used in this study with land surface elevation shown. The solid box (83-97°E, 15-30°N) shows the analysis region used throughout this paper. Area averaged values used throughout this paper are based upon all land grid points within this box.

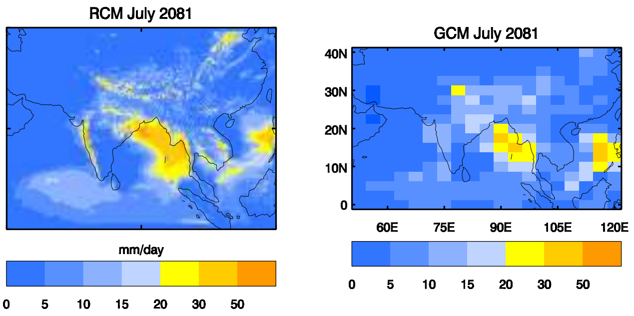

Figure 2: Comparison of the HadRM3P regional climate model (left) and the HadCM3 global climate model (right) resolutions (ensemble member Q0) over the equivalent south Asia domain for an example month of simulated precipitation in July 2081.

Most previous RCM model studies over the region have used a resolution of approximately 50km[8,29,30] so the increase to 25km would be expected to bring benefits in the level of detail being captured in the model, particularly for precipitation. A 25km version of HadRM3 has also been used in the HighNoon project[31,32], along with the REMO RCM[33], though in that project the focus was India and the simulations were based on a smaller overall domain size. A comparison of the grid resolutions of the RCM and GCM are shown in Figure 2 and the additional detail in the precipitation pattern captured by the RCM can be clearly seen.

Greenhouse gas emissions scenario

To assess the potential future impacts of increasing greenhouse gas emissions, scenarios are used which represent how emissions, and the associated atmospheric concentrations of greenhouse gases, might change in the future. The model simulations used here were driven by the widely used Special Report on Emissions Scenarios (SRES) A1B scenario[34]. SRES A1B was developed for the IPCC Third Assessment Report[35] and still underpins much recent research into climate impacts[36]. It is a medium-high emissions scenario and is based upon a future assumption of strong economic growth and the associated increase in the rate of greenhouse gas emissions.

The IPCC Fifth Assessment Report[10] uses a new set of scenarios called Representative Concentration Pathways (RCPs)[37]. SRES scenarios used socio-economic storylines as a starting point to develop emissions trajectories and determine climate outcomes, whereas RCPs start from the radiative forcing in 2100 and the associated greenhouse gas concentration trajectories. The different approach to scenario construction compared to SRES can make certain aspects of comparison challenging, although comparing climate responses to the differing scenarios has been carried out and it is possible to identify analogues between the SRES scenarios and RCPs[38]. SRES A1B lies between RCP6.0 and RCP8.5 in terms of the end of 21st century projected temperature increases and atmospheric CO_2 concentrations[38]. Figure 3 shows the global atmospheric CO_2 concentrations for SRES A1B along with the RCPs.

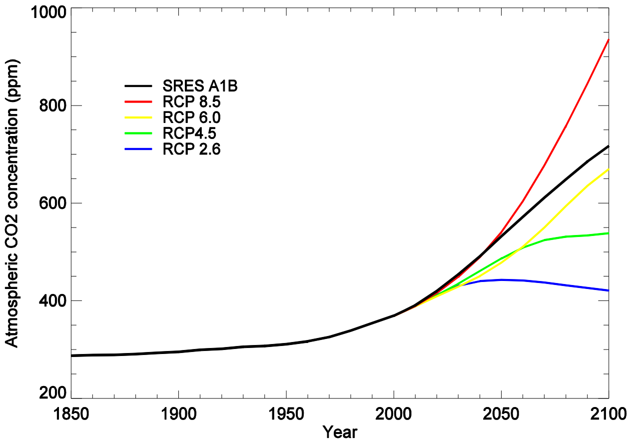

Figure 3: Atmospheric CO_2 concentrations (ppm) for the SRES A1B emissions scenario along with the four RCP scenarios.

Climate model uncertainty

There are three main categories of uncertainty in future climate projections, namely the natural climate variability, uncertainty in the greenhouse gas emissions scenario projections, and model uncertainty. Using an ensemble approach of multiple climate model simulations allows the uncertainty in different aspects of the projections to be explored. In this set of simulations HadCM3 is run as a 17 member ensemble using a perturbed physics ensemble (PPE) approach[39]. Each of the 17 global simulations was then used to drive an equivalent RCM simulation using HadRM3P for the south Asia region. A PPE approach is used in order to assess the uncertainty in a single climate model that is associated with uncertainty in a range of model parameters[40]. This is achieved by varying a selection of model parameters within a range of plausible values. Many model parameters are well constrained by observations, but there are others which are less well constrained. Different combinations of model parameters may give equally realistic simulations of present day climate, but could result in different projections for the end of the 21st century. As an example, one of the varying parameters is the critical relative humidity, which relates the model grid box atmospheric humidity to the amount of cloud in the grid box. Another example is the ice fall speed through cloud, which is important for cloud development and the type and amount of precipitation[39].

The ranges of the climate responses at both global and regional scales have been found to be larger in perturbed physics ensembles than for analyses of multi-model ensembles consisting of different GCMs[25]. The perturbed physics ensemble used here consists of 17 members, which represent a range of possible future outcomes for the same emissions scenario (i.e. SRES A1B). The individual ensemble members are referred to as Q0–16, where Q0 has the same parameter values used in the standard HadCM3 coupled GCM[39]. The 'Q' prefix comes from the name of the project which generated the GCM simulations, Quantifying Uncertainty in Model Predictions (QUMP)[39].

The 17 member HadCM3 ensemble was designed to sample a range of global climate sensitivities, which is an indication of the model global temperature response to a given amount of greenhouse gas forcing[39]. Q1 to Q16 are arranged in order of increasing global climate sensitivity in HadCM3, with a higher climate sensitivity indicating that the version of the model has a larger temperature response to a given increase in atmospheric CO_2. The range of climate sensitivities in the ensemble is between 2.26°C and 5.46°C. The standard ensemble member, Q0, has a value of 3.5°C and Q16 is the ensemble member with the highest climate sensitivity of 5.46°C. The IPCC AR5 gives a likely range in equilibrium climate sensitivities[10] of 1.5°C to 4.5°C, and very unlikely greater than 6°^{C}. It should be noted that regional and seasonal temperature responses should not be assumed to follow linearly i.e. the ensemble member responses over south Asia may not be ordered identically to the global sequence[41].

Whilst Q0 is the unperturbed version of HadCM3 it should not necessarily be considered as any more plausible than any of the other ensemble members. The 17 QUMP members were chosen from an original set of 280 to represent a set of well-performing models that span a wide range of the climate sensitivities seen in the 280 member ensemble[39]. It is thus important to note that none should be considered the most plausible and neither should they be regarded as equally likely.

Climate model validation

Observational datasets

Validating climate models can be challenging in some regions due to a lack of reliable and long-term observations, and also due to a lack of spatial coverage of observations. As a result of differences in their methodologies there may also be differences between observational datasets. In order to examine the RCM's ability to represent the present-day climate over south Asia we have utilized a number of high-resolution observational datasets for temperature and precipitation from a range of sources. For temperature, these consist of:

- Climatic Research Unit (CRU) TS3.10, with 0.5° x 0.5° resolution for 1901-2009[42].
- University of Delaware (UoD) air temperature with 0.5° x 0.5° resolution for 1950-1999[43], which has been reported to correlate well with the India Meteorological Department's 1° x 1° temperature dataset[44].

For precipitation, the observational datasets include:

- Climatic Research Unit (CRU) TS3.10, with 0.5° x 0.5° resolution for 1901-2009[42].
- University of Delaware (UoD) with 0.5° x 0.5° resolution for 1950-1999[43].
- The APHRODITE project's version 1003R1 dataset (Aph.v10) for monsoon Asia, with 0.25° x 0.25° resolution for 1951-2007[45].
- Global Precipitation Climatology Centre (GPCC) data with 0.5° x 0.5° resolution for 1951-2004 (http://gpcc.dwd.de/)

For the purpose of this work, the Bangladesh Meteorological Department (BMD) observational station dataset is not used directly due to its relatively low network density and poor spatial distribution[8]. However, BMD station data is incorporated into all of the gridded datasets that have been used in this study.

A number of challenges may arise when using multiple observational datasets for high resolution climate model validation. For example, while the spatial distribution across the precipitation datasets is relatively consistent, there are clear variations in the magnitude of maximum and minimum precipitation (see Figure 7). This gives an indication of the wide range of uncertainty across different datasets, which will need to be considered when assessing model performance. In addition to this uncertainty, the differences in resolution and gridding methods across observational datasets make them challenging to use in comparison to the RCM. The APHRODITE dataset is the only set of observations at an equivalent resolution to the RCM simulations at 0.25° x 0.25°, and therefore the other lower resolution datasets will not capture the fine-scale detail seen in these data or the RCM results. In order to fairly compare all observations and models on differing grids, all data is aggregated or interpolated to the lowest resolution across the observational datasets, which for this analysis is a 50 x 50 km grid for both temperature and precipitation. However, as the APHRODITE and RCM data are at a comparable resolution, it is reasonable to compare these two datasets directly. Taking these uncertainties into account, the validation of high-resolution RCMs over particularly small regions must consider the degree of uncertainty within observational datasets, and we therefore cannot expect to achieve a perfect match between the RCM and observations.

Spatial and seasonal model validation

A validation area is used to perform comparative analysis, such that the area encompassed by this region includes the country of Bangladesh and the wider region encompassing parts of the GBM river basins (Figure 4). We assess this region, which includes features such as the central Himalayas and the Himalayan foothills, to account for the fact that the impacts of climate in these regions (i.e. heavy rainfall/snowfall, river flow, etc.) have a strong influence on impacts experienced in Bangladesh. Within this domain, all of the observational and

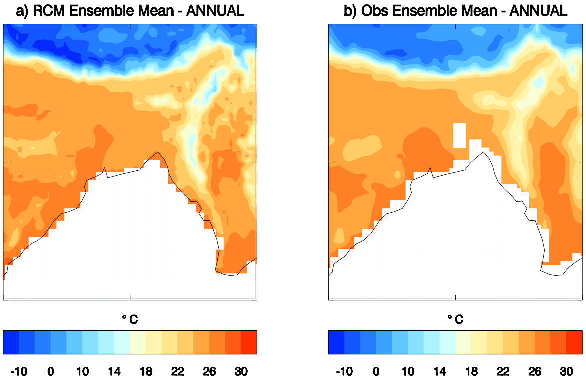

Figure 4: Annual mean surface temperature (°C) for (a) the mean of the 17 RCM ensemble members and (b) the observational ensemble mean for 1981-2000.

model datasets being used for comparison are regridded to a common 50 x 50km grid.

The RCM and observational ensemble means for annual surface temperature are depicted in Figures 4a and 4b, respectively. It is evident that the spatial distribution of surface temperature in the RCM matches closely with that of the observational mean, with temperature gradients across regions of complex topography (such as the Himalayan foothills) being realistically captured. The RCM ensemble is able to reproduce much of the observed climatological precipitation pattern (Figure 5), with maximum values over the Western Ghats and Himalayan foothills to the north and east of Bangladesh, and minimum values over much of central and north-western India. However, the RCM seems to slightly underestimate precipitation in central Bangladesh depicted through the lack of high rainfall regions when compared to the APHRODITE data. This could be arising due to complications in simulating orographical or deep-convective rainfall processes that are common to the GBM region.

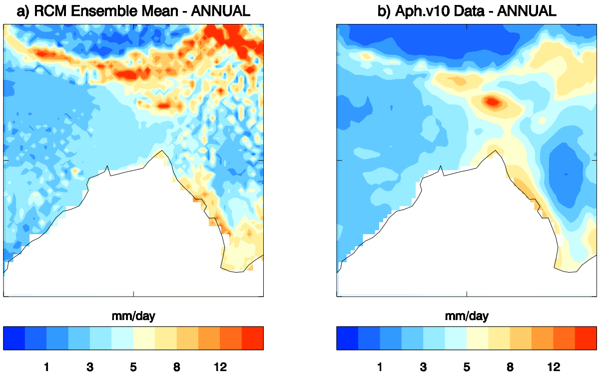

Figure 5: Annual precipitation rate (mm/day) for (a) the mean of the 17 RCM ensemble members and (b) the APHRODITE dataset for 1981-2000.

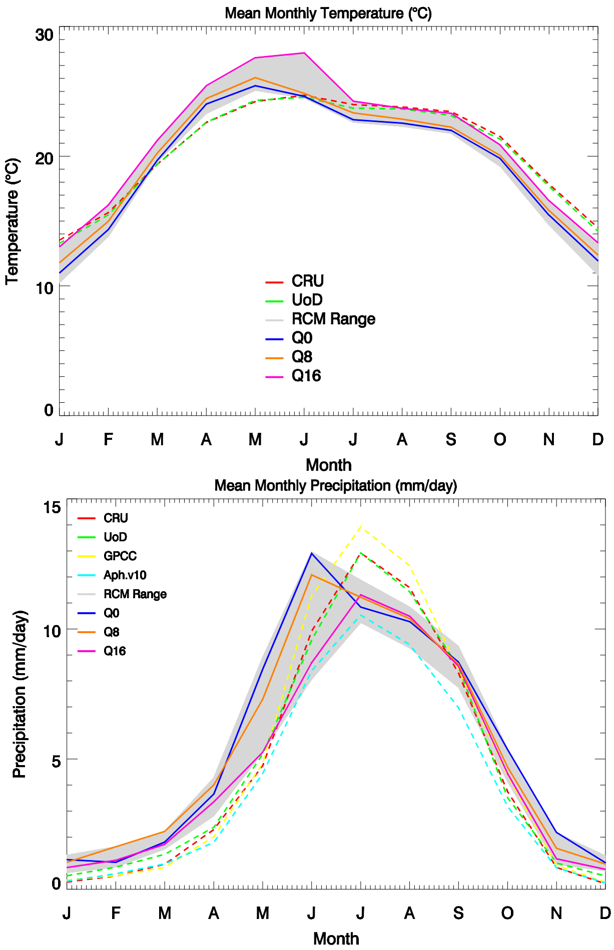

Figure 6: Mean monthly temperature (°C) (top) and precipitation (mm/day) (bottom) over the GBM sub-region (shown in Figure 1) for the period of 1981-2000 for the RCM 17 member ensemble range (shaded), three selected RCM ensemble members (Q0, Q8 and Q16), and the relevant observational datasets. Dashed lines indicate observations.

This highlights the challenge in realistically simulating the sensitivity of local precipitation processes, as observational datasets used for validation may not agree on the extent, magnitude and location of precipitation events.

The annual cycle depicted in the RCM results matches closely to both the CRU and UoD surface temperature datasets (Figure 6). The monthly mean temperatures calculated for the three highlighted RCM ensemble members (as well as the RCM ensemble mean, not shown), have a similar distribution to the observational datasets, with maximum temperatures for the ensemble occurring in the month of June. However, the RCM slightly overestimates temperatures during the months of May and June by ~1°C, and is slightly too cool during the remaining monsoon season by ~1°C. Also, the RCM consistently underestimates temperatures during the post-monsoon (ON) and winter seasons (DJF) by ~2-3°C. These biases are consistent with the comparative analysis results found in Islam *et al.*[8]

Realistic representation of the magnitude and extent of monsoon rainfall is important for climate modelling tasks in this region. However, the model's ability to realistically capture the timing of the monsoon season is of equal importance. Figure 6 also shows the monthly-averaged rainfall simulated by the RCM ensemble over the 20-year 'present-day' period for each month in the annual cycle, along with the four observational datasets used for comparative analysis. In general, it can be seen that all of the ensemble members are able to capture the start of the monsoon season in June, and its end in September. Also, the magnitude of summer monsoon rainfall in all of the RCM ensemble members falls within the range depicted by the four observational datasets. However, the ensemble members overestimate rainfall in times outside of the monsoon season, particularly during the pre-monsoon season (MAM), consistent with the results of Islam *et al.*[8]

Two of the selected ensemble members (Q0 and Q8) and the RCM ensemble mean indicate an early amplification of precipitation compared to observations and a peak in June as opposed to July in the observations. Similar results were found in a multi-model RCM study though using a different domain[46]. This found that HadRM3 simulated a peak in June precipitation in the Brahmaputra basin, whereas the observational ensemble mean indicated a peak in July. Similarly, the findings of Mathison et al.[31] also point to early monsoon onset in the RCMs, including HadRM3. However there is quite a large range of uncertainty between the different observational datasets for precipitation during the summer monsoon period as shown in Figure 6, with the RCM simulations falling within the observational range. As noted by Mathison *et al.*[31] it is difficult to attach uncertainty to precipitation observations in this region, particularly in areas of high elevation where observations may be limited.

Daily and extreme events

Changes in extreme rainfall characteristics could result in more frequent or severe flooding along with detrimental impacts on water resource management and agricultural productivity.

An analysis of the frequency of wet days during the present-day period (Figure 7) shows that the RCM does a good job of capturing the general spatial patterns and frequencies of wet days (defined as days with rainfall greater than 0.5 mm/day) compared with the APHRODITE observations. We then categorize daily rainfall into four types of events (light, moderate, heavy and very heavy) in order to investigate projected changes in rainfall intensity. These definitions use 20 years of JJAS daily data in the present-day time slice to define thresholds for each category based upon percentiles as follows: light, 0-25th percentile (0.5-6.6 mm/day); moderate, 25th-75th percentile (6.6-12.3 mm/day); heavy, 75th-99th percentile (12.3-23.8 mm/day) and very heavy, >99th percentile (>23.8 mm/day).

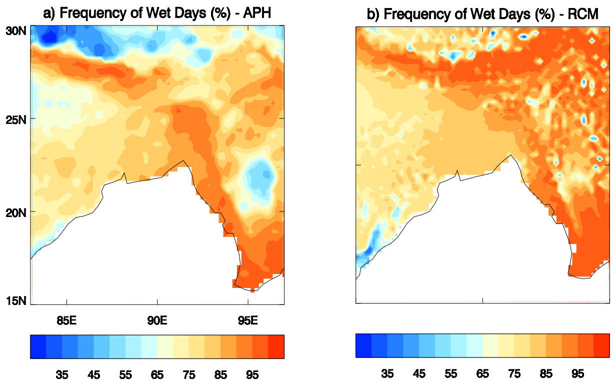

Figure 7: Frequency of summer (JJAS) wet days (r > 0.5 mm/day) model validation. Comparing the APHRODITE dataset to the present-day time slice of the RCM (1981-2000) for the mean of the 17-member ensemble. Units are % of days in the season.

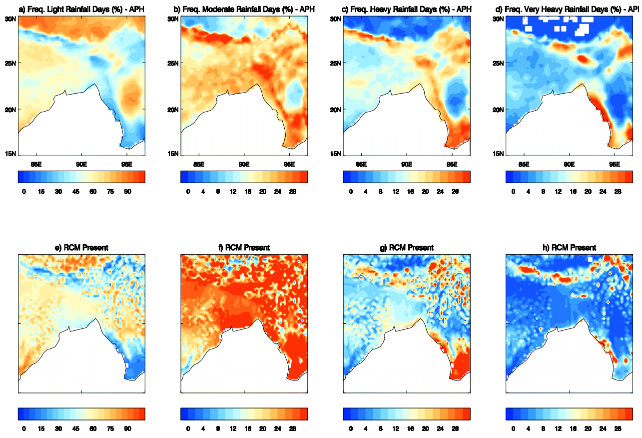

Figure 8: Observed and simulated precipitation patterns for four categories of rainfall days (light, moderate, heavy, very heavy) for the baseline period of 1981-2000 for summer (JJAS). Units are % of days in the season.

It can be seen in the present-day time slice that the majority of rainfall events within central Bangladesh can be categorized as light/moderate, with heavy and very heavy events occurring in regions of complex topography (Figure 8).

Climate change projections

Annual mean projections and ensemble member selection

The ESPA Deltas project involves a wide range of biophysical models in conjunction with social and economic scenarios[14]. It was decided that in order to keep the number of scenario combinations manageable, three climate ensemble members should be selected which capture a range of characteristics of 21st climate change within the 17 member ensemble.

	Temperature (°C)		Precipitation (%)	
	2041-2060	2080-2099	2041-2060	2080-2099
Q0	**+2.20**	**+3.90**	**+8.26**	**+11.75**
Q8	**+2.45**	**+3.98**	**-1.35**	**+13.01**
Q16	**+2.65**	**+4.75**	**+10.28**	**+23.66**

Table 1: Annual mean temperature and precipitation changes in the three selected ensemble members (Q0, Q8 and Q16) at the middle and end of the 21st century over the GBM sub-region shown in Figure 1.

However, selecting three ensemble members was a challenging process due to the variety of climate variables being directly used by the other impacts models, the effects of different timescales of variability, the mid- and end-of-century time slices being considered, and the differing geographical areas encompassed by the models e.g. the south western coastal region of Bangladesh[14], the GBM river basins[15,16,17], and the wider Bay of Bengal[18]. We opted to base the ensemble member selection on changes over the GBM region (represented by the solid box in Figure 1).

The annual mean changes from the present-day (1981-2000) in temperature and precipitation were considered for the mid-century (2041-2060) and end-of-century periods (2080-2099) and are shown in Figure 9. Three ensemble members (Q0, Q8 and Q16) were selected from the 17 ensemble members, to provide a range temperature and precipitation projections for the ESPA Deltas biophysical modelling and scenario development, where the time horizon of 2050 is of particular interest[47]. Q0 was used since it represents the standard model configuration. It projects moderate increases in temperature and precipitation and has a global climate sensitivity of 3.5°C. The second ensemble member, Q8, indicates a warmer but drier future in the mid-century, but warmer and wetter conditions by the end of the 21st century, with a climate sensitivity of 4.83°C. Q8 was selected in order to provide the ESPA Deltas biophysical modellers with a realisation that showed a small decrease in precipitation in the mid-century period, to capture an element of the decadal timescale variability which is seen in the precipitation projections. The third ensemble member, Q16, was selected as it projects the largest increase in temperature from the ensemble, and also relatively large increases in precipitation through to 2100 (Table 1). It has the highest climate sensitivity of the 17 member ensemble of 5.46°C. Changes are quoted relative to the 1981-2000 values for each ensemble member (hence the actual values for the present-day baseline vary slightly for Q0, Q8 and Q16).

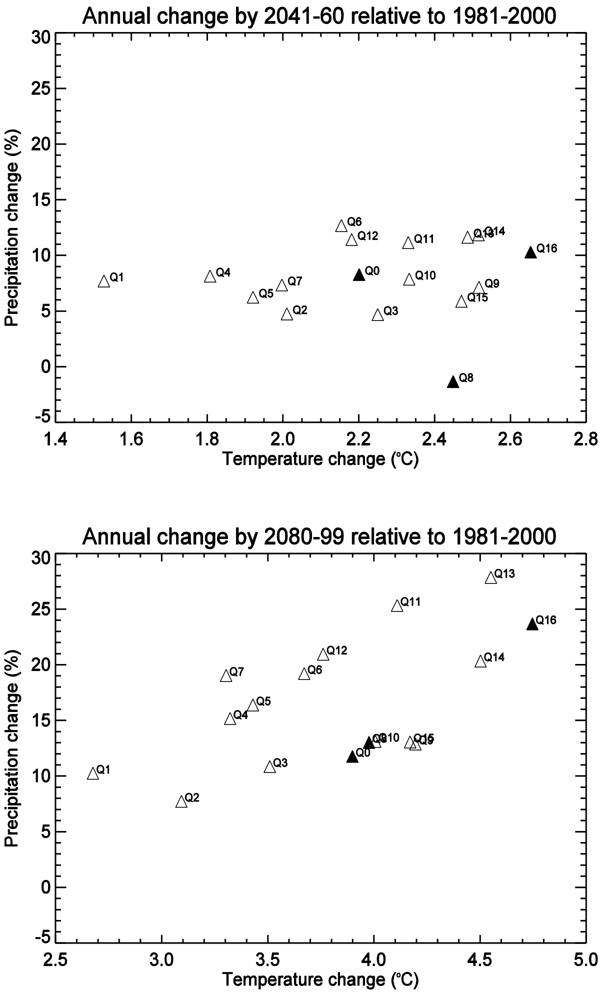

Figure 9: Annual mean temperature and precipitation responses in the 17 member PPE for HadRM3P over the GBM sub-region (shown in Figure 1) for 2041-60 (top) and 2080-99 (bottom). Filled triangles indicate the three ensemble members, Q0, Q8 and Q16, selected for further use within the ESPA Deltas project.

For annual mean temperature over the GBM region, all 17 ensemble members indicate positive increases over the 21st century ranging from around 2.7°C to 4.7°C relative to 1981-2000. Of the three selected ensemble members, Q16 shows the largest increase over this period, which is consistent with the driving GCM ensemble member having the highest climate sensitivity. The annual mean time series shown in Figure 10 indicates the positive temperature trends seen in all ensemble members, but with a larger trend for Q16.

Precipitation is more variable. Of all 17 ensemble members, Q0 displays the largest standard deviation indicating a larger year to year variability compared with the others.

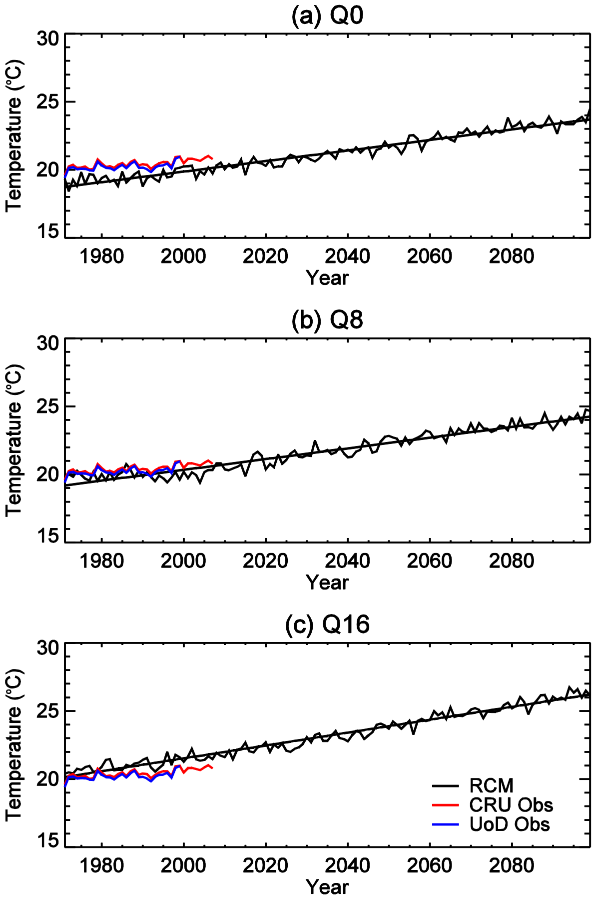

Figure 10: Annual mean time series and linear least squares trend of 1.5m temperature for each of the selected ensemble members from 1971-2099 inclusive for the GBM sub-region shown in Figure 1.

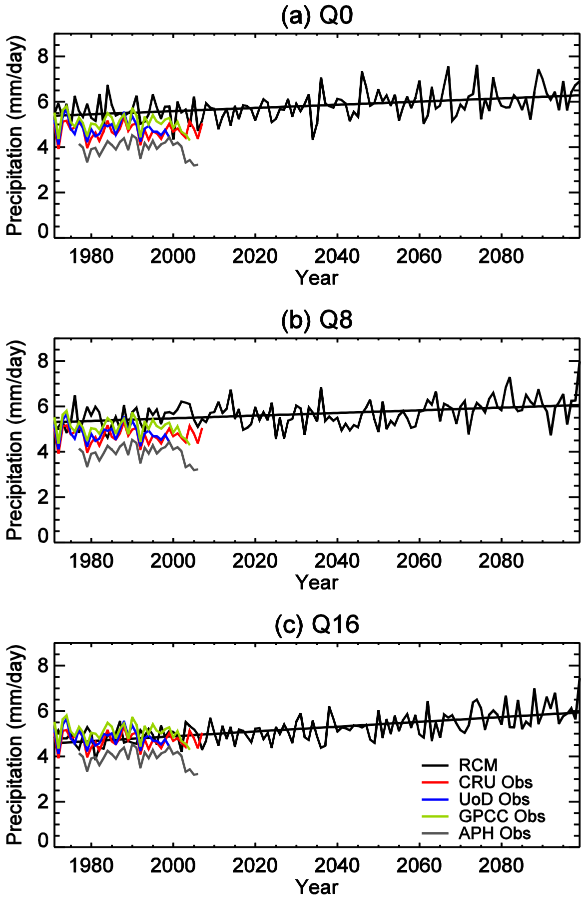

Figure 11: Annual mean time series and linear least squares trend of precipitation for each of the selected ensemble members from 1971-2099 inclusive for the GBM sub-region shown in Figure 1

By mid-century, both Q0 and Q16 indicate modest increases of between 5% and 10%, whereas Q8 actually indicates a slight decrease of around 1.5%. At the end of the century, Q0 indicates a increase of around 9%, Q8 slightly higher at just over 11%, and Q16 indicating an increase of just over 20%. The variability of the precipitation time series is shown in Figure 11. Whilst the linear trend is positive in all three ensemble members, the inter-decadal variability is apparent, for example with Q8 projecting a slight decrease in precipitation during the 2041-60 period relative to present day.

The GCM ensemble projections from the IPCC Fourth Assessment Report (AR4) which use the SRES scenarios show a temperature increase over the South Asia region of between 2°C and 5°C for the A1B scenario[3]. Precipitation in the IPCC ensemble is more variable and changes of between -15% and +20% are projected, though it should be noted that the AR4 projections are for a wider spatial area than we have considered here. Projections based on the RCPs in the more recent IPCC AR5 report are consistent with the AR4 projections[10].

Daily and extreme events

The future projections for the metrics considering daily precipitation indicate a decrease in the frequency of wet days (Figure 12) during the summer monsoon season over most regions of Bangladesh, though with the magnitude of the decrease increasing with distance from the coast.

The rainfall category thresholds used in Figure 8 were then applied to the future time slice (2080-99), such that any projected changes will be with respect to the particular ensemble member's present day climate. Projections of categorical daily rainfall suggest a general decrease in the frequency of light/moderate events, with a slight increase in heavy events and a large increase in very heavy events (Figure 13). Therefore, while the number of wet days is projected to decrease, the intensity of rainfall on these days is projected to increase.

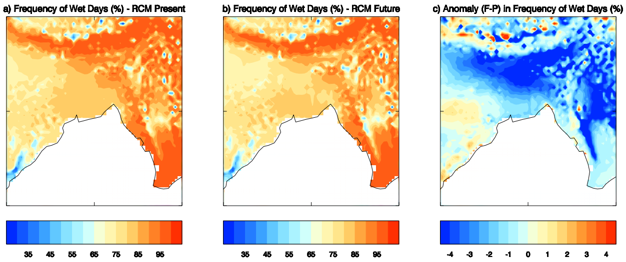

Figure 12: Frequency of wet days (r > 0.5 mm/day) in present-day (1981-2000) and future projections (2080-99) during the summer monsoon (JJAS) for the mean of the 17 ensemble members. Units are % of days in the season.

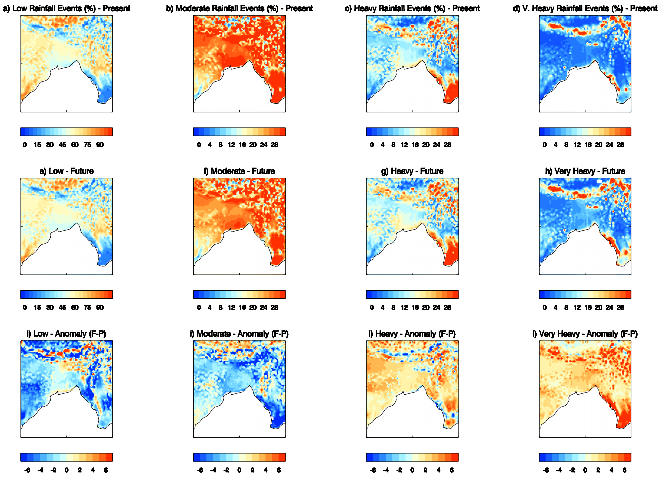

Figure 13: Present-day (1981-2000) and future (2080-2099) simulated precipitation patterns for four categories of rainfall days (light, moderate, heavy, very heavy) during the summer monsoon (JJAS) for the 17 ensemble members. Units are % of days in the season.

Conclusions

Results from regional climate model simulations for south Asia at a 25km spatial resolution have been validated against a range of observational datasets.

Of the 17 ensemble members, all indicate increased temperatures during the 21st century ranging from approximately 1.5°C to 2.7°C by the middle of the century and between 2.7°C to 4.7°C by the end of the century. All ensemble members indicate increasing precipitation ranging from around 8% to 28% by the end of the century. However, year to year variability is quite large and during the mid-century one ensemble member indicates a small decrease in mean precipitation.

Projections of categorical daily rainfall suggest a general decrease in the frequency of light/moderate events (below the 75th percentile), with a slight increase in heavy events (75th-99th percentile) and a large increase in very heavy events (>99th percentile). Therefore, while the number of wet days is projected to decrease, the intensity of rainfall on these days is projected to increase which could imply an increased risk of flash flooding, and an alteration to freshwater availability across Bangladesh

Although the more recent RCP scenarios were not used to drive the climate models for this study, comparisons from other studies at the global scale indicate that the climate responses to the SRES A1B scenario tend to fall between RCP6.0 and RCP8.5. We expect to address the RCPs in future work which will make use of output from the Coordinated Regional climate Downscaling Experiment (CORDEX) project[21]. Assessment of future changes in tropical cyclones frequency and intensity could be carried out through use of storm tracking methods[48] which could add particularly value to the assessment of storm surges and flooding, and to hazard assessment.

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