Current Opportunities and Challenges in Developing Hydro-Climatic Services in the Himalayas

Report of Pump Priming Project

November 2019

INDIA-UK
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भारत-ब्रिटेन जल कें द्र एमओईएस-एनईसीआरसी(यूके) जल सुरक्षा अनुसंधान के पूरक प्राथमिकताओ के बीच सहयोग और सहयोग को बढ़ावा देने के लिए करना है

Front cover image: Photo by Martin Jernberg on Unsplash

1. Contents

Executive Summary

This report assesses the significant issues for hydro-climatic modelling and service development in the mountain regions of northern India. It is the main output from an IUKWC Pump Priming Project that ran from March to August 2018 and has been produced by an author team of climate scientist, hydrologists and glaciologist from India and the UK. It is found that although state-of-the-art weather forecasting, climate, hydrological and glacier models are being used there are still substantial prediction uncertainties on all prediction timescales. There is a lack of detailed understanding of regional meteorological and hydrological processes, which results in potential misrepresentation of them in the models. Large-scale drivers of regional climate variability in the region have been identified but questions remain about their relevance on different timescales, their interaction, and their representation in global weather forecasting and climate models. Improving short-term predictions and climate change projections requires more meteorological, hydrological and glaciological observations in the Himalayas, improvements in data sharing, as well as additional efforts to integrate meteorological and hydrological modelling. There is also a need for improved communication of predictions to users, which should include their uncertainties.

The report is intended for workshop participants, India-UK Water Centre Open Network members and stakeholders.

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2. Introduction

2.1. Purpose and Structure of this Report

The purpose of this report is to identify opportunities and challenges in developing hydro-climatic services in the Himalayas, particularly within the Indian states. It is motivated by the fact that the livelihoods of people in the Indian Himalayas and in the river basins fed from this region depend strongly on hydrological and meteorological conditions, and are highly vulnerable to extreme events such as droughts and floods, as well as to possible long-term hydrological changes. Comprehensive and user-oriented glacio-hydrological and meteorological forecasts, long-term climate change projections, and long-term hydrological projections forced by climate change scenarios, would allow mitigation against the risks associated with glacio-hydrological and climate variability, and make optimal use of potential benefits.

Although meteorological forecasts and climate projections are available for India, there is substantial room for improvement with respect to predicting regional detail over the complex terrain of the Himalayas, integration with hydrological predictions, and providing essential forecast information on all timescales. Fostering progress on these issues and providing relevant information to various user groups is the remit of hydro-climatic services. According to the definition of the World Meteorological Organisation, “A climate service can be considered as the provision of climate information in such a way as to assist decision making. The service needs to be based on scientifically credible information and expertise, have appropriate engagement from users and providers, have an effective access mechanism and meet the users’ needs” (Vellingiri et al. 2015). Due to the very high relevance of hydrological information in decision-making in the Indian Himalayan water sector, we use the broader term hydro-climatic services (HCS). In order to guide the development of HCS and to foster communication between the meteorological and hydrological communities we follow a systematic approach by first reviewing in Section 3 what is known about the processes that govern climatic and hydrological variability on all timescales. In Section 4 we then assess the current state of predictive capabilities. In Section 5 these assessments are used to identify critical open scientific and practical questions, and the main opportunities and challenges for developing HCS in the Himalayas.

2.2. General Background

The Indian Summer Monsoon (ISM) provides the majority of the annual precipitation to the Indian Himalayas, as well as across the whole subcontinent. Due to the westward propagating nature of the monsoon season, there is a strong east-west gradient in monsoonal precipitation, leading to spatial variation ranging from 160 mm/yr in the north-west to 1800 mm/yr in the north-eastern states (Kishore et al. 2016).

Water in the eastern basins such as the Brahmaputra is largely sourced from the monsoon rainfall, whereas in the north-western Indian Himalayas in the Indus basin more than 50% of water is sourced from glacier and snow melt from the high Himalayas (Lutz et al. 2014).

The Himalayan region features the largest glacial coverage outside the polar regions (Frey et al. 2014) serving as ’water towers’ that support an estimated 1.3 billion people in Asia (Bookhagen & Burbank 2010, Orr et al. 2017). The river systems in India form the lifeline of the subcontinent due to their importance in sectors such as agriculture, energy, domestic water supply and industry. The livelihoods of people inhabiting the Himalayan basins are heavily dependent on agriculture, making them highly vulnerable to water shortages and flood events.

The Indus basin in particular is of exceptional political, economic and social importance to around 300 million people who inhabit it. The basin is the most important supplier of water to the world’s largest system of irrigated agriculture, particularly the Indian Punjab. The basin is densely populated with a predominantly rural population which is challenged by endemic poverty. Ninetyfive percent of available water in the basin is extracted for irrigation purposes, with twenty-six major irrigation barrages and hydropower schemes currently operating on the rivers fed from the basin. There is also a very substantial expansion of hydropower and reservoir storage now under-way (Zarfl et al. 2015). The main trunk of the upper Indus has 39 new Indian hydropower schemes (38 GW power) planned or under construction, equivalent to almost a fifth of India's total national generating capacity from all power sources. In the hilly regions, a larger fraction of the agriculture is sustained by rainfall as opposed to irrigation, thereby increasing the vulnerability to climatic changes (Mittal et al. 2008). Moreover, hilly regions are generally underdeveloped with lower income levels and poorer infrastructure resulting in outwards migration to urban centres in the plains, increasing the economic disparity within the region (Belwal 2007, Taragi & Chand 2017).

The valleys and plains on the south facing slopes of the Himalayan regions are often susceptible to floods and landslides due to extreme rainfall events, exacerbated by surface runoff from the steep topography of the mountains (Houze et al. 2017). Both western and eastern Himalayan basins have had catastrophic flood events in the recent past, such as the Leh flash flood of 2010, the Brahmaputra river flood during 2012, and the Uttarakhand floods during 2013. Drought across India over the last century has caused more than 6 million fatalities and 1 billion people have been directly affected (National Research Council and Committee on Population 2012).

The increasing frequencies of water shortages and floods, coinciding with anthropogenic climate change, mean that understanding the state and fate of Northern India's water resources is urgent (Pritchard 2017). However, the high natural variability of the ISM, and the effect of climate change on both the ISM and the glacial regions within the Himalayas provide a substantial challenge in predicting water availability and flood risks. Groundwater irrigation in particular is widespread across the Gangetic plains at the foot of the Himalayas, with important recharge zones in the Churia hills or Siwalik Hills, the last ridge before the plains. Groundwater in the region is replenished each monsoon, but there is a lack of data available as to the capacity of groundwater reserves, how much is exploited and even the quality of the water supply (Rajmohan & Prathapar 2013).

Most dams in India are intended as multi-purpose reservoir systems with flood control and agricultural water supply as the two major goals, followed by industrial and domestic supply and transportation. Water impounded by dams is delivered by canals to agrarian fields and accounts for 30% of India's irrigated agriculture (Government of India 2016). The storage capacity of reservoirs across India is above 253 billion cubic metres (Central Water Commission 2013). To put this number in context, the per capita water storage in India remains much lower than in developed nations, around 200 cubic meters per capita compared to for instance 6000 cubic meters in the US (Wisser et al. 2013). In addition, damages caused by flooding amounting to $1.2billion were reported for 2011 across India (Central Water Commission 2013). Thus, more efforts are needed for both demand and flood management. Whether these will be attained via dam construction or through multiple policy interventions is an open question. In India population growth, urbanisation, a rapidly expanding economy, and a large agricultural sector put growing pressure on increasingly scarce or variable water supplies. These pressures will be exacerbated by climate change, which will increase variability, and whose impacts are poorly understood at a regional level. There is thus a requirement to develop a better understanding of present and future water availability for the development of effective water management plans. These will be crucial for protecting lives and livelihoods and promoting sustainable development under conditions of climate change.

2.3. What Hydro-Climatic Information is Needed?

Here we briefly discuss the type of output from hydro-climatic prediction that is needed. Observations, process understanding, and modelling capacities that are required to address this need, as well as the current status, will be discussed in the main part of the report. Ideally predictions should comprise meteorological variables such as temperature, precipitation, wind speed, and solar radiation, as well as hydrological variables such as snow depth, snow water equivalent, glacier extent, river flow, sediment, and ground water levels. Information is needed on different timescales, namely short-term predictions with lead times of a few days, seasonal and decadal predictions, and climate change projections for the entire 21st century and beyond, for which the state of the Himalayan glaciers becomes crucial.

Short-term hydro-meteorological forecasts, which are deterministic, should provide specific values for these variables at a given time, together with a measure for the uncertainty, which is usually given through ensemble forecasts. Forecasts for longer lead times cannot provide specific values for individual days, but the means, and preferably the probability distributions of daily or monthly variables for a given period, should be given. In addition, for many applications statistical characteristics of spatial and temporal behaviour are relevant, for instance of spell-lengths distributions and extent of droughts. Characteristics of the seasonal cycle, such as the onset date of the monsoon, are also often of interest.

Meteorological and hydrological predictions require integrated understanding, modelling, and observation of all relevant system components, which are depicted in Figure 1. The climate system creates random variability on all timescales, such as the year-to-year variability in monsoonal rainfall. It also responds to anthropogenic greenhouse forcing either directly through changes in the local radiative balance, or indirectly through potentially complex circulation changes, which may be affected by teleconnections. Weather and climate variability directly impact the hydrology through precipitation, but also affect the glacier melt, which, as already mentioned, is a main water source for the Indus basin. Moreover, black carbon deposited on glaciers are thought to contribute to their retreat (Schmale et al., 2017). River flow and ground water levels are determined by water inputs, evapotranspiration, natural routing of the water on the surface and underground, as well as abstraction and water management. The glaciers respond directly to changes in temperature and precipitation through local changes in accumulation and ablation, but also through changes in glacial dynamics. In Section 3 these processes are discussed in more detail.

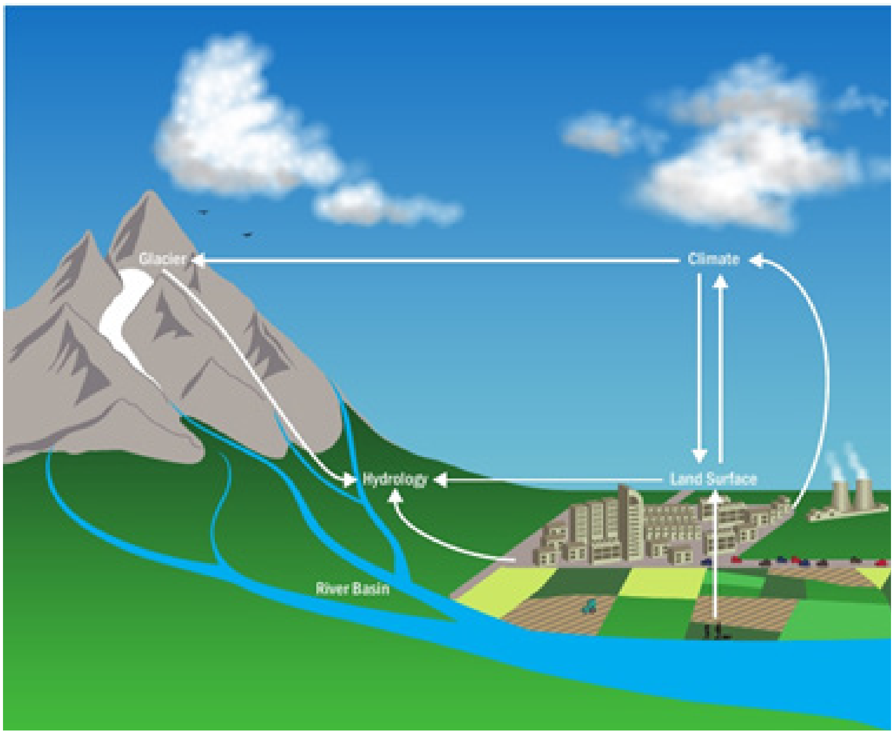

Figure 1. Components of the Earth system relevant for the hydro-climatology in the Himalayan region.

3. Processes

In this section we will give an overview on the specific processes that generate weather and climate variability over India, on the main characteristics and processes in the Himalayan glaciers, and on the most relevant hydrological processes. The climate of India is influenced by a wide range of processes from local to planetary spatial scales, leading to random daily to decadal and longer variability (Mondal et al., 2017). The different spatial and temporal scales for these processes are shown in Figure 2. In this report section 3.1 on climate is subdivided according to timescales, covering mean conditions, daily to intraseasonal variability, internal (i.e. non-forced) variability on inter-annual to decadal timescales, and anthropogenic climate change. Section 3.2, which covers glaciers, discusses the western and central/eastern glaciers separately, and also contains a subsection on the role of glaciers for the hydrology. Section 3.3, which covers hydrology, first gives a general overview followed by a separate subsection on extreme events.

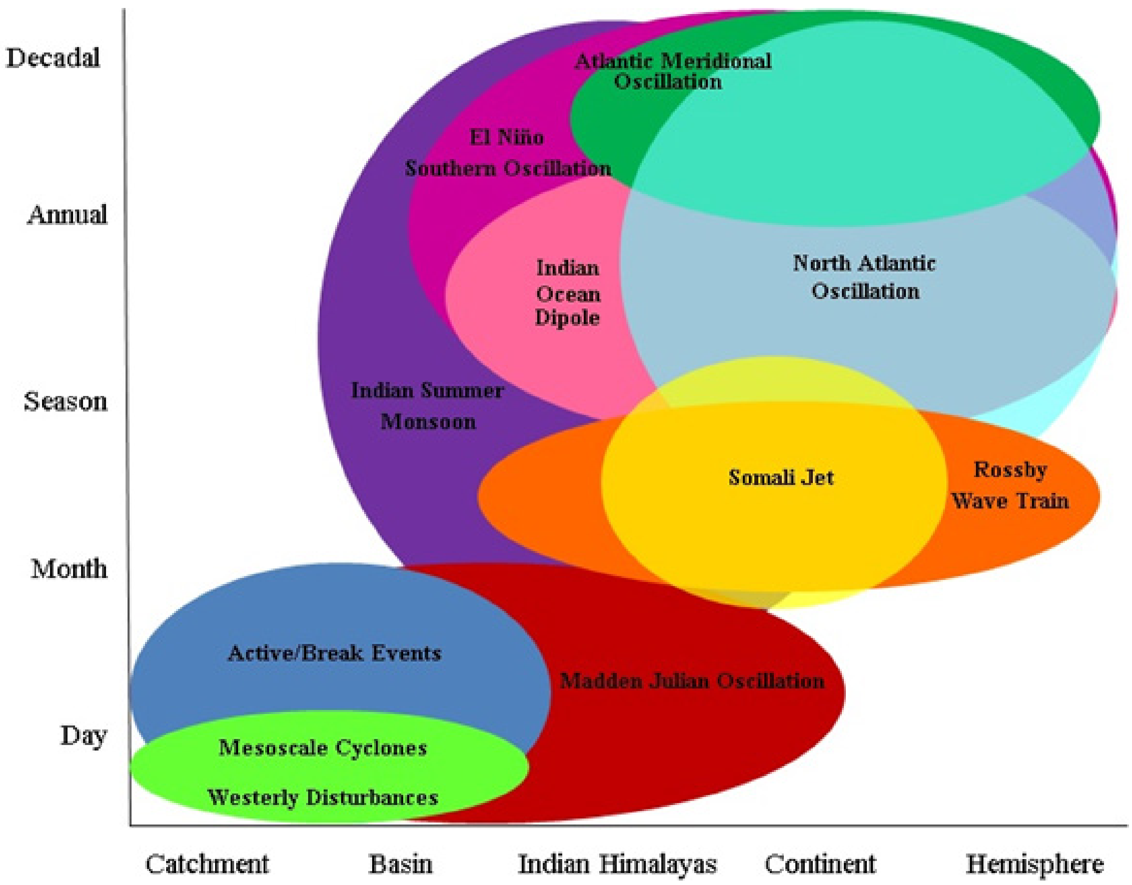

Figure 2. Processes causing natural climate variability and their approximate spatial and temporal scales.

3.1. Climate

3.1.1. Mean Conditions

The mean annual cycle of climate conditions over the Indian Himalayas is dominated by the Indian Monsoon, which is a complex wind regime characterised by wind reversals on seasonal timescales. During the boreal spring (March to May) the Southeast Asian land mass warms faster than the surrounding oceans. Through the creation of a meridional temperature gradient, low pressure forms from the northern Punjab plains to the eastern Bengal delta (Mondal et al., 2017). This low pressure area drags the initially south-easterly trade winds northward over the equator, where they change towards a south-westerly direction due to the opposite effect of the Earth rotation in the two hemispheres (Unnikrishnan et al., 2017). The Intertropical Convergence Zone (ITCZ), where the southerly and northerly trade winds converge and create a low-pressure belt of highly unstable weather, moves north towards the Ganga plain during spring (Banakar et al., 2017). The southerly trade winds travel now a long distance over the Indian Ocean, where the air picks up moisture and becomes oversaturated. This then leads to heavy rainfall over the Indian Peninsula along the ITCZ (Mohapatra et al., 2017). These basic explanations have been extended by detailed studies of monsoon dynamics which have shown that temperature gradients are only one contributing factor and are not sufficient to explain regional details or temporal variability in monsoons, and that Moist Static Energy plays an important role (Bordoni and Schneider 2008, Hurley and Boos 2013, Biasutti et al. 2018). Between June and September the ISM provides more than 80% of South Asia's annual rainfall (Turner & Annamalai 2012). A schematic representation of the ISM along with its onset dates is given in Figure 3.

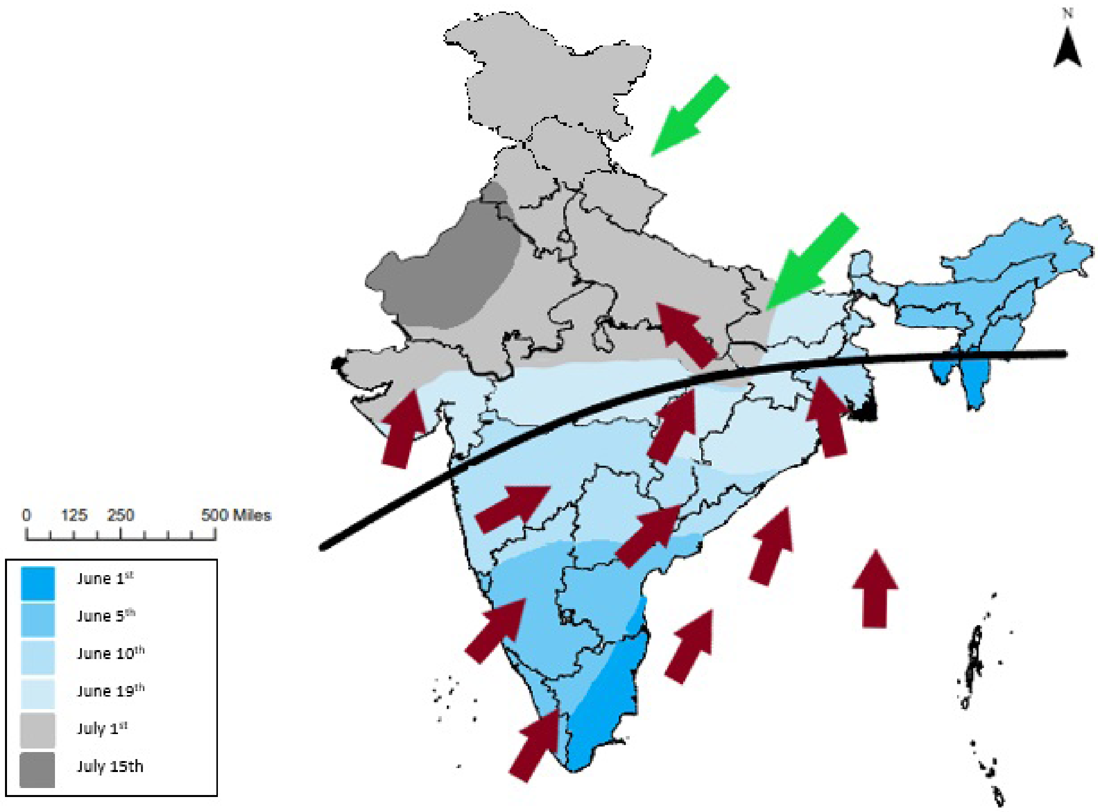

Figure 3. Average onset dates and prevalent wind directions of the Indian summer monsoon (adapted from Saravask 2007). Summer (winter) winds are shown as red (green) arrows. The solid black line depicts the position of the ITCZ in June/July.

3.1.2. Daily to Intraseasonal Variability

Although the monsoon system develops every year, begins and ends around the same time most years, and follows the same path, there is substantial intraseasonal variability with a large impact on water supply and agriculture (Yu et al. 2016).

The ISM intraseasonal variability is associated with northward propagating active and break periods in convection and rainfall, with changes in phase on timescales of 30-50 days (Rajeevan et al. 2010, Singh et al. 2017). The number and length of break events has a significant impact on the seasonal precipitation across the whole subcontinent, with prolonged breaks potentially causing drought (Gadgil & Joseph 2003). The active and break phases of the monsoon have been linked to the Madden Julian Oscillation (MJO) in some studies (Bhatla et al. 2017, Singh et al. 2017).

The MJO is an ocean-atmosphere phenomenon that causes major fluctuations in tropical weather, mainly in heavy rainfall and tropical storms (Wang et al. 2017), occurring in the boreal winter. It is the leading mode of intraseasonal variability of tropical convection with a frequency from 30 to 90 days, propagating eastward and providing teleconnections between the Pacific and the Indian Ocean regions (Madden & Julian 1971, Srivastava et al. 2014). Several studies based on observations (Jones 2016, Henderson et al. 2017) have associated the active and break phases with fluctuations in two convergence zones, one over the Indian continent and the other over the Indian Ocean. Idealised modelling studies (Bhatla et al. 2017) have suggested that the intraseasonal, quasi-periodic fluctuations in the monsoon region can occur from interactions between large-scale dynamics and moist convection. The phase of the MJO has also been linked to the onset of the ISM (Zhang 2005, Bhatla et al. 2016, 2017).

The initial phase of the MJO within the Indian region is first associated with increased Indian Ocean sea surface temperatures (SSTs), followed five to ten days later by a strengthening of precipitation over the southern tip of India. The propagating MJO also causes a distinct break in the monsoon cycle towards central India in July. The Boreal Summer Intraseasonal Oscillation (BSISO) acts as a counterpart for the MJO. It is a fluctuation in convective activity originally forming along the equator (Wheeler et al. 2017) on similar timescales as the MJO. It propagates northward following the ITCZ and also modulates extreme weather across the Indian subcontinent. In particular it leads to an increase in extreme active and break ISM phases across northern India (Ding & Wang 2009).

In addition, the intraseasonal variability of the Indian climate is strongly affected by the position of the Somali Jet, a low-level cross-equatorial flow that turns anti-cyclonically in the northern Indian Ocean, becoming the westerlies that then prevail across India during the boreal summer (Boos & Emanuel 2009). When the Somali Jet is northwards of its mean position, the ISM features more intense active spells, leading to heavier rainfall across India. In contrast, when the jet is positioned further southwards, there is an increase in break events and dry spells (Rai et al. 2017).

Well-organised Rossby wave trains that form in the upper troposphere over Eurasia also affect the intensity of active ISM phases. In weak ISM years, Rizou et al. (2012) found that the anomaly composite of 300 hPa meridional wind showed strong alteration to the mean state, with scattered anomalies and no specific orientation. They infer that the well organised Rossby wave train found is a response to the intensified Indian monsoon forcing.

Rasmussen et al. (2015) and Houze et al. (2011, 2016) address daily timescales with a focus on extreme precipitation events. They attribute the flood producing heavy precipitation events to deep and intense mesoscale convective systems (MCSs) with anomalously high pressure over the Tibetan Plateau and a strong low-pressure system extending across northern India, thus producing strong moist air incursions from the adjacent ocean (Bay of Bengal and Arabian Sea). Krishnan et al. (2016) also suggested that the role of moisture transport from the Bay of Bengal and Arabian Sea into the Indian Himalayan region results in a large build of buoyancy and pronounced vertical accelerations. Other studies point out the linkage of flood events in the Indian Himalayas to southward intrusion of upper-level mid-latitude baroclinic troughs, which interact with westward propagating monsoon synoptic systems over northern India (Vellore et al. 2014, Ranalkar et al. 2016). According to these studies, the resultant anomalous moisture flux is strong enough to support the flood producing storms. Other studies also suggested that the southward intrusion of mid-latitude weather systems associated with a persistent blocking high over Eurasian continent led to some of the extreme rainfall events over the Indian Himalayas (Allan & Ansell 2006, Priya et al. 2017).

Thus following the aforementioned studies, there are two primary pathways linking the oceanic moisture flux with the synoptic-scale environment favouring the Indian Himalayas floods: a westward extending monsoon low either coinciding with a southerly intrusion of mid-latitude westerly trough into the Indian Himalayan region or a ridge over Tibetan Plateau. Priya et al. (2017), while examining the historical rainfall records and reanalysis datasets, showed the increasing occurrences of heavy rainfall activity over Indian Himalayan region in recent decades. According to them the combined effect of weakened south Asian monsoon circulation, the enhanced southerly moisture transport and increased southward intrusion of mid-latitude troughs may be responsible for this trend.

Finally, during the northern hemispheric winter (December to February) there is a considerable amount of precipitation occurring in the western Himalayan region, usually in the form of snow. This comes from eastward moving low pressure synoptic systems known as westerly disturbances (Dimri et al. 2015, Tiwari et al. 2017). The disturbances originate over the Mediterranean and are fed with moisture from the Arabian Sea during their passage, losing it as they reach the high mountainous range.

3.1.3. Internal Variability on Interannual to Decadal Timescales

The ISM has substantial interannual to decadal variability. In this section we focus on internal variability, which is generated by natural fluctuations within the climate system. Anthropogenic climate change, which also influences decadal variability will be discussed in the next section. Many studies address the influence of SST variability on the ISM. It is quite well understood on annual timescales, but due to interactions between the different atmosphere-ocean modes of variability less is known about the links on decadal timescales.

We now consider specific modes of variability that influence the ISM. The El Niño Southern Oscillation (ENSO) is the dominant mode of interannual SSTs and wind variability over the equatorial Pacific Ocean, with preferred periods of about three to seven years. It is related to the ISM in a complex and not fully understood way. During the El Niño phase the central and eastern equatorial Pacific are anomalously warm, while during the La Niña phase they are colder than normal. The SST variability shifts the Walker circulation along the equator and leads to a weakening (strengthening) of the trade winds over most of the equatorial Pacific during El Niño (La Niña) conditions. Over India the shift in the Walker circulation leads to a strengthening (weakening) of the easterly wind components during El Niño (La Niña), which reduces (increases) moisture transport towards India from the Arabian Sea and the Bay of Bengal, leading in turn to a weakening (strengthening) of the ISM. In years when ENSO conditions feature warmer SST conditions over the equatorial Pacific and equatorial Indian Ocean, break phases are found to have be extended, potentially leading to droughts (Annamalai & Sperber 2016).

Azad & Rajeevan (2016) have shown that the strength of the ENSO-ISM link varies over the 20th century. Kumar et al. (2006) have demonstrated that it depends on the zonal position of the El Niño warming, with a stronger link when the warming is in the central Pacific and a weaker one when the warming is in the eastern Pacific, further corroborated by Ramu et al. (2018). Moreover, Turner & Annamalai (2012) have shown that the variations in this link are independent of changes in CO2 concentration, and Annamalai et al. (2007) have found these changes in control simulations with global climate models to be not in phase with the observed changes, both suggesting that the changes are due to internal variability rather than being externally forced.

The Indian Ocean Dipole (IOD) is an irregular SST oscillation with preferred timescales of 7.5 years and an anti-correlation between the western and eastern Indian Ocean. In the positive phase, where the western (eastern) part is anomalously warm (cold), the ISM tends to be stronger than normal, while the negative IOD phase has been linked to droughts (Jongaramrungruang et al. 2017). The link is established through a modulation of the strength of atmosphere-ocean coupling, altering intraseasonal convection and therefore monsoon circulation (Ajayamohan et al. 2008).

The Atlantic Multidecadal Oscillation (AMO) is a SST fluctuation across the entire North Atlantic with the same sign and a periodicity of about 65–80 years (Luo et al. 2011). It has been linked to multi-decadal ISM variability (Luo et al. 2011). In the negative AMO phase, which describes lower than average North Atlantic SSTs the ISM can withdraw earlier than normal in the late summer month, leading to a sharp decrease in seasonal rainfall. During a positive AMO phase the withdrawal of the ISM can be delayed (Krishnamurthy & Krishnamurthy 2016). Consistent with the finding on the link between the AMO and seasonal rainfall, 30 year epochs of high drought frequencies during the ISM coincide with the cold phase of the AMO and of the Pacific Decadal Oscillation (Vareed Joseph et al. 2013). The AMO influences the ISM through a modulation of the heat source for convection, and through changes to the southward displaced subtropical westerlies and the subtropical jet stream of the upper troposphere, and the generation of a large amplitude Rossby Wave train (Joseph 1978).

The North Atlantic Oscillation (NAO) and the Northern Annular Mode (NAM), which have high interannual as well as decadal variability, can also influence the ISM via the same mechanism by producing large-scale North Atlantic SST anomalies.

The slowly varying tropical SSTs can also influence the occurrence of daily precipitation extremes over the Indian Himalayas. For example, Mujumdar et al. (2012) showed an example of a La Niña situation characterised by a significant westward shift of the large-scale circulation over the Indo-Pacific sector (i.e. a westward shift of west pacific subtropical high) and subsequent intensification of rainfall and flooding over the Indian Himalayas. Priya et al. (2015) extended this study by analysing high-resolution simulations and found an increase in northward moisture transport from the Arabian Sea towards the Indian Himalayas contributing to the increase in rainfall extremes over the region.

3.1.4. Climate Change

In this section we discuss observed long-term climate trends. Future projections are discussed in Section 4. The IPCC’s 5th assessment report stated that global mean temperature has risen by 0.8°C since 1880 (IPCC, 2013). Past climate trends for the Indian Himalayas have been analysed in numerous studies which all agree on temperature changes.

Shrestha et al. (2012) summarised literature concerning temperature change across the Himalayas, highlighting that changes at the regional scale have yet to be documented. They generally found an increase of 1.5°C between 1982 and 2006, stating that the Indian Himalayas are experiencing rising temperature at a rate three times faster than the global average. Xu et al. (2016) more recently found a 2–2.5°C increase in temperature over the peak altitudes (5000m). Considering extreme temperature change, Sun et al. (2017) found a significant decrease in the number of extreme cold events, with a significant increase in the number of extreme warm events over the Himalayan region from 1961–2015.

The results on precipitation changes differ somewhat depending on the region and the analysed period. Palazzi et al. (2013) studied winter precipitation trends over periods varying from 30 to 60 years, finding no statistically significant changes. Fowler & Archer (2006) found no general long-term precipitation trends from 1895–2004. However, they suggested that from 1961–1990 there was an increase in winter and summer rainfall at some stations in the northern Himalayas. Whether this is due to the influence of westerly disturbances or the monsoon remains unclear. Khattak et al. (2011) found no significant precipitation trend in the upper Indus basin. Basistha et al. (2009) used observation data for precipitation in the region over a period of 80 years and found a decreasing trend in rainfall between 1965 and 1980. Cannon (2015) stated that the frequency and strength of westerly disturbances increased across the western Himalayas from

1971–2010, whereas they weakened across the central Himalayas, leading to a slight decrease in precipitation in the Ganges and Brahmaputra basins during winter.

There is evidence for an increase in intraseasonal monsoon variability, with the frequency of dry and wet spells (active and break events) increasing, the intensity of wet spells increasing, and the intensity of dry spells decreasing (Singh et al. 2014). Monsoonal precipitation shows a tendency towards a later peak and withdrawal (Sperber et al. 2013), and a weakening since the 1950s (Saha et al. 2014). The entire monsoon flow system has shifted westwards by around 2–3° longitudinally (Ghosh et al. 2012).

There is an increasing number of studies focusing on aerosol and climate interactions. The radiative effect of aerosols is thought to affect the intraseasonal and interannual variability of the ISM precipitation (Sanap & Pandithurai 2015). The suggested mechanism is an increase in the north-south tropospheric temperature gradient, leading to a northward shift of monsoonal precipitation and bringing about an early onset of the ISM by 1–5 days (D'Errico et al. 2015).

3.2. Glaciers

Glaciers in High Mountain Asia (HMA) are included within three subregions of the global Randolph Glacier Inventory: Central Asia, South Asia West and South Asia East, and together comprise 83,460 individual glaciers with a combined total area of 118,264 ± 24 km2 (Pfeffer et al. 2014). Glaciers within the Himalaya–Karakoram region are estimated to cover 40,775 km2, yet accurate information on their ice thickness distribution and total volume remains poorly known (Frey et al. 2014). Within this region, the glaciers of the Indus and Ganges river basins are particularly important. The Indus River supplies the world's largest system of irrigated agriculture, with 95% of the total river flow extracted to grow food to support 237 million people (Laghari et al. 2012, Pritchard 2017). Research on the state and fate of Himalayan glaciers has intensified in recent years following improved understanding of their societal importance and publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) (Solomon et al. 2007) which contained the erroneous statement that Himalayan glaciers would disappear by 2035 (Cogley et al. 2010).

The primary drivers of glacial change in the Himalaya are temperature (described more fully by the surface energy balance) and precipitation. These drivers influence ice accumulation and ablation, the sum of which is known as the glacial mass balance. In the Himalaya, the processes which dominate accumulation are precipitation by snowfall (followed by compaction), and snow redistribution by wind activity and avalanches. Ablation is dominated by melting of snow and ice but may also be affected by sublimation and iceberg calving into lakes. Glacier dynamics are incorporated into the total mass balance calculation by inclusion of a flux divergence term: the integral through the full glacier thickness of the vertical profile of the horizontal velocity or mass flux vector (Cogley et al. 2011). Very few in situ measurements of glacier mass balance exist in the Himalaya (Bolch et al. 2012) and precipitation is difficult to estimate due to poor distribution of weather stations, strong precipitation gradients caused by orography and rain shadow effects, and redistribution of fallen snow (Pritchard 2017). With temperatures increasing, snow cover declining and regional precipitation increasing, a detailed understanding of mass balance is required to reduce the uncertainty of the impacts of future climate change on Himalayan glaciers (Scherler et al. 2011).

The effects of glacier and landscape dynamics on mass balance are also poorly understood, in particular the complicating roles of periodic oscillations in glacier flow unrelated to climate (glacier surging) (Barrand & Murray 2006, Copland et al. 2011) and the effects on both ablation and ice flow of insulating debris cover (Quincey et al. 2011). Debris-covered glaciers are especially prevalent in the Himalayas, with between 14–18% of all glacial ice being covered (Kaab et al. 2012), whilst some regions have as much as 35% debris cover (Thakuri et al. 2014). The distribution of debris cover is skewed toward glacier ablation areas where it acts to insulate ice from melt (Ojha et al., 2017), meaning that it plays an important role in glacier response to climate change. The processes controlling melt under debris layers are still poorly understood, which together with incomplete knowledge of ice thickness and ice dynamic feedbacks mean that our ability to simulate future glacier evolution via both surface mass balance and ice flow is hampered. Additionally, debris-covered glaciers are also known to preferentially develop supraglacial and proglacial lakes which may act as both a temporary water store and a significant flood hazard to downstream communities (Quincey et al. 2007). Comprehensive data on glacial lake evolution remains both spatially and temporally limited.

Due to the different geographical position and elevations of the eastern and western regions of the Himalayas, temperatures, precipitation and glacial characteristics in the two regions differ. The glaciers in the north-western Himalayas extend to lower elevations, mainly due to the decrease in temperature as the latitude increases. The meteorological processes that shape regional weather and climate patterns also differ. The western Himalaya are dominated by wintertime westerly low pressure systems while the eastern Himalayas are dominated by the monsoon.

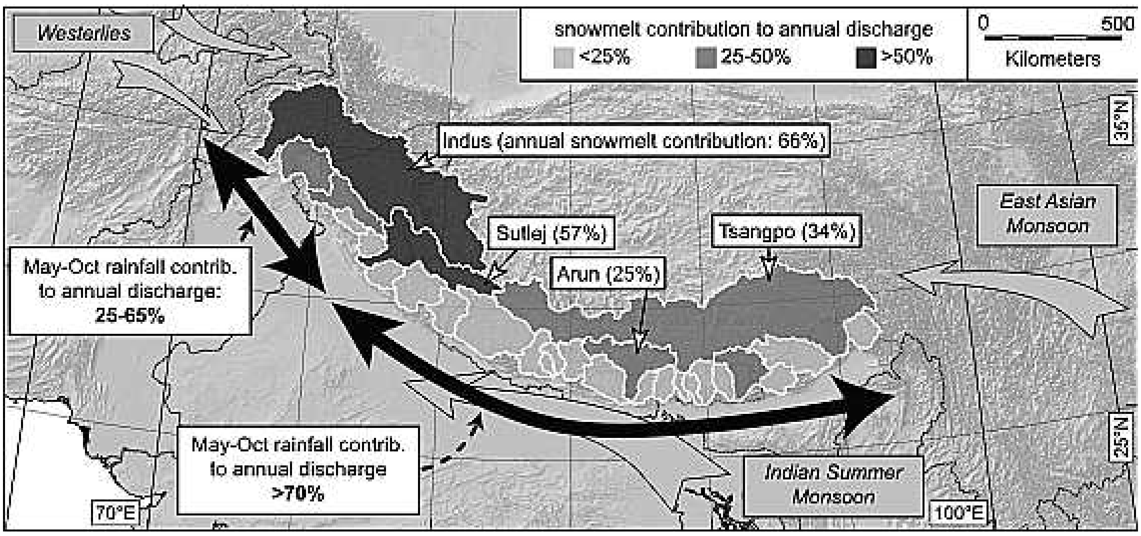

Figure 4. Conceptual climatic and hydrological model for the Himalayas indicating snow melt and monsoonal rainfall contributions to annual discharge (Bookhagen & Burbank 2010).

3.2.1. Wester Glaciers

The accumulation on western Himalayan glaciers is primarily caused by winter precipitation from low-pressure systems moving into the area from the west (Scherler et al. 2011). This results in ice accumulation predominantly in winter and ablation during the warmer summer months (Armstrong et al. 2010). The mass budget of western Himalayan glaciers has been close to balance or slightly positive in recent years, a phenomenon referred to as the 'Karakoram Anomaly' (Scherler et al. 2011, Gardelle et al. 2012). Only a few glaciers at lower elevations have shown signs of retreat (Immerzeel et al. 2010) though this picture is complicated by the dynamics of slow-flowing and downwasting debris-covered glacier tongues (Quincey et al. 2011). Estimates of glacier retreat and advance, which usually take place at the glacier tongue, are especially difficult where thick debris cover exists as it is difficult to distinguish between the spectrally similar ice margins and surrounding terrain (Kamp et al. 2011, Paul et al. 2013). Debris cover is influenced by topography as when snow falls on steep mountainsides, material loosened by glacial and periglacial activity cascades onto the ice surface and is transported downhill and down glacier, leading to large build-ups in the ablation zone (Benn & Owen 1998).

Recent geodetic analysis of remotely-sensed data have suggested that changes in ice thickness of debris-covered glaciers are more uniform across the whole range than previously thought (Ragettli et al. 2016). Measurements of ice volume of western glaciers have also proved difficult due the lack of high altitude monitoring stations, the impact of avalanches on height measurements (Bolch et al. 2012) and the extreme remoteness of the glaciers making direct geophysical measurement problematic. Moreover, the formation of exposed ice cliffs and supraglacial lakes, which melt at a faster rate than non-exposed ice, also make measurements of glacier mass balance in the west difficult. It is challenging to separate the contributions to stream flow in these basins from glacial meltwater and other stochastic sources (Miles et al. 2016).

3.2.2. Central and Eastern Glaciers

The central and eastern Himalayan glaciers are fed through the summer monsoon precipitation, and are therefore classed as summer-accumulation glaciers (Thakuri et al. 2016). These glaciers are behaving quite differently to those in the northwest (Karakoram) sectors, with Scherler et al. (2011) reporting that more than 65% of central and eastern Himalayan glaciers are reducing in area. Of this sample, those with heavy debris cover and low-gradient terminus areas remained stable, probably due to the insulating effects of supraglacial debris, and the slow-flowing dynamics of shallow termini.

The average air temperature in the region has increased by 0.9°C since the 1990s (Salerno et al. 2015), and as a response there has been a decrease in snowfall by 10%. Rainfall has also decreased by 47% due to monsoon weakening towards the north of India (Yao et al. 2012). Many of the larger glaciers in the region are debris covered, towards the Tibetan Plateau debris covered glaciers are almost non-existent. Gardelle et al. (2011) reviewed recent studies and found that the number of proglacial lakes has been constantly increasing since the 1960s, and now is the highest within the entire Hindu Kush Himalaya range, which indicates an overall glacial retreat in the central and eastern Himalayas.

3.2.3. Past Glacial Changes

Although the Indian Himalayas have the largest concentration of glaciers outside the Polar Regions, the remoteness and rough terrain leads to strong uncertainty as to how they are reacting in a changing environment due to a lack of understanding of processes and in situ measurements. As stated throughout Section 3.2.1, there are discussions as to whether the glaciers are retreating or expanding across the region. In order to estimate trends of past glacial changes, recession records must be collated from what sparse information is available (Kargel et al. 2011). The simplest approach are measurements of glacial length and spatial extent which have recorded losses for the previous 40 years (Mehta et al. 2011, Bhambri et al. 2012). However, these are found to have an indirect and delayed response to a warming environment (Pratap et al. 2016). Therefore, direct measurements of glacial mass balance are desirable.

Glacier mass balance is measured using glaciological, hydrological and geodetic methods. Due to the novelty of this approach, only two glaciers in the Indian Himalayas have partial mass balance records, the Chhota Shigri and Hamtah, which show overall negative mass balance (Azam et al. 2012). Although Bolch et al. (2012) analysed mean mass balance over the Indian Himalayas from what records are available and found a negative trend, they emphasised that records are very incomplete.

3.3. Hydrology

3.3.1. Hydrological Processes

Both the western and eastern Himalayan regions provide a vital contribution to the water supply of both the Himalayan region itself and downstream northern India (Benn & Owen 1998). The area is characterised by high precipitation rates and little evaporation due to the low air temperatures which results in longer snow coverage, therefore releasing sizable contributions of glacial and ice meltwater runoff to the downstream basins (Viviroli et al. 2007). Water availability in the region is driven by inputs, outputs and storage. As the vital input to the hydrology system, precipitation in the Indian Himalayas is caused both by the ISM and westerly disturbances (Dimri et al. 2015).

Within the region, water is stored in the catchment glaciers, permanent snow pack or seasonal snow, supraglacial ponds and lakes, groundwater and man-made reservoirs. The understanding of regional hydrology, in particular the contribution to each river from annual-mean glacial and snow melt contributions sourced in the Himalayas vary between studies. Xu et al. (2007) found a range from 45%, depending on the river, whereas Bookhagen & Burbank (2010) found 15–60% in the Indus basin and less than 20% in the central to eastern basins. More specifically, Schaner et al. (2012) reported that the glacial contribution on annual water availability is only 5–0% in the Ganges, highlighting the spatial variation.

The contribution of meltwater to stream flow is seasonally dependent, and the timings of the summer melt season and rainy seasons determine the relative contributions of rainfall and meltwater to the rivers. The summer melt season in the Himalayas occurs pre-monsoon, from April to July (Fadnavis et al. 2017), and during this time roughly 70% of stream flow feeding the more western rivers such as the Indus and Ganges is sourced from melting snow (Barnett et al. 2005). The ISM onset varies regionally (Figure 3). Over northern India the ISM reaches the eastern states earlier than the western ones. West Bengal to the very east of the Himalayas experiences the ISM onset around 10th June, whereas in the more central Uttar Pradesh the onset date is around 1st July. Punjab in the north-west does not experience the ISM until 1st August and ISM rainfall is much lower than in the central and eastern regions because of reduced moisture availability (Gadgil 2003). The relative contribution of the meltwater is highest when it coincides with the low precipitation season and thus maintains the provision of water to semi-arid regions such as Rajasthan and the north of Haryana (Kaltenborn et al. 2010).

Groundwater is one of the most important components of the Indian Himalayan hydrological system, yet not much is known about the amounts of water stored in this reserve. Numerous reasons exist for this uncertainty from a lack of measurements in the hostile terrain, along with a lack of understanding of the relationship between glacial and snowmelt and the groundwater replenishment rates. Mukherjee et al. (2015) estimated that every hydrological year over 4000 km3 of water enters the Indian subcontinental systems from the Himalayas, of which half is lost to processes such as surface discharge, overland flow, evaporation and evapotranspiration. The remaining water left in groundwater reserves was estimated to decrease at a rate of 54 km3/yr between 2001 and 2008 (Tiwari et al. 2009), a depletion rate which since appears to be sustained (National Research Council and Committee on Population 2012). Bookhagen & Burbank (2010) state that means to rectify this uncertainty such as satellite measurements are too coarse a resolution to distinguish between groundwater reserves, the contribution from ice melt and sediment.

3.3.2. Major Rivers

The Himalayas are drained by 19 rivers, of which the Indian Indus and Brahmaputra are the largest, covering a catchment area of over 520,000km2 in the mountains alone. The Indus basin in the west is the second largest catchment in India, covering 453,000km2 in the Himalayan lowlands. Its flow is fed predominately through a constant contribution of glacial meltwater and precipitation from the westerly disturbances in the winter and spring, with little influence from the ISM over the summer. In the high elevation parts of the catchment, precipitation can fall as snow, depending on the temperature. The lower parts of the catchment receive most of the precipitation through rainfall.

There has been a decrease in summer monsoon rainfall within the Indus basin from 1922–2004 (Bhutiyani et al. 2008). There is also a reduction in snow cover, a shortened melt season in some areas, as well as an extended ablation period in the high elevation zones. The combined effect of these changes on river flow has been suggested to increase annual mean river flow by 4%–6% (Singh & Bengtsson 2004).

In the central Himalayas, the flow in the Ganges is comprised of contributions from both glacial meltwater and monsoon rainfall. The interannual variability seen in the stream flow is primarily driven by changes in precipitation patterns, with meltwater from the eastern and central glaciers providing a consistent base flow during the dry season (Thayyen et al. 2007). There is a strong west to east gradient across the basin in rainfall as the monsoon weakens, during the season the Bhagirathi sub-basin in the west receives 60% of its rainfall whereas the Koshi catchment in the east receives between 72–81% (Nepal & Shrestha 2015).

The Brahmaputra basin in the east joins the Ganges River, becoming the largest basin within the Himalayas. The absolute amount of meltwater is similar to other basins, but due to the very high ISM rainfall, the flow variability is dominated by the ISM (Bookhagen & Burbank 2010, Shah & Mishra 2016). The upper reaches of the basin lay in the Himalayan rain shadow, where precipitation can be as low as 1200mm, compared to over 6000mm per year on the southern Himalayan slopes (Nepal & Shrestha 2015).

3.3.3. Extreme Events

With high population densities in the region, extreme events like floods and droughts cause major damage, both in and downstream of the Himalayas. The 2016 drought, caused by two weak monsoons, and the 2017 floods, caused by heavy monsoon rains, are two recent examples. Related to climate change there has been an increasing trend in the recurrence of extreme events in the Indian Himalayan region.

The 2017 floods affected 31 million people in the states of Assam, West Bengal, Bihar, and Uttar Pradesh, causing the death of over 100 people and the destruction of over 800,000 homes (NDTV 2017). Houze et al. (2017) studied the June 2013 flood event in Uttarakhand, which lasted 3 days, during which between 500mm and 1000mm of rain fell across the state. This resulted in a death toll exceeding 5,700, with 4,000 villages affected at a cost of $16 billion (Houze et al., 2017). Unlike most floods in the region which stem from exceptionally heavy monsoon rainfall (Rasmussen et al. 2015), the 2013 Uttarakhand flood was due to an eastward propagating trough in the westerlies extending further south than usual which merged with a monsoon low (Houze et al., 2017). This was orographically lifted across the mountainous region causing heavy continuous rainfall. Another devastating flood was seen in Leh, India, in 2010. This was caused by a strong mesoscale cyclone which flooded the high altitude region, causing the deaths of 548 people (Singh et al. 2016a). Extreme precipitation events causing floods within the Ganges basin increased from 1965 to 2000 (Sharma & Shakya 2006).

Although some flood events can last from days to months when influenced by high monsoonal rainfall, some areas within the Himalayas are prone to flash floods which typically affect an area in less than six hours. Nibanupudi & Shaw (2015) stated that flash floods causes the loss of at least 5000 people every year. Another flooding risk in the Himalayas is related to Glacial Lake Outburst Floods (GLOFs) and Landslide Lake Outburst Floods (LLOFs). Kumar et al. (2017) have analysed landslides in the Indian Himalayas caused by heavy monsoonal rainfall or glacial lake outbursts stemming from an increased melt season of the glaciers. In particular, in September 2014 Jammu and Kashmir experienced one of the worst floods due to unprecedented intense rains flooding the Jhelum River, causing at least 75 houses to be destroyed and burying 40 people under a thick layer of debris in Sadal village. Although the cause of landslides has been extensively studied (Chauhan et al. 2010, Kuthari 2007, Bathrellos et al. 2012), Kumar et al. (2017) state that negligible attention has been paid to understanding the evolution of landslides caused by heavy rain events. Dimri et al. (2016) give an overview of the various flood generating mechanisms in the Himalayan region and discuss example events. They also state that there are many gaps in the understanding of processes underlying flood development in the Himalayan region, due to the complex interactions and feedbacks.

Despite the fact that the Himalayan region is relatively wet compared to downstream regions and other parts of India, droughts can cause severe problems here as well. A weak monsoon or a delayed onset of the monsoon reduces water availability in reservoirs and groundwater. This has happened regularly in the recent and more distant past, as has been found from tree rings. Yadava et al. (2016) found a 12th to early 16th century dry phase and related it with historic social upheavals and invasions. Shah et al. (2014) found multi-year monsoon-failure related droughts in the 18th and 19th century and the worst recent drought was in 1918, in which almost 70% of India was affected.

Often glaciers are seen as buffer against precipitation deficits or meteorological drought (e.g. Pritchard 2017). Due to the large area of these glaciers, they provide both an important water storage reservoir and a buffer against water shortages during times of low flow (Milner et al. 2017). Meltwater from glaciers strongly influences the annual cycle of river flow in the major Indian rivers by storing water from snow accumulation during winter and releasing meltwater during late spring and summer when other contributions to flow may be small (Immerzeel et al. 2010). Himalayan glacial ice thus acts to protect against regional water shortages as meltwater supply can be sustained throughout periods of drought (Pritchard 2017). So, if the monsoon has a delayed onset or is particularly weak, meltwater can, at present, still be relied upon to avoid hydrological droughts (Xu et al. 2009). The buffering effect of glaciers will however change in the future with decreases in glacier extent (Immerzeel et al. 2010) and more research is needed on how droughts will influence water resource availability in the future.

Snow and glacial melt however also exhibit interannual variability, and temperature often plays an important role in the development of hydrological drought in this region (Van Loon et al. 2015). A high temperature in winter causes low snow accumulation, influencing river flow and reservoir storage in winter and subsequent spring, and a low temperature in spring and summer results in low snow and glacier melt, influencing river flow and reservoir storage in spring and summer. A coincidence of low monsoon rainfall with low snow and glacial melt can cause major problems downstream in the large rivers draining the area. There is hardly any research on the processes underlying these combined events with huge potential impact on people's lives and livelihoods. Another extreme event often related to drought is heat waves. Panda et al. (2017) analysed heat wave trends from 1951 to 2013, finding that the duration of daytime heat waves has increased considerably since 1980, with 2010 witnessing the warmest heat wave event recorded in India. Singh et al. (2016c) also noted that an observed increase in the frequency of heat wave events in the region increases number of fatalities and decreases personal productivity.

Several factors, including fragile ecosystems and widespread poverty, make the Himalayan region extremely vulnerable to physical hazards such as drought and flooding (Gurung et al. 2014). Water management, including prediction of extreme events and early-warning systems, is a crucial importance to reduce damage.

3.3.4. Water Use

The very nature of the trans-boundary mountain range makes estimations of water resource requirements, stress and over-exploitation difficult as so many countries rely on the ecosystem at local, regional and national levels. Recent studies have focused on finding efficient ways to govern the valuable commodity, from managing stakeholders, creating fairer water pricing and changing the way subsides operate in a bid to lessen the ever increasing demand for water for agricultural irrigation or large infrastructure construction (Shah 2010). As of yet, there is a lack of scientific consensus on the spatial and regional aspects of water resource availability and depletion, as well as how the implications of climate change will alter the physical processes providing this resource.

For the entire sub-continent the per capita water availability decreased from 1986m3 in 1998 to 1731m3 in 2005, with a projected further reduction to 1140m3 in 2050 (Gupta & Deshpande 2004). Data specifically for the Himalayan region are not available.

There is also a paucity of data detailing specific water demand within the Himalayan region. Inferences can be made through national statistics, agricultural demand for water constitutes a majority (84.9%), followed by domestic (6.6%), industrial (5.6%), and hydro-power (2.9%) (Infrastructure Development Finance Company 2011). In addition, over 70% of irrigated agriculture sources its water from groundwater sources, thus making groundwater a critical resource. The fact that extraction of groundwater occurrs at a rate 56% faster than the replenishment rate, is serious concern for the region, not only for the agricultural sector but also for human livelihoods and sustainable economic growth. Through over-extraction of groundwater in upstream areas, downstream communities face a higher risk of water scarcity. The major Indian rivers are also increasingly running the risk of not being able to dilute pollutants from industrial and domestic wastage, agricultural pesticides, erosion and religious practices, which all aid in threatening human wellbeing.

Although aware of the issues surrounding water quantity and quality, India has yet to harness its water resources effectively. Considering the technical limitations, water distribution patterns and poor management of resources, serious mitigation or adaptation techniques need to be applied as recognition of water as India's most threatened critical commodity in the face of climate change is cemented.

4. Predictions

4.1. Weather Forecasting and Seasonal Prediction

The Ministry of Earth Sciences (MoES), Government of India, under collaborative agreements with the UK Met Office and the National Center for Environmental Prediction/National Oceanic and Atmospheric Administration (NCEP/NOAA) in the US, has developed state-of-the-art weather and climate modelling systems for the Indian region based on global and regional models. They produce real-time weather and short-term climate forecasts and are used operationally by the India Meteorological Department (IMD) for various end usages, including water management and disaster related applications.

For medium-range forecasts the National Center for Medium Range Weather Forecasting (NCMRWF) has implemented the UK Unified Model (UM) based on global and regional models. The global model (up to 10-day forecasts) is configured at 17km horizontal resolution and the regional model (up to 3-day forecast) covers the whole Indian subcontinent with a horizontal resolution of 4km (Rajagopal et al. 2012). A UM-based global ensemble prediction system (NEPS) is run at 33km horizontal resolution with 45 members and produces probabilistic forecast up to 10-days.

The NCEP/NOAA Global Forecasting System (GFS) configured at 12km horizontal resolution is implemented by the Indian Institute of Tropical Meteorology (IITM) and the products are available through the IMD website. IITM has also implemented a GFS-based ensemble prediction system at 27km horizontal resolution and 20 members, and a GFS/CFS-based coupled modelling system for extended (ERPS) and seasonal prediction over India (Sahai et al. 2015). This ERPS is used to predict the weekly/pentad anomalies of rainfall over the Indian region. The GFS/CFS-based seasonal prediction is useful for seasonal monsoon rainfall outlook at seasonal scale. In the medium range the model has reasonable skill for water related applications, but needs systematic bias corrections to be applied (Mitra et al. 2011, Prakash et al. 2016a, b). IITM has also coupled the WRF regional model to the GFS model, using a double-nesting with 9km and 3km resolution.

These models are being further developed and a seamless prediction framework is being pursued at NCMRWF in collaboration with the UK Met Office (Mitra et al. 2013). It is expected to improve the skill of monsoon rainfall forecasts for all timescales from days to season. NCMRWF has recently implemented a UM-based coupled ocean-atmosphere-land modelling system with its ocean- and land-initialization components, which potentially will produce skilful prediction of the dry-wet spells of monsoon rain.

In spite of all these developments, the model output still shows substantial biases, and thus post-processing of the simulations is an important task to be undertaken at various space-time scales for water-related applications. Model validation is only available for special aspects, for instance by Shah et al. (2017), who found that for drought prediction the IITM forecast has a better skill than the NEPS forecast. However, a comprehensive evaluation of the forecast from different sources, including post-processes ones, should be undertaken for various hydrological applications (floods and low flow) for the catchments in the Himalayan region, and for various lead times.

4.2. Climate Predictions

4.2.1. GCM Simulations

Coupled atmosphere-ocean General Circulation Models (GCMs) are the primary source of information about future climate change. The most recent set of simulations have been conducted in the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5), which is the basis for the climate projections published in the 5th Assessment Report (AR5) of the IPCC (2013). AR5 uses the low emission scenario RCP2.6, the medium emission scenarios RCP4.5, RCP6 and the high emission scenario RCP8.5. For RCP4.5 the CMIP5 projections show an increase in global mean temperature between 1.0°C and 2.5°C by the end of the 21st century relative to the reference period 1986–2005. For the whole South Asian region the projected warming for the same emission scenarios is 1.0–2.7°C for June–August, and 1.5–3.5°C for December–February. For higher emission scenarios larger increases are simulated. In both seasons the warming over northern India is stronger than the average warming over South Asia (AR5, Annex I).

For South Asian precipitation during the monsoon season April–December the simulations project an increase of about 5–20% for RCP4.5. For higher emission scenarios the ensemble mean increase is slightly higher, and interestingly the ensemble spread increases substantially, with decrease or no change still within the range of possibilities. Over subregions the ensemble spread is high, for instance -10–+30% over north-western India for RCP4.5. For South Asian precipitation during October to March the range for all emission scenarios encompasses negative and positive changes. Some ensemble members simulate particularly high increases, up to 50% for RCP4.5, over the north-western parts of India.

The CMIP5 ensemble has been analysed specifically for the Himalayan range (Panday et al. 2015, Menegoz et al. 2013, Wu et al. 2017, Singh & Goyal 2016, Palazzi et al. 2015). Panday et al. (2015) analysed multi-model means, and found more extreme conditions in the future consistent with a warmer, wetter climate. In addition to the increase in mean precipitation the study found an increase in the occurrence of extreme monsoonal rainfall in the eastern Himalayas, and a wetter winter season in the western region. Wu et al. (2017) found an increase in mean precipitation and precipitation extremes for all but the north-western most regions. Palazzi et al. (2015) found generally wetter conditions in the Himalayas, especially during the monsoon, and no significant changes for winter precipitation.

The International Centre for Integrated Mountain Development (ICIMOD) conducted a climate change study in the Indus, Ganges, and Brahmaputra basins using the simple delta change method based on four GCMs (Lutz et al. 2014). For the period 2021–2050 temperature in all three basins is projected to increase by 1.7–2.9°C under RCP4.5, and between 2–3.5°C under RCP8.5. The projections for precipitation show a wider spread. Under RCP4.5 the estimates range from -10–+10% in the upper Indus and between +5–+15% in the upper Ganges and Brahmaputra. The projections for RCP8.5 show projections ranging from -15–+10% in the Indus, +5–+35% in the Ganges, and between +5–+15% in the Brahmaputra (Lutz et al. 2016).

Singh et al. (2016b) used Intensity-Duration-Frequency (IDF) curves to quantify the extreme precipitation occurrence. Sub-daily maximum intensities were obtained from the observed records from the observatory of the Department of Hydrology at IIT Roorkee, India. The IDF curves were developed using observed and projected data from the CMIP5 model ensemble. Analysis of the curves indicated an increase in precipitation intensities for all the RCP scenarios.

GCMs are not yet able to represent the ISM dynamics realistically, with models varying greatly with respect to the date of onset, the amount of precipitation and monsoon pathway (Lutz et al. 2016). Although there might be a contribution of internal variability to the model differences, this makes regional projections for the Himalayan region problematic.

4.2.2. Downscaling

The relatively coarse horizontal resolution of the CMIP5 GCMs, which is on the order of 150km, means that regional climate variability is not well-resolved. In addition, errors in the representation of sub-grid processes, which are included by parameterisations, may cause errors on the grid-scale and on larger scales. These errors can be expected to become smaller by using finer resolutions, partly because the effects caused by the local topography are better captured. Analogously to the set-ups for regional models in weather forecasting, regional climate models (RCMs) are run by driving them at their lateral boundaries with the GCM-simulated values. The domain size is typically a few thousand kilometres, and the horizontal resolutions are usually in the range 25–50 km, thus somewhat coarser than for regional models used in weather forecasting, due to computational constraints and the long simulation times needed. Regional climate modelling allows to obtain smaller-scale information that is consistent with the driving GCM and is known as dynamical downscaling. Statistical downscaling, which employs statistical models representing empirical relations between large and small scales, has the same objective. Both approaches are reviewed for instance in Maraun et al. (2010), and statistical downscaling is comprehensively discussed in Maraun & Widmann (2018). It requires local observations to fit the statistical models, which are sparse in the Himalayas, and which is one of the reasons that for this region there is an emphasis on dynamical downscaling.

The skill of RCMs over the Himalayas has been demonstrated by showing that reanalysis-driven RCMs (i.e. using almost perfect boundary conditions) have smaller biases than the coarser-resolution reanalyses (e.g. Dimri et al. 2013, Ménégoz et al. 2013, Kumar et al. 2013). However, these studies and similar ones for other regions (e.g. Kotlarski et al. 2014) have also shown that substantial biases still remain in RCM simulations. Mishra et al. (2014) have shown that RCMs do not significantly improve the representation of precipitation extremes over India compared to GCMs. Although bias correction methods, and more general Model Output Statistics (MOS) methods, that can remove some of these biases have been developed, they cannot correct all aspects of the simulation outputs that are potentially relevant in applications (Guttiérez et al. 2018; Maraun et al. 2017, 2018; Widmann et al. 2018). A comprehensive review and discussion of MOS methods is provided by Maraun & Widmann (2018).

Future climate projections for South Asia with three different 50km-resolution RCMs driven by several GCMs in 13 combinations have been conducted within the framework of the Coordinated Regional Climate Downscaling Experiment (CORDEX) South Asia and have been investigated for the Hindu Kush Himalayan by Sanjay et al. (2017). They found a relatively good agreement of the simulations in the hilly sub-regions within the Karakoram and north-western Himalayas but a wider spread in the central Himalayas. For the RCP8.5 scenario there is good model agreement on an intensification of the summer monsoon in the south-eastern Himalayas and Tibetan Plateau, and less confidence in precipitation changes in the central and north-western Himalayas, and the Karakoram. They concluded that the RCM uncertainty in projected temperature and precipitation changes for elevated areas within the region stems from an unrealistic representation of regional processes and feedbacks in the models. Choudhary & Dimri (2018) also analysed projected precipitation changes in the CORDEX simulations and found generally wetter (drier) conditions in the western (eastern) Himalayas, which becomes more intensified towards the end of the 21st century, but pointed out major uncertainties in predicting the elevation-dependence of precipitation changes. For the present climate the CORDEX simulations show a wide model spread of mean precipitation with a general dry bias in the foothills and a wet bias in higher elevations (Ghimire et al. 2018).

Future climate projections for India with three different 25km-resolution RCMs driven by three different GCMs have been analysed by Kumar et al. (2013). The study shows some modifications of the climate change signal by the RCMs, for instance smaller or no precipitation increases in parts of the Indian Himalayas at the end of the 21st century in the RCM ensemble mean in contrast to an increase in the GCM ensemble mean. The spread caused by using different GCMs was larger than that caused by different RCMs. Mittal et al. (2014) have analysed four 25-km resolution RCMs with respect to changes in temperature and precipitation extremes in the Ganges river basin, and found an increase in heavy precipitation during the monsoon period and an increase in dry spells during winter months.

RCM simulations with 25km resolution have also been used for impact studies, for instance by Whitehead et al. (2015b) who investigated the impact of future climate change and socio-economic change on flow and nitrogen fluxes in the Ganga river system. They have used one RCM (HadRM3P) driven by a 17-member perturbed physics ensemble of the HadCM3 GCM to provide input for a hydrology and water quality model. Direct statistical downscaling of GCMs, i.e. without using RCMs, by MOS quantile mapping has been used for studying the impact of climate change on river flow in the Ganges and Indus basins (Immerzeel et al. 2013). An RCM (WRF) with 30km and 10km resolution driven by the GSF analysis has been used by Maussion et al. (2014) to generate a High Asia Reanalysis for the period 2001-2011.

Collier & Immerzeel (2015) used an RCM to study atmospheric dynamics over the Nepalese Himalayas. Orr et al. (2017) investigated the sensitivity of the WRF RCM over the Himalayas to different parameterisations, and Karki et al. (2017) analysed added value of a very-high-resolution, convection-permitting RCM (WRF) over the Himalayas.

4.3. Glaciers and Hydrology

As stated in Section 3.2.3, modelling of glacier mass balance is a novel approach to evaluate the evolution of Indian Himalayan glaciers in a changing climate. Recent studies have focused on using simplified parameterisation techniques to cover such a large glaciered area as the Himalayas (Lutz et al. 2016). The general consensus across glacier studies is that of declining ice mass towards the end of this century, with an equilibrium state at high elevations reached rather than complete disappearance of the ice mass (Shea et al. 2015).

Immerzeel et al. (2013) simulated the changes to glaciers in the upper Indus and upper Ganges, up until 2100 using RCP4.5 and RCP8.5 in the CMIP5 ensemble. The study shows predictions of mass retreat and decline of glacial tributaries with vast differences between glacial changes under both scenarios. The RCP8.5 scenarios showed a loss of 33% and 54% respectively.

Lutz et al. (2014) simulated changes to the glaciers up to 2050, predicting decreases of between 20–28% in the Indus, 36–48% in the Ganges, and 31–45% in the Brahmaputra basins. Only a few studies focused specifically on the Indian Himalayan glaciers, and those focused on the entire Hindu-Kush-Himalayan range highlight many limitations within glacial modelling. There is a large uncertainty in future projections, stemming from various parameterisation approaches used, a lack of understanding of current glacial mass balance within the region and different scenarios of greenhouse gas emissions used in the models.

Most approaches to glacial modelling use a digital elevation model, vital for simulating climate and glacial changes in the high Himalayas. However, glacier outlines have to be assumed which is, as previously stated, a challenge when considering debris covered glaciers. Another key issue with glacial projections is that the evolution of a glacier is predominately influenced by climate, such as changes to precipitation, but climate change projections are uncertain. This also poses an issue for snow cover modelling, as snow cover evolution is strongly tied to precipitation.

The limitations in the glacial models are a fundamental issue when it comes to predicting the impact of climate change across the region. Glacial models are coupled with hydrological models to simulate streamflow, groundwater supply and flooding. Without reliable predictions of the change to the Himalayan glaciers, hydrological models are unable to simulate streamflow accurately.

River gauge measurements and observation-based, short-term river level predictions are provided by the Central Water Commission (CWC). The CWC has also made some efforts in using weather forecasts as input to hydrological models. However, coupling meteorological and hydrological models for India is still in a pioneering phase, as major challenges exist due to biases in the amount and location of the simulated precipitation that is used as input for the hydrological models, and the modelling systems are not yet used for operational forecasts.

There are considerable uncertainties in future projections of water resources in the region (Jeuland et al. 2013, Singh & Kumar 2015). Hydrological projections for larger rivers are derived by forcing a hydrologic model using downscaled climate model data (generally precipitation and temperature). Assessments on the catchment scale usually use meteorological data collected from local stations (Soncini et al. 2015). Both smaller and larger scale hydrological modelling in the Indian Himalayas is affected by the variability seen in climatic variables, spatially and vertically (Lutz et al. 2016). From this, challenges arise in downscaling climate data from course spatial resolutions and extrapolating data from the available meteorological stations. These challenges typically result in what is termed the forward propagation of uncertainties resulting in potentially large uncertainties in projections of streamflow (Wilby & Dessai 2010).

A major source of uncertainty in projections of future streamflow across India is the choice of climate models whose outputs are used to drive hydrologic models (Jeuland et al. 2013, Singh & Kumar 2015). In addition, there is a significant intra-basin variability in the projected changes of climate and glaciers, which then feeds into the hydrological models. For example, the multimodel ensemble mean changes in monsoon season precipitation vary from 10–25% in the Ganges basin (Mishra & Lilhare 2016), yet there are indications that streamflow will increase across the basin owing to projected increases in precipitation (Mishra & Lilhare 2016, Whitehead et al. 2015a). Immerzeel et al. (2013) analysed projections of surface runoff in the Ganges basin until the end of this century, concluding that under both RCP scenarios, there will be a constant increase in runoff compared to historical observations. The percentage increase ranged from 31–46% depending on which glacier was feeding the basin (the Langtang or Baltoro) under RCP4.5, and from 88–96% respectively under RCP8.5. An increase in glacial melt was held responsible for the increase in streamflow in the Baltoro simulation, whereas an increase in annual precipitation was deemed responsible for the increase seen in the Langtang streamflow. Lutz et al. (2014) estimated an increase in streamflow in the Indus, Ganges, and Brahmaputra basins until 2050. The increases in streamflow vary from the predominant source of water within the basins, glacial meltwater in the Indus and precipitation increases across the Ganges and Brahmaputra. Whitehead et al. (2015b) used the INCA hydrochemical model, driven by an RCM with 25km resolution, and found large increases in both mean and maximum flow in the Ganges basin by 2050. This is a result of increased monsoonal precipitation, which also leads to increased flood occurrences. The authors do emphasise that the quality of the observational data hinders the ability to test the model and assess the model uncertainty. Pechlivanidis et al. (2016) used CORDEX South Asia climate change projections, bias-corrected using the Distribution Based Scaling method to force the HYPE hydrological model. They found that an increase in precipitation, especially during the monsoon season leads to an increase in runoff in all basins, with high spatial variability. In their study, projections for the Indus basin and the Ganges show more signs of an increase than the Brahmaputra, most likely due to the influence of enhanced meltwater rates from the Himalayan glaciers.

Overall, hydrological models agree that streamflow in the Indian Himalayas will increase towards the end of this century, associated with increases in monsoonal rainfall and glacial melt. Recent models that include evapotranspiration require specific data on soil properties, land use and vegetation type, which makes their use in the Himalayas challenging because of the large variability in these variables combined with a lack of observations.

5. Challenges and Ways Forward

5.1. Current Status

Here we summarise key findings from the review of the scientific literature before discussing challenges and opportunities for the development of hydro-climatic services in detail in the next sections.

The large-scale controls for weather and climate variability have been identified, but open questions remain related to their relative importance, which depends on the timescale, and to their interactions with each other. It is also unclear how these different large-scale factors will be affected by climate change, and conversely how they will influence climate change in the Himalayas. The knowledge of small-scale meteorological processes, for instance the local effects of the topography or cloud microphysics, is limited: partly because there are not many high-resolution observations. Individual glaciers in the Himalayas, which play a major role in the hydrology of the region, have very different characteristics, for instance because they are located at different altitudes, in different reliefs, and have different sizes. There is considerable uncertainty about their historical mass-balance status, due to a lack of mass balance observations (as a result of major logistical and access constraints), which in turn makes it difficult to identify the processes that dominate extent and mass-balance of a given glacier. Understanding the specific hydrological processes in the major river basins is also hampered by the limited availability of hydrological observations, such as river flow measurements. There is also lack of knowledge about the river basin properties and how these modify the climate inputs (through basin storage and transfer processes) to generate river flow.

Substantial meteorological and hydrological modelling capabilities do exist, with state-of-the-art models being implemented and good computational resources available. However, the lack of observations, in particular for hydrological variables, makes calibration and validation of hydrological models, and defining the initial conditions for forecasts difficult. Meteorological models have good general skill for short-term forecasts, but the simulated precipitation has biases in location and amount, and longer-term to seasonal predictions remain a challenge, because of limited understanding of the relevant predictors, deficiencies in initialising the predictions, and fundamental predictability limits due to the chaotic nature of the climate system. Moreover the models are not comprehensively validated. The forecast information is available through the IITM and IMD websites. Climate projections for the 21st century from the CMIP5 global model ensemble show an overall increase in temperature and precipitation, but for precipitation considerable spread between the models, and it is not clear to what extent this reflects model deficiencies, which can potentially be reduced, and to what extent it is a consequence of natural variability and thus reflects irreducible uncertainty. Regional weather forecasting models are routinely run for short-term forecasts, and regional climate model simulations have also been conducted. This downscaling attempts to representing regional details in meteorological variables, caused for instance by processes related to the complex topography. However, for climate applications the potential remaining influence of large-scale GCMs errors needs further investigation.

There is a Regional Flood Information System (HKH-HYCOS) based on observations over the Ganges-Brahmaputra-Meghna and Indus basins, which encourages sharing of flood data and information for reduction of flood vulnerability. However, there are no predictions based on integrated meteorological and hydrological modelling.

The development of HCS requires climate and hydrological predictions, if possible for lead times from days to seasons, as well as projections for the 21st century. This can only be achieved by integrating meteorological, glaciological and hydrological models. Some effort in using weather forecasts as input to hydrological models has recently been made by the Central Water Commission for extending the lead time and accuracy of hydrological predictions. However, coupling meteorological and hydrological models for India at catchment as well as regional scale is still in a pioneering phase, as major challenges exist due to biases in the amount and location of the simulated precipitation that is used as input for the hydrological models. Moreover, not all important hydrological processes are incorporated, for example land use, groundwater, and human water use (reservoirs, groundwater, abstraction). The modelling systems are thus not yet used for real-time, operational forecasts. Regional climate change simulations have also been used as input for hydrological models, but again there are open questions related to the consequences of biases in the climate simulations. There are close links between the weather forecasting and climate change research communities, as well as between the hydrological and glaciological communities, and some, but limited, links between the two groups.

5.2. Challenges

As stated in Section 2.1 the purpose of HCS is to provide credible hydro-climatic information in such a way as to assist decision-making, meet user needs, have an effective access mechanism, and have engagement from users and providers (Vellingiri et al. 2015). Starting from these requirements and taking into account our assessment of the current status we now identify the main challenges for developing HCS for the Indian Himalayas. The challenges discussed in the subsections on ‘Predictions, Modelling and Processes’ and on ‘Observations’ are linked to the credibility of the information and to meeting user needs. The subsection on ‘Information, Communication and Advice’ addresses access mechanisms and participation from users and providers.

5.2.1. Predictions, Modelling, and Processes

In this section we list the challenges for short-term to seasonal weather and hydrological forecasting, and for long-term climate change projections. For the former they are:

- Bias correction of quantitative precipitation forecasts from regional meteorological models. This is needed to improve the forecast quality for essential information. It is also a prerequisite for integrating hydrological modelling and weather forecasting. Various bias-correction methods do exist and making a suitable choice requires understanding of the reasons for the biases and comprehensive validation.
- Integration of meteorological forecasts and hydrological modelling. This is an essential step for providing hydrological forecasts for short-term to seasonal timescales.
- Improve understanding of skilful predictors for seasonal meteorological forecasts and their assimilation in extended-range weather forecasting systems. Although the potential maximum skill of long-range forecasts is limited by the non-linear dynamics and practically

irreducible uncertainties in initial conditions, the current skill is likely to be much lower than this threshold.

- Forecasting of hydrological extremes. For floods, forecasting of intense rainfall, short-term snow and glacier dynamics, soil moisture and quick flow paths in the hydrological system are crucial. For droughts, forecasting of land-atmosphere feedbacks, evapotranspiration, snow- and glacier melt and hydrological storage in soil, groundwater, lakes and reservoirs are essential.
- Uncertainty analysis taking into account all components in the forecasting system, for instance by using an ensemble of hydrological forecasts that is not only based on the ensemble of meteorological forecasts.

Challenges for decadal to multi-decadal climate and hydrological projections are:

- Improve understanding of drivers and processes of forced climate change in this region, including local aerosols forcing, circulation changes, cryosphere-climate feedback, and land-use changes.
- Improve understanding of magnitude and processes of natural (multi-)decadal climate variability.
- Evaluation of the ability of climate models to represent random and forced decadal and longer variability, to assess the credibility of climate projections in the region, improve the models and guide model-selection if needed. This requires a process based validation, i.e. an assessment of how well the relevant process are represented.
- Improve understanding of regional-scale precipitation and temperature change patterns and of their representation in downscaled and bias-corrected climate models. Assess the relevance of climate model errors on downstream water availability, mountain ecosystems, glaciers and snowpack.
- Quantify uncertainties in regional projections using large multi-GCM, multi-RCM, multi-member ensembles and potentially emulators.
- Investigate whether very-high-resolution, convection-permitting regional models are required for capturing the climate change signal realistically.
- Improve understanding of the temperature lapse rate (i.e. change in temperature with height) and its representation in models, which is crucial to simulate the response of glaciers and snow pack to climate change.
- Investigate the sensitivity of global and regional climate simulations to parameterization schemes, in particular for clouds, radiation, cumulus, and boundary layer.
- Improve understanding of the processes responsible for glacier melt and their representation in glacio-hydrological models. A specific problem is unrealistic ‘snow towers’ building up in individual grid cells.
- Assimilation of information from a variety of sources (surface, air-borne, satellite) into hydro-glaciological models.
- Improve understanding of human influences, such as land-use changes, groundwater abstraction, reservoir impoundments, and the planned/proposed inter-basin water transfer. Ganga and Brahmaputra are perceived as water surplus basins and there are proposals to connect them to water ‘deficit’ basins of the south.
- Investigate the integrated effect on regional hydrology from potential climatic, land use, socio-economic and water management changes, in particular for floods and droughts. Policy changes at the central level may shift water usage patterns, which can affect hydrological regimes.

5.2.2. Observations

Meteorological, hydrological and glacier observations are needed for assessing past climate variability, validating models, observation-based short-term predictions, and initialising dynamical models for longer-term forecasts. The challenges related to observations are:

- Extend ground-based precipitation observations networks, in particular at high altitudes, which currently are sparse, Moreover, problems related to the precipitation undercatch in high winds and in measuring snow amounts need to be addressed. These issues make it very difficult to understand the high spatial variability of precipitation, and to quantify the accumulation and ablation of glaciers.
- Increase measurement of atmospheric processes and properties, which are lacking in this region. For instance, airborne or sonde atmospheric measurements would help constraining the representation of water vapour and cloud microphysical properties such as hydrometeor type and concentration in models. There is also a need to determine the size distributions of aerosols in order to determine their influence on clouds.
- Reduce uncertainty in estimates for glacier mass-balance by obtaining more measurements, which currently are extremely sparse. This is a key limitation for validating and developing glacier models, and leads to considerable uncertainty in projections of future glacier volume and meltwater availability. Issues related to measurement errors caused by debris cover and glacial lakes need to be addressed.
- Increase the availability of in-situ hydrological observations. The current scarcity of such measurements and their complete absence above 3,000m is a key limitation for validating and developing hydrological models. Moreover, they are carried out by different government agencies, e.g., India's Central Water Commission (CWC), Central Ground Water Board (CGWB), and India Meteorological Department (IMD), and access to these data is often limited. Observations should include hydrological storage in groundwater, lakes and reservoirs, which is crucial for hydrological modelling across the whole flow regime, and in particular during droughts.
- Measure water use, anthropogenic land-use change and other human influences on hydrological processes. These data are often difficult to obtain because of the small-scale nature and spatial variability, lack of recording, and difficult to use because of privacy.
- Increase capacity to use satellite data, mainly for hydrological variables that are difficult to measure, e.g. evapotranspiration and soil moisture.

5.2.3. Information, Communication and Advice

Hydro-climatic information from observations and models should be presented in a way that is purpose-oriented and accessible for different stakeholders. Understanding and addressing these needs requires a number of challenges to be addressed, including:

- Identify user groups and analyse which type of hydro-climatic information they need. User groups should include individuals, communities, local, regional and state agencies and administrations. Key sectors within the Indian Himalayan region that have to receive targeted hydro-climatic service information should be addressed. These are economics, ecology, urban and social, agriculture, the hydropower industry, tourism, transhumance, livestock, horticulture, and floriculture.

Addressing how hydro-climatic information can be provided in the most useful form, requires an understanding of the decision making processes and the role of hydro-climatic information in them. It also requires an understanding of the practical and fundamental limitations of what information can actually be provided. This can only be achieved by close collaboration between information providers and users, rather than by a top-down approach.

- Information should be provided on different aggregation levels. For instance academic and government scientists require access to raw data. Members of the public, government agencies, non-profit organisations or industrial corporations require analysed information, on micro to regional scales. Policy and decision makers may need reports and executive summaries of a manageable length and level of scientific detail.
- Lines of communication need to be identified. Government agencies dealing with water resources, floods or droughts, need to be in direct two-way communication with the providers of the HCS to obtain relevant and current information, whereas stakeholders such as industry and the general public are less-frequent, more indirect users of the information.
- For short-term to seasonal forecasting information should be accompanied by advice on action, for instance by using warning levels with recommendations. These recommendations can only be effective if they can realistically be followed, which means they should be based on a good understanding of the action options of the target groups.
- For climate-change projections information on changes in hydrologic extremes is needed.
- For all types of information communication of uncertainties in a way understandable for a given user group is crucial to aid decision making.
- The Indian Himalayas have a high rate of limited literacy with many different regional dialects so different forms of communication of hydro-climatic information must be addressed. This could be through mobile phone applications, printed weather information displayed at community centres in villages and towns, local radio programs or through television.
- Engaging schools and school children with information about climate change is necessary to engage the general public from an early age.

5.2.4. Opportunities and Ways Forward

Addressing the challenges can partly build on existing resources and structures, but exploring new avenues will be helpful too. Specific approaches for the challenges listed above need to be developed jointly by the scientific and user communities. The following points may serve as a guideline for the ways forward.

- India has a large and excellent scientific community in meteorology, climate research, hydrology, and glaciology. It also already has an observation-based Regional Flood Information System for the Ganges-Brahmaputra-Meghna and Indus basins. State-of-the-art meteorological and hydrological modelling capabilities are already implemented.
- This provides an excellent opportunity to move towards the next, essential, step which is integrated meteorological/climatological-glacio-hydrological modelling. In a first phase this requires interdisciplinary meetings to discuss the main challenges, such as bias correction, and the specific integration steps to be taken. However, the technical and scientific challenges are substantial and progress will only be possible if joint projects between meteorological/climate modellers and glacio-hydrological modellers for specific applications can be funded.
- Synergies with existing projects such as the EU-funded HighNoon project, which focuses on future changes in water resources in South Asia, specifically Northern India, should be also exploited
- The lack of meteorological and glacio-hydrological observations is a major obstacle for reducing the errors in regional climate models, and in glacio-hydrological models. Although increasing the observation density over the entire Himalayan region should be a medium-term goal, it seems unrealistic to achieve this quickly enough to immediately benefit the glacio-hydrological modelling and prediction efforts.

A realistic way of immediately improving the situation are hydro-climatological case studies for smaller areas, covering different characteristics and including high altitudes. Combining high-resolution observations and meteorological and glacio-hydrological modelling, they would increase process understanding, and provide benchmark catchments to evaluate and improve the models for the individual system components as well as coupled model version.

Additionally, the availability of cheap sensors and communication technology offers the opportunity for developing crowdsourcing approaches for hydro-climatological data. There is a lack of metadata for the existing measurements; a common platform, e.g. a webportal, where metadata and information about data quality can be accessed would improve the situation. In a next stage, one-point access to all the hydro-climatic data related to the Himalayan region, including model simulations and satellite data, would further facilitate interdisciplinary work.

- For the development of HCS and the provision of targeted and decision-relevant information it is crucial that the data providers understand the user needs, but also that the users understand the possibilities and limitations of hydro-climatic predictions on various timescales. Bringing together meteorological and hydrological agencies, research centres and user groups provides thus a straightforward opportunity to increase the understanding of these issues and to develop pilot products. It should be possible to start developing HCS through a better integration of the existing agencies and research centres. Whether additional structures are required in the future, needs to be re-evaluated after some experience with better linking the existing resources has been gained.

6. References

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