Report

Understanding and quantifying extreme precipitation events in South Asia

Part I – Understanding climate drivers through case studies

CARISSA Activity 4: Climate services for the water and hydropower sectors in South Asia

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Reviewed by Joseph Daron

Flooding in Kathmandu

Contents

1. Introduction

This report constitutes Part I in a series of reports documenting analysis of extreme precipitation in South Asia. This work contributes to two workstreams within the CARISSA (Climate Analysis for Risk Information and Services in South Asia)[1] Work Package of the ARRCC (Asia Regional Resilience to a Changing Climate)[2] programme; workstream 4 focused on developing climate services for the water and hydropower sectors, and workstream 6 focused on developing climate information for food security assessments.

During Year 1 of the CARISSA project, a regional workshop was held in Nepal bringing together users and providers of climate information in the water and hydropower sectors across South Asia (Met Office & ICIMOD, 2019). In addition, initial work was conducted for a pilot study to provide climate information to the hydropower sector in Nepal (Met Office, 2020). The outcomes of this exploratory work highlighted current and future changes to extreme precipitation as a primary concern amongst stakeholders, as extreme precipitation leads to flooding and other hazards that have wide-ranging impacts on the water and hydropower sector in the region.

Improved understanding of the causes of extreme precipitation events in the region, and how well climate models capture these, is required to improve confidence in climate information products focused on future changes in extreme precipitation. Therefore, the programme has focussed on underpinning analysis of extreme precipitation events with a view to informing the planned development of climate information products for the water, hydropower and food security sectors across the ARRCC focal countries; Afghanistan, Bangladesh, Nepal and Pakistan.

The overall aim of this work is to determine a set of plausible futures for extreme precipitation in South Asia, to support policy and planning in the identified sectors. This report constitutes the first in a series of reports focusing on the underpinning analysis. It focuses on exploring the drivers of extreme precipitation through case studies of extreme events that have occurred in South Asia in recent decades that have impacted the four focal ARRCC countries; Afghanistan, Bangladesh, Nepal and Pakistan.

Extreme events, such as flooding, can be caused by:

- localised extreme rainfall leading to flash flooding,
- extreme rainfall upstream causing flooding further downstream and/or rivers to burst their banks,

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[1] https://www.metoffice.gov.uk/services/government/international-development/climate-analysis-for-risk-information--services-in-south-asia-carissa

[2] https://www.metoffice.gov.uk/services/government/international-development/arrcc

- the impacts of an accumulation of above average rainfall throughout the season,
- multiple low pressure systems/storms developing over the region,
- the compound impacts of glacial melt and extreme rainfall.

There are many factors that determine the severity of an extreme event such as flooding. Precipitation is just one of these factors, and although high precipitation can lead to flooding, it is the nature and timing of the precipitation, together with other factors, that controls the extent and type of flooding.

In this analysis we explore the characteristics of extreme events that have impacted the South Asia region, with a particular focus on the nature of the precipitation that caused the extreme event. Case studies of specific events are explored to identify indicators of the synoptic patterns associated with typical or rare extreme precipitation events. The outcomes of this report will inform analysis evaluating the capability of climate models to replicate the large-scale drivers of extreme precipitation in South Asia (Part II in this series of reports). Subsequent analysis will place a specific focus on quantifying extreme precipitation in both the current and future climate in Nepal.

1.1 Drivers of extreme precipitation events in South Asia

The South Asian summer monsoon accounts for around 80% of annual rainfall across the region (Turner & Slingo, 2009). Extreme precipitation events generally occur in the monsoon season. The number and magnitude of extremes within a season are controlled by sub-seasonal processes.

Identifying extremes in the summer monsoon can be challenging due to the large spatial variation of the monsoon and lack of availability of long-term, high quality observation data. One measure that is often used is the All-India Summer Monsoon Rainfall anomaly (Figure 1), however note that this metric only measures rainfall over India and not the ARRCC focus countries.

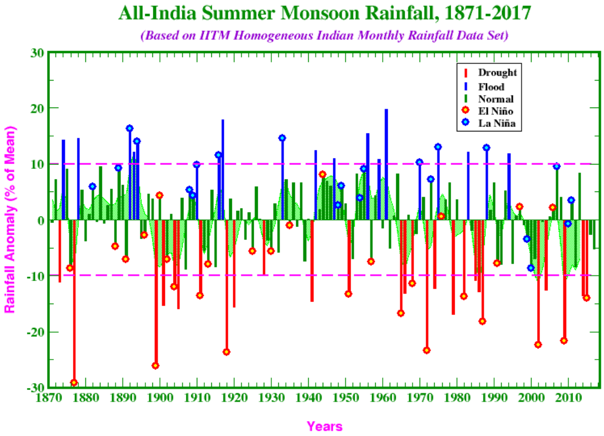

Figure 1 – The All-India Summer Monsoon Rainfall anomaly[3]

Extremes in this dataset are defined as excess or deficit of 10% of the long-term mean. However, the data only covers India and not the surrounding countries.

Other methods of characterising the South Asian summer monsoon include wind-based indices, such as the Indian Monsoon Index (Figure 2) and the Webster and Yang Monsoon Index (Figure 3).

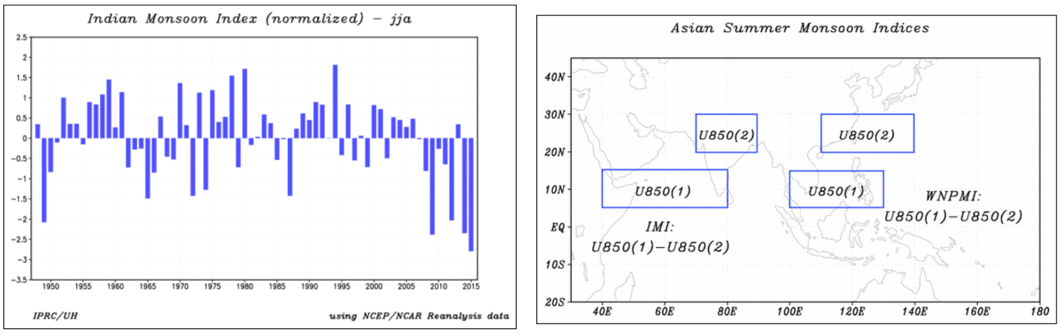

Figure 2 – Time series and definition of the Indian Monsoon Index[4] *(Wang et al., 2001; Wang & Fan, 1999)*

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[3] https://www.tropmet.res.in/~kolli/MOL/Monsoon/Historical/air.html

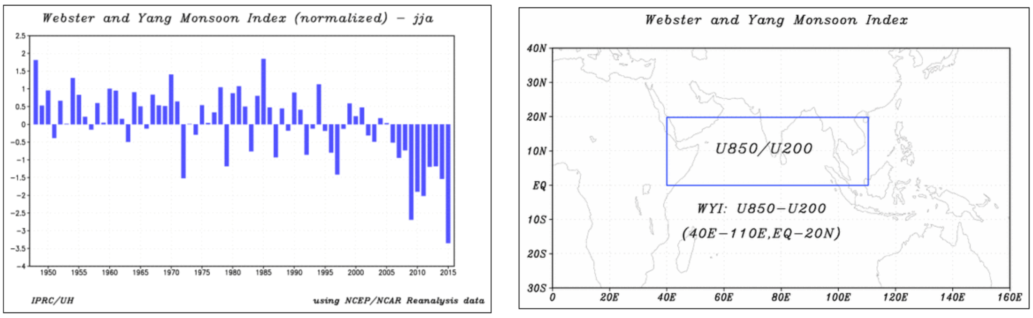

Figure 3 – Time series and definition of the Webster and Yang Monsoon Index[4] (Webster & Yang, 1992)

The two main large-scale drivers of the South Asian summer monsoon are the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The El Niño phase of ENSO acts to suppress monsoon rainfall and the La Niña phase acts to enhance rainfall (Pant & Parthasarathy, 1981; Sikka, 1980). In general the positive phase of the IOD correlates with increased monsoon rainfall and the negative phase with decreased rainfall (Ashok et al., 2001; Behera et al., 1999).

ENSO and IOD are closely related; monsoon circulation is more strongly influenced by ENSO during the El Niño or La Niña phases of the oscillation, whereas the IOD has more influence during neutral ENSO conditions (Ashok et al., 2001). Time series of the Niño 3.4 index and the IOD index (DMI) are shown in Figure 4 and Figure 5 respectively.

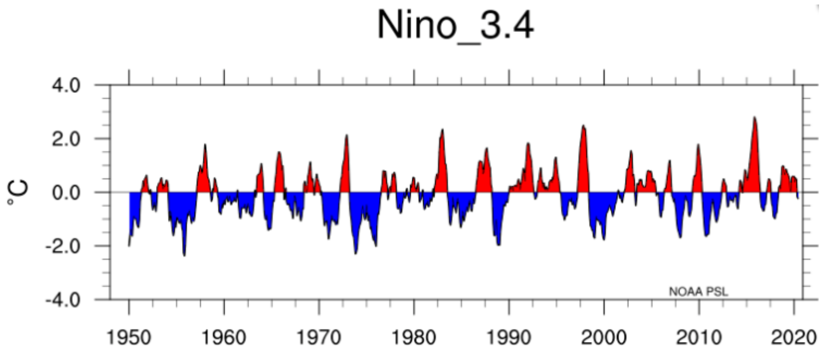

Figure 4 – Time series of the Niño 3.4 index. Source: NOAA PSL[5].

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[4] http://apdrc.soest.hawaii.edu/projects/monsoon/seasonal-monidx.html
[5] https://psl.noaa.gov/enso/dashboard.html

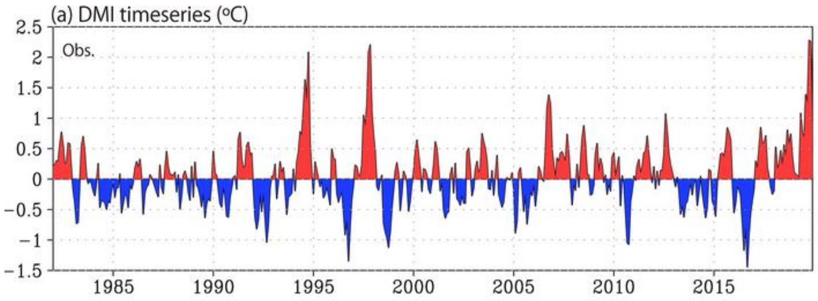

Figure 5 -Time series of the IOD. Source (Doi et al., 2020)

The Equatorial Indian pecan Oscillation (EQUINOO) is also a key driver in the variability of South Asian monsoon rainfall. The EQUINOO is defined as the oscillation in convection between the Western equatorial Indian Ocean (WEIO) and the Eastern equatorial Indian Ocean (EEIO) (Gadgil et al., 2004).

There is significant intra-seasonal variability in South Asian monsoon rainfall with periods of active and break conditions in the monsoon rains. The active phase of this cycle is defined when the rainfall is above average over central India and below average over northern India (foothills of the Himalaya) and southern India. The definition of the break phase is the reverse of this pattern (Annamalai & Slingo, 2001; Krishnamurthy & Shukla, 2000). These active/break cycles are driven by two large-scale modes of intra-seasonal variability; the Madden-Julien Oscillation (MJO) and the Boreal Summer Intraseasonal Oscillation (BSISO; Kikuchi et al., 2012). In general, the MJO dominates during boreal winter (December – April) and the BSISO dominates during boreal summer (June – October).

2. Case studies of extreme precipitation events

In this section we document extreme precipitation events that have occurred across South Asia and in each of the ARRCC focus countries; Afghanistan, Bangladesh, Nepal and Pakistan. In each region an extreme event is selected as a case study and the large-scale driving conditions that led to these extreme events is explored. The selection of the case studies did not follow a systematic process and instead was determined by a review of the available literature analysing the drivers of the specific event.

2.1 South Asia

2.1.1 Extreme precipitation events impacting South Asia

A selection of extreme precipitation events that have resulted in widespread impacts across the South Asia region in recent decades are documented in Table 1. These were selected via review of available literature and documentation. The flooding event of 2007 has been selected as a case study of a widespread flooding event across the South Asia region, and is discussed in more detail in Section 2.1.2.

Table 1 – A selection of extreme precipitation events that have impacted the South Asia region. The 2007 event has been selected as a case study and is highlighted blue.

Year	**Dates**	**Event**	**Details**	**References**
2019	Mid-July	Flood	Monsoonal downpours resulting in flooding in Bangladesh, China, India, and Nepal[6]. Lower than average rains at start of monsoon (68% of June average) but remaining months received higher-than-average rainfall, monsoon rains 10% higher than average in India[7].	WMO (2020)
2017	April - October	Flood	Widespread flooding during monsoon season with severe flooding impacts in Bangladesh, India, Nepal and Pakistan[8]. Significant due to the longer time period of the rains and several record-breaking pulses of high intensity rain, e.g. in early August[9,10].	WMO (2018) Srivastava et al. (2018)
2007	3rd July-15th August	Flood	Floods in India, Nepal, Bhutan, Pakistan and Bangladesh due to continual rain form unusual monsoon conditions[11]	WMO (2008) Rajeevan et al. (2008)

2.1.2 Case study: Floods across South Asia region in 2007

The 2007 summer monsoon led to widespread flooding across the South Asia region, the main areas affected are shown in Figure 6. Over the duration of the monsoon season, 2000 people were killed and tens of millions of people were affected by the floods[12].

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[6] https://en.wikipedia.org/wiki/2019_South_Asia_floods

[7] https://www.jbarisk.com/flood-services/event-response/2019-south-asia-monsoon/

[8] https://en.wikipedia.org/wiki/2017_South_Asian_floods

[9] https://www.jbarisk.com/flood-services/event-response/monsoonal-flooding-in-south-asia/

[10] https://ui.adsabs.harvard.edu/abs/2017AGUFMNH51D..01A/abstract

[11] https://en.wikipedia.org/wiki/2007_South_Asian_floods

[12] https://reliefweb.int/report/bangladesh/understanding-2007-floods-south-asia

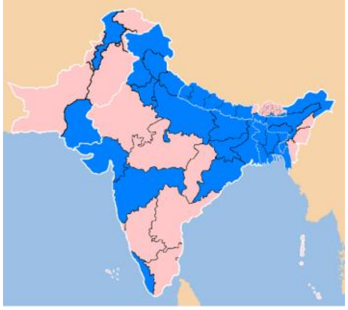

Figure 6 – Areas affected by the 2007 floods across South Asia (from https://en.wikipedia.org/wiki/2007_South_Asian_floods)

The 2007 monsoon season

The seasonal total monsoon rainfall was 6% above the long-term average (1961-1990) across the region, but the spatial and temporal distribution of rainfall events throughout the monsoon season was different to that usually experienced (WMO, 2008). The season was characterised by a combination of excess rainfall compared to the climatological average in some areas, leading to flooding, and deficit of rainfall and drought conditions in others. The widespread flooding can be associated with both the frequency and intensity of the events that occurred throughout the season, leading to a cumulative effect that exacerbated flooding conditions.

The season began with an early onset of the monsoon over southern India. However, there were multiple disruptions to the monsoon's progression, with some coastal areas receiving up to 50% more rain that average and more rainfall than average and inland parts receiving up to 30% less over the season (Figure 7 left panel). The time series of daily rainfall averaged over the monsoon region indicates periods of wetter and drier than average conditions throughout the season (Figure 7 right panel; Rajeevan et al., 2008). The monsoon progression also completed 10 days earlier than the climatological average.

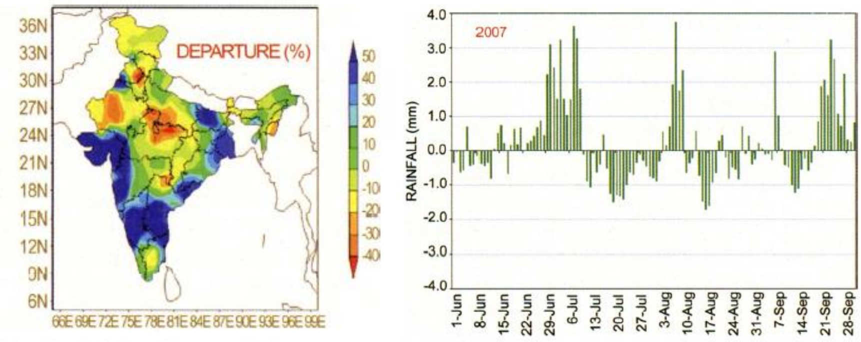

Figure 7 – Spatial pattern of the rainfall anomaly over the monsoon season in India (left panel) and time series of daily normalised rainfall over the monsoon region from June to September 2007 (right panel), from Rajeevan et al. (2008).

Other unique events that occurred over the 2007 monsoon season were the formation of two intense tropical cyclones over the Arabian Sea in June, one of which (cyclone Gonu) caused a 10-day disruption to the monsoon progression (Rajeevan et al., 2008).

The number of storms occurring during the season was above average with 11 low pressure systems occurring throughout the season. Five of these storms were deep monsoon depressions that formed over the Bay of Bengal, with three forming in quick succession between 21st June and 4th July. The position of the monsoon trough was also further south than the climatological average, which caused these low pressure systems to move south resulting in heavy rain and flooding. The daily rainfall record in semi-arid Kurnool in India was nearly 5 times the highest recorded since 1901 at 397mm in 24 hours (Rajeevan et al., 2008).

Large-scale drivers and teleconnections

In 2007 there was a rapid transition from an El Niño event to a La Niña event (Figure 4). The IOD was in a positive phase (Figure 5). Further detail on the large-scale drivers in 2007 in relation to the extreme rainfall experienced in Nepal in Section 2.4.

2.2 Afghanistan

2.2.1 Extreme precipitation events impacting Afghanistan

A selection of recent extreme precipitation events that have resulted in significant impacts in Afghanistan in recent decades are listed in Table 2. These were selected via review of available literature and documentation.

Afghanistan is most vulnerable to flooding during the spring (March to May) and in flat areas in the foothills of the mountainous region the northern parts of the country (Hagen & Teufert, 2009). Rivers are easily overwhelmed by heavy rainfall and/or increased flow from glacial melt, and the necessary infrastructure to mitigate these flooding events does not exist (Hagen & Teufert, 2009). Increases in precipitation have been observed in the region during both winter and spring seasons only, which could be adding to this type of flooding events where there is increased snow during winter, combined with higher rainfall in the spring (Hagen & Teufert, 2009).

Very little scientific literature is available studying the drivers of flooding events in Afghanistan Here we select the flooding event of 2014 as a case study as it represents an example of the conditions described above of springtime flash flooding in Afghanistan and some documentation about the impacts is available. The event is discussed in further detail in section 2.2.2.

Table 2 – A selection of recent extreme precipitation events that have impacted Afghanistan. The 2014 event has been selected as a case study and is highlighted blue.

Year	Dates	Event	Details	References
2020	August	Flooding	Torrential rain in the Charikar Parwan province causing deaths and destruction[13].	--
2014	April, May, June	Flooding	Flash flooding and landslides cause significant loss of life and widespread damage[14,15].	Srivastava et al. (2015)
2013	August	Flooding	Heavy rain and flooding in the mountainous northern regions and flash flooding in Kabul[16].	Srivastava et al. (2015)
2007	March, April	Flooding	Rain and melting snow combined to trigger floods and landslides in southwestern Afghanistan in March and April 2007.[17]	WMO (2008) Rajeevan et al. (2008)
2005	March, June	Flooding	Rain and melting snow triggered widespread flooding[18,19]	Shein (2006)

2.2.2 Case study: Afghanistan flooding 2014

A series of heavy rainfall events occurred in north-eastern districts of Afghanistan throughout April, May and June in 2014. The flash flooding and subsequent flood waters and landslides caused around 500 deaths, destroyed 6500 homes, and affected around 125,000 people in 27 provinces[14,15]. The extent of flooding during 2014 was 2-3 times the annual average[15].

Causes of the flooding events

The flooding resulted from a combination of heavy rainfall combined with the seasonal meltwater from the glaciers in the mountains to the northeast which feed the rivers. Seasonal total rainfall amounts for March-May were up to 200% higher than the 1981-2010 average (Figure 8, right panel). Although seasonal mean temperatures were below average over much of Afghanistan, they were slightly above average in the Hindu Kush mountain range, which could also have contributed to increased river flow from snow melt during the spring season.

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[13] https://www.reuters.com/article/us-afghanistan-floods-idUSKBN25M148
[14] https://reliefweb.int/report/afghanistan/situation-report-afghanistan-floods-issue-1-26-30-april-2014
[15] https://reliefweb.int/disaster/ff-2014-000060-afg
[16] https://www.bbc.co.uk/news/world-asia-23568689
[17] https://earthobservatory.nasa.gov/images/event/18146/floods-in-afghanistan
[18] https://earthobservatory.nasa.gov/images/5355/floods-in-afghanistan
[19] https://earthobservatory.nasa.gov/images/14714/floods-in-afghanistan

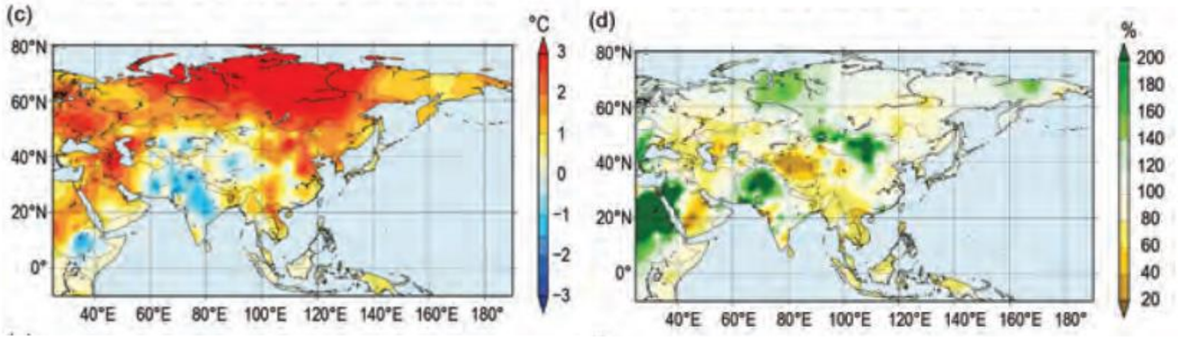

Figure 8 – Anomalies in observed seasonal mean temperature (left panel) and seasonal total precipitation (right panel) for March – May 2014,compared to the 1981-2010 average. From Renwick (2015).

Large-scale drivers and teleconnections

During 2014 there was a transition from neutral conditions to an El Niño event (Figure 4), and the IOD was in its negative phase (Figure 5).

2.3 Bangladesh

2.3.1 Extreme precipitation events impacting Bangladesh

A selection of recent extreme precipitation events that have resulted in significant impacts in Bangladesh in recent decades are listed in Table 3. These were selected via review of available literature and documentation

These events are generally characterised by localised heavy rainfall, often associated with low pressure systems or tropical cyclones forming in the Bay of Bengal and transiting northwards across the country. These localised rainfall events are often compounded with rainfall elsewhere contributing to the river flow further upstream and leading to riverine flooding events. The flooding event of 2017 is an example of this type of compound event and will be used as a case study; discussed in further detail in section 2.3.1.

Table 3 – A selection of recent extreme precipitation events that have impacted Bangladesh. The 2007 event has been selected as a case study and is highlighted blue.

Year	Dates	Event	Details	References
2019	14th July	Flood	Monsoonal downpours in Cox's Bazar – monthly rainfall (585 mm) received by mid-month[6]. Strong positive IOD.	WMO (2020)
2017	April – October (long monsoon) Specific storms in July and August	Flood	Pre-monsoon flooding in April. Heavy rain events causing flooding in July and August[20]. Monsoon seasonal mean close to climatology	Philip et al. (2019) Hossain et al. (2019) WMO (2018) Srivastava et al. (2018)
2010	Summer monsoon	Drought	Driest monsoon since 1994	Dastagir (2015)
2009	29th July	Flood	290mm rain in Dhaka – highest daily July total since 1949	Dastagir (2015)
2007	21st July – 15th August	Flood	Whole country affected as part of wide-spread flooding and continuous monsoon rains[11]	Dastagir (2015) WMO (2008)

2.3.1 Case study: Bangladesh floods 2017

In 2017 widespread flooding occurred across the South Asia region during the monsoon season. In August, Bangladesh experienced the worst floods in 40 years through a combination of heavy localised rainfall and water flow from upstream rivers in India leading to the rivers in northern Bangladesh bursting their banks (Philip et al., 2019).

Nearly 7 million people were affected by the floods which impacted 30 districts (Figure 9). There were 114 people reported dead, at least 297 250 people displaced and 593 250 houses were destroyed (Philip et al., 2019). The World Health Organisation reported more than 13,000 cases of waterborne diseases and respiratory infections during a three-week period in August (WMO, 2018).

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[20] https://en.wikipedia.org/wiki/Floods_in_Bangladesh#Details_of_the_2017_flood(s)_in_Bangladesh_%F0%9F%92%A6

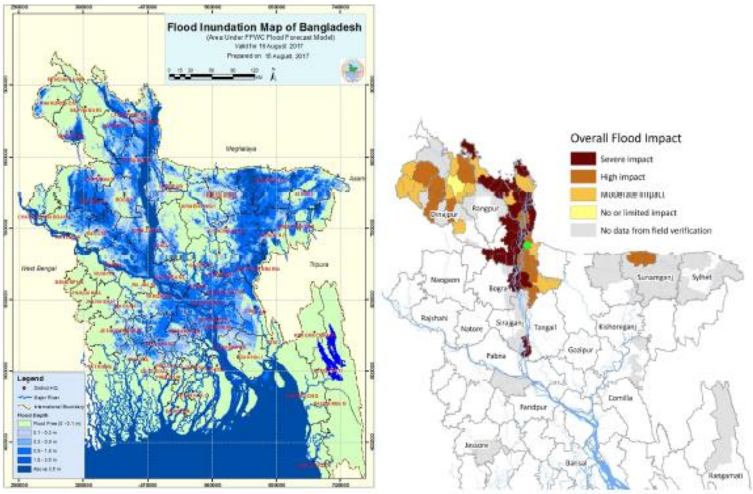

Figure 9 – Flood inundation map (left panel) and measure of flood impact (right panel) for the 2017 flood in Bangladesh, figure from (Philip et al., 2019).

The 2017 monsoon season

In 2017 the seasonal total monsoon rainfall in Bangladesh was close to average but there were rainfall deficits elsewhere in the South Asia region; India received 5% less rain than average and Pakistan received a deficit of around 22% (Srivastava et al., 2018). The season was characterised by high intra-season variability with active parts causing above average rainfall in the foothills of the Himalayas and break conditions leading to rainfall deficits in central India. (Hossain et al., 2019; Srivastava et al., 2018).

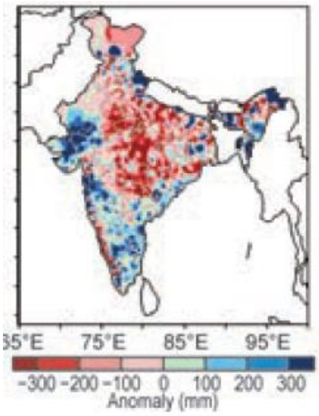

Figure 10 – Spatial pattern of the anomaly in seasonally averaged monsoon rainfall over India, from (Srivastava et al., 2018).

In Bangladesh the monsoon season started early, with heavy rainfall caused by a cyclonic storm in April. Another cyclonic storm which formed over the Bay of Bengal at the end of May made landfall over the Bangladesh coast and transited towards north-east India (Srivastava et al., 2018). This storm deposited additional rainfall across Bangladesh and also in north-eastern India, increasing the river flow which feed into the north of Bangladesh.

From 9th-12th August there was extremely heavy rainfall over northern Bangladesh, eastern Nepal and north-eastern India. Daily rainfall exceeded 400 mm near the India-Nepal border. The Rangpur district in northern Bangladesh received 360 mm of rain in a two-day period (11th-12th August) which is around the same amount expected over the month (Srivastava et al., 2018; WMO, 2018). This extreme rainfall was associated with a northward shift of the monsoon trough, and the location over the Brahmaputra River basin (Figure 11) and tributaries caused the water levels to rise rapidly (Hossain et al., 2019).

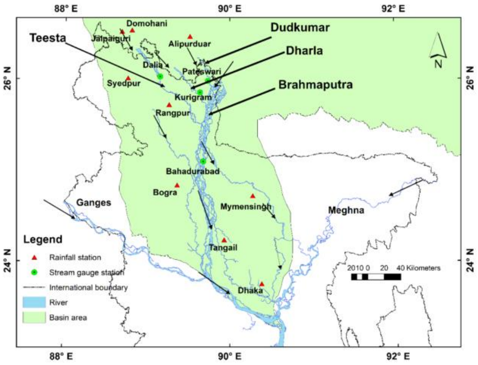

Figure 11 – Major river systems in Bangladesh; the Brahmaputra River basin is shown in green, from Hossain et al. (2019).

The combination of the two storms depositing above average rainfall over the Brahmaputra and its tributaries (the Teesta and Dharla rivers; Figure 12) resulted in the water levels exceeding 1m above their respective flood danger levels and breaking historical recorded levels (Hossain et al., 2019). Hossain et al. (2019) state that the key drivers of flooding of the Brahmaputra are the location and magnitude of extreme rainfall, with the 2017 event demonstrating an example of the combination of 'perfect' conditions of these drivers to cause an extreme flooding event.

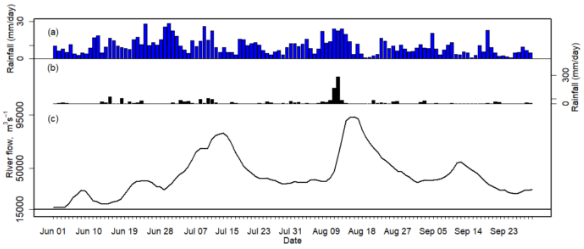

Figure 12 – Time series of a) the basin averaged rainfall, b) rainfall recorded at the Syedpur rain gauge, and c) river flow recorded at Bahadurabad, from Hossain et al. (2019).

Intra-seasonal monsoon variability and links to the Brahmaputra basin

Intra-seasonal variability in the monsoon causes active and break conditions, defined by rainfall amounts over central India. Active conditions in India are associated with lower than average rainfall in northern Bangladesh, whereas break conditions in India are associated with higher than average rainfall over northern Bangladesh (Figure 12; Hossain et al., 2019). These conditions occur due to the monsoon trough moving northward in break conditions which draws moisture northwards from the Bay of Bengal (Hossain et al., 2019).

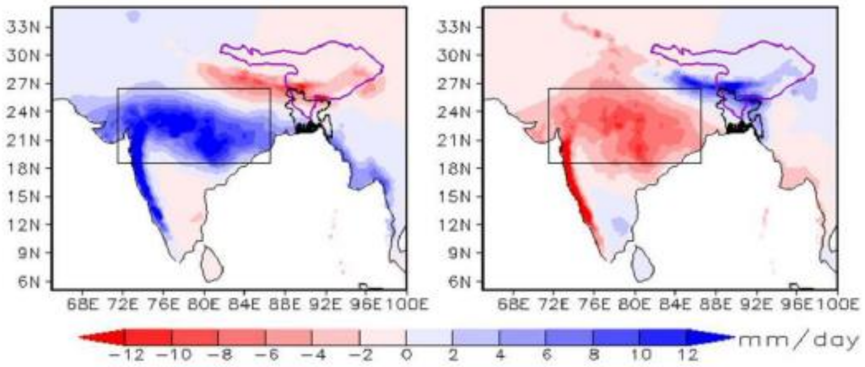

Figure 13 – Normalised rainfall for composite active (left panel) and break (right panel) conditions, from Hossain et al. (2019). The Brahmaputra basin is drawn in purple.

Synoptic conditions leading to the 2017 floods

During the two extreme rainfall events in July and August 2017 the monsoon trough shifted northwards to the foothills of the Himalayas, as is usually associated with the break conditions that were observed over India at the same time (Hossain et al., 2019). This can be seen in panels a and b of Figure 14, along with the south-westerly flow from the Bay of Bengal bringing moisture up to the Brahmaputra basin (Figure 14 panels a, b, e and f). The pressure gradient that drives this flow was stronger in the August event compared to July, resulting in higher anomalous rainfall (Figure 14 panels a, b, e and f).

Large-scale drivers and teleconnections

La Niña events are associated with slightly higher than average rainfall in the Brahmaputra basin (Hossain et al., 2019). During the 2017 summer monsoon ENSO was in a neutral to mild La Niña state as it was in the process of transitioning from the strong El Niño event of 2015/16 (Hossain et al., 2019; Figure 4). Similarly, there was a transition from a positive to negative IOD over the same time period (Figure 4).

There are two main modes of climate variability which govern the intra-seasonal variability of the summer monsoon; the Boreal Summer Intra-Seasonal Oscillation (BSISO) and the Madden-Julian Oscillation (MJO). During the 2017 summer monsoon the MJO was in phase 3 of its 8-phase cycle. The MJO is generally weaker over the summer months and was found to have had little influence on the synoptic conditions over the Brahmaputra basin in 2017 (Hossain et al., 2019).

The BSISO is a complex combination of low-frequency modes which propagate in different directions and the interactions between them (Kikuchi et al., 2012). During the 2017 summer monsoon there is evidence of strong northward propagation in the BSISO mode which could have influenced and contributed to the synoptic conditions experienced in 2017 (Hossain et al., 2019).

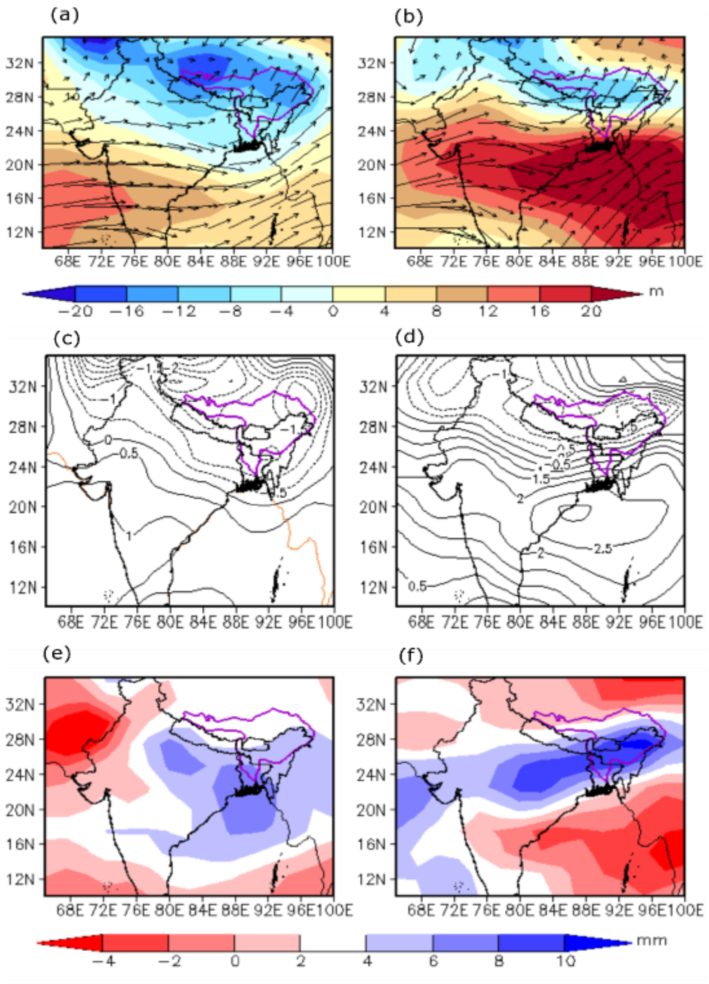

Figure 14 – Synoptic conditions for the two extreme rainfall events on 1-7 July (panels a, c, e) and 8-13 August 2017 (panels b, d, f). Panels a and b show 850 hPa geopotential height anomaly and absolute wind vectors, panels c and d show mean sea level pressure anomalies, and panels e and f show anomalies in precipitable water, from Hossain et al. (2019). The Brahmaputra basin is drawn in purple.

2.4 Nepal

2.4.1 Extreme precipitation events impacting Nepal

Due to the complex topography across Nepal, the drivers and impacts of extreme precipitation events are quite varied. Typical events include:

- Heavy localised rainfall, causing fluvial flooding, flash flooding, and landslides in mountainous areas;
- Glacial Lake Outburst Floods (GLOFs) which occur in the Himalayas and are dependent on rainfall amounts, temperatures causing glacial melt, and the geological status of the rock/moraine.

A selection of recent events that have resulted in significant impacts in Nepal in recent decades are listed in Table 4. These were selected via review of available literature and documentation.

Table 4 – A selection of recent extreme events that have impacted Nepal. The events that occurred in 2016 and 2017 have been selected as a case study and are highlighted blue.

Year	Dates	Event	Details	References
2019	12-14th July	Flood/landslides	Heavy rains began on 12th July[6].	WMO (2020)
2017	April	GLOF	A flood from the Barun River, Makalu-Barun National Park, eastern Nepal caused by rock fall and associated debris.	Byers et al. (2019)
2017	August	Flooding and landslides	1/3 of country flooded (in the south) – worst seen in several years[8]. High intra-seasonal variability during the monsoon season.	WMO (2018) Srivastava et al. (2018) Chhetri et al. (2020)
2016	June 16th	Flooding	Flooding in the Banke-Bardiya districts in the Terai – heavy rain and cloud burst events. High intra-seasonal variability during the monsoon season.	Srivastava et al. (2017) Chhetri et al. (2020)
2014	August	Flooding and landsides	Heavy rain caused massive landslides from the hillside in Jure in Nepal's Central Region on 2 Aug 2014. Heavy rain continued between 14 and 16 Aug.[21]	Srivastava et al. (2015)
2007	July	Flooding and landslides	Sequence of heavy rainfall events causing flooding and landslides across much of Nepal from 10th	WMO (2008), Rajeevan et al. (2008)

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[21] https://reliefweb.int/disaster/ls-2014-000103-npl

			July till end of the month. Specific extreme rainfall event on 19th July.	Bohlinger et al. (2019)
1985	August	GLOF	GLOF in the Khumbu Himal destroyed a nearly-completed small hydroelectric project valued at about USD 4 million.	Kattelmann (2003)

Although the impacts of GLOF events are of significant importance to Nepal, there are many factors which cause these events, including the status of the rock/moraine, the melting rate of the glacier, the presence and location of glacial lakes, in addition to the rainfall component. Given it is difficult to isolate climate variables as drivers of GLOFs, we choose to not select a GLOF event as a case study here and choose an event where there are more direct links with the climate drivers.

Drivers of extreme rainfall in Nepal

The typical synoptic conditions associated with heavy precipitation in Nepal and the Himalayas are monsoon low-pressure systems, mid-level troughs, break monsoon conditions and western disturbances (Bohlinger et al., 2017; Nandargi & Dhar, 2011). Heavy rainfall is often associated with low-pressure systems moving northwards from the Bay of Bengal, the presence of mid-level troughs and the orographic uplift effect causing precipitation upon approaching the Himalayan mountain range (Bohlinger et al., 2017). This process is summarised in the schematic diagram in Figure 15. Bohlinger et al. (2017) also find that a significant proportion of the available moisture comes from the land. Higher soil moisture due to earlier rainfall in the season can add to the available moisture.

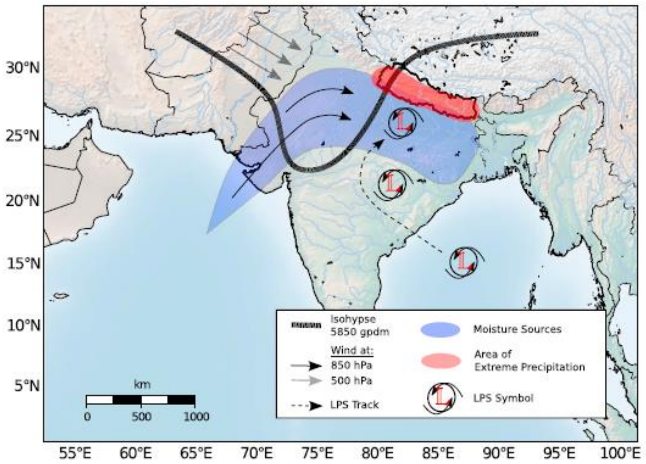


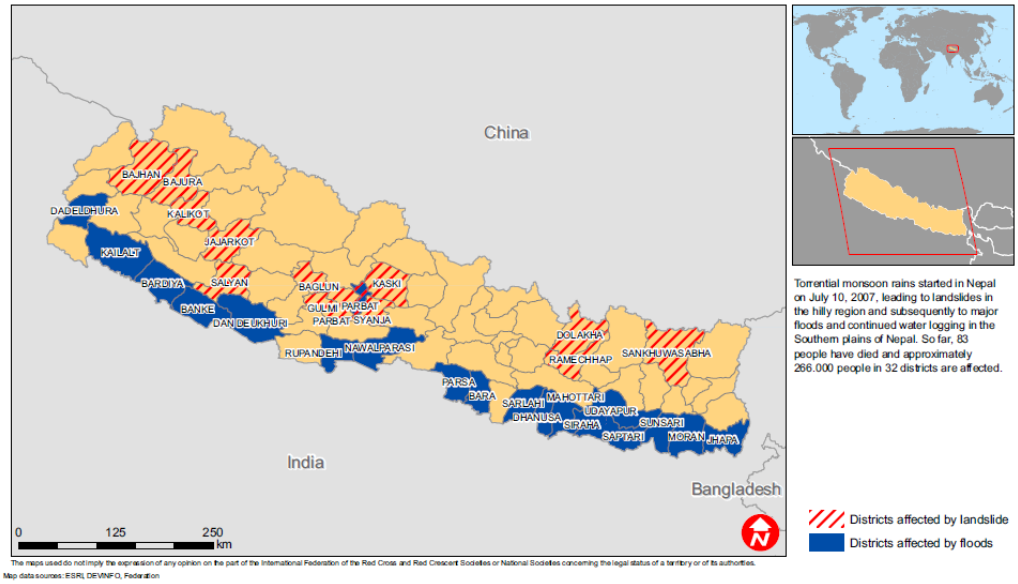
Figure 15 – Schematic of processes leading to extreme rainfall events in Nepal, from Bohlinger et al. (2017)

Nandargi & Dhar, (2011) have studied the occurrence of extreme one-day rainfall events between 1871 and 2007 and conclude that extreme rainfall events occur in both excess and deficit monsoon years. The extreme one-day rainfall events that occurred during monsoon deficit years were mostly El Niño years and often associated with monsoon break conditions. Similarly, extreme one-day rainfall events that occurred during monsoon excess years, often linked with Neutral or La Niña ENSO conditions, were also associated with monsoon break conditions.

The flooding event of 2007 in Central Nepal is selected as a case study as an example of typical drivers of extreme rainfall in Nepal. This event is discussed further in section 2.4.1.

2.4.1 Case study: Flooding in Central Nepal in 2007

As previously discussed in Section 2.1.2, the monsoon season in 2007 led to widespread flooding across the South Asia region. A series of heavy rainfall events impacting Nepal during July led to flooding and landslides causing eighty-four deaths, 9,700 families to be displaced, and 18,500 houses damaged or destroyed (International Federation of Red Cross and Red Cresent Societies, 2007). Around thirty districts were affected, shown in Figure 16.



Torrential monsoon rains started in Nepal on July 10, 2007, leading to landslides in the hilly region and subsequently to major floods and continued water logging in the Southern plains of Nepal. So far, 83 people have died and approximately 266.000 people in 32 districts are affected.

The maps used do not imply the expression of any opinion on the part of the International Federation of the Red Cross and Red Crescent Societies or National Societies concerning the legal status of a territory or of its authorities.

Map data sources: ESRI, DEVINFO, Federation

Figure 16 – Map showing districts of Nepal affected by floods and landslides during July 2007 (International Federation of Red Cross and Red Cresent Societies, 2007).

The 2007 monsoon season

The 2007 monsoon season has already been discussed in Section 2.1.2. This year is another example of near-average seasonal rainfall, but significant intra-seasonal variability both spatially and temporally across the season.

From 10th July till the end of the month there was sequence of heavy rainfall events over Nepal. One which occurred on the 19th July exceeded the 99th percentile at nine stations simultaneously (Figure 16, Bohlinger et al., 2019).

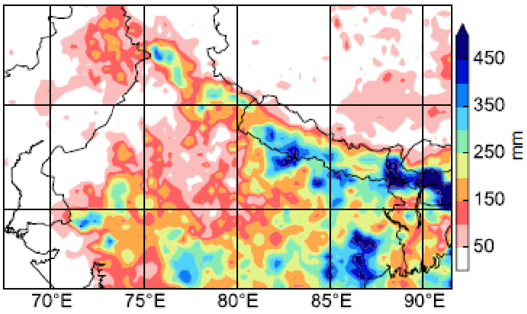


Figure 17 – Total precipitation in the 15 days prior to the event on 19th July, from (Bohlinger et al., 2019)

Synoptic conditions that led to extreme rainfall on 19th July

The extreme rainfall event of 19th July occurred during break monsoon conditions that persisted from 18th-22nd July (Bohlinger et al., 2019). This event demonstrates an example of the driving synoptic conditions of extreme rainfall over Nepal shown in Figure 15.

The synoptic conditions associated with this event are described in detail in Bohlinger et al. (2019). Prior to the event there was a trough in the upper troposphere (300hPa) which oriented the upper-level flow against the Himalayas, drawing warm, dry air from the Hindu Kush Himalayas southeast-wards. Also, a monsoon low-pressure system approached Nepal and the transited along the Himalayas. During the event, low-level flow from the Arabian Sea brought moisture across the land, drawing up further moisture from previous heavy rainfall events. This low-level flow was blocked and redirected by the western Ghats (Figure 18), a feature that is a characteristic of monsoon break periods, resulting in excess rainfall along the Himalayas where the low-level moist flow is directed onto and along the mountain range.

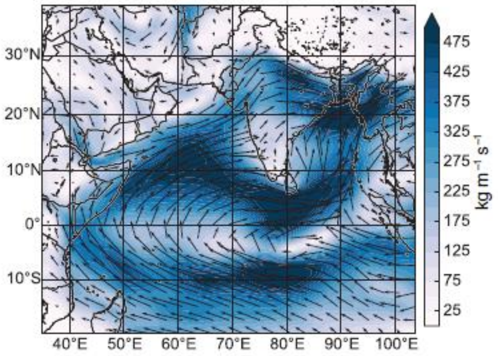


Figure 18 – Vertically integrated moisture flux on 19th-20th July 2007, from Bohlinger et al. (2019)

Figure 19 shows the moisture sources in the days preceding and during the event, highlighting the importance of moisture from the low-pressure systems transiting from the Bay of Bengal across eastern India, and also from the Arabian Sea across Central India. As this event occurred during a monsoon season with multiple extreme rainfall events leading to flooding across the wider region, this excess moisture in the ground contributed to the available moisture in the low-pressure flow, exacerbating the impact of this event (Bohlinger et al., 2017, 2019).

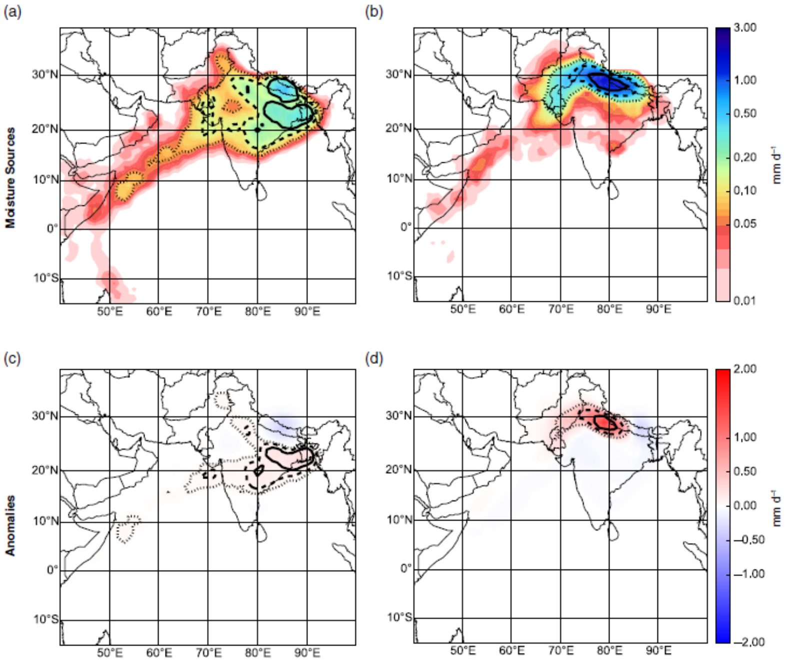


Figure 19 – Moisture sources (a and b) and moisture anomalies (c and d) in the days preceding the event (a and c), and during the event (b and d), from (Bohlinger et al., 2019).

Large-scale drivers and teleconnections

As previously mentioned in Section 2.1.2, ENSO there was a rapid transition from an El Niño event to La Niña in 2007 (Figure 4) and the IOD was in a positive phase (Figure 5). However, Bohlinger et al. (2017) find that the relationship between extreme rainfall in Nepal and ENSO breaks down above the 99th percentile.

The event has also been linked to the existence of a Rossby wave train from Europe, which may have enhanced the negative geopotential height anomaly over Nepal during the event (Bohlinger et al., 2019).

2.5 Pakistan

2.5.1 Extreme precipitation events impacting Pakistan

Extreme precipitation events that have resulted in significant impacts in Pakistan in recent decades are listed in Table 5. These were selected via review of available literature and documentation.

In general, these extreme precipitation events are associated with river flooding during the monsoon season due to extreme precipitation in the river basins themselves, and sometimes exacerbated by increased river flow further upstream due to snowmelt. Other types of extreme rainfall events that can occur in this region include monsoon depressions that develop in the Bay of Bengal and bring moisture to the Himalayan foothills in the north of Pakistan. The flooding event of 2010 represents an example of this type of flooding event in Pakistan and is used as a case study; discussed in further detail in section 2.5.2.

Table 5 – A selection of recent extreme precipitation events that have impacted Pakistan. The 2010 event has been selected as a case study and is highlighted blue.

Year	Dates	Event	Details	References
2017	21-22nd August 31st August	Flood	Separate incidents of heavy rain during long monsoon resulting in urban flooding in Karachi and Rawalpindi, the largest city in Pakistan[8].	WMO (2018) Srivastava et al. (2018)
2011	Mid-August – early September	Flood	Record breaking heavy rainfall over parts of Sindh province (347% of average). Over monsoon period the country received 172% of average rainfall, the 5th heaviest monsoon in past 52 years. Heavy rain in Sindh province attributed to mid-tropospheric cyclones.	Rajeevan et al., (2012)
2010	28-29th July	Flood	Unusual synoptic pattern – heavy continuous rainfall associated with mesoscale convective system usually located in Bay of Bengal transited to northern Pakistan.	Rajeevan et al. (2011) Synoptic studies: (Houze et al., 2011; Martius et al., 2013; P. J. Webster et al., 2011) Teleconnections: (Hong et al., 2011; Lau & Kim, 2012) Hydropower:

				(Hashmi et al., 2012)
2007	3rd July – 15th August	Flood	Flooding in south-east Sindh province and north-west Khyber Pakhtunkhwa provinces [11]	WMO (2008)

2.5.2 Case study: Pakistan floods 2010

The 2010 floods in Pakistan were a particularly rare event with significant impacts. Given the rare nature of this event, multiple studies have explored the driving conditions behind this event, and therefore the summary provided here is more comprehensive than for other case studies.

Impacts of the 2010 floods

In 2010 Pakistan was hit by unprecedented monsoon rains and floods, the worst flooding in the past 80 years (Hashmi et al., 2012). Approximately one-fifth of Pakistan's total land area was affected by floods, with the Khyber Pakhtunkhwa (KPK) province in the north-west facing the brunt of the damage and casualties (above 90% of the deaths occurred in that province)[22].

Across the country the scope and scale of the crisis was exceptional, affecting the lives of over 18 million people, washing away communities and livelihoods, destroying infrastructure, and forcing millions to flee from their homes[22]. The crisis took the lives of a confirmed 1,980 people and left an estimated 14 million in need of humanitarian assistance[22].

The extreme rainfall and flooding, combined with socioeconomic vulnerability, is an example of how natural disasters can lead to multiple disasters. For example, the actual flooding events are the ‘first disaster’, and a ‘second disaster’ triggered by a chain of cause-and-effect events relating to the first disaster, which is often larger in magnitude than the first disaster (Ahmad et al., 2011).

Impacts on the hydropower sector include damage to infrastructure, such as the Munda Amandra and Kurram Garhi Headworks and 605 transformers in the (KPK) province, and hydropower plants (Jagran and Malakand-III) were flooded. Impacts on the wider power sector included partial shut-down of large power houses due to flooding unavailability of fuel as a result of road/rail damage. Grid stations, transmission lines and distribution infrastructure were also damaged, and resulted in limits to the supply of electricity across the country (Hashmi et al., 2012). The lack of electricity, particularly during the hot months, often results in repeated strikes, public protests and disturbances.[23]

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[22] https://reliefweb.int/report/pakistan/pakistan-floodsthe-deluge-disaster-facts-figures-15-september-2010

[23] https://www.nytimes.com/2010/08/27/world/asia/27flood.html

The 2010 summer monsoon in Pakistan

The summer monsoon experienced higher than average rainfall over the monsoon period (June-September) in 2010. Following a drier than average June, caused by a disruption in the northward progression and temporary hiatus of the monsoon by Tropical Cyclone Phet in the Arabian Sea, the months of July, August and September all experienced above average rainfall (Rajeevan et al., 2011).

In Pakistan, exceptionally heavy rains were experienced on 28th-29th July in the north and from 2nd to 8th August further south. The heavy rains led to flooding through the entire Indus Valley over the following days. The seasonal rainfall totals were around 75% above average in northwest and central parts of the country, and the country-wide seasonal total was the fourth highest on record (last 50 years) and the highest since 1994 (Rajeevan et al., 2011a; Wang et al., 2011).

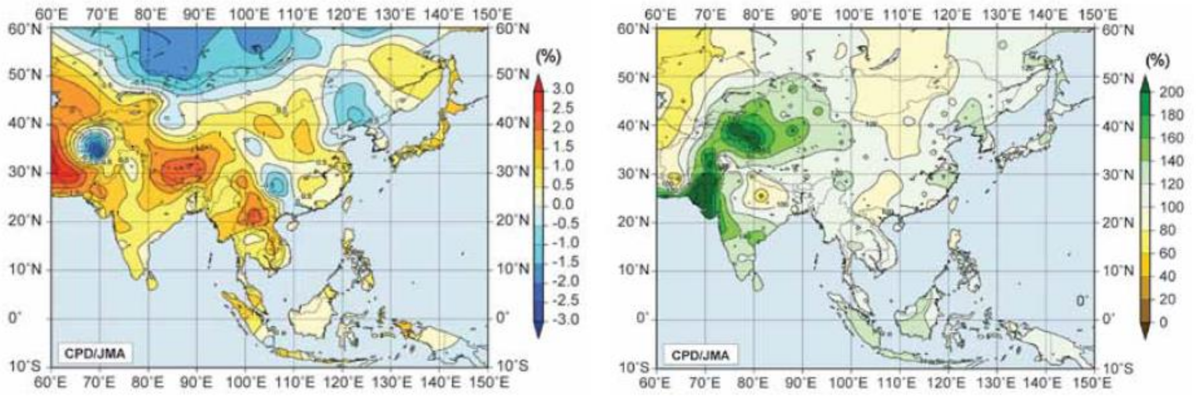

Figure 20 –Annual mean temperature anomalies (left panel) and annual precipitation as percentage of the climatological average (right panel) in 2010 using 1971-2000 reference period (Rajeevan et al., 2011).

Hong et al. (2011) identify four monsoon surges in the TRMM time series (Figure 21):

- 1st surge: 19-22 July,
- 2nd surge: 27-29 July (the largest with daily rainfall exceeding 25mm per day; 5 times larger than the climatological mean of ~5 mm per day),
- 3rd surge: 6-8 August,
- 4th surge: 10-12 August

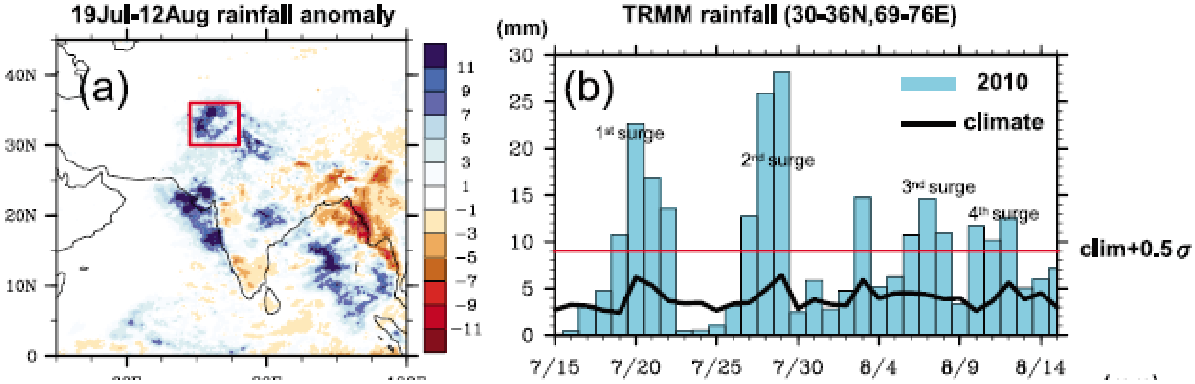

Figure 21 – Rainfall anomaly (panel a) and TRMM time series (panel b) from (Hong et al., 2011). A monsoon surge is defined here as when the daily rainfall over the box in panel a is larger than 9mm (climatological mean + 0.5 standard deviation) and persists for at least two days (Hong et al., 2011).

Were the rains unusual for this region?

Houze et al., (2011) show that the intensity and structure of the extreme rains experienced during the 2010 monsoon were unusual for Pakistan.

There are three typical rain storm types in this region, categorised by the radar echo using TRMM data (Houze et al., 2011), these are:

- storms with "deep convective" cells, where the buoyant updrafts produce extremely intense radar echoes at altitudes above 10 km MSL;
- storms containing "wide convective" rain areas, in which the extremely intense echoes extend contiguously over unusually large horizontal areas (> 1,000 km^2); and
- storms exhibiting "broad stratiform" rain areas, in which the spreading of old convective cells produces unusually large regions of stratiform radar echo (> 50,000 km^2 in area).

In the Western Himalayan Foothills, storms with deep convective cells are common and storms containing broad stratiform rain areas are rare. Some of the most intense and lightning-prone storms in the world occur in this region. These type of convective storms are locally intense but do not account for much rainfall. Figure 22 (left panel) shows the typical mid-level circulation anomalies for this type of storm; the low pressure anomaly brings dry air from the Afghan Plateau into the western Himalayan foothills which inhibits the growth of convective clouds into wider-spread storms.

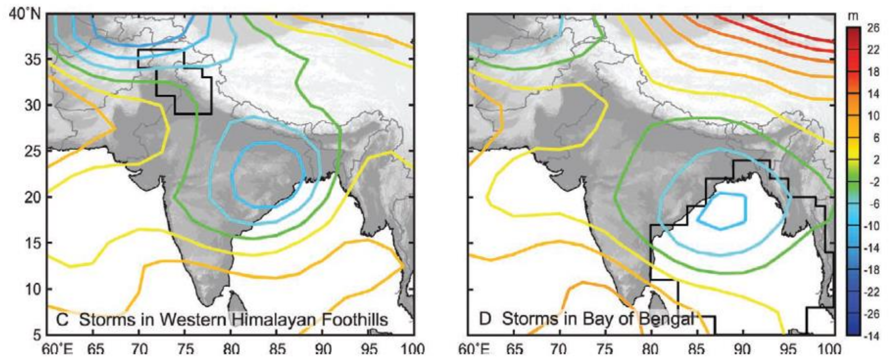

Figure 22 – Average anomalies associated with rain storms in Western Himalayan Foothills (left panel, region marked with black box) and the Bay of Bengal (right panel, region marked with black box).

Typical storms in the Bay of Bengal are of the 'broad stratiform' type associated with high rainfall across a wide region (Houze et al., 2011). These storms are associated with a low-pressure system, or 'depression', in the Bay of Bengal (Figure 22, right panel).

What happened in the summer monsoon 2010?

During late July 2010, the storm experienced in the Western Himalayan Foothills region was of the type usually experienced in the Bay of Bengal, i.e. a broad stratiform mesoscale convective system. This system was widespread and persistent over a fixed and highly vulnerable regional watershed, which is usually an arid region and does not experience these type of storms (Houze et al., 2011).

The 500 mbar height anomaly associated with this storm on 28th July 2010 is shown in Figure 23 and the process in which this anomaly pattern evolved along with observed rain in the days running up to 28th July is demonstrated in Figure 24.

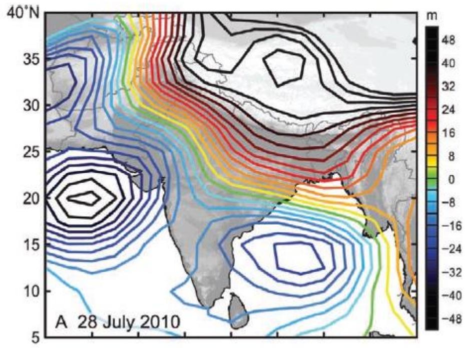

Figure 23 – 500 mbar anomaly on 28th July 2010 (Houze et al., 2011)

A broad stratiform depression over the Bay of Bengal was unusally intense on 25th July (Figure 24, panel A) and propagated westwards (Figure 24, panel B), centring over the Arabian Sea on 28th July (Figure 24, panel C). At the same time, another smaller-scale depression developed in the Bay of Bengal and the high pressure anomaly over Asia had propagated over the Tibetan Plateau and into northern India (Figure 24, panel C). There was little rain associated with this depression in the Bay of Bengal as much of the humid air had propagated westward. This situation resulted in a very strong pressure gradient in the Western Himalayan Foothills giving rise to a particularly humid south-easterly flow onto and over the face of the Himalayas in Pakistan (Figure 23; Houze et al., 2011), and intense rainfall (Figure 24, panel I). A similar synoptic situation occurred in 1949 and was associated with intense rainfall in north-eastern Pakistan (Martius et al., 2013).

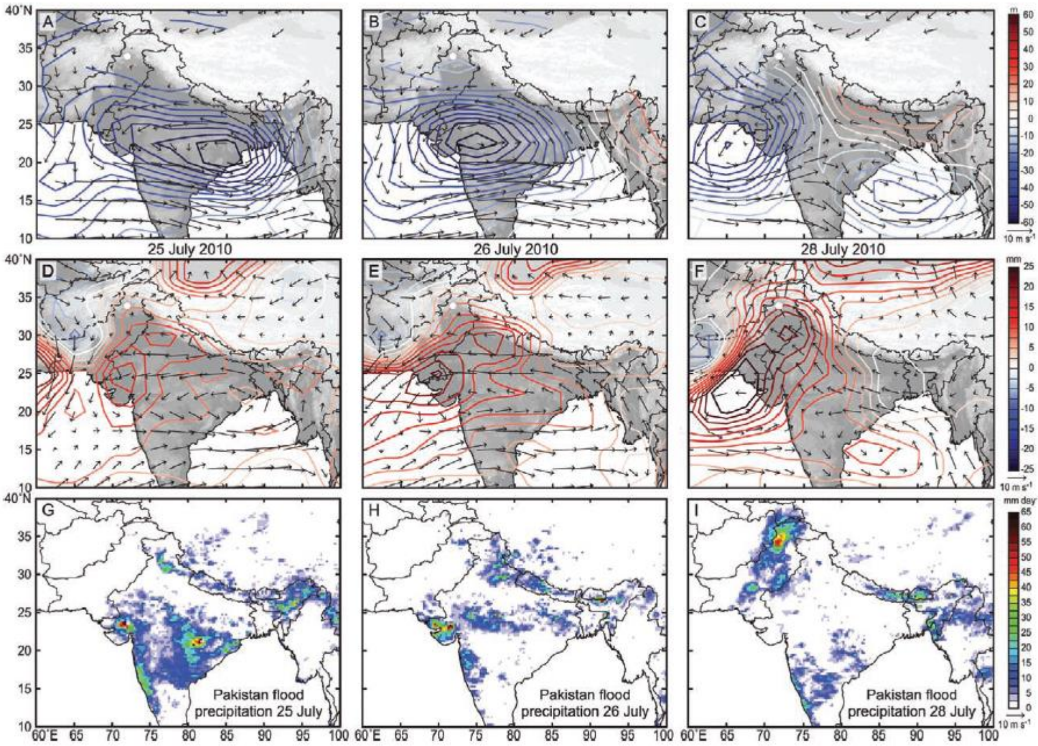

Figure 24 – Sequence of maps showing the evolution of the atmospheric structure prior to 28th July 2010 Pakistan rains – from (Houze et al., 2011), figure 2. Top row: 700mb average height anomalies and 700mb actual wind vectors, middle row: contours of vertically integrated precipitable water anomaly (mm) and 500mb actual wind vectors, bottom row: average rain rate from TRMM.

The vertical profiles of relative humidity and temperature for the storms over Pakistan in July 2010 are shown in Figure 25 and compared to a typical storm for the region, and also a typical storm in the Bay of Bengal. The profile is far more saturated and similar to that of a storm in the Bay of Bengal. Convective cells in this type of environment are expected to be less intense than in the typical case as the higher humidity inhibits buoyancy through the middle troposphere.

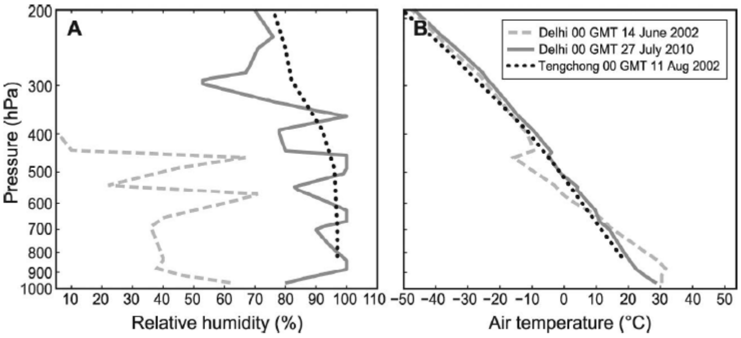

Figure 25 – Vertical profiles comparing the Pakistan storm in July 2010 (solid grey line) with a typical storm in the region (dashed grey line) and a typical storm in the Bay of Bengal (dotted black line). (Houze et al., 2011).

Large-scale drivers and teleconnections

The events in Pakistan in 2010 can be traced back to the specific states of the large-scale drivers of the monsoon and other related events.

In 2009 and 2010, a strong El Niño event that developed in 2009 underwent a rapid transition to a strong La Niña event in spring 2010 (Kim et al., 2011; Martius et al., 2013; Figure 1).

The synoptic conditions that led to the Pakistan floods have also been linked to a persistent blocking high pressure system over Russia in July and August 2010 (Hong et al., 2011; Lau & Kim, 2012; Martius et al., 2013). This blocking high was an extreme event in its own right, leading to an intense heatwave and associated such as forest fires and drought conditions severely reducing agricultural production (Grumm, 2011). These blocking anticyclones are also more prevalent during La Niña conditions (Martius et al., 2013).

Lau & Kim (2012) analyse the teleconnections with this blocking high over Russia to understand the unusual circulation pattern associated with the Pakistan floods. They consider the blocking pressure system over two separate 15 day periods; 10-24th July which was associated with the episodic rains in Pakistan and 25th July - 8th August which was associated with the steady rain (Figure 21).

In the first period (10-24th July) a 500 hPa blocking high was over western Russia which divided the 200 hPa jet in two (Figure 26 panel a, Figure 27 panel a). This blocking high was associated with an anticyclone in the lower troposphere (Figure 27 panel b) and, although the flow was fairly disorganised over Pakistan, there is evidence of an anomalous low-level easterly flow from the Bay of Bengal across India and also a southerly low-level flow over the northern Arabian sea (Figure 27 panel b).

In the second period (25th July - 8th August) the 500 hPa blocking high shifted slightly eastward and intensified, developing into a characteristic Ω blocking pattern (Figure 26 panel b). Two anomalous cyclonic pressure systems (C1 and C2 in Figure 27 panel c) developed west and south of Pakistan, with an anomalous high pressure system over the Tibetan Plateau (Figure

27 panel c). We see the low-level flow associated with this mid-troposphere circulation resulted in a strong anomalous south-easterly flow bringing moisture along the foothills of the Himalayas into Pakistan (Figure 27 panel d). This flow was intensified by the presence of a monsoon trough to the south.

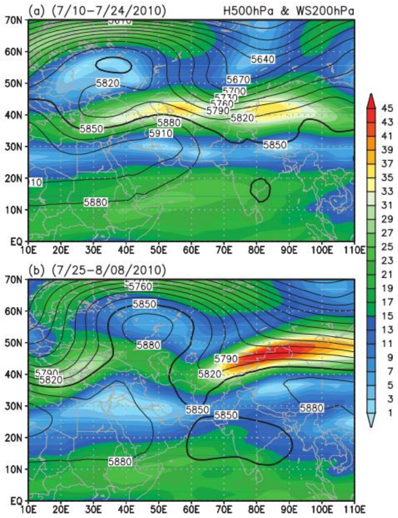

Figure 26 –Spatial patterns of the 500 hPa geopotential height (contours) and 200 hPa wind speeds over two periods in July and August 2010, from Lau & Kim (2012).

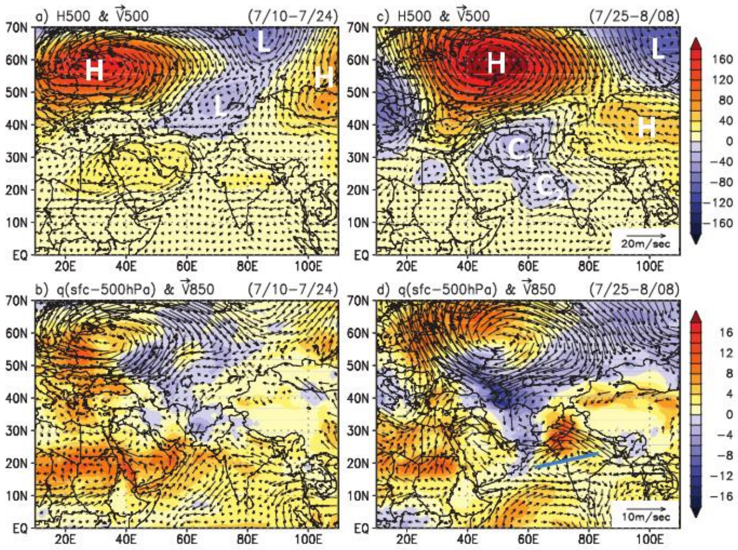

Figure 27 – Spatial patterns of the 500 hPa geopotential height anomalies and 500 hPa wind speeds for the two periods (top panels) and precipitable water anomalies and 850 hPa wind speeds for the two periods (bottom panels). Figure from Lau & Kim (2012).

3. Using the case studies to inform extremes analysis

The purpose of the case studies of extreme events presented in this report is to better understand the large-scale drivers of extreme precipitation events that have occurred across South Asia. This work will feed into planned work to identify plausible climate model projections for the region, by conducting a process-based evaluation of the available climate model projections based on the key processes associated with extreme rainfall events identified here. Also, these case studies will form the basis of communications material and storylines to use in engagement with key stakeholders and users of climate information, by relating the climate projections to recent extreme events.

The aim of this section is to identify relevant processes and indicators to inform the process-based evaluation, and also to identify suitable metrics for consideration when analysing the future climate model projections to inform the development of sector-specific climate services. Summaries of the case studies are provided in Table 6.

Table 6 – Table summarising the five cases studies. The ENSO and IOD phases have been drawn from the time series in Figure 28.

Location	**Year**	**Description**	**Causes**	**Large-scale drivers**
South Asia	2007	Widespread flooding across the region	Monsoon rainfall near average, some areas much wetter/drier Early monsoon onset and multiple disruptions High storm activity: 2 cyclones & 11 low pressure systems	*ENSO*: transition from El Niño to La Niña *IOD:* positive or neutral phase
Afghanistan	2014	Flash flooding in spring	Heavy localised rainfall Above average winter precipitation Warm winter leading to increased glacial melt	*ENSO*: transition from La Niña to El Niño *IOD*: negative phase
Bangladesh	2017	August flooding: localised heavy rainfall & northern rivers burst banks	Monsoon rainfall average for Bangladesh, deficits elsewhere High intra-seasonality – active/break cycles Break in India linked with active conditions in northern Bangladesh Strong pressure gradient & northward migration of monsoon trough	*ENSO*: transition from strong El Niño to La Niña *IOD:* transition from positive to negative phase *Other:* High BSISO (northward migration component)

Nepal	2007	Flooding and landslides associated with extreme rainfall during July	Break monsoon conditions, moisture brought across from Arabian Sea, warmer drier air higher up in troposphere, orographic uplift at Himalayas	*ENSO*: transition from El Niño to La Niña *IOD:* positive or neutral phase *Other:* Rossby wave train
Pakistan	2010	July/August flooding: localised heavy & continuous rainfall in arid region	Unusual synoptic conditions led to persistent convective rain**:** • Low pressure system developed in BOB & transited westwards • High pressure over Tibetan Plateau • Strong pressure gradient causing moist south-easterly flow	*ENSO*: transition from strong El Niño to La Niña *IOD:* transition from positive to negative phase *Other:* Strong blocking high over Russia, Rossby wave train

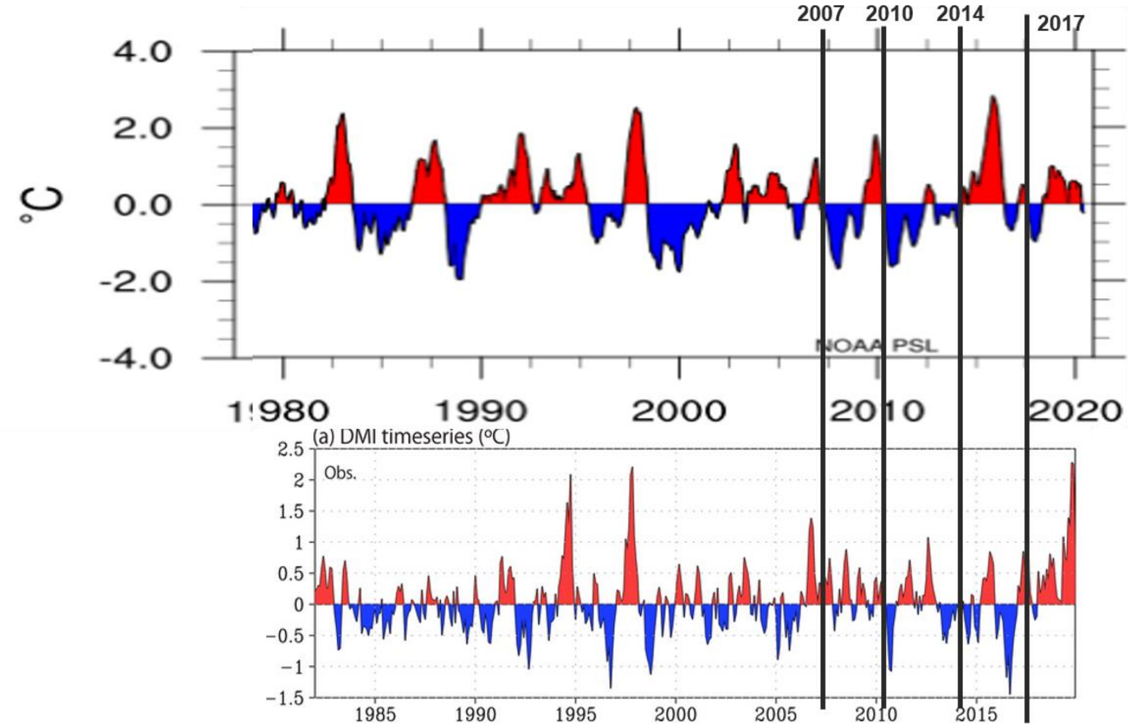

Figure 28 – Time series of the Niño 3.4 index (top panel; source: NOAA PSL[5]) and the IOD (bottom panel; (Doi et al., 2020) from Figure 4 and Figure 5. The case study years are identified with vertical black lines to highlight the phases of ENSO and IOD during these years.

From this case study analysis, we identify the following characteristics of extreme rainfall events:

- The total rainfall across the monsoon season and region is often not excessively high or low compared to the climatological average;
- The spatial and temporal distribution of the monsoon rainfall is critical, and large-scale spatial averages and seasonal means do not capture these events;
- The case study events are often associated with exceptionally heavy localised rainfall over short time periods;
- The impacts of localised heavy rainfall can be two-fold; localised flooding and/or riverine flooding downstream;
- Extreme flooding events can occur from either a single excess rainfall event, or an accumulation of excess rainfall events throughout the monsoon season;
- Glacial melt also contributes to riverine flooding events and factors that influence this include higher precipitation during the winter season and warmer than average temperatures during winter/spring;
- Many of years identified where extreme precipitation events occurred are associated with high intra-seasonal variability in the monsoon season with a high frequency of active/break cycles – these processes are governed by the BSISO;
- Active/break cycles are usually defined by the active or break conditions over India, but the opposing conditions occur in the foothills of the Himalayas during these cycles resulting in active conditions causing excess rainfall and flooding in the Terai, Nepal, and northern Bangladesh during a break phase in India;
- Heavy rainfall events that occur in the foothills of the Himalayas are often associated with a strong pressure gradient and orographic lift;
- Many of the years in which extreme events occurred were associated with a transition from El Niño to La Niña conditions;
- The synoptic conditions that led to the flooding in Pakistan in 2010 were particularly rare.

Based on these observations, Table 7 summarises the relevant metrics to capture the key driving processes of extreme rainfall events to inform the process-based evaluation. Table 8 summarises relevant metrics that could be used to quantify and assess extreme rainfall events in the present-day (for example, using the UNSEEN approach), and in the future projections.

Table 7 – Table summarising relevant metrics to inform the process-based evaluation.

Conditions to capture	**Reason/link to case study**	**Metric**
Frequency of strong La Niña conditions	La Niña events linked with heavy rainfall in South Asia	ENSO indices – negative phase
Frequency of transition from El Niño to La Niña	Case studies often feature transition from El Niño to La Niña	ENSO indices – positive to negative transition, rate of change
Strong pressure gradient over region:	Replicate Pakistan 2010 conditions	Pressure gradient threshold
High intra-seasonal variability in the monsoon	Replicate 2007, 2017 conditions where intra-seasonable variability was high	BSISO indices
Monsoon break conditions	Linked to active conditions in Himalayan foothills causing heavy rain in southern Nepal and northern Bangladesh	BSISO indices and metrics for active/break cycles

Table 8 – Table summarising relevant metrics that could be used as part of the process-based evaluation, quantification of the risk of extremes, and assessment of future projections relevant to extreme rainfall.

Conditions to capture	**Reason/link to case study**	**Metric**
Above average rainfall for specific months during monsoon period	Flooding often driven by intense rainfall over a few days which may result in monthly rainfall totals being above average compared to other months	J, J, A and S precip over defined region
High intensity rainfall	To capture heavy localised rainfall conditions	95th/99th percentile of climatological rainfall Rainfall intensity metrics
Consecutive wet days accumulated over monsoon period	To capture flooding events due to continuous rain and saturation on the ground, and increased moisture availability in precipitation events	CWD in JJAS over defined region
Increased river flow from glacial melt	To capture flooding events associated with increased river flow, potentially combined with heavy rainfall, i.e. to replicate Afghanistan 2014 case study	Higher than average winter precipitation over mountainous regions and higher than average temperatures during winter/spring.

Other metrics that could be considered in the extremes analysis include the monsoon indices presented in section 1.1 which measure the strength of the monsoon based on wind gradients. The timeseries of these indices indicates that case study years 2010 and 2014 were associated with negative phases of the Indian Monsoon Index (IMI) and Webster and Yang Monsoon Index (WYMI), and 2007 was also negative for WYMI. Although there are commonalities in the phase of these indices, the individual years do not stand out as 'extreme' in terms of the values of the indices. More recent data for these indices is required to assess the phase of the 2016 and 2017 years.

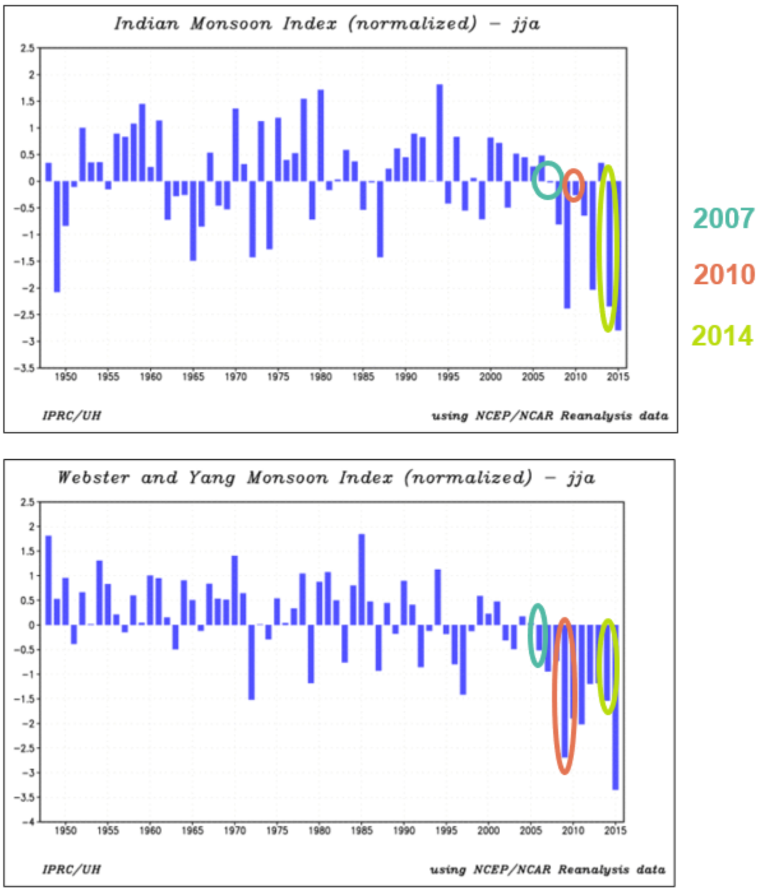

Figure 29 – Time series of monsoon indices as shown in Figure 2 and Figure 3, with the case study years 2007, 2010 and 2014 highlighted.

4. Summary and further work

This report has presented a summary of extreme precipitation events that have occurred across the South Asia region and in each of the four ARRCC focus countries; Afghanistan, Bangladesh, Nepal and Pakistan. A case study event from each of these five regions was selected and explored in further detail to understand the causes of the extreme events and the large-scale driving conditions associated with the monsoon in that year.

This case study analysis has two main purposes:

- to inform follow-on analysis of climate models to assess their suitability for use in the region and selection of plausible scenarios for use in developing sector specific climate services;
- to inform upcoming stakeholder engagement activities as part of the development of sector specific services by providing relatable and compelling storylines in discussions around use of future climate projections.

Through identification of key processes and large-scale drivers of these extreme events, this work will feed into a process-based evaluation of available global and regional climate model projections. Monsoon rainfall is not well represented in many climate models due to the complex topography of the region, and therefore evaluating the models by the key driving processes that are relevant to the incidence of extreme rainfall events provides an alternative approach to assessing the model's ability to project changes in the future. This work will aim to exclude any models which do not capture these key processes and to provide confidence in the remaining projections.

From the analysis presented in this report, the key driving processes that will be considered in the process-based evaluation will include how well the models capture the key characteristics of the monsoon flow and the drivers of interannual and intraseasonal variability such as ENSO, the IOD and the BSISO. Metrics that capture occurrence of extreme precipitation events include monthly means, extreme rainfall indices such as percentiles and severity metrics, and measures of cumulative wet days.

5. References

Ahmad, F., Kazmi, S. F., & Pervez, T. (2011). Human response to hydro-meteorological disasters: A case study of the 2010 flash floods in Pakistan. *Journal of Geography and Regional Planning*, *4*(9), 518–524. Retrieved from http://www.academicjournals.org/JGRP

Annamalai, H., & Slingo, J. M. (2001). Active/break cycles: diagnosis of the intraseasonal variability of the Asian Summer Monsoon. *Climate Dynamics*, *18*(1–2), 85–102. https://doi.org/10.1007/s003820100161

Ashok, K., Guan, Z., & Yamagata, T. (2001). Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophysical Research Letters*, *28*(23), 4499–4502. https://doi.org/10.1029/2001GL013294

Behera, S. K., Krishnan, R., & Yamagata, T. (1999). Unusual ocean-atmosphere conditions in the tropical Indian Ocean during 1994. *Geophysical Research Letters*, *26*(19), 3001–3004. https://doi.org/10.1029/1999GL010434

Bohlinger, P., Sorteberg, A., & Sodemann, H. (2017). Synoptic conditions and moisture sources actuating extreme precipitation in Nepal. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12,653-12,671. https://doi.org/10.1002/2017JD027543

Bohlinger, P., Sorteberg, A., Liu, C., Rasmussen, R., Sodemann, H., & Ogawa, F. (2019). Multiscale characteristics of an extreme precipitation event over Nepal. *Quarterly Journal of the Royal Meteorological Society*, *145*(718), 179–196. https://doi.org/10.1002/qj.3418

Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A., & Regmi, D. (2019). A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. *Landslides*, *16*(3), 533–549. https://doi.org/10.1007/s10346-018-1079-9

Chhetri, T. B., Dhital, Y. P., Tandong, Y., Devkota, L. P., & Dawadi, B. (2020). Observations of heavy rainfall and extreme flood events over Banke-Bardiya districts of Nepal in 2016–2017. *Progress in Disaster Science*, *6*, 100074. https://doi.org/10.1016/j.pdisas.2020.100074

Dastagir, M. R. (2015). Modeling recent climate change induced extreme events in Bangladesh: A review. *Weather and Climate Extremes*, *7*, 49–60. https://doi.org/10.1016/j.wace.2014.10.003

Doi, T., Behera, S. K., & Yamagata, T. (2020). Predictability of the Super IOD Event in 2019 and Its Link With El Niño Modoki. *Geophysical Research Letters*, *47*(7), 1–9. https://doi.org/10.1029/2019GL086713

Gadgil, S., Vinayachandran, P. N., Francis, P. A., & Gadgil, S. (2004). Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophysical Research Letters*, *31*(12). https://doi.org/10.1029/2004GL019733

Grumm, R. H. (2011). The central European and russian heat event of July-August 2010.

Bulletin of the American Meteorological Society, *92*(10), 1285–1296. https://doi.org/10.1175/2011BAMS3174.1

Hagen, E., & Teufert, J. F. (2009). Flooding in Afghanistan: A crisis. In J. A. A. Jones, T. G. Vardanian, & C. Hakopian (Eds.), *Threats to Global Water Security* (NATO Scien, pp. 179–185).

Hashmi, H. N., Siddiqui, Q. T. M., Ghumman, A. R., Kamal, M. A., & Mughal, H. ur R. (2012). A critical analysis of 2010 floods in Pakistan. *African Journal of Agricultural Research*, *7*(7), 1054–1067. https://doi.org/10.5897/ajarx11.036

Hong, C. C., Hsu, H. H., Lin, N. H., & Chiu, H. (2011). Roles of European blocking and tropical-extratropical interaction in the 2010 Pakistan flooding. *Geophysical Research Letters*, *38*(13), 1–6. https://doi.org/10.1029/2011GL047583

Hossain, S., Cloke, H., Ficchì, A., Turner, A., & Stephens, E. (2019). Hydrometeorological drivers of the 2017 flood in the Brahmaputra basin in Bangladesh. *Hydrology and Earth System Sciences Discussions*, (June), 1–33. https://doi.org/10.5194/hess-2019-286

Houze, R. A., Rasmussen, K. L., Medina, S., Brodzik, S. R., & Romatschke, U. (2011). Anomalous atmospheric events leading to the summer 2010 floods in Pakistan. *Bulletin of the American Meteorological Society*, *92*(3), 291–298. https://doi.org/10.1175/2010BAMS3173.1

International Federation of Red Cross and Red Cresent Societies. (2007). Nepal: floods & landslides. *DREF Bulletin no.MDRNP001*.

Kattelmann, R. (2003). Glacial lake outburst floods in the Nepal Himalaya: A manageable hazard? *Natural Hazards*, *28*(1), 145–154. https://doi.org/10.1023/A:1021130101283

Kikuchi, K., Wang, B., & Kajikawa, Y. (2012). Bimodal representation of the tropical intraseasonal oscillation. *Climate Dynamics*, *38*(9–10), 1989–2000. https://doi.org/10.1007/s00382-011-1159-1

Kim, W., Yeh, S. W., Kim, J. H., Kug, J. S., & Kwon, M. (2011). The unique 2009-2010 El Niño event: A fast phase transition of warm pool El Niño to la Niña. *Geophysical Research Letters*, *38*(15), 1–5. https://doi.org/10.1029/2011GL048521

Krishnamurthy, V., & Shukla, J. (2000). Intraseasonal and interannual variability of rainfall over India. *Journal of Climate*, *13*(24), 4366–4377. https://doi.org/10.1175/1520-0442(2000)013<0001:IAIVOR>2.0.CO;2

Lau, W. K. M., & Kim, K. M. (2012). The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorological extremes. *Journal of Hydrometeorology*, *13*(1), 392–403. https://doi.org/10.1175/JHM-D-11-016.1

Martius, O., Sodemann, H., Joos, H., Pfahl, S., Winschall, A., Croci-Maspoli, M., et al. (2013). The role of upper-level dynamics and surface processes for the pakistan flood of July 2010. *Quarterly Journal of the Royal Meteorological Society*, *139*(676), 1780–1797.

https://doi.org/10.1002/qj.2082

Met Office. (2020). *ARRCC CARISSA Work Stream 4. Pilot study progress report: Climate information for the hydropower sector in Nepal*.

Met Office, & ICIMOD. (2019). *Regional workshop on climate services for the water and hydropower sectors in South Asia, Proceedings*. Retrieved from https://lib.icimod.org/record/34708

Nandargi, S., & Dhar, O. N. (2011). Extreme rainfall events over the Himalayas between 1871 and 2007. *Hydrological Sciences Journal*, *56*(6), 930–945. https://doi.org/10.1080/02626667.2011.595373

Pant, G. B., & Parthasarathy, S. B. (1981). Some aspects of an association between the southern oscillation and indian summer monsoon. *Archives for Meteorology, Geophysics, and Bioclimatology Series B*, *29*(3), 245–252. https://doi.org/10.1007/BF02263246

Philip, S., Sparrow, S., Kew, S. F., Van Der Wiel, K., Wanders, N., Singh, R., et al. (2019). Attributing the 2017 Bangladesh floods from meteorological and hydrological perspectives. *Hydrology and Earth System Sciences*, *23*(3), 1409–1429. https://doi.org/10.5194/hess-23-1409-2019

Rajeevan, M., Revadekar, J., & Zubair, L. (2008). *South Asia [in Regional Climates, State of the Climate in 2007]*.

Rajeevan, M., Srivastava, K., Lareef, Z., & Revadekar, J. (2011). South Asia [in Regional Climates, State fo the Climate in 2010]. *Environment*, *92*(6), S127–S219.

Rajeevan, M., Srivastava, A. K., Lareef, Z., & Revadeka, J. V. (2012). South Asia [in Regional Climates, State of the Climate in 2011]. *Bulletin of the American Meteorological Society*, *94*(8), S188–S190.

Renwick, J. (2015). Asia [in Regional Climates, State of the Climate in 2014]. *Bulletin of the American Meteorological Society*, *96*(7), S200–S209. https://doi.org/10.1175/2015bamsstateoftheclimate.1

Shein, K. A. (2006). State of the Climate in 2005. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-89-7-StateoftheClimate

Sikka, D. R. (1980). Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. *Journal of Earth System Science*, *89*(2), 179–195. https://doi.org/10.1007/BF02913749

Srivastava, A. K., Revdekar, J. V., & Rajeevan, M. (2015). South Asia [in Regional Climates State of the Climate in 2014]. *Proceedings of the 20th USENIX Security Symposium*, 206–208.

Srivastava, A. K., Revadekar, J. V., & Rajeevan, M. (2017). South Asia [in Regional Climates, State fo the Climate in 2016], (August), 217–220.

Srivastava, A. K., Revadeka, J. V., & Rajeevan, M. (2018). South Asia [in Regional Climates, State of the Climate in 2017]. *Bulletin of the American Meteorological Society*, *99*(8), S239–S242. https://doi.org/10.1175/2018bamsstateoftheclimate.1

Turner, A. G., & Slingo, J. M. (2009). Uncertainties in future projections of extreme precipitation in the Indian monsoon region. *Atmospheric Science Letters*, *10*, 152–158. https://doi.org/10.1002/asl

Wang, B., & Fan, Z. (1999). Choice of South Asian Summer Monsoon Indices. *Bulletin of the American Meteorological Society*, *80*(4), 629–638. https://doi.org/10.1175/1520-0477(1999)080<0629:COSASM>2.0.CO;2

Wang, B., Wu, R., & Lau, K. M. (2001). Interannual variability of the asian summer monsoon: Contrasts between the Indian and the Western North Pacific-East Asian monsoons. *Journal of Climate*, *14*(20), 4073–4090. https://doi.org/10.1175/1520-0442(2001)014<4073:IVOTAS>2.0.CO;2

Wang, S. Y., Davies, R. E., Huang, W. R., & Gillies, R. R. (2011). Pakistan's two-stage monsoon and links with the recent climate change. *Journal of Geophysical Research Atmospheres*, *116*(16), 1–15. https://doi.org/10.1029/2011JD015760

Webster, P. J., & Yang, S. (1992). Monsoon and ENSO: Selectively interactive systems.

Webster, P. J., Toma, V. E., & Kim, H. M. (2011). Were the 2010 Pakistan floods predictable? *Geophysical Research Letters*, *38*(4), 1–5. https://doi.org/10.1029/2010GL046346

WMO. (2008). WMO statement on the status of the global climate in 2007. *World Meteorological Organization*, (1108), WMO-No. 1108. Retrieved from http://www.wmo.int/pages/mediacentre/press_releases/documents/WMO_1108_EN_web_000.pdf

WMO. (2018). *WMO Statement on the satus of the global climate in 2017*.

WMO. (2020). *WMO statement on the status of the global climate in 2019*. *World Meteorological Organization*. Retrieved from http://www.wmo.int/pages/mediacentre/press_releases/documents/WMO_1108_EN_web_000.pdf