# 1 Authors response

This document contains the authors response. The replies to all the comments made by the reviewers and editor are given in Sect.1.1. The major changes to the manuscript are summarized in a brief list in Sect.2. Section 3 is the marked up version of the manuscript.

## 1.1 Authors replies to all comments

The authors would like to thank the reviewers and editor for their comments on the manuscript. The authors have replied to each comment from each reviewer and explained how the manuscript will be modified in light of these comments. The reviews and the replies are in the order they were received.

### 1.1.1 Reviewer 1

- **In the introduction, the manuscript needs better articulation of the research gap that is going to be addressed**

  **Author reply**: I will amend the introduction to try and make the research gap and the aim/objective of the analysis clearer. There is a lack of climate simulations with a high enough resolution to capture the steep orography and water resource analysis is also limited by a lack of observations of the water cycle for the region. This paper seeks to use the highest resolution climate simulations currently available to develop our understanding of the water cycle in the context of the complete climate system for this region while acknowleging that more needs to be done to address the missing processes in climate models. I will make this clearer in the text.

- **It needs a better scientific embedding by comparing/discussing the streamflow simulations done with the GCM-RCMs here with streamflow simulations done with hydrological models, and explaining the added value of the RCMs.**

  **Author reply**: The introduction will be amended to explain the potential advantages of using an RCM and we will try to find other comparable simulations to add to the paper for this region.

- **It should also be explained why only two simulations (with one RCM) are used here. That makes the conclusions about expected trends in fu-**

**ture streamflow weak, as the climate scenarios for this region are very uncertain. I would expect at least a discussion of results as compared to other studies that project future streamflow for this region.**

**Author reply**: This study uses two models from the AR4 ensemble, HadCM3 and ECHAM5, which have been shown to capture the range of temperatures and variability in precipitation similar to the AR4 ensemble for South Asia although it is unlikely to capture the full range of these larger ensembles. An important feature of these two GCMs is their ability to capture the large scale circulation and simulate the Asian Summer Monsoon which many of the GCMs even in AR5 fail to do. The HighNoon project required at least 25km resolution climate simulations to run for 140 years with this comes a computational cost therefore only two GCMs were selected to provide a range of future climates. I will explain this more fully in the text.

- **Further, I think that the article could be much better if the writing would be done more concisely. The authors often use long sentences, there is a lot of repetition and I had difficulties with focussing while reading the manuscript. I think the article needs a better story line and can be much shorter.**

  **Author reply**: I will look at the length of the sentences and try to remove any repetition to make the story line clearer and make it more concise where possible.

- **Abstract is much too long. It should be focused on research gap/question and objective, method, results and one or two sentences about conclusions. Around 250 words should be the target length (as some journals even have that as a limit)**.

  **Author reply**: I will shorten the abstract and focus on making these aspects of clearer.

- **P. 5792. R 14. Both of these are changing.., in which direction? Could you be more precise?**

  **Author reply**: I will add some text to explain that Fujita & Nuimura (2011) show a negative mass balance for three benchmark glaciers in the Nepal Himalaya, however the picture is far from uniform across the Himalayan arc with the Karakorum glaciers showing an increase in mass balance, therefore mass balance is changing in both directions. The ASM is also changing but again there is no clear direction of change in the ASM. Christensen et al (2007) highlight a tendency toward a general weakening of the monsoonal flows while there is also a tendency toward increased precipitation due to enhanced moisture convergence.

- **P.5792. r 23. Immerzeel et al... Could you be more precise? Why could upstream water supply decrease? Where? Is there a difference between the three rivers?**

  **Author reply**: I will add more detail to the text referring to this reference. Immerzeel et al (2010) found that by the 2050s the main upstream water supply could decrease due to reduced snow and glacial melt (reductions of 8% for the upper Indus and more than 18% for the Ganges and Brahmaputra). Meltwater plays an important role for the Indus and Brahmaputra particularly, accounting for a larger percentage of the downstream flow than the Ganges (where meltwater is approximately 10% of the flow). However Immerzeel et al (2010) show that the reductions in snow and glacial melt are offset by an increase in precipitation in all three basins. Precipitation is important in understanding the glaciers and hydrology for the upper Indus basin, however it is underestimated by most of the gridded products available (Immerzeel et al, 2015) which are usually biased toward low elevations.

- **P5793. R 5. The aim of this analysis is not logical after the first few paragraphs of the introduction. Could you explain what research gap you try to address with this objective? What are 'these simulations', they are not mentioned before? Can you also explain why you want to do this analysis with the runoff generated by RCM's, rather than hydrological models? Can you also explain which projections of future river flows have already been performed in this regions, and what you add by this analysis?**

  **Author reply**: I will try to make the objectives clearer and mention the simulations earlier. I will also explain that RCMs are representations of the entire climate system including both the carbon and water cycle. RCMs are based on the same physical equations as GCMs, therefore there are some limitations due to some missing processes. However, RCMs are run at higher resolution than GCMs over a more limited area allowing better representation of smaller scale processes, especially in regions of complex topography such as the Himalaya. RCMs are designed to maintain the conservation of water, mass, energy and momentum essential for analysis on climate timescales. RCMs include a very detailed representation of surface exchange therefore the runoff is consistent with the atmospheric forcing; this is preferred to using a hydrological model to derive the runoff which would remove this consistency. The typical domain and resolution of RCM simulations enables the analysis of areas spanning multiple river basins than is usually possible with hydrological models, for example, models such as the Soil Water Assessment Tool (SWAT-Arnold et al. 1998) simulate individual basins. However, weather data in SWAT is either simulated within the model using a weather generator or it can use, if available, observations of daily precipitation and maximum/minimum temperature (Nyeko, 2015), this is not ideal for South Asia due to the high temporal and spatial variability in precipitation across the region. I will also discuss other hydrological studies for the region in the introduction.

- **P 5793 r12 and further. In order to avoid too much repetition and make the manuscript more readable, you should consider deleting this part of the introduction, as it is a summary of the methods that should not be presented here yet.**

  **Author reply**: I will delete this part of the introduction and draft any of the information needed from this paragraph into the Methodology section.

- **P5793. R14. Why was only part of the Highnoon ensemble used and not the full ensemble?**

  **Author reply**: I will explain in the text that the required data was not available for the two ensemble members run with the REMO model.

- **P.5794. It seems more logical to start with a desciption of the model you use. Specifically, there needs to be an explanation of the parameterizations of runoff generating processes and the routing, because that might also explain partly explain the overestimation in streamflow peaks that you observe later.**

  **Author reply**: I will change this around so that the observations come second in the Methodology section, however there is already a description of the runoff generation processes and the routing in the Models section.

- **P. 5797 r. 5. Which climate scenario do you use? Can you convince the reader that only two simulations is enough to capture the range of uncertainty similar to the whole AR4 ensemble?**

  **Author reply**: The HighNoon project used the A1B scenario, I will include this in the Methodology section. Please see the reply above to the query on why only two GCMS are used.

- **P.5797. r 11. If the ERA interim-RCM run is used as a benchmark, it doesn?t help in understanding the usefullness of RCMs in understanding streamflow in this region. It is unclear to me why this run is added, and why is used as a benchmark.**
  **P5800. R 21. Can you explain why ERA-interim is considered to do better? I miss a justification for using ERA-int-RCM as a benchmark.**

**Author reply to both comments on ERA-interim**: I will explain in the text that ERA-interim is a reanalysis product which uses a combination of model data and observations to provide a constrained estimate of the water balance for the region. Admittedly reanalysis has limitations, however for this region there is a lack of robust observations, particularly of the water cycle and therefore in this situation it provides a useful guideline. This approach has been also been used for the same reason in previous studies for this region.

- **P.5003. r 1-5. It is unclear to me why you add 1.5 SD around the simulations to rep-resent the variability, because it can be derived from the simulated time series themselves.I have the impression it should be drawn around the observations?**

  **Author reply**: See replies to editors comments.

- **P5807. There is a lot of overlap between the caption and the description of the figures in the text.**

  **Author reply**: The text will be modified to reduce repetition between caption and the description.

- **Figures 3-5. Difference between ECHAM5 and ERAint is very difficult to see in my print, it would be better to choose another color.**

  **Author reply**: This colour selection was chosen to ensure that those people with impaired colour vision could distinguish between the lines. In an effort to make the difference between the lines more obvious I will increase the thickness of the ERAint line in this plot rather than change the colours themselves.

- **Fig 3. Could you somewhere plot the outlines of the river basins? Eg. In fig 1 or 2?**

  **Author reply**: The TRIP basin outlines will be included in a new figure.

- **Fig4. Could you show daily values here? (or a 30day running mean)**

  **Author reply**: This is a plot of the climatology, with the idea being that it shows a typical year of monthly flows for the 30 year period in the GCM driven RCMs and a 15 year period for the ERAint driven RCM. The aim of this plot is to show the seasonal cycle of riverflows which would not be clearly shown from a 30-day running mean which would be a similar plot to that shown in Figure 3.

- **Fig 5. Smoothed average over how many years?**

**Author reply**: The smoothed average in this plot is a 20-year smoothing. This will be stated explicitly in the revised manuscript.

- **Fig9 and 10 are difficult to interpret, and I find the caption unclear. What does each dot stand for? It would also be better to keep the y axis the same for easy comparison.**

  **Author reply**: Caption will be modified in revised manuscript and Figures 9 and 10 modified to make the y-axis the same in each plot.

- **P 5795 r 22. Himachal Pradesh typo**
  **Author reply**: This will be corrected in revised manuscript

- **p. 5797 r 16 finest resolution CLIMATE modelling available...**
  **Author reply**: This will be corrected in revised manuscript

- **p. 5800 r 12. Although... (new sentence).**
  **Author reply**: This will be corrected in revised manuscript

- **p. 5808 r 26. Variability. Although... (new sentence).**
  **Author reply**: This will be corrected in revised manuscript

- **P. 5813 r 5 extractions (Biemans et al, 2013), these are....**
  **Author reply**: This will be corrected in revised manuscript

### 1.1.2 Reviewer 2

- **The authors have used the river flow rate for 12 gauges. Is it possible to include the virgin flows in the study including the river-routing model? The readings at GD sites may be affected by the dam affect (storage) and withdrawal of water to meet out the various demands. The study based on the virgin flows may provide some more useful information during the study.**

- **Results indicate an increasing trend in annual mean river flows. Jhajharia and Singh (2011) have reported increasing trends in temperature in parts of northeast India in monsoon and post-monsoon seasons. Some of the sites are situated in the Brahmaputra basin, and thus the results of Jhajharia and Singh (2011) may be discussed in the present paper in the above context.**

- **The precipitation patterns for each basin are useful for understanding the changes in the river flows. The authors are encouraged to read a paper on changes in rainfall, rainy days and 24 hours maximum rainfall over humid sites of Assam, one of the important states of NE India**

**(Jhajharia et al. 2012). The paper discusses the trends in above parameters using the rainfall data of 24 sites situated in and around the Brahmaputra basin. The authors may discuss the results of this study in view of their own results. Rainy days were found to be decreasing at most of the sites located in the Brahmaputra basin (Jhajharia et al. 2012).**

- **"These simulations the Ganges/Brahmaputra catchment shows an increasing trend in total precipitation". Jhajharia et al (2009 in Agri. For. Met., 2012 in Hydr. Process.) studied the changes in evaporation and evapotranspiration in humid climatic conditions of northeast India. The results of these studies may also be discussed in support of the observations during the analysis of the present study. They have reported the concurrent occurrences of Epan decreases and rainfall increases were found at Agartala in winter season and at Chuapara in yearly and pre monsoon season.**

- **McVicar and others (JOH, 2012) in their global review paper have reported that evaporation/ET have decreased over different parts of the globe, mainly due to the significant reduction in wind speed followed by radiation. The review paper contains a few important studies for the three river basins selected in this study. The authors are suggested to read it and may cite as well. Second, evaporation may play an important role in water budgeting. By including evaporation in the analysis, these observed decreases in evaporation/ET in the three basins may have positive influence on the water availabilityin the Himalayan region.**

**Author reply to all comments from reviewer 2:**

The model does not include dams or reservoirs although these are likely to have a significant affect on the river flows for this region. The GRDC data set is used because of its spread of gauges across the Himalayan arc. Virgin flows were not available from this dataset but would be interesting to look at in the future should the data become available. I will add text to explain this.

I will add the two suggested references to the text and include plots of the annual mean evaporation for the two basins with some text to explain them along these lines: The annual mean evaporation shows an increase in evaporation for the Ganges/Brahmaputra basin (approximately 10%) and no real trend for the Indus basin. The annual mean runoff efficiency, defined here as the ratio of annual runoff (streamflow per unit area) to annual precipitation, shows no real trend for either basin. There is an increase in the precipitation of approximately 20% for the Ganges/Brahmaputra region and using the most downstream gauge for this basin, the Farakka barrage, the riverflow for this basin approximately doubles. Therefore the changes in runoff over this whole area are likely to be driven predominantly by precipitation on the annual scale. For the humid northeastern region of India, analysis by Jhajharia et al (2012) and McVicar et al (2012) show that evaporation is reduced due to reduced radiation and wind; this could be an important contribution to a future increase in runoff for this part of South Asia.

### 1.1.3 Editor

- **Editors comment**: As already stated by the two reviews, this paper makes an important contribution on the hydrology of a world region where there are not many extensive studies on potential future river flows. It is, accordingly, of foremost importance to be extremely clear about the potential and limitations of the used methodology to project climate change impacts on river flow.

  **Author reply**: The methodology sections will be amended to make the limitations of the analysis clearer in the manuscript. See comment below on adding section on analysis methods to the methodology.

- **Editors comment**: I agree with reviewer 1, that in its current form, the manuscript does not concisely discuss how useful the routed RCM simulations are to understand changes in riverflow via simulation (one of the stated objectives of this paper). Hydrological climate change impact studies are challenging for many reasons; besides the fundamental question whether the used climate projection covers the range of pos- sible future situations, it is essential A) to assess wether the hydrological model is able to reproduce actual streamflow and B) future simulation results have to be assessed against natural variability.

  **Author reply**: The aim of the analysis of the comparison against the present day is to assess the ability of the RCM/TRIP to reproduce the streamflow. The aim of the analysis of the future simulation results is to understand how these simulations compare against present day high and low flows; i.e. present day natural variability. These two aims will be made clearer in the text. The conclusions section will be amended to discuss these aspects and therefore make the message on 'how useful the RCM simulations are for understanding changes in riverflow' clearer in the manuscript. I will add text to the conclusion to be clearer that in the downscaled GCM simulations the seasonal cycle of precipitation, a key influence on river flows is captured reasonably well compared to both observations and downscaled ERAint. Although observed precipitation is lower than in the model the underestimation inherrent in precipitation observations at higher elevations is likely to be an important factor in this analysis, which includes the high Himalaya. Therefore the RCMs are useful for providing the regional scale hydrology of the region. Comparison of the downscaled GCM river flows with river gauge observations and the downscaled ERAint riverflows shows that for most of the gauges, the simulations reproduce the observed river flow to within natural variability (see comment below on the justification for using 1.5SD). The future projections indicate an increase in surface water resources, this is mainly driven by precipitation which more than counters the evaporation caused by increasing temperatures in the model. This is consistent with other analyses of precipitation which also use the A1B climate scenario (Shreshta and Nepal, 2015), which is a useful result. There are missing processes in the RCM and these could impact the river flows; for example a positive bias in the simulated river flow when compared with the present day could be caused by lack of abstraction and groundwater recharge. The representation of glaciers as snowmelt could also be acting to enhance the seasonal cycle in the simulated riverflow in both present day and future projections as snow melts more readily than ice. There is no doubt these simulations could be improved by including missing hydrological processes and that these could change the signal in the projected changes in river flow.

- **Editors comment**: In the presented setting, the quality of the hydrological model (routed RCM out- puts) cannot be easily assessed via comparison to observed streamflow (lack of good observations, no glacier model, no groundwater recharge, no hydraulic infrastructure). Accordingly, I think that the methods section of the paper should give a concise presen- tation of the methodology developed to assess the quality of the streamflow simulations despite of the fact that the model does not simulate the same quantity as the observed one. How robust are the conclusions on potential changes given this model evaluation methodology?

  **Author reply**: The methodology section will be amended to include a subsection on the methods used in the analysis of the paper. The limitations of the models, observations and methods used in the analysis will therefore each be discussed in the relevant subsection of the methodology part of the manuscript. The robustness of the conclusions on potential changes in river flow, given these limitations, will be discussed in the results/conclusions section.

- **Editors comment**: In the presented work, natural variability is taken = 1.5 the standard deviation, which is an simplification and is perhaps not appropriate for environments with strong sea- sonal patterns.

  **Author reply**: We use 1.5SD over a 30 year period to define the inter-annual variability. A value of plus 1.5SD indicates an approx 1 in 10 year wet event, a value of minus 1.5SD indicates a 1 in 10 year dry event. This approach is taken to indicate the possible impact of such a change under the hypothesis that current socio-economic levels of climate adaptation can cope with in 1 in 10 year events. The change driving mechanism could be anthropogenic climate or decadal variability. The working assumption is that interannual variability is independent of climate change whether that is due to decadal variability or externally forced change. In this context it is indicative of the timing and magnitude of possible changes under the A1B emissions scenario. More work and ensemble members would be required to control for the role of decadal variability. The substantial computation expense in running high-res RCM experiments currently precludes the use of initial condition ensembles.

We clarify the approach in the text.

- **Editors comment**: Furthermore, in light also of the comments of reviewer 2, I think that the paper could do a better job in explaining which modifications of the climate regime actually cause the identified modifications of river flow.

  **Author reply**: This comment is addressed by new analysis described in the reply to reviewer 2.

- **Editors comment**: Part of the rather long section 4 discusses interesting issues but without direct relation to the presented results

  **Author reply**: In this section we have tried to put the analysis presented in the context of the broader challenges facing the region with references to the presented analysis mentioned throughout the section. However this section can be edited to try to both shorten the section and make the references to the presented analysis clearer.

- **Editors comment**: **Additional references**
  Consider to include a reference to the recent HESSD ¡ahref=”http://www.hydrol-earth- syst-sci-discuss.net/12/4755/2015/hessd-12-4755-2015-discussion.html”¿paper¡/a¿ by Immerzeel et al. The PNAS ¡a href=”http://www.pnas.org/content/107/47/20223.abstract”¿paper by Kaser et al. on the importance of glaciers for downstream regimes (including Indus, Ganges and Brahmaputra) might also be useful for the discussion of the results (there are several papers on the effect of climate change in Himalayan glaciers; it could be discussed how their projected changes would add up to findings presented here)

  **Author reply**: These references will be used in the results discussion. The HESSD paper by Immerzeel et al will also be useful in supporting the argument that there is a bias toward lower elevations in the available gridded observations of precipitation.

### 1.1.4 Reviewer 3

1. **Reviewer comment:** How is downscaling performed? The authors state that GCMs and ERA-interim drive the RCM but the details are missing. I assume GCMs provide coarse scale inputs to the RCM but the RCM perhaps requires finer scale forcing to produce 25 km outputs. Perhaps the RCM resolves the finer scale details but which details and how is not clear. A clear description of this downscaling strategy is needed in a step by step manner. Further, a justification for why driving RCM by a GCM can be called a downscaling exercise is needed.

   **Authors reply:** This should be addressed in the reply to comments from reviewer 1. A comparison of the driving GCMs and the RCMs is also completed in previous work Lucas-Picher et al (2011) and Mathison et al (2013). These references together with the other analysis of these simulations carried out as part of highnoon are included in the text in the results section. This reference will also be added at the appropriate part of the methods section in order to aid the explanation of the use of RCMs to downscale GCMs. This is a widely used and accepted method of adding regional detail to larger scale models and is for example used in the IPCC reports. Figure 2 of Mathison et al (2013) provides a flow chart showing the inputs, processes and outputs of an RCM.

2. **Reviewer comment:** I assume a comparison of streamflow at selected gauging stations based on 'downscaled' GCM via RCM with the observed (and ERA-interim-RCM derived streamflow) is supposed to be a validation of the performed downscaling exercise. However such a comparison is not convincing enough for it to be called validation. The authors may want to provide evidence that supports the robustness of the downscaling performed, perhaps based on better datasets available elsewhere (not limited to South Asia). Such validation need not be on observed streamflow but on other variables that the RCM simulates. Nonetheless, this does not disqualify the validity of the downscaling exercise itself – it appears (based on my limited understanding of 'downscaling' implemented here) that RCMs introduce physics based constraints on the process of disaggregating coarse scale variables to finer scale 25km resolution.

   **Authors reply:** Precipitation and evaporation are discussed as these variables are of direct relevance to the presented analysis. The representation of other variables in the RCMs such as temperature are discussed in the references at the beginning of the results section.

3. **Reviewer comment:** It is not clear if ERA-interim drives the same RCM as the GCMs? – should be HadRM3?

   **Authors reply:** HadRM3 is the regional climate model used throughout this analysis. This will be made clearer in the text.

4. **Reviewer comment:** Figure 3, cannot clearly see ERA-interim.. Need a different color

   **Authors reply:** This should be addressed from comments to reviewer 1

5. **Reviewer comment:** Page 5801 – not clear why the units of total annual precipitation is mm/day? Needs further clarification.

   **Authors reply:** This is a standard unit of precipitation used across climate science, it is relevant for use in analysis where the temporal averaging is over the month, season or year.

6. **Reviewer comment:** Figure 4, ERA-interim appears to be the same as GCMs while it is difficult to compare the 3 with the observed in Figure 5. I think the RCM constrained downscaling needs to be compared with a statistical/naïve downscaling

method for example rule based or statistical disaggregation of coarse scaled GCM variables to 25 km and usingit to drive a hydrological model. In addition, these should then be compared with a control simulation of no downscaling, i.e. the case of driving the hydrological model with the outputs of GCMs/ERA-interim. This can then highlight the value that RCM adds to the downscaling exercise. This will then also highlight whether we need RCM based (or any other) downscaling to arrive the conclusion that the region will see more high flow events in the future.

**Authors reply:** In the methodology references on the performance of TRIP using global models to provide the runoff are included. See reply to comment 9.

7. **Reviewer comment:** Page 5803: Why 1.5 stdev for GCM is used for the uncertainty bound? Why not the same of the observed? There may be other ways to further define these uncertainty bounds, e.g. based on a-priori knowledge about measurement errors etc.

   **Authors reply:** This comment is addressed in the reply to comments from the editor. Unfortunately GRDC could not provide an estimate of the errors in the gauges. This is mentioned in the text.

8. **Reviewer comment:** Line 20, page 5803: Ganges/Farakka gauging station is also sufficiently downstream in a basin where there is heavy GW extraction. Why is the same pattern not seen as in the Kotri gauge, where higher than observed simulations of GCMs and ERA-interim are attributed to the lack of extraction scheme in MOSES?

   **Authors reply:** There are significant differences in the patterns of precipitation from west to east across the Himalayan arc. The western most gauges like the Kotri gauge on the Indus are likely to be affected by western disturbances whereas the eastern most gauges like the Ganges will be more affected by the ASM. Estimates of extraction in the Ganges basin are also a much smaller proportion of the total flow for example the LPJml simulated extractions in Biemans et al (2013) suggest that extraction from the Indus basin is of the order $340 km^3 year^{-1}$ and the Ganges is in the region of $280 km^3 year^{-1}$. The Ganges basin covers a much larger area than the Indus and therefore may not exhibit the same characteristics in river flow.

9. **Reviewer comment:** Page 5806, figure 7: How about a similar figure for rainfall, i.e. precipitation climatology both for downscaled and coarse scaled (original) products. This and comment 6 will clarify the role (and the value) of downscaling in revealing the pattern of increasing high river flows.

   **Authors reply:** The justification for using HadRM3 is given in replies to comments from reviewer 1. The comparison between the driving GCM and the downscaling has been done in previous studies and for the HighNoon ensemble; references for this analysis have been included in the text. Though a specific analysis considering if the downscaling has a role in the projections of river flows would be interesting it is not the aim of this analysis.

10. **Reviewer comment:** Figure 5 should be split into two. One which shows past to present and the other which shows future projections for the two GCMs for clarity sake.

    **Authors reply:** Although this was considered in the writing of the manuscript, it was decided that there was not sufficient justification for having 2 figures of 12 plots that showed the same variable. However, if two separate plots for historical and future are considered essential perhaps the separated figures could be included in supplementary information?

11. **Reviewer comment:** Do future streamflow projections incorporate plausible land cover land use change as well as socio-economic scenarios? – if not then the produced annual river flow projections via a complex MOSES land surface model are perhaps as good as downscaling climate projections and using them to drive a simple water balance model in representing plausible futures. This also touches upon comment 9. The authors may again want to clarify the value added of using HadRM3 while responding to this commentwhy do I need such extravagant downscaling when it does not incorporate aspects of changing socio-hydrology of the basins – perhaps it provide an upper bound of sortsbut I doubt it.

    **Authors reply:** The A1B scenario used in these simulations is one of the scenarios, the IPCC published as part of the Special Report on Emissions Scenarios (SRES) in 2000. The SRES scenarios were devised according to the production of greenhouse gases and aerosol precursor emissions. The A1 storyline and scenario family represents a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. The A1B scenario represents this in a world where there is balance across energy sources i.e. a mixture of fossil fuels and non-fossil fuels. This scenario does not represent changes in landuse. Therefore the landuse remains fixed through the duration of these simulations. However this is still useful as this allows the effect of climate change to be examined in the absence of any adaptation to the changes. More detail on what the A1B scenario represents will be included in the text.

    The justification for using HadRM3 is addressed in the reply to comments from reviewer 1.

12. **Reviewer comment:** Figure 9 and elsewhere: Need to state in the caption that the counts for the two GCMs appears in the upper right corner of the figures.

    **Authors reply:** This will be corrected in the revised manuscript.

13. **Reviewer comment:** Implications of river flow projections for regional water management: How confident can we be of stated water management implications when the RCM used is weak in terms of incorporating plausible socio-hydrological trajectories in the region? MOSES does not incorporate GW extractions, plausible land cover and landuse futures, regional land surface-atmosphere feedbacks, plausible socio-economic futures such as population, demography and economic

growth etc. These implications are probably as good as those that one would arrive at if only downscaled precipitation and temperature variables are used and run through a simple and static water balance model (by static I mean that its parameters that correspond to landcover etc. do not change). Please see comment 11 as well. Perhaps another control simulation may need needed for comparison where in downscaled climate variables are used to force a very simple water balance model (for example a single bucket model with a threshold).

**Authors reply:** HadRM3 is a physical model based on the same physics as the driving GCM but at a higher resolution. It incorporates a complex land-surface model that feeds back on the atmosphere and therefore regional atmospheric feedbacks are present and represented in this analysis. This will be made clearer in the text. The part of this comment that refers to landuse/landcover and socio trajectories is addressed by the reply to the reviewers comment 11 with reference to the A1B scenario used. Further justification for using HadRM3 is provided in replies to comments from reviewer 1.

14. **Reviewer comment:** Page 5815, line 22: The authors mention that increasing variability poses a challenge for the region but no analysis is provided to justify the claim that river flow will be become more variable in the future.

    **Authors reply:** The comment on increasing variability in temperatures and precipitation is related to the findings of the latest AR5 IPCC report for this region. I will add this reference at the appropriate point in the text.

15. **Reviewer comment:** Page 5816, lines 16-17: Same as the above. The authors mention temperature and variability in precipitation but no analysis is provided to back the claim. The paper will be stronger if additional analysis for variables that are downscaled and its variability is provided. This also connected to comment 1, where the need for clarifying the downscaling process through a detailed description of various involved variables (in addition to other) has been expressed.

    **Authors reply:** The two GCMs used in this analysis are from the AR4 ensemble. This comment is in reference to the report on this ensemble, where it was found that there was a high variability in temperature and precipitation in this region. The reference to this report is given in the text.

16. **Reviewer comment:** Towards the conclusion, I am unable to see what the comparison between ERA and GCM downscaling tells us about the robustness of downscaling and simulation of river flows.

    **Authors reply:** In this analysis we aim to examine how useful RCM simulations are for understanding how river flows could change in South Asia in the future rather than justify the downscaling method. The aim of the comparison against observations is to demonstrate the RCM captures the regional patterns of precipitation and river flow. The analysis acknowledges the lack of observations and this is why the ERAint simulation is used as this is a reanalysis product that incorporates observations as well as modelling information. The justification for using this as a benchmark is addressed in the reply to comments from reviewer 1. If the lack of processes in the presented model limits the usefulness of the river flow projections then this is the driver for model development to include such processes in order to improve knowledge and understanding of water balance for this region.

17. **Reviewer comment:** I often encountered too long sentences, the authors may want to break them into smaller more digestible sentences.

    **Authors reply:** This should be addressed in the reply to comments from reviewer 1

# 2 List of manuscript changes

The manuscript has been substantially modified in light of the requested major revisions. Removal of any repetition, more concise shorter sentences have meant that some sections of text have been heavily edited, deleted or moved to a new location. This list aims to highlight the biggest changes to the manuscript.

1. **Abstract:** Redrafted to have a clearer objective of the research and the research gap the paper is addressing.

2. **Introduction:** Redrafted to be more concise with shorter sentences and improved justification of the downscaling method.

3. **Methodology:** The Methodology section has been substantially restructured. The section on the models has been moved to the beginning and separated into a three subsections: these include a description of the models and scenarios, observations and methods of analysis. The explanation of the models used has been separated into individual sections describing the GCM and RCM forcing, TRIP and an explanation of the emission scenario. A new section has been added to describe the methods used in the analysis.

4. **Results:** The discussion of the results has been improved and redrafted to be more concise and avoid repetition. The individual plots in each figure have been updated to include labels (a,b,c...etc). This is primarily to improve the referencing in the text which is in the format Fig.Xa, where X is the number of the figure. This will improve the readability of the manuscript. The ERAint plots now have thicker lines to aid readability.

5. **Implications of changes in future river flows:** The discussion of the potential implications has been edited to make it shorter and the relevance to the presented results clearer.

6. **Conclusions:** Redrafted to be clearer on how useful the simulations are for understanding future changes in water resources and the limitations of the analysis.

# 3 Marked up version of manuscript

Manuscript prepared for Hydrol. Earth Syst. Sci. Discuss.
with version 2014/07/29 7.12 Copernicus papers of the LaTeX class copernicus.cls.
Date: 25 September 2015

# South Asia river flow projections and their implications for water resources

**C. Mathison[1], A. J. Wiltshire[1], P. Falloon[1], and A. J. Challinor[2]**

[1]Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, UK
[2]School of Earth and Environment, Institute for Climate and Atmospheric Science, University of Leeds, Leeds, LS2 9AT, UK

Correspondence to: C. Mathison (camilla.mathison@metoffice.gov.uk)

## Abstract

South Asia is a region with a large and rising population, a high dependence on water intense industries, ~~and a high dependance on industries sensitive to water resource~~ such as agriculture and a highly variable climate~~. The climate is hugely variable with the region relying on both the Asian Summer Monsoon (ASM) and glaciers for its supply of fresh water~~. In recent years, ~~changes in the ASM,~~ fears over the changing Asian Summer Monsoon (ASM) and rapidly retreating glaciers together with increasing demands ~~rapid retreat of glaciers and the increasing demand~~ for water resources ~~for domestic and industrial use,~~ have caused concern over the reliability of water resources and the potential impact on intensely irrigated crops in ~~both in the present day and future for~~ this region. Despite these concerns, there is a lack of climate simulations with a high enough resolution to capture the complex orography and water resource analysis is limited by a lack of observations of the water cycle for the region~~The climate of South Asia means it is one of the most irrigated agricultural regions in the world, therefore pressures on water resource affecting the availability of water for irrigation could adversely affect crop yields and therefore food production~~. In this paper we present the first 25 km resolution regional climate projections of river flow for the South Asia region. Two ~~ERA-Interim, together with two~~ global climate models (GCMs), which represent the ASM ~~present day processes, particularly the monsoon,~~ reasonably well are downscaled (1960–2100) using a ~~using a~~ regional climate model (RCM). In the absence of robust observations, ERA-interim reanalysis is also downscaled providing a constrained estimate of the water balance for the region for comparison against the GCMs (1990–2006)~~for the periods; 1990–2006 for ERA-Interim and 1960–2100 for the two GCMs~~. The RCM river flow is routed using a river-routing model to allow analysis of present day and future river flows through comparison with available river gauge observations. We ~~, where available.~~

~~In this analysis we compare the river flow rate for 12 gauges selected to represent the largest river basins for this region; Ganges, Indus and Brahmaputra basins and characterize the changing conditions from east to west across the Himalayan arc. Observations of~~

precipitation and runoff in this region have large or unknown uncertainties, are short in length or are outside the simulation period, hindering model development and validation designed to improve understanding of the water cycle for this region. In the absence of robust observations for South Asia, a downscaled ERA-Interim RCM simulation provides a benchmark for comparison against the downscaled GCMs. On the basis that these simulations are among the highest resolution climate simulations available we examine how useful these simulations they are for understanding potential the changes in water resources for the South Asia region. In general the downscaled GCMs capture the seasonality of the river flows but , with timing of maximum river flows broadly matching the available observations and the downscaled ERA-Interim simulation. Typically the RCM simulations over-estimate the maximum river flows compared to the observations probably due to a positive rainfall bias and a lack of abstraction in the modelalthough comparison with the downscaled ERA-Interim simulation is more mixed with only a couple of the gauges showing a bias compared with the downscaled GCM runs. The simulations suggest an increasing trend in annual mean river flows for some of the river gauges in this analysis, in some cases almost doubling by the end of the century; this trend is generally masked by the large annual variability of river flows for this region. The future seasonality of river flows does not change with the future maximum river flow rates still occur occuring during the ASM period, with a magnitude in some cases, greater than the present day natural variability. Increases in river flow could mean during peak flow periods means additional water resource for irrigation, the largest usage of water in this region but , but also has implications in terms of inundation risk. These projected increases Low flow rates also increase which is likely to be important at times of the year when water is historically more scarce. However these projected increases in resource from rivers could be more than countered by changes in demand due to depleted reductions in the quantity and quality of water available from groundwater, increases in domestic use due to a rising population or expansion of water intense industries. Including missing hydrological processes in the model would make these projections more robust but could also change the sign of the projections. other industriessuch as hydro-electric power generation.

## 1 Introduction

South Asia, the Indo-Gangetic plain in particular, is a region of rapid socio-economic change where both population growth and climate change is expected to have a large impact on available water resource and food security. The region is home to almost 1.6 billion people and the population is forecast to increase to more than 2 billion by 2050 (United Nations, 2013). The economy of this region is rural and highly dependant on climate sensitive sectors such as the agricultural and horticultural industry, characterised by a large demand for water resources. As a result, over the coming decades, the demand for water from all sectors; domestic, agricultural and industrial is likely to increase (Gupta and Deshpande, 2004; Kumar et al., 2005).

The climate of South Asia is dominated by the Asian Summer Monsoon (ASM), with much of the water resource across the region provided by this climatological phenomena during the months of June–September (Goswami and Xavier, 2005). The contribution from glacial melt to water resources is less certain but likely to be important outside the ASM period during periods of low river flow (Mathison et al., 2013). Glaciers and seasonal snowpacks are natural hydrological buffers releasing water during the drier periods such as spring and autumn when the flows of some catchments in this region ~~catchments like the Ganges~~ are at their lowest. Similarly they may act to buffer inter-annual variability as well releasing water during warmer drier years and accumulating during wetter colder years (Barnett et al., 2005). However, Kaser et al. (2010) show that the influence of glacial melt reduces with distance downstream, as other influences such as evaporation and precipitation increase in importance. Immerzeel et al. (2010) found that by the 2050s the main upstream water supply could decrease due to a reduction in snow and glacial melt (reductions of 8 % for the upper Indus and more than 18 % for the Ganges and Brahmaputra). Meltwater plays an important role for the Indus and Brahmaputra particularly, accounting for a larger percentage of the downstream flow than the Ganges (where meltwater is approximately 10 % of the downstream flow). However Immerzeel et al. (2010) also show that these reductions in melt water are offset by an increase in precipitation in all three basins.

Immerzeel et al. (2010) use coarse resolution general circulation models (GCMs) known to have difficulties in capturing monsoon precipitation and in estimating the relationship between daily mean temperature and melting of snow and ice.

Recent studies have highlighted uncertainty in both glacier mass balance and ASM rainfall. Fujita and Nuimura (2011) show a negative mass balance for three benchmark glaciers in the Nepal Himalaya. Bolch et al. (2012) Recent studies have shown that both of these are changing (ASM rainfall – , and Gardelle et al. (2013) highlight losses more generally from western, eastern and central Himalayan glaciers. These observed changes in Himalayan glaciers can be attributed to the increase in temperature already experienced across the region, with warming more pronounced at higher elevations and during winter months (Shrestha and Aryal, 2011). There are however some glaciers in the Karakoram region showing increases in mass which has been attributed to a decrease in temperature for this region (Bolch et al., 2012; Gardelle et al., 2013). Projections of future glacial change are challenging due to poor understanding of glacial processes, diversity in climate extremes and the complex orography of the region (Bolch et al., 2012). Complex orography contributes to other processes such as avalanching and therefore debris cover. The relationship between debris cover and melt is complex with a wide variety of responses across different glaciers across the Himalayan arc (Gardelle et al., 2013). The thickness of debris cover is widely thought to significantly affect the response of the glacier to climate, with thick debris cover tending to slow down surface melting (Bolch et al., 2012; Scherler et al., 2011). However on the regional scale Kääb et al. (2012) found, using satellite data, similar thinning rates between clean and debris covered ice despite insulation by debris cover at some sites. Kääb et al. (2012) suggest that the insulating effect of debris layers with thicknesses exceeding a few centimetres depends on the continuity of the coverage. Therefore changes in the thickness of debris across a glacier could change the melt rate on a local scale even across a single glacier tongue. The ASM is also uncertain, Christensen et al. (2007) highlight two climate features that could influence the ASM, including a general weakening of monsoonal flows while enhanced moisture convergence could increase precipitation. Any reduction in water availability from either resource is likely to put glacier mass balance – ) putting more pressure on groundwater resources which is not sustainable in the longer term (Rodell et al., 2009). There is some disagreement in the literature regarding the main effects of climate change on this region. Gregory et al. (2005) suggest that the availability and quality of ground water for irrigation could be more important factors influencing food security than the direct effects of climate change, particularly for India. However, Aggarwal et al. (2012) suggest that an increase in extremes (both temperature and precipitation) could lead to instability in food production and it is this variability in food production that is potentially the most significant effect of climate change for the South Asia region.

Despite the general uncertainty in the reliability of water resources and the impacts of climate change for this region there are few simulations available with a high enough resolution for found that by the 2050s the main upstream water supply could decrease by approximately 18although this decrease was partly offset by an 8increase in precipitation. use general circulation models (GCMs) which have a coarse resolution and are known to have difficulty in capturing the complex topography of the Himalayan regionmonsoon precipitation and in estimating the relationship between daily mean temperature and melting of snow and ice.

The Indo-Gangetic plains have traditionally provided the staple crops of rice and wheat for India and South Asia as a whole, irrigation is an important part of this industry and any limitation of water resource needed to maintain yields of these crops could have implications on the food and water security of the region . The aim of this analysis is to examine how useful these simulations are for understanding how river flows could change in South Asia in the future and the implications this could have on water resources that are increasingly in demand. The water balance resources for the South Asia region as a whole is are generally poorly understood with limited limitations in the observing networks and data availability availability of data for both precipitation and river flows presenting a real challenge for validating models and estimates of water balance. This analysis seeks to use regional climate simulations to develop our understanding of the water cycle for the region in the context of the complete climate system, while acknowledging that more needs to be done to address the missing hydrological processes in the model. RCM simulations are a widely used method across climate science for downscaling GCMs, including the regional IPCC assessment but are used in many other regional climate projects (Christensen et al., 2007; Murphy et al., 2009; Jacob et al., 2007). RCMs are based on the same physical equations as GCMs and therefore represent the entire climate system including the carbon and water cycle. Though there are some limitations due to missing processes, their higher resolution allows a better representation of the regional scale processes; especially in regions of complex topography such as the Himalaya (Lucas-Picher et al., 2011). RCMs are designed to maintain the conservation of water, mass, energy and momentum, essential for analysis on climate timescales. Lucas-Picher et al. (2011) conduct a comprehensive assessment of RCMs run over South Asia, including the RCM used here, demonstrating their ability to capture the monsoon. Mathison et al. (2013) compare GCM and RCM outputs for temperature and precipitation specifically for the RCM used in this analysis. Figure 2 of Mathison et al. (2013) uses a flow chart to show the inputs, regional model processes and the outputs of an RCM. In additionthe water balanceof the region. In this analysis we use a 25resolution regional climate model (RCM ) with a demonstrated ability to capture the ASM to downscale ERA-interim re-analysis data and two GCMs able to capture the main features of the large-scale circulation . In the absence of robust observations, particularly for high elevation regions like the Himalaya, the ERA-interim simulation provides a constrained estimate of the water balance of the region. In a previous study, Akhtar et al. (2008) found that RCM data produced better results when used with a hydrological model than using poor-quality observation data; this implies greater confidence in the RCM simulated meteorology than available observational data for this region (Wiltshire, 2013). Akhtar et al. (2008) highlight several studies which use RCM data to drive hydrological models. In this paper the RCM generated runoff is used to estimate riverflow using a river-routing model in order to maintain consistency with the atmospheric forcing; this is not possible if the runoff is derived from a hydrological model. The typical domain and resolution of RCM simulations enables the analysis of areas spanning multiple river basins covering a larger area than is usually possible with hydrological models. For example, models such as the Soil

Water Assessment Tool (SWAT – Arnold et al., 1998) simulate individual basins. Weather data in SWAT is either simulated within the model using a weather generator or taken from observations of daily precipitation and maximum/minimum temperature (Nyeko, 2015). This approach may be appropriate for small domains within which there is consistency in rainfall patterns but may not be suitable for large domains in South Asia due to the high temporal and spatial variability in precipitation across the region (Hijioka et al., 2014). Gosain et al. (2006) use the SWAT model with 50 km resolution daily RCM weather data to conduct a climate change impact assessment of the hydrology of several individual basins over India for two 20-year periods representing the present day (1981-2000) and future (2041-2060). Gosain et al. (2006) compare the differences between the two periods, rather than focussing on absolute values, to find that climate change causes an increase in precipitation, river flow and evaporation for the Ganges basin. High variability across basins and sub-basins means that parts of the Ganges basin could experience seasonal or regular water-stressed conditions under climate change (Gosain et al., 2006) although it is not clear exactly which climate change scenario has been used for these simulations. Perhaps due to the lack of adequate resolution climate simulations available for this region, hydrology analysis in the literature is typically global using GCMs coupled with hydrological models (Milly et al., 2005; Hirabayashi et al., 2008; Falloon et al., 2011; Wiltshire et al., 2013a, b) or at the basin scale using stand-alone hydrological models like SWAT (Singh and Kumar, 1997; Singh and Bengtsson, 2005; Singh et al., 2008; Seidel et al., 2000). There are few regional riverflow analyses currently available, where the forcing data is consistent across the different basins in the analysis.

Therefore we present the first 25 km resolution regional climate projections of river flow for the South Asia region. The aim of this analysis is to examine how useful RCM simulations are for understanding how river flows could change in South Asia in the future. Irrigation is an important part of the agricultural industry for this part of the world, with the Indo-Gangetic plains traditionally providing the staple crops of rice and wheat (Aggarwal et al., 2000) for India and South Asia as a whole; the continued success of these crops is therefore important for the food and water security of the region. We discuss the potential implications of projected changes in the water resources needed to maintain yields of these crops in a changing climate. The models, observations and the analysis used are described in Sect. 2, while a brief evaluation of the driving data and the river flow analysis is presented in Sect. 3. The implications of the potential changes in river flows on water resources and conclusions are discussed in Sects. 4 and 5 respectively.

# 2 Methodology

## 2.1 Models

### 2.1.1 GCM and RCM forcing

This analysis utilizes 25 km resolution regional climate modelling of the Indian sub-continent to provide simulations across the Hindu-Kush Karakoram Himalaya mountain belt. These RCM simulations form part of the ensemble produced for the EU-HighNoon project (referred to hereafter as HNRCMs), for the whole of the Indian subcontinent (25° N, 79° E–32° N, 88° E), for the period 1960–2100. The other simulations in the HighNoon ensemble were unavailable for use in this analysis. To sample climate uncertainty, we use two GCM simulations that have been shown to capture a range of temperatures and variability in precipitation similar to the AR4 ensemble for Asia (Christensen et al., 2007). Although using just two ensemble members is unlikely to capture the full range of uncertainty of a larger ensemble, the two models used for these simulations have been shown to capture the main features of the large-scale circulation particularly the ASM (Kumar et al., 2013; Annamalai et al., 2007; Mathison et al., 2013) which is not true of all GCMs. The experimental design of the HighNoon ensemble compromises between the need for higher resolution climate information for the region and the need for a number of ensemble members to provide a range of uncertainty. The length of the simulations needed and the limited number of GCMs that are able to simulate the ASM also affect the number of ensemble members. These factors are all important given the limited computational resources available. The

GCMs; 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) and ECHAM5 (3rd realization – Roeckner et al., 2003) are downscaled using the HadRM3 RCM (Jones et al., 2004). These two GCMs capture the uncertainty in the sign of the projected change in precipitation with one showing an increase (HadCM3) and the other a decrease (ECHAM5). This feature is a key reason for the selection of these two GCMs. In addition to the GCMs, Therefore in this analysis, as in , in addition to the observations that are available, it is appropriate to use the ERA-interim data (Simmons et al., 2007) is also downscaled using the HadRM3 RCM. ERA-Interim is reanalysis product that combines model and observations to provide a constrained estimate of the water balance of the region. The ERAinterim simulation has also been shown to capture the role of steep topography on moisture transport fluxes and vertical flow for the western Himalayas (Dimri et al., 2013). Therefore, for this region, where there is a lack of robust observations, particularly of the water cycle (see Sects. 2.1.1 and 3.1), it provides a useful simulation as a benchmark against which to compare evaluate the GCM driven simulations. A similar approach is described in a previous study by Wiltshire (2013).

These RCM simulations are currently the finest resolution climate modelling available for this region (Mathison et al., 2013; Moors et al., 2011; Kumar et al., 2013). HadRM3 has 19 atmospheric levels and the lateral atmospheric boundary conditions are updated 3 hourly and interpolated to a 150 s timestep. These simulations include a detailed representation of the land surface in the form of version 2.2 of the Met Office Surface Exchange Scheme (MOSESv2.2, Essery et al., 2003) regional simulations. The RCM includes a land-surface model which includes a full physical energy-balance snow model (Lucas-Picher et al., 2011). MOSESv2.2 treats subgrid land-cover heterogeneity explicitly with separate surface temperatures, radiative fluxes (long wave and shortwave), heat fluxes (sensible, latent and ground), canopy moisture contents, snow masses and snowmelt rates computed for each surface type in a grid box (Essery et al., 2001). However the air temperature, humidity and wind speed above the surface are treated as homogenous across the gridbox and precipitation is applied uniformly over the different surface types of each gridbox.

The relationship between the precipitation and the generation of runoff is complicated, depending on not only the intensity, duration and distribution of the rainfall but also the characteristics of the surface. The infiltration capacity of the soil, the vegetation cover, steepness of the orography within the catchment and the size of the catchment are important influencing factors on runoff generation (Linsley et al., 1982). In GCMs and even 25 km RCMs such as the one presented here, the resolution is often too coarse to explicitly model the large variations of soil moisture and runoff within a catchment and therefore the major processes are parameterized (Gedney and Cox, 2003). The method used within MOSES2.2 for generating surface and subsurface runoff across a gridbox is through partitioning the precipitation into interception by vegetation canopies, throughfall, runoff and infiltration for each surface type (Essery et al., 2003). The Dolman and Gregory (1992) infiltration excess mechanism generates surface runoff; this assumes an exponential distribution of point rainfall rate across the fraction of the catchment where it is raining (Clark and Gedney, 2008). Moisture fluxes are allowed between soil layers; these are calculated using the Darcy equation, with the water going into the top layer defined by the gridbox average and any excess removed by lateral flow (Essery et al., 2001). Excess moisture in the bottom soil layer drains from the bottom of the soil column at a rate equal to the hydraulic conductivity of the bottom layer as subsurface runoff (Clark and Gedney, 2008). The performance of MOSESv2.2 is discussed in the context of a GCM in Essery et al. (2001), however no formal assessment of MOSESv2.2 and the runoff generation in particular has been done for the RCM.

### 2.1.2 River routing model

In this analysis the simulated 25km gridbox runoff is converted into river flow using the 0.5° ~~providing an estimate of the gridbox runoff which is then used to drive the~~ Total Runoff Integrating Pathways river routing scheme ~~model~~ (TRIP; Oki and Sud, 1998) as a post-processing step. TRIP is a simple model that moves water along a pre-defined 0.5° river network; the Simulated Topological Network at 30 min resolution (STN-30p, version 6.01; Vörösmarty et al., 2000a, b; Fekete et al., 2001) in order to provide mean runoff per unit area of the basin; this can be compared directly with river gauge observationspresent 25resolution regional climate projections of riverflow for the South Asia region. TRIP has been used previously in Falloon et al. (2011) which used GCM outputs directly to assess the skill of a global river-routing scheme. The TRIP model has been shown to agree well with observed river flow gauge data (Oki et al., 1999) and largely showed good skill when comparing runoff from several land surface models (Morse et al., 2009). Implementation of TRIP in two GCMs; HadCM3 and HadGEM1 is described by Falloon et al. (2007) and was found to improve the seasonality of the river flows into the ocean for most of the major rivers. Using TRIP ensures the river flow forcing is consistent with the atmospheric forcing, however it also assumes that all runoff is routed to the river network and as such there is no net aquifer recharge/discharge. This may not be the case in regions with significant ground water extraction which is subsequently lost though evaporation and transported out of the basin. These simulations do not include representation of extraction, reservoirs or dams. Many of the river gauges used in this analysis and described in Section 2.2 are located at large dams along rivers in these basins and therefore the comparison between the simulations and the river gauges could be affected by these large features. Extraction, particularly for irrigation purposes is large in this region (Biemans et al., 2013); this means that the extraction-evaporation and subsequent recycling of water in a catchment (Harding et al., 2013; Tuinenburg et al., 2014) is not considered in this analysis. The routed runoff of the HNRCM simulations are referred to hereafter using only the global driving data abbreviations; ERAint, ECHAM5 and HadCM3.

### 2.1.3 Emission Scenario

These simulations use the SRES A1B scenario (Nakicenovic et al., 2000). The SRES scenarios were devised according to the production of greenhouse gases and aerosol precursor emissions TRIP is applied here to runoff from a subset of the 25resolution RCM simulations completed as part of the AR4 IPCC report (Christensen et al., 2007). The A1 storyline and scenario family represents a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. The A1B scenario specifically, represents this future world where there is balance across energy sources i.e. a mixture of fossil and non-fossil fuels (Nakicenovic et al., 2000). This scenario does not represent changes in landuse which remains fixed through the duration of these simulations. This is useful for understanding the effect of climate change in the absence of any adaptation.

## 2.2 Observations

This analysis uses observations of precipitation and riverflow to assess the present day RCM hydrology. The precipitation observations are from the Asian Precipitation-Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE – Yatagai et al., 2012) dataset. APHRODITE is a daily, 0.25° resolution gridded dataset.

The river flow analysis focuses on a EU HighNoon project (HNRCM) to provide river flow rates for South Asia. A selection of river gauges from the Global Runoff Data Centre flow gauges , mainly from the GRDC (GRDC, 2014) that are located within the three major river basins for South Asia; the Indus and the Ganges/Brahmaputra. These gauges network provide observations which are used, in addition to downscaled ERA-interim river flows, to evaluate the downscaled GCM river flows. The selection of for the major catchments of the South Asia region; these river gauges aims aim to illustrate from the perspective of river flows as modelled in an RCM, that the influence of the ASM on precipitation totals increases, from west to east and north to south across the Himalayan mountain range, while that of western disturbances reduces (Wiltshire, 2013; Dimri et al., 2013; Ridley et al., 2013; Collins et al., 2013). The differing influences across the Himalayan arc result in complex regional differences in sensitivity to climate change; with western regions dominated by non-monsoonal winter precipitation and therefore potentially less susceptible to reductions in annual snowfall (Wiltshire, 2013; Kapnick et al., 2014). The selection of these gauges and the models used are described in Sect. **??**, while a brief evaluation of the driving data and the river flow analysis is presented in Sect. 3. The implications of the potential changes in river flows on water resources and conclusions are discussed in Sects. 4 and 5 respectively.

## 3 Methodology

### 2.1 Observations

The total precipitation within each of the downscaled GCM simulations are compared against a downscaled ERAinterim simulation and precipitation observations from the Asian Precipitation-Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE – ) dataset in Sect. 3.1 focusing on the main river basins in the region and included in the river flow analysis (in Sect. 3.2); the Indus and the Ganges/Brahmaputra. The precipitation patterns for each basin are useful for understanding the changes in the river flows within the catchments, however, rain gauges in the APHRODITE dataset are particularly sparse at higher elevations (see , Fig. 1) which leads to underestimation of the basin wide water budgets particularly for mountainous regions . Therefore the reanalysis product ERAinterim is also used as a benchmark to compare the downscaled GCMs against. All of the gauges selected for the river flow analysis presented here lie within these river catchments and are chosen to characterize the conditions along the Himalayan arc using river flow data from the Global Runoff Data Centre . A brief geographical description of the rivers and the chosen gauges is given in this section, their locations are shown in Fig. 1 and listed in Table 1 (including the abbreviations shown in Fig. 1 and the gauge location in terms of latitude and longitude).

The Indus, originates at an elevation of more than 5000 m in western Tibet on the northern slopes of the Himalayas, flowing through the mountainous regions of India and Pakistan to the west of the Himalayas. The upper part of the Indus basin is greatly influenced by western disturbances which contribute late winter snowfall to the largest glaciers and snow fields outside the polar regions; the meltwaters from these have a crucial role in defining the water resource of the Indus basin (Wescoat Jr, 1991). In this analysis the Attock gauge is the furthest upstream and the Kotri gauge, located further downstream provide observations on the main trunk of the Indus river. The Chenab river, located in the Panjnad basin and in this analysis represented by the Panjnad gauge, is a major eastern tributary of the Indus, originating in the Indian state of Himachal PradeshPardesh.

In the upper parts of the Chenab sub-basin western disturbances contribute considerably to precipitation while the foothills are also influenced by the ASM (Wescoat Jr, 1991).

The Ganges river originates on southern slopes of the Himalayas (Thenkabail et al., 2005) and traverses thousands of kilometres before joining with the Brahmaputra in Bangladesh and emptying into the Bay of Bengal (Mirza et al., 1998). The Ganges basin has a population density 10 times the global average making it the most populated river basin in the world (Johnston and Smakhtin, 2014), it covers 1.09 million $km^2$ with 79 % in India, 13 % in Nepal, 4 % in Bangladesh and 4 % in China (Harding et al., 2013). The main trunk of the Ganges is represented in this analysis by the gauge at the Farakka barrage, located at the India–Bangladeshi border, to the East of the Himalayas. The Bhagirathi river, located in "the ~~the region often referred to as the~~ Upper Ganga basin", is one of the main head streams of the Ganges. The Bhagirathi river originates from Gaumukh 3920 m a.s.l. at the terminus of the Gangotri glacier in Uttarakhand, India (Bajracharya and Shrestha, 2011). The Tehri dam is located on this tributary, providing the most central data point on the Himalayan arc in this analysis (~~this is~~ not a GRDC gauge).

The Karnali river (also known as Ghaghara), drains from the Himalaya originating in Nepal flowing across the border to India where it drains into the Ganges. The Karnali is the largest river in Nepal and a major tributary of the Ganges (Bajracharya and Shrestha, 2011) accounting for approximately 11 % of the Ganges discharge, 5 % of its area and 12 % of its snowfall in the HNRCMs. Two of the river gauges in this analysis; the Benighat and the Chisapani are located on this river. Two other sub-catchments complete those covering the Ganges basin; the Narayani river (or ~~also known as the~~ Gandaki River, represented here by the Devghat river gauge); reportedly very dependant on glaciers at low flow times of the year with over 1700 glaciers covering more than 2200 $km^2$ (Bajracharya and Shrestha, 2011). The Arun river, part of the Koshi river basin originates in Tibet, flows south through the Himalayas to Nepal. The Arun, represented in this analysis by the Turkeghat gauge joins the Koshi river which flows in a southwest direction as a tributary of the Ganges.

The Brahmaputra originates from the glaciers of Mount Kailash at more than 5000 m a.s.l., on the northern side of the Himalayas in Tibet flowing into India, and Bangladesh before merging with the Padma in the Ganges Delta. The Brahmaputra is prone to flooding due to its surrounding orography and the amount of rainfall the catchment receives (Dhar and Nandargi, 2000). The Brahmaputra is represented in this analysis by three gauges; Yangcun, the highest upstream gauge, Pandas in the middle and Bahadurabad furthest downstream but above the merge with the Padma.

There are no known observation errors for the GRDC observations (personal communication, GRDC). Estimates of observation errors for river gauges vary in the literature with a recommendation in Falloon et al. (2011) for GCMs to be consistently within 20 % of the observations while Oki et al. (1999) suggest that errors of 5 % at the 95 % confidence interval might be expected. McMillan et al. (2010) propose a method for quantifying the uncertainty in river discharge measurements by defining confidence bounds. In this analysis, these methods are hindered by the lack of observations concurrent with the model simulations. Therefore the method for approximating the inter-annual variability in this analysis is based on the model variability and is described in Sect. 2.1.

## 2.1 ~~Models~~

## 2.1 Methods

There are two stages to ~~This analysis utilizes 25resolution regional climate modelling of~~ the analysis presented, comparison of the simulations with observations (for both RCM precipitation and river flows) and analysis of future climate. The comparison against observations aims to assess if the RCM reproduces the regional hydrology in terms of precipitation and river flow compared with available observations. The objective of the analysis of future climate is to understand how these simulations compare against the present day high and low flows i.e. present day natural variability. In this section we describe the methods used in each stage of the analysis; the comparison against observations is described in Sect. 2.1.1 and the analysis of future river flows in Sect. 2.1.2.~~Indian sub-continent to provide simulations across the Hindu-Kush Karakoram Himalaya mountain belt. To sample climate uncertainty, two GCM simulations that have been shown to capture~~

a range of temperatures and variability in precipitation similar to the AR4 ensemble for Asia and that have been shown to simulate the ASM ; The Third version of the Met Office Hadley Centre Climate Model and ECHAM5 are downscaled using the HadRM3 RCM . An ERA-interim driven RCM simulation is also shown to provide a benchmark for comparison against the GCM driven simulations in the absence of good quality observations (see Sects. 2.2 and 3.1). The RCM simulations are performed at 25, part of the ensemble produced for the EU-HighNoon program, for the whole of the Indian subcontinent (25N, 79E–32N, 88E)and are currently the finest resolution modelling available for this region . There are 19 atmospheric levels and the lateral atmospheric boundary conditions are updated 3hourly and interpolated to a 150s timestep. The experimental design of the HighNoon ensemble compromises between the need for higher resolution climate information for the region, the need for a number of ensemble members to provide a range of uncertainty and the limited number of GCMs that are able to simulate the ASM. These factors are all important given the limited computational resources available.

### 2.1.1 Comparison against observations

The total precipitation from each of the downscaled GCM simulations are compared against a downscaled ERAinterim simulation and APHRODITE observations. This comparison is on the basin scale, focussing on the basins included in the river flow analysis (see Sect. 2.2); the Indus and In these simulations the land surface is represented by version 2.2 of the Ganges/Brahmaputra. The TRIP model basin boundaries for each of these basins are shown in Fig. 3. The Ganges and Brahmaputra catchments are considered together in this analysis as these rivers join together in the Ganges Delta and are not clearly delineated in TRIP (see Fig. 3b). The precipitation patterns for each basin are useful for understanding the changes in the river flows within the catchments although rain gauges in the APHRODITE dataset are particularly sparse at higher elevations (see Yatagai et al., 2012, Fig. 1). This leads to underestimation of Met Office Surface Exchange Scheme . MOSESv2.2 treats subgrid land-cover heterogeneity explicitly with separate surface temperatures, radiative fluxes (long wave and shortwave), heat fluxes (sensible,

~~latent and ground), canopy moisture contents, snow masses and snowmelt rates computed for each surface type in a grid box . However the air temperature, humidity and wind speed above the surface are treated as homogenous across the gridbox and precipitation is applied uniformly over~~ the basin wide water budgets particularly for mountainous regions (Andermann et al., 2011). This is confirmed by Immerzeel et al. (2015) for the Indus basin where they find a high altitude precipitation of up to ten times higher than current gridded datasets is needed to close the water balance for this basin. We compare the observations and simulations in terms of their annual timeseries and the climatology for each basin. The climatologies are calculated using the 1971-2000 period for HadCM3 and ECHAM5 and 1990-2006 for the ERAint simulation in order to capture a typical seasonal cycle for each simulation and basin.

This analysis is repeated for river flows in Sect. 3.2 for each of the 12 gauges described in Sect. 2.2. We also calculate the 1.5 standard deviation (SD) over a 30 year period to define the inter-annual variability. A value of plus 1.5 SD indicates an approx 1 in 10 year wet event, a value of minus 1.5 SD indicates a 1 in 10 year dry event. This approach is taken to indicate the possible impact of such a change under the hypothesis that current socio-economic levels of climate adaptation can cope with in 1 in 10 year events. The change driving mechanism could be anthropogenic climate or decadal variability. This assumes that interannual variability is independent of climate change whether that is due to decadal variability or externally forced change. In this context it is indicative of the timing and magnitude of possible changes under the A1B emissions scenario. More work and ensemble members would be required to control for the role of decadal variability while the substantial computation expense in running high-resolution RCM experiments currently precludes the use of initial condition ensembles.

#### 2.1.2 Future analysis

In Sect. 3.3 we use the annual timeseries of the whole simulation period to highlight any trends in future precipitation, evaporation (at the basin scale) and river flows (for each gauge) over the century. We also calculate the climatologies for two future 30-year periods; 2040-2070 (referred to as the 2050s) and 2068-2098 (referred to as the 2080s). The monthly climatology for the two periods is compared against the 1971-2000 range of natural variability. The purpose of different surface types of each gridbox. The relationship between the precipitation and the generation of runoff is complicated, depending on not only the intensity, duration and distribution of the climatology analysis is twofold. The first objective is to establish if there is any change in the seasonality of the river flow. The second objective is to establish if there is any increase in the future 30-year mean river flows that is outside the present day variability, thereby indicating an increase in future events that are equivalent to the 1971-2000 1 in 10 year wet (dry) events (see Sect. 3.3.1). rainfall but also the characteristics of the surface e.g. the infiltration capacity of the soil, the vegetation cover, steepness of the orography within the catchment and the size of the catchment. In GCMs and even 25RCMS such as the ones presented here, the resolution is often too coarse to explicitly model the large variations of soil moisture and runoff within a catchment and therefore the major processes are parameterized . The method used within MOSES2.2 for generating surface and subsurface runoff across a gridbox is through partitioning the precipitation into interception by vegetation canopies, throughfall, runoff and infiltration for each surface type . The infiltration excess mechanism generates surface runoff; this assumes an exponential distribution of point rainfall rate across the fraction of the catchment where it is raining . Moisture fluxes are allowed between soil layers; these are calculated using the Darcy equation, with the water going into the top layer defined by the gridbox average and any excess removed by lateral flow. Excess moisture in the bottom soil layer drains from the bottom of the soil column at a rate equal to the hydraulic conductivity of the bottom layer as subsurface runoff . The performance of MOSESv2.2 is discussed in the context of a GCM in , however no formal assessment of MOSESv2.2 and the runoff generation in particular has been done for the RCM.

Analysis of the In this analysis the simulated runoff is converted into river flow using the TRIP river routing scheme as a post-processing step.TRIP is a simple model that moves water along a pre-defined 0.5river network; the Simulated Topological Network at 30 year mean is useful for understanding the general climatology of the region but often it is min resolution in order to provide mean runoff per unit area of the basin which can be compared directly with river gauge observations. The TRIP model has been shown to agree well with observed river flow gauge data and largely showed good skill when comparing run off from several land surface models . Implementation of TRIP in two GCMs; HadCM3 and HadGEM1 is described by and was found to improve the seasonality of the river flows into the ocean for most of the major rivers. Using TRIP ensures the river flow forcing is consistent with the atmospheric forcing, however it also assumes that all runoff is routed to the periods of high and low river flow that are critical in terms of water resources. Mathison et al. (2013) highlight the importance of potential changes in the seasonal maximum and minimum river flows for the agricultural sector. The analysis in Sect. 3.3.2 uses Kernal Density Estimation (KDE, (KDE, Scott, 2009; Silverman, 1986)) to calculate the probability density functions (pdfs) of the river flows for each river gauge and 30 year period. The main aim of this analysis is to establish if there is any change in the distribution of the highest and lowest river flows for network and as such there is no net aquifer recharge/discharge. This may not be the case in regions with significant ground water extraction which is subsequently lost though evaporation and transported out of the 2050s and 2080s compared with the 1971-2000 period (see Sect. 3.3.2). Given these distributions, we then attempt to quantify the changes highest and lowest river flows for the two future periods by focussing on the changes in the lowest and highest 10 % of flows using two different approaches. In the first approach in Sect. 3.3.3 we apply the upper and lower 10% of river flows for the 1971-2000 period as thresholds for the 2050s and 2080s. In Sect. 3.3.4, we take the principle of the threshold analysis one step further by calculating the 10th and 90th percentile threshold for decade, simulation and gauge. The aim of this second approach is to establish if there is any systematic change in the upper and lower parts of the distribution through the centurybasin. These simulations do not include extraction, which for this region is large, particularly for irrigation purposes ; this means that the extraction-evaporation and subsequent recycling of water in a catchment is not considered in this analysis .

The routed runoff of the HNRCM simulations are referred to here using only the global driving data abbreviations; ERAint, ECHAM5 and HadCM3.

## 3 Results

The results are divided into three sections. Precipitation has a key influence on river flows, therefore in Sect. 3.1 we consider the previous

### 3.1 Comparison of present day driving data with observations

In this section we summarise the main points from previous analysis and evaluation of the HNRCM simulations comparing the RCM precipitation for major South Asia basins with observations and ERAint. In Sect. 3.2 we focus on riverflows themselves for 12 gauges within these basins distributed across the Himalayan arc. The methods used in Sect. 3.1 and 3.2 are described in Sect. 2.1.1). In Sect. 3.3 we analyse the future projections of precipitation, evaporation and river flow to understand the water cycle of the region (see that provide the driving data for the river flow projections . We also look again at the total precipitation for these simulations focussing on the major river basins for the region before presenting the river flow projections for individual gauges in Sect. 2.1.2 for the methods used).

### 3.1 Comparison of present day driving data with observations

The HNRCM simulations have been evaluated in several previous publications. 3.2. Lucas-Picher et al. (2011) evaluates the ability of RCMs to capture the ASM using ERA-40 data. , Kumar et al. (2013) analysed the , as part of the HighNoon project, completes analysis using the HNRCMs forced with ERA-Interim data. The GCM and HNRCM simulations are also themselves evaluated against a range of observations for the Ganges/Brahmaputra river basin in Mathison et al. (2013). In Figure 2 shows the spatial distribution of total precipitation for the monsoon period (June to September; ) for APHRODITE observations together with the downscaled ERAint and GCM driven simulations. Figure 2 highlights that, in general the HNRCM simulations capture the spatial characteristics of the ASM, successfully reproducing regions of high convective precipitation, maximum land rainfall and the rain shadow over the east coast of India (Kumar et al., 2013). In order to illustrate this, Figure 2 shows the spatial distribution of total precipitation for the monsoon period (June to September; Goswami and Xavier, 2005). ~~as described in more detail in .~~ The RCMs are also able to reproduce the inter-annual variability of the region although they underestimate the magnitude of the variation (Kumar et al., 2013). The ~~In general the~~ GCMs in the AR4 ensemble tend to exhibit cold and wet biases compared to observations both globally (Nohara et al., 2006) and for South Asia (Christensen et al., 2007). Although ~~, although~~ these are generally reduced in the RCM simulations there is a ~~-~~cold bias in the RCM that is probably carried over from the larger bias in the GCMs (Mathison et al., 2013; Kumar et al., 2013).

The simulations shown in Fig. 5 ~~Figures 4 and 5 show the annual mean and the monthly climatology of the total precipitation for the RCM simulations , compared with 25resolution APHRODITE observations, for the main basins in this analysis; the Indus and the Ganges/Brahmaputra.The Ganges and Brahmaputra catchments are considered together in this analysis as these rivers join together in the Ganges Delta and within TRIP there is no clear delineation between the two catchments. In general the models~~ appear to over estimate the seasonal cycle of total precipitation ~~(Fig. 5)~~ compared with the APHRODITE observations; this is highlighted by the annual mean of the total precipitation shown in Fig. 4. However given the limitations ~~, the sparsity~~ of the observations at high elevations discussed ~~dicussed~~ in Sect. 2.1.1 we compare HadCM3 and ECHAM5 against ~~2.2 make it difficult to attach error bars to the observations particularly for mountainous regions and therefore~~ an ERAint simulation~~is used to provide a benchmark for comparison against the two downscaled GCM simulations~~. The annual mean (Fig. 4) and the monthly climatology (Fig. 5) show that, for these catchments, the ERAint simulation lies between the two HighNoon ensemble members for much of the year. However, ~~except~~ during peak periods of precipitation ~~when~~ the magnitude of total precipitation for ERAint ~~the total precipitation in the ERAint simulation~~ is larger.

The seasonal cycles of total precipitation are distinctly different between the basins shown. The Indus basin (Fig. 5a~~, left~~), indicates two periods of precipitation; one smaller peak between January and May and another larger one between July and September.

The timings of the largest peak compare well, however the smaller peak occurs later than both ERAint and APHRODITE for ECHAM5 and HadCM3~~the observations for the downscaled GCM simulations while the timing of the larger peak compare well between the observations, ERAint and the downscaled GCM simulations~~. The magnitude of the peaks in precipitation in the APHRODITE observations are consistently lower throughout the year than the simulations. The magnitude of the ERAint total precipitation is typically the largest ~~larger than both GCM driven simulations~~ while the ECHAM5 simulation is the lowest and closest to the APHRODITE observations. ~~,~~ HadCM3 is between ECHAM5 and ERAint for most of the year. In contrast the Ganges/Brahmaputra catchment (Fig. 5b~~, right~~) has one strong peak between July and September. In general this seasonal cycle is ~~; this cycle is also~~ captured reasonably well by the simulations, both in terms of magnitude and timing of the highest period of precipitation. However there is a tendency ~~tendancy~~ for the simulations to overestimate rainfall between January and June compared to the observations, thus lengthening the wet season (Mathison et al., 2013). Mathison et al. (2013) also show that in these simulations, the region of maximum precipitation along the Himalayan foothills is displaced slightly to the north of that shown in the observations. One explanation for this could be that the peak in total precipitation is due to the distribution of observations already discussed. Alternatively it could be due to the model resolution, which may ~~, at 25~~still be too coarse to adequately capture the influence of the orography on the region of maximum precipitation~~and therefore it is displaced from where it actually occurs~~. The downscaled ERAint simulation also indicates a higher total precipitation for January–May that is within the range of uncertainty of the GCM driven simulations. However for the remainder of the Monsoon period, ERAint has a higher total precipitation than the GCM driven simulations. ~~; this is highlighted by the spatial distribution of total precipitation shown in~~ Fig. 2 illustrates this, showing ~~which shows that ERAint has~~ a slightly larger and more intense area of maximum rainfall over the eastern Himalayas for ERAint ~~Eastern Himalayas~~ than shown in the other simulations or APHRODITE~~observations~~.

## 3.2 Present day modelled river flows

In this section we compare present day modelled river flows with observations and a downscaled ERAint simulation using annual average river flows (see Fig. 7) and monthly climatologies (see Fig. 8). It is clear from

~~The annual average river flow rates for each river gauge (described in Sect. 2.2) are shown by the paler lines in~~ Fig. 7 that ~~(red line-HadCM3, blue line-ECHAM5) with the darker lines showing a smoothed average to highlight any visible trends in the simulations. The plots show the model data for the whole period of the simulations including the historical period for each of the simulations and the available observations (– black line) for that location. It is clear from this plot that~~ observed river flow data is generally limited which makes statistical analysis of the observations difficult. River flow data for this region is considered sensitive and is therefore not readily available particularly for the present day. For each of the gauges shown here, there are generally several complete years of data but often the time the data was collected pre-dates the start of the model run. The ERAint simulation is also shown (cyan line-ERAint) to provide a benchmark in the absence of well-constrained observations (See Sect. 3.1). The comparison between the model and observations shown in Figs. 7 and 8 is therefore to establish if the model and observations are comparable in terms of the average seasonal cycle and mean river flow rate without over-interpreting how well they replicate the observations. The

~~The multi-year monthly mean modelled river flows for ECHAM5 (blue line), HadCM3 (red line), for the period 1971–2000 and ERAint (cyan line) for the period 1990–2007 are shown for each river gauge location in Fig. 8. The multi-year mean for all the available observations are also shown (Fig. 8, black line – except for the~~ Tehri Dam on the Bhagirathi river is not a GRDC gauge therefore ~~for which~~ observations are not shown. Observations for this gauge ~~but~~ were received via personal communication from the Tehri Dam operator and therefore could not be adequately referenced.~~). The shaded regions show the 1.5 standard deviation (SD) from the mean for each GCM driven model for the 1971–2000 period which represents the variability of the region and provides a plausible range of river~~

~~flows in the absence of any known observation errors for the GRDC observations (personal communication, GRDC). Estimates of observation errors for river gauges vary in the literature with a recommendation in for GCMs to be consistently within 20of the observations while suggest that errors of 5at the 95confidence interval might be expected. propose a method for quantifying the uncertainty in river discharge measurements by defining confidence bounds. Therefore in this analysis, where the 1.5 SD range encompasses the observations and ERAint, given the variability of the region and the limitations of the observations, this is considered a reasonable approximation.~~

The Kotri gauge on the Indus (Fig. 8a~~, 1st row, left column~~) and the Yangcun gauge on the Brahmaputra (Fig. 8k~~, 6th row, left column~~) are the only two gauges where the modelled river flow is higher than the observations and not within the estimated variability (1.5 SD) of the region. The ERAint simulation is also outside the estimated variability (1.5 SD) for the Benighat gauge on the Karnali river (Fig. 8e~~, 3rd row, left column~~). The differences in these gauges are also reflected in the annual mean river flows (Fig. 7) for these river gauges which are higher than observed. The high bias in modelled ~~explanation for the~~ river flow at the Kotri gauge ~~being too high~~ could be due to the extraction of water which is not included in the model. The Indus has the largest irrigation scheme in the world and a semi-arid climate (Immerzeel et al., 2015) which means the extraction rate for this basin is large (Biemans et al., 2013). This gauge is also ~~; this is particularly plausible for this gauge as this is a downstream gauge~~ located relatively close to the river mouth to the west of the Himalayas (see Fig. 1 and Table 1), therefore the riverflows are less likely to be affected by the ASM and more likely to be affected by meltwater from winter precipitation~~and the Indus has a relatively large extraction rate~~. The Yangcun gauge is a more upstream gauge and the differences between the model and observations for this gauge are more likely to be related to the precipitation distribution. Fig. 2 shows a region of intense precipitation in the simulations (Fig. 2b, c and d) for the ASM period close to this gauge. The APHRODITE data (~~which is high at this location, particularly during the ASM (see~~ Fig. 2a) also shows a region of higher rainfall although this is not as large as that shown for the simulations. This ~~); this~~ could be having a direct effect on the riverflow.

The ~~At the~~ other two gauges on the Brahmaputra are located downstream of the Yangcun gauge; the Pandu (Fig. 8j) and Bahadurabad (Fig. 8l). At these two gauges, ~~6th row, right column and 5th row, right column respectively),~~ the seasonal cycle of river flow has a very broad peak particularly in the modelled river flows compared to the other gauges. In the simulations the snowfall climatology for the Ganges/Brahmaputra basin (not shown) has a similar seasonal cycle to that of the river flow for the Bahadurabad and the Pandu gauges. It is therefore likely that the broad peak in river flow is related to the broad peak in snowfall and subsequent snowmelt. The Pandu gauge is also one of only two gauges where the modelled river flow is less than the observations for at least part of the year, the other being the Devghat gauge on the Narayani river (Fig. 8g). Both ~~, 4th row, left column); both~~ of these gauges are located in the Himalayan foothills close to the region of simulated maximum total precipitation. If the simulations put the location of this maximum below these gauges this could cause the river flows at the gauges to be lower than observed. The river flow on the main trunk of the Ganges at the Farakka barrage (shown in Fig. 8i~~, 5th row, left column~~), is a reasonable approximation to the observations in terms of magnitude, however the timing of the peak flow seems to be later in the models. It could be argued this also happens in some of the other gauges although it is more noticeable for the Farakka barrage. All the gauges shown here are for glacierized river basins. Snow fields and ~~and although snow fields and therefore~~ snow melt are represented in the simulations in this analysis and will therefore ~~and the models will~~ replicate some aspects of melt affecting river flow. However ~~,~~ glacial melt is not explicitly represented in the RCM used for these simulations. Including glacial processes specifically could act to reduce runoff because more snow is stored as ice or increase runoff where there is an increased melting (Bolch et al., 2012). Therefore including glacial processes could ~~; this could~~ be important for the timing and magnitude of the maximum and minimum river flows for these catchments.

### 3.3 Future river flows

In this section we consider the future HNRCM simulations.~~This section considers the future simulations from the RCM in terms of both precipitation and river flows to establish any~~

implications for future water resources.The future annual means of both total precipitation (for the two main basins covering the gauges in this analysis) and river flows (for each gauge) are shown in Figs. 4 and 7 respectively. In both Figs. 4 and 7 the annual average is shown for the two model simulations (red line-HadCM3 and blue line-ECHAM5) by the unsmoothed (paler) lines; the smoothed (darker) lines aim to highlight any trends in the data that might be masked by the high variability shown in the annual mean of the future projections of both precipitation and river flow.

Figure 4 also highlights the variability in the future projections of total precipitation for South Asia between basins. In ; in these simulations the Ganges/Brahmaputra catchment shows an increasing trend in total precipitation and there is considerable more variation between the simulations (Fig. 4b). The , right)than the Indus basin (Fig. 4a), however, has a , left), which has a much flatter trajectory to 2100 and the simulations are more similar. The annual timeseries of evaporation (Fig. 6) over these catchments shows a similar picture, with an increasing trend for the Ganges/Brahmaputra basin (Fig. 6b) but no real trend for the Indus (Fig. 6a). The annual mean runoff efficiency (not shown), defined here as the ratio of annual runoff (streamflow per unit area) to annual precipitation, shows no real trend for either basin. The trends in river flow (see 2100.

The trends shown by the smoothed (darker) lines overlaid on top of the annual mean river flows shownin Fig. 7) vary between gauges, although none indicate decreasing river flows. There is highlight an upward trend in river flows at some of the gauges, in particular, the Narayani-Devghat (Fig. 7g, 4th row, left column), Arun-Turkeghat (Fig. 7, h4th row, right column) and Ganges-Farakka (Fig. 7i). These gauges suggest , 5th row, left column)all show an upward trend toward the 2100s that actually represents a doubling of the river flow rate. The increase in riverflow for which could be important for water resources for the region.

In the following analysis in Sects. 3.3.1 and 3.3.3 we focus on the modelled river flow for two future periods; 2040–2070 (referred to as 2050s) and 2068–2098 (referred to as 2080s).In Sect. 3.3.1 we consider the mean seasonal river flow for the two periods, to establish if there are changes in the Narayani-Devghat gauge (Fig. 7g) are consistent with analysis by Shrestha and Aryal (2011) using a hydrological model for the Narayani basin. Ganges-Farakka is the most downstream gauge in the Ganges/Brahmaputra basin in this riverflow analysis therefore providing an approximation for the whole Ganges basin. These simulations show an increase in precipitation for the Ganges/Brahmaputra basin of approximately 20 % (See Fig. 4) and an increase of approximately seasonality of river flows in the future before focussing on the upper and lower 10 % in evaporation (See Fig. 6), over the course of the century. This suggests the changes in runoff over the Ganges catchment are predominantly driven by precipitation on the annual scale. However regional analysis by DeepakJhajharia et al. (2012) covering the humid northeastern part of India and a global analysis by McVicar et al. (2012) suggest there has been a decline in the evaporation caused by lighter surface winds and reduced radiation. A future reduction in evaporation could also contribute to future increases in runoff. Analysis using a conceptual hydrological model by Singh and Bengtsson (2005) suggests that the type of precipitation being received at different elevations and of the changes in melt and evaporation from snowpacks in a warmer climate could also be important for changes in runoffriver flows for the two future periods in Sect. 3.3.3. Section 3.3.4 continues to focus on the highest and lowest flows but uses the 10th and 90th percentile for each decade to compare models for each gauge.

### 3.3.1 Climatology analysis

In this section we use climatologies to compare future river flows with the present day inter-annual variability (defined in Sect. 2.1.1). The seasonal cycle of modelled river flows at each of the river gauge locations are shown in Fig. 9 for two future periods; 2050s (solid lines)and 2080s (dashed lines) for the two ensemble members (HadCM3 – red lines, ECHAM5 – blue lines). The shaded part of the plot represents the present day natural variability using the 1.5 SD of the 1971–2000 period from each model. South Asia is a very variable region, yet these models suggest the future mean river flow could lie outside the present day variability for peak flows for some of the gauges in this study. This ; this could have important implications for water resources for the region. The gauges that show an increase in maximum river flows (see in Fig. 9) are mainly those in the middle of the

Himalayan arc (see as shown in Fig. 1). The seasonal cycle for with the western most (Indus gauges) and the eastern most (Brahmaputra gauges) are typically still within the range of present day variability. This could be due to the changes in the influence on river flow from west to east becoming more influenced by the ASM and less by western disturbances, with basins in the centre of the Himalayas and to the north influenced by both phenomena. Figure 9 also suggests that the maximum river flows still occur mainly during the ASM for many of the gauges shown.

As mentioned in Sect. 3.2 glacial melt is not explicitly represented in the RCM used for these simulations and this could have implications for the timing and magnitude of the future high and low river flows for these catchments.

Analysis of the 30year mean is useful for understanding the general climatology of the region but often the mean does not provide the complete picture particularly when it is the periods of high and low river flow that are critical in terms of water resources . highlight the importance of potential changes in the seasonal maximum and minimum river flows for the agricultural sector. The analysis in Sect. 3.3.2 considers the distribution of river flows across the region using the same river gauges and also considers changes in the upper and lower parts of the distribution of river flow.

### 3.3.2 High and low flow analysis

The analysis of the high and low flows is of particular importance to water resources and future availability, therefore in this section we calculate the The distributions of the river flows for each of the gauges (see Sect. 2.1.1). These are shown in the form of probability density functions (pdfs) , calculated using Kernal Density Estimation in Fig. 10 for the 1971–2000, 2050s and the 2080s. Figure 10 illustrates how the lowest flows dominate the distributions for each of the three periodsdistribution. In most of the gauges and both models the 1971–2000 period has the highest frequency of the lowest flows, the curves then tend to flatten in the middle of the distribution before tailing off toward zero for the highest flows. The two future periods also follow a similar trajectory, although in general there is a reduction in the frequency of the lowest flows and an increase in the magnitude of the highest flows for all of the gauges and both simulations towards 2100.highest flows.

The Yangcun gauge on the Brahmaputra (Fig. 10,k6th row, left column) shows the least change of all the gauges between the 1971–2000 period, future periods and simulations. The models, however the the distributions for the gauges downstream of Yangcun; the Pandu (Fig. 10l, 6th row, right column) and the Bahadurabad (Fig. 10j, 5th row, right column) are notable for their differences from all the other gauges. All the other gauges shown have a single peak . The Pandu and Bahadurabad gauges have two distinct peaks in frequency, one toward the lower end of the river flow distribution. The Pandu and Bahadurabad gauges have two distinct peaks in frequency with a second peak occurring toward , consistent with the other gauges shown, and another in the middle of the distribution, where the distribution for most other gauges flattens out. This is consistent with the broader peak in the 30-year mean seasonal cycle shown for these gauges in Fig. 9 and is probably similarly could be explained by snowmelt (see Sect. 3.2). In some of the other gauges there is a small increase this peak in the middle of the river flow distribution but this range of river flows is evident to a much lesser degree but tends to be smaller and restricted to the two future periods and is not evident in the present day distribution e.g. the two Karnali river gauges (Fig. 10e and f)., 3rd row). For the two future periods there is a similar shape to the distributions for each of the river gauges compared to the 1971–2000, however there is a tendancy for a reduction in the frequency of the lowest flows and an increase in the magnitude of the highest flows for both models across the gauges.

In the analysis that follows, the changes in the lowest and highest 10of flows are considered in more detail using two alternative approaches; one comparing the 10th and 90th percentile for each model for each decade and the other takes the relevant percentiles for the 1971–2000 period and uses these as thresholds for the two future periods.

### 3.3.3 Threshold analysis

The In the pdfs shown in Fig. 10 and described in Sect. 3.3.2 suggest future changes in the lower and upper ends of the river flow distribution. In this section we consider these parts of the distribution in order , the individual distributions for the gauges shown suggest that the occurrance of the lowest flows is reducing and the magnitudes of the higher flows are increasing toward the end of the century. This analysis aims to confirm this pattern. We compare by comparing the two future periods (2050s and 2080s) against the 1971–2000 period explicitly using thresholds defined by the 10th and 90th percentiles for this present day period for each river gauge. Graphical examples from the results of this analysis are shown for all three periods (historical–top, 2050s–middle, 2080s–bottom) for the Farakka Barrage on the River Ganges in Fig. 11 , which shows the number of times river flows are less than the (1971–2000) 10th percentile and Fig. 12. , which shows the number of times river flows are greater than the (1971–2000) 90th percentile. Each of the plots in Figs. 11 and 12 show a different decade; historical (top), 2050s (middle) and 2080s (bottom). In Fig. 11 the number of months where river flow times the model is below the present day 10th percentile 1971–2000 threshold reduces in each of the future decades. However for flows greater than the present day 90th percentile there is an increase and in Fig. 12 the number of points increases in each of the future decades (Fig. 12). Table 2 summarises the main results for each of the gauges from this analysis by providing the percentage change in the number of times the model simulations is less than the 10th or greater than the 90th percentile for the 1971–2000 thresholds. Table 2 illustrates that the patterns shown in Figs. 11 and 12 are generally true for almost every other gauge in the analysis. The Tehri Dam (Bhagirathi) is the only exception of the gauges shown in Table 2, showing an increase of 12 % in the number of incidences where the riverflow river flow is less than the 1971–2000 10th percentile for the 2080s. This ; this is mainly due to the ECHAM5 model which has a high number of incidences. The Yangcun gauge (Brahmaputra) is the only gauge where there is no change in the number of incidences where the river flow is less than the 10th percentile for 1971–2000 in either of the future periods. This is the 2050s or the 2080s, probably because the lowest river flows are already very low at this gauge.

At In every gauge there is an increase in the number of incidences where river flows are greater than the 90th percentile for 1971–2000 for the two future periods. Several in the 2050s and 2080s in these model runs, with several of the gauges have suggesting increases in the number of events above the 90th percentile for the 1971–2000 period of more than 100 %. This confirms the conclusions drawn visually from the analysis in Fig. 10 that the general distributions move toward the higher flows both low and high flows appear to increase in these model runs for these gauges and simulationswhile allowing these changes to be quantified.

### 3.3.4 Decadal percentile analysis

The annual timeseries shown in Fig. 7 is very variable and systematic changes throughout the century could be masked by this variability. On the basis that there are changes in the upper and lower parts of the future river flow distributions, the therefore in this section the 10th and 90th percentiles for each decade and each simulation are calculated. At the lower end of the distribution, there is little change in the model run are considered to see if there is any systematic change on a decadal basis through to 2100. There is little difference between the two models for the 10th percentile (not shown) for most of the gauges, probably because of very low this is mainly due to the very low river flows at the lowest flow times of the year. Only the Pandu and Bahadurabad gauges on the Brahmaputra and the Farakka gauge on the Ganges show a non-zero value for the lowest 10 % of river flows through to the 2100s. These three gauges indicate a slight increase for the 10th percentile for each decade through to 2100.

Figure 13 shows the 90th percentile for both models calculated for each decade from 1970 to 2100 for each of the river gauges specified in Table 1. The 90th percentile values (Fig. 13) are generally much more variable throughout the century than those for the 10th percentile , particularly in terms of changes through to the 2100s. We consider Considering the gauges according to their location across the Himalayan arc from west to east (see Fig. 1). The , the HadCM3 simulation projects an increase in river flows for the most westerly gauges in this analysis; the flow for the two gauges on the Indus (Attock and Kotri gauges located on the Indus (see , shown in Fig. 13a and b, 1st row) and the Chenab-Panjnad gauge (see Fig. 13c). , 2nd row, left column), however ECHAM5, on the other hand, shows is generally indicating a much flatter trajectory for these gauges. This may be explained by the HadCM3 simulation depicting an increase in the occurance of western disturbances and an increase in total snowfall which is not simulated by ECHAM5 (Ridley et al., 2013).~~or decreasing river flow on these rivers.~~

The gauges located toward the middle of the Himalayan arc generally show increases across the decades to 2100 in both models; these are the ~~in this analysis; namely~~ Bhagirathi-Tehri (Fig. 13d), both ~~, 2nd row, right column),~~ Karnali river gauges (Benighat - ~~– Benighat and Chisapani (~~Fig. 13e and Chisapani-Fig. 13f~~, 3rd row~~), Narayani-Devghat and Arun-Turkeghat (Fig. 13g and h)~~, 4th row)generally show increases across the decades to 2100 in both models~~. There is very close agreement between the two simulations for the Narayani-Devghat, Arun-Turkeghat (Fig. 13g and h~~, 4th row~~) and Bhagirathi-Tehri (Fig. 13d) gauges, ~~2nd row, right column) gauges~~with the former two showing less variability between decades than the others in the analysis. The Karnali-Benighat gauge (Fig. 13e~~, 3rd row, left column~~) also has less variability between the decades, however there is a systematic difference between the two simulations that remains fairly constant across the decades. From the subset of gauges in this analysis that are the most central on the Himalayan arc, the ~~The~~ Karnali-Chisapani gauge (Fig. 13f~~, 3rd row, right column~~) has the largest variability between simulations and decades. However ~~of the models in the analysis that are most central on the Himalayan arc,~~ this gauge still shows an increase overall in both simulations with a steeper increase for HadCM3 than ECHAM5. The closer agreement between simulations at these more central gauges may be due to the reducing influence of the western disturbances in the ~~models although the gradient of this increase is smaller for ECHAM5 than~~ HadCM3 simulation from west to east across the Himalaya therefore resulting in smaller differences between the the two simulations.

The Farakka-Ganges gauge (Fig. 13i) and two of ~~, 5th row, left column) and~~ the Brahmaputra gauges – Bahadurabad (Fig. 13j) and Pandu (Fig. 13l~~,5th row, right column and 6th row, right column, respectively~~), represent three of the most easterly river gauges in the analysis. These ~~; these~~ gauges show an increase in both simulations through to the 2100s, in this case ~~although this is~~ more pronounced in ECHAM5 than HadCM3 for these two ~~the~~ Brahmaputra gauges. There is much closer agreement between the two simulations at the Farakka-Ganges gauge (Fig. 13i, 5th row, left column) which is located slightly further west than the two Brahmaputra gauges. The other Brahmaputra gauge, the Yangcun (Fig. 13k) is very variable through the century, there is a period with consecutive decades of increasing river flows in the middle of the century but over the whole century neither model shows a consistent change.

This analysis shows suggests that neither simulation is consistently showing a systematic increase in the 90th percentile of river flows across all the gauges. Instead it highlights the changing conditions and the different behaviour of , however it does highlight the different behaviour in the two simulations across the Himalayan arc.Himalayas. The HadCM3 simulation shows increases in western river flows which are not evident in the ECHAM5 simulation; this may be explained by the HadCM3 simulation depicting an increase in the occurance of western disturbances and an increase in total snowfall which is not evident in the ECHAM5 simulation. In contrast, for the eastern gauges, both simulations show an increase in river flow, although the ECHAM5 simulation shows larger increases than HadCM3. The central gauges suggested a more mixed result, with the models more in agreement with each other; this may be due to the reducing influence of the western disturbances in the HadCM3 simulation from west to east across the Himalaya therefore resulting in smaller differences between the the two simulations at these gauges.

## 4 Implications of changes in future river flows

In this section we consider the implications of the projected future changes in river flows for South Asia on water resources. We highlight the broader challenges facing the region and where the current RCMs need development to represent key processes for this region. The key , the key points from this discussion are summarised in Table 3. In the present day, water resources in South Asia are complicated, precariously balanced between excess and shortage. Parts of South Asia receive receiving some of the largest volumes of precipitation in the world and are therefore at therefore the frequent risk of flooding and yet other regularly endure water stressregularly enduring water shortages. The complexity is increased by the competition between states and countries for resources from rivers that flow large distances crossing state and country borders, each with their own demands on resource. There is a considerable Annually India receives about 4000of precipitation with 3000falling during the ASM period. A proportion, estimated to be just over 45of this precipitation (approximately 1869), finds its way into the river and replenishable groundwater system which form the basis for the water resources of the country. Of the water that actually finds its way into the system only 60of it is currently put to beneficial use, in terms of volume; this is approximately 690of surface water and 433of ground water . This means there is a gap between the amount of water resource flowing through South Asia and the actual usable amount (Aggarwal et al., 2012)useable amount , for example the total flow for the Brahmaputra basin is approximately 629 $\mathrm{km}^3$ of which only 24 $\mathrm{km}^3$ is usable (Kumar et al., 2005). There is therefore huge potential for improvements in the efficiency of systems for irrigation and the domestic water supply that could ease some of the pressures on water resources, currently and predicted, as demand currently experienced already and predictedin the future for some areas as the demand for water increases.

In the last 50 years there have already been efficiency improvements, such as development of irrigation systems and use of high yielding-water efficient crop varieties. These improvements yielding crop varietiesthat have fuelled the rapid development in agriculture across South Asia making the region more self-sustained and alleviating poverty (Kumar et al., 2005). However these advances have also ; however this has had a large impact on the regions river ecosystems resulting in habitat loss, and reduced biodiversity (Sarkar et al., 2012) and water pollution (Vörösmarty et al., 2010). . find that in developing regions, where investment in water infrastructure is low and water security is threatened there tends to be a coincident risk of biodiversity loss, with the main threat due to water resource development and increased pollution from the use of pesticides and fertilizer. estimate that a minimum storage of 385is needed across all the basins in India to balance seasonal flows and irrigate 760000although how this translates to an individual river in terms of the river flows needed to maintain ecosystems and biodiversity (also referred to as environmental flows) is a complex problem. Historically arbitrary thresholds based on a percentage of the annual mean flow have been used to estimate minimum flows, but these simplistic estimates do not take account of the flow variability that is crucial for sustaining river ecosystems (Arthington et al., 2006; Smakhtin et al., 2006), referred to as environmental flows. Environmental flows are defined by Smakhtin and Anputhas (2006) as the ecologically acceptable flow regime designed to maintain a river in an agreed or predetermined state. The variability in river flows through the year have important ecological significance; for example low flows are important for algae control and therefore maintaining water quality. High , while high flows are important for wetland flooding and preserving the river channel. When considering the implications of future changes in climate on river flows and therefore surface water resources, estimates of flow variability and minimum flows an estimate of the environmental requirement, both in terms of the flow variability as well as the minimum flows , are an important consideration. However these These important ecological thresholds together with the flows which cause inundation and crop damage have been calculated for individual basins, such as the lower Brahmaputra river basin by and the East Rapti River in Nepal by , however they are not easily quantified in general terms for different rivers with many methods requiring calibration for applications to different regions and basins. In our simulations there is an intensification of the seasonal cycle and therefore an increase in the flow variability and a reduction in the occurrance of the lowest flows. These changes could have implications for the biodiversity of these catchments..

In India the domestic requirement for water is the highest priority but is only 5 % of the total demand(this equates to approximately 30of which 17is from surface water and the rest groundwater). Irrigation is the second highest priority accounting for a much greater proportion, approximately 80 % of India's total demand for water. A significant proportion of domestic and irrigation resource comes from both ground and surface water; this equates to more than 520with 320from surface water and 206from groundwater . Biemans et al. (2013) study future water resources for food production using LPJml and the HNRCMs. LPJml also simulates ground water extractions (Biemans et al., 2013) these are thought to be important for the Indus and parts of the Ganges but not the Brahmaputra. HNRCMS. The LPJml simulated extraction varies considerably between basins; the largest occuring in the Indus (343 $km^3$ $year^{-1}$) followed by the Ganges (281 $km^3$ $year^{-1}$) and Brahmaputra (45 $km^3$ $year^{-1}$). The Brahmaputra has the smallest percentage of irrigated crop production (approximately 40 %) followed by the Ganges (less than 75 %) and the Indus where more than 90 % of crop production is on irrigated land. The Indus has the largest proportion of water sourced from rivers and lakes of the three basins and the largest proportion of the river flow is glacial melt (Immerzeel et al., 2010).. LPJml also simulates ground water extractions these are thought to be important for the Indus and parts of the Ganges but not the Brahmaputra. The model simulations presented in this analysis do not explicitly include groundwater, primarily focusing on river flows and therefore the surface water component of resource for this region. There is also no irrigation included in these simulations, which could be important particularly on the basin scale. The impacts of extensive irrigation on the atmosphere are complex but could have a positive impact on water availability due to evaporation and water being recycled within the basin, for example, estimate that up to 35of additional evaporation is recycled within the Ganges basin.

Wiltshire et al. (2013a) use a perturbed physics ensemble of HadCM3 GCM simulations (Murphy et al., 2004) and find an increase in water resources for South Asia at the annual timescale due to climate change. The analysis shown here shows a similar result with increases in river flow, particularly In general the analysis here shows that the magnitudes of the higher river flows at these gaugescould increase for these gauges(see Table 1), in some cases these increases are above the range of variability used for this analysis (1.5 SD). However, the analysis shown here on the monthly timescale, also highlights that these increases in resource tend While this could be positive in terms of surface water resources for irrigation, the potential changes seem to occur during the ASM, season and therefore when river flow is at its maximum. This could mean that the benefits of an increase in water resource ; therefore this increase may not be realised due to the timing of this increase within the year. Although these projected changes in river flow are not critical for water resources they but could still be beneficial where there is the capacity to store the additional flow for use during periods of low flow. Additional water storage capacity for example through rainwater harvesting, could greatly increase the useable water resource for the Ganges–Brahmaputra catchments (Kumar et al., 2005) and potentially alleviate the increased risk of flooding during the ASM when rainfall is most persistent and rivers are already at their peak flow. South Asia, even in the current climate, is particularly susceptible to flooding due to the high temporal and spatial variability of rainfall of the region. It is estimated that , for example approximately 20 % of Bangladesh floods annually (Mirza, 2002). Several studies have highlighted increases in both the extremes (Sharma, 2012; Rajeevan et al., 2008; Goswami et al., 2006; Joshi and Rajeevan, 2006) and the variability (Gupta et al., 2005) of precipitation in recent years that cause , where extreme rainfall events resulting have resulted in catastrophic levels of river flooding. Over 30 million people in India alone are affected by floods and more than 1500 lives are lost each year (Gupta et al., 2003), the economic cost of flooding is also considerable with the cumulative flood related losses estimated to be of the order of USD 16 billion between 1978 and 2006 (Singh and Kumar, 2013).

The timing of the peak flows of major rivers in this region is also very important in terms of flooding. In 1998 the peak flows of the Ganges and the Brahmaputra rivers occurred within 2 days of each other resulting in devastating flooding across the entire central region of Bangladesh. Approximately inundating aproximately 70 % of the country was inundated, the flood waters then remained above danger levels for more than 60 days (Mirza, 2002). This event caused extensive loss of life and livelihood in terms of damaged crops, fisheries and property and with the slow recedance of flood waters hindered hindering the relief operation and recovery of the region. This analysis does not suggest any change to the timing of the peak flows, only the magnitude. However , however given the high probability of two rivers in this region having coincident peak flows in any given year (Mirza, 2002) and the likelihood that severe flooding will result, means that an increase in the magnitude of the peak could still be significant. Flooding can have a large impact on crops, for example in Bangladesh over 30 % of the total flood related damages are due to the loss of crops. The ; the estimated crop damage from the 1998 floods was estimated to be 3.0 million t (Gain et al., 2013). The slow receding Slow receeding of flood water can also mean the ground is not in a suitable condition to sow the next crop, restricting the growing time and potentially affecting crop yields for the following year.

Another proposed though controversial method aimed at alleviating flooding in the South Asia region is inter-basin transfer through the National River Linking Project (NRLP); this is an attempt to redistribute the water between rivers by linking those rivers with a surplus to those with a deficit . The success of these projects depends on the elevation of the catchment providing the water being above that of the receiving catchment so catchments with a low elevation such as the Brahmaputra can only transfer a small amount despite having large problems with flooding. On the other hand a limited amount of flooding could also be a benefit, particularly for rice crops. Inundation , as the inundation of clear water can benefit crop yield, benefits crop yield due to the fertilization effect of nitrogen producing blue-green algae in the water (Mirza et al., 2003).

In our simulations the reduced occurrence these simulations the occurrance of the lowest flows potentially reduces in the future, which could translate into an increase in the surface water resource in this region especially during , for periods when the river flows are traditionally very low and water is usually scarce. This could mean that the current and increasing pressure on ground water (Rodell et al., 2009) may be alleviated in future years. Alternatively increases in the lowest flows may enable adaptation to a changing climate and the modification of irrigation practises. Current projections of future climate suggest that temperatures could also increase for this region (Cruz et al., 2007). Increasing temperatures poses a , this poses a threat to crop yields of a different kind because this is a region where temperatures are already at a physiological maxima for some crops (Gornall et al., 2010). Rice yield, for example, is adversely affected by temperatures above 35 °C at the critical flowering stage of its development (Yoshida, 1981). Wheat yields could also be and wheat yields could be also affected by rising temperatures, with estimated losses of 4–5 million tonnes per degree of temperature rise through the growing period (Aggarwal et al., 2012). Additional water resource for irrigation at previously low flow times of the year could allow sowing to take place at a different time of the year in order to avoid the highest temperatures, thereby reducing the likelihood of crop failure. However with increasing variability and extremes, a potential feature of the future climate for this region (Hijioka et al., 2014), there is also the increased risk of longer periods with below average rainfall and potentially more incidences of drought. This ~~; this~~ could lead to additional demand for water for irrigation to prevent crops becoming water stressed (Aggarwal et al., 2012). There may also be increases in demand from other sources other than agriculture, for example the increasing population (United Nations, 2013) or the reduced availability of ground water of an acceptable quality for domestic use (Gregory et al., 2005). Any of these factors, either individually or combined, could effectively cancel out any or all increases in resource from increased river flow due to climate change.

In addition there are a number of processes missing from the models used for these simulations that could change the sign of the projected changes. There is no irrigation included in these simulations, which could be important particularly on the basin scale. The impacts of extensive irrigation on the atmosphere are complex but could have a positive impact on water availability (Harding et al., 2013) due to evaporation and water being recycled within the basin. Tuinenburg et al. (2014) estimate that up to 35 % of additional evaporation is recycled within the Ganges basin. Therefore this aspect of the regional water cycle is not accounted for in these simulations. There is also no representation of glaciers which could act to increase or reduce river flows depending on the occurance of negative or positive mass balance respectively. In these simulations snowmelt is represented, however representing glacial processes as snowmelt could act to enhance the seasonal cycle in the simulated riverflows for both present day and future projections as snow melts more readily than ice. These simulations also do not explicitly include groundwater, primarily focusing on river flows. Groundwater is a highly exploited part of water resources for South Asia. Representation of this would give a more complete picture of the total water resources for this region.

## 5 Conclusions

We present In this analysis the first 25 km resolution regional climate projections of riverflow for the South Asia regionare presented. A sub-selection of the HNRCMs are used to provide runoff to a river routing model in order to provide river flow rate which can be compared directly with ERAInt a downscaled ERAint simulation and any available river gauge data for observation data for river basins in the South Asia region. This analysis focuses on the major South Asia river basins which originate in the glaciated Hindu-Kush Karakoram Himalaya; the Ganges/Brahmaputra and the Indus. The aim of this analysis is two-fold; firstly to understand the river flows in the ECHAM5 and HadCM3 simulations and secondly examine RCM in the two simulations and how useful they are for understanding the changes in water resources for South Asia. We also consider and secondly to understand what the projected changes in river flow to the 2100s might mean for water resources across the Himalaya region.

The driving GCMs (ECHAM5 and HadCM3) have previously been shown to two simulations in this analysis cannot capture the full range of variability, however the two GCMs that are downscaled using this RCM do capture a range of temperatures and variability in precipitation similar to the AR4 ensemble for the much larger domain of Asia (Christensen et al., 2007). However using just two ensemble members cannot capture the full range of these larger ensembles. In this analysis the seasonal cycle of precipitation, a key influence on river flows, is captured reasonably well for the downscaled GCMs compared to both observations and the downscaled ERAint simulation. Although observed precipitation is lower than in the model the underestimation inherrent in precipitation observations at higher elevations is likely to be an important factor for this analysis, which includes the high Himalaya.

which is for a much larger domain than the HighNoon domain analysed here . A number of GRDC gauge stations (GRDC, 2014), selected to capture the range of conditions across the Himalayan arc and sample the major river basins, provide the observations of river flow for comparison against the HNRCM simulations. The lack of recent river flow data limited the gauges that could be selected for analysis. In the , however using the downscaled ERAint simulation provides a constrained estimate of the South Asia water cycle in the absence of robust observations we use a downscaled ERAint simulation ~~and is used~~ in addition to the available observations to provide a useful benchmark against which to compare the downscaled GCM simulations. In general there is a tendancy for overestimation of river flow rate across the selected gauges compared with ~~to the~~ GRDC observations, however comparison against the ERAint simulation is more mixed with some gauges showing higher and others with lower river flows than ERAInt. In ~~for the downscaled GCMs compared with ERAint. However in~~ general most of the simulations broadly agree with observations and ERAint to within the range of natural variability (of ~~chosen to be~~ 1.5 SD~~for this analysis~~) and agree on the periods of highest and lowest river flow. Therefore ~~,~~ indicating that the RCM is able to capture the main features of both the climate and hydrology of this region for the present day~~the region~~.

The future projections indicate an increase in surface water resources, with river flow rates at some of the gauges almost doubled by the ~~simulations suggest that the annual average river flow is increasing toward the 2100s, although these trends are often masked by the large inter-annual variability of river flows in this region, for some of the gauges the river flow rates are almost doubled by the~~ end of the century. These increases in river flow occur for the gauges in the Ganges/Brahmaputra basin, which also shows an increasing trend in both evaporation and precipitation. Therefore the changes in riverflow are likely to be mainly driven by precipitation on the annual scale which more than counters the evaporation caused by increasing temperatures in the model. This is consistent with other analyses of precipitation which also use the A1B climate scenario (Nepal and Shrestha, 2015), which is a useful result. The trajectories of the annual average river flow, evaporation and precipitation for the Indus are much flatter, showing little or no trend.

The increases in the annual mean ~~century. These increases in~~ river flows are reflected in the seasonal cycles of river flow ~~cycle~~ for the two future periods (2050s and 2080s) which indicate that most of the changes occur during peak flow periods. Some of the gauges toward the middle of the Himalayan arc, show ~~with some gauges showing~~ changes above the range of present day natural variability. This ~~These gauges tend to be toward the middle of the Himalayan arc, so this~~ could be due to the increasing influence of the

ASM and reducing influence of western disturbances from west to east having an additive effect. The gauges located furthest west and east in this analysis seem to lie within the present day natural variability. There were also differences between the two simulations across the Himalayan arc with HadCM3 suggesting increases in riverflow at the upper end of the distribution for western gauges that was not evident in ECHAM5. The analysis shown here does not suggest a systematic change in the models for the timing of the maximum and minimum river flows relative to the present day suggesting an over all increase in water resources at the top and bottom of the distribution. This has positive and negative implications with potentially more resource during usually water scarce periods. However there are also implications but also carries implications for an already vulnerable population in terms of increased future flood risk during periods where the river flow is particularly high. Increases Bangladesh is particularly susceptible to flooding, therefore any increase in maximum flows for rivers in this region could be important in terms of loss of life,livelihoods, particularly agriculture and damage to infrastructure.

Historically management policies for rivers in this region have focussed on percentage of the average annual flow which does not take into account the importance of flow variability as well as minimum flows, which are important for sustaining river ecosystems.

While this analysis suggests increasing surface water resources a general increase in potential water resources from rivers for this region to 2100 due to climate change, there are a number of other factors that could affect this result, both in terms of this analysis and uncertainties surrounding the region itself. The South Asia region is changing rapidly, therefore other factors could factors which could have a large larger effect on water resources for this region. A and effectively cancel out any increase. For example rising population, expansion of industry (other than agriculture) and the continued depletion of ground water could change the demand for surface water resource from other parts of the South Asia economy, increases in demand for water from sources other than agriculture. In addition increasing variability of an already changeable the South Asia climate could lead to extended periods throughout the year of rainfall below the annual average, leading to an increase in long periods with below average rainfall which could also increase the demand for irrigation resource. In terms of this analysis, there are missing hydrological processes in the RCM and river flow model that could impact the river flows directly. The RCM and river flow model do not include abstraction and irrigation, groundwater recharge or explicitly include glacial processes and their . Further more the results shown here do not currently explicitly include the glacial contribution to river flowfor these catchments and gauges. Including glacial processes in the form of a glacier model together with river routing within the land-surface representation will be useful to establish if the contribution from glaciers changes the timing and/or magnitude of both the lowest and highest flows in these gauges. Likewise including representation of water extraction (both from rivers and groundwater) particularly for irrigation, the biggest user of water in the region, will help to provide a more complete picture of the demand for water resources for the South Asia region. Including irrigation and therefore the associated evaporation will capture part of the water cycle not possible with the current model and maintain the regional water balance. Including representation of these processes in the RCM or river flow model would improve the robustness of the future projections of water resources and further our understanding of the water balance for this region. These processes could have a large impact on the water balance in the model potentially changing the signal of the projected changes in river flow. Understanding the interactions between availability of water resources, irrigation and food production for this region by using a more integrated approach, such as that used in Biemans et al. (2013) may also help with understanding how pressures on resources could change with time. In support of this work and others, there is also a need for good quality observations of both precipitation and river flow that is available for long enough time periods to conduct robust water resource assessments for this region.

*Acknowledgements.* The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no 603864. Camilla Mathison, Pete Falloon and Andy Wiltshire were supported by the Joint UK DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). Thanks to Neil Kaye for his GIS expertise.

**References**


Aggarwal, P., Talukdar, K., and Mall, R.: Potential yields of rice-wheat system ~~Yields of Rice-Wheat System~~ in the Indo-Gangetic plains ~~Plains~~ of India, Rice-wheat consortium paper series, ~~Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, Rice-Wheat Consortium Paper Series,~~ 10, 16, 2000.

Aggarwal, P., Palanisami, K., Khanna, M., and Kakumanu, K.: Climate change and food security of India: adaptation strategies for the irrigation sector, World Agriculture~~Agr.~~, 3, 20–26, http://www.world-agriculture.net/article/44/Climate-change-and-food-security-of-India-adaptation-strategies-for-the-irrigation-sector, 2012.

Akhtar, M., Ahmad, N., and Booij, M.: The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya ~~Hindukush–Karakorum–Himalaya~~ region under different glacier coverage scenarios, Journal of Hydrology~~J. Hydrol.~~, 355, 148–163, http://dx.doi.org/10.1016/j.jhydrol.2008.03.015~~doi:~~, 2008.

Andermann, C., Bonnet, S., and Gloaguen, R.: Evaluation of precipitation data sets along the Himalayan front, Geochemistry, Geophysics, Geosystems, ~~Geochem. Geophy. Geosy.,~~ 12, n/a–n/a~~Q07023~~, doi:10.1029/2011GC003513, http://dx.doi.org/10.1029/2011GC003513, 2011.

Annamalai, H., Hamilton, K., and Sperber, K.: The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations, Journal of ~~J.~~ Climate, 20, 1071–1092, doi:10.1175/JCLI4035.1, http://dx.doi.org/10.1007/s00382-008-0477-4, ~~doi:,~~ 2007.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART I: MODEL DEVELOPMENT1, JAWRA Journal of the American Water Resources Association, 34, 73–89, doi:10.1111/j.1752-1688.1998.tb05961.x, http://dx.doi.org/10.1111/j.1752-1688.1998.tb05961.x, 1998.

Arthington, A. H., Bunn, S. E., Poff, N. L., and Naiman, R. J.: The challenge of providing environmental flow rules to sustain river ecosystems, Ecological Applications~~Ecol. Appl.~~, 16, 1311–1318, doi:10.1890/1051-0761(2006)016[1311:TCOPEF]2.0.CO;2, http://dx.doi.org/10.1890/1051-0761(2006)016[1311:TCOPEF]2.0.CO;2, ~~doi:,~~ 2006.

Bajracharya, S. and Shrestha, B.: The Status of Glaciers in the Hindu Kush-Himalayan Region, Kathmandu:ICIMOD, ~~available at:~~ http://lib.icimod.org/record/9419, ~~last access: November 2014,~~ 2011.

Barnett, T., Adam, J., and Lettenmaier, D.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303 – 309, doi:10.1038/nature04141, http://dx.doi.org/10.1038/nature04141, 303–309, doi:, 2005.

Biemans, H., Speelman, L., Ludwig, F., Moors, E., Wiltshire, A., Kumar, P., Gerten, D., and Kabat, P.: Future water resources for food production in five South Asian river basins and potential for adaptation - A — a modeling study, Science of The Total Environment, 468-469, Supplement, Sci. Total Environ., 468–469, S117–S131, doi:http://dx.doi.org/10.1016/j.scitotenv.2013.05.092, http://dx.doi.org/10.1016/j.scitotenv.2013.05.092, doi:, 2013.

Bolch, T., Kulkarni, A., Kääb, Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M.: The State and Fate of Himalayan Glaciers, Science, 336Christensen, J., 310–314Hewitson, doi:10.1126/science.1215828, http://0-www.sciencemag.org.wam.leeds.ac.uk/content/336/6079/310.abstract, 2012.

Christensen, J., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R., Kwon, W.-T., Laprise, R., na Rueda, Rueda, V. M., Mearns, L., Meneńdez, C., Räisänen, J., Rinke, A., Sarr, A., and Whetton, P.: Regional Climate Projections. Inclimate projections, in: Climate Change 2007: The the Physical Science Basis. Contribution of Working Group I, Fourth Assessment Report of the Intergovernmental Panel on Climate Change, https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch11.html, available at: , last access: October 2014, 2007.

Clark, D. B. and Gedney, N.: Representing the effects of subgrid variability of soil moisture on runoff generation in a land surface model, Journal of Geophysical ResearchJ. Geophys. Res., 113, 111, doi:doi:10.1029/2007JD008940D10111, doi:, 2008.

Collins, D. N., Davenport, J. L., and Stoffel, M.: Climatic variation and runoff from partially-glacierised Himalayan tributary basins of the Ganges, Science of The Total Environment, 468-469, Supplement, S48 – S59Sci. Total Environ., 468–469, S48–S59, doi: , doi:http://dx.doi.org/10.1016/j.scitotenv.2013.10.126, http://www.sciencedirect.com/science/article/pii/S0048969713013028, changing water resources availability in Northern India with respect to Himalayan glacier retreat and changing monsoon patterns: consequences and adaptation, 2013.

Cruz, R., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C., and Huu Ninh, N.: Asia. Climate Change change 2007: Impacts, Adaptation and Vulnerability. impacts, adaptation and vulnerability, in: Contribution of Working Group II, Fourth Assessment

Report of the Intergovernmental Panel on Climate Change, pp. 469–506, https://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch10.html, ~~available at: , last access: October 2014,~~ 2007.

DeepakJhajharia, Dinpashoh, Y., Kahya, E., Singh, V. P., and Fakheri-Fard, A.: Trends in reference evapotranspiration in the humid region of northeast India, Hydrological Processes, 26, 421–435, doi:10.1002/hyp.8140, http://dx.doi.org/10.1002/hyp.8140, 2012.

Dhar, ~~-~~O. and Nandargi, ~~-~~S.: A ~~-~~study of floods in the Brahmaputra basin in India, International Journal of Climatology~~Int. J. Climatol.~~, 20, 771–781, doi:10.1002/1097-0088(20000615)20:7<771::AID-JOC518>3.0.CO;2-Z, http://dx.doi.org/10.1002/1097-0088(20000615)20:7⟨771::AID-JOC518⟩3.0.CO;2-Z, ~~doi:,~~ 2000.

Dimri, ~~-~~A., Yasunari, ~~-~~T., Wiltshire, ~~-~~A., Kumar, ~~-~~P., Mathison, ~~-~~C., Ridley, ~~-~~J., and Jacob, ~~-~~D.: Application of regional climate models to the Indian winter monsoon over the western Himalayas, Science of The Total Environment~~Sci. Total Environ.~~, 468, S36–S47, 2013.

Dolman, ~~-~~A. J. and Gregory, ~~-~~D.: The Parametrization of Rainfall Interception In GCMs, Quarterly Journal of the Royal Meteorological Society~~parametrization of rainfall interception in GCMs, Q. J. Roy. Meteor. Soc.~~, 118, 455–467, doi:10.1002/qj.49711850504, http://dx.doi.org/10.1002/qj.49711850504, ~~doi:,~~ 1992.

Essery, R. ~~-R.~~ L. H., Best, ~~-~~M. J., and Cox, ~~-~~P. M.: MOSES 2.2 technical documentation, Hadley Centre Technical Note, 30, http://www.metoffice.gov.uk/archive/hadley-centre-technical-note-30, ~~available at: , last access: February 2015,~~ 2001.

Essery, R. ~~-R.~~ L. H., Best, ~~-~~M. J., Betts, ~~-~~R. A., Cox, ~~-~~P. M., and Taylor, ~~-~~C.: Explicit Representation of Subgrid Heterogeneity in a ~~representation of subgrid heterogeneity in a~~ GCM Land Surface Scheme, Journal of Hydrometeorology~~land surface scheme, J. Hydrometeorol.~~, 4, 530–543, doi:doi: 10.1175/1525-7541(2003)004<0530:EROSHI>2.0.CO;2~~doi:~~, 2003.

Falloon, ~~-~~P., Betts, ~~-~~R., and Bunton, ~~-~~C.: New global river routing scheme in the unified model, Hadley Centre Technical Note, 72, http://www.metoffice.gov.uk/archive/hadley-centre-technical-note-72, ~~available at: , last access: February 2015,~~ 2007.

Falloon, ~~-~~P., Betts, ~~-~~R. A., Wiltshire, ~~-~~A., Dankers, ~~-~~R., Mathison, ~~-~~C., McNeall, ~~-~~D., Bates, ~~-~~P., and Trigg, ~~-~~M.: Validation of river flows in hadgem1 and hadcm3 with the trip river flow model, Journal of Hydrometeorology~~J. Hydrometeorol.~~, 12, 1157–1180, doi:doi: 10.1175/2011JHM1388.1, http://dx.doi.org/10.1175/2011JHM1388.1, ~~doi:,~~ 2011.

Fekete, ~~-~~B. M., Vörösmarty, ~~-~~C. J., and Lammers, ~~-~~R. B.: Scaling gridded river networks for macroscale hydrology: Development~~development~~, analysis, and control of error, Water Resources

Research~~Resour. Res.~~, 37, 1955–1967, doi:10.1029/2001WR900024, http://dx.doi.org/10.1029/2001WR900024, ~~doi:,~~ 2001.

Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers, Proceedings of the National Academy of Sciences~~P. Natl. Acad. Sci. USA~~, 108, 14 011–14 014~~14011–14014~~, 2011.

Gain, A. K., Apel, H., Renaud, F. G., and Giupponi, C.: Thresholds of hydrologic flow regime of a river and investigation of climate change impact the case of the Lower Brahmaputra river Basin, Climatic Change, 120, 463–475, doi:10.1007/s10584-013-0800-x, http://dx.doi.org/10.1007/s10584-013-0800-x, ~~doi: ,~~ 2013.

Gardelle, J., Berthier, E., Arnaud, Y., and Kääb, A.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, The Cryosphere, 7, 1263–1286, doi:10.5194/tc-7-1263-2013, http://www.the-cryosphere.net/7/1263/2013/, 2013.

Gedney, N. and Cox, P.: The Sensitivity of Global Climate Model Simulations to the Representation of Soil Moisture Heterogeneity, Journal of Hydrometeorology~~sensitivity of global climate model simulations to the representation of soil moisture heterogeneity, J. Hydrometeorol.~~, 4, 1265–1275, doi:10.1175/1525-7541(2003)004<1265:TSOGCM>2.0.CO;2~~doi:~~, 2003.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. ~~J.~~ F. B., and Wood, R. A.: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, Climate Dynamics~~Clim. Dynam.~~, 16, 147–168, doi:10.1007/s003820050010, http://dx.doi.org/10.1007/s003820050010, ~~doi:,~~ 2000.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., and Wiltshire, A.: Implications of climate change for agricultural productivity in the early twenty-first century, Philosphical Transactions of the Royal Society B: Biological Sciences~~Philos. T. Roy. Soc. B~~, 365, 2973–2989, doi:doi: 10.1098/rstb.2010.0158, http://rstb.royalsocietypublishing.org/content/365/1554/2973.abstract, ~~doi:,~~ 2010.

Gosain, A. K., Rao, S., and Basuray, D.: Climate change impact assessment on hydrology of Indian river basins, Current Science, 90, 346–353, http://www.currentscience.ac.in/Downloads/article_id_090_03_0346_0353_0.pdf, 2006.

Goswami, B. and Xavier, P. K.: Dynamics of "internal"~~“internal”~~ interannual variability of the Indian summer monsoon in a GCM, Journal of Geophysical Research: Atmospheres~~J. Geophys. Res.~~, 110, n/a–n/a~~D24104~~, doi:10.1029/2005JD006042, http://dx.doi.org/10.1029/2005JD006042, 2005.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., and Xavier, P. K.: Increasing Trend of Extreme Rain Events Over ~~trend of extreme rain events over~~ India in a Warming Environment ~~warming environment~~, Science, 314, 1442–1445, doi:10.1126/science.1132027, http://www.sciencemag.org/content/314/5804/1442.abstract, ~~doi:,~~ 2006.

GRDC: The Global Runoff Data Centre, D-56002 ~~56002~~ Koblenz, Germany, edited, 2014.

Gregory, P., Ingram, J., and Brklacich, M.: Climate change and food security, Philosophical Transactions of the Royal Society B: Biological Sciences~~Philos. T. R. Soc. B~~, 360, 2139–2148, doi:10.1098/rstb.2005.1745, http://rstb.royalsocietypublishing.org/content/360/1463/2139.abstract, ~~doi:,~~ 2005.

Gupta, A. D., Babel, M. S., Albert, X., and Mark, O.: Water Sector ~~sector~~ of Bangladesh in the Context of Integrated Water Resources Management: A Review, International Journal of Water Resources Development~~context of integrated water resources management: a review, Int. J. Water Resour. D.~~, 21, 385–398, doi:10.1080/07900620500037818, http://dx.doi.org/10.1080/07900620500037818, ~~doi:,~~ 2005.

Gupta, S. and Deshpande, D.: Water for India in 2050: first order assessment of available options, Current Science~~Curr. Sci. India~~, 86, 1216–1224, 2004.

Gupta, S., Javed, A., and Datt, D.: Economics of Flood Protection ~~flood protection~~ in India, Natural ~~Nat.~~ Hazards, 28, 199–210, 2003.

Harding, R., Blyth, E., Tuinenburg, O., and Wiltshire, A.: Land atmosphere feedbacks and their role in the water resources of the Ganges basin, Science of The Total Environment, 468-469, Supplement, S85 – S92~~Sci. Total Environ., 468–469, S85–S92, doi:~~, doi:http://dx.doi.org/10.1016/j.scitotenv.2013.03.016, http://www.sciencedirect.com/science/article/pii/S0048969713003070, changing water resources availability in Northern India with respect to Himalayan glacier retreat and changing monsoon patterns: consequences and adaptation, 2013.

Hijioka, Y., Lin, E., Pereira, J., Corlett, R., Cui, X., Insarov, G., Lasco, R., Lindgren, E., and Surjan, A.: Asia. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II, Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1327–1370, 2014.

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., and Kimoto, M.: Global projections of changing risks of floods and droughts in a changing climate, Hydrological Sciences Journal, 53, 754–772, 2008.

Immerzeel, W., van Beek, L., and Bierkens, M.: Climate Change Will Affect ~~change will affect~~ the Asian Water Towers~~water towers~~, Science, 328, 1382–1385, doi:10.1126/science.1183188, http://www.sciencemag.org/content/328/5984/1382.abstract, ~~doi:,~~ 2010.

Immerzeel, W. W., Wanders, N., Lutz, A. F., Shea, J. M., and Bierkens, M. F. P.: Reconciling high altitude precipitation in the upper Indus Basin with glacier mass balances and runoff, Hydrology and Earth System Sciences Discussions, 12, 4755–4784, doi:10.5194/hessd-12-4755-2015, http://www.hydrol-earth-syst-sci-discuss.net/12/4755/2015/, 2015.

Jacob, D., Bärring, L., Christensen, O. B., Christensen, J. H., de Castro, M., Déqué, M., Giorgi, F., Hagemann, S., Hirschi, M., Jones, R., Kjellström, E., Lenderink, G., Rockel, B., Sánchez, E., Schär, C., Seneviratne, S. I., Somot, S., van Ulden, A., and van den Hurk, B.: An inter-comparison of regional climate models for Europe: model performance in present-day climate, Climatic Change, 81, 31–52, doi:10.1007/s10584-006-9213-4, http://dx.doi.org/10.1007/s10584-006-9213-4, 2007.

Johnston, R. and Smakhtin, V.: Hydrological Modeling of Large river Basins: How Much is Enough?, Water Resources Management~~Resour. Manag.~~, 28, 2695–2730, doi:10.1007/s11269-014-0637-8, http://dx.doi.org/10.1007/s11269-014-0637-8, 2014.

Jones, R. G., Noguer, M., Hassell, D. C., Hudson, D., Wilson, S. S., Jenkins, G. J., and Mitchell, J. F.: Generating high resolution climate change scenarios using PRECIS, Met Office Hadley Centre, Exeter, UK, pp. 0–40, http://www.metoffice.gov.uk/media/pdf/6/5/PRECIS_Handbook.pdf, ~~available at: , last access: February 2015,~~ 2004.

Joshi, U. and Rajeevan, M.: Trends in precipitation extremes over India, National Climate Centre Research report, 3, http://www.imdpune.gov.in/ncc_rept/RESEARCH%20%20REPORT%203.pdf, ~~available at: , last access: February 2015,~~ 2006.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, Nature, 488, 495–498, doi:10.1038/nature11324, http://dx.doi.org/10.1038/nature11324, 2012.

Kapnick, S. B., Delworth, T. L., Ashfaq, M., Malyshev, S., and Milly, P. ~~P.~~ C. D.: Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle, Nature Geoscience~~Nat. Geosci.~~, 7, 834 – 840, doi:10.1038/ngeo2269, http://dx.doi.org/10.1038/ngeo2269, ~~834–840, doi:,~~ 2014.

Kaser, G., Großhauser, M., and Marzeion, B.: Contribution potential of glaciers to water availability in different climate regimes, Proceedings of the National Academy of Sciences,

doi:10.1073/pnas.1008162107, http://www.pnas.org/content/early/2010/11/01/1008162107.abstract, 2010.
Kumar, -P., Wiltshire, -A., Mathison, -C., Asharaf, -S., Ahrens, -B., Lucas-Picher, -P., Christensen, -J. H., Gobiet, -A., Saeed, -F., Hagemann, -S., and Jacob, -D.: Downscaled climate change projections with uncertainty assessment over India using a -high resolution multi-model approach, Science of The Total Environment, 468-469, Supplement, S18 – S30Sci. Total Environ., 468–469, S18–S30, doi: , doi:http://dx.doi.org/10.1016/j.scitotenv.2013.01.051, http://www.sciencedirect.com/science/article/pii/S004896971300106X, changing water resources availability in Northern India with respect to Himalayan glacier retreat and changing monsoon patterns: consequences and adaptation, 2013.
Kumar, -R., Singh, -R., and Sharma, -K.: Water resources of India, Current ScienceCurr. Sci. India, 89, 794–811, 2005.
Linsley, -R., Kohler, -M., and Paulhus, -J.: Hydrology for Engineers, McGraw-Hill series in water resources and environmental engineering, McGraw-Hill, available at: http://books.google.co.uk/books?id=9vROAAAAMAAJ, last access: February 2015, 1982.
Lucas-Picher, -P., Christensen, -J. H., Saeed, -F., Kumar, -P., Asharaf, -S., Ahrens, -B., Wiltshire, -A. J., Jacob, -D., and Hagemann, -S.: Can Regional Climate Models Represent regional climate models represent the Indian Monsoon?, Journal of Hydrometeorology?, J. Hydrometeorol., 12, 849–868, doi:doi: http://dx.doi.org/10.1175/2011JHM1327.1doi:, 2011.
Mathison, -C., Wiltshire, -A., Dimri, -A., Falloon, -P., Jacob, -D., Kumar, -P., Moors, -E., Ridley, -J., Siderius, -C., Stoffel, -M., and Yasunari, -T.: Regional projections of North Indian climate for adaptation studies, Science of The Total Environment, 468-469, Supplement, Sci. Total Environ., 468–469, S4–S17, doi:http://dx.doi.org/10.1016/j.scitotenv.2012.04.066, http://www.sciencedirect.com/science/article/pii/S0048969712006377, doi:, 2013.
McMillan, -H., Freer, -J., Pappenberger, -F., Krueger, -T., and Clark, -M.: Impacts of uncertain river flow data on rainfall-runoff rainfall–runoff model calibration and discharge predictions, Hydrological ProcessesHydrol. Process., 24, 1270–1284, 2010.
McVicar, T. R., Roderick, Mirza, M. L., Donohue, R. J., Li, L. T., Niel, T. G. V., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N. M., Mescherskaya, A. V., Kruger, A. C., Rehman, S., and Dinpashoh, Y.: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, Journal of Hydrology, 416–417, 182–205, doi:http://dx.doi.org/10.1016/j.jhydrol.2011.10.024, http://www.sciencedirect.com/science/article/pii/S0022169411007487, 2012.

Milly, P. C. D., Dunne, K. A., and Vechhia, A.: Global pattern of trends in streamflow and water availability in a changing climate, Nature, 438, 347–350, 2005.

Mirza, M. M. M. Q.: Global warming and changes in the probability of occurrence of floods in Bangladesh and implications, Global Environmental Change, 12, 127 – 138, doi:http://dx.doi.org/10.1016/S0959-3780(02)00002-X, http://www.sciencedirect.com/science/article/pii/S095937800200002X, 127–138, , 2002.

Mirza, M. -M. Q., Warrick, R., Ericksen, N., and Kenny, G.: Trends and persistence in precipitation in the Ganges, Brahmaputra and Meghna river basins, Hydrological Sciences Journal, 43, 845–858, doi:10.1080/02626669809492182, http://dx.doi.org/10.1080/02626669809492182, 1998.

Mirza, M. -M. Q., Warrick, R. A., and Ericksen, N. J.: The Implications of Climate Change on Floods of the Ganges, Brahmaputra and Meghna Rivers in Bangladesh, Climatic Change, 57, 287–318, doi:10.1023/A:1022825915791, http://dx.doi.org/10.1023/A%3A1022825915791, 2003.

Moors, –E. J., Groot, –A., Biemans, –H., van Scheltinga, –C. T., Siderius, –C., Stoffel, –M., Huggel, –C., Wiltshire, –A., Mathison, –C., Ridley, –J., Jacob, –D., Kumar, –P., Bhadwal, –S., Gosain, –A., and Collins, –D. N.: Adaptation to changing water resources in the Ganges basin, northern India, Environmental Science & Environ. Sci. Policy, 14, 758 – 769, doi:http://dx.doi.org/10.1016/j.envsci.2011.03.005758–769, doi: , http://www.sciencedirect.com/science/article/pii/S1462901111000372, adapting to Climate Change: Reducing Water-related Risks in Europe, 2011.

Morse, Morse, A., Prentice, -C., and T.CarterCarter, T.: Assessments of climate change impacts, Ensembles: Climate change and its impacts: Summary of research and results from the ENSEMBLES project, pp. 107–129, http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdfavailable at: , last access: February 2015, 2009.

Murphy, J. M., Sexton, D. M. H., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M., and Stainforth, D. A.: Quantification of modelling uncertainties in a large ensemble of climate change simulations, Nature, 430, 768–772, doi:10.1038/nature02771, http://dx.doi.org/10.1038/nature02771, 2004.

Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Boorman, P. M., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., and Wood, R. A.: UK Climate Projections Science Report: Climate change projections., Met Office Hadley Centre, pp. 124–131, http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87894&filetype=pdf, 2009.

Nakicenovic, N., Alcamo, J., Grubler, A., Riahi, K., Roehrl, R., Rogner, H.-H., and Victor, N.: Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0, last access Sept 2015, 2000.

Nepal, S. and Shrestha, A. B.: Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature, International Journal of Water Resources Development, 31, 201–218, doi:10.1080/07900627.2015.1030494, http://dx.doi.org/10.1080/07900627.2015.1030494, 2015.

Nohara, D., Kitoh, A., Hosaka, M., and Oki, T.: Impact of Climate Change on River Discharge Projected by Multimodel Ensemble, Journal of Hydrometeorologyclimate change on river discharge projected by multimodel ensemble, J. Hydrometeorol., 7, 1076–1089, doi:10.1175/JHM531.1doi:, 2006.

Nyeko, M.: Hydrologic Modelling of Data Scarce Basin with SWAT Model: Capabilities and Limitations, Water Resources Management, 29, 81–94, doi:10.1007/s11269-014-0828-3, http://dx.doi.org/10.1007/s11269-014-0828-3, 2015.

Oki, T. and Sud, Y. C.: Design of Total Runoff Integrating Pathways (TRIP). A Global River Channel Network, Earth Interactions global river channel network, Earth Interact., 2, 1–37, doi:10.1175/1087-3562(1998)002<0001:DOTRIP>2.3.CO;2, http://dx.doi.org/10.1175/1087-3562(1998)002⟨0001:DOTRIP⟩2.3.CO;2, doi:, 1998.

Oki, T., Nishimura, T., and Dirmeyer, P.: Assessment of annual runoff from land surface models using Total Runoff Integrating Pathways (TRIP), Journal of the Meteorological Society of Japan. Ser. IIJ. Meteorol. Soc. Jpn., 77, 235–255, doi:10.1080/02626668509490989, http://dx.doi.org/10.1080/02626668509490989, doi:, 1999.

Pope, V., Gallani, M. L., Rowntree, P. R., and Stratton, R. A.: The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3, Climate DynamicsClim. Dynam., 16, 123–146, doi:10.1007/s003820050009, http://dx.doi.org/10.1007/s003820050009, doi:, 2000.

Rajeevan, Rajeevan, M., Bhate, J., and K.Jaswal, A.Jaswal, A. K.: Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data, Geophysical Research LettersGeophys. Res. Lett., 35, L18707, doi:10.1029/2008GL035143, http://dx.doi.org/10.1029/2008GL035143, 2008.

Ridley, J., Wiltshire, A., and Mathison, C.: More frequent occurrence of westerly disturbances in Karakoram up to 2100, Science of The Total Environment, 468-469, Supplement, Sci. Total Environ., 468–469, S31–S35, doi:http://dx.doi.org/10.1016/j.scitotenv.2013.03.074doi: , http://www.sciencedirect.com/science/article/pii/S0048969713003781, changing water resources availability in Northern India with respect to Himalayan glacier retreat and changing monsoon patterns: consequences and adaptation, 2013.

Rodell, M., Velicogna, I., and Famiglietti, J.: Satellite-based estimates of groundwater depletion in India, Nature, 460, 999 – 1002, doi:10.1038/nature08238, http://dx.doi.org/10.1038/nature08238, ~~999–1002, doi:,~~ 2009.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., and Tompkins, A.: The atmospheric general circulation model ECHAM 5. PART I: Model description, Max Planck Institute for Meteorology Rep. 349, http://www.mpimet.mpg.de/fileadmin/publikationen/Reports/max_scirep_349.pdf, ~~available at: , last access: February 2015,~~ 2003.

Sarkar, ~~Sarkar,~~ U. K., K.Pathak, A.~~Pathak~~, ~~A. K.,~~ Sinha, R. K., Sivakumar, K., Pandian, A. K., Pandey, A., Dubey, V. K., and Lakra, W. S.: Freshwater fish biodiversity in the River Ganga (India): changing pattern, threats and conservation perspectives, Reviews in Fish Biology and Fisheries~~Rev. Fish Biol. Fisher.~~, 22, 251–272, http://dx.doi.org/10.1007/s11160-011-9218-6~~doi:~~, 2012.

Scherler, D., Bookhagen, B., and Strecker, M.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nature Geoscience, 4, 156 – 159, doi:10.1038/ngeo1068, http://dx.doi.org/10.1038/ngeo1068, 2011.

Scott, D.: Multivariate density estimation: theory, practice, and visualization~~Density Estimation: Theory, Practice, and Visualization~~, vol. 383, ~~mainly chapter 6,~~ John Wiley & Sons, ~~USA,~~ 2009.

Seidel, K., Martinec, J., and Baumgartner, M. F.: Modelling runoff and impact of climate change in large Himalayan basins, in: International Conference on Integrated Water Resources Management (ICIWRM), pp. 19–21, Citeseer, 2000.

Sharma, D.: Situation analysis of flood disaster in south and southeast Asia - a ~~– a –~~ need of integrated approach, International Journal of Science, Environment and Technology, 1, 167–173, 2012.

Shrestha, A. B. and Aryal, R.: Climate change in Nepal and its impact on Himalayan glaciers, Regional Environmental Change, 11, 65–77, doi:10.1007/s10113-010-0174-9, http://dx.doi.org/10.1007/s10113-010-0174-9, 2011.

Silverman, B.: Density Estimation for Statistics and Data Analysis~~W.: Density estimation for statistics and data analysis~~, Monographs on Statistics and Applied Probability, ~~Chapman and Hall, London,~~ 26, ~~mainly chapters 3 and 4,~~ 1986.

Simmons, A., Uppala, S., Dee, D., and Kobayashi, S.: ERA-Interim: New ~~new~~ ECMWF reanalysis products from 1989 onwards., ECMWF Newsletter - ~~, ECMWF, Shinfield, Reading, UK, Newsletter –~~ Winter 2006/07, 110, 0–11, 2007.

Singh, O. and Kumar, M.: Flood events, fatalities and damages in India from 1978 to 2006, Natural ~~Nat.~~ Hazards, 69, 1815–1834, 2013.

Singh, P. and Bengtsson, L.: Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region, Journal of Hydrology, 300, 140 – 154, doi:http://dx.doi.org/10.1016/j.jhydrol.2004.06.005, http://www.sciencedirect.com/science/article/pii/S0022169404002872, 2005.

Singh, P. and Kumar, N.: Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river, Journal of Hydrology, 193, 316 – 350, doi:http://dx.doi.org/10.1016/S0022-1694(96)03142-3, http://www.sciencedirect.com/science/article/pii/S0022169496031423, 1997.

Singh, P., Haritashya, U. K., and Kumar, N.: Modelling and estimation of different components of streamflow for Gangotri Glacier basin, Himalayas, Hydrological Sciences Journal, 53, 309–322, doi:10.1623/hysj.53.2.309, http://dx.doi.org/10.1623/hysj.53.2.309, 2008.

Smakhtin, V. and Anputhas, M.: An assessment of environmental flow requirements of Indian river basins, IWMI Research Report 107, http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB107/RR107.pdf, ~~available at: , last access: October 2014,~~ 2006.

Smakhtin, V. U., Shilpakar, R. L., and Hughes, D. A.: Hydrology-based assessment of environmental flows: an example from Nepal, Hydrological Sciences Journal~~Hydrolog. Sci. J.~~, 51, 207–222, doi:10.1623/hysj.51.2.207, http://dx.doi.org/10.1623/hysj.51.2.207, ~~doi:,~~ 2006.

Thenkabail, P. S., Schull, M., and Turral, H.: Ganges and Indus river basin land use/land cover LULC) and irrigated area mapping using continuous streams of MODIS data, Remote Sensing of Environment~~Sens. Environ.~~, 95, 317 – 341, doi:http://dx.doi.org/10.1016/j.rse.2004.12.018, http://www.sciencedirect.com/science/article/pii/S0034425705000180, ~~317–341, doi:,~~ 2005.

Tuinenburg, O. A., Hutjes, R. ~~R.~~ W. A., Stacke, T., Wiltshire, A., and Lucas-Picher, P.: Effects of irrigation in india on the atmospheric water budget., Journal of Hydrometeorology, ~~, J.Hydrometeorol.,~~ 15, 1028–1050, doi:10.1175/JHM-D-13-078.1, http://dx.doi.org/10.1175/JHM-D-13-078.1, ~~doi:,~~ 2014.

United Nations: Fertility Levels and Trends as Assessed in the 2012 Revision of World Population Prospects, Department of Economic and Social Affairs, Population Division, ~~available at:~~ http://esa.un.org/unpd/wpp/index.htm, ~~last access: August 2014,~~ 2013.

Vörösmarty, C., Fekete, B., Meybeck, M., and Lammers, R.: Geomorphometric attributes of the global system of rivers at 30-minute 30min spatial resolution, Journal of HydrologyJ. Hydrol., 237, 17 – 39, doi:http://dx.doi.org/10.1016/S0022-1694(00)00282-1, http://www.sciencedirect.com/science/article/pii/S0022169400002821, 17–39, doi:, 2000a.

Vörösmarty, C., Fekete, B., Meybeck, M., and Lammers, R.: Global system of rivers: Its its role in organizing continental land mass and defining land-to-ocean linkages, Global Biogeochemical CyclesBiogeochem. Cy., 14, 599–621, doi:10.1029/1999GB900092, http://dx.doi.org/10.1029/1999GB900092, doi:, 2000b.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., and Davies, P. M.: Global threats to human water security and river biodiversity, Nature, 467, 555–561, doi:10.1038/nature094, http://dx.doi.org/10.1038/nature09440, doi:, 2010.

Wescoat Jr., J.: Managing the Indus River basin in light of climate change: Four four conceptual approaches, Global Environmental ChangeEnviron. Chang., 1, 381 – 395, doi:http://dx.doi.org/10.1016/0959-3780(91)90004-D, http://www.sciencedirect.com/science/article/pii/095937809190004D, 381–395, doi:, 1991.

Wiltshire, A. A. J.: Climate change implications for the glaciers of the Hindu-Kush, Karakoram and Himalayan Hindu Kush, Karakoram and Himalayan region, The Cryosphere Discussions, 7, 3717–3748, doi:10.5194/tcd-7-3717-2013, http://www.the-cryosphere-discuss.net/7/3717/2013/, 2013. 8, 941–958, doi: , 2014.

Wiltshire, A., Gornall, J., Booth, B., Dennis, E., Falloon, P., Kay, G., McNeall, D., McSweeney, C., and Betts, R.: The importance of population, climate change and {CO2} plant physiological forcing in determining future global water stress, Global Environmental Change, 23, 1083 – 1097, doi:http://dx.doi.org/10.1016/j.gloenvcha.2013.06.005, http://www.sciencedirect.com/science/article/pii/S0959378013001040, 2013a.

Wiltshire, A. J., Kay, G., Gornall, J. L., and Betts, R. A.: The Impact of Climate, {CO2} and Population on Regional Food and Water Resources in the 2050s, Sustainability, 5, 2129–2151, doi:10.3390/su5052129, 2013b.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A.: Aphrodite: constructing a long-term daily gridded precipitation dataset for asia based on a dense network of rain gauges., Bulletin of the American Meteorological SocietyB. Am. Meteorol. Soc., 93, 1401–1415, doi:http://dx.doi.org/10.1175/BAMS-D-11-00122.1doi:, 2012.

Yoshida, S.: Fundamentals of rice crop science, Manila, Philipines, ~~available at:~~ http://books.irri.org/9711040522_content.pdf, ~~last access: October 2014,~~ 1981.

**Table 1.** Table listing the rivers and gauges (including their location) used in this analysis; all the observations shown here are from GRDC. The abbreviations used in Fig. 1 are given in column one. The Years of data column includes the number of years that data is available since 1950 with c to denote where data is continuous and u to show where the data is available for that number of years but not as a continuous dataset.

| Map abbreviation | River name | Gauge name | Latitude | Longitude | Years of data |
|---|---|---|---|---|---|
| IND_KOT | Indus | Kotri | 25.37 | 68.37 | 14u (1950–1978) |
| IND_ATT | Indus | Attock | 33.9 | 72.25 | 6c (1973–1979) |
| CHE_PAN | Chenab | Panjnad | 29.35 | 71.03 | 6c (1973–1979) |
| BHA_TEH | Bhagirathi | Tehri Dam | 30.4 | 78.5 | 3c (2001–2004) |
| KAR_BEN | Karnali River | Benighat | 28.96 | 81.12 | 25u (1963–1993) |
| KAR_CHI | Karnali River | Chisapani | 28.64 | 81.29 | 31c (1962–1993) |
| NAR_DEV | Narayani | Devghat | 27.71 | 84.43 | 23u (1963–1993) |
| ARU_TUR | Arun | Turkeghat | 27.33 | 87.19 | 10c (1976–1986) |
| GAN_FAR | Ganges | Farakka | 25.0 | 87.92 | 18u (1950–1973) |
| BRA_BAH | Brahmaputra | Bahadurabad | 25.18 | 89.67 | 12u (1969–1992) |
| BRA_YAN | Brahmaputra | Yangcun | 29.28 | 91.88 | 21u (1956–1982) |
| BRA_PAN | Brahmaputra | Pandu | 26.13 | 91.7 | 13u (1956–1979) |

**Table 2.** Table showing the average percentage change for the two models in the number of times the modelled river flow is less than the 10th percentile and greater than the 90th percentile of the 1970–2000 period for the 2050s and 2080s future periods.

| River | Gauge | $<$ 10th percentile % change | | $>$ 90th percentile % change | |
|---|---|---|---|---|---|
| | | 2050s | 2080s | 2050s | 2080s |
| Indus | Kotri | −55.4 | −89.2 | 60.8 | 55.4 |
| Indus | Attock | −70.3 | −95.9 | 70.3 | 81.1 |
| Karnali River | Benighat | −39.2 | −73.0 | 63.5 | 81.1 |
| Karnali River | Chisapani | −27.0 | −56.8 | 60.8 | 79.7 |
| Narayani | Devghat | −21.6 | −54.1 | 75.7 | 110.8 |
| Arun | Turkeghat | −63.5 | −90.5 | 66.2 | 116.2 |
| Brahmaputra | Yangcun | 0 | 0 | 20.3 | 36.5 |
| Brahmaputra | Pandu | −59.5 | −79.7 | 47.3 | 113.5 |
| Brahmaputra | Bahadurabad | −48.6 | −64.9 | 67.6 | 114.9 |
| Ganges | Farakka | −36.5 | −52.7 | 68.9 | 102.7 |
| Bhagirathi | Tehri Dam | −4.1 | **12.2*** | 13.5 | 41.9 |
| Chenab | Panjnad | −58.1 | −83.8 | 43.2 | 50.0 |

* This value is the only positive value in the table.

**Table 3.** Table of implications of changes in water resources.

| Types of change | Implications for water resource | Adaptation options | Other issues |
|---|---|---|---|
| Large annual variability | Abundance some years and scarcity in others make it difficult to plan budgets for different users. | Building storage capacity e.g. rainwater harvesting. Improvement of irrigations systems. Development of water efficient, high yielding crop varieties. | Type of water storage is important e.g. reservoirs/dams have both political and ecological implications. Developing new crops takes time. |
| Changes in peak flow – timing and magnitude | Increases in peak flows could be positive for irrigation and domestic supply but could increase the risk of flooding. Peak flows occurring later and/or decreases in peak flows could reduce availability of water for irrigation at crucial crop development stages negatively impacting yields. | Improving river channel capacity. Diverting excess water to a different valley. Storing the excess water for low flow periods e.g. through rainwater harvesting. Improving drainage and water recycling. Adopting varieties of crops that grow when water for irrigation is more readily available | Flood protection levels do not match demographic trends so vulnerability to flooding remains high in this region (Gupta et al., 2003). Market development for new crops takes time |
| Changes in low flows – timing and magnitude | Increases in the magnitude of the low flows could be positive for irrigation and domestic supply. Decreases could mean less resource available for irrigation leading to reduced yields | Adaptations to avoid flooding during peak flow periods could provide resource during low flow periods. Development of water efficient, high yielding crop varieties | |

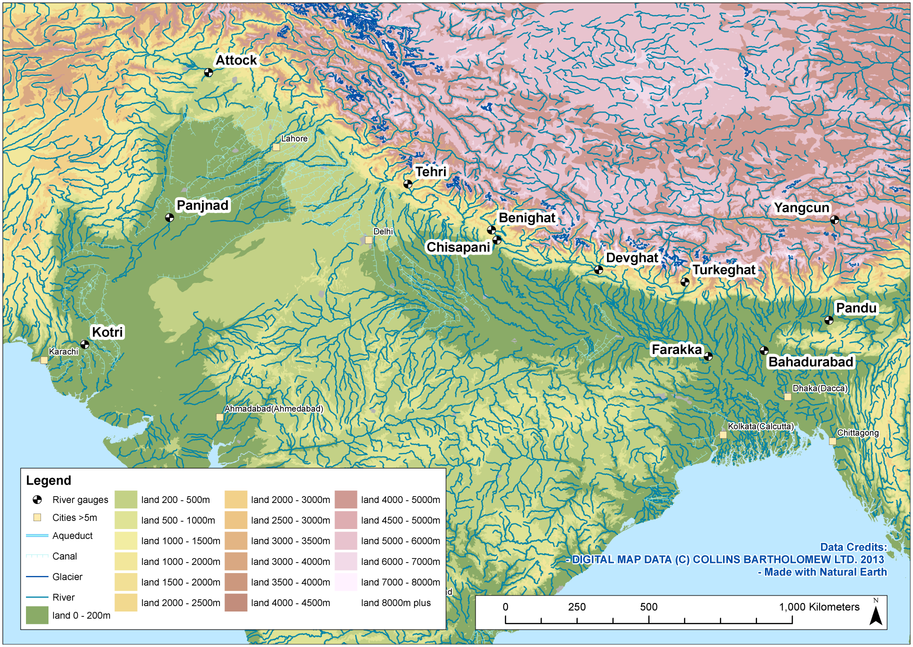



**Figure 1.** A map showing the locations of the river gauges used in this analysis.

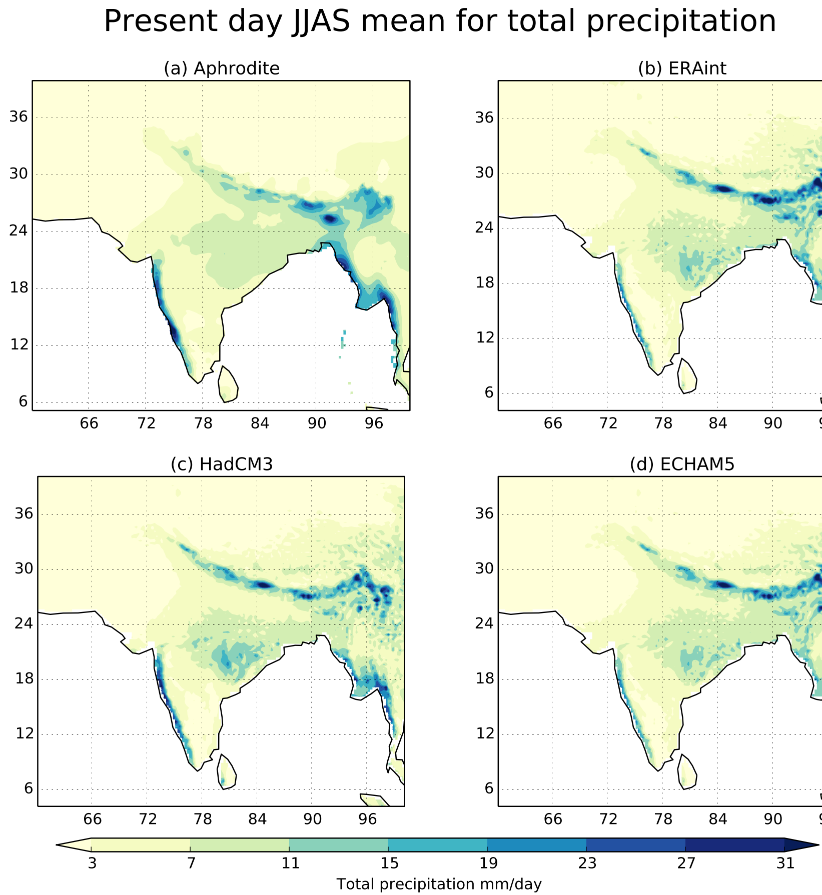



**Figure 2.** The spatial distribution of the seasonal mean total precipitation for the monsoon period (June, July, August, September) for APHRODITE observations (top left), ERAint (top right), HadCM3 (bottom left) and ECHAM5 (bottom right).

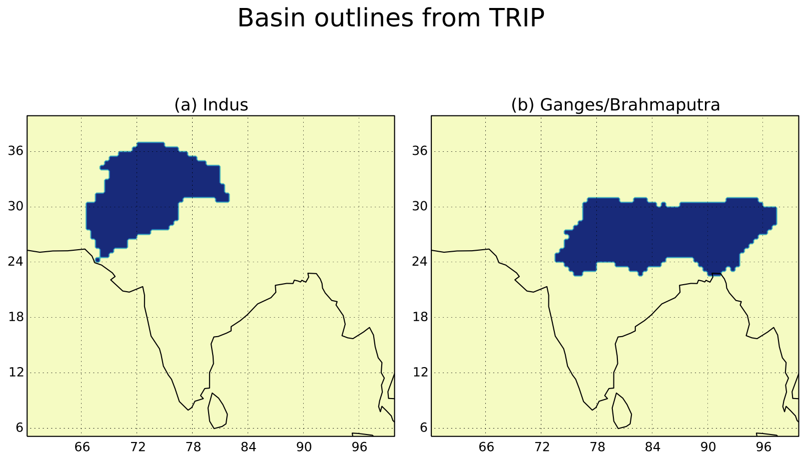



**Figure 3.** The outline of ~~Annual mean total precipitation for~~ the basins within the TRIP model; Indus (left) and Ganges/Brahmaputra (right)~~catchments for each model run (HadCM3 – red, ECHAM5 – blue, ERAint – cyan lines) plotted against APHRODITE observations (black line)~~.

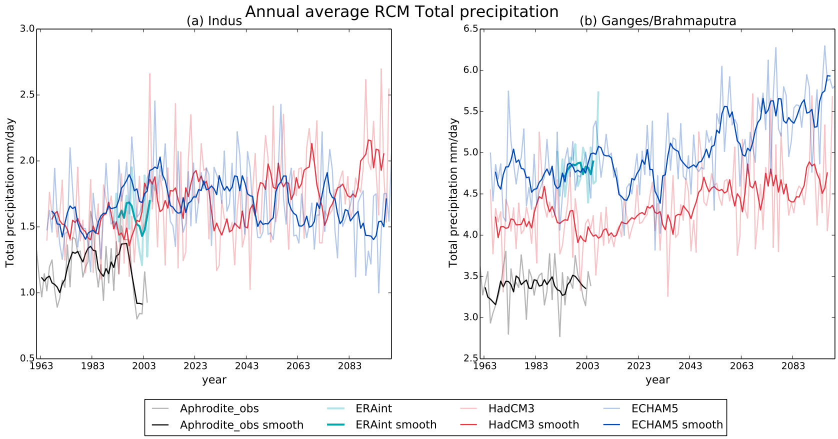



**Figure 4.** Annual mean total precipitation for the Indus (left) and Ganges/Brahmaputra (right) catchments for each model run (HadCM3 – red, ECHAM5 – blue, ERAint – cyan lines) plotted against APHRODITE observations (black line). Paler observations are annual averages and darker lines are a 5-year rolling smoothed average.

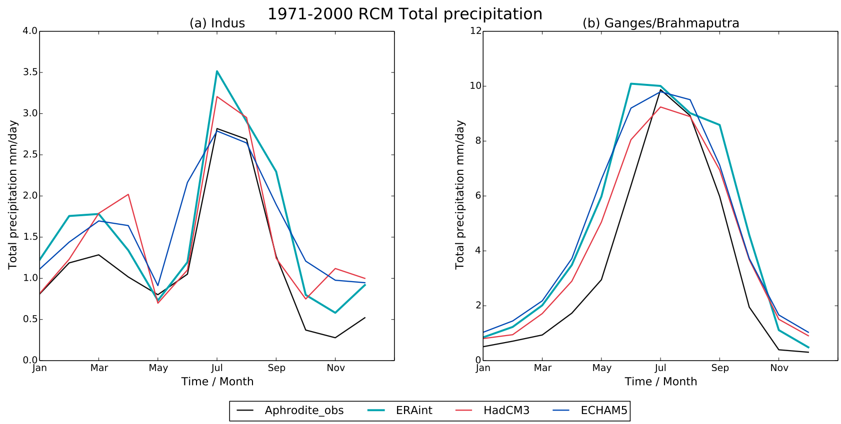



**Figure 5.** Seasonal cycle of total precipitation for the Indus (left) and Ganges/Brahmaputra (right) catchments for each model run (HadCM3 – red, ECHAM5 – blue, ERAint – cyan lines) plotted against APHRODITE observations (black line).

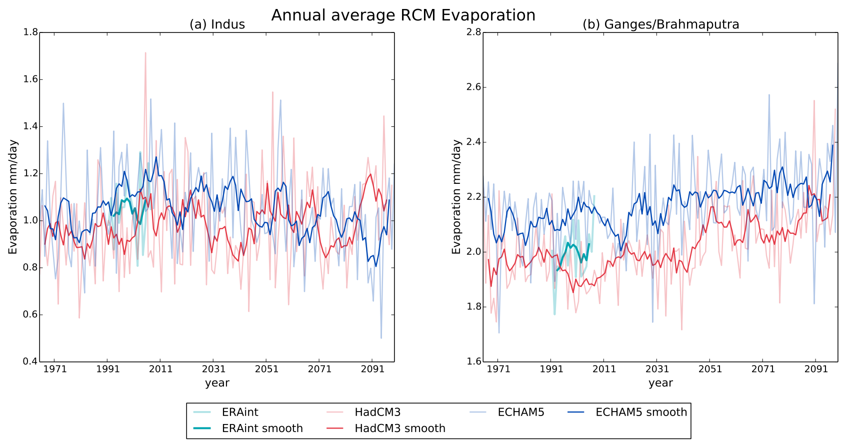



**Figure 6.** Annual mean evaporation for the Indus ~~Timeseries of river flows showing available observations~~ (left~~black~~) and Ganges/Brahmaputra ~~RCM runs~~ (right) catchments for each model run (HadCM3 – red, ECHAM5 – blue, ERAint – cyan lines) from 1971–2100. Paler lines are annual averages and darker lines are a 5-year rolling smoothed average.

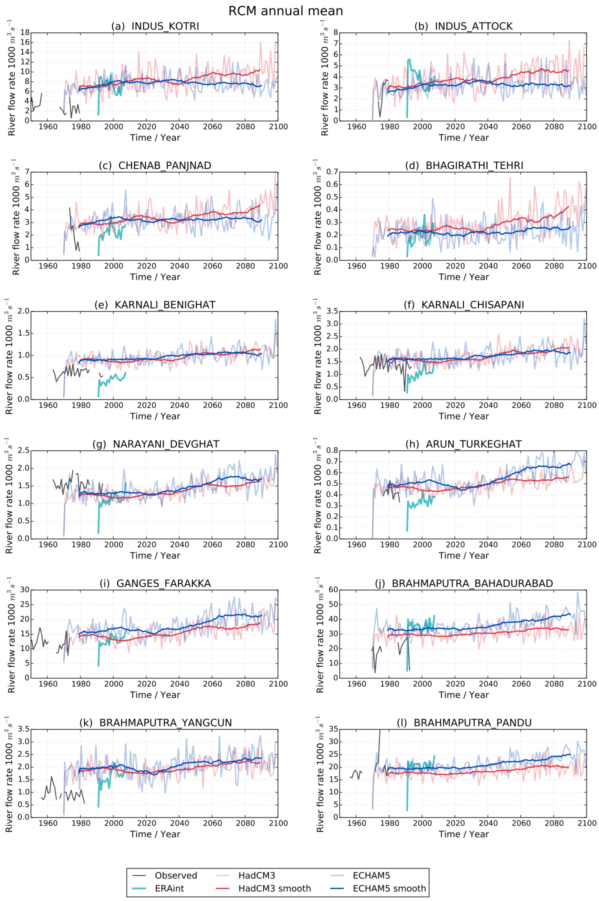



**Figure 7.** Timeseries of river flows showing available observations (black) and RCM runs (HadCM3 – red, ECHAM5 – blue, ERAint – cyan lines) from 1971–2100. Paler lines are annual averages and darker lines are a 20-year rolling smoothed average.

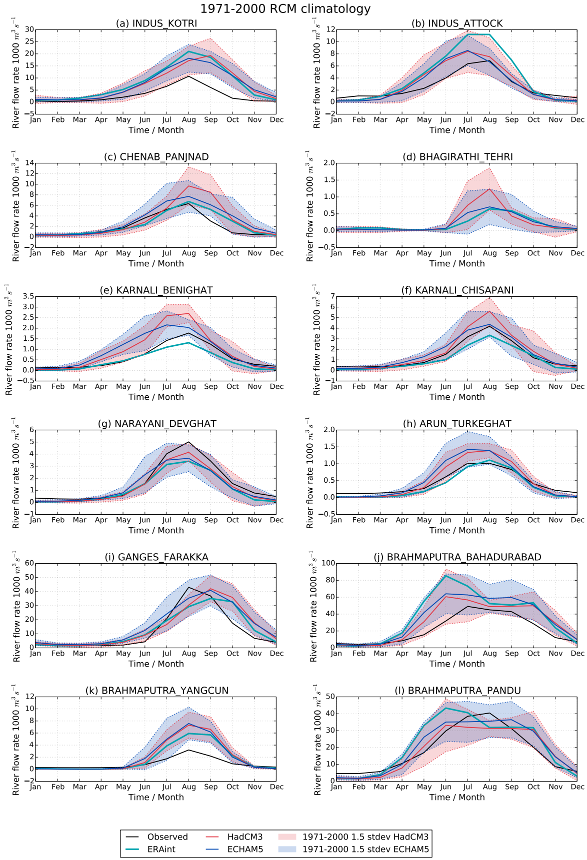



**Figure 8.** Seasonal cycle of river flow at individual river gauges; observed (black solid line) and for each of the RCMs (HadCM3 – red, ECHAM5 – blue, ERAint – cyan lines) for 1971–2000; with shaded regions showing 1.5 SD from the mean for the two simulations for the same period.

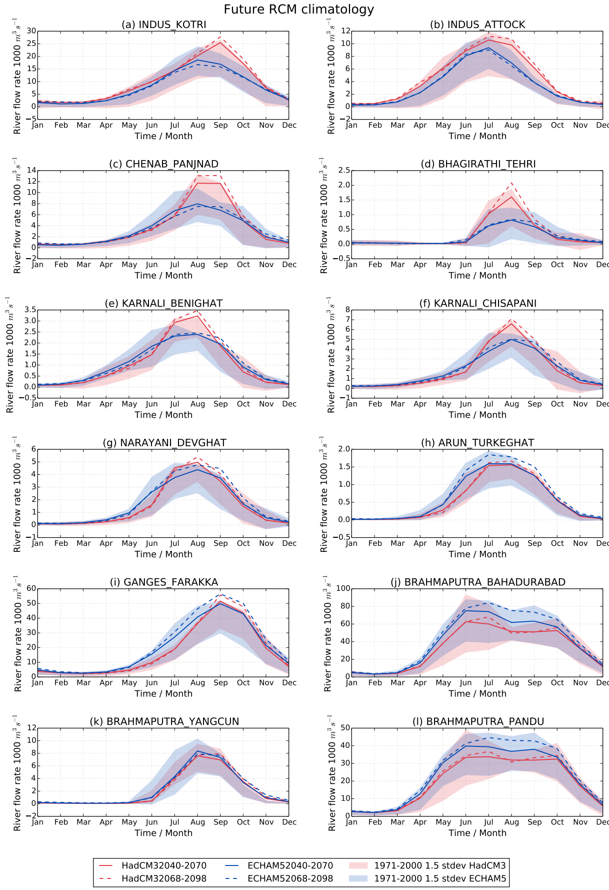



**Figure 9.** Seasonal cycle of river flow in each of the RCMs (HadCM3 – red, ECHAM5 – blue) for the two future periods: 2050s (solid lines) and 2080s (dashed lines), with shaded regions showing 1.5 SD from the mean for 1971–2000 for each river gauge.

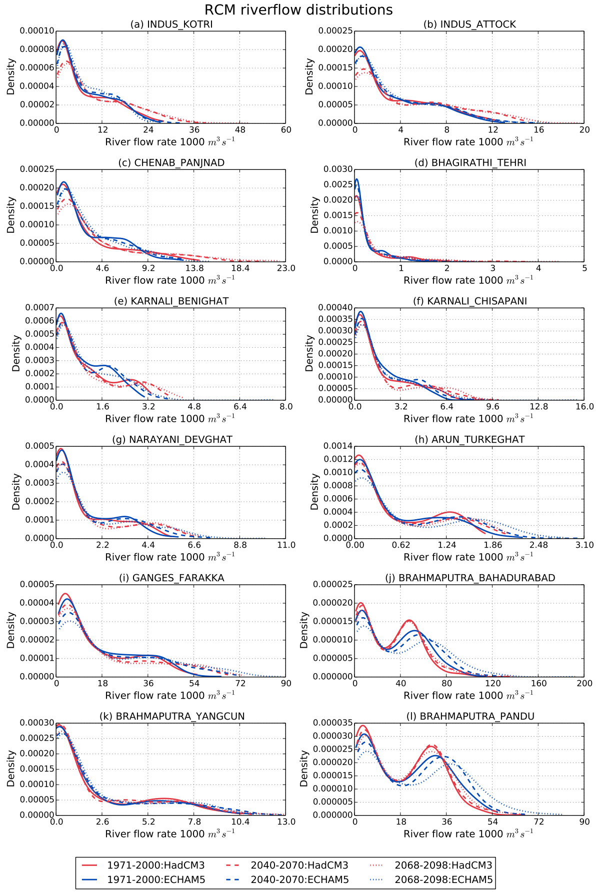



**Figure 10.** The distribution of the river flow in the HadCM3 and ECHAM5 (HadCM3 – red, ECHAM5 – blue) runs for three periods: historical (1971–2000 – solid lines) and two future periods (2050s – dashed lines and 2080s – dotted lines) plotted as a pdf for each river gauge.

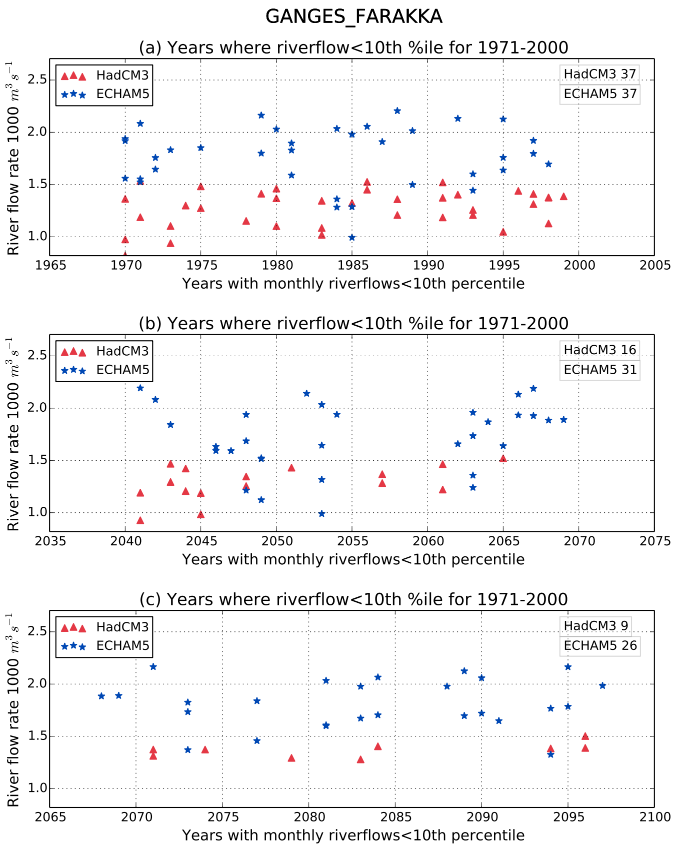
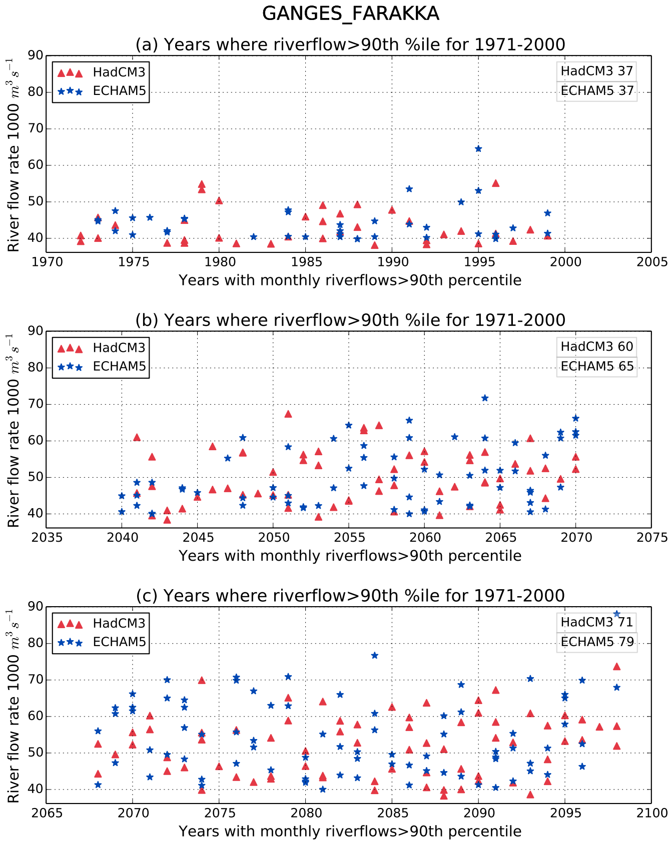

GANGES_FARAKKA
(a) Years where riverflow<10th %ile for 1971-2000
HadCM3
ECHAM5
HadCM3 37
ECHAM5 37
River flow rate 1000 $m^3 s^{-1}$
Years with monthly riverflows<10th percentile
(b) Years where riverflow<10th %ile for 1971-2000
HadCM3 16
ECHAM5 31
(c) Years where riverflow<10th %ile for 1971-2000
HadCM3 9
ECHAM5 26

**Figure 11.** Comparison of the lowest 10 % of monthly river flows at the Farakka barrage on the Ganges river against the 10th percentile for the 1971–2000 period for 1971–2000 (top), 2050s (middle) and 2080s (bottom) for HadCM3 (red triangles) and ECHAM5 (blue stars). Each star or triangle represents a month within the 30 year period where the value is less than the 10th percentile of the 1971-2000 period with the total number for each of the simulations given in the top right corner of each plot.



GANGES_FARAKKA
(a) Years where riverflow>90th %ile for 1971-2000
HadCM3
ECHAM5
HadCM3 37
ECHAM5 37
River flow rate 1000 $m^3 s^{-1}$
Years with monthly riverflows>90th percentile
(b) Years where riverflow>90th %ile for 1971-2000
HadCM3
ECHAM5
HadCM3 60
ECHAM5 65
River flow rate 1000 $m^3 s^{-1}$
Years with monthly riverflows>90th percentile
(c) Years where riverflow>90th %ile for 1971-2000
HadCM3
ECHAM5
HadCM3 71
ECHAM5 79
River flow rate 1000 $m^3 s^{-1}$
Years with monthly riverflows>90th percentile

**Figure 12.** Comparison of the highest 10 % of monthly river flows at the Farakka barrage on the Ganges river against the 90th percentile for the 1971–2000 period for 1971–2000 (top), 2050s (middle) and 2080s (bottom) for HadCM3 (red triangles) and ECHAM5 (blue ~~bluen~~ stars). Each star or triangle represents a month within the 30 year period where the value is greater than the 90th percentile of the 1971-2000 period with the total number for each of the simulations given in the top right corner of each plot.

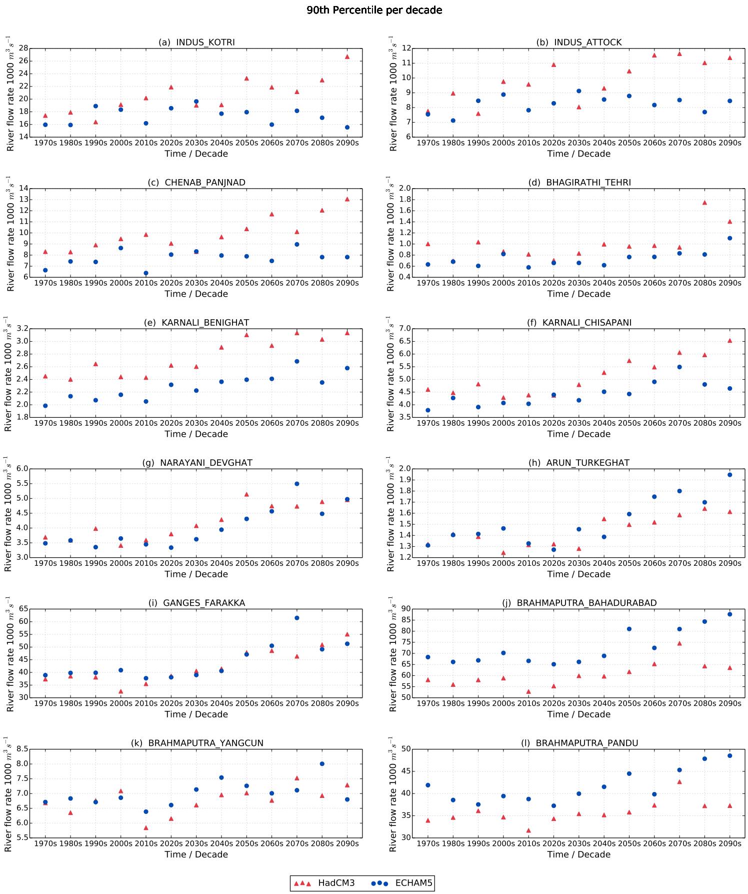



**Figure 13.** The 90th percentile of river flow for each decade for HadCM3 (red triangles) and ECHAM5 (blue circles) for each river gauge.