Advancing South Asian monsoon climate change projections: Challenges and opportunities

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Advancing South Asian monsoon climate change projections: Challenges and opportunities

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ABSTRACT

The significance of regional monsoon systems for water resources, agriculture and the economy cannot be overstated, which points to the fact that developing reliable projections of monsoon precipitation in a changing climate is central to formulating policy. However, regional monsoons are characterized by strong internal variability and their dynamics include contributions both from global climate drivers and complex local processes, which are not fully understood. Therefore, robust attributions of human influence on changes in regional monsoon precipitation are inherently challenging. In this article, we discuss the observed and projected changes in the South Asian monsoon, and the sources of uncertainty in these projections. We also discuss avenues for improving monsoon projections by a balanced approach involving basic research, building next-generation climate models and exploiting emerging techniques such as machine learning. We also suggest that the strategies for advances in this area must include specialised educational programmes in meteorology and climate science at the undergraduate level and beyond.

INTRODUCTION

Monsoon systems across the globe are characterized by strong seasonal reversals of wind and precipitation between the local summer and winter (Wang et al., 2021). Regional monsoon systems constitute a key component of the global water cycle and are crucial for sustaining agricultural operations, power-generation, ecosystems and livelihoods of more than two-thirds of the Earth's population (IPCC, 2014a,b; Krishnan et al., 2020; Wang et al., 2021). Excess and deficient monsoon precipitation years have seen major impacts on food and water security in several regions among other impacts (Gadgil and Gadgil, 2006; Swaminathan and Kesavan, 2012; de Carvalho and Jones, 2016; Dhara and Krishnan, 2020). For these reasons, one of the most societally pertinent questions in the context of anthropogenic climate change is: "what will be the future response of the regional monsoons to the rapid changes in atmospheric composition brought about by human activities*?"* This question poses a fundamental challenge for climate science because of the inherent complexities of the precipitation dynamics of the regional monsoons, their response to a variety of natural and human-induced forcings, as well as the coupled feedback mechanisms of the individual monsoon systems on different space and time scales (Mohtadi et al., 2016; Biasutti et al., 2018). This article discusses the observed and projected changes in the South Asian summer monsoon (SAM), uncertainties and key scientific challenges, as well as the opportunities and avenues to advance our skill of the SAM projections in a changing climate.

SOUTH ASIAN MONSOON CLIMATE CHANGE

The annual cycle of solar insolation initiates the SAM circulation and cross-equatorial winds during the late pre-monsoon and early summer monsoon months by setting up a large-scale land-sea thermal contrast and north-south pressure gradient between the Indian landmass and the subtropical Indian Ocean (Figure 1a); and this large-scale setup is subsequently maintained by vigorous feedback between the moist winds and latent heat, release by the monsoon cloud systems through the boreal summer monsoon (June-September) season (Krishnamurti and Surgi, 1987; Webster et al., 1998; Gadgil, 2003; Turner and Annamalai, 2012). The monsoon winds enhance evaporation and moisture fluxes from the adjoining Indian Ocean, Arabian Sea and Bay of Bengal, leading to build-up of moist-static energy, moist convection, organized cloud systems and release of latent heat of condensation in ascending moist motions over the Indian subcontinent and adjoining areas, in turn reinforcing the continental-scale monsoon winds and large-scale monsoon overturning circulation (Krishnamurti and Bhalme, 1976; Webster et al., 1998; Boos and Emanuel, 2009; Nie et al., 2010; Choudhury and Krishnan, 2011; Turner and Annamalai, 2012; Rajagopalan and Molnar, 2013; Mohtadi et al., 2016). In short, the SAM is a convectively coupled phenomenon wherein moist convection couples the large-scale monsoon circulation and precipitation.

Observed and future projected changes

Natural and anthropogenic forcing are recognized as drivers of long-term variability and change in the SAM as evidenced in observations, paleoclimate records and climate model simulations (IPCC, 2013; Kitoh et al., 2013; Braconnot et al., 2019; Wang et al., 2020; Krishnan et al., 2021). Interannual-to-multi-decadal variations and long-term changes in the SAM precipitation have been extensively documented using paleoclimate data (Sinha et al., 2015, 2018; Mohtadi et al., 2016; Nagoji and Tiwari, 2017).

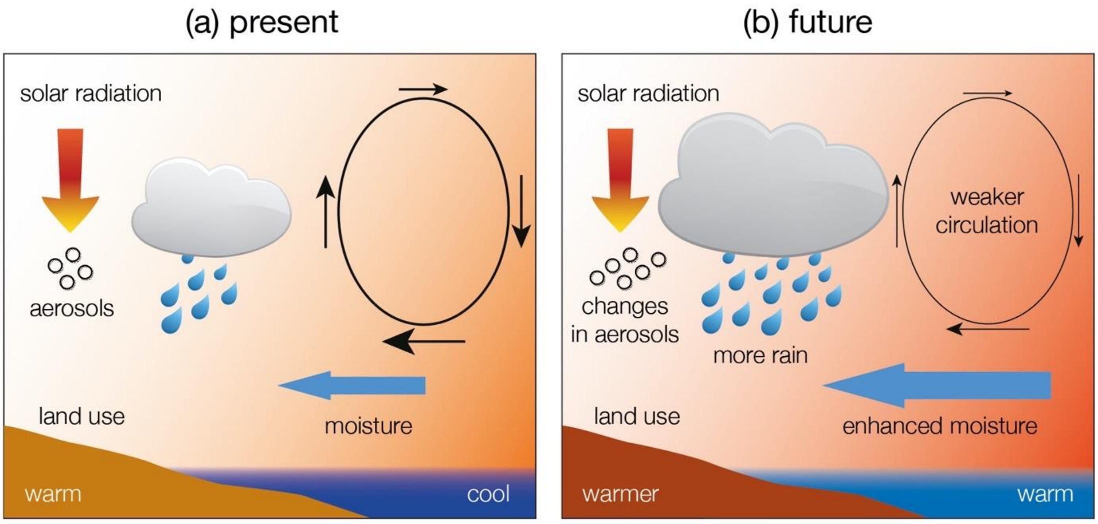

Figure 1. Schematic diagram illustrating the main ways that human activity influences monsoon rainfall. As the climate warms, increasing water vapour transport from the ocean into land increases because warmer air contains more water vapour. This also increases the potential for heavy rainfalls. Warming-related changes in large-scale circulation influence the strength and extent of the overall monsoon circulation. Land use change and atmospheric aerosol loading can also affect the amount of solar radiation that is absorbed in the atmosphere and land, potentially moderating the land–sea temperature difference. Adapted from IPCC AR5.

Periodic changes in the Earth's orbital parameters are recognized as key drivers of monsoon precipitation changes through their influence on the magnitude and hemispheric distribution of solar insolation. A noteworthy example is the intensification of the West African and SAM during the early-to-mid Holocene (approximately 9000 to 6000 years before present, BP) in response to the enhanced northern hemispheric summer solar insolation, as evidenced from paleoclimate records and climate model simulations (Kutzbach, 1981; Claussen and Gayler, 1997; deMenocal et al., 2000; Mohtadi et al., 2016; Braconnot et al., 2019). There is also evidence that the SAM weakened, while the winter monsoon strengthened, during cold climatic epochs, such as the last glacial maximum about 18000 years before present (Sarkar et al., 1990). In addition to orbital forcing, regional monsoon precipitation changes can be influenced by changes in vegetation and land cover, atmospheric aerosols, modes of climate variability such as the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and the Indian Ocean Dipole (IOD) on different time-scales, involving a variety of feedback mechanisms (Mohtadi et al., 2016; Krishnan et al., 2016; Kulkarni et al., 2020).

While orbital forcing is an important driver of climate variability on paleo time-scales, human activities have been largely responsible for observed climate change since the 19th century and are expected to influence future climate (IPCC, 2013). Burning of fossil fuels, deforestation, and land use land cover changes, among other human (anthropogenic) activities, have led to a rapid increase of atmospheric greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases, which are known to trap the radiation emitted by the Earth and warm the planet. In particular, CO_2 which is the main long-lived GHG in the atmosphere increased from 280 parts per million during 1850 to over 415 parts per million on average in 2021. It is virtually certain that the approximate 1.1°C warming of the Earth's surface during the last 150 years has been driven largely by anthropogenic forcing (IPCC, 2021). A direct consequence of rising surface temperatures is the increase of atmospheric water vapor content at a rate of about 7% for each 1-K increase in temperature (Held and Soden, 2006), which is expected to intensify the SAM precipitation due to enhanced moisture convergence (Kitoh et al., 2013).

Contrary to expectations, however, the SAM precipitation has declined significantly since the middle of the 20th century by about 6% in the period 1950 – 2015 (Bollasina et al., 2011; Krishnan et al., 2013, 2016, 2020; Roxy et al., 2015; Kulkarni et al., 2020). There is a growing consensus that increases in anthropogenic aerosol loading over the Northern Hemisphere has contributed significantly to this decline of SAM precipitation by offsetting the expected precipitation enhancement due to GHG forcing

(Bollasina et al., 2011; Polson et al., 2014; Krishnan et al., 2016; Undorf et al., 2018; Ayantika et al., 2021; Douville et al., 2021). Aerosol forcing tends to offset warming by GHGs by cooling the surface through scattering or absorption of solar radiation (direct effect) or by enhancing cloud formation (indirect effect) (Myhre et al., 2013). Additionally, aerosol-induced surface cooling and atmospheric absorption above the boundary layer tends to decrease evaporation and moisture fluxes by slowing down the low-level winds through increased static stability, in turn leading to decreases in the SAM precipitation (Ayantika et al., 2021). In addition to anthropogenic aerosols, land use and land cover changes over south and southeast Asia since the 19th century, and the rapid warming trend of the equatorial Indian Ocean seem to have influenced the decrease of SAM precipitation during recent few decades (Roxy et al., 2015; Singh, 2016; Krishnan et al., 2016).

With continuation of global warming and reductions in anthropogenic aerosols, the SAM precipitation is projected to increase during the 21st century as seen from the Coupled Model Inter comparison Project – Phase 5 (CMIP5) multi-model projections (IPCC, 2013; Kitoh et al., 2013; Kitoh, 2017; Kulkarni et al., 2020), and also the latest CMIP6 multi-model projections (Douville et al., 2021; Krishnan et al., 2021; Wang et al., 2021), which is indicative of the precipitation response to increases in moisture content with warming under various emission scenarios. Here, it is important to mention that a large spread is noted in the projected SAM precipitation across CMIP5 and CMIP6 models (Wilcox et al., 2020; Wang et al., 2021), as with projections over most land monsoon domains (Figure 2).

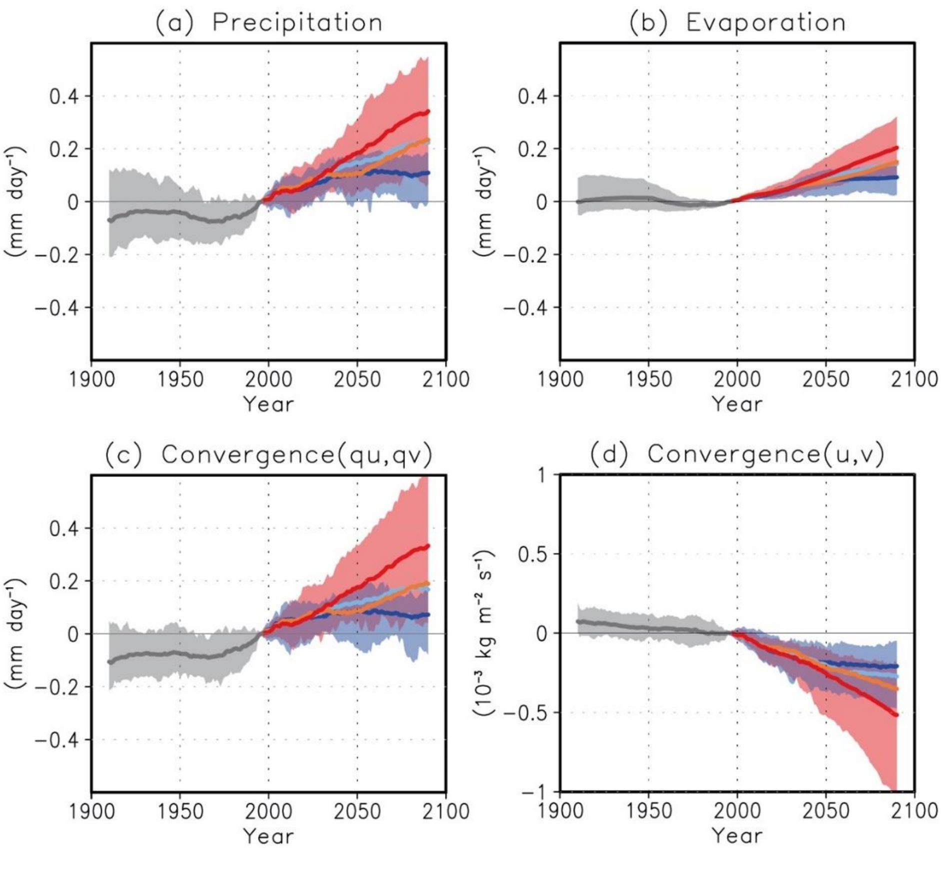

Figure 2. Time series of simulated anomalies, smoothed with a 20-year running mean over the global land monsoon domain for **(a)** precipitation (mm day^{-1}), **(b)** evaporation (mm day^{-1}), **(c)** water vapour flux convergence in the lower (below 500 hPa) troposphere (mm day^{-1}), and **(d)** wind convergence in the lower troposphere (10^{-3} kg m^{-2} s^{-1}), relative to the present-day (1986–2005), based on CMIP5 multi-model monthly outputs. Historical (grey; 29 models), RCP2.6 (dark blue; 20 models), RCP4.5 (light blue; 24 models), RCP6.0 (orange; 16 models), and RCP8.5 (red; 24 models) simulations are shown in the 10th and 90th percentile (shading), and in all model averages (thick lines). Adapted from IPCC AR5.

Natural versus anthropogenic response

The SAM exhibits a rich variety of natural variability on different time scales ranging from intra-seasonal to multi-decadal, which are seen in past climate reconstructions inferred from paleoclimate proxies and instrumental records (Turner and Annamalai, 2012; Sinha et al., 2015; Mohtadi et al., 2016). Variations in the SAM precipitation are known to arise in response to natural external forcing such as orbital changes and volcanic eruptions, as well as the influence of various modes of climate variability on different time-scales involving teleconnections to sea surface temperatures (SSTs) variations in the Pacific, Atlantic and Indian Oceans and large-scale atmospheric circulation variations (Turner and Annamalai, 2012; Mohtadi et al., 2016; Kulkarni et al., 2020; Roxy et al., 2020; Singh et al., 2020; Wang et al., 2021).

Following the industrial revolution, the world experienced an exponential rise in the use of physical resources, including that of fossil fuels (Dhara and Singh, 2021). The attendant changes in the atmospheric concentration of GHGs and aerosols along with changes in land use and land cover (LULC) from agricultural expansion and urbanisation through human activities, are key drivers of anthropogenic global climate change. Enhanced absorption of terrestrial long wave radiation by the increasing concentration of atmospheric GHGs has caused a radiation imbalance i.e. radiative forcing (RF), of over 3.1 Wm^{-2} at the top of the atmosphere https://www.esrl.noaa.gov/gmd/aggi/aggi.html).

While the IPCC AR5 estimated the aerosol effective RF to lie in the range of – 0.1 to – 0.19 Wm^{-2} (excluding black carbon on snow and ice) in the global mean, there are uncertainties in the aerosol RF at regional scales arising due to large spatio-temporal variations (Nair et al., 2017; Fadnavis et al., 2020). The radiative impacts of these changes have become increasingly important in driving changes in climate over the past century, and are expected to be dominant drivers of global and regional climate change during the 21st century (IPCC, 2013; Krishnan et al., 2020).

Since the 1950s a declining trend in the monsoon precipitation over India has emerged (Guhathakurta and Rajeevan, 2008; Roxy et al., 2015; Krishnan et al., 2016; Ayantika et al., 2021). Concurrently, a weakening trend of the large-scale monsoon circulation has also been identified during the same period (Krishnan et al., 2013). These changes have been studied extensively in recent years to detect and attribute the possible contribution of anthropogenic forcings (Ramanathan, 2001; Shukla et al., 2014; Cook et al., 2015; Krishnan et al., 2016; Singh et al., 2019). Recent theoretical work suggests greater sensitivity of precipitation changes to solar forcing (e.g., the aerosol direct effect) than to longwave forcing (e.g., GHG radiative effect) (Dhara, 2020). The net effect of aerosol loading over the subcontinent is to cool the surface and might have masked over half of the warming by GHGs alone (Krishnan and Ramanathan, 2002; Dileepkumar et al., 2018). Scattering aerosols reduce the column solar energy absorption while absorbing aerosols tend to increase the static stability, inhibiting convection and leading to a decrease in cloud cover (Wild et al., 2004; Wild, 2012, 2017; Undorf et al., 2018; Ayantika et al., 2021). There is increasing consensus that forcing due to northern hemispheric anthropogenic aerosols, in particular, may have played a significant role in the declining SAM precipitation since the mid-20th century, by counteracting the increase in precipitation expected from the rise in GHGs (Bollasina et al., 2011; Polson et al., 2014; Krishnan et al., 2016; Undorf et al., 2018).

There is considerable spread, however, across CMIP5 models in the magnitude of the aerosol-induced SAM precipitation decrease (Undorf et al., 2018). Furthermore, accurate estimation of the anthropogenic forced signal in the observed SAM precipitation changes is intrinsically challenging in view of the large natural variability of the climate system (Salzmann and Cherian, 2015).

Uncertainties

Given that the anthropogenic signals of regional monsoon change are mixed with the large natural variability, future projections of the Indian monsoon are inherently saddled with multiple uncertainties. Quantifying and reducing these uncertainties are important to improve the accuracy of projections, particularly at regional scales. Previous studies (Hawkins and Sutton, 2009; Terray and Boé, 2013) have identified three major sources of uncertainties in the future projections: (i) internal variability, (ii) model uncertainty, and (iii) scenario uncertainty. These are discussed below.

Internal variability and teleconnections

While anthropogenic drivers of global climate change have become increasingly important over the past century, the backdrop of large intrinsic natural variability poses a major scientific challenge in attribution of anthropogenic forcing to the observed monsoonal changes. Adding to this complexity is that the ocean SSTs and circulation themselves respond strongly to anthropogenic changes such as warming and ice melt. It is therefore vital to deepen our understanding of the sensitivity of the monsoon to the major natural drivers so that we may be able to better attribute the observed changes to anthropogenic forcing, and thereby improve the accuracy of projections for the future.

The SAM precipitation variations on different time-scales have linkages to several modes of natural variability (Kulkarni et al., 2020). Large interannual and decadal scale variability is evident in the observational record of the SAM going back over 150 years (Kripalani and Kulkarni, 2001; Preethi et al., 2017). These are closely linked to SST patterns associated with phenomena such as the El Niño Southern Oscillation (ENSO) (Kumar et al., 2006; Mishra et al., 2012), the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002; Krishnan and Sugi, 2003), and the Indian Ocean Dipole (IOD) (Saji et al., 1999; Yamagata et al., 2003 among others).

The ENSO, corresponding to periodic oscillation of the west-east SST gradient in the Pacific, is a leading mode of interannual variability of the SAM with a periodicity between 2–7 years (Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983). The El Niño phase of ENSO refers to an anomalous warming of the equatorial eastern-central Pacific decreasing the west-to-east SST gradient and shifting the rising branch of the Walker circular to the central/eastern part of the tropical Pacific. El Niño events are generally associated with suppressed SAM precipitation and monsoon droughts over India (Mujumdar et al., 2020). The relationship between ENSO and SAM precipitation appears to have weakened in recent decades with possible connections to global warming (Kumar et al., 1999; Azad and Rajeevan, 2016; Kulkarni et al., 2020). Understanding the evolution of ENSO-SAM linkages in a warming world will be central to improving the accuracy of monsoon projections.

Furthermore, decadal-scale variations of global monsoon are closely tied to the PDO, which is characterized by large-scale SST anomalies in the tropical and extra-tropical Pacific with a time-scale of about 15– 25 years (Mantua and Hare, 2002). The 'warm phase' of the PDO has been suggested as negatively impacting the summer monsoon rainfall (Krishnan and Sugi, 2003). However, a new study by (Mann et al., 2021) has argued that interdecadal 'oscillations' in the Atlantic and the Pacific, instead of being independent modes of variability, may instead be manifestations of SST changes brought about volcanic eruptions. While more evidence may be necessary to validate the conclusions in Mann et al. (2021), it is clear that improving the projections of ENSO and PDO in a warming world is central for improving the accuracy of SAM near-term projections (Huang et al., 2020).

Model uncertainties and biases

While weather and climate models make predictions by simulating the evolution of the atmosphere and oceans from the initial state into the future, physical processes operating at smaller spatial scales (i.e., less than size of the model grid) require to be parameterized in terms of large-scale variables (Palmer ,2001). A major bottleneck in climate models is the realism of representing sub-grid moist atmospheric convection – a key process that shapes climate and hydrologic sensitivities, but is yet poorly understood (Emanuel, 1997; Sherwood et al., 2014a); inadequacies in its representation constitute a dominant source of error in global models (Jung et al., 2010). A prominent manifestation of this inadequacy is the large simulated range in climate sensitivity that has afflicted successive generations of climate models for the past five decades (Sherwood et al., 2014b; Eyring et al., 2016). It is anticipated that improvements in parameterization schemes should lead to better representations of tropical convection, and eventually lead to more reliable projections of future changes (Willetts et al., 2017).

Another important source of model uncertainty arises from aerosol-cloud interactive processes. Aerosols are micron sized solid or liquid suspended particles of both natural and anthropogenic origins. These include dust, sea spray, pollen, black carbon, sulphates and nitrates. The *direct* effect of aerosols is largely due to the scattering or absorption of solar radiation. Being heavier than GHGs, aerosols are not well mixed in the atmosphere, and as a result, aerosol RF is highly heterogenous in space and time (Penner et al., 2001).

Aerosols additionally act as 'cloud condensation nuclei' (CCN) around which water vapour can condense and coalesce to form clouds. The presence of aerosols in the atmosphere can change cloud properties substantially. For instance, an increase in CCN produces more cloud droplets of smaller size, increasing its efficiency in scattering solar radiation – an effect known as the cloud-albedo feedback or the first indirect effect of aerosols. Clouds are also efficient black body absorbers of longwave radiation which makes changes in their physical properties such as size and lifetime strongly modulate the greenhouse effect. Thus, aerosol interactions with clouds fundamentally alters the radiation budget in both shortwave and longwave regions of the electromagnetic spectrum. The microphysics of aerosol-cloud interactions is however highly complex and large uncertainties remain in quantifying how these interact with each other and affect the climate system (Stevens and Feingold, 2009). The major societally pertinent question is, how will changes in aerosol loading in the future affect the monsoon? One of the most important and challenging scientific questions confronting us today is to refine our understanding of aerosol-cloud interactions and how these may be better simulated in Earth System Models (Stevens and Feingold, 2009).

Scenario uncertainties

Scenario uncertainty arises from the fact that future emissions trajectories are unknown since they involve a host of unpredictable factors (IPCC, 2013). Kirtman et al. (2014) noted that the contribution of the scenario uncertainty to near-term projections is dwarfed by the uncertainty due to internal variability and model spread.

OTHER UNCERTAINTIES: VOLCANIC ERUPTIONS

Large volcanic eruptions are considered one of the most important natural forcings driving interannual-to-decadal scale variability of temperature and hydrological cycle (Sigl et al., 2015). Since eruptions cannot be predicted in advance, they may be considered an additional source of uncertainty that may affect climate on interannual-to-decadal timescales. The main effect of large, explosive volcanic eruptions is to inject sulphate aerosols into the stratosphere which scatter a part of the incoming solar radiation and cause planetary cooling of the surface over a timescale of 2-3 years. As the cooling is generally more prominent over land, a weaker summer monsoon circulation should result from the reduced land-sea thermal gradient. Explosive eruptions may additionally cause a reorganization of the Hadley cell and a shift of the ITCZ away from the cooling Hemisphere (Ridley et al., 2015). While these simple theoretical arguments appear compelling, models and paleoclimate evidence provide a conflicting picture. While models suggest that large volcanic eruptions favour a weaker East Asian monsoon circulation, tree-ring data of the past 750 years suggest an anomalously wet southeast Asia in the year of the eruption (Anchukaitis et al., 2010; Man et al., 2014). Paleo-proxies also reveal a strong phase synchronisation between the SAM precipitation variations and ENSO, following large volcanic eruptions (Singh et al. 2020). The ENSO, being one of the major modes of interannual variability of the global hydrologic cycle, has particularly important implications for the behaviour of the monsoon following large volcanic eruptions.

KEY SCIENTIFIC ISSUES

Considerable progress has been made in recent decades in understanding the influence of natural and anthropogenic drivers of change in global and regional climate (IPCC, 2013; Krishnan et al., 2020). There has been a gradual improvement in simulating the SAM by successive generations of climate models, yet systematic biases and uncertainties afflict models across generations, such as the large dry bias in the summer monsoon precipitation in the previous generation of climate models (CMIP5) (Annamalai et al.. 2007, 2017; Sperber et al.. 2013), which persists in the latest generation CMIP6 models, although considerably reduced (Gusain et al., 2020; Wang et al., 2020). Improvements in CMIP6 are prominent in simulating stronger orographic rainfall in the Western Ghats while also appearing to capture the seasonal climatology better than CMIP5 models. However, these improvements are not consistent across models (Racherla et al., 2012).

There is also a persistently wide spread in projections of future changes in the SAM precipitation across models, which poses difficulties in policy making (Sperber et al., 2013; Wilcox et al., 2020; Almazroui et al., 2020). These biases and spread are a manifestation of the substantial knowledge gaps that remain in our understanding of fundamental processes affecting the regional climate. In the following sections, we will discuss two key aspects viz., monsoon circulation and large-scale gradients in the tropical SST, that are very relevant for advancing our understanding of the regional monsoon climate change.

Monsoon circulation change

Despite a projected increase in the mean monsoon precipitation with continued global warming during the 21st century, most of the climate models indicate a weakening of the SAM circulation strength which is compensated by a rapid increase in atmospheric moisture content with warming (Figure 2c,d) (Annamalai et al., 2007; IPCC, 2013; Krishnan et al., 2013; Kitoh, 2017; Wang et al., 2021). Held and Soden (2006) used simple thermodynamic principles to suggest that the strength of the tropical circulation would reduce with global warming. This theoretical argument and model outcomes suggest a general weakening of the SAM circulation in the future (Figure 1b). An exception to the circulation-weakening response of most models to warming is an atmosphere-only GCM with telescopic zooming over the subcontinent (grid size < 35 km), which showed a strengthening of monsoon circulation response to GHG warming (Krishnan et al., 2021). A GHG-only historical experiment with this model simulated a robust increase in the strength of the monsoon circulation suggesting that coarse resolution models may be over-emphasizing thermodynamic effects at the expense of important dynamical effects such as the coupled variability of the orographic precipitation in the Western Ghats and large-scale monsoon winds (Krishnan et al., 2016, 2021).

Sabeerali et al. (2015) reported that CMIP5 models produce excessive convective precipitation over the SAM environment arising from large biases in simulating stratiform and convective precipitation-types. It is also known that erroneous representation of monsoon convective and stratiform precipitation-types introduce large biases in the vertical structure of latent heating and the associated monsoon and tropical circulation response (Ramanathan et al., 2001; Schumacher et al., 2004; Romatschke and Houze, 2011; Choudhury and Krishnan, 2011). Given the systematic errors in representing cumulus convection in CMIP5 models (Sabeerali et al., 2015), the large-scale monsoon circulation response to global warming remains unclear, as yet. This is an important topic warranting further scientific research.

Large-scale SST gradients and tropical circulation

In line with the hypothesized weakening of tropical large-scale circulation in response to global warming (Held and Soden, 2006), generations of global climate models have projected a weakening of the Pacific tropical west-to-east SST gradient and the associated Walker circulation in a warming world (Knutson and Manabe, 1995; Vecchi et al., 2006; IPCC, 2013) (Figure 3).

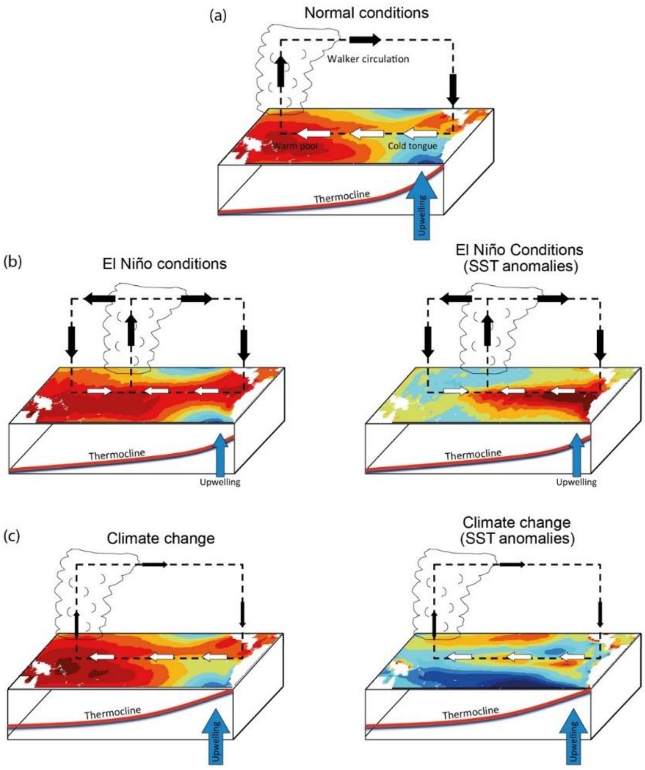

Figure 3. Idealized schematic diagrams showing atmospheric and oceanic conditions of the tropical Pacific region and their interactions during normal conditions, El Niño conditions, and in a warmer world. **(a)** Mean climate conditions in the tropical Pacific, indicating sea surface temperatures (SSTs), surface wind stress and associated Walker Circulation, the mean position of convection and the mean upwelling and position of the thermocline**.** **(b)** Typical conditions during an El Niño event. SSTs are anomalously warm in the east; convection moves into the central Pacific; the trade winds weaken in the east and the Walker Circulation is disrupted; the thermocline flattens and the upwelling is reduced. **(c)** The likely mean conditions under climate change derived from observations, theory and coupled General Circulation Models (GCMs). The trade winds weaken; the thermocline flattens and shoals; the upwelling is reduced although the mean vertical temperature gradient is increased; and SSTs (shown as anomalies with respect to the mean tropical-wide warming) increase more on the equator than off. Diagrams with absolute SST fields are shown on the left, diagrams with SST anomalies are shown on the right. For the climate change fields, anomalies are expressed with respect to the basin average temperature change so that blue colours indicate a warming smaller than the basin mean, not a cooling (Collins et al., 2010). Adapted from IPCC AR5.

In nature, however, what has transpired during the past century has been the opposite. Reconstructions of Pacific SSTs in the period 1900 – 2013 have revealed an increasing trend in the west-east Pacific SST gradient (Coats and Karnauskas, 2017). While models overwhelmingly simulate a weakening SST gradient over the same period, even the minority of models simulating an increasing trend were found to have magnitudes much less than the reconstructions. An important caveat, however, is that it is yet unclear whether the increasing gradient in the observational datasets has a significant contribution from anthropogenic forcing. Recently, Seager et al. 2019 revisited the fundamental dynamics of the tropical ocean-atmosphere system with simplified models to argue that correcting for a systematic bias in state-of-the-art models make their simulations consistent with the observed strengthening of the tropical Pacific west-to-east SST gradient. According to the authors, the erroneous trends in present climate models are the result of a systematic cold bias across models in the equatorial cold tongue, a strip of relatively cool water stretching along the equator from Peru into the central Pacific. While a greater anthropogenic signal may be necessary to evaluate these arguments, it is clear that these developments raise concerns about the accuracy of future projections by state-of-the-art models. Determining how the large-scale tropical SST gradients and circulation will change with global warming is of particular significance for tropical precipitation systems that are most affected by the Pacific SST variations, including the SAM.

Opportunities and avenues for improving monsoon projections

Improving the reliability of monsoon projections is contingent on improving the representation of key physical processes in climate models. A balanced strategy combining developments in theory, observations and modelling with emerging techniques such as machine learning would help advance this goal (Held, 2005; Palmer and Stevens, 2019; Reichstein et al., 2019; Emanuel, 2020; Wedi et al., 2020). We pick a concrete example to illustrate the utility of such an approach – improving the convective parameterization in climate models.

Basic research

Advancing the representations of sub-grid-scale cumulus convection in weather and climate models is an inherently challenging issue given the complexities of coupling among several key elements of moist convection viz., surface fluxes, sub-grid scale turbulence, mid-tropospheric moisture, clouds, latent heating, large-scale circulation; while parameterization schemes used in numerical models depend on many parameters that are not well constrained by observations (Emanuel, 2019). Basic research involving a combination of theoretical approaches and observations is therefore essential for developing conceptual understanding that is required for improving the realism of cumulus convection in numerical models. Likewise, improving the treatment of stratiform and convective precipitation systems in climate models (Romatschke and Houze, 2011; Choudhury and Krishnan, 2011), as well as warm rain processes, orographic precipitation, cloud-aerosol microphysics and land-atmosphere interactions (Konwar et al., 2014; Utsav et al., 2017; Shige et al., 2017; Barton et al., 2020) is crucial for refining the representation of monsoon precipitation dynamics.

Machine learning

Recent advances in data analysis and machine learning (ML) together with the deluge of observational data of the past few decades have opened new opportunities to obtain insights into climate system processes, including improved parameterization of unresolved processes (Reichstein et al., 2019). Proof-of-principal studies have demonstrated that neural networks trained on observed data, or on the output of high-resolution convection permitting models can be used to improve the representation skill of unresolved moist convection in coarse resolution models (Gentine et al., 2018; Rasp et al., 2018; Brenowitz and Bretherton, 2018). These techniques are found to be fast and accurate, thereby demonstrating their potential for improving the accuracy of models. However, developing confidence in the predictions from ML techniques will require detailed assessments of their skill in regions where the model has not been trained, and of their applicability to the study of future climate.

Next-generation climate models and ‘exascale’ computing

Another approach for improving the representation of convection and other currently parameterized processes is to explicitly resolve them in “convection permitting” models (for a recent review, please see Satoh et al., 2019). These models run at km-scale resolutions for the entire globe – a resolution high enough to allow a quasi-explicit representation of convection. Recent developments include a season-long simulation at km-scale resolution resulting in a more realistic representation of large- scale circulation among other dynamical features (Wedi et al., 2020). Similar studies have also noted an improvement in tropical precipitation (Stevens et al., 2020). Promising though these developments are, substantial challenges remain to be overcome. Performing climate projections using a convection permitting model at global scale will require ‘exascale’ computing (computing at exaflop speeds, where 1 exaflop = 10^3 petaflops = 10^{18} floating point operations per second) (Shukla et al., 2010; Palmer and Stevens, 2019). Other challenges aside, a single exa-scale computer may consume the power equivalent of small nuclear power plant, raising the question whether the presumed benefits may be outweighed by their enormous cost (Emanuel, 2020).

Education

While the avenues discussed above are promising, they also pose many technical and logistical challenges. Long term planning and capacity building is necessary to develop the skills and expertise within the country to take up these challenges. Developing high quality technical education programmes will be crucial to this end. Whereas a few generations ago, educational programmes for meteorology and climate science focussed mainly on the observed behaviour of Earth system, and on mathematical methods and conceptual models, students today must also train in analysing extraordinarily large datasets, multiple coding languages, and in designing and running complex earth system models. (Emanuel, 2020) This calls for bold new educational programmes that can confer the necessary knowledge and skills.

We propose that advancing climate science would greatly benefit from instituting new undergraduate programmes specialising in meteorology and the climate sciences with an emphasis on the wide range of subsequent career opportunities such as in meteorology, aviation, remote sensing, shipping, defence, agriculture, fisheries, forestry, renewables, insurance and financial services, risk and disaster management, policy institutes and think tanks, aside from research careers in academia. Several such programmes exist at universities around the world such as *Geoecology* at the University of Bayreuth, Germany (http://www.geooek.uni-bayreuth.de/geooek/bsc/) or the programme at the Department of Atmospheric Sciences at the University of Washington, Seattle, USA (https://atmos.uw.edu/students/undergraduate-program/). These structured programmes cover core courses in mathematics, statistics, physics and chemistry aside from their focus on atmospheric and oceanic science, ecology, data analytics, etc. In conclusion, we propose that emergent escalating problems such as climate change necessitate new approaches to teaching and research in these subjects. With a view to long term benefits, it would be prudent to institute high quality undergraduate programmes across the country and attract interested and motivated students to join them.

SUMMARY

Future changes in the SA monsoon are immensely consequential to the inhabitants of the subcontinent. Improving the reliability of future projections is very important, yet scientifically challenging. In this article, we have identified key scientific issues and relevant physical processes that require urgent attention in order to advance future monsoon projections in a changing climate. We have outlined some promising avenues for research and education that may help reach these ends.

Compliance with Ethical Standards

The authors declare no conflict of interest and adhere to copyright norms.

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