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How Robust the Indian Summer Monsoon Circulation Is Going to Be with Climate Change

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ABSTRACT

Irrespective of the fact that accurate simulation of South Asian monsoon rainfall still remains a challenge in climate models, it is evident that the adverse impacts of climate change in India would include extreme heatwaves, erratic monsoons, heavy rainfall and cloudbursts, floods, severe droughts, and stronger cyclones bringing miseries to the most populated region of the world. From the drizzle for a week about a decade ago at any location, now we see intense rains for a day and dry weather for rest of the week. The observed warming has already given rise to heavy rainfall events and cloud bursts have tremendously increased over the years in the past two decades. Extreme rainfall events are projected to rise in intensity throughout the 21st century across the Indian sub-continent, particularly during the summer monsoon. Climate change induced extreme climate events will take a toll on human health, security, livelihoods, and poverty levels, affecting different parts of India in various ways. The growing pace of urbanization will also have unequal effects on citizens and infrastructure. With the increase in extreme rainfall events and several artificial obstructions due to construction and debris dumping, the behavior of Himalayan rivers is becoming unpredictable. With the rapid melting of glaciers in the Himalayas, abrupt floods are becoming common, causing significant harm to life and property. These glacier retreats are also resulting in the creation of glacial lakes due to elevated temperatures, which pose potential dangers of floods and landslides to the downstream population. As floods and droughts become more frequent and intense, poverty will worsen in some areas, especially as it impacts crucial crops like rice, leading to increased food prices and a higher cost of living for vulnerable communities. Compounded by the pressure stemming from rapid urbanization, industrialization, and economic growth in India, the consequences of these combined stresses will significantly impact the sustainable development prospects.

Keywords: Global warming, Indian summer monsoon, Rainfall and its interannual variability, Weather extremes and disasters, Snow melt in Himalayan Region and Rural Livelihood.

Indian Summer Monsoon and its Variability: Key Facts

Indian Summer Monsoon (ISM) is part of a planetary-scale phenomenon involving the annual migration of the Inter Tropical Convergence Zone (ITCZ) between its northern and southern limits within the land–ocean–atmosphere coupled system (Webster *et al.,* 1998)**.** The limits of the ITCZ vary according to the land–sea heating contrast and the northern extent of the monsoon over the Indian subcontinent is influenced by the Himalaya-Tibetan Plateau (South Asian landmass exhibits significant surface variations, with elevation ranging from meters to thousands of meters within a short distance). It occurs due to the transport of substantial amounts of moisture during June to September months across the Indian Ocean toward the Indian subcontinent. Indian summer monsoon has a dominant westerly component and a strong tendency to ascend and produce copious amounts of rain (because of the condensation of water vapor in the rising air). The intensity and duration of the rainy season, however, are not uniform from year to year (Gadgil, 2003). In Central and North India, rainfall also occurs when moist ocean air is lifted upwards by the mountain ranges, surface heating, convergence at the surface and divergence aloft (low pressure systems along monsoon trough), or from storm-produced outflows at the surface. Indian agriculture (which accounts for 25% of the GDP and employs 70% of the

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population) is heavily dependent on the summer monsoon rains (accounts for about 80% of the annual total rainfall in India), for growing crops especially like cotton, rice, oilseeds and coarse grains (Gadgil, 2006**).** A delay of a few days in the arrival of the monsoon can badly affect the economy, as evidenced in the numerous droughts in India since the 1970s.

A study of the ISM's variability over the past million years revealed that precipitation resulting from the monsoon was significantly reduced during glacial periods compared to interglacial periods like the present day. The Indian Summer Monsoon underwent several intensifications during the warming following the Last Glacial Maximum, as indicated by vegetation changes in the Tibetan Plateau displaying increases in humidity brought by an intensifying ISM. The intra-seasonal, interannual and long-term variability of the monsoon and a better understanding regarding its spatial variability over the Indian subcontinent can be of great implication if attended with spatial and temporal distribution due to huge uncertainty in both **(Figure 1)**.

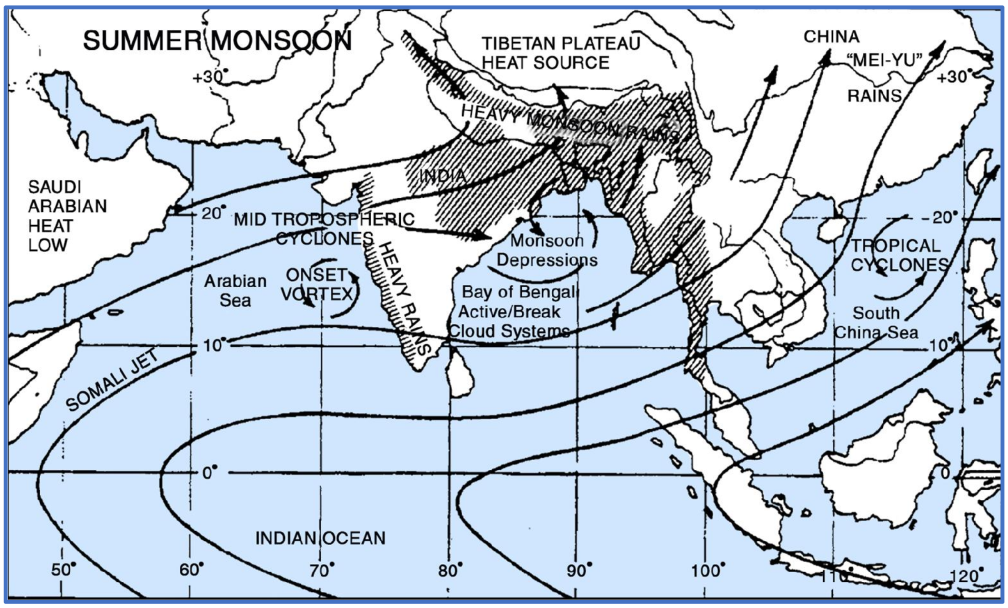

Fig. 1: The key westward and northward propagating synoptic systems responsible for rainfall during Indian summer monsoon

The intra-seasonal components including prominent westward and northward propagating synoptic system (Monsoon Intra-Seasonal Oscillations, MISOs) consisting of active and break monsoon phases lead to the fluctuations of two broad scales of 10–20 and 30–60 days (Yasunari,1979). Several factors at the decadal and multidecadal scale also contribute to the intra-seasonal to seasonal variability of rainfall under ISM (Hartmann and Michelsen,1989) (associated with the predictable mode of El Niño-Southern Oscillation (ENSO). ENSO was known to be the main driver of the Indian monsoon during 20th Century. Recent studies have, however, established that large-scale SST forcings such as SSTs over the Indian Ocean (Equatorial Indian Ocean Oscillation in Indian Ocean Dipole mode), Atlantic Ocean (Atlantic Meridional Oscillation), and several areas over the Pacific Ocean (Pacific Decadal Oscillation) directly or indirectly affect the Indian monsoon (Saha, *et al.,* 2021). These studies on spatial patterns (clusters/composites) of monsoon rainfall anomalies during the period 1901-2018 suggest that large-scale hydroclimatic teleconnections from sea surface temperatures (SSTs) drive moisture over the Indian subcontinent causing a particular spatial pattern of the rainfall during ISM.

The human-induced climate change has immensely affected the magnitude of Indian summer monsoon rainfall (ISMR) and its spatial variability in past two decades. The impacts of global-scale greenhouse gas (GHG) emissions and aerosols and the local-scale changes such as urbanization and changes in land use have contributed largely to the perturbations in rainfall distribution within ISM. The studies on long-term variability of the Indian summer monsoon in terms of decadal-scale statistics of rainfall and frequency of extremes during the 1871–2020 period have suggested a weakening trend over the central-east and northern regions of the Indian subcontinent and south of the Western Ghats region. The spatial pattern featured a prominent horseshoe pattern showing the reduction in summer rainfall over central-east India during the past decades.

Recent studies suggest that a decrease in monsoon rainfall is caused by warming trends over the tropical oceans, especially the Central-Eastern Pacific, Atlantic Ocean and the Western Indian Ocean (Gastineau and Frankignoul, 2015). Although the Pacific Ocean does not show any significant warming trend, the Western Indian Ocean, the Southern Indian Ocean and the Atlantic Ocean have been warming in the past few decades (Indian Ocean is warming faster than other basins due to human-induced climate change, leading to oxygen-depleted surface waters and endangering marine productivity in the northern Indian Ocean). The Atlantic Meridional Oceanic Circulation (driven by contrasts between different masses of warm and salty, and colder and less salty, water and distributes both warmer and colder water between both poles via a network of deep and near-surface ocean currents) could disrupt the global heat pump that acts like a thermostat to keep parts of the planet from overheating through the global ocean conveyor belt thus maintaining the relative warmth of the Northern Hemisphere. The Indian Ocean, also the warmest among the world's oceans and part of the Indo-Pacific warm pool (SST > 28°C), plays a pivotal role in maintaining deep atmospheric convection and tropical circulation. Indian Ocean Sea Surface Temperatures (SST) strongly influence monsoon rainfall in India, vital for rain-fed agriculture and providing 80% of South Asia's annual precipitation. The Indian Ocean is also the birthplace of critical climate phenomena like the Madden-Julian oscillation (an intermittent wave of enhanced tropical convection that transits west to east through the entire tropics in 30 to 60 days) (Madden and Julian,1972, Zhang, 2005) and monsoon intra-seasonal oscillations, which impact rainfall and tropical cyclones on shorter timescales (Dey *et al.,* 2022).

If the Atlantic Meridional Overturning Circulation weakens because of increasing freshwater inflows from melting ice sheets and rivers swelled by global warming, it would disrupt and shift the Asian monsoon rainfall patterns. A recent heat redistribution from the Pacific to the Indian Ocean has significantly contributed to regulating global mean surface temperatures, with the Indian Ocean accounting for about a quarter of the global ocean's heat gain since 1990. Interestingly, even after the warming of the Indian Ocean drives moisture over oceanic parts, it does not necessarily attract more moisture toward the subcontinent. In fact, the land–sea thermal gradient is expected to drop due to the warming over oceans, which could modulate the strength and flow of the monsoon circulation in a warmer climate with more frequent extreme rainfall over the Indian subcontinent (Katzenberger *et al.,* 2022).

Is Global Climate Change Impacting the Indian Summer Monsoon?

Climate change, once considered gradual, is now accelerating with record-breaking temperatures. Global temperatures in 2023 was the hottest year on record, 1.48°C warmer than pre-industrial levels (beating the previous warmest year 2016 by a record-setting margin of 0.15°C) driven by human-caused climate change, a moderately strong El Niño event and a decrease of Earth's albedo linked to melting of polar ice **(Figure 2).** Global surface temperature in December 2023 was 1.43°C above the 20th century average—the warmest December on record (WMO, 2024). Almost every day since July 2023 has seen a new global air temperature high for the time of year (NOAA, 2024). The recent 12 month global mean temperatures since February 2023 have breached the climate target of limiting warming to 1.50°C pledged by more than 200 countries in the Paris Agreement in 2015.

Interestingly, global sea surface temperatures have also hit a record high since April 2023, indicating a significant deviation from the long-term average **(Figure 3).** North Atlantic Sea surface temperatures have risen significantly and the ocean heat content (Cheng and Co-authors, 2023) has also been increasing steadily **(Figure 4).** Rising ocean temperatures bolster the energy exchanges from ocean to atmosphere, increase the quantity of atmospheric moisture, and change the patterns of precipitation and temperature (IPCC, 2019) Arctic and Antarctic Sea ice levels are dwindling,indicating worsening climate change in the coming years and decades. Sea ice extent was much lower than previous records, with Antarctic Sea ice being the lowest, and Arctic Sea ice ranking as the smallest in 2023 **(Figure 5).** Marine heatwaves have more than doubled in frequency between 1982 and 2020 (when temperatures at the water's surface are higher than 95% of the values from the past 30 years for at least five consecutive days), and have become more intense and longer since the 1980s. The western Indian Ocean region has witnessed the largest increase in marine heatwaves at a rate of about 1.5 events per decade. The region witnessed 66 marine heatwave events.

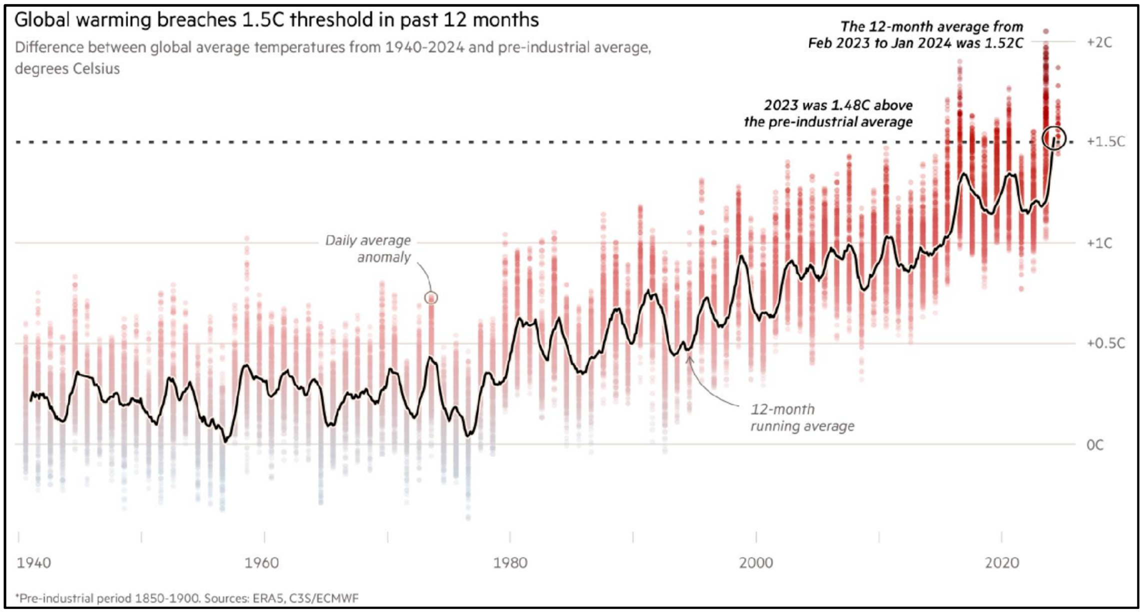

Fig. 2: Global mean surface temperature anomalies have peaked to 1.52ºC during the past 12 months (Data Sources: ERA5, C3S/ECMWF)

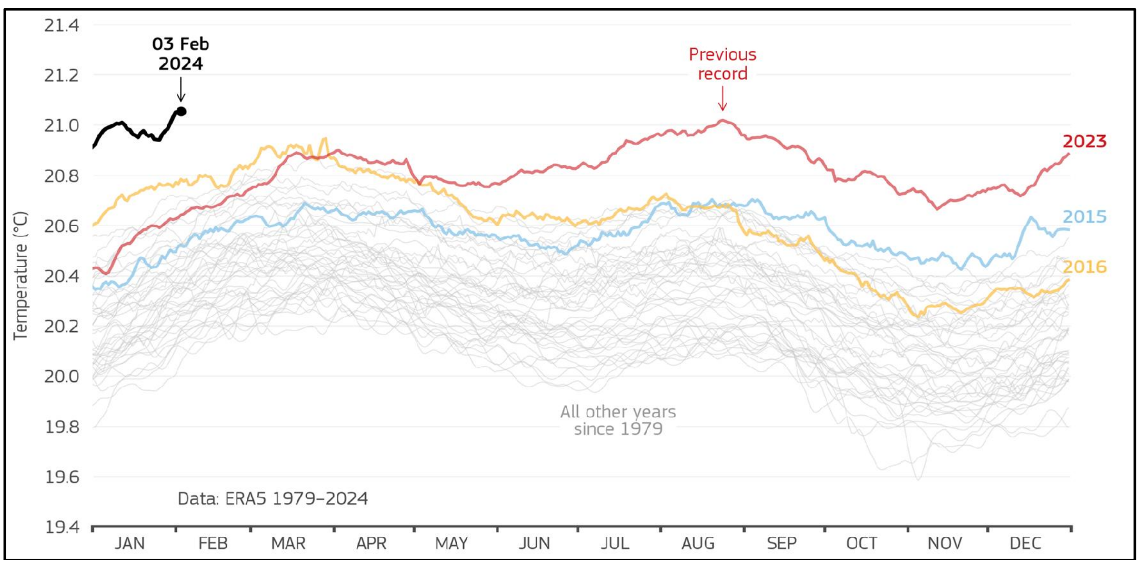

Fig. 3: Ocean's daily average surface temperatures (between latitudes 60ºN and 60ºS) are highest on record Since 1979 (Source: ERA5, C3S/ECMWF)

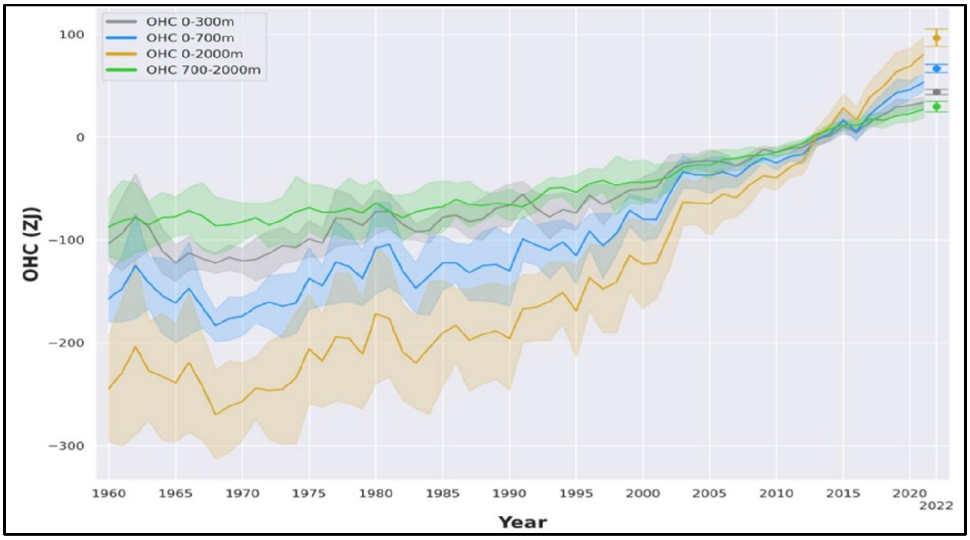

Fig. 4: Ensemble mean time series of ocean heat content (in zeptojoule) and trends for different depths during 1960-2022 (Source: Mercator Ocean international, based on Copernicus Marine Data).

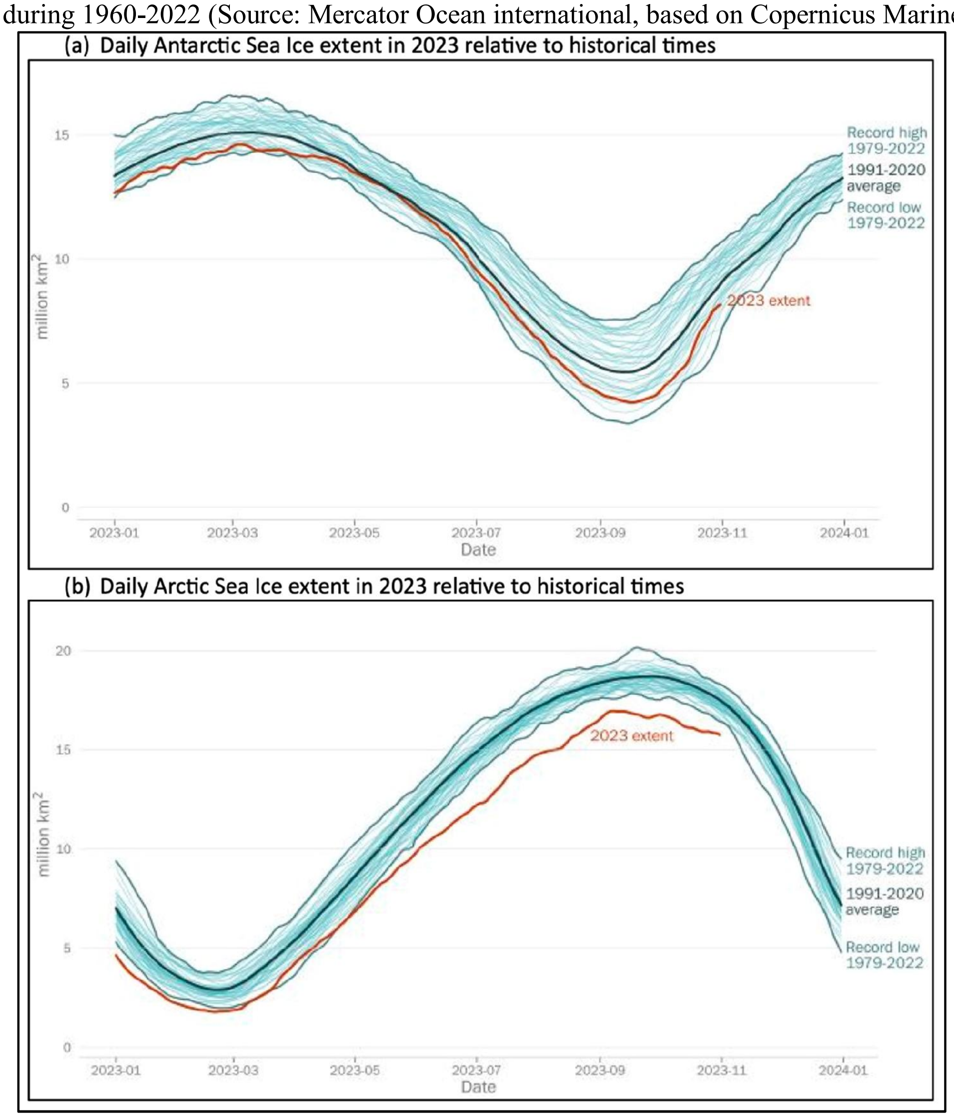

Fig. 5: Daily sea ice extents in (a) Antarctic and (b) Arctic polar regions in 2023 relative to historical times (Source: NOAA - National Snow and Ice Data Center).

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The intensity increased the marine heatwave events by four-fold in the tropical Indian Ocean (Saranya *et al.,* 2022). Future increases in the intensity (almost 10 times by the end of this century) and frequency (20 to 50 times by the end of this century) of the marine heatwaves will impact the monsoon rainfall over India. Recent records of rapidly intensifying tropical cyclones and widespread wildfires are linked to human-induced climate change, and such extreme events are expected to become more frequent even if swift action is taken to reduce emissions and build resilience in critical regions. The frequency and intensity of extreme weather events like heatwaves, forest fires, and floods have increased worldwide due to human-induced climate change now. Deadly heat, catastrophic storms and collapsing ice sheets, and species extinction would become more likely after 1.5°C warming (IPCC, 2018). This climate crisis demands immediate attention to avert impending risks. We must eliminate the greenhouse gas emissions and that means rapidly phasing out coal, oil and gas, which account for 80% of energy use worldwide. In developing world, we can expect more frequent and severe extreme weather events, heatwaves, floods, and droughts unless we implement adaptation strategies to build resilience in critical regions across the globe.

Despite being the smallest of the major oceans, the Indian Ocean holds immense importance, with over 20 countries bordering its shores, home to a significant portion of the world's population. These nations, often with developing economies or as island states, face vulnerabilities to extreme weather events, changing monsoon patterns, and climate fluctuations. Recent studies paint an alarming picture of the future climate's impact on the Indian subcontinent. The impact of climate change here is overwhelming and clearly visible in the localized warming trend. Effects already felt include unprecedented heatwaves, erratic monsoons, heavy rainfall episodes, severe droughts, and stronger cyclones. Many cities in India and neighboring countries experience record-high temperatures, associated with human-induced climate change. An increasing number of school-going children and rural workers here face dangerously high temperatures for extended periods. The land only surface air warming reached 1.0°C in 2020 and is headed to about 3.5°C by the end of this century **(Figure 6).** Short duration heat waves (3–5 days) may be 2–10 times more frequent at +1.5°C and +2°C, and prolonged heat waves (7-9 days) could increase by 10–30 times with associated increases in wet bulb temperatures (higher humidity with enhanced water holding capacity of the warmer air). This more rapid lethal heat and humidity threshold also could extend to regions not previously prone to heat waves in India.

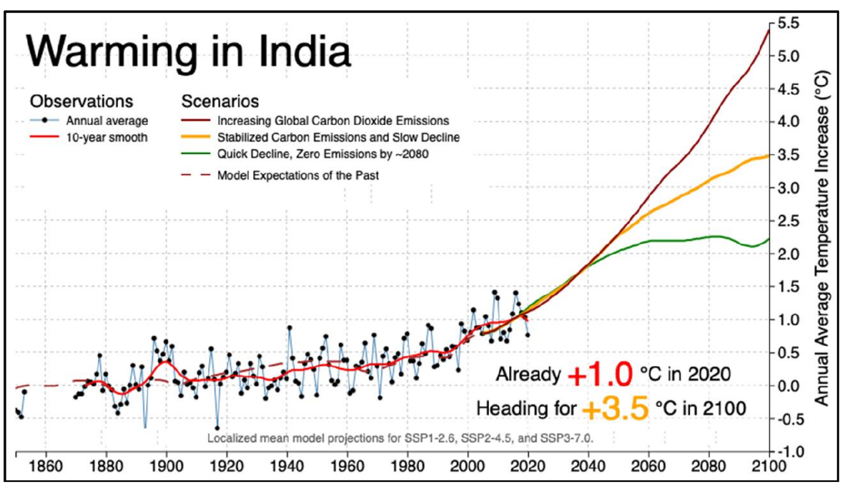

Fig. 6: Observed warming averaged over India and the future projections for the end of this century (Source: Berkley Earth)

Another interesting factor is the ongoing changes in Diurnal Temperature Range (DTR) which have received considerable attention in recent years. The surface warming since the 1950s has been associated with larger increases in T_{max} than in T_{min}, i.e., decreases in DTR (changes are subject to many factors, including cloud cover, solar radiation, aerosols, precipitation, planetary boundary layer height, land use change and deforestation), which is commonly known as night warming or *asymmetric warming*. During the recent decades (1991–2020), a global decrease in cloud cover has led to an increase in solar radiation at the surface over almost three-quarters (74%) of the land area than that reported for the period 1961–1990. Decreasing soil moisture in recent periods may also have contributed to the acceleration of T_{max} increases and thus decreasing DTR, possibly due to less effective daytime evaporation cooling on air temperature during dry conditions. This reversing asymmetric warming (larger increases in day time temperature than the night-time temperature) is quite discernible in regional increasing DTR trends in South Asia (Ziqian Zhong *et al.,* 2023)**.** Heatwaves are, under these conditions, expected to become hotter and longer-lasting during the coming years, with global warming intensifying extreme weather events such as the occurrence of high-intensity rainstorms as well as prolonged droughts in the future. The extremely heavy precipitation events in monsoon season are projected to significant increase (25–80%) across India during the second half of this century. However, a 10–20% decrease in rainfall during pre-monsoon (March–May) and early monsoon months (i.e., June and July) are also likely in some states of India. The scale of disasters in India will likely exceed official response capabilities. With considerable interannual sea surface temperature variability **(Figure 7),** the Indian Ocean's heat content due to rising CO_2 levels, is expected to increase significantly by 2050. The Arabian Sea could warm faster than the Bay of Bengal, leading to more severe cyclones, particularly during pre-monsoon season.

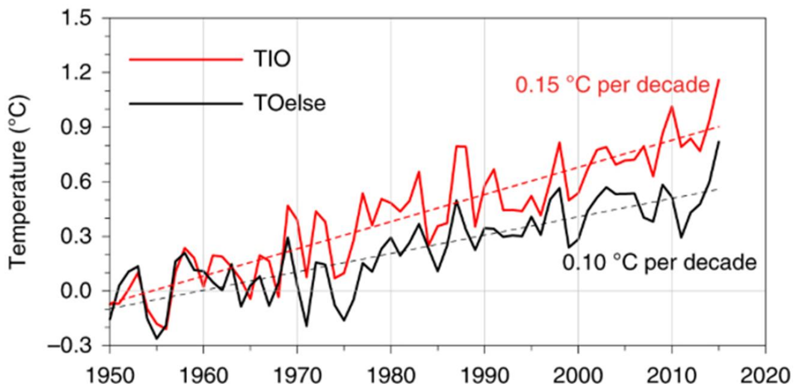

Fig. 7: Sea Surface Temperature anomalies over Tropical Indian Ocean (Red line) and over Tropical Ocean elsewhere (Black line) (Data Source: NCEI-NOAA/NASA GHRSST). Considerable interannual variability is observed over the Indian Ocean of which only some can be attributed to El Niño and a large percentage remains unexplained.

Floods and Disaster Hotspots in India's Hilly States

The Himalayas are typically young mountains, weak and recently developed ranges, made of sedimentary rocks. So, landslides are quite common in this terrain. The Southwest monsoon in India is influenced by the reduction of glacial conditions on the Tibetan Plateau, triggering a strong monsoon. These critical stressors are adversely affecting the socio-ecology of the Himalayan region. This year (2023), the monsoon has not been kind to the States straddling the Himalayas in North India. Increases in heavy precipitation by up to 50% during wet season have been reported in recent years at some locations in the Himalayan belts. Just a month after record showers killed more than 100 people over two weeks in parts of the region, heavy rains that began over the weekend on August 12 once again triggered floods and landslides, leaving at least 81 people dead and many others affected. Similarly, in Uttarakhand State, which was yet to recover from the horrors of the 2021 flash floods that killed nearly 200 people and washed away several houses, several people have died in the monsoon rains this season. Extreme rainfall events are repeatedly signalling the ecological mess in the Himalayas.

The Hindukush-Karakoram-Himalayan (HKH) region is warming faster than global mean and the majority of Himalayan glaciers are melting / retreating at varying rates in different regions leading to change in hydrological regime in the region **(Figure 8).** The mean temperature is significantly increasing in the HKH region with an average observed trend of +0.28°C per decade. The rate of warming is amplified with elevation and highest trends are observed for the Tibetan Plateau, and Brahmaputra basins resulting in the conversion of solid precipitation to liquid precipitation due to warmer air temperatures at lower elevations. There have been increases in climate- and weather-related disasters in mountain regions over the last three decades (where a permafrost area loss of about 965 km^2 in the Uttarakhand Himalaya in ~40 years has taken place), and that the frequency of hydrological disasters has shown an increasing trend in the HKH. Climate-induced changes have been observed like increased rainfall variability and frequent heavy rainfall incidences and these lead to more landslides in the rainy season. Global warming has increased the average temperature in the Himalayas accelerating the glacial retreat in the region. The rapid melting of glaciers in the Himalayas are creating abrupt floods, causing significant harm to life and property. These glacier retreats are also resulting in the glacial lake outburst flooding (GLOF) posing potential dangers to the downstream population. In the recent past we have heard of cloudbursts, degradation of land, etc. The intra-seasonal and inter-annual vulnerability of such events has increased and is enforced with man-made construction (rapid urbanisation is accompanied by an increase in urban infrastructure in both cities and the peri-urban areas), thus increasing the intensity of the impact being felt all over the places. Proper land use planning and infrastructure design will be crucial in minimising loss and damage and to ensure that development within the mountainous region is sustainable and climate resilient.

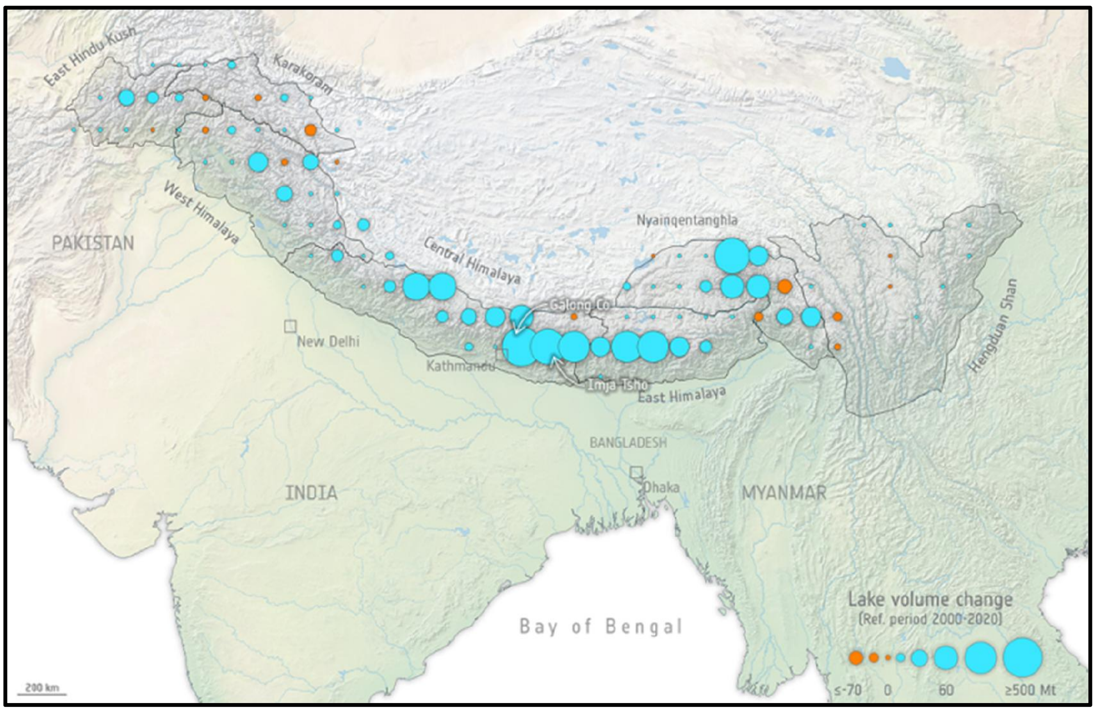

Fig. 8: The Increase in Glacial Lake Volumes from 2000 to 2020 in Hindukush Himalayan Region (Source: Zhang *et al.,* 2023)

There is strong evidence that snowmelt volume in HKH region will decrease in future and peak flow will shift, with large variability between basins. Snowfall is projected to become less frequent but heavier and increasing temperatures will affect the volume of the snowpack negatively. Projections suggest future increases in annual precipitation in the HKH of 5%–20% over the 21st century. The frequency and intensity of extreme rainfall events are also projected to increase throughout the 21st century across the Himalayan–Tibetan Plateau during the summer monsoon. This suggests a transition toward more episodic and intense precipitation, especially in the eastern part of the Himalayan range.

Western Disturbances (WDs) are important synoptic-scale cyclonic weather systems advected over northern India by the subtropical westerly jet stream that are responsible for most of the rain and snow during winter (both climatological and extreme) over northern India which replenishes Himalayan glaciers. These upper-level jet stream winds are likely to accelerate under climate change (the fastest winds will speed up more than 2.5 times faster than the average wind); each degree Celsius of warming will increase the speed of these winds by 2 percent, likely leading to a set of impacts, including more accelerated storm systems. The WDs are responsible for extreme events in the hydrological cycle in northern India, from avalanches in the Himalayan foothills to flooding in the downstream plains thus disturbing the region's water security, farming and tourism. However, the frequency of western disturbances are observed to be decreasing in the last 40 years (Hunt *et al.,* 2019) (sharper decline in intense WDs across the core WD zone while the frequency of feeble and moderate WDs has risen by 10%) and a decline in winter rainy days is noticeable in the region (Javed *et al.,* 2023). Over this century, the frequency decline by about 10 - 15% is likely by 2050 which could be partially attributed to changes (weakening and widening) in the subtropical jet, as well as decreasing meridional wind shear and upstream baroclinic vorticity tendency, which also explains the changes in intensity.

The winter snowfall in the Indus Basin, as reported in recent studies, is projected to decrease by 30%–50%, in the Ganges by 50%–60%, and in the Brahmaputra by 50%–70% in the last three decades of this century compared to the average snowfall between 1971 and 2000 (Nischal *et al.,* 2022; Sarwar and Mahmood, 2023). Interestingly, glacial lake growth has been the most rapid in the central Himalaya during 2000-2020. Continued monitoring of these glacial lakes and their susceptibility to GLOFs is crucial in the face of ongoing climate change. A combination of snow melt, pronounced warming with elevations and frequency and intensity of precipitation will favor chain reactions and cascading processes resulting in increased floods and landslides due to glacier retreat (glaciers of the HKH are expected to lose at least 30% – 50% of their volume by 2100 relative to 2015), slope instabilities, and heavy precipitation can have devastating impacts downstream, well beyond the site of the original event. Attending to the implications of climate change on the glaciated river basins in an integrated manner would be necessary to enhance our efforts to secure sustainable and desirable futures for the people living in (and beyond) the HKH.

Of particular importance are rainfall (liquid precipitation) extremes owing to their instantaneous triggering of runoff and association with floods, landslides and soil erosion. The warming induced increases in rainfall extremes in high-elevation snow-dominated regions of the North India are likely to be amplified, averaging 15% per degree Celsius of warming—double the rate expected from increases in atmospheric water vapour due to a warming-induced shift from snow to rain. This suggests that high-altitude regions such as those in Uttarakhand and Himachal Pradesh (where recurrent cloud bursts and very heavy rainfall for the past two months this year have caused unprecedented devastation to infrastructures) should be identified as '**hotspots**' that are vulnerable to future risk of extreme-rainfall-related hazards, thereby requiring robust climate adaptation plans to alleviate potential risk. Long-term planning and adaptation strategies are necessary to safeguard the well-being and safety of communities residing in these vulnerable regions.

Why the concern about monsoon predictability in a warmer atmosphere?

Monsoon is regarded as a family of phenomena in the coupled tropical land-ocean-atmosphere system that involves the interaction of solar radiation, atmospheric and oceanic dynamics and thermodynamics, and land surface processes. The monsoon delivers most of India's rainfall and a weak or erratic monsoon can wipe out India's food productivity and livelihood of Indian farmers. However, Indian summer monsoon is not steady but characterized by the large amplitude sub-seasonal oscillations, active-break spells as well as inter-annual variability **(Figure 9)** largely controlled by positive longwave radiative effect due to clouds. Increases in sea surface temperatures and enhanced air sea interaction would also play a dominant role in future intra-seasonal variability in monsoon rainfall across India.

Global climate models (GCMs) have evolved since 1950s as research tools to underpin decision-making in our understanding of the influence of climate change. However, most climate models systematically overestimate the stability of the AMOC because they don't accurately account for freshwater input from poles. Projecting future precipitation changes at regional scales is complex in these GCMs. Forecasts of state level or local summer monsoon rainfall in India, often based on global climate models (they are rarely examined for representativeness of local climate or the plausibility of their projected changes), are yet unreliable and can mislead farmers and the public. Simulation errors in precipitation distribution and driving mechanisms are still evident across GCMs. Biases in meridional differential heating play a critical role in determining monsoon onset, seasonal precipitation, and monsoon depression trajectories. Errors in simulating the pre-monsoon heat low and atmospheric latent heating over the Himalaya-Karakoram Range can also affect localized atmospheric circulations. Lack of timely precipitation sources in monsoon depressions exacerbates errors by limiting moisture recycling

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and latent heating from convection. Precisely simulating South Asian monsoon rainfall influenced by land-atmosphere-ocean interactions (Krishnamurthy and Kinter, 2003) remains a significant challenge in GCMs contributing to uncertainty in climate simulations.

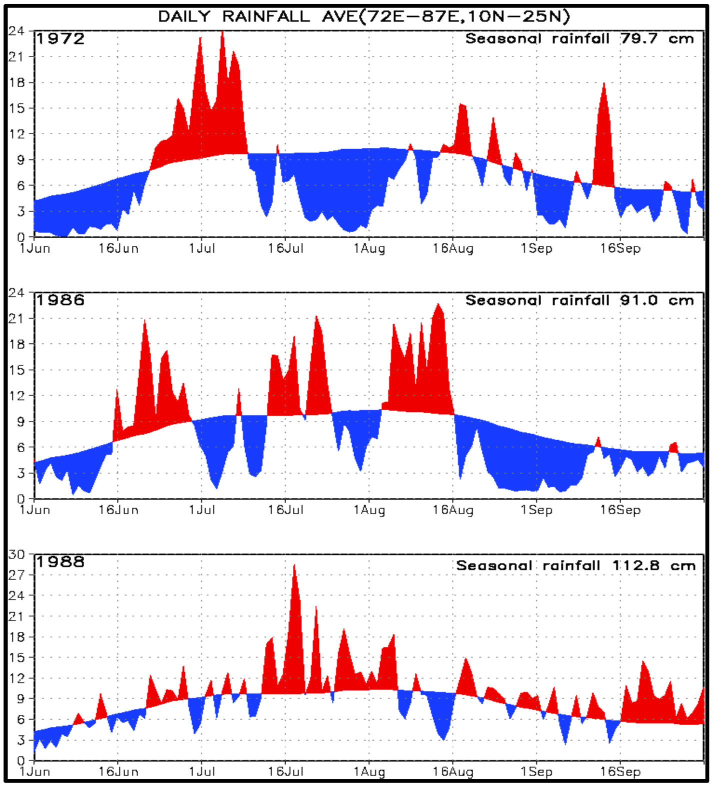

Fig. 9: Intra-seasonal and inter-annual variability in active-break spells in summer monsoon rainfall across India (Source: IITM, Pune)

The regional climate in the tropics is strongly influenced by the Inter Tropical Convergence Zone (ITCZ), also known as the monsoon trough over the Indian subcontinent. Understanding the physical processes that determine the ITCZ's location, strength, and width, and how it responds to radiative forcing and natural variability, is crucial (Grise *et al.,* 2018). Recent Indian Ocean warming has been linked to anomalies in the lower and upper troposphere, driven by increased latent heat uplift due to ocean convection. This warming intensifies convection over the ocean while leading to subsidence over land, reducing convection over the subcontinent and causing a drying trend (Cook *et al.,* 2018)**.** Another significant factor contributing to decreased rainfall since the mid 20th century is the narrowing of the ITCZ (Byrne and Schneider, 2016), related to changes in upper tropospheric relative humidity, cloud-radiative feedbacks, and the associated belt of ascending motion and rainfall over India. This narrowing is associated with various factors, including moisture diffusion, cloud-radiative and water vapor-radiative effects, and the skewness of vertical velocity distribution (Hoskins *et al.,* 2020)**.** The exact processes responsible for the narrowing of the ITCZ with global warming are still under investigation.

As a consequence of shift in monsoon trough, Rajasthan, Delhi, Punjab, Haryana, Jammu & Kashmir, Uttarakhand and Himachal Pradesh have witnessed intense weather patterns with the monsoon season this year becoming more erratic and less dependable. The capital city of Delhi received 384.66 mm rainfall over the course of the month this year—the third most for July in the past two decades. The poleward shift of the Hadley circulation is a robust response to a warming climate in global climate models **(Figure 10).** In the Northern Hemisphere (NH), the direct radiative effects of CO_2 enhance the land-sea temperature contrast, shifting the circulation poleward. However, SST warming in tropical oceans reduces the land-sea temperature contrast and shifts the circulation equatorward. The specific pattern of SST warming in tropical oceans and coupled atmosphere-ocean variability is crucial for understanding how the NH JJA Hadley cell edge contracts over the 21st century. It's worth noting that any northward shift of the monsoon trough over India **(Figure 11)** during the summer can complicate the distribution of future monsoon rainfall over major river basins in north-central India.

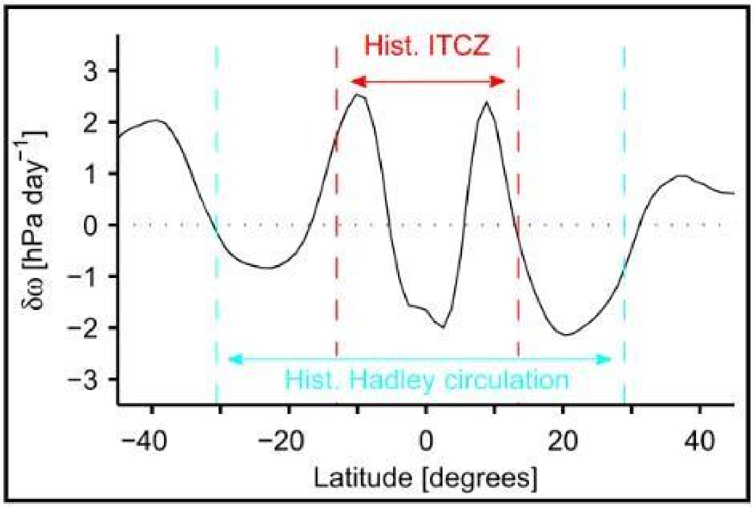

Fig. 10: The multi-model mean change in annual zonal vertical velocity averaged between 300 hPa and 700 hPa (black line). Red lines denote the multi-model mean edges of the historical ITCZ as defined using the mass stream function technique, and dashed blue lines show the edges of the historical Hadley circulation (Source: Byrne and Schneider, 2016)

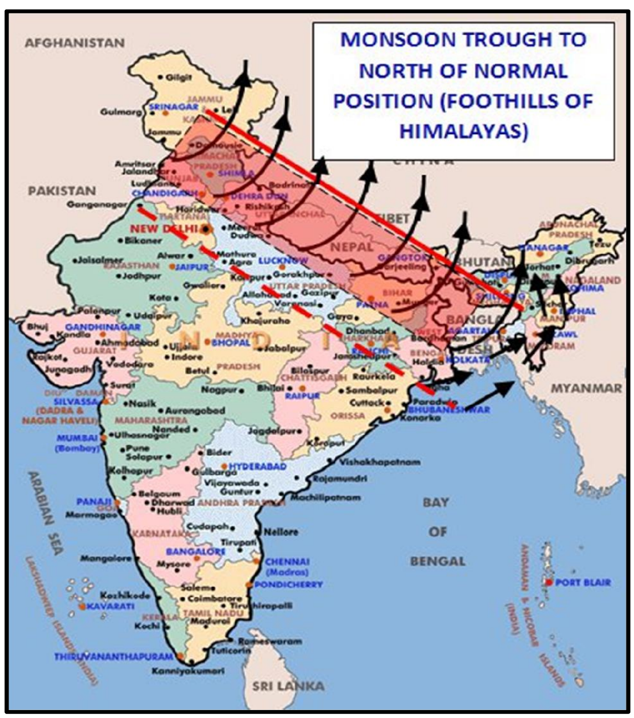

Fig. 11: Northward shift and / or shrinking of the monsoon trough would be disastrous for hilly regions of India in terms of hydrometeorological disasters.

The active and break spells of monsoons over India are influenced by the North Hemisphere (NH) summer intra-seasonal oscillation, which impacts monsoon rainfall (Annamalai and Slingo, 2001).

Generally, a warmer environment suggests more rainfall, but climate change introduces anomalies in circulation fields, such as the Hadley and Walker circulations (tropical circulation weakens by about 10-15% with the lifting of the tropopause height over the twenty-first century in CMIP6 simulations) (Xia *et al.,* 2020; Wu *et al.,* 2021)**.** These anomalies, particularly over Central India, require further investigation. Historical observations indicate that regional Hadley circulation, driven by the North Atlantic Oscillation in the northern hemisphere and the Indian Ocean Dipole in the southern hemisphere, may influence Indian monsoon behavior. While these features are observed, climate models often do not capture these links due to inconsistencies in representing regional teleconnection features. It is important to explore the coupling mechanism of the ocean and atmosphere via the Hadley and Walker circulations in the tropics.

The expansion of greenhouse gases and aerosol forcing in the NH, along with stratospheric ozone depletion in the southern hemisphere, has led to a poleward shift of the subtropical edges of Earth's Hadley circulation during summer and monsoon seasons. This shift is evidenced by reanalyzed data from the past five to six decades, showing a contraction of the Hadley circulation by about 0.5º latitude per decade. The weaker winds and reduced monsoon circulation due to a warmer Indian Ocean in recent decades may have contributed to reduced rainfall in the latter half of the 20th century (Birner *et al.,* 2014)**.**

The active and break spells of monsoons over India are regulated by the NH summer intra-seasonal oscillation, which propagates north from the equator into the Indian monsoon region and substantially affects the monsoon rainfall. Thermodynamic scaling argument suggests more rainfall in a warm environment. However, in climate change scenario, the direction of anomalous change in circulation fields (Hadley and Walker circulations) and their relative strength, mainly over the Central India region requires further attention (Schwendike *et al.,* 2014). Historical observations suggest that regional Hadley circulation, via North Atlantic Oscillation in the northern hemisphere and Indian Ocean Dipole in the southern hemisphere (Tandon *et al*., 2013)**,** may have a role in the change in Indian Monsoon behaviour **(Figure 12)**. Such features though captured well in the observations, most climate models do not reproduce this link due to their inconsistency in representing regional teleconnection features (Hasanean *et al.,* 2023)**.** The coupling mechanism of ocean and atmosphere via the Hadley and Walker circulation in Tropics should be explored more thoroughly.

In response to increasing greenhouse gases (and aerosol forcing in NH while stratospheric ozone depletion in SH), the subtropical edges of Earth's Hadley circulation is reported to have shifted poleward during summer and monsoon seasons (March to August) as evidenced in ERA5 reanalysed data for the past five to six decades. The observed trends in the location of the NH Hadley cell edge and contraction of the Hadley circulation by about 0.5º latitude per decade is controlled by the transition from zonal-mean surface easterlies to zonal-mean surface westerlies, the subtropical sea level pressure maximum, the latitude of the subtropical jet, and the altitude break in tropopause height in the sub-tropics (Zhou *et al.,* 2019) [36]. The weaker winds and a reduced monsoon circulation due to a weakened tropical overturning circulation in the warmer Indian ocean during recent decade could have been responsible for observed decrease of rainfall during second half of the 20th century.

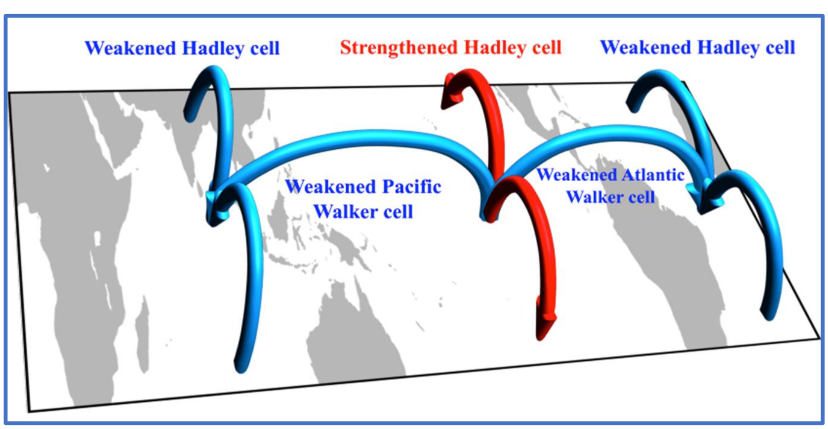

Fig. 12: Schematics of the perturbed Walker and Hadley circulations in association with El Niño, IOD and NAO

Multi-Scale Factors Affecting the Monsoon Variability at Varying Scales

The El Niño - Southern Oscillation (ENSO) is one of the most important tropospheric modes of variability that affects different regions around the globe through teleconnection. The ENSO's influence on Indian summer monsoon (ISM) is one of the most crucial one. It has been established since close to a century that India experiences less monsoon rainfall during El Niño years and more rainfall during La Niña years (Goswami and Xavier, 2005**.** Another strong influence on ISM comes from the North Atlantic Oscillation (NAO). From 1970s, the relationship between the ISM and ENSO has weakened but the NAO's influence on the ISM has enhanced. When the correlation between ENSO and ISM is weaker, the relationship between IOD and ISM is strengthened and vice versa.

The predictability of precipitation at seasonal timescales is typically associated with large-scale variability of sea surface temperature (SST), a principal forcing driver of global atmospheric circulation. Indian Ocean Dipole (IOD) and ENSO have complementarily affected the ISM during similar period such that when the correlation between ENSO and ISM is weaker, the relationship between IOD and ISM is strengthened and vice vers*a* (Ham *et al.,* 2017). Another strong influence on ISM on a regional scale comes from the North Atlantic Oscillation (NAO). When the relationship between the temperature of west Eurasia and ISM is stronger, the relationship between the ISM and ENSO has weakened. The connection between IOD, ISM and NAO are in favour of a linkage (Vittal *et al.,* 2020) that involves regional Hadley circulation and ITCZ.

A prominent pattern of variability in the Indian Ocean is a seesaw in sea surface temperature (SST) between the eastern and western sides of the Ocean basin, called the Indian Ocean Dipole (IOD). The anomalous SST gradient between the west and east equatorial Indian Ocean drives a dipole in equatorial precipitation anomalies and anomalous low-level circulation that would, in isolation, lead to a wetter than normal Indian summer monsoon across the monsoon season including June and September. Occurrences of IOD mostly result from coupled air–sea interactions in the tropical Indian Ocean (El Niño–Southern Oscillation in the tropical Pacific Ocean and has an interactive influence on the IOD) (Xiao *et al.,* 2022**.** A positive IOD event brings about warm and cold sea surface temperature (SST) anomalies in the tropical western and south-eastern Indian Ocean, respectively, while a negative IOD event does the opposite. IOD is recognized as a potential trigger of summer monsoon rainfall. Within the monsoon season, the mean structure of moisture convergence and meridional specific humidity distribution undergoes significant changes in contrasting IOD years, which in turn can influence the meridional propagation of north-south oscillations in the monsoon trough position and hence the related precipitation anomalies over India.

The Indian summer monsoon circulation over the tropical Indian Ocean provides a favourable triggering mechanism for the development of the IOD. Early onset of the Bay of Bengal summer monsoon triggers a positive IOD by inducing the equatorial easterly wind anomaly. Strong or weak Indian summer monsoon conditions induce stronger sea surface temperature anomaly amplitudes over the eastern and western poles of the IOD, respectively. Concurrently, equatorial easterly wind anomalies and northerly wind anomalies off the East Africa induce warming of the IOD western pole. Also, wind–thermocline–SST positive feedback contribute to the development of the IOD in summer and autumn. The Arabian Sea anomalous anticyclone, associated with a southeast-propagating Rossby Wave induced by the March NAO, is also important to IOD development. Considering the key role of the winter–spring NAO on the subsequent ENSO and the Indian summer monsoon and the close linkage between the ENSO as well as the Indian summer monsoon and the IOD, it is reasonable to infer that the preceding winter–spring NAO could influence the development of a subsequent IOD. However, just over the half (54%) of the positive IOD events are found to coincide with the positive March NAO events. The West North Pacific circulation anomalies linked to the March NAO are a key connection between the March NAO and subsequent IOD.

The non-stationarity of the climate system naturally appears in the simulations generated for climate projections by general circulation models, and it is especially important in the analysis of teleconnections. A changing climate may manifest even in local regime shifts and appearance of tipping cascades in such a coupled system. Such cascading events in the North Atlantic Ocean–ENSO system may cause qualitative changes also in local dynamics and in the teleconnections of the climate system (Levine *et al.,* 2017**.** Climate change can also result in chaotic synchronization between certain regions which behave as chaotic oscillators, e.g., implying a change in the relationship between the Atlantic, Indian and Pacific Ocean sectors. The question of whether the climate change during 2021–2100 has any impact on the strength of the teleconnections between the ENSO phenomenon and the alterations of ISM precipitation is also crucial for predicting the summer monsoon rains across Indian sub-continent **(Figure 13).** Interactions among the Pacific, Atlantic and Indian Oceans through ocean-atmosphere coupling can initiate and/or modulate climate variability and must be explored further.

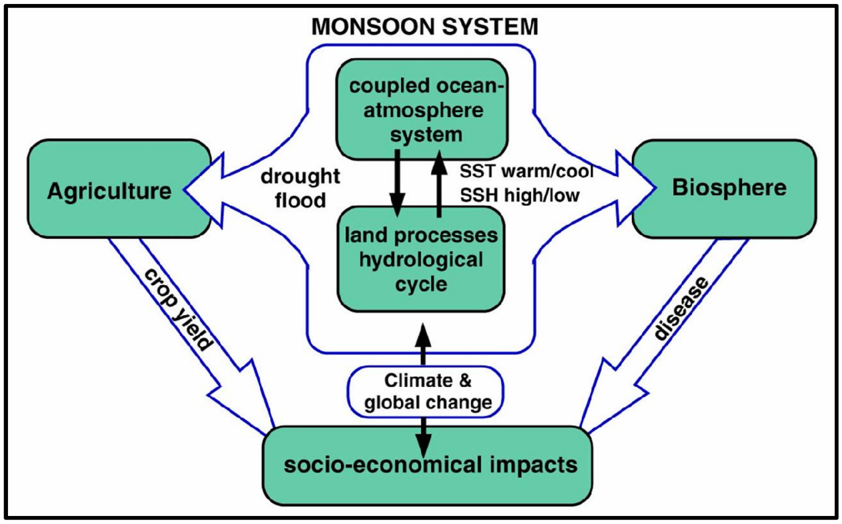

Fig. 13: A comprehensive understanding of the coupled ocean-atmosphere system is essential for accurately predicting the occurrence of a number of socially relevant climate impacts in India

Interannual variability of All India rainfall and the frequency distribution analyzed from state-of-the-art coupled global climate models (CMIP6) to derive robust signals reveals *no consensus among the model*s on the seasonal cycle of Indian summer monsoon rainfall and particularly for the early-stage monsoon rainfall onset (many questions remain regarding climate processes, including the location and strength of the ITCZ, Hadley circulation, and the influence of phenomena like El Niño and the Indian Ocean Dipole). Historical rainfall data in central India shows a decreasing trend in summer monsoon rainfall in the second half of the 20th century. However, CMIP6 models project a consistent increase in June-to-September mean rainfall under various future scenarios (Katzenberger *et al.,* 2020). Most climate models project increased rainfall, especially in the Himalayas, north-east Bay of Bengal, and the west coast of India. High interannual variability and an increased frequency of extremely wet years and high-intensity rainfall events are also anticipated (Falga and Wang, 2022). The robustness of these projections will depend on various factors, including the influence of greenhouse gases and aerosol forcing, the global circulation patterns associated with accelerating climate change, and the monsoon's sensitivity to these factors.

The Indian Ocean has warmed rapidly and notably at a faster rate than the other tropical ocean basins in the latter half of the twentieth century. Weakening in the monsoon circulation associated with a pair of anticyclonic anomalies straddling the equator in the low level with climate change could weaken the cross-equatorial monsoonal flow from the southern hemisphere. In the North Indian Ocean, there has been a decline in mean annual tropical cyclone numbers, with a more significant decrease after 1950, coinciding with the warming of the Indian Ocean. While tropical cyclones have become less frequent since 2001, the number of severe cyclones has increased, and modeling suggests that ocean heat content in the Indian Ocean will continue to rise due to anthropogenic CO_2 emissions. This will likely lead to more severe cyclones, storm surges, and heavy rainfall along the Indian coastline.

How will the Climate Disasters affect the Security & Livelihood in India?

Irrespective of the fact that accurate simulation of South Asian monsoon rainfall still remains a challenge in climate models, it is evident that the adverse impacts of climate change in India would include extreme heatwaves, erratic monsoons, heavy rainfall and cloudbursts, floods, severe droughts, and stronger cyclones bringing miseries to the most populated region of the world. From the drizzle for a week about a decade ago at any location, now we see intense rains for a day and dry weather for rest of the week. The observed warming has already given rise to heavy rainfall events and cloud bursts have tremendously increased over the years in the past two decades. An increase in the frequency of extreme rainfall is crucial not only for useful impact assessments and planning but for mitigation and adaptation too.

Climate change induced extreme climate events will take a toll on human health, security, livelihoods, and poverty levels, affecting different parts of India in various ways. Extreme rainfall events are projected to rise in intensity throughout the 21st century in the Himalayan-Tibetan Plateau region, particularly during the summer monsoon. The growing pace of urbanization in the hilly regions will also have unequal effects on citizens and infrastructure. The unplanned construction, urbanization and overdependence on tourism have already been wreaking havoc, further disturbing the ecological balance of nature. The deforestation for land use or construction purposes has also made the hill slopes fragile and unstable. With the rapid melting of glaciers in the Himalayas, abrupt floods are becoming common, causing significant harm to life and property. These glacier retreats are also resulting in the creation of glacial lakes due to elevated temperatures, which pose potential dangers of floods and landslides to the downstream population. With the increase in extreme rainfall events and several artificial obstructions due to construction and debris dumping, the behavior of Himalayan rivers is becoming unpredictable. As floods and droughts become more frequent and intense, poverty will worsen in some areas, especially as it impacts crucial crops like rice, leading to increased food prices and a higher cost of living for vulnerable communities. Compounded by the pressure stemming from rapid urbanization, industrialization, and economic growth in India, the consequences of these combined stresses will significantly impact the sustainable development prospects, putting immense pressure on our natural resources and environment.

Why Global warming must be halted?

The record-breaking temperatures across the globe this year are a stark reminder of climate change's harsh reality. Crossing the threshold of limiting global temperature rise to 1.5°C above pre-industrial levels could lead to more severe climate impacts. For more than a century, the world's appetite for fossil fuels has been expanding relentlessly and fossil fuel emissions have continued to increase. GHG emissions have climbed steadily over the past decade, reaching 59 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) in 2019 — approximately 12% higher than in 2010 and 54% greater than in 1990. Global warming is already causing widespread disruption worldwide, including droughts, extreme heat, record floods and storms, food insecurity, wildfires, the harming of species and ecosystems as well as the enabling of vector-borne disease transmission. We cannot address climate catastrophe without tackling its root cause: fossil fuel dependence. To keep the long-term temperature goal set out in article 2 of the Paris Agreement and limit global temperature rise to 1.5°C, countries need to significantly cut global emissions in half by the end of this decade. Global ambition stagnated over the past year and national climate plans are strikingly misaligned with the science. Under current national plans, global greenhouse gas emissions are set to increase 9% by 2030, compared to 2010 levels as the current policies point to at least 2.8°C warming by the end of the century. The science is clear: emissions must fall by 45% by the end of this decade compared to 2010 levels to meet the goal of limiting global temperature rise to 1.5 degrees. Any delayed climate action thus poses irreversible risks, with a narrow window of opportunity to realize a sustainable and liveable future. Every tenth of a degree of additional warming is bound to escalate threats to people, species and ecosystems across the globe.

Despite improvement in countries' mitigation and adaptation targets, and despite numerous corporate pledges to achieve net-zero emissions in the future, governments are literally doubling down on fossil fuel production (production targets of around 110% more fossil fuels by 2030). Global fossil-fuel subsidies jumped to a record $7 trillion in the year 2022 while many countries plan to keep increasing coal production until 2030, and oil and gas production decades beyond that. With 151 countries and 257 cities having announced net-zero targets, it is clear that much of society now understands the need to achieve net-zero carbon dioxide emissions by mid-century in order to limit dangerous warming. However, the world's most comprehensive public database on the industry reveals a bleak picture for the future of coal with only 71 companies out of 1,433 operating along the thermal coal value chain, announcing coal exit dates. Many major fossil-fuel-producing governments are still planning near-term increases in coal production and long-term increases in oil and gas production. These projections would lead to an increase in global production until 2030 for coal, and until at least 2050 for oil and gas, creating increasingly large production gaps over time.

Renewables are set to play a central role, constituting nearly half of the world's energy mix-a historic milestone. However, perhaps a sole reliance on renewables won't suffice as demand for oil, gas, and coal will peak sooner than anticipated although fossil fuel phaseout is inevitable to ensure the global temperature remains within the 1.5°C target set by the Paris Agreement. We need credible commitments to ramp up renewables, phase out fossil fuels, and boost energy efficiency, while ensuring a just, equitable transition. Urgent action is needed to reduce greenhouse gas emissions, and available technologies can help achieve net-zero emissions. It's time therefore to break our addiction to fossil fuels and invest in a just and equitable transition. Developed countries must commit to reaching net-zero emissions as close as possible to 2040 and large emerging economies as close as possible to 2050 with support from developed countries to do so. A decisive action against the relentless expansion of coal, oil, and gas required the urgency for governments to adopt a Fossil Fuel Non-Proliferation Treaty in COP28 in November 2023 *for a safe, sustainable and fair future*. The final declaration in COP28 stated, however, that the world should "transition away from fossil fuels in energy systems, in a just, orderly and equitable manner, accelerating action in this critical decade, so as to achieve net zero by 2050." Perhaps, COP28 has signalled the beginning of the end of the "fossil fuel era" establishing the foundation for transition to renewables as this was the first time the term "fossil fuels" appeared in a COP formal outcome since UN climate negotiations began 30 years ago. None-the-less, in pathways that limit warming to 1.5ºC with no or limited overshoot global use of coal must fall by 95% by 2050, oil to decline by about 60% and gas by about 45%. However, UAE's state energy company ADNOC confirmed it would continue to expand oil and gas production, and COP29 host Azerbaijan plans to boost its fossil fuel production by a third over the next decade. Meanwhile, despite its significant progress on expanding renewable energy, India also plans to double coal production to meet its energy demand for sustained development and economic growth. Furthermore, all major oil companies have continued to rely almost exclusively on extraction of fossil fuels and expand their operations to meet the demand of industrial economies while multiplying their profits. Perhaps, governmental environmental regulation alone will not force fossil fuel companies to change their business model, and a deeper political change that challenges the postcolonial and extractive nature of developed countries is needed to spell the end of the fossil fuel era. Power generation, buildings, industry, and transport are responsible for close to 80% of global emissions while agriculture, forestry and other land uses account for the remainder. Deep emission cuts are now warranted across all of society to combat the climate crisis.

COP28 in Dubai saw an encouraging slate of actions to address methane pollution, a greenhouse gas 20 times more powerful than carbon dioxide. A historic agreement on loss and damage funding with commitments exceeding USD 600 million was also made to help vulnerable communities recover from adverse climate impacts. Countries agreed to halt and reverse deforestation (biodiversity conservation) and pledged for methane reduction by 2030, and on targets for the Global Goals on Adaptation, enhancing efforts to strengthen resilience to the effects of a changing climate. Moving forward, countries need to show greater ambitions in their 2025 national climate action plans (NDCs) with transformative domestic legislation and policies, including ramping up renewables and fossil-free transport and tamping down fossil fuels at every turn. This is true for countries such as Canada, China, Egypt, India, New Zealand and South Korea, whose climate policies and emission mitigation commitments towards limiting the global warming to 1.5ºC at par with the Paris Agreement are highly insufficient for effective climate action.

India has experienced an unparalleled growth rate of urbanization over the past three decades which influenced the characteristics of seasonal precipitation in India. Unprecedented changes in urbanization, irrigation practices, and land usage have also brought discernible changes in regional rainfall (increase of mean daily rainfall and possible extreme events) over India. Impacts of climate change are already occurring, and both physical and socioeconomic thresholds are being exceeded calling for having concurrent governance efforts to both adapt to climate change and mitigate greenhouse gas emissions. They also reinforce the reality that engaging now in anticipatory adaptation is the best chance of avoiding a break-down in democratic governance. Urban Heat Islands phenomenon needs climate adaptation, heat stress mitigation, and an understanding of urban micro-climates influencing non-stationary characteristics of rainfall extremes while transitioning from rural to urban areas. The country must accelerate efforts to respond to climate change risks, particularly related to water resources, to avoid the higher costs of delayed adaptation. Large-scale resilience building is needed to address the combined effects of climate change, increased water demand, and environmental pollution in India. Large winter snowfall deficits across the northern regions of Ladakh, Jammu & Kashmir, Himachal Pradesh and Uttarakhand such as those observed in India early this year has become a concern as winter snow feeds the glaciers which, during the summer months, slowly release water that rejuvenates springs, feeds the rivers and also provides water for irrigation. Once warming hits a certain threshold, the snowpack in the Himalayas is set to diminish in nonlinear fashion with each additional degree of warming, disappearing faster and the receding glaciers around steep slopes would become highly vulnerable and become hotspots for disasters such as GLOFs. The urgency of addressing climate change and its impacts on the HKH region and beyond highlights the importance of mitigation efforts to reduce emissions and adaptation measures to build resilience in the face of a changing climate. Additionally, it emphasizes the need for active involvement of communities in disaster risk reduction and sustainable livelihood.

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