Seasonal Forecasting in South Asia: A Review of the Current Status

Asia Regional Resilience to a Changing Climate (ARRCC)

Work Package 2: Strengthening Climate Information Partnerships – South Asia (SCIPSA)

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Authors

Jessica Stacey - Climate Services Scientist, Met Office
Dr Katy Richardson – Senior Climate Information Scientist, Met Office
Dr Justin Krijnen – Applied Scientist, Met Office
Tamara Janes – Science Manager, Met Office

Reviewers

Francis Colledge – Senior Scientific Consultant, Met Office
Andrew Colman – Senior Climate Scientist, Met Office
Prof Richard Jones – Science Fellow, Met Office
Dr Gill Martin – Science Manager, Met Office

The authors also acknowledge valuable discussion, contributions and review from:
Dr Govindarajalu Srinivasan, RIMES
Dr D. S. Pai, Regional Climate Centre Pune - India Meteorology Department
Sayed Reza Mousawi, Afghanistan Meteorological Department
Quamrul Hassan, Bangladesh Meteorology Department
Dr Indira Kadel, Department of Hydrology and Meteorology, Nepal
Sohail Babar Cheema, Pakistan Meteorology Department

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Contents

Acronyms

AMO	Atlantic Multidecadal Oscillation
BSISO	Boreal summer Intra-Seasonal Oscillation
CCA	Canonical Correlation Analysis
CPT	Climate Predictability Tool
ENSO	El Niño Southern Oscillation
IMD	India Meteorological Department
IOD	Indian Ocean Dipole
ISV	Intra-Seasonal Variability
MJO	Madden-Julian Oscillation
MME	Multi-model ensemble
NAO	North Atlantic Oscillation
NMHS	National Meteorological and Hydrological Service
PDO	Pacific Decadal Oscillation
QBO	Quasi-Biennial Oscillation
RCC	Regional Climate Centre
RIMES	Regional Integrated Multi-hazard Early Warning System for Africa and Asia
SAM	South Asian Monsoon
SASCOF	South Asia Climate Outlook Forum
SST	Sea Surface Temperature
SVSLRF	Standardized Verification System for Long-Range Forecasts
WD	Western Disturbance

Executive Summary

South Asia has a diverse climate which is dominated by a monsoon system. Rainfall associated with the South Asian monsoon experiences considerable spatiotemporal variability, which has profound socioeconomic impacts on the region. Understanding the factors that drive this variability is critical to advancing seasonal forecasting in South Asia.

Slowly-evolving climate drivers provide a source of predictability on seasonal timescales. Identifying how these drivers affect the South Asian climate is critical to advancing its predictability. Various metrics have been established to define the relationship between summer monsoon rainfall and the large-scale circulation patterns driving the monsoon system, as well as the timing of the southwest monsoon onset.

The key seasonal drivers of the South Asian climate are the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). These are irregular coupled atmosphere-ocean oscillations which drive variability in monsoon rainfall from year-to-year. In general, the warm (cool) phase of ENSO results in a drier (wetter) monsoon season, whilst a positive (negative) phase of the IOD results in wetter (drier) monsoon season. Variability also exists within the season, driven by intraseasonal oscillations such as the Madden-Julian Oscillation.

Seasonal forecasts predict how average temperature or precipitation in an upcoming season will compare to the past climatology of a region. For example, a forecast can give you information on whether the season is likely to be wetter or drier than the climatological average.

Seasonal forecasts can be made using statistical or dynamical approaches, or a combination of the two. Statistical methods use observational records to identify relationships between local weather patterns and key climate drivers. Whereas dynamical methods use coupled atmosphere-ocean models to represent all complex interactions within the climate system.

Higher skill has been demonstrated using coupled model systems, which exceed the skill of statistical methods. However, further development is required to improve the skill of dynamical models at seasonal forecast timescales. For example, predicting the specific date of the monsoon onset is not currently possible for seasonal dynamical models.

Seasonal forecast experts produce a consensus-based seasonal forecast for the region during the South Asian Climate Outlook Forum (SASCOF). The forum is also an

opportunity for interaction between national, regional and international users and providers of climate services. The concept of SASCOF is then extended to the national level through National Climate Outlook Forums.

Knowledge gaps and future work identified include:

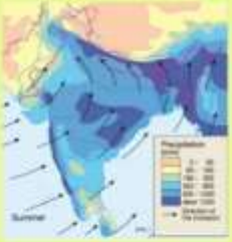
- The need for forecast verification and skill assessments at the national level, through building the capacity of National Meteorological and Hydrological Services to undertake standardised verification techniques as set out in the World Meteorological Organization’s guidance on verification of operational seasonal climate forecasts (World Meteorological Organization, 2018).
- The prediction of monsoon onset for the South Asia region and subsequent assessment of skill, using an objectively-defined method for identifying an early/late onset.
- Improving the uptake and understanding of seasonal forecast information through the tailoring of products and services relevant to a range of decision-making contexts at the regional and national level.

An infographic summarising this review is provided on the following page.

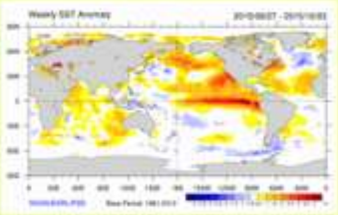
Seasonal Forecasting in South Asia: A Review of the Current Status

Asia Regional Resilience to a Changing Climate (ARRCC)
Strengthening Climate Information Partnerships – South Asia (SCIPSA)

1: South Asia has a diverse climate which is dominated by a monsoon system.



2: Slowly-evolving climate drivers provide a source of predictability on seasonal timescales

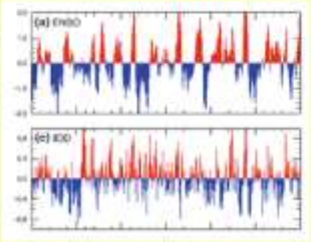


3: The key seasonal drivers of the South Asian climate are:

ENSO

and

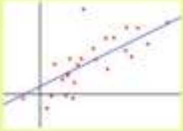
IOD



4: Seasonal forecasts predict how average conditions in an upcoming season will compare to the past climatology of a region

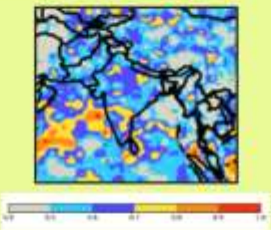
5: Seasonal forecasts can be made using the following approaches:

Statistical or **Dynamical**

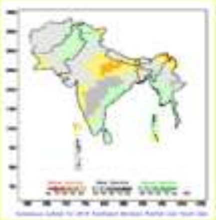


or a combination of the two

6: The skill of coupled model systems, exceeds the skill of statistical methods.



7: Seasonal forecast experts produce a consensus-based user-relevant seasonal forecast at SASCOF



8: Knowledge gaps and future work identified includes:

- Forecast verification and skill assessments at the national level
- Prediction of monsoon onset
- Improve uptake and understanding of seasonal forecasts

References

Box 1: South-west monsoon characteristics (Diercke International Atlas)
Box 2: Observed SST anomaly for El Niño event in 2015
Box 3: ENSO and IOD time series from Hoell and Funk 2013
Box 6: GloSea5 ROC scores for JJA 2019 for above normal rainfall
Box 7: SASCOF-14 seasonal forecast for rainfall

1. The climate of South Asia and its seasonal drivers

1.1 Climate of South Asia

The region of South Asia comprises the countries Afghanistan, Bangladesh, Bhutan, India, Maldives, Myanmar, Nepal, Pakistan and Sri Lanka. It is home to about one quarter of the world's population, making it the most populous as well as the most densely populated geographical region in the world. This vast region is geographically diverse (Figure 1), bounded by the Indian Ocean to the south and the Himalayas, the biggest mountain range in the world, to the north. The region's immense geographical scale and varied topography leads to starkly different microclimates, as shown in Figure 1 ranging from arid desert in the northwest, alpine tundra and glaciers in the north, to humid tropical regions supporting rainforests in the southwest and island territories. Most of the region will typically experience four seasons; pre-monsoon, monsoon, post-monsoon and winter, but the characteristics and timing of these varies drastically across the region. The average contribution of the rainfall for each season to the annual total is displayed in Figure 2.

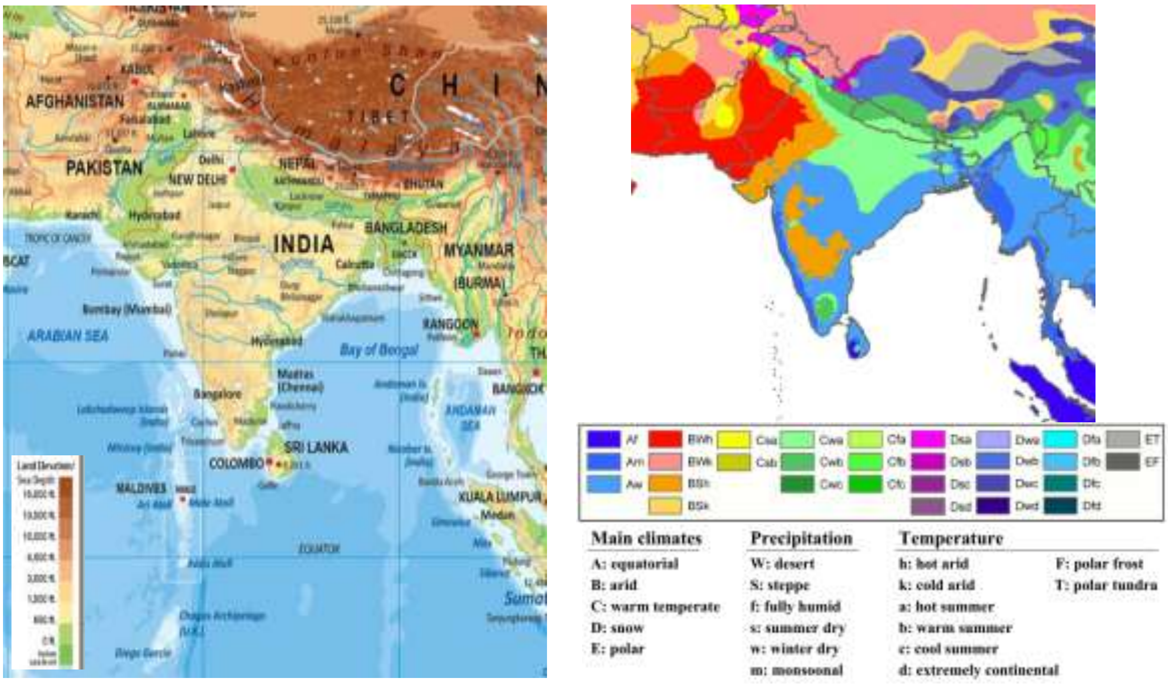


Figure 1. Left panel: topographic map of South Asia. Source: Adapted from World Maps online[1]. Right panel: Köppen-Geiger climate classifications of South Asia. Source: Peel et al., (2007).

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[1] https://www.worldmapsonline.com/academia/academia_asia_physical_map.htm

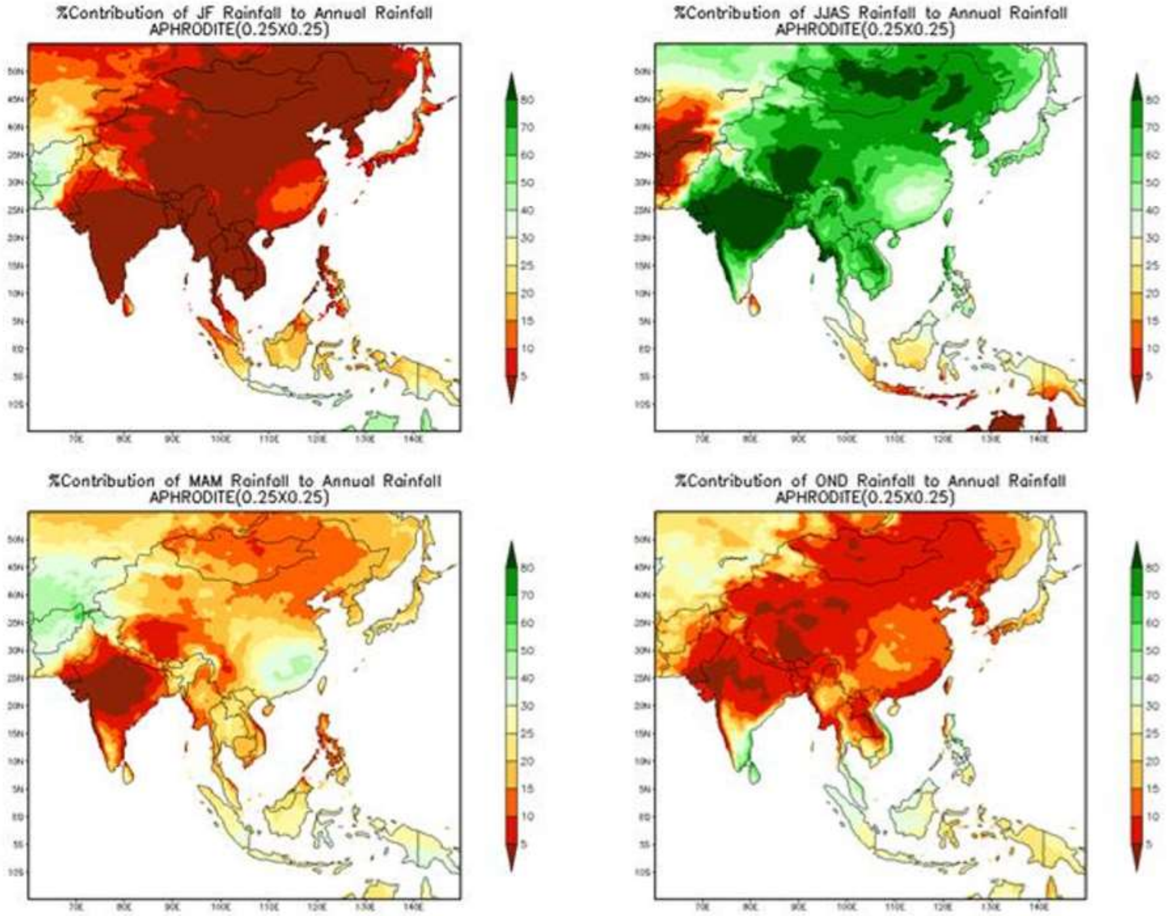

Figure 2: Percentage contribution of total annual precipitation in different seasons (JF: winter, MAM: Pre-monsoon, JJAS: SW monsoon, OND: post-monsoon or NE monsoon). Source: MMS and RIMES (2017). Data source: APHRODITE (0.25 x 0.25) data set (Yatagai et al., 2012)

1.1.1 Tropical Monsoons

The term 'monsoon' is used to signify any annual climate cycle with a dominant seasonal wind reversal. There are seven regional monsoon systems across the world which form part of a global monsoon system. This is a response of the coupled atmosphere-land-ocean-cryosphere-biosphere system to annual variation of solar forcing (Wang et al., 2011). Land has a much lower heat capacity than the ocean, meaning the tropical continents in early summer warm up more quickly than adjacent oceans, producing heat lows and areas of low-level atmospheric convergence. This sets up the monsoon circulation, which generally gives rise to two distinct phases: 'wet' and 'dry', depending on the location and direction of the circulation.

In the case of the Asian monsoon system, both the Indian and Pacific Oceans, and the largest landmass on earth, the Eurasian continent, play significant roles. The Tibetan Plateau also acts as a major elevated heat source strengthening the circulation of the Asian monsoon, particularly in the summer (Wu et al., 2007). The rainy season characteristics of the Asian monsoon can be divided into three sub-regions, the South Asian Monsoon (SAM) (referred to as the Indian summer monsoon (ISM) in Figure 3), the western North Pacific summer monsoon (WNPSM) and the East Asian summer monsoon (EASM). It is the SAM that characterises the South Asian climate.

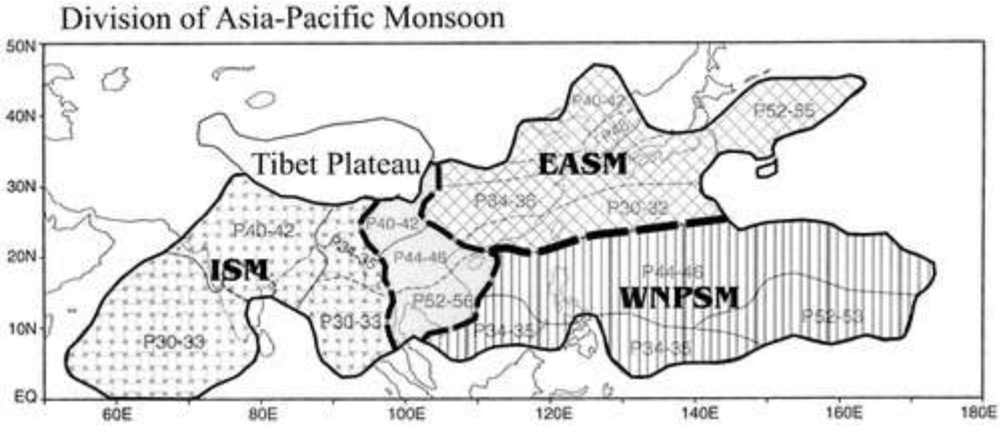

Figure 3. Asian-Pacific monsoon divided into three sub-regions. Source: Wang and LinHo (2002).

1.1.2 South Asian Monsoon

The SAM is the most important climatological feature and a principle source of water for much of South Asia. However, it is only partly understood and notoriously difficult to predict. The SAM can be split into two periods based on the direction of the rain-bearing winds: the southwest, or summer, monsoon typically occurs from June to September and the northeast, or winter, monsoon usually occurs from October to December.

1.1.2.1 Southwest Monsoon

The mechanism for the onset of the southwest monsoon begins during the pre-monsoon season from March to May, when rapid solar heating takes place over the land compared to the adjacent oceans, increasing the land-sea temperature gradient. The surface pressure over the land decreases with a trough of low pressure located across the Indo-Gangetic plains, and this sets up an atmospheric circulation. A simplified diagram of the southwest monsoon circulation is illustrated in Figure 4.

The air, which flows in from the Indian Ocean to the sub-continent, is humid, unstable and has considerable vertical extent, and as it is forced to rise over the land, it releases widespread, occasionally torrential rainfall. The rainfall often arrives as a sudden downpour over the state of Kerala, which is known as the ‘burst’ of the monsoon and this much-anticipated event heralds the start of the summer monsoon season in India. The SAM then gradually moves across most of South Asia; the average onset dates are shown in Figure 5 and the average rainfall and wind direction are shown in Figure 6. The southwest monsoon accounts for a considerable 70-90% of annual rainfall over the majority of South Asia, as shown in Figure 2, and has a profound socio-economic impact on the region. Rainfall patterns exhibit large variability both spatially and temporally. The most intense rainfall is usually observed over the northeast of the region, including northeast India, Bangladesh and Myanmar as well as the southwest coast of India due to orographic uplift of warm, moist air. The southeast of India, and Sri Lanka, remain comparatively dry at this time due to the rain shadow effect from the Western Ghats mountains along the west coast of the peninsula.

The southwest monsoon begins to steadily retreat from September, at a much slower pace than the onset, whilst the prevailing northeasterly trade winds gain strength over the region. As with the onset of the monsoon, the main mechanism for the withdrawal is due to the land-sea temperature gradient, with the oceans now comparably warmer towards the end of the boreal summer.

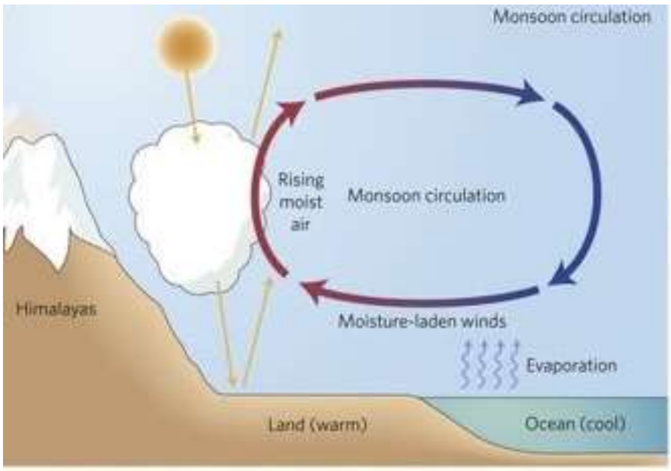

Figure 4. Simplified schematic of the summer monsoon circulation. Source: adapted from Singh (2016).

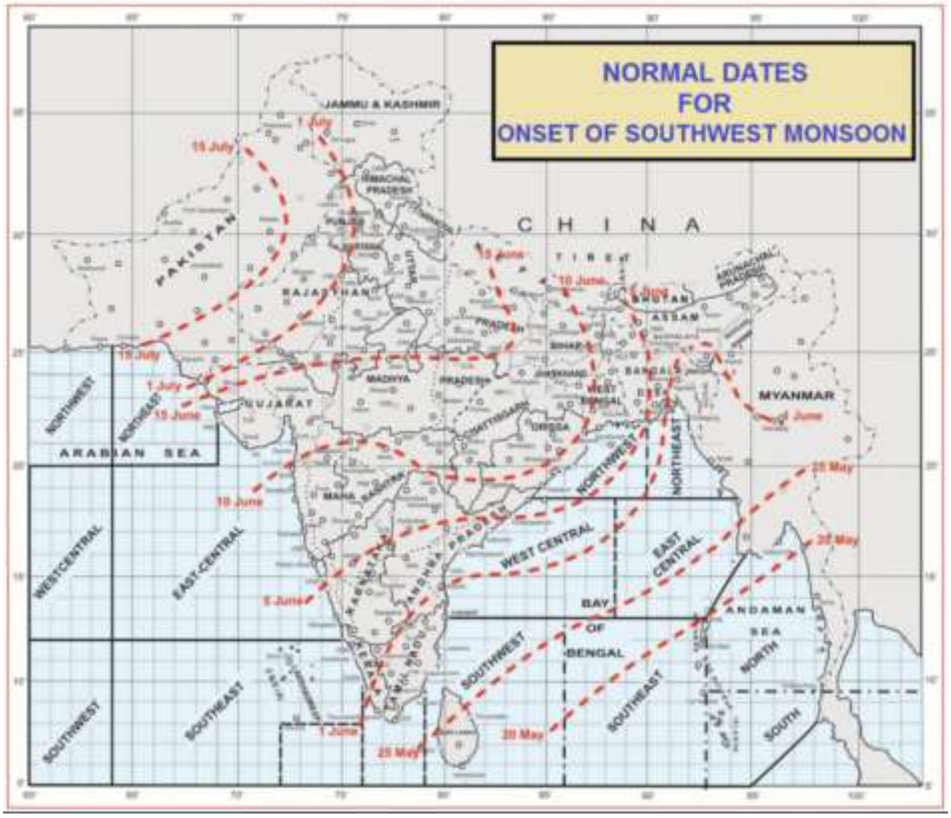

Figure 5. Normal dates of onset of southwest SAM as presented by the Indian Meteorological Department. Source: http://www.imd.gov.in/pages/monsoon_main.php?adta=JPG&adtb=1.

1.1.2.2 Northeast Monsoon

The northeast monsoon becomes established from around October, when the surface pressure pattern and monsoon circulation become a complete reversal of the southwest monsoon. The air from the northeast is comparatively drier, more stable and of less vertical extent than the air from the southwest, and thus rainfall is generally less widespread and intense and much of South Asia remains largely dry during this time. Although, as shown in Figure 2 and Figure 6, the southern tip of India and Sri Lanka receive a significant proportion of their annual rainfall during the northeast monsoon, and this has immense societal significance as it supports the main cultivation season in these regions.

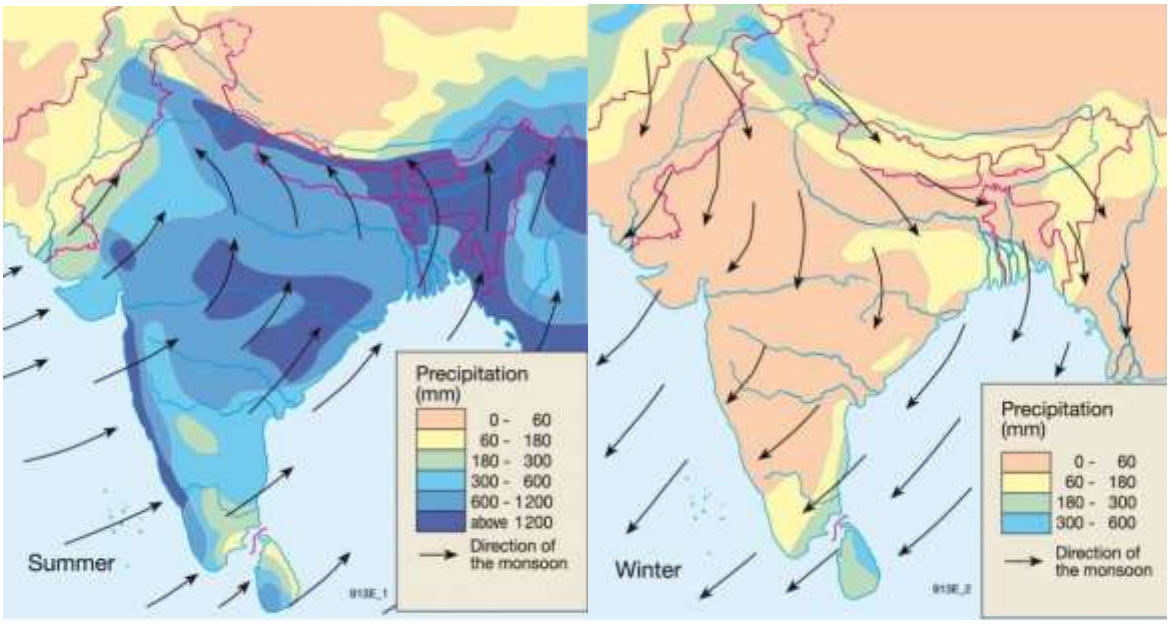

Figure 6. Average precipitation and surface wind direction during the southwest (left panel) and northeast (right panel) monsoon. Source: Diercke International Atlas[2].

1.1.2.3 South Asian Monsoon Variability

SAM rainfall experiences considerable spatiotemporal variability both from year-to-year (interannual) and within the monsoon season (intraseasonal). On the intraseasonal timescales, enhanced rainfall associated with the SAM is known as an “active” phase and suppressed rainfall associated with the SAM is known as a “break” phase. This variability, especially in rainfall amounts, has significant societal consequences across South Asia; too little rainfall at the wrong time can result in droughts, crop failure and famine and too much rainfall can result in floods and the associated loss of crops, property and life. Ultimately, forecasting and understanding this variability is of utmost importance for the region. By understanding the seasonal climate drivers and their relationship with the SAM, as discussed in section 1.2, it may be possible to predict the variability in SAM rainfall to a certain degree, potentially even months ahead.

1.1.3 Monsoon Depressions and Tropical Cyclones

SAM precipitation is significantly modulated by synoptic-scale tropical low-pressure areas, the strongest of which are known as monsoon depressions. The depressions usually originate over the north of the Bay of Bengal from June to September, then propagate west-northwestward along the axis of the monsoon trough to the Indian subcontinent, lasting 3 to 5 days on average (Godbole, 1977). Figure 7 illustrates monsoon depression tracks between

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[2] http://www.diercke.com

1979 and 2014. Saha et al., (1981) found that monsoon depressions are usually associated with predecessor disturbances propagated from westward moving low pressure systems or tropical storms which originated in the South China Sea or surrounding regions.

Monsoon depressions are often responsible for strong winds and heavy precipitation events, and also maintain activity of the monsoon trough by transporting heat and moisture upwards. Hunt and Fletcher (2019) showed that most synoptic rainfall over India is attributable to short-lived low-pressure areas originating at the head of the Bay of Bengal, though longer-lived systems are required to bring rain to west India and east Pakistan. Secondary contributions from systems originating in the Arabian Sea and south Bay of Bengal were shown to be important for west Pakistan and Sri Lanka respectively.

As defined by the Indian Meteorological Department, low-pressure systems are referred to as ‘depressions’ if surface winds are between 8 and 16 m/s, and ‘tropical cyclones’ if they exceed 16 m/s. Monsoon depressions rarely grow into tropical cyclones, as they are not long over oceanic areas before reaching landfall and are also inhibited by the presence of strong easterly vertical shear limits (Godbole, 1977). However, when they do occur, which is most likely in the post-monsoon season, they can bring a significant proportion of the seasonal rainfall in just a few days, and also pose the threat of storm surges to the coastal regions of east India, Bangladesh and Myanmar.

The number of monsoon depressions and tropical cyclones shows considerable interannual variability, ranging from none for several years, to as many as 12-15 in a single season. On average, the Indian monsoon trough region experiences 3-6 depressions during the average summer and these are markedly stronger during the active phase of the monsoon (Hunt et al., 2016).

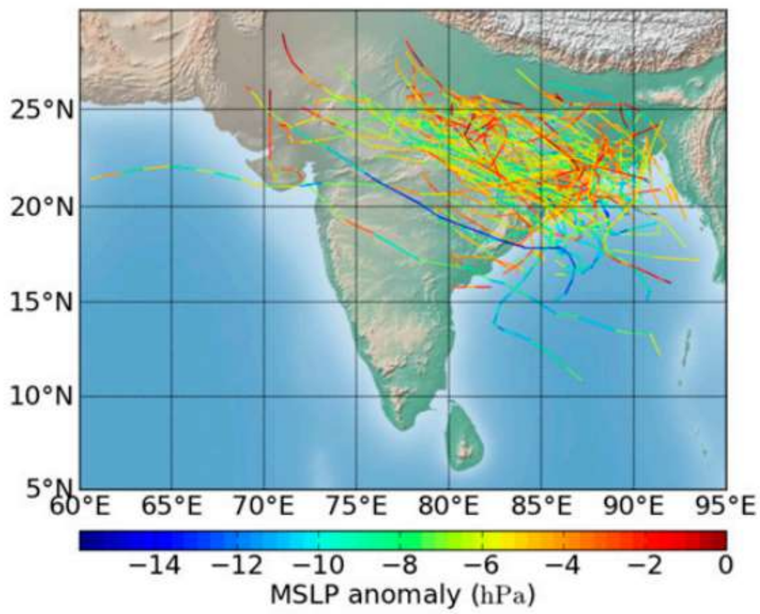

Figure 7: Depression tracks from the 106 depressions from 1976 to 2014 used in a study by Hunt et al. (2016). Colour indicates depression intensity using mean sea level pressure (MSLP) anomaly to a 21-day running mean.

1.1.4 Western Disturbances

The northwest of the region, including Pakistan and Afghanistan, remains mostly dry during the monsoon season and receives its largest contribution of rainfall in the winter and spring months (Figure 2) due to the passage of western disturbances (WDs). WDs are a type of extra-tropical cyclone, which exhibit mid-latitude frontal characteristics. Typically, a warm front will give rise to thickening cloud and light to moderate rain or hill snow followed by heavier convective precipitation with the passage of the cold front.

The depressions usually form over the Mediterranean, Caspian or Black Sea, and migrate eastwards embedded in the subtropical westerly jet stream, as shown in Figure 8, and can affect South Asia between October and June (Pant and Rupa Kumar, 1998), but are most common from January to March. Although WDs are not usually areas of marked cyclogenesis, they can result in extreme rainfall events in the northwest of South Asia during boreal winter (Hunt et al., 2018). During the remainder of the year, their tracks shift poleward away from South Asia.

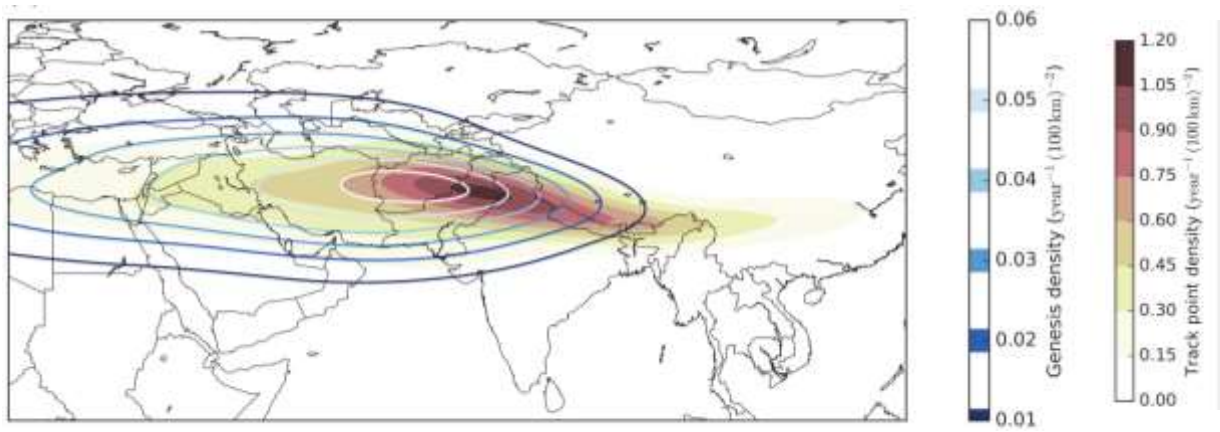

Figure 8 - Representation of some bulk spatial statistics of WD tracks, displaying contour plots of genesis (lines) and track point (solid) densities. Source: Hunt et al. (2018).1.2 Seasonal climate drivers of South Asia

1.2 Seasonal climate drivers of South Asia

The climate of South Asia varies from year-to-year due to the influences of large-scale climate drivers that vary on interannual and intraseasonal timescales. The key drivers of this variability are described in this section, along with discussion on how they are known to influence the climate of South Asia.

1.2.1 El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is a coupled atmosphere-ocean phenomenon that occurs in the tropical Pacific Ocean and has been observed to influence weather across much of the globe.

ENSO events alternate between a warm phase known as El Niño and cool phase known as La Niña. An El Niño (La Niña) event is characterised by higher (lower) than normal sea surface temperatures (SSTs) in the central and eastern Pacific. While their frequency can be irregular, ENSO events occur on average every two to seven years and will last typically nine to twelve months. The atmospheric component of ENSO is measured by the Southern Oscillation Index (SOI), which is based on the observed mean sea level pressure (MSLP) differences between Tahiti (eastern Pacific) and Darwin (western Pacific). A prolonged negative (positive) phase of the SOI represents below (above) normal MSLP in the eastern Pacific corresponding to an El Niño (La Niña) event. Figure 9 illustrates the atmospheric and oceanic characteristics of El Niño and La Niña.

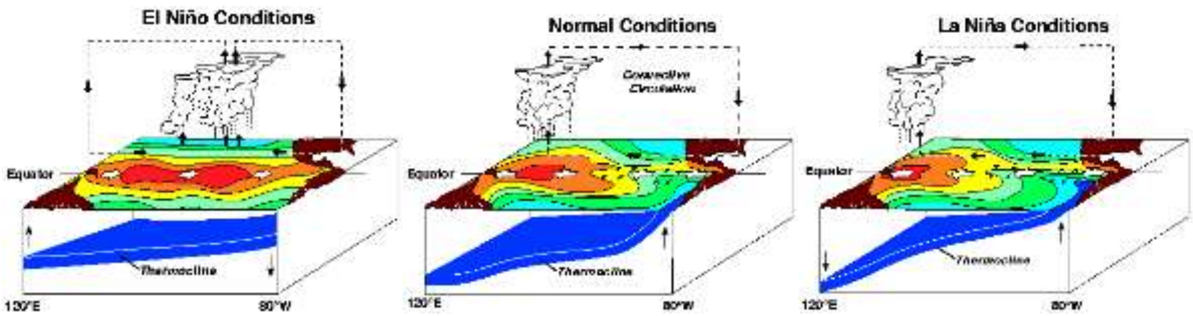

Figure 9. Typical atmospheric and oceanic characteristics of El Niño (left), normal (centre) and La Niña (right) conditions over the Pacific Ocean. Source: National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory[3] .

Walker (1924) was the first to suggest a possible connection between ENSO and SAM rainfall, and since then, observations from over 100 years show clear evidence of an established relationship. Anomalous SSTs associated with ENSO events shift the ascending and descending branches of the 'Walker Circulation' (Figure 10) and alters the upper and lower level flow patterns (Bjerknes, 1969). During an El Niño event, an area of anomalous subsidence suppresses rainfall over the South Asian region. This is supported by numerous observational studies which report that in general during the southwest monsoon, El Niño events act to suppress rainfall and La Niña events act to enhance rainfall (Figure 11; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983; Sikka, 1980)

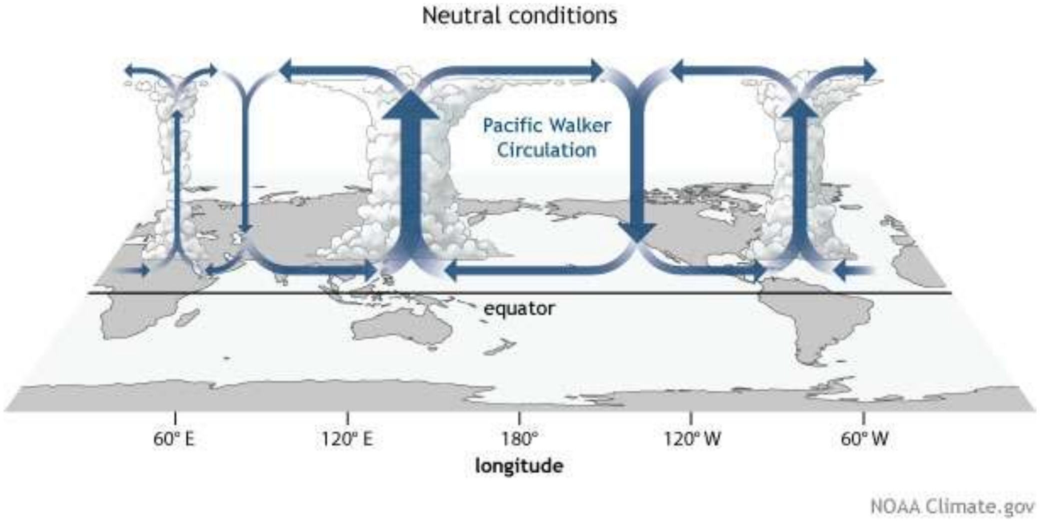

Figure 10. Generalised Walker circulation (December-February) during ENSO neutral conditions. Source: NOAA Climate.gov[4].

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[3] https://www.pmel.noaa.gov/elnino/schematic-diagrams

[4] https://www.climate.gov/sites/default/files/Walker_Neutral_large.jpg

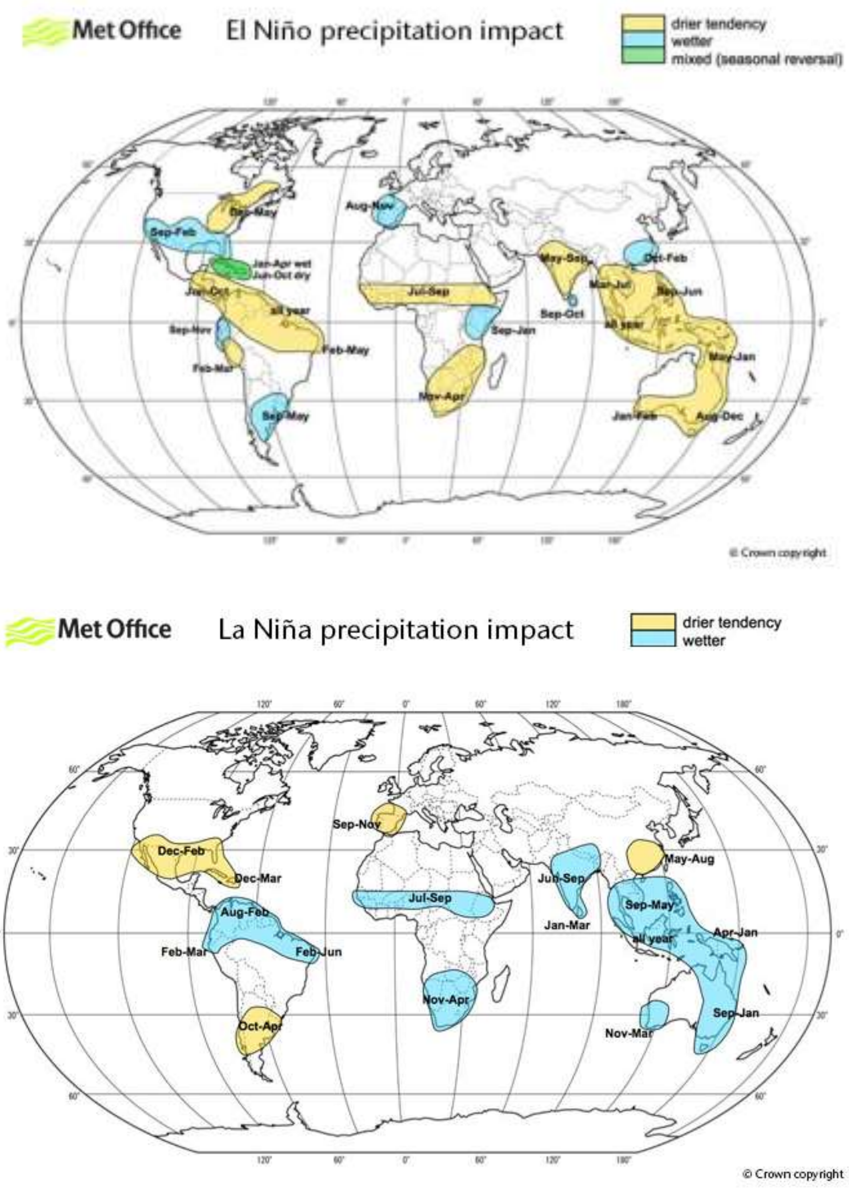

Figure 11. Schematic maps indicating the location and seasonality of the typical precipitation effects favoured during El Niño (left panel) and La Niña (right panel) events. Source: Met Office[5] based on Davey et al. (2014).

However, reports in recent decades have suggested that the relationship between ENSO and summer monsoon rainfall has collapsed (Kumar et al., 1999). There are a number of theories for this, including global warming (Ashrit et al., 2001), the Indian Ocean Dipole mode (Ashok et al., 2001) and decadal variability (Kripalani et al., 2003).

A significant relationship has also been identified between ENSO and northeast monsoonal rainfall over Sri Lanka (Rasmusson and Carpenter, 1983; Suppiah, 1989). The relationship is

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[5] https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/gpc-outlooks/el-nino-la-nina/enso-impacts

opposite to the southwest monsoon, as studies reveal that rainfall is generally enhanced during El Niño and suppressed during La Niña years (Suppiah, 1997). Furthermore, Zubair et al. (2006) and Kumar et al. (2007), unlike the southwest monsoon, there is no evidence to suggest that the relationship between northeast monsoon rainfall and ENSO is weakening but may in fact be strengthening.

In addition to influencing the SAM, a link has also been found between ENSO and both monsoon depressions and tropical cyclone activity. Singh et al. (2000) found that during El Niño events, there is a reduction in tropical cyclone activity over the Bay of Bengal between May and November. Another study by Hunt et al., (2016) reported that monsoon depressions were significantly stronger during La Niña events compared to El Niño.

1.2.2 Indian Ocean Dipole

The Indian Ocean Dipole (IOD) was relatively recently identified by Saji et al. (1999) as an irregular oscillation of sea-surface temperatures in the tropical Indian Ocean, in which the western part becomes alternately warmer (positive phase) or colder (negative phase) than the eastern part. The atmospheric component of the IOD is known as the Equatorial Indian Ocean Oscillation (EQUINOO), which represents the east-west oscillation in convection anomaly following the higher ocean temperature anomalies (Gadgil et al., 2004).

In general, positive (negative) IOD events correlate with increased (decreased) southwest monsoon rainfall totals over central parts i.e. the monsoon trough region (Ashok et al., 2001; Behera et al., 1999). The strengthening (weakening) of the SAM circulation arises from the enhancement (reduction) of the cross-equatorial flow, increasing (decreasing) moisture transport into the South Asian region. A similar correlation has been found with the northeast monsoon, with a positive (negative) IOD phase enhancing (suppressing) rainfall over the southern part of the region (Kripalani and Kumar, 2004). Figure 12 depicts the typical characteristics during each of the IOD phases.

The IOD and ENSO are closely inter-connected. During times of low (high) ENSO-monsoon correlation, the IOD usually has more (less) influence on the SAM circulation (Ashok et al., 2001). The phase of the IOD also plays an important role in either modulating or enhancing the influence of ENSO on SAM rainfall. An example of this occurred during the strong El Niño of 1997/98, when the presence of a strong, positive IOD event, resulted in unexpectedly high rainfall totals (Ashok et al., 2001). Ultimately, the variability of SAM rainfall is highly influenced by the strength and relationship of these two climate drivers, and hence why this is currently a topic of great interest in the research community.

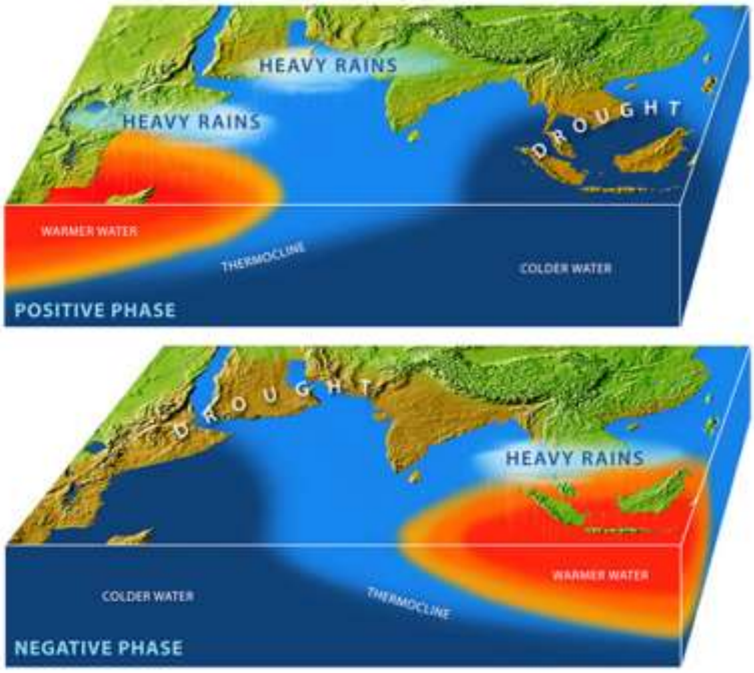

Figure 12. Regional influences of the positive and negative IOD modes. Source: illustration by E. Paul Oberlander, ©Woods Hole Oceanographic Institution.

1.2.3 Intraseasonal oscillations: Madden-Julian Oscillation and Boreal Summer Intraseasonal Oscillation

The SAM experiences vigorous intraseasonal oscillations (ISOs) in the form of active-break cycles of precipitation that exhibit periods around 30-90 days (Nanjundiah et al., 1992; Sikka, 1980; Yasunari, 1979). Intraseasonal variability (ISV) of the SAM has a major influence on the amount and spatial distribution of seasonal rainfall, and therefore understanding and predicting this variability is of utmost importance for South Asia. There are two dominant modes of ISV affecting the SAM: the Madden-Julian Oscillation (MJO) and the Boreal Summer Intraseasonal Oscillation (BSISO). In general the MJO dominates during boreal winter (December-April) and the BSISO dominates during boreal summer (June-October), and May and November are the months of transition when either could dominate (Kikuchi et al., 2012).

The MJO (named after its discoverers, Madden and Julian (1971)) is the main source of intraseasonal predictability in the tropics. This MJO is characterised by a steady eastward progression of a large-scale coupled pattern in atmospheric circulation, moving along the equatorial plane, which drives large regions of enhanced convection followed by suppression (Figure 13). Commonly, the MJO is split into 8 phases, as illustrated in Figure 14, and its influence is mainly observed over the Indian and Pacific oceans. The oscillations are characterized by poleward movement of weather anomalies, including rainfall, wind and cloudiness (Singh and Kripalani, 1985).

During boreal summer, the eastward-propagating MJO becomes notably weaker (Madden et al., 1972), and this is when the BSISO becomes the main driver of ISV on the South Asia climate (Wang et al., 1997). The BSISO is considerably more complicated than the MJO, due to the coexistence of multiple (eastward, westward and northward) propagating low-frequency modes and the interactions between them. In South Asia, the BSISO is mainly characterised by a belt of organised convection which starts in the equatorial Indian Ocean and moves north over the South Asian monsoon regions on a 2- to 6-week time scale (Knutson et al., 1987; Wang and Rui, 1990; Yasunari, 1979). The BSISO is known to affect total rainfall amounts during the southwest SAM (Krishnamurthy et al., 2007), the timing of the SAM onset (Kang et al., 1999; Wang and Xie, 1997) and the active-break phases of the SAM (Annamalai and Slingo, 2001; Goswami, 2005), and has also been demonstrated to significantly modulate tropical cyclone activity over the Indian Ocean (Goswami et al., 2003).

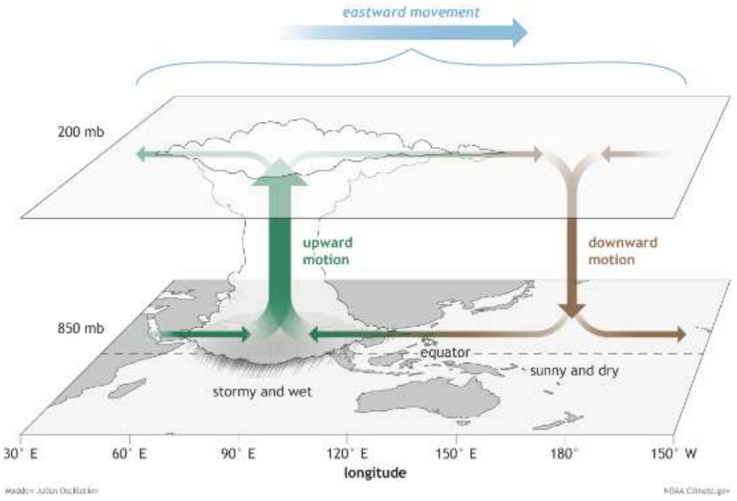

Figure 13. The main characteristics of an MJO atmospheric circulation. Source: NOAA Climate.gov.

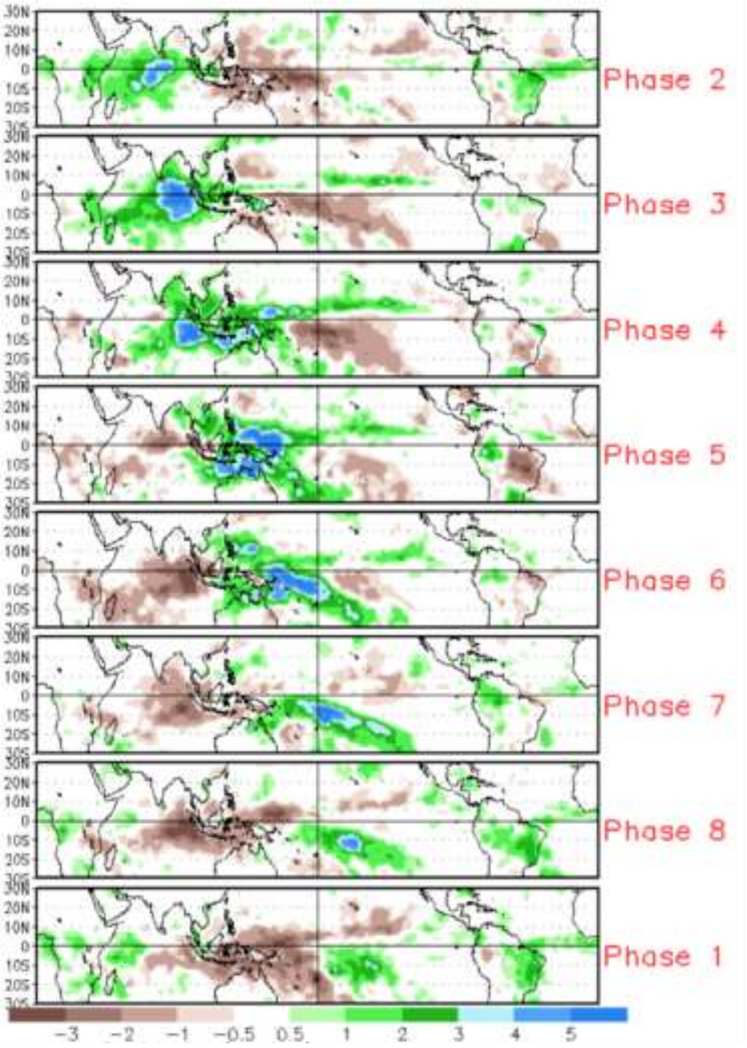

Figure 14. Mean precipitation anomaly for all MJO events from 1979-2012 for November-March during the 8 phases of the MJO. Source: NOAA Climate.gov.

1.2.4 North Atlantic Oscillation

Whilst the North Atlantic is far removed from South Asia, there is some evidence in the literature that the North Atlantic Oscillation (NAO) can affect the monsoon in the north-western and eastern parts of South Asia (e.g. Yadav et al. (2009) and Wang et al. (2018) respectively). Hence, a brief description of this climate mode is given here.

In the North Atlantic, the NAO is the dominant mode of winter climate variability (Marshall et al., 2001). The NAO is defined as an index of normalized, time-averaged pressure differences between the stations representing its two centres of action, the Azores and Iceland (Marshall et al., 2001). Pressure differences between Gibraltar, Spain and Reykjavik, Iceland are also used (Osborn, 2011) as are pressure differences between Lisbon, Portugal and Reykjavik, Iceland (Hurrell, 1995).

The NAO index is characterised by two phases, the positive NAO index phase and the negative NAO index phase (Osborn, 2011). Direct impacts associated with these NAO phases are limited to Europe and the eastern seaboard of the United States and are not discussed here.

Wang et al., (2018) focus on how the summer NAO (SNAO) may regulate East Asian summer rainfall. Whilst this region may lie at the eastern and northern extremity of the South Asia region, Figure 15 offers an insight into a plausible mechanism that could apply to other regions further west and/or south.

Dugam et al. (1997), in addition to Yadav et al. (2009), find statistically significant correlations of the winter NAO index with Indian summer monsoon rainfall and north-western Indian winter rainfall, respectively. This is likely to be associated with an NAO teleconnection mechanism akin to that shown in Figure 15, although the exact mechanism is an ongoing area of research.

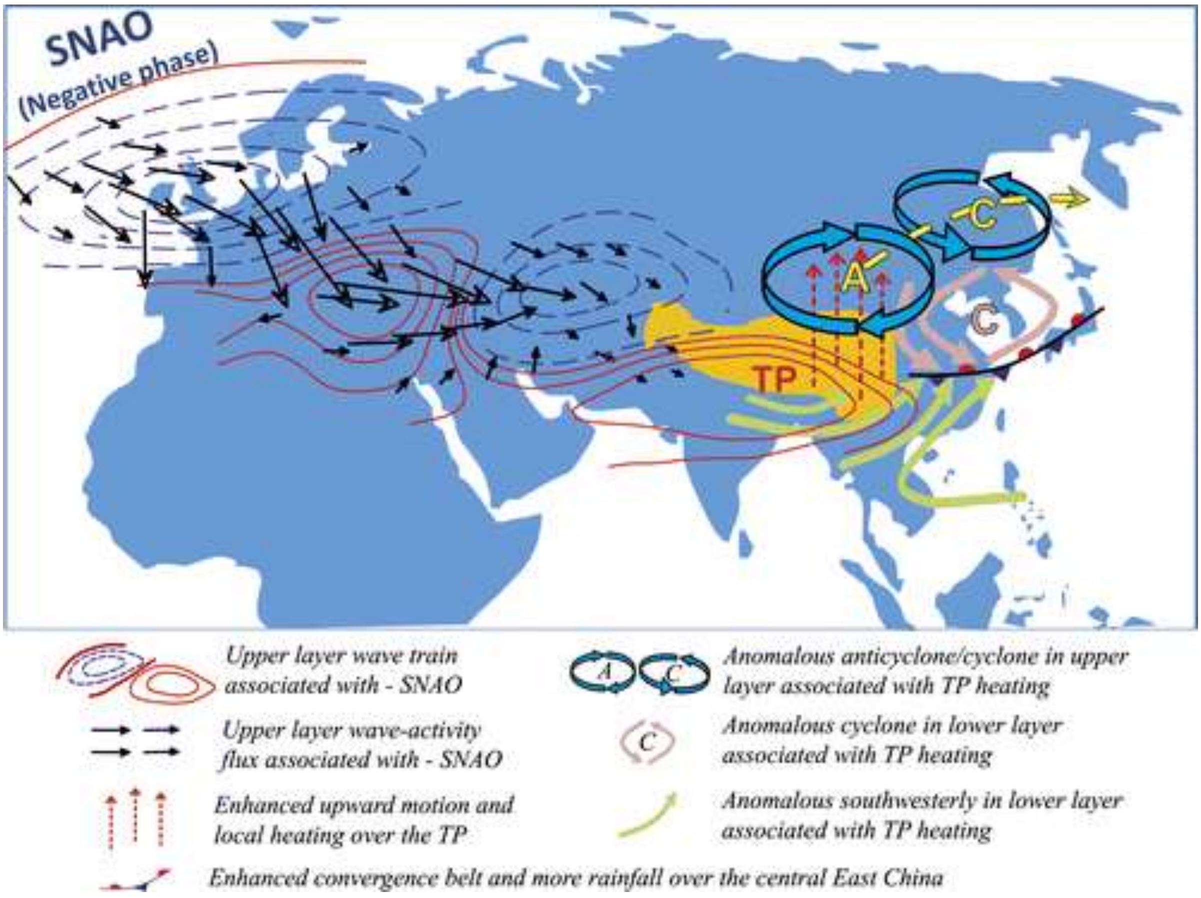

Figure 15. Schematic diagram showing the overall structure of the Tibetan Plateau's (TP) bridge effect in the teleconnection between the summer NAO (SNAO) and East China summer rainfall (from Wang et al., 2018).

1.2.5 Eurasian snow cover

Over a century ago, Blanford (1884) was the first to suggest an inverse relationship between Himalayan snow cover and monsoon rainfall over India. Later, with the availability of satellite observations, Hahn et al. (1976) used snow cover data to confirm a negative and statistically significant correlation between winter Eurasian snow cover and the following summer SAM rainfall. Therefore, winters with extensive (little) snow cover over Eurasia tend to be followed by summers with less (more) monsoonal rainfall. Furthermore, Bamzai et al., (1999) recorded that the correlation was higher with snow cover over the western part of Eurasia compared to the eastern part (Bamzai et al., 1999).

Large-scale snow cover anomalies can cause significant changes in the temperature of both the land surface and its overlying atmosphere. Snow cover has a much higher albedo than other surface conditions, and therefore will reflect a higher proportion of solar radiation. Also, part of that radiation will be utilised for melting snow or evaporating the soil moisture. Thus, only a small amount of radiation will be left for heating the surface as well as the atmosphere (Shukla, 1987). This means that excessive snow cover during the winter and spring can delay and reduce the land-sea temperature gradient that initiates and strengthens the SAM circulation.

However, it is worth noting that this snow-monsoon relationship in the warming atmosphere due to climate change remains controversial. A recent study by Zhang et al. (2019) suggests that this relationship has weakened since 1990 and Eurasian snow cover may no longer be a faithful predictor of summer SAM rainfall.

1.2.6 Other Drivers of South Asian Climate

The main drivers which affect interannual and intraseasonal variation of the South Asian climate have been discussed in this section. However, it is not enough to rely entirely on these drivers, as there are many other factors that are known to impact the predictability of the monsoon. Some of the other factors include:

- Quasi-Biennial Oscillation (QBO): Claud et al. (2007) suggest the QBO phase could influence convective activity associated with the SAM, especially later in the SAM season. Chattopadhyay & Bhatla (2002) also found a connection between the QBO and ENSO-SAM rainfall relationship, whereby the correlation between ENSO and SAM rainfall was highly enhanced during east years of QBO over Niño 3 region and highly reduced during the west years of QBO.
- Pacific Decadal Oscillation (PDO): Krishnamurthy et al. (2014) found that the warm (cold) phase of the PDO is associated with deficit (excess) rainfall over the Indian sub-

continent. Furthermore, during the warm PDO period, the impact of El Niño (La Niña) on SAM rainfall is enhanced (reduced).

- Atlantic Multidecadal Oscillation (AMO): Zhang and Delworth (2006) found that a positive correlation exists between AMO and SAM rainfall.
- Anthropogenic aerosols: Ramanathan et al. (2005) found that an increase in anthropogenic aerosols over the Indian sub-continent and the surrounding regions leads to a reduction of SAM rainfall, but an enhancement in pre-monsoon rainfall from March to May.

1.2.7 Potential Impacts of Climate Change

South Asia is a region at high risk of the potentially devastating impacts of climate change. As monsoon systems are the dominant climate phenomena over much of the Asian continent, the factors that influence monsoonal flow and associated precipitation are of central importance for understanding the effects of climate change in the South Asia region. Associated with a stronger land-sea temperature contrast in a warming climate, numerical studies have simulated a northward shift of monsoonal flow and associated precipitation (Ashrit et al., 2003, 2001; Bhaskaran et al., 1996). Despite a strengthening of the land-sea temperature gradient, a large number of climate modelling experiments have portrayed a diminished 3-dimensional SAM circulation pattern associated with all possible greenhouse gas emission scenarios (Kripalani et al., 2007; May, 2004; Sabade et al., 2011). However, a significant increase in precipitation associated with the SAM is simulated over much of the Indian subcontinent in a number of climate modelling experiments (Janes et al., 2019; Kripalani et al., 2007; May, 2004; Sabade et al., 2011). Precipitation is affected by both the strength of the SAM circulation and the amount of water vapour transport into the region, therefore it is widely believed that enhanced moisture convergence over the subcontinent region due to a warmer, moister atmosphere will dominate over the projected weakening of the SAM circulation (Christensen et al., 2013; Giorgi et al., 2001; Sabade et al., 2011). Accurate modelling of monsoonal systems is continually improving but remains a challenging aspect of regional climate modelling in the Asian domain.

Variability in the SAM system is an important topic to consider for the future climate of Bangladesh. Year-to-year variability is projected to increase under a warming climate, with the reasoning behind this increase being attributed to both a warming of the Indian Ocean, and a warming in the tropical Pacific Ocean. It has been suggested by Meehl and Arblaster (2003) that increases in tropical Pacific Ocean SSTs, accompanied by enhanced evaporation variability, is the dominant mechanism fuelling SAM rainfall variability through interactions with the Walker circulation and the role of Indian Ocean SST anomalies is secondary, however this is an area of continuing research and investigation.

1.3 Seasonal climates of the SASCOF countries

The seasonal climates of the individual countries in the South Asia region are all slightly different due to the temporal progression of the monsoon rains and the topography of the region. Figure 16 shows the annual cycle of rainfall in the countries included in the South Asia Regional Climate Outlook Forum (SASCOF; more detail on SASCOF is provided in Section 3.3.1, and more detail is provided on the key seasons and drivers of variability in Table 1.

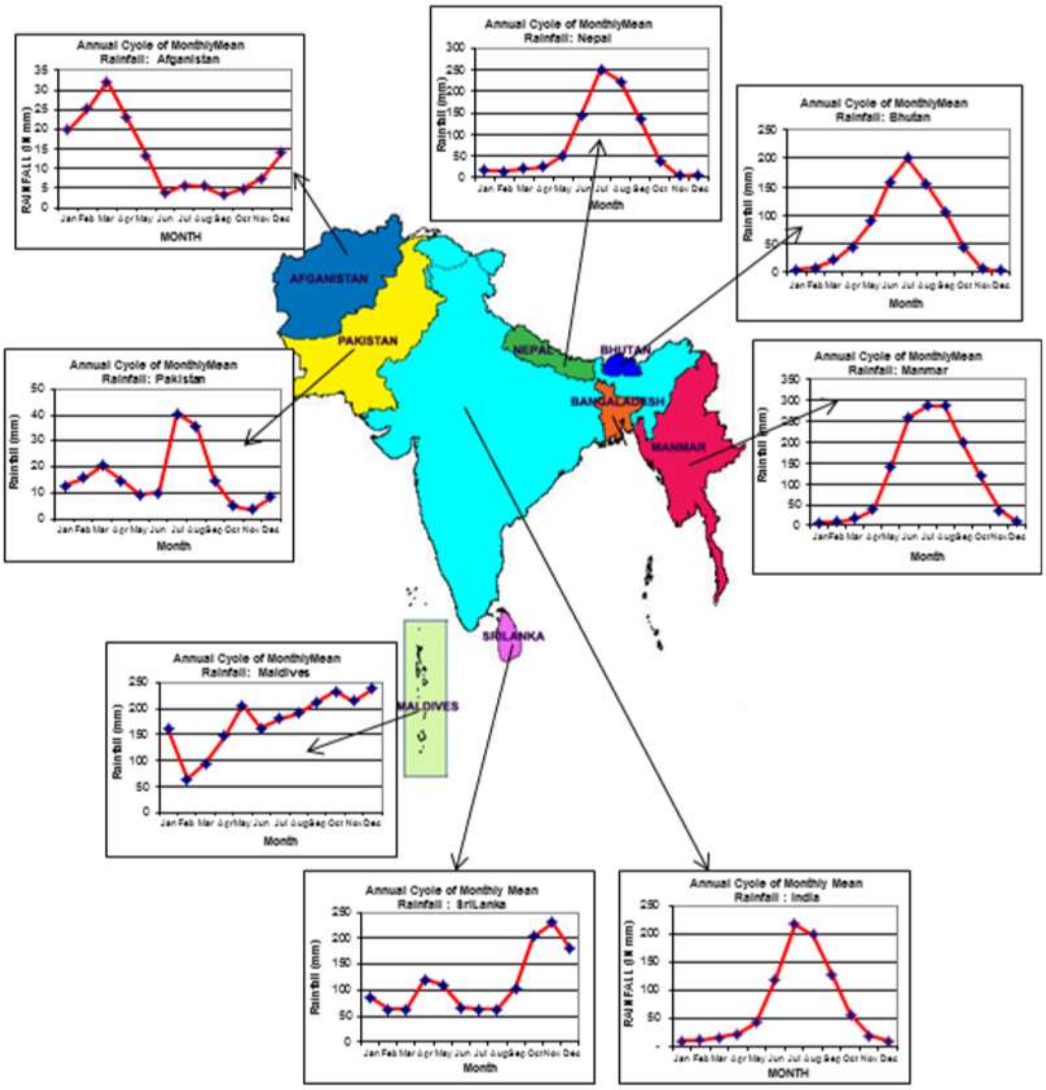

Figure 16. Annual cycle of monthly mean precipitation using data from 1951-2000. Source: SASCOF-11 report[6]. Data source: For Maldives: mean rainfall based on 5 land stations 1980-2007; all other countries: APHRODITE's Water Resources: http://www.chikyu.ac.jp/precip/english/index.html.

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[6] Note that the rainfall profile for Bangladesh was not included in the original figure in this report.

Table 1. Table of key seasons in the SASCOF countries and the drivers of seasonal variability

Country	**Key seasons**	**Main drivers of variability**
Afghanistan	Afghanistan has a dry, subtropical continental climate with significant differences across the region. The climate is characterised by the following seasons: • *Winter (December to February):* Western disturbances occasionally drive spells of precipitation, especially in the north, where snow and blizzards are a notable feature. Otherwise dry, with bitterly cold conditions in the north. • *Spring (March to May):* Mainly dry with temperatures increasing. Western disturbances continue to bring spells of precipitation in early spring. • *Summer (June to August):* Hot and dry. Strong dry winds can occasionally bring dust storms. • *Autumn (September to November):* Cooler than summer with higher humidity.	NAO
Bangladesh	Bangladesh has a sub-tropical monsoon climate, characterised by the following seasons: • *Winter (December to February):* Relatively warm and dry. • *Summer or pre-monsoon (March to May):* Hot and humid, with occasional heavy showers and thunderstorms. • *Southwest monsoon (June to September):* Monsoon rainfall is prolonged and especially abundant in July. • *Autumn or northeast-monsoon (October to November):* The monsoon rains begin to retreat, with depressions or tropical cyclones occasionally bringing strong winds and rain.	ENSO, IOD, MJO
Bhutan	Bhutan has a diverse climate, dominated by the Himalaya mountains in the north. The climate is humid and subtropical in the south and east, but cooler and continental elsewhere, with seasons: • *Winter monsoon (December to February):* Cold, frosty and snow is common over the higher elevations. The northeast monsoon brings gale-force winds down through high mountain passes. • *Spring or pre-monsoon (March to May):* Generally warm and dry, with occasional heavy showers later in the season. • *Summer monsoon (June to September):* Most of annual rainfall falls during the summer monsoon, which brings heavy rains and high humidity from the southwest.	ENSO, IOD

	• *Post-monsoon (October to November):* Overall dry with decreasing temperatures, with occasional showers.	
India	India comprises a wide range of weather conditions across a vast area and varied topography. In general, its climate is characterised by these four seasons: • *Winter (December to February):* Relatively warm and dry. Occasional heavy rain and snow affect the far northwest with the passage of western disturbances in January and February. • *Summer or pre-monsoon (March to May):* The hottest months and generally dry. • *Southwest or summer monsoon (June to September):* The onset of the monsoon rains begins in the south-east in June and migrates northwards throughout the beginning of June resulting in the majority of the country being exposed to the monsoon rains by mid-June (Ananthakrishnan, 1977). • *Northeast or post-monsoon (October to November):* The monsoon rains begin to steadily withdraw from the north-east in early October towards the south-east by the end of November/beginning of December (Ananthakrishnan, 1977). Southern parts of India can receive significant rainfall during this season.	ENSO, IOD, MJO
Maldives	Maldives, consisting of approximately 1,190 coral islands, is the lowest lying in the world, and has a tropical monsoon climate. Two seasons dominate Maldives weather characterised by the reversal in winds: • *Southwest monsoon (May to October):* Heavy tropical showers and strong winds are a frequent occurrence throughout. • *Northeast monsoon (January to March):* As the southwest monsoon retreats, the comparably drier northeasterly winds bring mostly dry conditions, but still with occasional showers. • *Transition phases occur during the months of December and April*	ENSO, IOD, MJO
Myanmar	Myanmar has a tropical monsoon climate in the lowlands in the south, and temperate dry climate in the high mountainous regions to the north. Weather conditions in south and north contrast greatly. • *Winter (December to February):* Relatively warm and dry. • *Summer or pre-monsoon (March to May):* Hot and mostly dry. The monsoon rains begin in the south of the region in May. • *Southwest monsoon (June to September):* Monsoon rains spread across the country. • *Northeast or post-monsoon (October to November):* The transition to northeasterlies brings drier weather to Myanmar, with cooler temperatures.	ENSO, IOD, MJO

Nepal	Nepal has tremendous geographic diversity owing to the Himalayan mountain range. It's climate ranges from sub-tropical in the south to arctic in the mountainous north. Nepal's seasons are: • *Winter (December to February):* Relatively cold and dry. • *Summer or pre-monsoon (March to May):* Hot and humid, with occasional heavy showers and thunderstorms. • *Southwest monsoon (June to September):* Monsoon rainfall usually arrives in the east in June and progresses west and is most active in July and August. • *Autumn or northeast-monsoon (October to November):* The northeast monsoon is marked by occasional short spells of rain and snow in October.	ENSO, IOD
Pakistan	Pakistan has a mainly dry climate, characterised by extreme temperatures, although heavy precipitation events are not uncommon, usually driven by western disturbances in the winter. The seasons are: • *Winter (December to March):* Mostly cool and dry. Western disturbances occasionally drive rain and snow to the northwest of the region. • *Spring (March to May):* Mainly dry and hot, with occasional dust storms. Western disturbances bring spells of precipitation to the northwest in early spring. • *Summer or southwest monsoon (June to September):* Very hot and mostly dry at first, with sporadic thunderstorms. The southwest monsoon drives occasionally heavy and prolonged rainfall, which arrives in the south usually from mid-July onwards and retreats from September. • *Autumn (October to November):* Dry with falling temperatures.	ENSO, IOD, NAO
Sri Lanka	The island of Sri Lanka has a tropical monsoon climate. The high plateau in central Sri Lanka with the central highlands sculpts the Sri Lankan climate, which is marked by four seasons: • *Southwest monsoon (mid-May to mid-October):* Heavy rains on mountain slopes and southwest part of the island, whereas the leeward slopes in the east and northeast receive little rain. • *Post-monsoon (mid-October to November):* During the inter-monsoonal season, periodic squalls and sometimes tropical cyclones can affect the island. • *Northeast monsoon (December to March):* Monsoon winds from the northeast, bring heavy rains to the northeast of the island. • *March to mid-May:* The transition inter-monsoon period is usually characterised by light winds and evening showers and thunderstorms.	ENSO, IOD, MJO

2. Seasonal predictability

2.1 What makes the South Asian climate predictable?

Seasonal predictability is made possible through slowly evolving variations in the land-surface, ocean and cryosphere (i.e. sea-ice). These components of the Earth system can store large quantities of heat and moisture and it is this reservoir of heat and moisture that can predispose the atmosphere to respond in a predictable manner. For example, as discussed in section 1.2.1, during an El Niño event, a warm sea-surface temperature (SST) anomaly in the tropical Pacific Ocean leads to increased heat exchange from the ocean to atmosphere. The additional heat released into the atmosphere will impact the atmospheric circulation and lead to changes in climatic anomalies in remote regions of the globe (Doblas-Reyes et al., 2013)

In relation to the South Asian climate, specifically the SAM, ENSO provides the most dominant predictable signal. However even at its peak, ENSO only explains approximately 40% of SAM interannual variability (Goswami and Chakravorty, 2017). Therefore, there are other drivers that also affect the SAM rainfall variability and hence its predictability. Other than the drivers outlined in section 1, extratropical sea-surface temperatures (SST) may also be contributing to this variability. The slowly varying extratropical SST causes a shift in the jet stream and storm tracks, thereby generating stationary waves leading to a large persistent tropospheric temperature anomaly over northern India and southern Eurasia thereby enhancing or reducing the tropospheric temperature gradient and strengthening or weakening the SAM (Goswami and Chakravorty, 2017). Extratropical SST variability is governed by climate modes such as the PDO, AMO and NAO. In order to make skilful predictions of monsoon rainfall, dynamical coupled models[7] should simulate both tropical and extratropical climate drivers.

2.2 Metrics and indicators of seasonal predictability

Metrics have been developed that assist in objectively assessing the ability of dynamical models to simulate the intensity of the South Asian monsoon season. First and foremost, it is important to assess whether the dynamical model is able to capture the atmospheric circulation patterns of the region, and one way to do this is to compare the upper and lower level wind speeds and directions with observations. Anomalies in these large-scale circulation patterns can act as a proxy for the transport of moisture to the region and therefore the rainfall anomalies Park et al., (2018). An objective way in which to assess whether dynamical models

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[7] Dynamical models, also known as General Circulation Models (GCMs) solve the appropriate fluid and thermodynamic equations in order to simulate the evolution of atmospheric circulation patterns and, more generally, key aspects of the Earth system as a whole.

can capture important features of the South Asian monsoon is to develop metrics that link the atmospheric physical mechanisms, such as the circulation patterns, to the variable of interest (in most cases rainfall anomalies).

2.2.1 Monsoon rainfall metrics

Park et al., (2018) and references therein give a useful overview of the different types of monsoon metrics that are used to define the relationship between monsoon rainfall and large-scale circulation patterns elsewhere. Table 2 shows the different types of monsoon indices that have been developed along with the relevant sources, and the locations of the indices are shown in Figure 17.

These indices are used to assess skill of dynamical models to predict the SAM (using the WYI, WSI1 and IMI indices), the Western Northern Pacific Summer Monsoon (using the WSI2 and WNPMI indices), and EASM (using the NEASMI index). Further details are given in Park et al., (2018).

Table 2. Definitions of the summer monsoon indices used in Park et al., (2018). U850 and U200 denote the zonal wind at 850 and 200 hPa respectively.

Index	**Definition**	**Source**
WYI	Zonal wind shear (U850–U200) averaged over 0°–20°N, 40°–110°E	Webster & Yang (1992)
WSI1	Westerly shears (U850–U200) averaged over 5°–20°N, 40°–80°E	Wang & Fan (1999)
IMI	U850 (5°–15°N, 40°–80°E) (IM_SI) minus U850 (20°–30°N, 70°–90°E) (IM_NI)	Wang et al., (2001)
WSI2	Westerly shear (U850–U200) averaged over 0°–10°N, 90°–130°E	Wang & Fan, (1999)
WNPMI	U850 (5°–15°N, 100°–130°E) (WNPM_SI) minus U850 (20°–30°N, 110°–140°E) (WNPM_NI)	Wang et al., (2001)
NEASMI	U850 (25–35N, 110–150E) (NEASM_SI) minus U850 (45–55N, 110–150E) (NEASM_NI)	Park et al., (2018)

Index	**Definition**	**Source**

WYI	Zonal wind shear (U850–U200) averaged over 0°–20°N, 40°–110°E	Webster and Yang (1992)
WSI1	Westerly shears (U850–U200) averaged over 5°–20°N, 40°–80°E	Wang and Fan (1999)
IMI	U850 (5°–15°N, 40°–80°E) (IM_SI) minus U850 (20°–30°N, 70°–90°E) (IM_NI)	Wang et al., (2001)
WSI2	Westerly shear (U850–U200) averaged over 0°–10°N, 90°–130°E	Wang and Fan, (1999)
WNPMI	U850 (5°–15°N, 100°–130°E) (WNPM_SI) minus U850 (20°–30°N, 110°–140°E) (WNPM_NI)	Wang et al., (2001)
NEASMI	U850 (25–35N, 110–150E) (NEASM_SI) minus U850 (45–55N, 110–150E) (NEASM_NI)	Park et al., (2018)

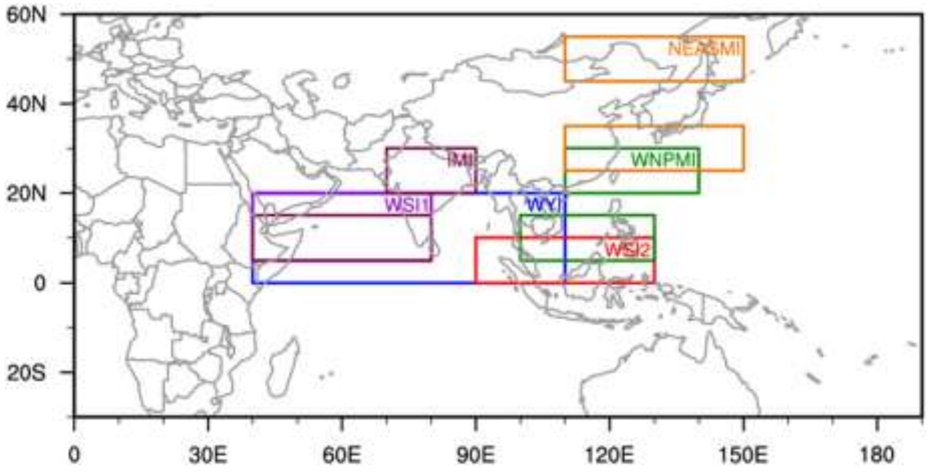

Figure 17. Domains of the summer monsoon indices used in Park et al. (2018)

2.2.2 Monsoon onset indices

The aforementioned indices are mainly used to relate the intensity of the summer monsoon precipitation. Of equal usefulness are indices that have been developed to objectively determine the onset of the summer monsoon season. Predicting the monsoon onset is very important for the region to plan for water resources management for example (Chevuturi et al., 2019). The onset over Kerala is declared by the India Meteorological Department (IMD) and its definition is based on rainfall, winds and outgoing longwave radiation (see Appendix 1 for the full definition).

Table 3 details a number of monsoon indices that are used to assess the skill of coupled Global Climate Models (GCMs) in forecasting the onset of the monsoon rains. Details of the methodology used in addition to the spatial extent of the monsoon onset indices above are given in (Chevuturi et al., 2019)

Table 3. Details of monsoon onset indices from Chevuturi et al., (2019a)

Index	**Onset**	**Reference**
Tropospheric Temperature Gradient Index (TTGI)	Onset defined when TTGI time-series for each year becomes positive	Xavier et al., (2007)
Webster and Yang Index (WYI)	Onset defined when seven-day running average of WYI timeseries crosses threshold value (mean ERA-Interim value on climatological onset, 30May)	Webster and Yang (1992)
Hydrological Onset and Withdrawal Index (HOWI)	Onset defined when HOWI time-series for each year becomes positive	Fasullo and Webster (2003)
Wang and Fan Index (WFI)	Onset defined when seven-day running average of WFI timeseries becomes positive	Wang and Fan, (1999)
Wang and LinHo Index (WLI)	Onset on pentad when the five-pentad running average of WLI time-series for each gridpoint for each year crosses the threshold of 5 mm/day^{-1}	Wang and LinHo (2002)

3. Seasonal forecast methods and skill

Although it is not possible to predict the day-to-day weather seasons ahead, forecasts of changes in seasonal averages, such as seasonal mean temperature or seasonal mean rainfall are possible due to the predictability in the climate system (as described in Section 2). Seasonal forecasts are probabilistic in nature as opposed to deterministic predictions of weather variables. This means that the forecasts tell us how likely it is that conditions will be different to climatology, relative to a reference period.

The two main methods used to generate a seasonal forecast are statistical-empirical methods and process-based dynamical models, or a combination of these. A summary of these approaches is provided in Section 3.1 and a summary of the seasonal forecast methods currently used in the SASCOF countries is given in Section 3.2.

3.1 Seasonal forecasting methods

3.1.1 Statistical forecasting methods

Statistical forecasting methods use known statistical relationships to predict one variable using observations of others (Doblas-Reyes et al., 2013; Smith et al., 2012). For example, predicting monsoon rainfall in South Asia using observed SSTs in the Pacific Ocean. Statistical methods range from simple linear regression to more complex non-linear approaches (Ding and Ke, 2013; Gerlitz et al., 2016; Krakauer, 2019; Kumar et al., 1995)

Although statistical models have the benefit of being fast to perform as they do not require the use of complex computer models, they are simplified representations of the relationships and do not account for the complexities in the coupled ocean-atmosphere system. As statistical models are developed using observations, a long observation record is required to develop the best possible statistical model. In addition, the relationships developed within the statistical model are assumed to remain the same in future and therefore do not account for any changes in the climate that may have occurred over the observational period.

3.1.2 Dynamical forecasting methods

Dynamical forecasting methods use complex process-based general circulation models to create seasonal forecasts for the seasons ahead. Similar to weather forecast models which use observations of the current weather to predict the weather in the coming days, these seasonal prediction systems use versions of global climate models which are initialised with the current state of the climate system through observations of the ocean, atmosphere and land surface conditions (Doblas-Reyes et al., 2013; Smith et al., 2012).

There are two types of dynamical seasonal forecast model systems:

- Tier-two systems use atmospheric models with prescribed SSTs
- Tier-one systems use both atmosphere and ocean models and the models are coupled enabling interaction and feedbacks. There is higher predictive skill in coupled models compared to uncoupled (i.e. tier-two systems; Doblas-Reyes et al., 2013)

A key source of uncertainty in initialised climate model prediction is that associated with the initial conditions used to drive the model, i.e. the SST observations and the uncertainty arising from measurements and interpolation onto model grids. An initial condition ensemble is used to address this uncertainty; the model is run multiple times with slightly different initial conditions each time. All climate prediction systems use this technique to generate an ensemble of individual seasonal forecasts and the average across these ensemble members (the ensemble mean) is used for the final forecast.

Similarly, ensembles of hindcasts are generated using the same model run over a period in the past. These hindcasts are compared with observations over the same time period to analyse the model's performance and determine the extent of any model 'bias'. The future forecast can then be adjusted to account for such biases; a process known as 'calibration'. The forecast is typically presented as a forecast anomaly, by comparing the model forecast with the hindcast; i.e. wetter/drier than normal or warmer/cooler than normal for the season ahead. Large ensembles of forecasts and hindcasts are required due to the low signal to noise ratio problem in seasonal forecasting (Scaife et al., 2014).

In general, the forecast information is split into three categories known as terciles; these represent three categories indicating normal, above normal or below normal conditions. The consensus across the ensemble members for each of the terciles gives an indication of the strength of the signal of the forecast. For example, a high proportion of the ensemble members forecasting the 'above normal' tercile would indicate a strong signal from that prediction system, if associated with skill for that tercile, whereas the ensemble members spread across the terciles would indicate a lack of consensus on the forecast. Sometimes five categories (quintiles) are used, i.e. very hot - hot - normal – cold - very cold, or very wet – wet – normal – dry - very dry.

Another source of uncertainty in seasonal forecasting systems is that associated with the model itself and its ability to accurately simulate the observed mean climate and variability. A standard way of accounting for model uncertainty is to use a Multi-Model Ensemble (MME), i.e. using forecasts from a range of different models. There are 13 Global Producing Centres (GPCs) recognised by the World Meteorological Organisation (WMO) which produce seasonal forecasts each month using multiple forecast and hindcast ensemble members. The models[8] and their specific details are listed in Table 4.

Methods for combining the forecasts from individual models in an MME is a key area of research. The WMO recognised approach is based on objective assessment of the consensus across the models where there is skill, by experts in the field. This is the approach taken at the Regional Climate Outlook Forums (RCOFs) to generate a consensus seasonal forecast for the region (more detail is provided in Section 3.3).

Quantitative approaches using multi-model means are not useful as the averaging process can cancel out the detail from the individual forecasts, particularly where there is a lack of

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[8] Other seasonal forecast models exist, but for consistency with WMO procedures, only models from the WMO-approved GPCs have been included.

consensus. Also, standard averaging of the MME does not take into account the skill of the model, although methods are being developed to weight models based on their skill.

The skill of dynamical modelling systems to predict the climate in a region of interest, e.g. in South Asia, relies on the model's ability to represent the relevant teleconnections and drivers of the climate in that region, e.g. ENSO, IOD (see Section 1 for more detail). The skill of the models can be assessed by analysing the correlation between the hindcasts from the model and observations for specific variables or metrics, e.g. SSTs in the Pacific to assess ability to simulate ENSO or various monsoon indices as discussed in Section 2. A long time period is required for these correlation assessments, i.e. preferably 30 years or the length of available hindcasts. These correlation assessments also highlight any systematic biases in the models and calibration of the models can be performed to account for these known biases.

The skill in probabilistic seasonal forecasts from dynamical modelling systems can be assessed by calculating Relative Operating Characteristic (ROC) scores (Kharin and Zwiers, 2003). ROC scores provide a measure of 'hit' rates compared to 'false alarms' for different probability scenarios, for example the above/below normal terciles or specific user defined thresholds. Skilful forecasts have higher 'hit' rates than 'false alarms'. The reliability of forecasts is also important to consider (Weisheimer and Palmer, 2014). Reliability diagrams indicate how closely the forecast probabilities of an event correspond to the actual chance of observing the event and can also help to identify biases in the models. Other measures of skill in seasonal forecasts can also be used, such as the Brier Skill Score which assesses the degree of improvement a forecast for a specified event has compared to the climatology (Brier, 1950).

Table 4. Details of the WMO Global Producing Centres and their skill in South Asia. Source: WMO World Lead Centre for Long-Range Forecast Multi-Model Ensemble[9].

GPC Name	**Model Name**	**Coupled model?**	**Hindcast years**	**Ensemble size for hindcast**	**Ensemble size for forecast**	**Length of forecasts**	**Relevant references**
Beijing	BCC	Yes	1991-2010	24	24	13	Wu et al. (2014)
CPTEC	CPTEC	No	1979-2010	10	15	7	Cavalcanti et al. (2002)
ECMWF	ECMWF-S4	Yes	1981-2016 (calibration period 1993-2016)	25	51	7	Molteni et al. (2011)
Exeter	GloSea5	Yes	1993-2016	28	42	6	Maclachlan et al. (2015)
Melbourne	POAMA2	Yes	1980-2011	99	33	9	Cottrill et al. (2013)
Montreal	CanCM4	Yes	1981-2010	20	20	12	von Salzen et al.(2013)
Moscow	NCEP/HMC	---	1981-2010	10	20	4	Kim et al. (2012a)
Offenbach	MPI-LR	Yes	1990-2017	30	50	6	Baehr et al. (2015)
Pretoria	ECHAM4.5	Yes	1982-2009	10	40	9	Beraki et al., (2011)
Seoul	GloSea5GC2	Yes	1991-2010	12	42	6	Maclachlan et al. (2015)
Tokyo	JMA-CGCM2	Yes	1979-2014	10	51	7	Takaya et al. (2017)
Toulouse	ECMWF	Yes	1993-2016	25	51	7	--
Washington	CFS	Yes	1981-2010	20	40	9	Saha et al. (2014)

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[9] https://www.wmolc.org/contents2/index

3.1.3 Hybrid statistical/dynamical forecasting methods

Hybrid methods make use of the best characteristics of dynamical and statistical methods in order to deliver an optimum forecast. For example, dynamical models may perform well at predicting large (ocean/continental) scale circulation but may not capture all of the regional and local detail due to insufficient resolution and inaccurate parametrisation of some relatively small-scale atmospheric processes such as the formation of convective clouds. Canonical Correlation Analysis (CCA; Anderson, 2003) is an example of a technique used to create hybrid forecasts taking advantage of a dynamical forecast system's ability to predict large scale patterns such as those related to ENSO and IOD and use them to make optimal predictions for locations of interest, such as rainfall over South Asia. CCA is the main technique used by the International Research Institute's Climate Predictability Tool (CPT), which is a regularly used tool to help produce consensus forecasts at RCOFs.

CCA is used to analyse a set of trial dynamical forecasts (hindcasts) and discover their association with corresponding observations. CCA identifies pairs of patterns, the occurrence of which is correlated over time, for example if pattern A is identified in the model output, its partner pattern A tends to occur in the corresponding observations. Such pairs of patterns can thus be used to form a regression-like forecast system. CCA predictions using CPT have been successfully used to make seasonal forecasts for East Africa (Kipkogei et al., 2017; Colman et al., 2019) and West Africa (Colman et al., 2017).

3.1.4 Seasonal forecast skill in South Asia

The assessment of seasonal forecast skill in South Asia is an area of active research, with much of the focus being on the assessment of dynamical forecast systems in their accurate representation of monsoon-associated rainfall. It is agreed that there is a high level of predictability in monsoon variability due to its spatial coherence over large regions (Jain et al., 2018). This predictability is even greater during years of strong ENSO forcing (Chevuturi et al., 2019; Kim et al., 2012). However, this predictability does not necessarily result in high skill across all seasonal forecast models. The actual observed prediction skill for monsoon-associated rainfall is considerably lower than the potential prediction skill estimated by atmospheric GCMs (r=0.65) (Jain et al., 2018; Krishna Kumar et al., 2005; Kucharski and Abid, 2017) .

Previous studies have indicated poor performance of seasonal forecast models in predicting rainfall for the South Asia region, with dynamical models still not able to fully simulate the mean and interannual variability of South Asian monsoon rainfall (Jain et al., 2018; Kang et al., 2002; Kang et al., 2004; Krishnamurti et al., 2006a; Mishra et al., 2018). There is, however, relatively high skill in predicting wind and large-scale flow patterns for South Asia (Chevuturi et al., 2019; Johnson et al., 2017). As model developments progress with improved resolutions, parameterizations and data assimilation techniques, it is expected that forecast skill will continue to improve. Currently, forecast systems often show differences in the location and intensity of climatological rainfall over South Asia, typically depicting wet biases over the ocean and regions of orographic uplift and dry biases over large land-masses, which are likely to be linked to errors in predicting ENSO-monsoon relationship characteristics (Jain et al., 2018). When averaged over a larger, common 'monsoon region', many models depict a wet bias with errors of 10-20%, which is typical of seasonal forecasts in other tropical regions (Kumar et al., 2013; Scaife et al., 2017). However, forecast skill is often highest when using a large, spatially coherent domain, as averaging over a large area helps to reduce uncertainty in the forecast.

One method to improve skill in dynamical forecast systems is to ensure the use of coupled model systems. Studies have demonstrated that skilful prediction of monsoon rainfall is possible using coupled forecast models that are initialized in May, and that this exceeds the skill in empirical (statistical) methods (Delsole and Shukla, 2012; Jain et al., 2018). It is thought this improved skill in coupled systems results from a more skilful prediction in SSTs. An additional method for improving skill is to utilize a multi-model ensemble approach. Some studies have demonstrated a significant improvement in skill when using output from multiple models, whereas others have demonstrated only marginal improvements when compared to a single skilful model (although skill across individual models can vary widely; Jain et al., 2018).

As mentioned above, the predictability of monsoon-associated rainfall seems to be linked to the amplitude of forcing from ENSO. The ENSO-monsoon relationship is a highly-debated subject, with some studies depicting an observed change in the correlation between monsoon rainfall and tropical Pacific SSTs (evolving from negative correlation to nearly no correlation; Kim et al., 2012a), while other studies suggest the observed changes in the ENSO-monsoon relationship are likely due to sampling variability, and the relationship itself is viewed as stationary (Jain et al., 2018). It may be that a seasonal forecast model's inability to capture this dynamic relationship is what leads to a model's poor skill in prediction monsoon-associated rainfall (Kim et al., 2012). More research is required to better understand this complex relationship and how it might affect the skill of seasonal predictions in monsoon rainfall for South Asia.

3.1.5 Forecasting for monsoon onset

As previously described, seasonal forecasts from dynamical prediction systems can provide forecasts for the predicted mean climate over a three-month period, e.g. the seasonal mean temperature or rainfall. Forecasting for the monsoon onset is particularly challenging, and it is currently not possible to produce a forecast for specific dates, such as the date the monsoon is predicted to start.

However, recent research has shown that there is some skill in the GloSea5 model to simulate monsoon onset indices (as described in Section 2.2.2) at a lead time of 2 to 3 months (Chevuturi et al., 2019). Although it is not possible to forecast for a particular onset date, there is some skill in predicting onset tercile categories, for example, early, late or normal.

3.2 Forecast methods used in the SASCOF countries

A variety of both dynamical and statistical methods are used in the production of seasonal forecasts in the SASCOF countries. A summary of the methods used in each of the countries, gained through discussion with the National Meteorological and Hydrological Services (NMHS), is provided in Table 5. The forecasts are disseminated through a range of methods including fax, email, website, SMS and social media. Users of seasonal forecasts across the South Asia region are predominantly those working in agriculture, fisheries, water management, health and hydropower.

Table 5: Summary table of the methods currently used to produce seasonal forecasts in the SASCOF countries, gained through discussion with the NMHSs.'

Country	**Seasonal forecast methods used**
Afghanistan	• Seasonal forecast products online, such as the NASA and NOAA seasonal forecasts for central and South Asia.
Bangladesh	• Seasonal forecasts from dynamical models, including the North America Multi-Model Ensemble (NMME), Copernicus data store (C3S) and other NMHS such as the Japan Met. Agency (JMA). • Use of CPT to calibrate dynamical models with observations over Bangladesh.
Bhutan	• Use of CPT to calibrate dynamical models with observations over Bhutan, along with various statistical methods. • Consideration is also given to other GPC dynamical models (ECMWF, etc.) • ITACS (Interactive Tool for Analysis of the Climate System, JMA) and CLIK (Climate Information Toolkit, WMO)
India	• Seasonal forecasts are produced using MMCFS model (monsoon mission) – a modified version of CFS for India only • This information is enhanced through assessing GPC outlooks from lead centres, as well as CPT to calibrate multiple dynamical models
Maldives	• Dynamical models produced by GPCs, LC-LRFMME and products of IRI. • Forecast calibrated using CPT
Myanmar	• Dynamical models produced by GPCs.

	- Forecasts calibrated using CPT.
Nepal	- Dynamical models produced by GPCs. - Forecasts calibrated using CPT. - Have developed a statistical model to forecast country averaged rainfall based on observed (reanalysis) data.
Pakistan	- Downscale model data which is bias-corrected for Pakistan. - Produce seasonal forecasts dynamically by simulation of WRF from CFS data. - Statistical methods.
Sri Lanka	- Statistical downscaling of GPC output using Climate Predictability Tool (CPT), APEC Climate Center CLimate Information ToolKit (CLIK) and RIMES FOCUS System.

3.3 Forums for dissemination

3.3.1 South Asia Climate Outlook Forum

The WMO established the concept of RCOFs across the world with an overarching mandate to produce and disseminate information on the current state of the regional climate with an outlook for the upcoming season.

South Asian nations, supported by the WMO, established the South Asia Climate Outlook Forum (SASCOF) in 2010. Initially, the SASCOF sessions were organised on an annual basis before the summer monsoon[10] season. Recognising the importance of the winter seasonal[11] climate to key user sectors, winter sessions of the forum commenced in 2015. The India Meteorological Department (IMD), who are the WMO Regional Climate Centre (RCC) for South Asia (herein denoted as RCC Pune), typically coordinate SASCOF events, which include contributions from Afghanistan, Bangladesh, Bhutan, India, Maldives, Myanmar, Nepal, Pakistan and Sri Lanka. RCC Pune is embedded within IMD and holds the regional mandate to deliver operational climate services including the SASCOF Consensus Statement. The Regional Integrated Multi-hazard Early Warning System for Africa and Asia (RIMES) support the SASCOF proceedings and dissemination of forecast information at the national level alongside the NMHSs. RIMES are an international institution involved in the generation and application of early warning information. During the forum, experts collaboratively produce a consensus-based climate outlook statement detailing the forecast for the upcoming season. A joint SASCOF Climate Service User Forum (CSUF) also provides a platform for interaction between users and providers of operational climate services, promoting the use of seasonal

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[10] June, July, August, September (JJAS)

[11] During the winter months, South Asia's climate is influenced by both tropical (October, November, December - OND) and temperate mid-latitude (December, January, February or DJF) circulation systems.

forecasts by engaging representatives of the user community from climate-sensitive user sectors (including agriculture and food security, health, energy, water resources, disaster risk reduction and response, and the media). The first SASCOF CSUF was conducted in 2014, and more recently at SASCOF-13 and -14, the CSUF has had a focus on the agriculture and water sector.

Funding for SASCOF activities has mainly come from WMO programmes of work, supported by agencies such as The United States Agency for International Development (USAID), and Environment and Climate Change Canada's "Implementing the Global Framework for Climate Services at Regional and National Scales" programme (completed in March 2018). The Asia Regional Resilience to a changing Climate programme (ARRCC) has more recently funded SASCOF-13 (September 2018) held in Colombo, Sri Lanka and SASCOF-14 (April 2019) held in Kathmandu, Nepal, and more recently SASCOF-15 (Sept 2019) held in Kerala, India. The participation of experts from GPCs, RCC Pune and the Indian Institute for Tropical Meteorology (IITM) is funded by the respective institutions.

In 2017, the WMO performed a global RCOF review which highlighted the following limitations:

- The format is unsuitable for applications in specific decision making.
- The forecast skill is not routinely evaluated or communicated.
- There is a lack of opportunities to implement new measures reflecting progress in science.
- There is no systematic approach to provide regular updates as the target season evolves.
- There is very limited use of RCOF products or value addition at the national level.
- There is a lack of user-tailored or targeted product packages that engage users at the regional level.

One outcome of this review is a newly-defined WMO initiative to move towards a more objective-based forecasting process to be used within the COF process. Currently, the process for developing the consensus-built seasonal forecast is as follows:

1. Analyse available forecast data from the GPCs (the SASCOF process currently relies on the ensemble of models available from the IRI data library[12], which does not currently host forecast data from all GPCs);
2. Identify the models with the highest skill;
3. Bias correct the chosen model with a 'good' observational dataset for a 30-year period;

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[12] http://iridl.ldeo.columbia.edu/

4. Calibrate the forecasts using CPT (currently, CPT can only use one model at a time – this is an opportunity for further work);
5. Combine calibrated forecasts to produce a grid-point regional forecast product (this needs to be documented as some sort guidance on an agreed common approach).

3.3.2 National Climate Outlook Forums

To further facilitate the dissemination of seasonal climate information at the national level, the concept of SASCOF is extended to the national level through National Climate Outlook Forums (NCOFs). The WMO states that "the NCOF serves as a national platform for regular dialogue among stakeholders seeking improved societal outcomes associated with natural hazards, climate variability, extremes and change. It also links the weather and climate information generated by NMHSs with national stakeholder decision-making processes to improve the application of climate information, particularly seasonal climate outlooks". The NMHSs in each of the South Asian countries have the mandate to deliver weather and climate services tailored to the national, sub-national and local levels. The capacity for this mandate is varied across the region.

NCOFs in the South Asia Region, also known as National Monsoon Forums (NMFs), have been conducted in Bangladesh, Bhutan, Myanmar, Nepal, Pakistan and Sri Lanka since 2013-14. RIMES has been involved in supporting the organization of Monsoon Forums/NCOFs in close cooperation with respective NMHSs with funding support from donors such as the United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP[13]), the Food and Agriculture Organization (FAO[14]), the WMO Global Framework for Climate Services (GFCS[15]) and the United Nations Office for Disaster Risk Reduction (UNDRR[16]). Monsoon Forums have now evolved to be the main user interface platforms for climate information at the national level in most countries in the region.

3.3.3 Application of outlook information

The awareness levels among sector users in the application and use of seasonal outlook information is currently very low. The capacity for producing seasonal prediction products varies across the South Asian NMHS', with very few producing operational seasonal products using standardized, well-informed scientific processes. Additionally, NCOF processes have been interrupted in some instances due to issues like lack of funding, technical support and

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[13] https://www.unescap.org/
[14] http://www.fao.org/
[15] https://gfcs.wmo.int//
[16] https://www.unisdr.org/

capacities available for organization, and also coordination with key stakeholders. Previous work undertaken by RIMES under the WMO GFCS project has indicated that sector agencies would like to receive and utilise seasonal predictions and would benefit from improved awareness and exposure to programs.

4. Knowledge gaps and further work

This review document has mapped the current understanding of seasonal prediction and predictability in the South Asia region, and has allowed us to identify gaps in this scientific knowledge and institutional capacity, as well as areas which require further efforts and investigation. These knowledge gaps can be clustered into three distinct themes: 1) seasonal forecast production, 2) seasonal forecast dissemination, and 3) stakeholder understanding and interpretation. Other further work on the potential applications of weather regimes in South Asia can be found in Appendix 2.

1. **Seasonal Forecast Production**
   1.1. *Towards objective-based forecast production*: In order to ensure replicable forecast production that upholds scientific integrity, it is important for the SASCOF process to evolve towards using objective-based forecast methods, as recommended by the WMO. Through this process, it is hoped that subsequent forecast information could be more easily tailored to national-level contexts within each NMHS. This is an activity that SCIPSA hopes to support in the coming SASCOFs, alongside our colleagues at the WMO.
   1.2. *Seasonal forecast verification*: Forecast verification is an essential component of seasonal forecasting, without which it is difficult to demonstrate their value to decision-making contexts. For South Asia, the application of a standardised approach to forecast verification (i.e. the WMO Standardized Verification System for Long-Range Forecasts; SVSLRF) is needed both at the regional and national levels. These verification activities should be initially targeted on the GPC outlooks used within the SASCOF process, and subsequently focus on assessing seasonal forecast skill on a national level through building this capability in the NMHSs.
   1.3. *Prediction of monsoon onset*: As stated previously, a number of definitions currently exist for predicting monsoon onset over different regions of South Asia. Many of these definitions depend on subjective thresholds that may only be relevant to a specific area of interest. What's needed is an objective definition of monsoon onset that could be applied to the dynamical GPC output, such that a resulting forecast of an early/late monsoon could be possible (and with a reasonable level of skill).

2. **Seasonal Forecast Dissemination**
    2.1. *Tailoring of user-relevant products and services on seasonal timescales:* Once the South Asia NMHSs are confidently producing and interpreting seasonal forecast information (both on a regional and national level), it will then be necessary to tailor this information to specific decision-making contexts being faced by key stakeholders at the national level. The capability for this co-production of services is currently varied across the ARRCC focal NMHSs (Afghanistan, Bangladesh, Nepal and Pakistan). The SCIPSA project of the ARRCC programme (Strengthening Climate Information Partnerships – South Asia) hopes to address this knowledge gap through targeted capacity building and stakeholder-engagement activities alongside colleagues in each of the focal NMHSs. A preliminary workshop at SASCOF-15 is planned to discuss the importance of understanding decision-making contexts, using a common language/terminology, communicating information in a manner that is easily understandable, and promoting a common ground when engaging with stakeholders.

3. **Stakeholder understanding and interpretation**
    3.1. *Improved understanding and appreciation for seasonal information*: Once seasonal forecast information has been appropriately tailored through a co-developed process with stakeholders, it is important to promote an accurate understanding and appreciation of that forecast information within these stakeholder groups. This type of activity allows stakeholders to feedback any issues or concerns they have with using seasonal information in their decision-making activities, and therefore needs open, two-way dialogue between forecast providers and end-users. SCIPSA aims to help NMHSs bridge the gap between forecast provider and stakeholders through proposed joint co-exploration activities, such as those being planned for SASCOF-15. If successful, SCIPSA will look to scale and support these types of activities to the national level.

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Appendices

Appendix 1 – Onset definition for the South Asian Monsoon

There are numerous definitions for the onset of the South Asian Monsoon. The official definition used by the Indian Meteorological Department (IMD) is as follows[17]:

> *"The guidelines to be followed for declaring the onset of monsoon over Kerala and its further advance over the country are enlisted below:*
>
> ***a) Rainfall***
>
> *If after 10th May, 60% of the available 14 stations enlisted*, viz. Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuzha, Kottayam, Kochi, Thrissur, Kozhikode, Thalassery, Kannur, Kudulu and Mangalore report rainfall of 2.5 mm or more for two consecutive days, the onset over Kerala be declared on the 2nd day, provided the following criteria are also in concurrence.*
>
> ***b) Wind field***
>
> *Depth of westerlies should be maintained up to 600 hPa, in the box equator to Lat. 10ºN and Long. 55ºE to 80ºE. The zonal wind speed over the area bounded by Lat. 5-10ºN, Long. 70-80ºE should be of the order of 15 – 20 Kts. at 925 hPa. The source of data can be RSMC wind analysis/satellite derived winds.*
>
> ***c) Outgoing Longwave Radiation (OLR)***
>
> *INSAT derived OLR value should be below 200 wm-2 in the box confined by Lat. 5-10ºN and Long. 70-75ºE. "*

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[17] http://www.imd.gov.in/pages/monsoon_main.php?adta=PDF&adtb=4

Appendix 2 – Weather regimes identified over India

A recent study by Neal et al. (2019) presents a new set of objectively-derived weather patterns for the Indian subcontinent. The 30 weather patterns were generated by clustering daily wind fields and represent rainfall variability within the different phases of the Indian climate. For example, certain weather patterns are associated with western disturbances, and some have been linked with an active or break phase of the monsoon (a full list can be found in Table A1). Figure A1 shows an example of two contrasting weather patterns. By applying the same process to the rest of South Asia, there is potential for seasonal forecast tools to be created for the region, whereby ensemble members can be assigned to the closest matching weather pattern. This could enable objective analysis of the predictability of different weather patterns or regime groupings over South Asia.

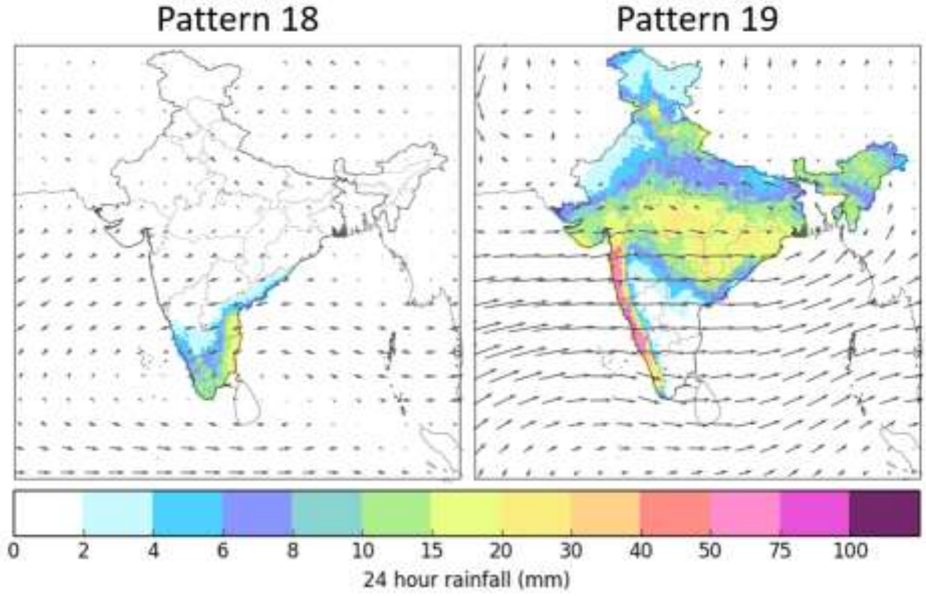
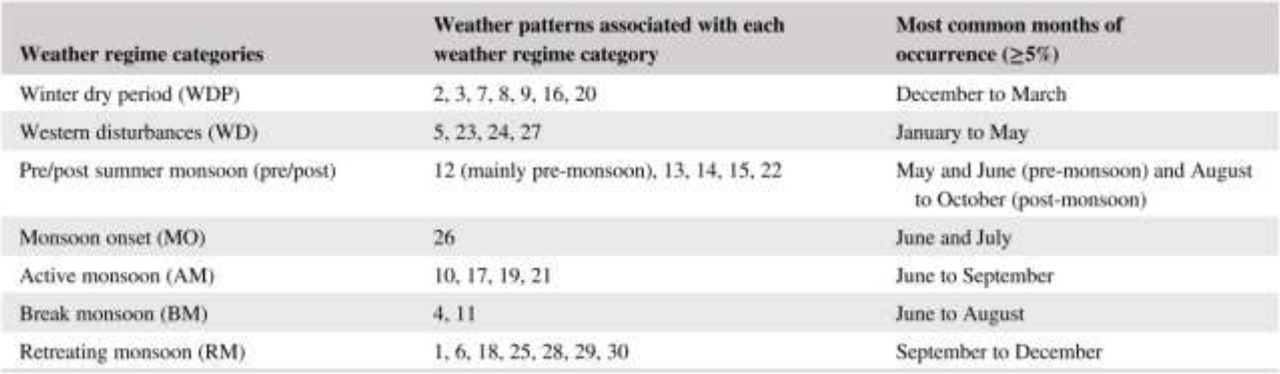


Figure A118: An example of two contrasting weather patterns from the set of 30 showing mean wind speed and direction at 850-hPa and daily mean rainfall. Weather pattern 18 is a retreating monsoon type and weather pattern 19 is an active monsoon type. Source: Neal et al. (2019).

Table A1: Weather regime allocations for each weather pattern including most common months of occurrence.



Weather regime categories	Weather patterns associated with each weather regime category	Most common months of occurrence (≥5%)
Winter dry period (WDP)	2, 3, 7, 8, 9, 16, 20	December to March
Western disturbances (WD)	5, 23, 24, 27	January to May
Pre/post summer monsoon (pre/post)	12 (mainly pre-monsoon), 13, 14, 15, 22	May and June (pre-monsoon) and August to October (post-monsoon)
Monsoon onset (MO)	26	June and July
Active monsoon (AM)	10, 17, 19, 21	June to September
Break monsoon (BM)	4, 11	June to August
Retreating monsoon (RM)	1, 6, 18, 25, 28, 29, 30	September to December