Snowfall in the Himalayas: an uncertain future from a little-known past. Reply to reviewers

Anonymous referee # 1

We thank the reviewer for taking the time to read and comment on our manuscript. Our response is given for each comment below.

Comment 1: *The authors in this study collate evidence that our present day knowledge of snowfall across the Himalayas is highly uncertain based on a variety of spatially explicit data sources. They extend this to include climate model projections from CMIP5 to make projections of snowfall in the region in the 2080s under climate scenarios RCP2.6 and RCP8.5. Overall, in my opinion the scope and aims of the manuscript are timely and of wide interest to the research community.*

The first part of the manuscript focuses on present day snowfall. In my opinion this is a good effort at understanding present day snowfall across the Himalayas and associated uncertainties, which are large. This in itself is a worthy result. The second part focuses on projected climate change. This is done using bias corrected climate data from CMIP5 simulations. The first question this raises, is why immediately bias correct? It seems the snowfall product provides an excellent basis for assessing the performance of the climate models at their original coarse resolution and snowfall data is available from CMIP5. A need for bias correction may become clear from this assessment, or this may already be clear to the authors.

Response 1: The resolution of the CMIP5 models varies from model to model, but is in general much lower than the MERRA data used as a basis for bias-corrections. We think it's reasonable to assume that the higher-resolution and observation-based MERRA reanalysis has a higher quality than the CMIP5 models. Thus we have used the present-day MERRA data as a basis and added the changes from the CMIP5 models, instead of using the CMIP5 models directly.

Comment 2: *Further to this, in the bias correction for future change the authors use the absolute change in temperature and the 'fractional' change in precipitation. Thus implying that in the case of temperature the change is independent of any present day bias. However, in the case of precipitation a model with a high bias now will have a biased high precipitation change. The reasoning for this approach is not clear within the text – however it most likely breaks the physical consistency in the future climate projections, something the authors point to in the use of reanalysis data. I would like to see a plot of the anomaly against present day bias to justify the 'fraction' approach as well an attempt using the 'additive' approach consistent with temperature.*

Response 2: Technically, both approaches could have been used. However, we do not know of any studies that use the additive change in precipitation and have considered it less appropriate also in our case. We're not sure we understand the comment that "a high bias now will have a biased high precipitation change." This may be true for an additive change, but for a fractional change the opposite seems more likely to us. Adding an absolute change in precipitation to a model with a high amount of precipitation would result in a smaller fractional change than adding the same amount to a model with little precipitation. Also, with an additive change, we would get negative precipitation values at some time steps – values that would then have to be set to zero. In addition to changing the total, this would change the number of precipitation events, which must also then be corrected for.

Comment 3: *I would also like to see the bias correction applied to a different baseline dataset sampling the low end uncertainty in snowfall. It may be that given this variety of approach and sampling of uncertainty leads to a larger uncertainty in future snowfall.*

Response 3: We have done this. The effect of future changes in temperature and precipitation (Section 4) are presented both for the highest (MERRA) and the lowest (APHRODITE) present-day estimates.

B. Bookhagen

Thank you for taking the time to read our manuscript! We found your comments very valuable and have used them to improve both the text and several of the figures.

Comment 1: *The manuscript by Viste and Sorteberg is timely and addresses an important question: How do the water resources in the Himalaya change in the coming decades. There will be large interest among several scientific communities on this topic because of the far-reaching consequences of snowfall in the high-elevation regions and the high population density in the downstream areas. It is important that the science is sound and solid.*

Overall, the manuscript is well written and has useful figures. The introduction is very well done, and presents an up-to-date and broad overview of climate science in the region. One improvement would be the addition of absolute values for precipitation in the different regions mentioned (pg 443, lines 15-20), as the authors simply mention that 'meltwater is important in the otherwise dry spring', and then group 'the monsoondominated central Himalayas and the Tibetan Plateau' into the same summer-fed precipitation regime. It is somewhat misleading to only talk about annual percentages when the absolute amounts are so drastically different, as well as quite different topographies.

Response 1: Good point! We have added a paragraph with absolute numbers, as described below.

Text change in response to Comment 1: On page 443, we have added a paragraph before line 15, and merged the two paragraphs on line 16–30. The result reads:

"Precipitation varies greatly between inner and outer parts of the Himalayas (Singh et al., 1997;Bookhagen and Burbank, 2006;Winiger et al., 2005). While there are regions in the Himalayan foothills and along the Himalayan ridge with an annual mean rainfall of more than 4000 mm, most of the Tibetan Plateau on the leeward side receives less than 500 mm (Bookhagen and Burbank, 2010).

The Indian summer monsoon creates markedly different seasonal cycles in eastern and western parts of the HKH, both in precipitation and in the accumulation of snow and ice. In the monsoon-dominated central Himalayas and on the Tibetan Plateau, more than 80 % of the annual precipitation falls during summer. Precipitation maxima in the western regions occur in connection with westerly disturbances in winter. In the Hindu Kush and Karakoram, as well as in the easternmost Himalaya, summer precipitation amounts to less than 50 % of the annual precipitation (Bookhagen and Burbank, 2010). The seasonal cycle of snowfall varies accordingly. In the western HKH, snow accumulates during winter, while the summer is the main melting season. Further east, the summer is the main season, not just for ablation, but also for accumulation (Rees and Collins, 2006). According to Bookhagen and Burbank (2010), the east-west gradient and the effect of the summer monsoon is most pronounced in the lowlands, below 500 m a.s.l., while the difference is less at higher elevations. “

Comment 2: *I don’t think the debate is quite as settled on the changing strength of the monsoon as they predict on pg 447, lines 10-17. This citation (Ramanathan, V., et al. "Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle." Proceedings of the National Academy of Sciences of the United States of America 102.15 (2005): 5326-5333.) notes the possibilities of extra black carbon/smog reducing sea surface temps and thus reducing water availability. I am not sure how well this is accounted for in the CMIP models, but would be an interesting thing to discuss.*

Response 2: We agree that the question of how well the CMIP models are able to reproduce precipitation and changes in precipitation in the region is open. As both our references and our Figure 8 (9 in the new version) show, there are large differences between the models, though the model mean is positive. The reviewer’s point about aerosols is highly relevant, and we have changed the text based on a more recent reference to ensure that the reader is aware of that. The article we refer to, Guo et al., (2014), is currently a discussion paper in Atmospheric Chemistry and Physics, available at http://www.atmos-chem-phys-discuss.net/14/30639/2014/acpd-14-30639-2014-discussion.html. We would have preferred to see a final version of it published before referring to any details, and have thus made a rather general statement in the text.

Text change in response to Comment 2: Lines 18–26 on page 447 have been changed to:

“It should be emphasized that there is a large inter-model spread in precipitation projections. Guo et al. (2014) found that CMIP5 models with a more realistic representation of aerosols had a more negative impact on the monsoon than models that include only the direct effect of aerosols on radiation. Overall, the IPCC AR5 concludes that there is medium confidence in the increase in summer monsoon precipitation over South Asia (Christensen et al., 2013). But although precipitation projections are less reliable than temperature projections, agreement between models increases with time and anthropogenic forcing (Chaturvedi et al., 2012). Also, the CMIP5 multi-model mean has been considered to represent the monsoon and the actual climate in India better than any individual model (Chaturvedi et al., 2012;Sperber et al., 2013).”

Comment 3: *There are a few key issues that should be properly addressed before this manuscript is published: (I am not trying to be picky here, but try to address some of the key issues of the manuscript. The spatial-temporal resolution and topographic relief of this area is a challenging factor for every researcher in this area!) (1) Correction factors for MERRA data. Greater attention should be given to the corrections used on the MERRA data, as talking about a ’topographic correction’ as simply one line is not sufficient. Downscaling this data is quite complex, and a simple elevation correction is unlikely to improve the data.*

Response 3: We have used the MERRA 2 m temperature and atmospheric lapse rate to downscale the temperature to a higher-resolution terrain grid. We do not see any reason why such a correction, based on a more realistic elevation together with the atmospheric temperature gradient, should not improve the data. However, from the reviewer’s comments, we realize that we have not described our procedure clearly enough. Thanks for pointing that out for us! In the updated version of the manuscript, we have described this more clearly. We have also added a cartoon showing the data used, as well as the difference between MERRA and GLOBE terrain. We would like to point out that the elevation correction has been performed on temperature data only. For precipitation we agree that elevation-based corrections would probably not add any value, and we have not attempted to correct precipitation based on the terrain.

Text change in response to comment 3: A new figure (2) has been added. On page 451, line 2 and the following paragraph has been changed to:

"$$T_{adj} = T_0 - \frac{\Delta T}{\Delta z}\Delta z_0 = T_0 - \frac{T_2 - T_1}{z_2 - z_1}\left(z_{merra,0} - z_{globe}\right), \quad (2)$$

where T_0 is the MERRA 2 m temperature, T_1 is the temperature at the lowest pressure level above the ground, T_2 the temperature at the next pressure level, and z_2 and z_1 the height of these levels. $z_{merra,0}$ and z_{globe} are the elevations of the MERRA and GLOBE topography, respectively, and Δz_0 the difference between them. The variables are illustrated in Figure 2. The procedure combines the vertical temperature gradient in MERRA with the MERRA 2 m temperature and the elevation difference between MERRA and GLOBE. We have assumed that the most representative temperature gradient ($\Delta T/\Delta z$) for this purpose, is that of the MERRA layer nearest to, but not touching, the MERRA ground."

Comment 4: *The Dai 2008 study that forms the basis of the authors' snowline determination was tuned over land stations which are not representative of the terrain in HMA. As there are quite limited stations at high elevations, this Temp/Pressure snowfall gradient should at least include error bars, which could/should be propagated into their results and discussion.*

Response 4: Dai's function was based on weather reports from 15000 globally distributed synoptic land stations. We realize that the results are not tuned to the Himalayas, but are not aware of any better alternatives. The only realistic alternative would be to use a constant threshold between snow and rain. In either case, this is not likely to be a major source of error, compared to errors in the input data of precipitation (and temperature). This can be seen from the values in Table 4 in Section 3.2, but was not discussed in the original version of the manuscript. We agree that this should be done and have added a paragraph describing the results.

Text change in response to comment 4: The following paragraph has been added in Section 3.2 (page 455, after line 22):

"The MERRA reference snowfall deviates about 10 % from the original MERRA reanalysis snowfall; negatively in the Indus and Brahmaputra, and positively in the Ganges. Two effects contribute to this: the use of elevation-adjusted temperature, and the use of the function from Dai (2008) when relating precipitation type to temperature. The effect of the function may be seen from the 'MERRA T2m' in Table 4. For this variable, the Dai function was applied directly to the MERRA 2 m temperature, i.e., without the elevation adjustment. Comparing this with the original MERRA reanalysis snowfall ('MERRA') indicates that the Dai function acts to reduce the snow fraction. The elevation-adjustment of temperature depends on the MERRA vertical temperature gradient, as well as the topography of MERRA and GLOBE. GLOBE is the result of merging various other elevation data, and the quality in each region depends on the available input data. Globally, half of the data points have been estimated to have a vertical accuracy of less than 30 m, whereas some points in Antarctica may be as much as 300 m off (Hastings and Dunbar, 1999, 1998). The effect of elevation-adjusting the temperature, or of using the Dai function, each amounts to changes in the order of 5–20 %. This is much less than the effect of bias-corrections with observation-based data."

Comment 5: *There should also be further discussion of how they treat snowfall permanence, or if they only look at instantaneous snowfall by a temperature/precipitation value per month. For example, snow is more likely to stick and accumulate if the temperature over the following few days is below freezing, rather than at 0-1.2C which are within the 'snowfall threshold' but are unlikely to lead to permanent snow. As the snow must last through some of the season to be helpful in the 'dry seasons', it might be better to consider non-permanent snow as 'rain', as it will not contribute to late-season runoff.*

Response 5: We find it hard to disagree with the reviewer that the final result of value to dry-season hydrology is the accumulated snow at the end of the season. But the aim of this study is to look only at the first-stage input to accumulation and snowmelt analyses: precipitation falling in the form of snow. We have not considered whether the snow melts within a short time or remains frozen for months. One of our points is to show the uncertainty in precipitation and snowfall values; uncertainties that will then be carried on if using these data sets as input to melt models.

Our monthly sums are added up from values calculated for each hour. This is described on page 450, line 7–8, and with the display of monthly results. To make this clearer, we have added information about the monthly sums in the subsequent paragraph (result shown below).

Text change in response to comment 5: On page 450, a sentence in line 11–12 has been changed to:

"The results were then aggregated to monthly sums for the Indus, Ganges, and Brahmaputra Basins."

Comment 6: *On pg 451, lines 1-3, the authors discuss an elevation-derived temperature correction, which is downsized from two atmospheric temperatures, neither of which is a LST. The T2 discussed is also simply stated as the temperature at 'the next level'. A better explanation of how this correction was derived is needed, as well as a discussion of what global elevation grid was used in MERRA and how this differs from GLOBE.*

Response 6: More details of the elevation-adjustment procedure were surely needed and have been added, as described in Response 3. The figure added there (the new Figure 3a) also shows an example of the difference between MERRA and GLOBE. We have also added information about the accuracy of GLOBE in the paragraph added in response to Comment 4 (see Text change in response to Comment 4).

Comment 7: *Pg 452, lines 15-22, where their distribution mapping procedure is described. I am not convinced that correcting one biased dataset with two other biased datasets will improve results. Especially by using APHRODITE as a correction factor, and then later comparing the MERRA data to the APHRODITE data. Issues with TRMM snowfall should also make this correction somewhat suspect.*

Response 7: The reviewer is not convinced that bias-correcting MERRA with observation-based data sets will improve the results. Neither are we. Rather, it demonstrates the wide range of "ground truths". Our point in doing this is to estimate the possible range of snowfall, based on data sets that are widely used by the scientific community. Seeing the large differences between the data sets, we decided not to judge whether one is better or worse than the other, rather just show the possible snowfall estimates one gets by using each set. And we do consider it likely that the ensemble represents upper and lower bounds for the true snowfall values.

Comment 8: *Along the same lines: TRMM 3B42 data are mostly rainfall data and do only partially include snowfall. Measuring snowfall with IR remote-sensing technology is very tricky. I suggest to carefully consider this point and add some caveats in the text. As an addition to this point: Please check the usage of precipitation – I think there are some cases where rainfall would be more appropriate.*

Response 8: We are aware of the limitations of the TRMM data when it comes to representing snowfall and have discussed this in lines 6–13 on page 457. Considering the under-catch of snow by traditional precipitation gauges, the problem also applies to the observation-based CRU TS and APHRODITE. The likely under-representation of precipitation in these data sets is discussed in Section 3.2 (line 18 on page 456 – line 13 on page 457). We understand the reviewer's concern about the use of the word precipitation vs. rainfall, but as TRMM includes some snowfall, we have chosen to keep using the word precipitation. We note that the reviewer, in Bookhagen and Burbank (2010), though generally using the term rainfall, also refers to TRMM 3B42 as an estimate of precipitation.

Comment 9: *Pg 453, section 2.4. It seems that their rain-snow line model doesn't account for topographic factors such as relief or aspect, which may have a strong control not only on type of precipitation, but also on how long the snow remains snow. This is probably very hard to correct for, however, and may be impossible at this data scale. It may help to show the relation between relief and slope as compared to shits in snowline. It seems that the authors posit that steep topography will be less affected by temperature changes, although this may simply be an artifact of how they calculate the rain-snow line. It could make sense that steep topography will be somewhat insulated from climate shifts. A figure may help to elucidate this.*

Response 9: That is correct: Our rain-snow line definition is based on temperature only. Apart from elevation, we do not consider the effect of topographical features. Steepness is not considered and we cannot see that we mention that anywhere. We agree that a more sophisticated definition would be valuable, but do not see how we could produce such a measure with the available data.

Comment 10: *Figure 2 really needs scale bars for each bar graph, as it is very hard to compare the values when they are not on a single x axis, but are instead floating in space.*

Response 10: We have added scale bars to each subplot in the figure, both in the form of vertical axes and as marks crossing the bars at each 100 mm.

Comment 11: *Figure 8 and 9: I am wondering if it makes sense to only show the model means here. I have a difficult time deciphering between the different models because most of the lines are on top of each other.*

Response 11: We agree that it was hard to distinguish between the lines in these figures, though we think it's important to show all the data. Showing only model means would hide the uncertainty represented by the spread in individual model projections. We have made new versions of the figures, with both mean values and individual models represented by horizontal marks.

Comment 12: *Figure 11+12 are very data rich and useful, but difficult to read. Is there a way to split up the figure to enhance readability?*

Response 12: We agree that the figure is complex. However, we would prefer not to split it up, as it would then be difficult to compare the subplots. As it is, precipitation, snowfall and rain-snow line values may be compared on a monthly basis, by reading the figure from the top to the bottom. If we split up the figure or changed the arrangement of the subplots, the reader would lose that possibility. As a total, that would make the arguments we make in Section 4.2 more difficult to follow.

References in the response document

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Snowfall in the Himalayas: An uncertain future from a little-known past

Ellen Viste, Asgeir Sorteberg

Geophysical Institute, University of Bergen, and Bjerknes Centre for Climate Research
Allégaten 70, 5007 Bergen, Norway

Key words: Himalaya, snow, precipitation

Abstract

Snow and ice provide large amounts of meltwater to the Indus, Ganges and Brahmaputra rivers. This study combines present-day observations and reanalysis data with climate model projections to estimate the amount of snow falling over the basins today and in the last decades of the 21st century. Estimates of present-day snowfall based on a combination of temperature and precipitation from reanalysis data and observations, vary by factors of 2–4. The spread is large, not just between the reanalysis and the observations, but also between the different observational data sets. With the strongest anthropogenic forcing scenario (RCP 8.5), the climate models project reductions in annual snowfall by 30–50 % in the Indus Basin, 50–60 % in the Ganges Basin and 50–70 % in the Brahmaputra Basin, by 2071–2100. The reduction is due to increasing temperatures, as the mean of the models show constant or increasing precipitation throughout the year in most of the region. With the strongest anthropogenic forcing scenario, the mean elevation where rain changes to snow – the rain/snow line – creeps upward by 400–900 meters, in most of the region by 700–900 meters. The largest relative change in snowfall is seen in the upper, westernmost sub-basins of the Brahmaputra. With the strongest forcing scenario, most of this region will have temperatures above freezing, especially in the summer. The projected reduction in annual snowfall is 65–75 %. In the upper Indus, the effect of a warmer climate on snowfall is less extreme, as most of the terrain is high enough to have temperatures sufficiently far below freezing today. A 20–40 % reduction in annual snowfall is projected.

1 Introduction

In the dry spring months preceding the Indian summer monsoon, much of the water in the Himalayan rivers comes from melting snow and ice (Bookhagen and Burbank, 2010;Siderius et al., 2013;Schaner et al., 2012). Concern has been raised that global warming may reduce the glaciers and their capacity to store water, as well as the amount of seasonal snow available for melting. Whether the meltwater comes from snow or glacier ice, stable snowfall is required to maintain the flow in the long run. Observations of present-day snowfall in the region are limited, meaning that there is also limited knowledge of the normal state and of historical trends. In this study we use temperature and precipitation data from a reanalysis and from observations to estimate snowfall in the Indus, Ganges and Brahmaputra Basins today. We then incorporate the projected changes in temperature and precipitation from a suite of climate models and follow the same procedure to estimate snowfall in 2071–2100.

Ellen Viste 9.4.2015 11:19
Slettet: future

The catchments of the Indus, Ganges and Brahmaputra rivers, as referred to in this article, are shown in Figure 1. The rivers run from the Hindu Kush - Karakoram - Himalaya (HKH) mountain range through the lowlands of Pakistan, India and Bangladesh. Both rainwater and meltwater from snow and ice contribute to all three rivers, with the highest meltwater fraction in the Indus and the lowest in the Ganges (Immerzeel et al., 2010;Bookhagen and Burbank, 2010;Singh et al., 1997). Even in the Ganges, meltwater is important in the otherwise dry spring (Siderius et al., 2013).

Precipitation varies greatly between inner and outer parts of the Himalayas (Singh et al., 1997;Bookhagen and Burbank, 2006;Winiger et al., 2005). While there are regions in the Himalayan foothills and along the Himalayan ridge with an annual mean rainfall of more than 4000 mm, most of the Tibetan Plateau on the leeward side receives less than 500 mm (Bookhagen and Burbank, 2010).

The Indian summer monsoon creates markedly different seasonal cycles in eastern and western parts of the HKH, both in precipitation and in the accumulation of snow and ice. In the monsoon-dominated central Himalayas and on the Tibetan Plateau, more than 80 % of the annual precipitation falls during summer. Precipitation maxima in the western regions occur in connection with westerly disturbances in winter. In the Hindu Kush and Karakoram, as well as in the easternmost Himalaya, summer precipitation amounts to less than 50 % of the annual precipitation (Bookhagen and Burbank, 2010). The seasonal cycle of snowfall varies accordingly. In the western HKH, snow accumulates during winter, while the summer is the main melting season. Further east, the summer is the main season, not just for ablation, but also for accumulation (Rees and Collins, 2006). According to Bookhagen and Burbank (2010), the east-west gradient and the effect of the summer monsoon is most pronounced in the lowlands, below 500 m a.s.l., while the difference is less at higher elevations.

Ellen Viste 14.4.2015 10:30
Slettet: ... [1]

1.1 Observed trends in snowfall, temperature and precipitation

Using satellite data, Rikiishi and Nakasato (2006) found that the mean annual snow cover area in Himalaya and on the Tibetan Plateau had been reduced by ~1 %/yr during 1966–2001. Few studies include snowfall data from stations on the ground, especially for periods long enough to detect trends. Studies of temperature and precipitation provide some information, though the picture is far from complete. Temperatures have increased in most of the region, whereas precipitation studies show varying results, depending on the location and time period. Whereas higher temperatures act to reduce the snow fraction, increased precipitation may have compensated in some regions.

Positive temperature trends have been observed throughout the HKH (Immerzeel, 2008;Xu et al., 2008b;Bhutiyani et al., 2007;Bhutiyani et al., 2010;Immerzeel et al., 2009;Shrestha et al., 1999;Shekhar et al., 2010;Fowler and Archer, 2006). The only exception to the regional warming is the Karakoram range, where both maximum and minimum temperatures have decreased since the mid-1980s (Shekhar et al., 2010). Both in Nepal (Shrestha et al., 1999) and the Upper Indus (Immerzeel et al., 2009), temperatures have increased more at higher elevations than in the lower terrain, implying that regions with snow may have been more strongly affected than indicated by regional means.

Increasing temperatures (Xu et al., 2008b) have most likely been the driver behind reductions in the snow cover on the Tibetan Plateau. During 1966–2001, the length of the snow season was reduced by 23 days (Rikiishi and Nakasato, 2006). The annual precipitation on most of the Tibetan Plateau increased over the same period (Xu et al., 2008a;Xu et al., 2008b;You et al., 2008); only in the western part was there a decrease (Xu et al., 2008b).

Few studies include data from the high-elevation parts of the Brahmaputra and Ganges Basins. Immerzeel (2008) found no clear precipitation trends for Brahmaputra as a whole for 1901–2002. For the same period Guhathakurta and Rajeevan (2008) found no significant precipitation trends relevant to snowfall in eastern parts of India, and neither did Shrestha et al. (2000) for stations in Nepal in the shorter period 1959–1994.

More studies of snow and ice have been performed for the Indus Basin than for the Ganges and Brahmaputra, possibly because meltwater constitutes a larger fraction of the run-off in this basin (Bookhagen and Burbank, 2010;Immerzeel et al., 2010). Also, as large parts of the Indus get little rain in late spring and summer, the link between melting snow and river discharge is perhaps more intuitive than in the regions further east, where the top of the meltwater season coincides with the Indian summer monsoon rain (Rees and Collins, 2006). No consistent precipitation trends have been found for the mountain regions of the Indus Basin as a whole, and epochs of more and less precipitation have alternated (Sontakke et al., 2008;Bhutiyani et al., 2010).

Some of the recent interest may also have been sparked by Karakoram glacier growth. After decades of recession, Karakoram glaciers were seen to expand in the late 1990s (Scherler et al., 2011;Gardelle et al., 2012;Hewitt, 2005). An observed combination of increased winter precipitation and decreased summer temperatures have been suggested to be the cause (Archer and Fowler, 2004;Fowler and Archer, 2006), and reduced summer discharge in rivers coming from the Karakoram is in accordance with the observed glacier growth (Fowler and Archer, 2006;Sharif et al., 2013). In contrast, Hartmann and Andresky (2013), found only insignificant negative trends in Karakoram precipitation during 1986–2010, and Cook et al. (2013) reported increased discharge in the Upper Indus after 1998. As pointed out by Hewitt (2005) and supported by Kääb et al. (2012), the glacier growth applies only to higher elevations in the central Karakoram, while glaciers in other parts and at intermediate elevations have continued to decline. Increased transport of moisture to higher altitudes may be part of the explanation (Hewitt, 2005).

Comparing the Karakoram with three other mountain ranges in the western Himalayas during 1984–2008, Shekhar et al. (2010) found that snowfall had been reduced in all the ranges, though less in the innermost Karakoram than in the outer ranges. As opposed to temperature increases in the other ranges, the Karakoram range experienced decreasing temperatures. The reduction in snowfall on the outside of the outermost range, Pir Panjal, during the last decades was supported by Bhutiyani et al. (2010), who found that the duration of the snowfall season had been reduced by about 5–6 days per decade.

Documented trends in other parts of the Indus basin vary, and alternating epochs indicate that the choice of time period may influence the results. In Jammu & Kashmir and Himachal Pradesh, Bhutiyani et al. (2010) found a significant decreasing trend in summer precipitation during the 20th century. There was no trend in winter precipitation at the three stations used, but epochs of dry and wet winters had alternated, and winter precipitation was above average in 1991–2006. Previously, a long-term increase in summer and annual precipitation in Jammu & Kashmir was documented by Guhathakurta and Rajeevan (2008), and in Himachal Pradesh by Singh et al. (2008). Sontakke et al. (2008), on the other hand found no trends in this part of India since the 19^{th} century, but noted a dry epoch since 1968. It should be pointed out that their data set contained stations in the outer ranges, only, and not in e.g. the Karakoram.

Further west in the Upper Indus Basin, at stations mainly in Pakistan, (Archer and Fowler, 2004) observed no trends in precipitation over the 20th century, but a significant increase in winter, summer and annual precipitation at several stations starting in 1961. The increase was accompanied by increasing winter temperatures, but decreasing summer temperatures (Fowler and Archer, 2006). Hartmann and Andresky (2013) found significant, positive trends in precipitation in the Hindu Kush and the Sulaiman mountains for 1986–2010.

Satellite-based studies of trends in the present century (2000–2008/2001–2007) have documented a decrease in winter snow cover area in the Upper Indus (Immerzeel et al., 2009), but an increase in the Indus water volume stored in snow and ice (Immerzeel et al., 2010).

1.2 Future projections of snowfall, temperature and precipitation

In the last decades of the 21st century, the temperature over India is projected to be on average 2.0–4.8 °C higher than today, depending on the anthropogenic forcing scenario (Chaturvedi et al., 2012). In the Himalayas, a temperature increase of more than 7 °C is seen with the strongest forcing, the Representative Concentration Pathway (RCP) 8.5 (Chaturvedi et al., 2012;Collins et al., 2013). Independently of precipitation changes, higher temperatures will decrease the fraction of precipitation falling as snow. Whether snowfall will increase or decrease thus depends on whether precipitation will increase enough to compensate for the reduced snow fraction.

Climate models from CMIP5, the most recent Coupled Model Inter-comparison Project (Taylor et al., 2011), project a general increase in precipitation over India, growing with anthropogenic forcing and with time, both annually (Chaturvedi et al., 2012) and during the summer monsoon (Menon et al., 2013). An increase was also seen in data from the previous model comparison project, CMIP3 (Turner and Annamalai, 2012). Menon et al. (2013) found that changes in the low-level winds suggest a northward shift in the monsoon by the end of the 21st century for the strongest forcing scenario, although the total zonal strength of the monsoon remained fairly constant.

It should be emphasized that there is a large inter-model spread in precipitation projections. Guo et al. (2014) found that CMIP5 models with a more realistic representation of aerosols, had a more negative impact on the monsoon than models that include only the direct effect of aerosols on radiation. Overall, the IPCC AR5 concludes that there is medium confidence in the increase in summer monsoon precipitation over South Asia (Christensen et al., 2013). But although precipitation projections are less reliable than temperature projections, agreement between models increases with time and anthropogenic forcing (Chaturvedi et al., 2012). Also, the CMIP5 multi-model mean has been considered to represent the monsoon and the actual climate in India better than any individual model (Chaturvedi et al., 2012;Sperber et al., 2013).

The IPCC AR5 has high confidence that the snow cover area in the northern hemisphere will be substantially reduced with anthropogenic forcing as in the strongest scenarios (Collins et al., 2013). For the range of RCPs 2.6–8.5, CMIP5 models simulate 7–25 % reductions in the spring snow cover extent by 2080–2100. For snowfall and snow water equivalents (SWE), the projections show more variation. While warming decreases the amount of snow, both through melting and through decreasing the snow fraction, more precipitation may increase snowfall in some of the coldest regions (Räisänen,

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2008;Brutel-Vuilmet et al., 2013). Though shown to apply mainly to the northern parts of Eurasia and North America, there is a possibility that some of the higher-lying terrain in the HKH may be similarly affected.

1.3 Aims and scope

For the HKH, uncertainty in projections of future precipitation and snowfall comes on top of uncertainty in present time conditions. Observations are limited, especially in remote, high-elevation regions (Anders et al., 2006;Immerzeel, 2008;Tahir et al., 2011b;Winiger et al., 2005). Insufficient knowledge of the amount of snow falling over the region today, makes the contribution to both seasonal snowmelt and storage in glaciers correspondingly uncertain.

Recognizing this uncertainty, this study provides an ensemble of monthly mean snowfall estimates for all sub-basins of the Indus, Ganges and Brahmaputra, today and for 2071–2100. For the present time estimates, we have combined MERRA reanalysis data (Rienecker et al., 2011) with observationally based data sets of precipitation and temperature: CRU TS (Harris et al., 2014), TRMM (Huffman et al., 2007) and APHRODITE (Yatagai et al., 2012;Yasutomi et al., 2011). Whereas Ménégoz et al. (2013) and Wiltshire (2014) analyzed Himalayan snowfall by downscaling reanalysis data with regional climate models, we have applied a simple terrain adjustment of the reanalysis temperature field.

The ensemble of present-day estimates is presented in Section 3. Future snowfall was then calculated based on the present-day snowfall and projected changes in temperature and precipitation in 14 and 15 CMIP5 models for the RCPs 2.6 and 8.5, respectively. These results are presented in Section 4. The data and methods for both the present time and the future case are described in Section 2.

Three main features may be involved in precipitation changes in the HKH: changes in the summer monsoon, changes in western disturbances during winter, and the general changes that occur in the thermodynamic properties of the air as the temperature increases and the air contains more water vapor. We have not considered the role of the different factors, only looked at how changes in temperature and precipitation affect snowfall. Unless otherwise specified, any reference to snow refers to precipitation falling as snow, not to the snow cover on the ground.

2 Data and methods

In addition to the original MERRA reanalysis snowfall, we estimated snowfall using different combinations of temperature and precipitation data. An overview of the combinations is shown in Table 1 and the data sets used presented in Table 2 and Table 3.

Present-day snowfall estimates were based on:
1) MERRA 2 m temperature adjusted to a higher-resolution elevation grid, and MERRA precipitation (Section 2.1). This was used as a basis for the other estimates and is referred to as MERRA reference snowfall. The adjusted temperature is referred to as terrain-adjusted.
2) MERRA 2 m temperature and precipitation.
3) The MERRA data in 1) bias-corrected with observation-based data for temperature and precipitation (Section 2.2).

Estimates for the last decades of the 21th century were based on:
4) The MERRA data in 1) plus the changes in temperature and precipitation in a group of CMIP5 models over the coming century (Section 2.3).
5) Bias-corrections with one of the data sets in 3) – APHRODITE – plus the mean changes in temperature and precipitation in the CMIP5 models used in 4). This was done to account for the spread in the present-day estimates.

With the exception of original MERRA snowfall data, all snowfall estimates were based on the relationship between temperature and snowfall derived by Dai (2008). Based on observations, the conditional snow frequency over land was formulated as

$$F(T_s) = a\big[\tanh\big(b(T_s - c)\big) - d\big], \tag{1}$$

where T_s is the surface air temperature [°C], and a = –48.2292, b = 0.7205, c = 1.1662, and d = 1.0223. This may be interpreted as the probability, or fraction, of precipitation falling as snow at a given temperature. We calculated hourly snowfall as the product of F and the amount of precipitation. Cut-offs for no rain and no snow were set at –10 and 10 °C, respectively, as this was the range of the data used by Dai (2008).

All snowfall estimates were made for the sub-basins defined in the HydroSHEDS data set (Lehner et al., 2008). The results were then aggregated to monthly sums for the Indus, Ganges, and Brahmaputra Basins.

Within each major basin, we also grouped the sub-basins into regions with similar characteristics of snow and precipitation. This was done with k-means clustering (MacQueen, 1967), using the square Euclidean distance as the distance measure. The seasonal cycles of precipitation, snow and snow fraction were first clustered separately, with the MERRA reference data and data bias-corrected with CRU TS data as input. We then adjusted the clusters manually, prioritizing similarity of the relative seasonal cycles of snow and snow fraction, and checking that both data sets gave similar results. Five groups were defined for the Indus, and four for each of the other basins. This included a no-snow group in each basin.

2.1 Reference present-day snowfall

The horizontal resolution of the MERRA reanalysis data in the Himalayas is about 55 km latitude and 70 km longitude. To account for smaller-scale temperature variations in the rugged terrain, we used the vertical temperature gradient in MERRA to adjust the ground temperature to the GLOBE topography (Hastings and Dunbar, 1998). The elevation-adjusted ground temperature was calculated as

$$T_{adj} = T_0 - \frac{\Delta T}{\Delta z}\Delta z_0 = T_0 - \frac{T_2 - T_1}{z_2 - z_1}(z_{merra,0} - z_{globe}), \quad (2)$$

where T_0 is the MERRA 2 m temperature, T_1 is the temperature at the lowest pressure level above the ground, T_2 the temperature at the next pressure level, and z_2 and z_1 the height of these levels. $z_{merra,0}$ and z_{globe} are the elevations of the MERRA and GLOBE topography, respectively, and Δz_0 the difference between them. The variables are illustrated in Figure 2. The procedure combines the vertical temperature gradient in MERRA with the MERRA 2 m temperature and the elevation difference between MERRA and GLOBE. We have assumed that the most representative temperature gradient ($\Delta T/\Delta z$) for this purpose, is that of the MERRA layer nearest to, but not touching, the MERRA ground.

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To reduce calculation time compared to using the original 1 km GLOBE resolution, both MERRA and GLOBE data were interpolated to a 4 km grid. Snowfall was calculated for each grid-point, and then aggregated for each sub-basin for each month.

Snowfall based on elevation-adjusted MERRA temperature and MERRA precipitation is used as a reference throughout this article. This is because the elevation-adjusted temperature and the 4 km grid was used as the starting-point in all subsequent calculations. It does not mean that we consider these snowfall values to be closer to the truth than any of the other estimates.

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2.2 Bias-corrected, present-day snowfall

A second group of present-day snowfall estimates was made from MERRA precipitation and elevation-adjusted temperature bias-corrected with observationally based data sets: APHRODITE daily temperature and precipitation for 1979–2007, CRU TS monthly temperature and precipitation for 1979–2011, and TRMM 3B42 3-hourly precipitation for 1998–2012. Bias-corrections were performed on daily or monthly scales, depending on the input data, and the result distributed over the hourly time-steps of the MERRA temperature and precipitation. As a result, the diurnal cycle in MERRA is maintained in all estimates. Snowfall was then calculated following the same procedure as for the

MERRA reference snowfall (Section 2.1). When referring to APHRODITE snow or CRU snow anywhere in this article, this is the snowfall calculated using MERRA precipitation and temperature both bias-corrected with these data sets.

Temperature data are generally assumed to be normally distributed, and as described in Teutschbein and Seibert (2012) and references therein, the data can be bias-corrected through a Gaussian distribution mapping. We thus bias-corrected the elevation-adjusted MERRA temperature with the observationally based APHRODITE V1204 daily temperature, by mapping the distribution of the MERRA data to the Gaussian distribution of the observations.

As the CRU TS 3.20 includes monthly mean daily minimum and maximum temperatures, the method described by (Wang and Zeng, 2013) was used. Bias-corrected, daily maximum temperatures were defined as

$$T_{d,max} = T_{merra,d,max} - (T_{merra,mn,\max} - T_{cru,mn,max}) , \qquad (3)$$

where d denotes daily and mn monthly. Daily minimum temperatures were then corrected by adjusting the diurnal range,

$$T_{d,min} = T_{d,max} - \Delta T_{merra,d} * \frac{\Delta T_{cru,mn}}{\Delta T_{merra,mn}} , \qquad (4)$$

where ΔT represents the diurnal and monthly temperature range.

The distribution mapping procedure described by Ines and Hansen (2006) was used to bias-correct MERRA precipitation with APHRODITE V1101R2 daily precipitation and daily accumulated TRMM 3B42 3-hourly precipitation. This is a two-step procedure involving frequency and intensity adjustments. We defined precipitation days as days with at least 0.1 mm in the observations. The frequency was first adjusted by setting the number of precipitation days in MERRA equal to that of the observations. This was done by removing the lowest daily values. The intensity was then adjusted by fitting the remaining days to the gamma distribution of the observations.

Bias-corrections with CRU TS 3.20 monthly precipitation were done with a simple correction factor to adjust the monthly MERRA total to that of CRU (e.g. Ines and Hansen (2006)).

2.3 Projected snowfall

The MERRA reanalysis was also the basis for estimates of future snowfall. The changes in temperature and precipitation from 1971–2000 to 2071–2100 were added to the reanalysis data and snowfall calculated following the same procedure as for the present time. Climate change input came from models that were part of the Coupled Model Inter-comparison Project 5 (CMIP5 (Taylor et al., 2011)), for the Representative Concentration Pathways (RCP) 2.6 and 8.5 (Moss et al., 2010;van Vuuren et al., 2011). The models used are listed in Table 3.

Due to the different spatial resolution of the models, changes were defined as monthly mean changes on the sub-basin level. For temperature, the absolute change was used, and for precipitation, the fractional change. Future projected snowfall was calculated with reference to elevation-adjusted MERRA snowfall for each model. Due to large deviations in estimates of present-day snowfall (Section 3), we also calculated snowfall for the CMIP5 multi-model mean changes with reference to the lowest present time estimate, APHRODITE snowfall.

2.4 The rain-snow line

Not all temperature changes affect snowfall. We defined the rain-snow line as the elevation where the temperature suggests a shift from rain to snow. Technically, this is a conditional rain-snow line, as no precipitation was required. For every hour, all grid cells that had a snow fraction/probability between 0.25 and 0.75, corresponding to a temperature between 0.9 and 1.3 °C, were identified. The monthly rain-snow line was then set as the mean elevation of these grid cells and time steps. For present-day conditions this was done for elevation-adjusted MERRA temperature and temperature bias-corrected with APHRODITE. Projected temperature changes in the CMIP5 RCP 8.5 were then added to these temperatures and the procedure repeated.

3 Present-day snowfall

3.1 Seasonal cycles of precipitation and snowfall

Figure 3 gives an overview of the seasonal cycle of rain and snow in different parts of the HKH, based on MERRA precipitation and MERRA reference snowfall (Section 2.1). The upper Indus basin gets more snow than rain; in other sub-basins of the Indus, Ganges and Brahmaputra, rainfall dominates. This difference is caused by different precipitation cycles, as well as elevation differences. Whereas the summer monsoon dominates in the Central Himalayas, winter depressions bring most of the precipitation in the upper Indus – at a time when low temperatures mean that precipitation falls as snow in larger areas than it would in summer. Although snow fractions are lower in the upper Brahmaputra, monsoon precipitation produces a substantial amount of summer snow at high elevations.

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In the northwesternmost cluster in the Indus, I4, March is the wettest month and also the month with the highest total amount of snowfall. Precipitation has a second peak during July and August, but the temperature is then too high to allow much snowfall. Further east, in cluster I5, more terrain at higher elevations cause higher snow fractions during summer, but winter and spring is still the dominant snow season. The summer peak in precipitation in this cluster is caused by the two eastern sub-basins. There is little summer precipitation in the west.

In Brahmaputra's cluster B4 and Ganges' G4, maximum snowfall occurs during the summer monsoon. Higher temperatures during summer means that the snow fraction is lower than in winter, but as there is much more summer precipitation, the amount of snow is also higher. Rare occurrences of precipitation during the cold winter, together with the combination of snowfall and snowmelt during summer, makes the seasonal cycle of snow depth in the Central Himalayas unpronounced (Ménégoz et al., 2013). In the upper-level basins in Brahmaputra's B3, the summer is also the main precipitation season, but the peak is less sharp than further west. As a result, snowfall is at a maximum in March–April.

3.2 Comparison of snowfall estimates

The MERRA reference snowfall described in section 3.1 differs greatly from snowfall based on bias-corrected temperature and precipitation. Large differences between temperature and precipitation data sets for the HKH cause corresponding deviations in snowfall – not only between MERRA-based estimates and bias-corrected data, but also between estimates based on bias-corrections with different data sets. This can be seen from Table 4, which displays annual snowfall estimates for combinations of the bias-corrections described in Section 2.2, aggregated to the major basins. Data for the individual sub-basins are included as supplementary material.

With the exception of snowfall based on MERRA precipitation and MERRA temperature bias-corrected with CRU TS in the Ganges basin, all estimates based on bias-corrected data are lower than the MERRA reference snowfall. The lowest estimates are those based on bias-corrections with APHRODITE precipitation and temperature. This combination produced only 33 % of the reference snowfall in the Indus Basin, 22 % in the Ganges Basins, and 17 % in the Brahmaputra Basin. While the difference is large in all sub-basins that have snow today, it is especially large in the upper parts of the Indus and Brahmaputra Basins (Figure 4). In comparison, bias-corrections with CRU TS temperature and precipitation produce 54 % of the reference snowfall in the Indus, 75 % in the Ganges, and 42 % in the Brahmaputra – factors of 2–4 compared to APHRODITE. It should be noted that, as the time periods covered by the data sets are not equal, the results are not strictly comparable, but tests

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using different MERRA periods (not shown) indicate that there would be no major difference in the monthly means.

The MERRA reference snowfall deviates about 10 % from the original MERRA reanalysis snowfall; negatively in the Indus and Brahmaputra, and positively in the Ganges. Two effects contribute to this: the use of elevation-adjusted temperature, and the use of the function from Dai (2008) when relating precipitation type to temperature. The effect of the function may be seen from the 'MERRA T2m' in Table 4. For this variable, the Dai function was applied directly to the MERRA 2 m temperature, i.e., without the elevation adjustment. Comparing this with the original MERRA reanalysis snowfall ('MERRA') indicates that the Dai function acts to reduce the snow fraction. The elevation-adjustment of temperature depends on the MERRA vertical temperature gradient, as well as the topography of MERRA and GLOBE. GLOBE is the result of merging various other elevation data, and the quality in each region depends on the available input data. Globally, half of the data points have been estimated to have a vertical accuracy of less than 30 m, whereas some points in Antarctica may be as much as 300 m off (Hastings and Dunbar, 1999, 1998). The effect of elevation-adjusting the temperature, or of using the Dai function, each amounts to changes in the order of 5–20 %. This is much less than the effect of bias-corrections with observation-based data.

The large difference between MERRA reference snowfall and snowfall based on bias-corrected data, results from differences in both temperature and precipitation, but differences in the precipitation pattern have the greatest effect. Estimates where only the precipitation has been bias-corrected are lower than those where only the temperature has been bias-corrected (Table 4). This is not solely an effect of more precipitation in MERRA than in the observation-based data, although MERRA is wetter than all the data sets in the Indus, and for APHRODITE also in the Ganges and the Brahmaputra. An inland and upward shift in the MERRA precipitation adds to the differences. As shown in Figure 5, all the observation-based precipitation data sets are wetter than MERRA in most of the lowlands and in the foothills of the HKH, but drier in the higher-elevation regions further inland. In MERRA, the precipitation belt is shifted higher up in the Himalayas, where temperatures are lower, and more of the precipitation falls as snow.

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In addition, HKH temperatures are lower in MERRA than in APHRODITE, and in the upper Indus also than in CRU TS (Figure 6). The lower temperatures in MERRA cause higher snow fractions, further increasing the difference between the MERRA reference snowfall and APHRODITE snowfall. Oppositely, CRU TS is colder than MERRA throughout the Ganges, leading to higher snowfall estimates when bias-correcting MERRA temperatures with CRU TS (Table 4).

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We do not see any reason to consider any of the observation-based data sets, nor the reanalysis, the ground truth. The reanalysis has the benefit of being physically consistent, though precipitation is a pure model product. In the other data sets, the number of observations vary greatly within the region.

The lack of observations in the HKH has been pointed out in many studies. Most meteorological stations are located in the valleys and do not necessarily represent weather conditions in higher terrain. As demonstrated by Palazzi et al. (2013) station-based data sets like APHRODITE and CRU TS are merely mathematical interpolations in major parts of the HKH and on the Tibetan Plateau. Immerzeel (2008) showed that the number of observations going into version 2.1 of the CRU data set in the Himalayan region varies greatly. A drop in the mid-1990s suggests that caution should be taken when interpreting data at later times. Maps (not shown) of station coverage in version 3.20, used in this study, show that this problem persists.

The fact that more of the precipitation falls as snow at higher elevations, may in itself lead to an under-estimation of precipitation in the mountains. In addition to the lack of observations in high terrain, gauges tend to capture snow less easily than rain, leading to a possible under-registration of precipitation at the few high-elevation stations that exist. Comparing stations along a vertical profile in the Karakoram, Winiger et al. (2005) found that precipitation multiplied by a factor of 5–10 from 2500 m a.s.l. to 5000–6000 m a.s.l. This maximum is much higher than reported in most other studies, and they attributed this to the valley-dominance of stations normally used.

Indications of too little precipitation at higher elevations were also given by Tahir et al. (2011b), as APHRODITE precipitation was too low to account for the observed discharge in the Hunza river in the Karakoram. Anders et al. (2006) reported that TRMM radar data underestimated precipitation at higher elevations in the Himalayas, due to the low ability of the radar to detect very low precipitation and low–moderate snowfall rates. On the other hand, Krakauer et al. (2013) found that both TRMM and APHRODITE had too much precipitation compared to observations from the few existing stations at elevations above 3000 m a.s.l. in Nepal.

Satellite data are a promising future alternative for measuring snowfall, but presently of limited use. MODIS and LANDSAT satellite data have been used in several studies of snow and ice in the Himalayas (Tahir et al., 2011a;Tahir et al., 2011b;Bookhagen and Burbank, 2010;Hewitt, 2005;Krishna, 2005;Negi et al., 2009;Jain et al., 2009;Butt, 2012;Gao et al., 2012;Kulkarni et al., 2010;Immerzeel et al., 2009), but these data contain only snow cover area, with no measure of the snow thickness or snow water equivalents. The NASA AMSR-E SWE data set distributed by the National Snow and Ice Data Center could have been used, but correlations between AMSR-E SWE and ground observations have been shown to be poor (Tedesco and Narvekar, 2010;Byun and Choi, 2014;Kumar et al., 2006). As AMSR-E SWE has been found to underestimate snow depth, we

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concluded that incorporating these data into our ensemble would not likely constrain the results, nor add new information.

Defining snowfall based on MERRA precipitation and elevation-adjusted temperature as a reference, was done mainly to have a single reference when comparing the data sets against each other. Also, we believe the elevation-adjustment of temperature represents an enhancement compared to the original MERRA reanalysis. MERRA was chosen mainly because it has an hourly resolution, allowing diurnal temperature variations to affect snowfall. But even though this estimate is much higher than all the bias-corrected estimates, it cannot be discarded. It has been argued that reanalysis data and regional climate models may in some cases be as good as, or better, than observations in the HKH (Wiltshire, 2014;Ménégoz et al., 2013;Akhtar et al., 2008). Akhtar et al. (2008) got better results when modeling river discharge in three upper Indus catchments with an RCM-based hydrological model, than with one based on the few observations available within the region. They concluded that it was preferable to use RCM data directly as input to hydrological models in this region.

As shown in the small, inset maps in Figure 5, MERRA precipitation is higher than observed precipitation throughout the HKH, and the same has previously been shown for ERA-Interim reanalysis precipitation (Palazzi et al., 2013). In MERRA, the precipitation belt is shifted upward in the terrain, compared to in the observation-based data sets. Whether this shift is realistic, cannot be determined as long as observations from upper-level terrain are either missing or likely too low.

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4 Projected future snowfall

Whether higher temperatures lead to less snowfall, depends on whether the temperature changes from below to above freezing, and whether this change occurs at a time when there is precipitation. The maps in Figure 7 illustrate where a temperature increase is most likely to affect snowfall and snowmelt. In the red zones, where the monthly temperature today is between –5 and 0 °C, the projected temperature increase of 2–7 °C (Chaturvedi et al., 2012;Collins et al., 2013;Wiltshire, 2014), may be considered critical. Such a change would change snowfall to rain and also cause a change from freezing to melting of snow and ice. The pink zones, with monthly mean temperatures of 0–5 °C, would similarly change from a climate where precipitation may often fall as snow, to one that is snow-free.

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In January (Figure 7a), only the lower parts of the Himalayas is affected, as most of the region would still have temperatures well below the freezing point. The small, inset map shows precipitation in the red zone; a narrow band along the range. Oppositely, in July (Figure 7c), the temperature is already above 5 °C in most of the region, though at higher elevations along the Himalayan range and in the

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Karakoram, the change can be critical. The most widespread changes are seen in spring and fall. In April and October (Figure 7b,d), large areas in the HKH and on the Tibetan Plateau risk a change from below to above freezing.

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Incorporating CMIP5 precipitation changes, we find that the projected temperature increase has a larger impact, so that snowfall will be reduced in the Indus, Ganges, and Brahmaputra Basins by 2071–2100 compared to today. Details for the major basins are presented in Section 4.1. How much increased temperatures reduce snowfall within a region, depends on the location of the rain/snow line today, compared to the terrain distribution. Results for selected upper-level sub-basins in the Indus and Brahmaputra will be discussed in that context, in Section 4.2

The large deviations in the estimates of present-day snowfall (Section 3) means that there will be correspondingly large deviations in projected values. To account for this, most results are shown with reference to the highest and lowest present-day estimates: MERRA reference snowfall and to APHRODITE-based snowfall. Future estimates relative to CRU and TRMM are assumed to lie between those of MERRA and APHRODITE.

4.1 Basin-scale projections

In the Indus, Ganges and Brahmaputra Basins, the CMIP5 models project a mean increase in both temperature (Figure 8) and precipitation (Figure 9) in the region by 2071–2100, for both RCPs 2.6 and 8.5. The RCP 8.5 multi-model mean change in temperature varies through the year, with a 4.9–6.2 °C increase in the Indus, 3.6–5.2 °C in the Ganges and 4.2–6.0 °C in the Brahmaputra. The increase is smallest during the summer months. The dip in the summer is also seen, though less pronounced, with the RCP 2.6. The summer is also the season with the largest absolute increase in precipitation.

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Compared to present-day estimates, the CMIP5 models project less snowfall in the Indus, Ganges, and Brahmaputra Basins in the last decades of this century. This can be seen from Figure 10. The projected multi-model mean is lower than today in all calendar months, for both RCPs 2.6 and 8.5. With the RCP 2.6, some models suggest an increase in some months, mainly in winter and spring. This is also the case for one or two models with the RCP 8.5, whereas other models indicate that the snowfall in the same months will be only half of today's values.

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In the Ganges Basin (Figure 10b) the seasonal distribution of snowfall today is mainly flat, with equal amounts of snowfall from January through September. Reductions in summer snowfall with the RCP 8.5 would change the seasonal cycle into a winter-dominated one. To a lesser degree, this is also the case for RCP 2.6. As summer precipitation is projected to increase in all of the Ganges (not shown, but consistent with Menon et al. (2013)), this indicates that large areas are at elevations where a small

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increase in the summer temperature may cause a shift from snow to rain. This is seen as the red band along the upper Ganges in Figure 7c. Reductions in summer snowfall are also large in the Brahmaputra (Figure 10b), whereas in the Indus, the largest total changes occur in March–May (Figure 10a).

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As the MERRA reference snowfall for today is much larger than APHRODITE snowfall (Section 3.2), projected absolute changes for 2071–2100 are also much larger in MERRA. The relative changes are more similar, though larger with reference to APHRODITE. Annual snowfall changes for each major basin are presented in Table 5, for changes in temperature, precipitation or both, and with reference to MERRA and Aphrodite present-day snowfall. Changes at the sub-basin level are shown in Figure 11. In the Ganges Basin, both MERRA- and APHRODITE-based multi-model mean snowfall is reduced by about 20 % with the RCP 2.6 and 50 % with the RCP 8.5. In the Indus and Brahmaputra Basins, the differences between MERRA- and APHRODITE-based changes are larger, but not as large as for the absolute values. With reference to MERRA and APHRODITE, respectively, the reduction in snowfall in the Indus Basin, is 30 % and 50 %, with the RCP 8.5. The corresponding reductions in the Brahmaputra Basin are 50 % and 70 %.

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The projected changes in temperature have greater effect on snowfall than the changes in precipitation. When taking into account only changes in precipitation, all snowfall estimates are positive (ΔP, Table 5). This indicates that the mean annual total reduction for each major basin is governed by the temperature change. In some CMIP5 models (values in brackets in Table 5) the effect of precipitation changes (ΔP) on snowfall are of the same magnitude as the effect of temperature changes (ΔT), but for the CMIP5 multi-model mean, temperature changes cause snowfall changes 4–10 times as large as those due to changes in precipitation. This is with reference to the present-day MERRA reference snowfall, and for both RCPs 2.6 and 8.5. With reference to APHRODITE snowfall, the effect of temperature changes compared to precipitation changes is even greater.

4.2 Regional projections

If temperatures are far below freezing everywhere, warming may have little effect on snowfall. The same applies if only the highest peaks receive snow today. The largest reduction in snowfall in a basin occurs if today's rain/snow line is at an elevation just below the dominant elevation of the basin. Then, large regions will see a shift from snow to rain.

In the Indus Basin, the largest relative snowfall reduction by 2071–2100 is seen in the southwestern sub-basins, where snowfall is limited today (Figure 11). The largest total reduction is seen in the snow-rich sub-basins of Kabul/Swat/Alingar in the west and in the east, and a smaller reduction in the inner-most basins of Gilgit/Hunza, Indus 1, and Nubra/Shyok. Together with the upper regions of the

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Brahmaputra, these sub-basins, clusters I4, I5, B3, and B4 in Figure 3, were selected for a closer analysis. In addition to having the most snow, these clusters are the most homogeneous when considering the seasonal cycle of snowfall and snow fraction. The values presented in this section are all from the RCP 8.5, for changes from today to 2071–2100.

4.2.1 Upper Indus, western part

Cluster 4 consists of the sub-basins Astor, Kabul/Swat/Alingar, and Krishen Ganga. As seen from the elevation profile at the top of Figure 12a the elevation span is large, and there is an almost equal proportion of the terrain at all levels from heights close to sea level to about 5000 m a.s.l. The most important change for this cluster, is a large reduction in the total amount of snowfall in winter and spring.

With a few exceptions, all CMIP5 models project less snowfall in all months of the year (Figure 12a i,ii). The largest total multi-model mean reduction in snowfall (ii) occurs in February–April, without notable change in the multi-model mean precipitation (iii). Thus, the reduction is caused by increasing temperatures, represented by the rain/snow line in Figure 12a iv. As seen from the change in the rain/snow line elevation, the projected temperature increase in these months would imply that large areas that receive snow today would receive only rain. About 40 % of the ground in this cluster lies below 2000 m a.s.l. and receives precipitation as rain throughout the year. In summer, precipitation (iii) is at a minimum, and the rain/snow line (iv) is already so high that only a small fraction of the area receives snowfall today. Thus, although the relative change in snowfall (i) is largest in summer, the change in the amount of snowfall (ii) is small. It should also be noted that the change in the rain/snow line elevation (iv) in summer is much smaller; 400–600 m compared to 600–900 meters in December–April.

4.2.2 Upper Indus, eastern part

Further east, the largest changes are projected for the spring season. Cluster 5 in the Indus Basin consists of the sub-basins Gilgit/Hunza, Indus 1, Nubra/Shyok, and Zanskar. As shown in Figure 12b, this is high-elevation terrain, with 80 % of the ground lying above 4000 m a.s.l. As a result, almost all winter precipitation is snow (Figure 12b iii). For the multi-model mean, no big changes are projected in January–February. This is partly because of little change in precipitation (iii) and because the rain/snow line (iv) in these months is sufficiently low in the terrain today. With the 500–600 m shift projected with the RCP 8.5, 80–90 % of the area will still have temperatures low enough for snow. The largest changes occur in March–October, when higher temperatures push the rain/snow line above large areas that receive snow today. Increasing summer precipitation (iii) causes the snowfall reduction in summer to be less than it would otherwise be. The effect of higher temperatures is smaller

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on the APHRODITE snowfall than on the MERRA reference snowfall (ii), as APHRODITE has very little summer snowfall today. The difference arises both from less precipitation (iii) in APHRODITE than MERRA today, and from a higher rain/snow line (iv) in APHRODITE. Note that, as the change in precipitation was defined as a fraction of the present-day value (Section 2.3), the relative changes in APHRODITE and MERRA precipitation are equal.

4.2.3 Upper Brahmaputra, western part

In the westernmost part of the upper Brahmaputra Basin, large snowfall changes are projected for the summer. As cluster 5 in the Indus Basin, Brahmaputra's cluster 4 is limited to higher grounds. Less than 6 % lies outside of the 4000–6000 m a.s.l. range. The cluster consists of Maquan He, Yarlung Zangbo, Dogxung Zangbo / Maiqu Zangbo., Shang Chu / Yarlung Zangbo / Nyang, Lhasa He / Razheng Zangbo, and Yamzho Yumco. The summer monsoon fully dominates the seasonal cycle of precipitation in this region (Figure 13a iii), resulting in a unimodal snow cycle, with a maximum in July–September. In APHRODITE the seasonal cycle of snowfall is similar, but less pronounced, than in the MERRA reference. The summer also sees the greatest reduction in CMIP5 projected snowfall, both in absolute (ii) and relative (i) terms, despite increasing summer precipitation in all models (iii). The reason can be seen from the change in the rain/snow line elevation (iv). In the warmest months, July and August, elevation changes of 400–500 m would shift the rain/snow line from a level where at least 5–10 % of the ground lies above the line, to a level where only 1 % of the area would receive precipitation as snow. In comparison, with reference to MERRA, the 300–400 m shift seen in January–February would cause only a small absolute change in snowfall (ii) because there is little precipitation in these months (ii), and a small relative change (i) because the rain/snow line would still be low in the terrain (iv). With reference to APHRODITE, the relative snowfall change in winter would be larger than with reference to MERRA, as temperatures today are higher, resulting in a higher rain/snow line (iv).

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4.2.4 Upper Brahmaputra, eastern part

Like further west, the Indian summer monsoon dominates the precipitation cycle in the eastern part of upper Brahmaputra (Figure 13b iii), but the seasonal cycle of snowfall peaks in spring and fall (iii). This is also the time of the largest projected changes.

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Cluster 3 in the Brahmaputra consists of the sub-basins Yarlung Zangbo2, Nyang Qu, Yarlung Zangbo3, Yi'ong Zangbo / Parl., Siyom, Zaya Qu / Luhit / Di. About 70 % of the ground lies between 3000 and 6000 m a.s.l., but there is also land almost at sea level, mainly in the Zaya Qu / Luhit / Dingba Qu sub-basin. During summer, most of the terrain lies below the rain/snow line (iv). In spring, temperatures are lower than in summer, and pre- monsoon precipitation is stronger in this part of the

Himalayas than further west in cluster 3 (Figure 13a iii vs. Figure 13b iii). As a result, March–April gets the most snow.

Reductions in snowfall are projected for all months (ii), comparable in magnitude, but largest in the snow-rich spring, and late summer. The CMIP5 multi-model mean shows increasing, or no change in precipitation in all months (Figure 13b iii), so the reduction in snowfall is due solely to higher temperatures. The largest absolute reductions, in April and May, occur with a 700–800 m shift in the rain/snow line elevation, leaving 30 % more of the terrain in the rain. The largest relative reduction in future snowfall are projected for July and August (Figure 13b i), when the rain/snow line shifts so high that only the highest peaks can get precipitation as snow (iv). This would be despite the lowest changes in the rain/snow line; only about 300 m in APHRODITE.

4.3 Potential effects of reduced snowfall on water availability

With a few exceptions, the CMIP5 multi-model mean precipitation change over the coming century is positive in all months in the upper Indus and Brahmaputra (Section 4.2). Thus, the projected reduction in snowfall is due solely to higher temperatures. However, there is a large spread in precipitation projections among the models. If temperatures increase as much as projected with the RCP 8.5, could any realistic precipitation change in the HKH compensate and maintain present-day snowfall? Results indicate that this may happen in parts of the upper Indus, but is out of the reach in the upper Brahmaputra. As for water availability, reduced snowfall may still cause more severe problems in the Indus than in the Brahmaputra.

In cold regions, where temperatures remain below freezing, more winter precipitation may increase both the snow cover area, the length of the snow season and the SWE (Collins et al., 2013;Brutel-Vuilmet et al., 2013;Räisänen, 2008;Gao et al., 2012;Wiltshire, 2014). Räisänen (2008) showed this to be the case in eastern Siberia and the northernmost part of North America. At the southern edge of the seasonal snow cover, relevant for this study, precipitation did not compensate, and there was a reduction in SWE. Wiltshire (2014) concluded that there would be small changes in snowfall in very cold and very warm regions of the HKH. Snowfall in Nepal, Bhutan and Himachal Pradesh, where winters are warmer than in most parts of the range, was most vulnerable to higher temperatures. The data presented in Section 4.2 generally support the previous studies.

One of the reasons that precipitation does not compensate, is that the highest projected precipitation increase in the HKH is seen in the summer, when the temperature today is so high that only the highest terrain is in the snow zone. Shifting the rain/snow line upward, even by only a few hundred meters, reduces the area that receives snow greatly, requiring very large increases in precipitation to compensate. The summer is the season with the largest relative reduction in snowfall in all the clusters

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described in Section 4.2. Except in the western upper Indus (cluster I4, Section 4.2.1), which has very little summer snowfall today, the reduction in summer snowfall is notable in all clusters in the MERRA data, in the Brahmaputra clusters also in APHRODITE.

The largest change in snowfall is seen in the western part of the Brahmaputra (cluster B4, Section 4.2.3), where a 400–500 meter upward shift in the rain/snow line during summer reduces the area with temperatures low enough for snowfall by a factor of 5–10 (Figure 13a iv, values not shown). As a result, the summer peak in the seasonal cycle of snowfall is replaced by a dip (Figure 13a ii). With an even distribution of precipitation with elevation, the area that still receives snow, would have to receive 5–10 times as much precipitation to compensate for the lost snowfall. Assuming, more realistically, that precipitation decreases above a certain height, would require an even higher increase in precipitation. In the model with the highest increase, a doubling of the July precipitation by the end of the century, SWE is less than 25 % of today's value in that month (Figure 13a iii).

With a winter-dominated precipitation cycle, the relative change in snowfall is smaller in the upper Indus than in the upper Brahmaputra. Downscaling a high-emission scenario (A1B) in two CMIP3 models with a regional model, Wiltshire (2014) found that by the 2080s, precipitation increased more than enough to compensate for higher temperatures in the Karakoram, Hindu Kush and Jammu & Kashmir in one of the models, the HadCM3. In the other model, ECHAM5, precipitation increased less, and snowfall increased only in the higher parts of the Karakoram. In our ensemble of CMIP5 models, multi-model mean precipitation in the upper Indus clusters increases mainly in the summer season, when the inter-model spread is also the largest (Figure 12a iii and Figure 12b iii). Among the models, 4–5 project increased winter precipitation in the upper Indus, and in the uppermost cluster, I5, this is associated with an increase in winter snowfall (Figure 12b ii).

Although it is the part of the HKH where snowfall is least reduced by increasing temperatures (Figure 11b), the Karakoram and inner parts of the upper Indus may still be the region where the changes have the largest impact on river run-off. Compared to the monsoon-dominated regions further east, there is little summer precipitation, and much of the water in the rivers during summer is meltwater (Bookhagen and Burbank, 2010;Immerzeel et al., 2010). As melting of snow and ice has not been analyzed in this study, we cannot quantify the effect of reduced snowmelt on river run-off, but it is obvious that eventually, reduced snowfall will lead to reduced melting. In western parts of the HKH, this may lead to changes in the seasonal cycle of the river flow.

As pointed out by Wiltshire (2014), increasing precipitation in the eastern HKH implies that water resources are likely to increase with climate change. As snowfall and snowmelt are both at maximum during summer (Rees and Collins, 2006), meltwater does not have the same importance for river flow in dry parts of the year as in the Indus. Reduced snowfall may reduce glaciers, but – not considering

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potential changes in the amount of evaporation – there is no indication that there will be less water coming from the upper Brahmaputra.

5 Concluding summary

In this study we have presented a suite of estimates of present-day snowfall in the Indus, Ganges and Brahmaputra Basins; and the changes in snowfall that would follow from CMIP5 projected changes in temperature and precipitation from 1971–2000 to 2071–2100. The results show that if the temperature increases as much as in the RCP 8.5, there will be much less snowfall, despite increasing precipitation in most of the region. Limiting anthropogenic forcing to the RCP 2.6 level would still cause reductions, though smaller.

Estimates of present-day snowfall based on a combination of temperature and precipitation from reanalysis data and observations, vary by factors of 2–4. The MERRA reanalysis gives higher estimates than TRMM 3B42, CRU TS and APHRODITE; but the spread is also large between the estimates based on the different observationally based data sets. This demonstrates the difficulties in assessing vulnerability to climate change in the region. With limited knowledge of the current state, future conditions are bound to be uncertain.

Future changes in temperature and precipitation projected by climate models can still provide an indication of the relative change in snowfall. With the RCP 8.5, the climate models project mean reductions in annual snowfall by 30–50 % in the Indus Basin, 50–60 % in the Ganges Basin and 50–70 % in the Brahmaputra Basin, by 2071–2100. With the RCP 2.6, the corresponding reductions would be 10–20 % in the Indus, about 20 % in the Ganges and 20–30 % in the Brahmaputra. The reductions are due to increasing temperatures, as the mean of the models show constant or increasing precipitation throughout the year in most of the region.

How much increasing temperatures reduce snowfall in a region, depends on how much of the terrain that is below and above the freezing point today, and on whether the terrain profile is such that the temperature increase transforms large areas from snow to rain zones. With the RCP 8.5, the mean elevation where rain changes to snow – the rain/snow line – creeps upward by 400–900 meters, in most of the region by 700–900 meters.

The largest relative change in snowfall is seen in the upper, westernmost sub-basins of the Brahmaputra, despite increasing precipitation and the lowest rain/snow line elevation change (400–500 m). This is because a major part of this region is near the freezing point today. With the RCP 8.5, most of this region will have temperatures above freezing, especially in the summer, which is the wettest part of the year. The projected reduction in annual snowfall is 65–75 %.

In the upper Indus, the effect of a warmer climate on snowfall is less extreme, as most of the terrain is high enough to have temperatures sufficiently far below freezing today. Winter and spring brings most of the precipitation, and the projected 600–800 m change in the rain/snow line elevation during these seasons, would leave most of the terrain below the freezing point. Still, a 20–40 % reduction in annual snowfall is projected with the RCP 8.5.

The range of our estimates of present-day snowfall illustrates how little that is known about conditions that influence the availability of drinking water in some of the most densely populated parts of the world. There is both a scientific and a societal need for more information about precipitation in the HKH. As a full-scale, long-time observational program covering all parts of the Himalayan range is not a likely possibility, the only hope for improved future knowledge of Himalayan snowfall lies in the improvement of satellite data and regional climate models.

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Merknad [3]: The following references have been added since the first version. I was not able to make Word track this change.
1) Guo et al. 2014
2) Hastings & Dunbar 1999

Tables

Table 1. Combinations of data types used in snowfall estimates. T: temperature, P: precipitation. f(P,T) indicates that snowfall is calculated as a function of P and T.

	Precipitation	Temperature	Snowfall	Time
MERRA			MERRA	Present
MERRA reference	MERRA	Terrain-adjusted MERRA	f(P,T)	Present
MERRA T2m	MERRA	MERRA T2m	f(P,T)	Present
Bias-corrected with obs. T	MERRA	Bias-corr. terrain-adj. MERRA	f(P,T)	Present
Bias-corrected with obs. P	Bias-corr. MERRA	Terrain-adjusted MERRA	f(P,T)	Present
Bias-corrected with obs. T, P	Bias-corr. MERRA	Bias-corr. terrain-adj. MERRA	f(P,T)	Present
CMIP5 T	MERRA	Terrain-adj. MERRA + ΔT	f(P,T)	Future
CMIP5 P	MERRA * ΔP	Terrain-adj. MERRA	f(P,T)	Future
CMIP5 T, P	MERRA * ΔP	Terrain-adj. MERRA + ΔT	f(P,T)	Future
Bias-corr. CMIP5 T	Bias-corr. MERRA	Bias-corr. terrain-adj. MERRA + ΔT	f(P,T)	Future
Bias-corr. CMIP5 P	Bias-corr. MERRA * ΔP	Bias-corr. terrain-adj. MERRA	f(P,T)	Future
Bias-corr. CMIP5 T, P	Bias-corr. MERRA * ΔP	Bias-corr. terrain-adj. MERRA + ΔT	f(P,T)	Future

Table 2. Data sets used in calculations of present-day snowfall.

Product	Time	Hor. res.	Description
MERRA	1979–2012	0.5° lat, 0,7°lon	Hourly atmospheric reanalysis data (Rienecker et al., 2011)
APHRODITE V1204/V1101	1979–2007	0.25 °	Daily temperature and precipitation based on observations (Yatagai et al., 2012;Yasutomi et al., 2011)
CRU TS 3.20	1979–2011	0.5 °	Monthly temperature and precipitation based on observations (Harris et al., 2014)
TRMM 3B42 V7	1998–2012	0.5 °	3-hourly satellite-based precipitation (Huffman et al., 2007)
GLOBE		1 km	Topography data set (Hastings and Dunbar, 1998)

Table 3. CMIP5 models and RCPs used (x) in calculations of 2071–2100 snowfall.

Model	RCP 2.6	RCP 8.5
CanESM2	x	x
CCSM4	x	x
CESM1-CAM5		x
CNRM-CM5		x
GFDL-CM3	x	x
GFDL-ESM2G	x	
GISS-E2-R	x	x
HadGEM2-ES	x	x
IPSL-CM5A-LR	x	x
IPSL-CM5A-MR	x	x
MIROC-ESM	x	x
MIROC-ESM-CHEM	x	x
MIROC5	x	x
MRI-CGCM3	x	x
NorESM1-M	x	x
NorESM1-ME	x	x

Table 4. Annual snowfall estimates for the Indus, Ganges, and Brahmaputra Basins. S: Snow [km^3 SWE]. P: Precipitation [km^3]. %S and %P: Percent of MERRA reference snowfall and MERRA precipitation. First horizontal section: no bias-corrections. Second, third and fourth section: bias-corrections with T, P and both T and P.

	Indus Basin				Ganges Basin				Brahmaputra Basin			
Input	S	%S	P	%P	S	%S	P	%P	S	%S	P	%P
MERRA reference	148	100	422	100	54	100	1147	100	119	100	733	100
MERRA	166	112	422	100	49	90	1147	100	129	109	733	100
MERRA T2m	154	104	422	100	42	77	1147	100	109	92	733	100
T APHRODITE	113	76	422	100	30	55	1147	100	74	62	733	100
T CRU	126	85	422	100	81	151	1147	100	109	92	733	100
P APHRODITE	66	44	315	75	22	42	1020	89	35	30	567	77
P TRMM	72	49	404	96	31	57	1244	108	63	54	835	114
P CRU	84	56	398	94	30	56	1100	96	53	45	716	98
P, T APHRODITE	49	33	315	75	12	22	1020	89	20	17	567	77
P APHRODITE, T CRU	62	42	315	75	34	63	1020	89	33	28	567	77
P TRMM, T APHRODITE	54	36	390	92	18	34	1195	104	39	33	815	111
P TRMM, T CRU	65	44	403	96	46	85	1254	109	58	49	813	111
P CRU, T APHRODITE	65	44	395	94	17	31	1106	96	31	26	718	98
P, T CRU	80	54	398	94	41	75	1100	96	49	42	716	98

Table 5. Projected change in annual snowfall from 1971–2000 to 2071–2100, with reference to terrain-adjusted MERRA and APHRODITE. ΔS_{abs} [km^3] is the absolute change, ΔS_{rel} [%] is the relative change compared to the present-day MERRA reference snowfall. Values are presented with the CMIP5 multi-model mean as the main value, and the span of individual models in brackets (MERRA only). ΔTP indicates that changes in both temperature and precipitation are included, whereas ΔP and ΔT denotes changes only in precipitation or temperature, respectively.

		Indus		**Ganges**		**Brahmaputra**	
		ΔS_{abs} [km^3]	ΔS_{rel} [%]	ΔS_{abs} [km^3]	ΔS_{rel} [%]	ΔS_{abs} [km^3]	ΔS_{rel} [%]
RCP 8.5	MERRA, ΔTP	-49 [-83/-9]	-33 [-56/-6]	-27 [-36/-14]	-50 [-66/-25]	-64 [-93/-39]	-54 [-79/-33]
	MERRA, ΔT	-51 [-67/-34]	-34 [-45/-23]	-28 [-34/-21]	-51 [-64/-39]	-71 [-87/-53]	-60 [-73/-44]
	MERRA, ΔP	5 [-25/44]	4 [-17/30]	7 [-4/17]	12 [-7/31]	20 [-17/50]	17 [-15/42]
	APHRO, ΔTP	-25	-51	-7	-56	-13	-67
	APHRO, ΔT	-25	-52	-7	-57	-14	-71
	APHRO, ΔP	1	1	1	6	3	16
RCP 2.6	MERRA, ΔTP	-15 [-40/6]	-10 [-27/4]	-10 [-19/-3]	-18 [-36/-5]	-25 [-42/-5]	-21 [-35/-4]
	MERRA, ΔT	-18 [-27/-9]	-12 [-18/-6]	-12 [-21/-6]	-21 [-39/-11]	-29 [-47/-13]	-25 [-40/-11]
	MERRA, ΔP	3 [-18/25]	2 [-12/17]	3 [-2/10]	5 [-4/19]	7 [-8/28]	6 [-6/23]
	APHRO, ΔTP	-9	-18	-2	-20	-6	-29
	APHRO, ΔT	-10	-19	-3	-23	-6	-32
	APHRO, ΔP	1	1	0	4	1	6

Figure captions

Figure 1. Map of the region, with the Indus, Ganges and Brahmaputra basins outlined in white. Thinner outlines are national borders. Background: NASA Visible Earth.

Figure 2. Procedure for elevation-adjustment of MERRA temperature. a) Comparison of MERRA and NOAA GLOBE (reduced to 4 km resolution) topography along 75 °E from 30 to 40 °N. b) Enlargement of the marked sub-section in (a), demonstrating the variables in equation (2). z_{globe} is the height of the topography in GLOBE, $z_{merra,0}$ that of MERRA and Δz_0 the difference between the two. z_1 is the height of the MERRA pressure level that is closest to the ground, and z_2 the height of the next pressure level above this. T_0 is the 2 m temperature in MERRA and T_{adj} the final, adjusted temperature. $\Delta T/\Delta z$ is the vertical temperature gradient in the layer between z_1 and z_2. This is combined with Δz_0 to adjust the MERRA temperature (T_0) from the MERRA elevation to the NOAA GLOBE elevation (T_{adj}).

Figure 3. Monthly mean MERRA precipitation and MERRA reference snowfall in sub-basin clusters of the Indus (I), Ganges (G) and Brahmaputra (B). Total bar height: MERRA precipitation (P) [mm]. Colored bars: Snowfall (S) [mm SWE] based on MERRA precipitation and terrain-adjusted MERRA temperature, in the region with the same color. Cluster 1 in each basin is considered snow-free, and the seasonal cycles are not shown. All subplots have the same scale.

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Figure 4. The effect of bias-corrections with APHRODITE temperature and precipitation. a) MERRA reference snowfall. b) Snowfall based on bias-corrections with APHRODITE c) APHRODITE (b) minus MERRA reference snowfall (a).

Figure 5. Difference between MERRA precipitation and observation-based data. a) Annual mean MERRA precipitation. b, c, and d) Annual mean MERRA precipitation bias-corrected with observations: APHRODITE, CRU TS and TRMM 3B42. For each data set, the small, inset maps show the observations minus MERRA.

Figure 6. Difference between MERRA temperature and observation-based data. a) Annual mean MERRA temperature. b and c) Annual mean MERRA temperature bias-corrected with observations: APHRODITE and CRU TS.

Figure 7. Regions where increasing temperatures are likely to cause a shift from snow to rain. Data: Monthly mean MERRA temperature, terrain-adjusted to a 4 km GLOBE grid. Red: Temperature between -5 and 0 degrees, considered critical. Small, inset maps: Monthly MERRA precipitation in the critical zones.

Figure 8. Projected future temperature change from 1971–2000 to 2071–2100 in the a) Indus, b) Ganges, and c) Brahmaputra Basins. Thin lines show the individual CMIP5 models, stronger lines the multi-model mean.

Figure 9. Projected future precipitation in the a) Indus, b) Ganges, and c) Brahmaputra Basins. Gray bars: MERRA 1979–2008. Thin lines and horizontal marks on the bars show the individual CMIP5 models and the multi-model mean for 2071–2100.

Figure 10. Projected future snowfall in the a) Indus, b) Ganges, and c) Brahmaputra Basins, with reference to MERRA reference snowfall. Gray bars: MERRA reference snowfall for 1979–2008. Thin lines and horizontal marks on the bars show the individual CMIP5 models and the multi-model mean for 2071–2100, based on changes in temperature and precipitation, as described in Section 2.3.

Figure 11. Projected future changes in snowfall in sub-basins of the Indus, Ganges, and Brahmaputra Basins. a) Absolute change [km^3] with reference to MERRA reference snowfall. b) Absolute change [km^3] with reference to APHRODITE snowfall. c,d) Corresponding relative changes [%] with reference to MERRA and APHRODITE.

Figure 12. Monthly CMIP5 RCP 8.5 change in snowfall, precipitation and rain/snow line elevation in the upper Indus clusters 4 (a) and 5 (b), from 1971–2000 to 2071–2100, with reference to the MERRA reference (red) and APHRODITE (blue). CMIP5 multi-model means are shown as horizontal marks, individual models as dots. Cluster location and terrain profile are shown above the graphs. (i) Fractional change in snowfall. (ii) Future snowfall [km^3] (dots) compared to today (bars). (iii) Future precipitation [km^3] (dots), compared to today (bars). Snowfall today is shown as darker parts of bars. (iv) Rain/snow line elevation [m a.s.l.]. Gray background: elevation histogram with the % of total ground area lying in the marked 2000-m intervals. Bars: change from today (bottom) to CMIP5 multi-model mean (top).

Figure 13. Monthly CMIP5 RCP 8.5 change in snowfall, precipitation and rain/snow line elevation in the upper Brahmaputra clusters 4 (a) and 3 (b). See Figure 12 for a description of the content.

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Slettet: Figure 11