Climate change and water in south Asia

Overview and literature review

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## Abbreviations and acronyms

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<tbody>
<tr>
<td>AIR</td>
<td>All India Rainfall</td>
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<tr>
<td>APHRODITE</td>
<td>Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of water resources</td>
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<tr>
<td>AR4, AR5</td>
<td>Assessment Report 4, 5 (of the IPCC)</td>
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<tr>
<td>CMIP</td>
<td>Coupled Model Intercomparison Project</td>
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<td>CORDEX</td>
<td>Coordinated Regional Climate Downscaling Experiment (<a href="http://www.cordex.org">www.cordex.org</a>)</td>
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<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
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<td>EDW</td>
<td>Elevation Dependent Warming</td>
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<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
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<tr>
<td>ERA-40</td>
<td>ECMWF Re-Analysis</td>
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<td>ET</td>
<td>Evapotranspiration</td>
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<tr>
<td>GCM</td>
<td>Global Climate Model (also General Circulation Model)</td>
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<td>HKH</td>
<td>Hindu-Kush Himalaya</td>
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<td>HKK</td>
<td>Hindu-Kush Karakoram</td>
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<tr>
<td>HKKH</td>
<td>Hindu-Kush Karakoram Himalaya</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>ISM</td>
<td>Indian Summer Monsoon</td>
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<td>ISMR</td>
<td>Indian Summer Monsoon Rainfall</td>
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<td>LULCC</td>
<td>Land use and land cover change</td>
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<td>MME</td>
<td>Multi-Model Ensemble</td>
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<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
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<td>NAO</td>
<td>North Atlantic Oscillation</td>
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<td>RCM</td>
<td>Regional Climate Model</td>
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<td>RCP</td>
<td>Representative Concentration Pathway</td>
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<td>SA</td>
<td>South Asia</td>
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<td>SCA</td>
<td>Snow Cover Area</td>
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<td>SDIP</td>
<td>Sustainable Development Investment Portfolio</td>
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<td>SOI</td>
<td>Southern Oscillation Index</td>
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<td>SRM</td>
<td>Snow Runoff Model</td>
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<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
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<td>TRMM</td>
<td>Tropical Rainfall Monitoring Mission</td>
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<td>UIB</td>
<td>Upper Indus Basin</td>
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<tr>
<td>WD</td>
<td>Western Disturbance</td>
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<td>WWF</td>
<td>World Wildlife Fund</td>
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Key points

- South Asian climate has strong spatial gradients and seasonality due to its extreme orography (Himalayas) interacting with Indian and eastern monsoons and westerly climate systems.
- Hydrological responses vary across the region given differences in streamflow sources from north-west (glacier and snowmelt dominated) to east and south (rainfall dominated).
- Projected increases in intensity of future heavy precipitation events will have considerable impact, particularly on extreme flood risk.
- Warming is evident across the region. Faster rates of temperature increase are found at higher altitudes and in the winter.
- Observed precipitation trends are inconsistent, driven by natural variability (ENSO and NAO), global warming related circulation changes and regional aerosol (Asian brown cloud) effects. Observed monsoon rainfall declines since the mid-20th century have been attributed to increased aerosol loads.
- Future projections indicate continued warming, however precipitation changes are less certain. Most GCMs project increased monsoon precipitation driven by atmospheric-oceanic circulation associated with global warming and reductions in aerosol concentration.
- Confidence in modelled hydrological response is low due to climate projection uncertainties, data limitations, and limited understanding of the complex interactions and feedbacks between flow generation processes and glaciers, precipitation (rainfall and snowfall and their timing) and temperature.
- Peak flow sourced from high altitudes is projected to occur earlier as warming influences both snow cover area and snow and glacier melt rates.
- RCM climate downscaling has been widely applied across South Asia, however the RCMs do not generally reproduce the observed temperature or precipitation trends, nor necessarily reduce the projection uncertainties.
- Climate change impact studies should consider the full range of projections from GCMs (e.g. SDIP climate change database from analyses of 42 CMIP5 GCMs) as well as regionally focussed RCM modelling. The uncertainty in the future climate projections must be interpreted in the context of the hydrological modelling and climate change adaptation studies.
Summary

South Asia is characterised by strong climate gradients from the south to north and the west to east, together with high seasonal and year to year variability. Two main climate drivers, the westerlies (western disturbances) and the monsoon (Indian summer monsoon and to a lesser extent eastern monsoon), interact with the extreme orography of the Himalayas to produce the observed spatial and temporal climatological variability. Thus the hot, wet and tropical south contrasts with the cold, arid and mountainous north. The monsoon impacts the whole region, providing a larger contribution to annual precipitation in the east whilst the north-west is dominated by westerlies where precipitation is predominantly snowfall in the winter and spring.

The interaction between climate drivers and orography results in variation in hydrological processes, with the rivers of the north and north-west dominated by glacier and snowmelt sources whereas the southern and eastern rivers are rainfall dominated. Thus hydrological response to climate variability and trends varies from west to east and with elevation. Changes in the flow of the glacier and snowmelt dominated north-western rivers (e.g. Indus) will be impacted by changes in western disturbances, and their interactions with the monsoon. Temperature changes influence increased contribution from glacier melt and the changing partition of precipitation between snow and rain, resulting to changes in both magnitude and seasonality of flow. In contrast, flow changes in the southern and eastern rivers (e.g. Brahmaputra) will be impacted predominantly by changes to the Indian summer monsoon strength, length and seasonality. Additional stresses will result from future increases in the intensity of extreme precipitation in a warming climate.

Historical warming trends are evident across South Asia. Studies have found winter temperatures to be increasing faster than summer temperatures. Warming rates are also greater at higher elevations (elevation dependant warming) with a positive feedback as warming reduces snow cover, reducing surface albedo and hence warming more. All future projections indicate warming will continue.

Observed precipitation trends are not consistent, varying from region to region and between seasons. Long term decreasing total monsoon rainfall trends are evident over recent decades with several studies suggesting the role of aerosols (localised cooling due to the ‘Asian brown cloud’). However, the large majority of GCM projections (CMIP3 and CMIP5) suggest increased South Asian total monsoon rainfall as the century progresses, although on a regional basis projections are less consistent. A caveat relates to the reduction of aerosol concentrations in CMIP5 scenarios, as increasing precipitation may not occur if aerosol emissions do not decline as assumed in the driving scenarios. Practically all studies indicate that extreme rainfall will be more intense enhancing flood risks.

Hydrological modelling of the flow response to projected climate changes varies west to east as the dominance of glacier contribution to flow decreases. The non-linear flow response to warming and precipitation changes are complex as increased glacier melt can compensate for reduced snow melt and increased monsoon season precipitation can compensate for reduced snow accumulation in winter and spring. Several studies indicate increased flow in eastern basins due to increased rainfall and in north-western basins due to accelerated glacier melt. Glacier retreat,
while initially increasing flow (for several decades) will in the long term result in decreased flow, increasing the importance of precipitation derived flow. Timing of maximum discharge is projected to move earlier in the year due to reduced snowpack combined with earlier glacier melt, due to warmer conditions both enhancing melting and resulting in more precipitation falling as rain rather than snow.

Downscaling has been promoted as providing better understanding and quantification of the regional responses to climate change, particularly given the strong orographic effect in the Himalayan upper basins where most of the flow is produced. However, biases in RCM downscaling simulations are not necessarily less than those of their host GCMs. For example, four RCMs produced differing precipitation amounts and regional distributions with boundary conditions forced by ERA-40, suggesting important feedbacks and processes are still poorly simulated or unaccounted for in the downscaling models. The lack of irrigation in the RCMs is proposed as a cause of precipitation bias, as large scale irrigation (as undertaken in Pakistan and India) cools the land, with the resulting change in temperature gradients impacting regional circulation and hence precipitation. Even the latest RCM (CORDEX) simulations do not capture the observed ISM precipitation decline or the correct magnitude of observed warming, calling into question their suitability for projecting impacts on water resources.

Climate change impact studies should therefore consider the full range of projections from GCMs as well as regionally focussed RCM modelling. The uncertainty in the projections must be adequately represented in the context and objectives of the hydrological modelling and integrated water resources management studies. The SDIP climate change database (Zheng et al., 2015) provides projected future changes to monthly, seasonal and annual temperature, potential evaporation and precipitation for 0.5° grids across South Asia simulated by the 42 CMIP5 GCMs.
1 Introduction

Figure 1 presents the spatial extent of the Sustainable Development Investment Portfolio (SDIP) study region, highlighting the locations of the basins under investigation. The South Asian climate is dominated by the summer monsoon as the main source of annual precipitation (Pant and Kumar, 1997). While this is the case for most of the region, the north-west (e.g. Upper Indus Basin) climate is strongly influenced by western disturbances, with monsoon precipitation a secondary contributor (Dimri et al., 2015). Thus changes in both the monsoon and western disturbances will directly impact South Asian water resources. Additionally, monsoon variability has a strong impact on hydrological response through its influence on mean daily temperatures and vapour pressures, incoming short-wave and long-wave radiation, precipitation frequency, and on wind speeds and directions. Changes in future monsoon onset, duration and intensity will thus not only impact direct hydrological response to precipitation but also glacier melt and accumulation processes (Shea et al., 2015).

Figure 1 Study region and basins
2 Whole of region studies

Ahmed and Suphachalasai (2014) report on regional climate modelling (RegCM4 nested in ECHAM5 and MRI) undertaken for the whole South Asia domain at a resolution of 30 km for IPCC AR4 scenarios A2, A1B and B1 for the 2030s, 2050s and 2080s. They concluded steadily progressing warming will be widespread across the region with increases of 4°C to 5°C by the 2080s for the A2 scenario. Precipitation increases were projected for eastern and northeastern areas for the monsoon season, becoming an identified signal only toward the end of the century. The drier winter months see smaller projected changes or decreasing trends.

Biemans et al. (2013) assessed current and future agricultural water requirements for five South Asian basins (Indus, Ganges, Brahmaputra, Godavari and Krishna), focussing on whether improved irrigation efficiency and/or increased reservoir storage capacity can address projected water scarcity. Their future scenarios are from two RCMs (HadRM3 and REMO) driven by two CMIP3 GCMs (HadCM3 and ECHAM5) for the historical period 1971-2000 and the A1B scenario for 2036-2065. They concluded additional storage would benefit the Godavari and Krishna basins but would not reduce water scarcity in the Ganges and Indus. Increasing irrigation efficiency would benefit all basins, more so in the Indus and Ganges as it would reduce reliance on groundwater and storages.

Savoskul and Smakhtin (2013) reviewed the status of meltwater (glacier runoff and seasonal snowmelt runoff) resources across the major river basins of South Asia (Indus, Ganges, Brahmaputra, Syr Darya, Amu Darya and Mekong) for baseline (1961-1990) and current (2001-2010) periods, as well as assessing likely future changes. They defined ‘glacier runoff’ as the combined discharge from ice melt, snowmelt and rainwater of an ice-covered area (noting rainwater contribution on ice areas is negligible). Seasonal snowmelt contributes to flow typically over half a year or more, starting several months earlier than glacier melt. The snowmelt period is longer than the glacier melt period as snowmelt occurs across a wider range of elevation bands, with seasonal peaks that progress from lower to higher elevations. Typically, maximum snowmelt contribution occurs 2-3 months prior to maximum glacier contribution. Glacier melt contributes to river flow for 2-3, maximum 4 months, mainly from early/mid-summer, till late summer/early autumn and reaches its maximum in July-August. Glaciers and seasonal snow were found to be of negligible contribution to flow in the Mekong Basin (<1%) and insignificant for the Ganges and Brahmaputra basins (7% and 3%, respectively). In the Indus Basin, meltwater contributed around 35-40% to the total flow with seasonal snowmelt and glacier runoff share being approximately equal. From 1961-1990 to 2001-2010, meltwater components decreased by 6-25% in all the basins, apart from Mekong where snowmelt increased by 30% due to a slight increase in the snow cover extent. Meltwater contribution to annual flow decreased at the same time by 5% in the Indus. Regarding future climate change, they state precipitation regimes changes coupled with effects of temperature rise on evapotranspiration will impact future hydrological regimes much more significantly than changes to glacier and seasonal snow extent (changes to which will result mainly in changes to flow seasonality).

A report by WWF (2014) highlights the importance of change to extremes, stating regional studies have shown that in monsoon dominated Himalayan catchments a single extreme weather event
can account for as much as 10% of a catchment’s yearly water intake. Up to 50% of yearly rainfall can occur within a 10-day period in monsoon regions (Bookhagen, 2010; Dahal and Hasegawa, 2008; Wulf et al., 2010).
3 Regional historical trends

There is strong evidence that many parts of South Asia are experiencing long-term warming trends (Hijioka et al., 2014). Bhutiyani et al. (2007) analysed long-term temperature trends in the Northwestern Himalaya region of India for three stations (Srinagar and Shimla for 1901–2002 and Leh for 1901–1989) together with winter temperature records for seven additional stations in the region for the last three decades. The long-term warming was found to be 1.6°C over the last century, with winters warming at a faster rate and a concurrent significant increasing trend in diurnal temperature range (i.e. maximum temperature rising faster than minimum temperature). Anomalous warming began in the late-1960s and has rapidly increased over the past two decades. An earlier study by Shrestha et al. (1999) investigated maximum temperature trends for 49 stations in Nepal for the 1971 to 1994, finding higher rates of warming since 1977 for high elevation stations and lower warming rates or even cooling in lower elevation southern Nepal.

The Mountain Research Initiative (2015) reviewed the growing evidence that warming at higher elevations is occurring at a faster rate than lower elevations in many mountain ranges globally. This elevation dependent warming (EDW) is potentially caused by many factors including snow albedo and surface-based feedbacks; water vapour changes and latent heat release; surface water vapour and radiative flux changes; surface heat loss and temperature change; aerosols; and interannual to decadal variability in large-scale circulation. Most modelling studies that show EDW suggest snow-albedo feedback as a likely mechanism (i.e. retreating snowline).

Rainfall trends are less consistent, varying from region to region, however a weakening of the summer monsoon is seen in observational studies for recent decades (Dash et al., 2009). Annamalai et al. (2013) assessed the role of increasing SST trends on South Asian precipitation changes. Investigating historical trends, they find All-India Rainfall (AIR) shows a steady decline since the early 1950s, breaking previous multi-decadal periodicity. They conclude that SST trends (warming over the tropical western Pacific) together with the effect of aerosols have caused an east-west shift (enhanced rainfall over tropical western Pacific and decreased rainfall over South Asia) that has amplified drying over South Asia since the 1960s and this trend is anticipated to continue. Correspondingly, Varikoden and Babu (2015) find that a previously highly significant correlation between ISMR and southwest Pacific SST has markedly degraded since the 1980s.

Early monsoon rainfall increases concurrent with decreases in the main monsoon season are linked to the impact of aerosols in several studies (Gautam et al., 2009; Lau and Kim, 2010). Trends in the northwest regions, that are influenced by western disturbances, are mostly inconsistent with some evidence of winter increases (Archer and Fowler, 2004; Bhutiyani et al., 2010; Bocchiola and Diolaiuti, 2013; Hasson et al., 2015; Khattak et al., 2011). Dimri and Dash (2012) note western Himalayan winter (DJF) precipitation shows slightly decreasing, though inconsistent, trends for the 1975 to 2006 period with increasing temperatures that could result in a shift from solid to liquid precipitation, potentially decreasing snow cover area – thus reducing snowmelt flow in the summer season.

Kumar et al. (2015) investigated the temporal variability of WDs influencing winter (December to March) precipitation over Himachal Pradesh (northern India) for 1977 to 2007. They found a
significant decreasing trend in the frequency of WDs over the region, resulting in decreasing trends in total winter precipitation, frequency of wet and rainy days, moderate and heavy precipitation days, but no trend in precipitation intensity. Madhura et al. (2015) also assessed changes in western Himalayan winter and spring (DJFMA) precipitation related to WDs in the historical record and concluded whilst there was no long-term (1951-2006) trend in mean precipitation there has been an increase in precipitation extremes (90th percentile) related to increased WD activity.
4 IPCC Fifth Assessment Report

The fifth assessment report (AR5) of the IPCC (Hijioka et al., 2014) summarises observed and projected climate change on a regional basis. Its findings for South Asia are summarised as follows.

Observed Climate Change:

- Increasing annual mean temperature trends at the country scale have been observed during the 20th century in Afghanistan, Bangladesh, India, Nepal, Pakistan and Sri Lanka.
- Seasonal mean precipitation shows inter-decadal variability with an overall declining trend and more frequent deficit monsoons, with regional inhomogeneities. The frequency of heavy precipitation events has increased, while light precipitation events have decreased.
- Over India, the increase in the number of monsoon break days and the decline in the number of monsoon depressions are consistent with the overall decrease in seasonal mean precipitation. An increase in extreme precipitation events has occurred with concurrent reduction in weaker precipitation events over the central Indian region and surrounding areas.

Projected Climate Change:

- CMIP5 simulations under all four Representative Concentration Pathway (RCP) scenarios indicate warming is very likely for all land areas of Asia in the mid- and late-21st century.
- Mean annual temperature changes are projected to exceed 3°C above a late-20th-century baseline from the mid-21st century under RCP8.5. Projected changes are less than 2°C in both the mid and late-21st century under RCP2.6.
- Precipitation increases are very likely over southern Asia by the late-21st century under the RCP8.5 scenario. Under the RCP2.6 scenario it is likely that changes at low latitudes will not substantially exceed natural variability.
- There is low confidence in region-specific projections of frequency and intensity of tropical cyclones. Precipitation will likely be more extreme near the centres of tropical cyclones making landfall.
- There is medium confidence that a projected poleward shift in the North Pacific storm track of extratropical cyclones is more likely than not. There is low confidence in the magnitude of regional storm track changes and the impact of such changes on regional surface climate. [From this, it follows that changes to westerlies influencing the source of precipitation for the UIB snowpack are uncertain.]
- There is medium confidence in Indian summer monsoon precipitation increase in the future. Model projections diverge on smaller regional scales.

Future increases in precipitation extremes related to the monsoon are very likely. All CMIP5 models and all scenarios project an increase in Indian summer monsoon mean and extreme precipitation. The interannual standard deviation of seasonal mean precipitation also increases in the projections, indicating enhanced variability.
5 GCM historical performance and projections

Kripalani et al. (2007) assessed 22 CMIP3 GCMs (as used in AR4) for their ability to reproduce observed South Asian summer monsoon precipitation (timing of monsoon precipitation maximum, mean precipitation amount, inter-annual variability, and long term trends). Climate change projections (doubling CO2 scenario) were examined for the six GCMs with the most realistic monsoon climatology. Monsoon precipitation changes from these selected GCMs ranged from increases of 2.9% to 16.6%, with a mean increase of 8%. Increases of up to 20–24% were projected for the Arabian Peninsula, adjoining regions of Pakistan, northwest India and Nepal. Both extreme excess and deficit monsoons were projected to intensify. Kripalani et al. (2007) suggest that increased moisture advection from the Bay of Bengal and Arabian Sea is the main mechanism producing the increased monsoon precipitation, attributed to intensification of the heart low over northwest India, in turn attributed to a projected decrease in snowfall over western Eurasia and the Tibetan Plateau concurrent with increasing winter snowfall of eastern Eurasia and Siberia.

Kumar et al. (2011) reviewed historical and projected Indian monsoon precipitation and temperature. Historical variations were assessed using All-India monthly rainfall and maximum and minimum temperature, with satellite estimates of rainfall (Xie and Arkin, 1997) and gridded monthly temperature (HadCRU3v) used to allow inclusion of adjacent oceans. Projections were from 22 CMIP3 GCMs for the A1B scenario to 2100, as well as 1961-90 and 2071-2100 time-slice results from the regional model PRECIS over India nested in the Hadley Centre’s GCM for the A2 scenario. Temperature increases were projected with confidence however precipitation projections were highly uncertain, indicating moderate increases over the monsoon season (ensemble mean 8 to 10% increase by 2100). PRECIS projected increased extreme precipitation amounts, with a concurrent reduction in the number of wet days and increase in intensity over many parts of India.

Chaturvedi et al. (2012) investigated all of India temperature and precipitation projections from 18 CMIP5 GCMs. The GCMs were assessed on the basis of their ability to reproduce current climate mean climatology, but not on their ability to reproduce trends. The projected ensemble mean warming for the 2080s, relative to the 1880s, ranged from 2 °C to 4.8 °C, for RCP2.6 and RCP8.5 respectively. Projected ensemble mean precipitation for the 2080s, relative to a 1961-1990 baseline, increased by 6%, 10%, 9% and 14% for RCP2.6, RCP4.5, RCP6.0, and RCP8.5 respectively. They also looked at projected changes in extreme daily rainfall for one GCM (MIROC-ESM-CHEM) selected on the basis of its Indian region precipitation climatology. Increased rainfalls over extreme daily thresholds (e.g., 40 mm/day) were projected for the 2060s onwards for RCP4.5, relative to an 1861-1870 baseline.

In a global study of changes to heavy precipitation events, Scoccimarro et al. (2013) assessed CMIP5 (20 GCMs, RCP8.5) projected changes in difference between the 90th and 99th percentile daily precipitation (i.e. widening of the upper right tail). Regions where the projected increases were found to be greatest included India, southern China and Southeast Asia, with the difference increasing by 10 mm/day for 2061-2100 relative to 1966-2005. Deshpande and Kulkarni (2015), focussing on 1-day duration 5 cm or greater rainstorms covering at least 40,000 km² of the Indus...
Basin within India, found PRCIS RCM simulations under CMIP3 projected future increases in intensity and decreases in frequency.

Turner and Annamalai (2012) reviewed the current understanding of, and ability of GCMs to simulate, South Asian summer monsoon rainfall. They found mean future projections for increased rainfall were in agreement with present physical understanding. They also suggested future interannual variability will increase, while noting intraseasonal processes (breaks and extreme rainfall) are currently poorly simulated. They suggested the large increasing trend in aerosol concentrations over South Asia may be inhibiting the emergence of greenhouse-forced increasing seasonal monsoon rainfall. They also noted land-cover changes may have influenced regional precipitation changes.

Jourdain et al. (2013) analysed and selected 10 CMIP5 GCMs based on their ability to reproduce observed summer monsoon mean rainfall, amplitude of interannual variability, seasonal cycle, monsoon-ENSO, and monsoon-IOD relationships. Their RCP8.5 projections simulated increased summer monsoon rainfall for India and South Asia (for 9 out of the 10 GCMs) of 5 to 20% increases for 2050-2099 relative to the pre-industrial period. Most of the Indian increase occurs over the Himalayas.

Kitoh et al. (2013) assessed future projections of monsoon precipitation over land for 29 CMIP5 GCM globally. They found an overall increase of monsoon precipitation (area and intensity) over land, predominantly due to increases in convergence of moisture flow, even though the Asian summer monsoon circulation may weaken. In another global study, Seth et al. (2013) also found increased moisture convergence and precipitation in late summer in all monsoon regions, in their examination of CMIP5 projected changes to the annual cycle of monsoon region precipitation. Menon et al. (2013) found all 20 CMIP5 GCMs investigated projected an increase in Indian summer monsoon rainfall under the RCP8.5 scenario by the end of the century. They also reported a projected increasing trend in interannual variability.

Sperber et al. (2013), in comparing CMIP3 to CMIP5 simulations of the Asian monsoon, found both have systematic biases of too late onset and poor representation of the annual cycle of the Indian monsoon. They suggested five better performing GCMs, across the CMIP3 and CMIP5 models, for Indian monsoon performance. Ramesh and Goswami (2014) noted no improvement between CMIP3 and CMIP5 in simulating observed features of continental Indian monsoon mean and trend.

Ogata et al. (2014) assessed Asian monsoon historical performance and compared projections for 20 CMIP3 and 24 CMIP5 GCMs. They found CMIP5 GCMs better reproduced Asian summer monsoon rainfall and 850 hPa zonal winds compared to CMIP3. Projections from both CMIP3 and CMIP5 (2081-2100 for A1B and RCP4.5, respectively) indicated rainfall increases whereas, paradoxically, monsoon circulation over the northern Indian Ocean was weaker in CMIP3 but stronger in CMIP5 simulations.

Salzmann et al. (2014) emphasised the impact of aerosols in modelled Asian summer monsoon precipitation trends in historical and projected CMIP5 simulations. They note "In spite of the recent scientific progresses, the observed overall trend of precipitation in the Asian summer monsoon region shows a rather complex regional pattern ... that remains difficult to explain, especially since projections from individual climate model simulations generally show little agreement regarding the regional distribution of rainfall trends." The modelling study by Salzmann et al. (2014) determined that aerosol cooling has had a greater impact on summer monsoon
circulation during the second half of the 20th century than greenhouse-gas warming, thus contributing to the observed decreasing mean precipitation trend. Focussing on north central India, they found 1950-1990 precipitation trends were influenced by both aerosols and internal variability, finding it unlikely that the observed drying trend was independent of an aerosol influence. They also found the spread across realisations from an individual model was as large as the spread between models, suggesting “that internal variability can restrict the prediction of regional scale multidecadal precipitation trends even under a fairly strong forcing.”

Srivastava and DelSole (2014) concluded that South Asian summer monsoon precipitation is robustly projected (23 CMIP5 GCM’s RCP8.5 JJAS mean rainfall) to increase due to anthropogenic climate change. They found the response to anthropogenic change emerged from internal variability by the middle of the 21st century, with more uncertainty at the regional scale (at the scale of countries, e.g. India, models may disagree even on the sign of change).

Freychet et al. (2015) assessed projected ensemble-averaged mean and extreme precipitation change of 30 CMIP5 GCMs for their RCP8.5 simulations. With moderate confidence, more intense and frequent extreme precipitation was projected for the Indian region due to changes in atmospheric moisture content and circulation.

Sharmila et al. (2015) assessed Indian summer monsoon daily-to-interannual variability changes, as projected by 20 CMIP5 models, comparing simulations for the historical period (1951-1999) to those projected for the RCP8.5 pathway for the future (2051-2099). Based on ability to simulate historical variability, a subset of four models (BNU-ESM, MPI-ESM-LR, MIROC5 and NorESM1-M) were selected and their projections indicate all-India summer monsoon rainfall magnitude will increase together with a lengthening of the season due to later monsoon withdrawal. Intensity and frequency of both strong and weak monsoons are projected to increase. Daily variability changes indicate increases in heavy rainfall events (>40 mm/day) and decreased low rain-rate events (<10 mm/day) and wet day frequencies. Additionally, enhanced propensity for shorter active and longer break spells is projected.

Mei et al. (2015) analysed a suite of CMIP5 GCMs to understand the mechanisms behind the projected net increase in South Asian summer monsoon precipitation extent and intensity during the twenty-first century. They suggest warmer temperatures increase atmospheric moisture content, overwhelming weakening monsoon circulation, thus increasing both moisture convergence and summer monsoon precipitation over South Asia. Their results also indicate that historic measures of the monsoon dynamics may not be well suited for prediction of the nonstationary moisture-driven South Asian summer monsoon precipitation response in the twenty-first century.

Saha et al. (2014) determined that the majority of the 42 CMIP5 GCMs assessed failed to reproduce the observed post-1950 decreasing trend in Indian Summer Monsoon Rainfall (ISMR). They assessed the GCMs against two hypothesised drivers of the observed ISMR decline (Annamalai et al., 2013; Chung and Ramanathan, 2006). The GCMs underestimated the Southern Indian Ocean (SIO) surface warming that weakens the north-south SST gradient that in turn weakens the Hadley circulation, hence reducing the ISMR. The GCMs also greatly underestimated trends in western Pacific MSLP reduction that results in weakened monsoon circulation. Also, not all of the GCMs that reproduced the SIO SST and Pacific MSLP trends reproduced the correct ISMR trend, indicating that additional short-comings are degrading their performance. They concluded
that the selection of which GCMs to include in multimodel projections for climate adaptation should carefully assess their performance, particularly given that the majority of CMIP5 GCMs project increased monsoon rainfall in contrast to the observed trends.

Palazzi et al. (2015) assessed 32 CMIP5 GCMs for their ability to reproduce the observed 1901-2005 precipitation climatology (mean and trend) of the Hindu-Kush Karakoram (HKK) and the Himalaya regions. Given the drivers of regional precipitation seasonality, they focussed on two seasons – the winter season (DJFMA) of relevance to HKK westerly sourced winter and spring precipitation and the summer season (JJAS) relevant to the monsoon precipitation of the more eastern Himalaya. They determined it was difficult to select better performing models as none reproduced all features, i.e. annual cycle as well as seasonal precipitation trend. They also assessed precipitation changes for RCP4.5 and RCP8.5 for 2021–2015 and 2071–2100, relative to 1971–2000. Noting the robust finding that all models indicate an increase in summer (i.e. monsoon) precipitation for the Himalaya, they however caution against using projections with confidence given the limitations for historical-period performance. They particularly caution against relying on the multi-model ensemble mean given the wide spread of projected changes.

Sabeerali et al. (2015) also caution against using multi-model ensemble projections as they found most CMIP5 GCMs produce too much convective precipitation and too little stratiform precipitation when compared to observed ISMR. They suggest, instead, that more reliable projections can be obtained by selecting GCMs that can reproduce important characteristics of the south Asian monsoon such as (a) the decreasing trend over the last six decades, (b) the biennial tendency, (c) the amplitude of observed interannual variation, (d) 50–80 year multi-decadal mode of variability and (e) the ENSO-monsoon teleconnection. However they find all CMIP5 GCMs investigated produced unrealistic ISMR projections due to excessive convective relative to stratiform precipitation and so recommend improved cloud microphysics formulations are required before projections will be reliable.

Li and Ting (2015) compare the observed ENSO-monsoon relationship to that modelled by CMIP5 GCMs. They suggest the ability of GCMs to simulate a similar correlation and variability as observed could be used as a basis for selecting GCMs. Running correlations show prominent decadal variability of the ENSO-monsoon relationship in observations. The role of natural variability dominates the ENSO‐monsoon relationship variations during the 20th century. In the 21st century, the forced component is dominated by enhanced monsoon rainfall associated with SST warming, which may contribute to a slightly weakened ENSO-monsoon relation in the future.

Several recent papers have assessed the role of aerosols on historical and projected monsoon rainfall over South Asia. Sanap et al. (2015) propose a physical mechanism for the direct effect of aerosols on monsoon circulation and precipitation over the Indo-Gangetic plains. Aerosols absorb incoming solar radiation, reducing surface solar absorption leading to land cooling; this weakens the land sea temperature contrast, weakening the monsoon overturning circulation thus reducing moisture advection into the continent, further suppressing convection, resulting in decreased cloud and precipitation. Sanap and Pandithurai (2015) reviewed observational and modelling studies of the aerosol impact on ISMR and conclude “… it is reasonably difficult to quantify the various aerosol effects on monsoon precipitation and circulation either from modelling or observational studies alone”. They refer to the IPCC 5th assessment report conclusions that current understanding of aerosol–cloud–precipitation interaction is low to moderate, they are not
well represented in the climate models, and are thus a major source of uncertainty in future projections.

Guo et al. (2015) investigated the relative effect of anthropogenic aerosols (direct and indirect effect) and enhanced greenhouse gas concentrations on the South Asian monsoon as simulated by 24 CMIP5 GCMs, 15 of which include the indirect aerosol effect. The historical runs with all-forcings were most similar to the aerosol-only forcing runs, both with declining precipitation trends, whereas the greenhouse gas only runs gave an increasing trend. Correspondingly, the MME-mean of precipitation in the direct aerosol only runs increased whereas it decreased in the runs that also included indirect aerosol effects. Given RCPs incorporate declining emissions of black carbon and sulphate, including over India and China after around 2020–2040 (depending upon the RCP), they suggest projections of increased precipitation may be overly optimistic as the future evolution of monsoon precipitation may depart significantly from CMIP5 projections if the aerosol emissions do not decline as assumed in the RCPs.

Li et al. (2015) investigated the South Asian monsoon response to aerosol and greenhouse gas forcings, also finding precipitation increases due to GHG forcing and decreases due to aerosol forcing. They concluded the relative impact of dynamic and thermodynamic contributions to the total mean moisture convergence determines monsoon precipitation trends, with GHG forcing dominating the thermodynamic change of mean moisture convergence, while aerosol forcing dominates the dynamic change in mean moisture convergence. Historical monsoon rainfall changes are dominated by the changes in monsoon circulation, i.e. dynamical contribution from aerosol forcing, while thermodynamic mechanisms dominate in the future, i.e. GHG forcing.

Roxy et al. (2015), using multiple observed datasets, highlighted a significantly weakening 1901–2012 summer precipitation trend over the central-east and northern regions of India, along the Ganges-Brahmaputra-Meghna basins and the Himalayan foothills. Rapid warming in the Indian Ocean, concurrent with a relatively subdued warming over the subcontinent, has decreased the land-sea thermal gradient over South Asia. This weakened land-sea thermal contrast dampens the summer monsoon Hadley circulation, therefore reducing precipitation over parts of South Asia.
6 Hydrological projections

Immerzeel et al. (2010) assessed the importance of meltwater contribution to flow, and hence susceptibility to climate change, for five major Asian rivers, including the Indus, Ganges and Brahmaputra rivers in South Asia. They found the Indus and Brahmaputra are most susceptible to flow reductions from climate change due to their large snow and glacier melt contribution to total flow; with upstream areas (elevations > 2000 m ASL) contributing 60% of total flow in the Indus and 21% in the Brahmaputra. Assessing potential impacts of climate change, using five GCM’s A1B scenario projected trends in temperature and snowfall to 2050, their modelling suggested decreases in upstream flow of 8.4% for the upper Indus, 17.6% for the Ganges, and 19.6% for the Brahmaputra. These changes are the combined result of decreased melt water compensated by mean upstream rainfall increases of 25% in the Indus, 8% in the Ganges and 25% in the Brahmaputra. Likewise, Immerzeel and Bierkens (2012) determine the Indus Basin is highly vulnerable to climate change induced reductions in water availability given demand increases of a rapidly growing population combined with supply uncertainty due to “unpredictable glacier melt, severe groundwater depletion and an uncertain future precipitation regime.”

Lutz et al. (2014) assessed potential changes to water availability for the Indus, Ganges, Brahmaputra, Salween and Mekong rivers, with increased runoff projected to 2050 for the upper Ganges, Brahmaputra, Salween and Mekong primarily due to projected precipitation increases and for the Indus due to accelerated glacier melt in the upper basin. Increased precipitation was projected for each basin except the Indus, which had decreasing precipitation projections. As Indus flow is dominated by the temperature-driven glacier melt, projection uncertainty was relatively small as all GCMs investigated projected similar temperature increases. Larger uncertainties in change occur for the basins with greater snow and rainfall runoff contributions. The Ganges future flow projections have large uncertainty due to uncertainty in projected changes to precipitation. Projected precipitation increases (all GCMs) for the monsoon lead to increased flows during the discharge peak monsoon season. Brahmaputra flow is also projected to increase due to precipitation increases all year around, as monsoon precipitation increase is relatively small.

Vaux Jr. et al. (2012) reviewed the current state of knowledge regarding climate change trends and impacts on water resources and water security across the Hindu Kush-Himalayan (HKH) region. In the east (i.e. Ganges) discharge changes will be dominated by shifts in the location, intensity and variability of rain and snow rather than by glacial retreat, with glacial melt contribution only important in the west (i.e. Indus). They concluded that social changes (e.g. rising standards of living, improving and changing diets, greater energy use) will have a larger impact on water security than environmental factors affecting water supply over the next few decades.

Yu et al. (2013) assessed the impacts of climate risk and alternative development options on water and agriculture in the Indus Basin within Pakistan. Given the wide range of projected change in future precipitation timing and magnitude, with uncertain hydrological response given the complex orography of the UIB, they postulate “...the primary impact of all but the most extreme
climate change scenarios could be a shift in the timing of peak runoff, and not a major change in annual volume.”

Wiltshire (2014) examined how climate change, projected by the HadRM3 regional climate model of moderate resolution (25 km) downscaling two GCM’s A1B simulations, impacts the glaciers of the Himalayas and Hindu Kush. The two GCMs (ECHAM5 and HadCM3) were selected on the basis that they are able to capture the dynamics of the monsoon, the synoptic patterns influencing winter precipitation in the region (i.e., western disturbances) and their projections span an uncertainty range from possible future precipitation decreases to increases. Although noting many limitations, biases and uncertainties, they conclude the projected warming will have a greater impact on the warmer eastern NB and HP glaciers that accumulate mass during the summer monsoon than the western HK and KK which are winter accumulation (western disturbance) dominated. Highlighting the uncertainties, one GCM projected increased snowfall due to increased strength western disturbances that could increase accumulation in the western HKH initially, although progressively greater warming throughout the 21st century will result in increased ablation dominating, whilst the other GCM showed initial increases transitioning to an overall decrease with higher warming. Thus the eastern HKH may experience an increase in water resource availability (predominantly due to precipitation increasing over the 21st century) whilst the western HKH and Indus a decrease in precipitation and hence vulnerability to long-term glacial loss.

Singh et al. (2006) assessed summer runoff response of a Himalayan highly glacierised basin (Dokriani Glacier, Bhagirathi River basin in the Garhwal region of northern India) to warmer and drier and warmer and wetter prescribed scenarios. Estimates of glacier melt and rainfall contribution to the total runoff are 87% and 13%, respectively. They found streamflow increased 28% for a 2 °C temperature increase with ±10% changes in rainfall resulting in ±3.5% changes in streamflow.

Miller et al. (2012) concluded that the eastern glaciers feeding the Ganges and Brahmaputra do not provide a significant contribution to downstream total annual discharge. This is primarily because monsoon rains coincides with the warmest temperatures at higher altitudes, with the contribution from glacier meltwater at such time insignificant compared to the volume of runoff generated by monsoon rainfall. In contrast, river basins in the western parts of the region are highly sensitive to climate change because the basins are drier and less influenced by monsoon rainfall. The relatively higher dependence on meltwater is due to the large glaciarized fraction and persistent snow cover in the large expanses at higher altitudes, providing meltwater during the warmer seasons whilst not receiving the same level of summer monsoon rains as in the east. Predicted—but uncertain—increases in rainfall as a result of climate change will likely drive higher annual discharge in the river Ganges, where reductions to glacier mass will have negligible impact on the total annual discharge change. In contrast, increased glacier melt as a result of climate change will provide short-term (i.e. next several decades) increases in the contribution to discharge of the Indus River, followed by likely decreases in the future as glaciers diminish. There is, however, uncertainty in how these decreases will be offset by changing rainfall. The seasonality of the runoff from glacier and snowmelt may be a more important factor, with evidence indicating that a change in timing due to increasing temperatures or decreased winter precipitation could have significant downstream impacts in spring. Increased snow and ice melt in the headwaters of the Brahmaputra are expected to lead to long-term decreasing discharge, but will be offset by
increased rainfall in lower reaches—leading to an overall increase in the downstream annual and mean peak discharge.

Lutz et al. (2014) note that in contrast to the upper Ganges, Brahmaputra, Salween and Mekong basins, where the main driver of runoff increase is the projected increase in precipitation, the main driver of flow change in the upper Indus basin (UIB) is accelerated melt. The contradictory precipitation projections for this basin make water availability in the UIB highly uncertain in the long run, requiring further research. As a consistent increase in runoff is expected for these five basins at least until 2050, they recommend a change of focus to coping with extreme events and intra-annual shifts (i.e. seasonality) in water availability.

Terzago et al. (2014) assessed current and future HKKH snowpack in CMIP5 GCMs, finding models with high spatial resolution (up to 1.25”) simulated the winter snowpack spatial pattern in greater agreement with each other, with observations, with reanalysis datasets, and with the orographic features of the region, compared to most lower-resolution models. In the HKK, projected warmer temperatures and drier winters would result in a thinner and less durable snowpack, especially in the second half of the 21st century. For the Himalaya region a projected a shift in the snow depth maximum from March to February resulted in an earlier spring snowmelt and a consequent shift in the timing of water discharge. While the net balance may be decreasing over the entire region (predominantly winter temperature driven), current field data and several glacier mass balances show that snow depth and snow water equivalent in the HKK are increasing at some high-elevation locations whilst decreasing at lower elevations. They note resolving this behaviour would require much higher resolutions than those of the current CMIP5 models.

Masood et al. (2015) present results from five CMIP5 GCMs showing that, by the end of the 21st century relative to a 1979–2003 baseline (a) the combined Ganges, Brahmaputra and Meghna (GBM) is projected to warm by ~4.3 °C; (b) the changes of mean precipitation (runoff) are projected to be +19.8% (+33.1 %), +16.3% (+16.2 %), and +29.6% (+39.7 %) in the Ganges, Brahmaputra, and Meghna, respectively; and (c) evapotranspiration is projected to increase for the entire GBM (Ganges: +13.6 %, Brahmaputra: +16.4 %, Meghna: +12.9 %) due to increased net radiation as well as warmer temperatures.

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7 Downscaled projections

Akhtar et al. (2008) simulated hydrological response to climate change for three river basins (Astore, Gilgit and Hunza) in the Hindukush Karakorum Himalaya (HKH) using two downscaling approaches driven by the HadAM3P GCM. One was a form of statistical downscaling using the ‘delta change’ approach and another dynamical downscaling using the PRECIS regional climate model at 25km resolution. Hydrological modelling was undertaken for present climate (1961-1990) and for downscaled A2 scenario (2071-2100) projections whilst imposing three scenarios of glacier coverage (current, 50% reduction and 100% reduction). The mean annual precipitation changes simulated by PRECIS are increases of 13%, 21% and 19% for the Astore, Gilgit and Hunza respectively. For the current glaciation coverage scenario, the mean annual discharge response is for 88% and 60% increases for the delta-change and dynamical downscaling respectively. For the 50% glacier coverage scenario the discharge changes are 10% and 24% increases, respectively, and for the 0% glacier coverage scenario a decrease of up to 94% for the delta-change and 15% for the dynamical downscaling. They conclude the delta-change approach is not reliable given the large outliers in discharge simulated, which they attribute to the poor quality of the observed data, inability to change the frequency of rain days and inadequate accounting for change in day to day variability of temperature.

Ashfaq et al. (2009) used a high-resolution nested climate modelling system (25-km RegCM3 nested in NASA FVGCM for A2 scenario) to investigate the response of South Asian summer monsoon dynamics to anthropogenic increases in greenhouse gas concentrations. They found that enhanced greenhouse forcing resulted in overall suppression of summer precipitation, a delay in monsoon onset, and an increase in the occurrence of monsoon break periods. Weakening of the large-scale monsoon flow and suppression of the dominant intra-seasonal oscillatory modes were instrumental in the overall weakening of the South Asian summer monsoon. These results contrast the other studies indicating monsoon precipitation increases.

Lucas-Picher et al. (2011) assessed the ability of four RCMs (CLM, HadRM3, HIRHAM5, and REMO) to simulate the Indian summer monsoon using ECMWF ERA-40 lateral boundary forcing for the 1981-2000 period. As precipitation amounts and regional distributions differed substantially across the four RCMs, they concluded regional scale inconsistencies are an indication that important feedbacks and processes are poorly simulated or not taken into account. CLM, HIRHAM5, and REMO are too warm over northern India, possibly due to surface cooling due to irrigation being unaccounted for. This warm bias resulted in lower surface pressure which perturbs the lands-sea temperature contrast, potentially biasing the large-scale dynamics.

Kumar et al. (2013) produced projections over South Asia using three RCMs (CLM, HadRM3 and REMO) forced by two GCMs (ECHAM5 and HadCM3) for the A1B scenario. They focused on precipitation and temperature projection results for India. An ensemble mean RCM warming of 1.5 °C and 3.9 °C by mid and end of century (relative to 1970-1999). Ensemble mean RCM precipitation projections show summer monsoon season increases of 20 to 40% over the peninsular and 10 to 20% over the northeast and Western Gns by the end of the 21st century, even when the driving GCM ensemble mean indicates decreases in some parts of the peninsular.
Prasch et al. (2013) used RCM outputs to drive a process-based glacier and hydrological model of the Lhasa River basin, the largest tributary in the middle reach of the Upper Brahmaputra. Bias corrected COSMO-CLM RCM output of the past (1971-2000) and future (A1B for 2011-2040 and 2051-2080) driven by ECHAM5 was further downscaled to 1 km resolution using the SCALMET scaling tool. They find glacier melt continues to be a minor contributor, at less than 5%, whereas snowmelt contribution to runoff will reduce, changing water availability.

Halder et al. (2015) used the regional climate model RegCM4.0 coupled with the land surface model CLM3.5 to assess the contribution of land use and land cover change (LULCC) on Indian climate changes. They note since the mid-20th century mean and extreme temperatures have increased and over central India extreme precipitation has increased while moderate precipitation has significantly decreased, resulting in no overall trend in total precipitation. They conclude the observed LULCC (forest to crop) has contributed to reduced total moisture flux and large-scale convective instability that are important to moderate precipitation events that comprise 85% of monsoon precipitation.

Mishra et al. (2014) examined Indian extreme rainfall as simulated by CMIP5 GCMs and RCMs, finding that only two of four RCMs simulate extreme precipitation with less bias than their host GCMs. They conclude observed trends in the extremes were not adequately captured by either the GCM or RCM ensembles, thus neither the GCMs nor the RCM outputs are currently adequate to inform hydrologic design.

Mishra (2015) assessed precipitation and temperature simulations across the Himalayas (i.e. the Indus, Ganges, and Brahmaputra basins) for 1973 to 2007 from four CORDEX RCMs (host GCMs): COSMO-CLM (MPI-ESM-LR), RegCM4-GFDL (GFDL-ESM2M), RegCM4-LMDZ (IPSL-CM5A-LR) and SMHI-RCA4 (EC-EARTH). The simulations were assessed against observed products APHRODITE, CRU, GPC, NOAA’s PREC, and University of Delaware (UDEL) for precipitation and APHRODITE, CRU, Global Historical Climatology Network (GHCN) and UDEL for temperature. Mishra notes that Palazzi et al. (2013) found advantages and drawbacks when comparing APHRODITE, CRU, GPC, Global Precipitation Climatology Project, and Tropical Rainfall Measuring Mission (TRMM) and determined that none of these products can be used to provide a ground truth or reference for precipitation in the Karakoram-Himalayan region. Most of the precipitation data sets that use station observations are based on only rainfall measurements and not snow, thus underestimating total precipitation.

Mishra (2015) concluded the CORDEX-RCMs underestimated temperature, while overestimated precipitation in the winter season. Overestimations in the models can be partially attributed to the fact that most of the observations do not include solid precipitation. In the monsoon season, the CORDEX-RCMs underestimated air temperature and precipitation in the Ganges and Brahmaputra basins. The CORDEX-RCMs overestimated winter warming in all the three river basins during the period of 1973–2007. Decline in the summer monsoon precipitation was shown by most of the observational data sets in the Himalayan water towers during the period of 1951–2007, which was not captured by the CORDEX-RCMs. The host GCMs that were used as boundary conditions in the CORDEX-RCMs simulate winter climate better than the CORDEX-RCMs. Thus reliability of future climate projections may not be high given there is a large uncertainty in simulating precipitation and temperature in the region. Warming in the winter and monsoon seasons is revealed by both observations and the CORDEX-RCMs; however, there is a strong disagreement in the magnitude of
warming, which may lead to uncertainty in the impact assessment and water resource management.

Shashikanth et al. (2014) examined Indian summer monsoon rainfall statistically downscaled (linear regression) to different resolutions (0.05°, 0.25° and 0.5°) from 19 CMIP5 GCMs. Results were combined using multi model averaging (MMA) and Bayesian model averaging (BMA). Changes in mean rainfall for the different resolutions for 2020, 2050 and 2080 periods obtained from the MMA and the BMA were comparable. Although the finer resolution produces results more realistic of local climatology, it does not add value in terms of the changes, uncertainty or signal to noise ratio of the projections. They thus concluded “that a finer resolution in statistical downscaling does not improve the reliability of projected changes; however an optimal resolution for downscaling is necessary to capture the major local and orographic factors and other region-specific convective processes related to the land–atmosphere–ocean interactions.”

Syed et al. (2014) assessed RCM downscaled properties of the South Asia summer monsoon for present day climate (1971-2000) using the RegCM4 and PRECIS RCMs boundary forced by ERA40 reanalysis and the ECHAM5 GCM, as well as downsampling ECHAM5 A1B for 2071-2100. They assessed mean and interannual variability of temperature, precipitation and circulation. They found the RCMs have systematic biases, independent of the driving datasets, which appear to come from the physics parameterizations of the RCMs. The projected end of century changes show warming of 2.5 to 5 °C, with the largest warming over their northern Pakistan and India sub-region, and a 30% increase in summer monsoon precipitation over north eastern India, Bangladesh and Myanmar.

Saeed et al. (2013) concluded that during the summer months of July and August, the heat low developed over land areas due to central Asian high that causes advection of moisture from external sources towards UIB, such as the Arabian Sea, are insufficient to account for the large amount of precipitation that is experienced over the UIB. They conclude, through modelling, that the necessary moisture is supplied by the evapotranspiration of irrigated water, causing convection and hence resulting in precipitation which is further supported by the complex topography of the region (Saeed et al., 2009; Saeed et al., 2013). Tuinenburg et al. (2014) modelled the effect of large-scale irrigation on the climate of northern India (western and eastern Ganges regions) using regional (HIRHAM, HadRM3, and RAMS) and global (ECHAM) climate models with and without irrigation. They conclude: (1) Irrigation leads to lower temperatures and a higher evaporation locally, but local precipitation is not directly affected; (2) Up to 35% of any additional evaporation is recycled within the Ganges basin. Thus, of any marginal evaporation increase, up to a third of the moisture is conserved as a water resource for the basin; (3) If, however, irrigation is applied on a large scale, the large-scale circulation will change and shift the moisture away from the Ganges plain toward the Indus basin and Pakistan. Cook et al. (2015), in a global study of irrigation impact on regional climate, also determined that irrigation reduces South Asian monsoon precipitation due to changes to the evaporative regime having secondary effects on temperature and cloud cover, rather than changes to net energy budget directly. They concluded that, given modelling and empirical studies provide broad evidence for a significant impact of irrigation on climate, irrigation should be included in the set of standard historical anthropogenic climate forcing in future multi-model assessments, such as CMIP6.
Niu et al. (2015) assessed historical simulations and investigated projections of Indian Peninsular summer monsoon climate change for 2041–2060 (A1B) using three GCMs and seven RCMs driven by ECHAM5. Overall, the MME projected wetter conditions with significant increases in monsoon rainfall over southern India, with intermodel spread ranging from -8.9% to +14.8%. Consistent precipitation changes are projected by most RCMs over the regions south of 15°N, but simulated changes are inconsistent over the northern Indian Peninsula. By examining the inter-RCM variability and multi-RCM credibility in projecting ISM precipitation, they concluded that only southeast Indian Peninsula is confident to have increased ISM precipitation in the future. Overall a stronger Indian summer monsoon is projected by most of climate models during 2041–2060.

Pervez and Henebry (2014) downscaled from the CGCM3.1 GCM A1B and A2 projections using SDSM, for 43 stations across the Ganges and the Brahmaputra basins. Precipitation during and after the monsoon was projected to increase in both basins under the A1B and A2 emission scenarios; whereas, the pre-monsoon precipitation was projected to decrease. Peak monsoon precipitation was projected to shift from July to August.

Rajbhandari et al. (2014) applied the PRECIS RCM over the entire Indus river basin for an A1B scenario. The model was found to reproduce spatial and seasonality patterns for temperature and precipitation, although with biases in magnitude. Projections simulated an increase in precipitation over the upper Indus basin and decrease over the lower Indus basin with winter precipitation decreases particularly evident over the southern part of the basin. Warming was greater over the upper than the lower Indus, with greater warming in winter than in the other seasons. There was an overall increase in the number of rainy days over the basin, but in the border area between the upper and lower basins (where the rainfall amount is highest) there was a decrease in the number of rainy days accompanied by an increase in rainfall intensity.

Karmacharya et al. (2015) investigated systematic errors in South Asian summer monsoon simulated by the Met Office Unified Model by comparing global and regional model simulations with targeted changes to the domain, forced with atmospheric reanalysis. They found that excluding remote drivers of systematic errors from the direct area of interest allowed the application of RCMs for process studies of the monsoon, despite the large errors in the parent global model.

Mathison et al. (2015) applied the regional climate model HadRM3 across the whole of South Asia at a 25 km resolution, downscaling observed (ERA-Interim, 1990-2006) and projected (two AR4 GCMs, HadCM3 and ECHAM5, 1960-2100). Their results suggest that the annual average river flow will increase to 2100s. Although trends are often masked by the large inter-annual variability of river flows in this region, for some of the gauges the river flow rates are projected to almost double by the end of the century. One important caveat is that they did not account for future changes in glacial contribution to flow.

Dash et al. (2014), downsampling one GCM (GFDL-ESM2M) with one RCM (RegCM4), reproduced areas of decreased monsoon precipitation found in the historical period and simulated a projected decrease in monsoon precipitation over mid-continental India in disagreement with the driving GCM. Their results projected decrease in JJAS rainfall under the RCP8.5 scenario over the central, eastern, and peninsular India by the end of the century is in the range of 30–40% of their mean reference period values. These changes are found to be statistically significant at 95% confidence.
level. Under the RCP4.5 scenario, similar decreasing estimates lie in the range of 15–25 %, also significant at 95 % level.

Ramarao et al. (2015) coupled a stretched-grid variable-resolution GCM (Sabin et al., 2013), zoomed to 35 km resolution over the South Asian monsoon region and tropical Indian Ocean, with a sophisticated land-surface model. For simulations using RCP4.5 forcing, they find a continuation of summer monsoon rainfall declines with corresponding soil moisture decreases until the end of the 21st century, noting their findings are at odds with the majority of CMIP5 future rainfall projections that generally show increases over the Indian region. They also find the evapotranspiration (ET) reduction accompanying the soil moisture drying has an elasticity factor of approximately 2 (i.e. a 1% decrease in soil moisture results in a 2% decrease in ET).
South Asia is characterised by strong climate gradients from the south to north and the west to east, together with highly seasonal and year to year variability. Two main climate drivers, the westerlies (western disturbances) and the monsoon (Indian summer monsoon), interact with the extreme orography of the Himalayas to produce the observed spatial and temporal climatological variability. The hot, wet and tropical south contrasts with the cold, arid and mountainous north. The monsoon impacts the whole region, providing a larger contribution to annual precipitation in the east as the west is dominated by westerlies where precipitation is predominantly snowfall in the winter and spring.

The interaction between climate drivers and orography results in variation in hydrological processes, with the rivers of the west dominated by glacier and snowmelt sources whereas the central and eastern rivers are rainfall dominated. Thus hydrological response to climate variability and trends varies from west to east and with elevation. Changes in the flow of the glacier and snowmelt dominated western rivers (e.g. Indus) will be impacted by changes in western disturbances, and their interactions with the monsoon, and temperature changes are a key factor influencing increased contribution from glacier melt and changing partition of precipitation between snow and rain. These will change both magnitude and seasonality of flow. In contrast flow changes in the central and eastern rivers (e.g. Brahmaputra) will be impacted predominantly by changes to the Indian summer monsoon strength, length and seasonality. Additional stresses will result from expected increases in the intensity of extreme precipitation in a warming climate.

Historical warming trends are evident across South Asia. Studies have found winter temperatures to be increasing faster than summer temperatures and maximum temperatures rising at a faster rate than minimum temperatures (hence increasing diurnal temperature range trends). Warming rates are also greater at higher elevations (elevation dependant warming) with a positive feedback as warming reduces snow cover, reducing surface albedo and hence warming more. All projections indicate warming will continue.

Observed precipitation trends are not consistent, varying from region to region and between seasons. Long term decreasing total monsoon rainfall trends are evident over recent decades with several studies suggesting the role of aerosols (localised cooling due to the ‘Asian brown cloud’). Virtually all GCM projections (CMIP3 and CMIP5) suggest increased South Asian total monsoon rainfall as the century progresses, however on a regional basis projections are less consistent. A caveat relates to the reduction of aerosol concentrations in CMIP5 scenarios, as increasing precipitation may not occur if aerosol emissions do not decline as assumed in the driving scenarios. Studies investigated projected changes to extreme rainfall see increases in the intensity of extreme events.

Hydrological modelling of the flow response to projected climate changes varies west to east as the dominance of glacier contribution to flow decreases. The non-linear flow response to warming and precipitation changes are complex as increased glacier melt can compensate for reduced snow melt and increased monsoon season precipitation can compensate for reduced snow accumulation in winter and spring. Several studies indicate increased flow in eastern basins due to
increased rainfall and in western basins due to accelerated glacier melt. Glacier retreat, while initially increasing flow (for several decades), will in the long term result in decreased flow and increase the importance of precipitation derived flow. Timing of maximum discharge is projected to move earlier in the year due to reduced snowpack combined with earlier glacier melt, due to warmer conditions both promoting melting and resulting in more precipitation falling as rain rather than snow.

Downscaling has been promoted as providing better understanding and quantification of the regional responses to climate change, particularly given the strong orographic effect in the Himalayan upper basins where most of the flow is produced. Statistical downscaling and ‘delta change’ scaling has not been applied as much as dynamical downscaling. Biases in RCM simulations are not necessarily less than those of their host GCMs. Four RCMs produced differing precipitation amounts and regional distributions when boundary forced by ERA-40, suggesting important feedbacks and processes are poorly simulated or unaccounted for. The lack of irrigation in the RCMs is proposed as a cause of precipitation bias, as large scale irrigation (as undertaken in Pakistan and India) cools the land, with the resulting change in temperature gradients impacting regional circulation and hence precipitation. Even the latest RCM (CORDEX) simulations do not capture the observed ISM precipitation decline or the correct magnitude of observed warming, calling into question their suitability for projecting impacts on water resources.

Climate change impact studies should therefore consider the full range of projections from GCMs as well as regionally focussed RCM modelling. The uncertainty in the projections must be adequately represented in the context and objectives of the hydrological modelling and integrated water resources management studies. The SDIP climate change database (Zheng et al., 2015) provides projected future changes to monthly, seasonal and annual temperature, potential evaporation and precipitation for 0.5° grids across South Asia simulated by the 42 CMIP5 GCMs.
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Climate change and water in south Asia - overview and literature review

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