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Discussions

Interactive comment on "South Asia river flow projections and their implications for water resources" *by* C. Mathison et al.

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1 Authors reply to reviewers 1 and 2 and comments from the editor

The authors would like to thank the reviewers and editor for their comments on the manuscript. In the following pages the authors have replied to each comment from each reviewer and explained how the manuscript will be modified in light of these comments.

2 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 future 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.**

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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.

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- **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.

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- **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 usefulness 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.

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- **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

3 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**

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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**

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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

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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.

4 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

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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

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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 by Immerzeel et al. The PNAS 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

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(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.

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