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CMIP5 climate change projections for hydrological modelling in South Asia

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Abstract: Climate change will impact water and related sectors. Temperature and potential evaporation will be higher. Changes in future precipitation will be amplified in the river flows. Security of water supply will be compromised due to longer and more severe droughts, more precipitation falling as rain rather than snow, increased seasonality of river flow and retreat of glaciers. Flood risk will increase due to more intense heavy precipitation events.

This paper presents the analyses of all the CMIP5 global climate model (GCM) runs to derive a consistent baseline climate change projection database for the South Asia region (5.25°–40.25° S, 60.25°–100.75° E) for the Sustainable Development Investment Portfolio (SDIP) run by the Department of Foreign Affairs and Trade (DFAT). The database presents 'empirical scaling factors' for 0.5° grids (~50 km) that reflect changes in six climate variables (precipitation, heavy precipitation, potential evaporation, daily average temperature, daily maximum temperature and daily minimum temperature) for a future (2046–2075) period relative to current. The projected changes in the climate variables are derived for each of the 12 months, four seasons and annual values for two future representative greenhouse gas concentration pathways. These are presented for each ensemble modelling run from each of the 42 CMIP5 GCMs, as well as the median and range (uncertainty) of plausible projections. These consistently derived climate change projections will be used in various hydrological modelling and integrated water management projects across South Asia to inform water management, planning and development, and their interactions with the energy and food sectors.

There is strong agreement between the GCMs in the temperature projections. Averaged across the South Asia region, the median projection for RCP4.5 and RCP8.5 is an increase in daily average temperature of 2.1°C and 2.9°C respectively by 2046–2075 relative to current. The projected increases are slightly higher for minimum daily temperature and slightly lower for maximum daily temperature as compared to the daily average temperature. The projected temperature increase is slightly higher in winter than in summer, and greater in the high altitude areas in the north. Averaged over the South Asia region, potential evaporation is projected to increase by 4.5% and 6.2% respectively by 2046–2075 relative to current. The projected increase in potential evaporation is mainly driven by the increase in temperature.

There is much greater uncertainty in the precipitation projections, with significant variations between GCMs, and in the different seasons and regions. The range of projections from multiple ensemble runs of some GCMs can also be as high as the range of projections from the different GCMs. Nevertheless, a higher proportion of GCMs project an increase in precipitation, particularly in the north-east and much more so in the summer monsoon than winter. The projections also indicate likely intensification in the high extreme precipitation. The results also indicate that weighting the projections towards the better GCMs, assessed against their ability to reproduce the observed historical annual precipitation amounts and variability, do not reduce the range of uncertainty in the projections. As such, it is probably best to use the entire set of available GCMs in climate change impact studies to represent the entire range of plausible uncertainty.

Keywords: *Climate change projections, South Asia, CMIP5 GCMs, precipitation, water*

1. INTRODUCTION

There is strong evidence that many parts of South Asia are experiencing long-term warming trends that will continue into the future with anthropogenic climate change (Hijioka et al., 2014). The warmer future climate will increase evapotranspiration and hence increase demand for water in irrigated agriculture, urban centres and water-dependent ecosystems. The projected changes in precipitation will be amplified in the changes in river flows. The climate change impact will be reflected not only in the averages but also in other river flow characteristics. Hydrologic variability will be enhanced, with longer droughts and longer wet periods. In high altitude and cold regions, more precipitation will fall as rain rather than snow, and the snow will melt earlier, resulting in earlier peak flow and more winter and less spring and summer flows. The seasonality in river flow is also likely to increase with wet seasons becoming wetter and dry seasons becoming drier. The retreat of glaciers will increase river flows in the short term, but the contribution of glacier melt will gradually fall as glaciers shrink. This enhanced hydrologic variability and decrease in snow and ice storage will reduce the reliability of water supply, thus compounding water management and climate adaptation challenges. Heavy precipitation events will become more intense in the future. This will increase flood damage to settlements, infrastructures like roads and bridges, livestock and crops.

This paper presents the analyses of all the CMIP5 (the fifth phase of the Coupled Model Inter-comparison Project) global climate model (GCM) runs to derive a consistent baseline climate change projection database for the South Asia region (5.25°–40.25° S, 60.25°–100.75° E). The database presents 'empirical scaling factors' for 0.5° grids (~50 km) that reflect changes in six climate variables (precipitation, heavy precipitation, potential evaporation, daily average temperature, daily maximum temperature and daily minimum temperature) for a future (2046–2075) period relative to current. The projected changes in the climate variables are derived for each of the 12 months, four seasons and annual values. These are presented for each ensemble modelling run from each of the 42 CMIP5 GCMs, as well as the median and range (uncertainty) of plausible projections. The large uncertainty in the future precipitation projections and the influence of GCM choice on the projections are also explored. These consistently derived climate change projections will be used in various hydrological modelling and integrated water management projects across South Asia to inform water management, planning and development, and their interactions with the energy and food sectors.

2. DATA SOURCE

The range of future climate scenarios in this paper is derived from the CMIP5 database (http://cmip-pcmdi.llnl.gov/cmip5/). CMIP5 is sponsored by WCRP's Working Group on Coupled Modelling (WGCM) with input from the IGBP AIMES project. It involves GCM experiments from more than 20 climate modelling groups around the world). All the 42 CMIP5 GCMs with both historical and future outputs on 15 March 2013 (the same date as that adopted by IPCC AR5) are used here.

The transient climate experiments in CMIP5 are conducted in three phases. The first phase covers the start of the modern industrial period through to the present day, years 1850–2005. The second phase covers the future, 2006–2100, and is described by a collection of representative concentration pathways (RCPs) adopted in IPCC AR5 (Moss et al., 2010; Taylor et al., 2010). The third phase is described by a corresponding collection of Representative Concentration Pathways (Meinshausen et al., 2011). For the projections here, RCP4.5 and RCP8.5 are used, representing radiative forcing of +4.5 and +8.5 W/m^2 respectively in the year 2100 relative to pre-industrial values. Emissions in RCP4.5 peak around 2040 and then decline, while emissions in RCP8.5 continue to rise throughout the 21st century. The median global mean temperature (median of simulations from the different GCMs) in 2046–2065 relative to 1986–2005 is 1.4°C and 2.0°C higher for RCP4.5 and RCP8.5 respectively.

The gridded climate surface datasets of South Asia used to evaluate the performance of the CMIP5 models come from Chen et al. (2014), which includes dataset from Aphrodite (Yatagai et al., 2012), Princeton (Sheffield et al., 2006) and IMD (Sridhar et al., 2014). The Aphrodite (Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation of the Water Resources) is a database of 0.25° (~25 km) gridded daily precipitation for continental Asia from 1951–2007. The Princeton data product is a global 0.5° (~50 km) gridded dataset of daily climate data from 1948–2008. The IMD (India Meteorological Department) dataset provides 0.25° (~25km) gridded daily rainfall data across India from 1901–2013.

3. EMPIRICAL SCALING FACTOR OF CLIMATE VARIABLES

The empirical scaling factor is defined as the change in future climate condition relative to current (or historical) climatology, where the "historical" and "future" here are represented by the GCM simulations for the period 1976–2005 and 2046–2075 respectively. The empirical scaling factor for the climate variables is expressed as the ratio of change,

$$\mathrm{SF} = \mathrm{X_f}/\mathrm{X_h} \quad (1)$$

where X_f and X_h are the GCM simulation for the future and historical periods respectively. The scaling (or difference) factor of the temperature is calculated as the difference between the two periods:

$$\mathrm{SF} = \mathrm{X_f} - \mathrm{X_h} \quad (2)$$

The scaling factors for each of the GCMs (the GCMs have different spatial resolutions) are re-sampled to present the results for common 0.5° x 0.5° grids (~50 km × 50 km) across the South Asia region. These scaling factors can be used to modify historical daily climate sequences for input into hydrological models, using the empirical scaling or delta change method, to assess potential climate change impact on water availability and hydrological and river flow characteristics (Chiew et al., 2009a). Using the large range of GCMs provides a good indication of the plausible range (and uncertainty) of future climates and impact on water and related sectors.

The empirical scaling factors, for every ensemble run for each of the 42 CMIP5 GCMs for monthly, seasonal and annual values, are derived for precipitation, heavy precipitation (1st, 5th and 10th percentile highest daily precipitation), potential evaporation, daily average temperature, daily maximum temperature and daily minimum temperature. The potential evaporation for each GCM grid is estimated from the CMIP5 simulations of daily solar radiation, maximum and minimum temperatures and actual vapour pressure using Morton's wet environment or equilibrium evaporation formulation (Morton, 1983).

4. PROJECTED CLIMATE CHANGES IN SOUTH ASIA

Figures 1, 2 and 3 summarise the range of projected changes in the daily average temperature, potential evaporation and precipitation, presented for the 12 months, four seasons and annual, as the median, 25–75th percentile range and 10–90th percentile range from the 40 CMIP5 GCMs for RCP4.5 (there are 40 GCMs with runs for RCP4.5 and 42 GCMs with runs for RCP8.5). The projected changes (and the range of projections) are greater for the higher RCP8.5 greenhouse gas emission trajectory.

The range of climate projections presented here is relatively similar to those in the IPCC AR5 atlas of global and regional climate projections (IPCC, 2013). However, the projections here come from a much larger set of global climate models to more reliably inform hydrological modelling across South Asia to assess the potential range of climate change impact on water and related sectors.

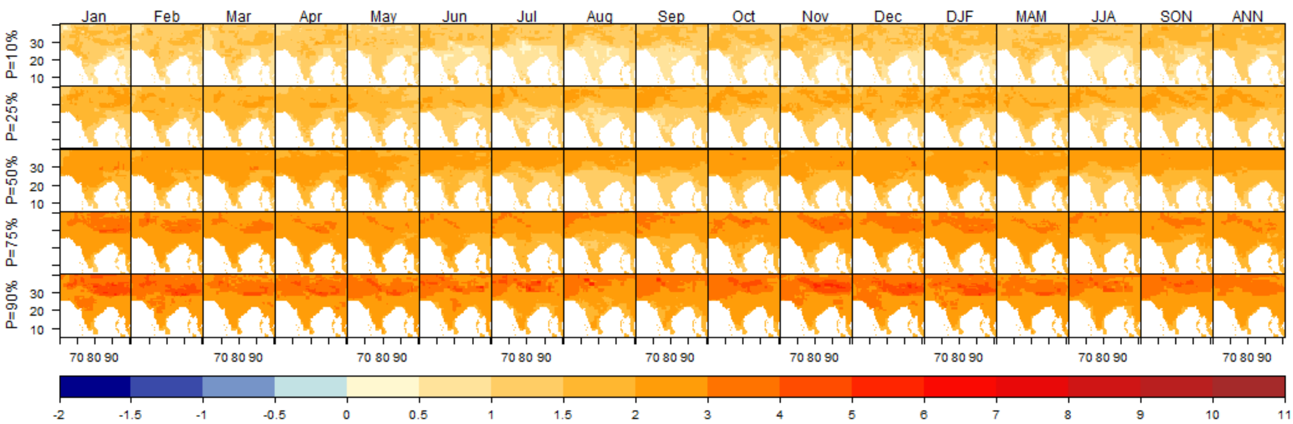

Figure 1. Projected range of degree change (median, 10th, 25th, 75th and 90th percentiles from the 40 GCMs) in daily average temperature for RCP4.5 for 2046–2075 relative to current for the 12 months, 4 seasons and the annual scale.

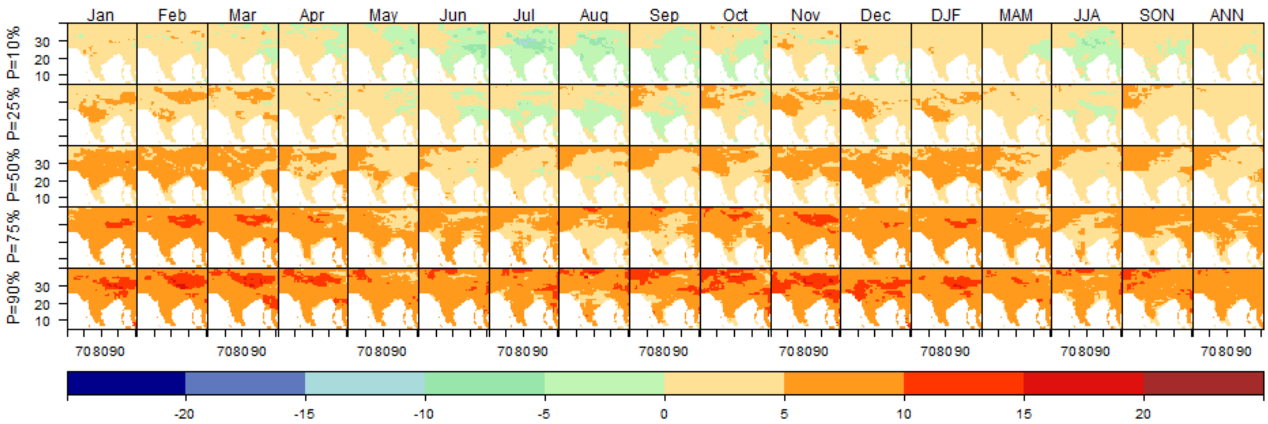

Figure 2. Projected range of change ratio (median, 10th, 25th, 75th and 90th percentiles from the 40 GCMs) in potential evaporation for RCP4.5 for 2046–2075 relative to current for the 12 months, 4 seasons and the annual scale.

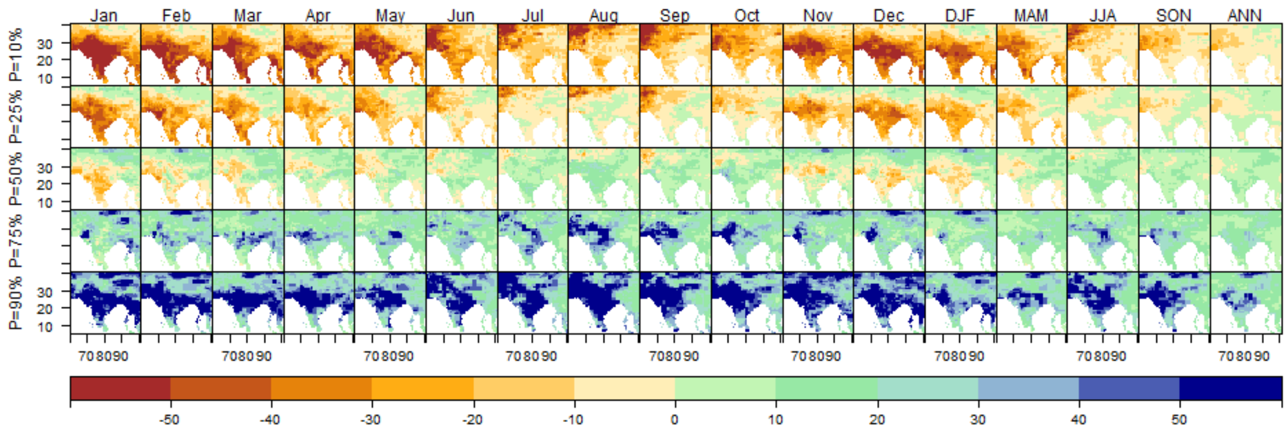

Figure 3. Projected range of change ratio (median, 10th, 25th, 75th and 90th percentiles from the 40 GCMs) in precipitation for RCP4.5 for 2046–2075 relative to current for the 12 months, 4 seasons and the annual scale.

4.1. Projected changes in temperature

As shown in Figure 1, there is strong agreement between the GCMs in the temperature projections. Averaged across the South Asia region, the median projection for RCP4.5 is an increase in daily average temperature of 2.1 °C by 2046–2075 relative to current, with a 25–75th percentile range of 1.7 to 2.4 °C and 10–90th percentile range of 1.4 to 2.8 °C. The median projection for RCP8.5 is an increase in daily average temperature of 2.9 °C by 2046–2075 relative to current, with a 25–75th percentile range of 2.6 to 3.5°C and 10–90th percentile range of 2.3 to 4.0 °C. The projected increase in daily minimum temperature is slightly higher and the projected increase in daily maximum temperature is slightly lower than the projected increase in daily average temperature. Seasonally, the projected temperature increase is slightly higher in winter (DJF) than summer (JJA). Spatially, the projected temperature increase is noticeably higher in the north (high altitude regions) than in the south.

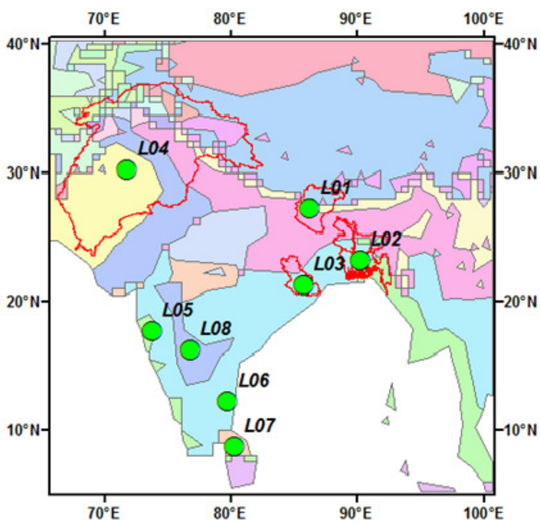

Figure 4. Locations where range and uncertainty in the precipitation projections are explored in more detail.

4.2. Projected changes in potential evaporation

There is also general agreement between the GCMs in the potential evaporation projections (Figure 2). The projected increase in potential evaporation is driven mainly by the increase in temperature. Most models show an increase in relative humidity (which will reduce potential evaporation), but show little change and agreement between models in the direction of change of other variables (solar radiation and wind speed) that influence potential evaporation. Averaged across the South Asia region, the median projection for RCP4.5 is an increase in mean annual potential evaporation of 4.5% by 2046–2075 relative to current, with a 25–75th percentile range of 3.2 to 5.7% and 10–90th of 2.1 to 6.8%. The median projection for RCP8.5 is an increase in mean annual potential evaporation of 6.2% by 2046–2075 relative to current, with a 25–75th percentile range of 4.8 to 7.6% and 10–90th of 3.4 to 8.8%. Some models project a decrease in potential evaporation in summer mainly due to higher relative humidity, and possibly decrease in wind speed and solar radiation. Seasonally, the projected increase in potential evaporation is considerably greater in winter (DJF) than summer (JJA). Spatially, the projected increase in potential evaporation tends to be greater in the north-west.

4.3. Projected changes in precipitation

There is much greater uncertainty in the precipitation projections, with significant variation between models, and in the different seasons and regions (Figure 3). Nevertheless, a higher proportion of GCMs project an increase in precipitation, particularly in the north-east and much more so in the monsoon summer (JJA) than winter (DJF). The projections also suggest possible intensification in the high extreme precipitation (i.e. the highest 99.9% daily precipitation, not shown here), but with the same disagreement between models and not much difference in the relative projected changes compared to the mean annual precipitation.

Uncertainty within and across CMIP5 GCMs

The range and uncertainty in the projected changes in future precipitation are explored for eight selected locations shown in Figure 4. Figure 5 shows all the projected changes in future mean annual precipitation (2046–2075 relative to current) for each of the ensemble GCM runs for each of the 40 GCMs for RCP4.5 for two of the eight locations. The first column in the plots shows the results from the first run of each of the 40 GCMs, which is used to describe the range of projections presented in Figure 3. It is interesting to note that the range of projections from ensembles of some GCMs can be as large as the range of projections between the different GCMs.

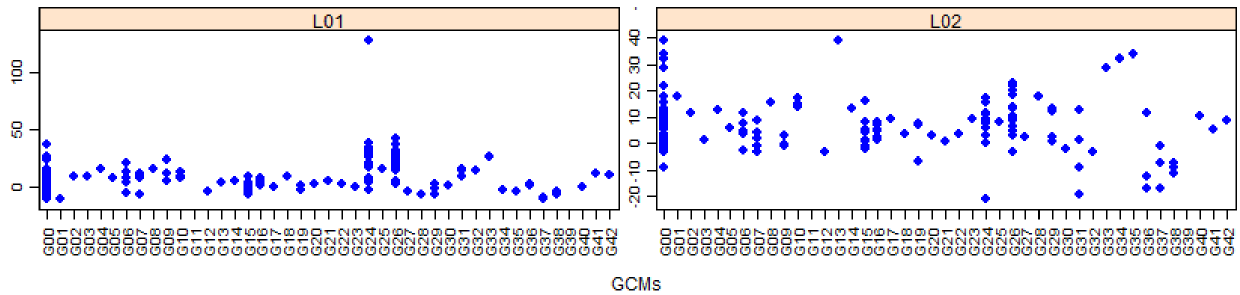

Figure 5. Projected changes in future mean annual precipitation (2046–2075 relative to current) from ensemble runs from the 40 GCMs for RCP4.5 (G01 to G42, see Table 1 to identify the GCMs) and range of results from first run of the 40 GCMs (G00 in first column).

Influence of GCM choice on precipitation projections

We explore here whether the use of the 'better' GCMs can improve and/or reduce the uncertainty in the projected changes to mean annual precipitation. The criteria used to evaluate the GCMs are the root-mean-squared-error (RMSE) of the ranked simulated annual precipitation against ranked observed annual precipitation for the period 1976–2005. A lower RMSE (or higher RMSE weight) means better simulation in the amount and probability distribution of annual rainfall. The RMSE weight is the inverse of the proportion of the RMSE from the GCM to the total RMSE from all the GCMs.

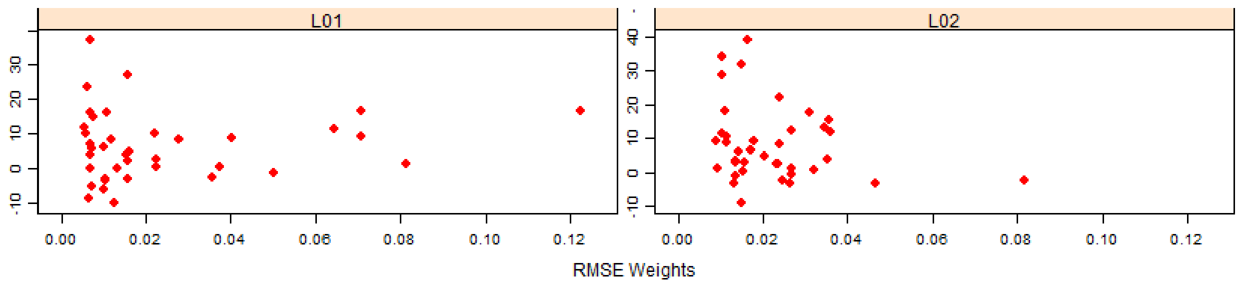

Figure 6. Percentage change in future annual precipitation simulated by the 40 GCMs versus their RMSE weighting for RCP4.5 (2046–2075 relative to current).

Figure 6 shows the projected change in mean annual precipitation in each of the 40 GCMs for RCP4.5 plotted against the RMSE weight. There is no clear trend in Figure 6 showing different projections between the 'better' (right hand side of plots) and 'poorer' (left hand side of plots) GCMs. Figures 7a shows the range of projections for two of the eight locations for RCP4.5 using all the GCMs and the best 10 and best 25 GCMs measured by the RMSE indicating the GCM ability in simulating the historical annual precipitation amounts and variability. Figure 7b shows the range of projections for the two locations for RCP4.5 using all the GCMs up to 25%, 50% and 75% of accumulated relative RMSE weightings. There is also no clear trend in Figures 7, although using the better GCMs in a couple of locations can give different results than using all GCMs, but with little difference in the range (e.g. L01 in Figures 7).

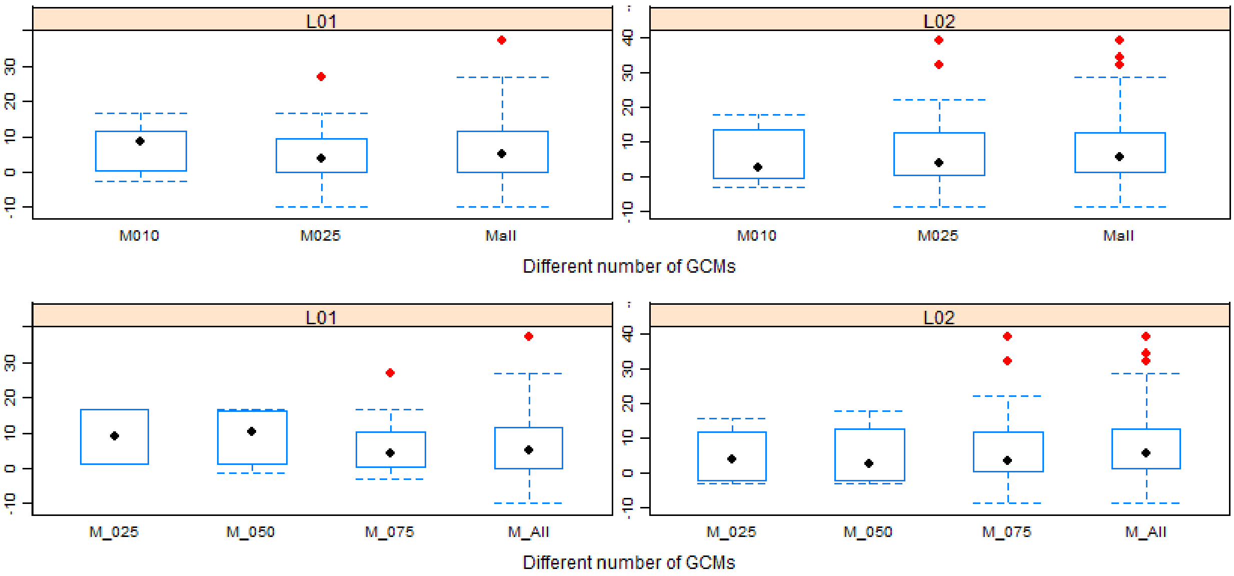

Figure 7. Range of projected change in mean annual precipitation for RCP4.5 (2046–2075 relative to current) for the eight locations (a) using all 40 GCMs and the best 10 and best 25 GCMs measured by the RMSE indicating their ability to simulate historical precipitation (up); (b) using all 40 GCMs and the best GCMs up to 25%, 50% and 75% accumulated RMSE weightings (bottom).

The results here suggest that it may be worth exploring assessing and weighting projections towards the better GCMs in detailed catchment or regional studies. However, assessing the GCMs against different criteria (e.g. against precipitation or other variables, against precipitation or correlation between large scale drivers and precipitation, against average precipitation or precipitation characteristics (e.g. monsoon) influencing runoff, etc…) may give different results. As such, for broad-scale hydrological modelling across South Asia, or probably also for detailed regional studies, with current GCM capabilities it is probably best to use the entire set of available GCMs to represent the entire range of plausible uncertainty (Chiew et al., 2009b).

5. SUMMARY

The paper presents the analyses of all the 42 CMIP5 GCM runs to derive a consistent baseline climate change projection database for 0.5° grids across the South Asia region. These are presented as the median and projected range of changes in six climate variables (precipitation, heavy precipitation, potential evaporation, daily average temperature, daily maximum temperature and daily minimum temperature) for a future (2046–2075) period relative to current, for two future representative greenhouse gas concentration pathways.

Averaged across the South Asia region, the median projection for RCP4.5 and RCP8.5 is an increase in daily average temperature of 2.1°C and 2.9°C respectively by 2046–2075 relative to current. The projected temperature increase is slightly higher in winter than in summer, and greater in the high altitude areas in the north. There is large uncertainty in the precipitation projections, with significant variations within and between GCMs, and in the different seasons and regions. Nevertheless, a higher proportion of GCMs project an increase in precipitation, particularly in the north-east and much more so in the summer monsoon than winter. The weighting of the projections towards the better GCMs did not reduce the range of uncertainty in the projections, and it is probably best to use the entire sent of available GCMs in climate change impact studies to represent the entire range of plausible uncertainty.

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