TIPPING POINTS IN THE EARTH SYSTEM

Indian summer monsoon projections under regional and global forcings

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Summary for publication

The aim of this report is to establish the state of the Indian monsoon within future climate scenarios, and to define safe operating spaces to exclude dangerous conditions over the Indian region. This is accomplished through climate modelling studies and comparison of the results to previous studies.

The Indian summer monsoon (hereafter referred to as the Indian monsoon) is a globally significant meteorological event, bringing widespread precipitation annually between May and September. A monsoon consists of a seasonal reversal of wind direction near the surface, changing the large-sale circulation. The Indian monsoon system is particularly complex with respect to other global monsoons, due to the unique topography of the Indian continent with the Himalayas to the north and the oceans to the east and west. Its dynamical nature makes the response to various forcings difficult to predict. Regional and global scale forcings on a range of timescales can impact the Indian monsoon, including internal variability, oceanic phenomena and land-surface processes. The Indian monsoon is strongly coupled with the East Asian monsoon, so a holistic approach that considers the wider effects from both South and East Asia is needed.

In a future climate, land and sea surface temperatures are expected to rise, enabling greater moisture uptake. However, the global circulation is expected to weaken. The net effect is a more intense monsoon with higher rainfall rates, as the thermodynamic response dominates over the dynamic response. Regionally, there is considerable variation in projected rainfall trends. Over southern India, rainfall is expected to increase, whilst over northwest India, it is expected to decrease. Trends for other regions are highly debated. More frequent and intense rainfall events are predicted for India, in line with global predictions. To reduce uncertainty in future climate projections, focus should be given to correctly simulating the timing of monsoon phases (i.e. onset, active/break spells, withdrawal), as well as accurate representation of ocean processes & phenomena.

The Indian monsoon system has been identified as a possible tipping element, highlighting its importance in future global climate. It is thought that if some critical threshold is exceeded, the current state of the Indian monsoon will become unstable, triggering a potentially irreversible transition to a new state. The intensification or breakdown of the Indian monsoon would have far-reaching consequences to the environment and to the economy and from a humanitarian perspective. Changes to the timing, intensity and distribution of rainfall are some of the most crucial aspects to determine. In relation, it is important to establish shifts in the frequency and severity of monsoon depressions. Extreme rainfall events regularly cause floods, endangering livelihoods.

To assess the future response of the Indian monsoon to various factors of a changing climate, simulations are conducted with an intermediate complexity climate model. The roles of absorbing aerosols and greenhouse gases are considered. An absorbing aerosol forcing, applied in the form of mid-tropospheric heating to regions in Asia, causes surface cooling, weakens circulation and suppresses precipitation. Doubling the carbon dioxide concentration partially offsets the aerosol effect, with the associ-

ated warming acting to slow the precipitation decline, but leads to further weakening of the circulation.

Whilst increasing aerosol forcing in the regions of India, Southeast Asia and East China leads to decreasing precipitation locally, the forcing over East China is additionally linked to increasing precipitation over India. The net result is an overall decrease in precipitation over India, but the decrease is less than for the other regions. Each region responds differently, in terms of precipitation, to the imposed aerosol forcing. South India is least affected. North India shows a near-linear decline in precipitation as the forcing increases. East China experiences an abrupt transition around 60W to a low precipitation regime. Southeast Asia shows a steeper decrease in precipitation than North India, but without the abrupt transition of East China. As the aerosol forcing is increased to 60W, the precipitable water remains constant, and thereafter decreases. Given that the precipitable water does not decrease in a similar way to the precipitation, it is not a lack of moisture that causes the precipitation decrease, but a reduction in precipitation efficiency.

In a changing climate, the response of the Indian monsoon is uncertain, as there are many factors to consider. Differences in certain aerosol concentrations, altering the radiative forcing, affects both air and sea temperatures. The large-scale atmospheric circulation and cloud processes react to these changes, impacting the development of the monsoon. The situation is complicated as each factor can affect multiple aspects of the monsoon system, sometimes with competing influences. For example, whilst an increase in the amount of carbon dioxide warms the atmosphere, enabling greater moisture uptake and thus a stronger monsoon, an increase in sulphate aerosols acts to suppress the effects. Additionally, global modes of climate variability like El Niño-Southern Oscillation (ENSO) have a strong impact on the Indian Monsoon. Through further modelling studies, the impact of different regional and global forcing scenarios can be better understood and anticipated, facilitating response strategies.

Work carried out

This report represents Deliverable 3.4, “Indian summer monsoon projections under regional and global forcings”, as part of Work Package 3 (“Analysis and modelling of Tipping Elements in future climates”), for the Horizon 2020 project “Tipping Points in the Earth System” (TiPES). Referring to the project proposal, this deliverable relates to Task 3.3 “Response of the Indian summer monsoon to anthropogenic forcing”, which includes the sub-tasks 3.3.1 “Constraining the future evolution of the Indian summer monsoon” and 3.3.2 “Definition of safe operating spaces for the Indian summer monsoon”. Our work incorporates Theme 1 “Tipping element in data and models” and Theme 2 “Climate response theory”, and contributes to Objective 3 “Characterise climate response in the presence of Tipping Points” and Objective 4 “Define and identify safe operating spaces”.

We begin by reviewing the existing literature regarding the future climate response of the Indian monsoon, with a focus on modelling studies. The Indian monsoon system is one of the key tipping points in the Earth’s climate and there remains considerable uncertainty in how the system will respond to future climate forcing scenarios. Consolidating the progress made in terms of understanding the complex dynamical interactions within the system, as well as advances in model development, helps inform the direction of research activities. We begin with the IPCC6 report (Intergovermental Panel on Climate Change (IPCC), 2021), followed by several review papers (Ding et al., 2015; Ul Hasson et al., 2016; Li et al., 2016; Kitoh, 2017; Naveendrakumar et al., 2019; Hrudya et al., 2020), before focusing on specific model studies. There are few parametric-style studies regarding the Indian monsoon as a tipping element, but a multitude of articles on the future climate of the Indian monsoon in Coupled Model Intercomparison Project Phase (CMIP) 5 and CMIP6 standard models.

To address Task 3.3, we design and implement several simulations with a general climate model to investigate the response of the Indian monsoon to various anthropogenic forcing scenarios. In particular, we determine the conditions under which the monsoon circulation breaks down and the precipitation is drastically reduced. The impact of absorbing aerosols and greenhouse gases, which have opposing effects on the Indian monsoon, is considered. Specifically, we determine the tipping points at which the monsoon almost disappears, by gradually increasing the absorbing aerosol forcing. Additionally, we quantify the extent to which greenhouse gas forcing moderates the absorbing aerosol effect on the monsoon.

Literature review

A brief review of the present-day climate is presented, before focusing on predicted changes to the Indian monsoon system in the future climate. An understanding of the present-day internal dynamics and response to external forcings on a range of spatial and temporal scales is required in order to constrain uncertainty in future projections. Relationships between the Indian monsoon and atmospheric and oceanic phenomena are expected to remain robust in the future climate.

Present-day climate

An overview of the mechanisms behind the formation of the present-day Indian monsoon is given, as well as a discussion of external factors that are known to influence the monsoon. Established relationships such as the impact of the El Niño-Southern Oscillation (ENSO) on the variability of the monsoon rainfall are highlighted. Understanding the processes and dynamical interactions affecting the Indian monsoon is important for both the present-day and future climate predictions. The section is concluded with a description of observed trends over the last 50 years, focusing on rainfall.

Dynamics of the Indian monsoon

The onset of the Indian monsoon is initiated by a seasonal change in the large-scale circulation, setting up a low-level southwesterly flow that brings an influx of moisture from the Arabian Sea. The atmosphere in the southeast becomes favourable for moist convection, encouraging the development of cumulus and congestus clouds and leading to increased rainfall over the region. The Indian monsoon first onsets in the southern region of Kerala in early June, then propagates to the northwest against the mean mid-level wind field. Approximately six weeks after first onset, the entire Indian peninsula experiences the full monsoon, which is associated with unsettled weather and widespread rainfall. The summer monsoon season lasts about three months. In September, the large-scale circulation reverts back to winter conditions and the monsoon withdraws. Figure 1 shows the relative humidity and large-scale circulation at low (850 hPa) and high (200 hPa) levels. Monsoon conditions are represented in the left panels, whilst the right panels show the atmospheric state in winter.

Early explanations of the initiation of the Indian monsoon are based around the classical thermal theory, first presented by Edmund Halley in 1686, which describes the monsoon as a giant sea breeze (Walker, 1972). As the Asian land mass receives more solar radiation and becomes hotter, a temperature gradient develops between the land and the sea, and a heat low forms over north India. Figure 2 illustrates the temperature differences over the land and ocean during the summer monsoon, compared to winter conditions. A vertical pressure gradient is created, with low pressure at the surface and high pressure aloft, modifying the large-scale circulation. Moist air from the Arabian Sea is drawn in over southern India, with convergence at the surface triggering convective processes and leading to rainfall. More recently, the Indian monsoon has been viewed as a regime shift in conjunction with the seasonally migrating Intertropical Convergence Zone (ITCZ) (Bordoni and Schneider, 2008), which

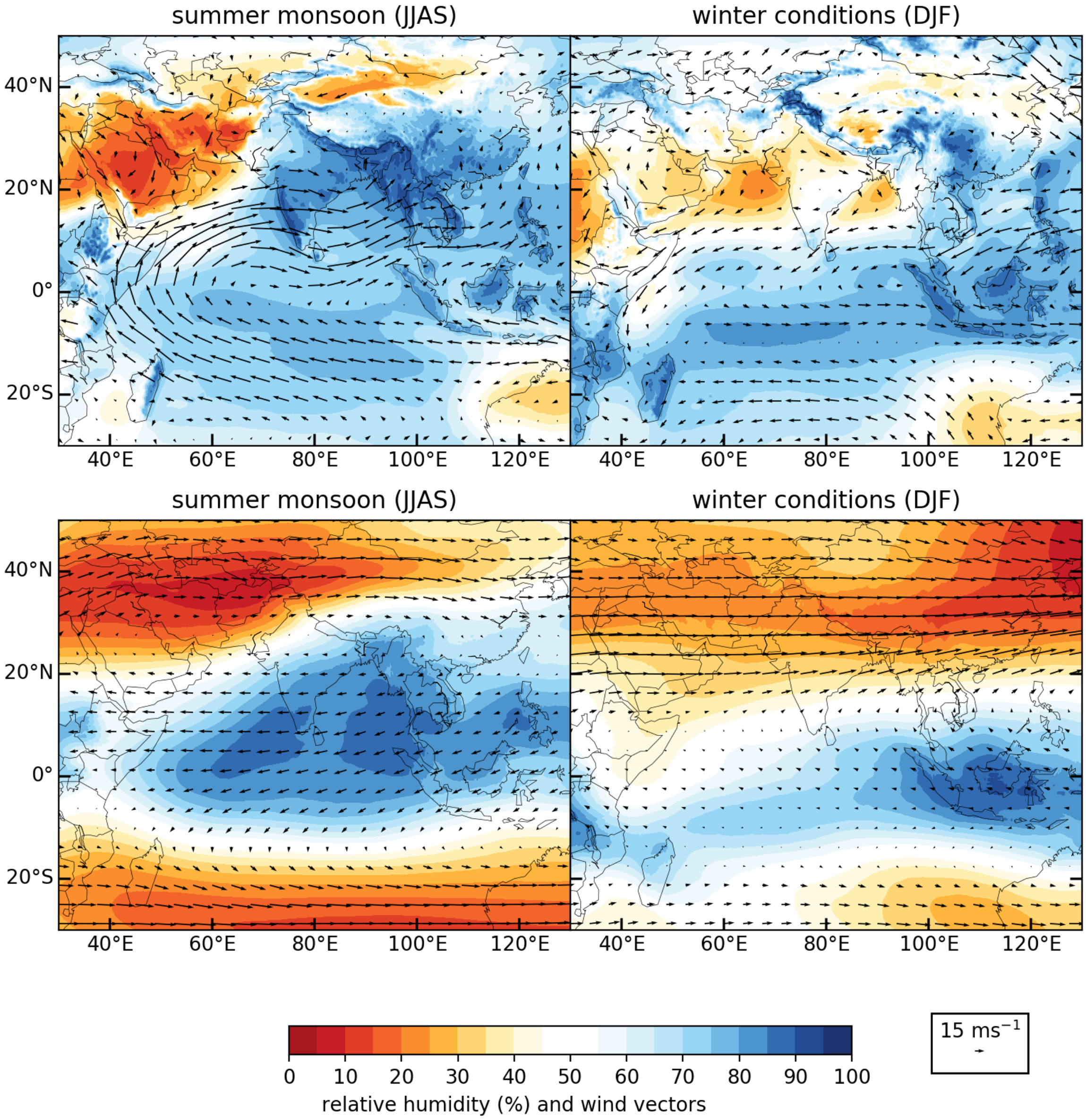

Figure 1: Relative humidity (shading, %) and wind (vectors, ms^{-1}) at the 850 hPa level (top) and the 200 hPa level (bottom), for the Indian summer monsoon (June–September) and winter (December–February). Produced from ERA5 reanalysis data (Copernicus Climate Change Service, 2017), averaged over years 1988–2017.

follows the poleward movement of the moist static energy maximum, from the equator (Schneider et al., 2014). Further work is needed to unite the energy budget and dynamic perspective in order to develop a comprehensive monsoon theory (Geen et al., 2020).

Influences on the Indian monsoon

There are many influences, both internal and external, that affect the variability of the Indian monsoon. These influences act on a range of timescales, from hours to decades, which adds complexity to the monsoon system. Figure 3 shows the interactions between various influences on the monsoon climate. From a modelling perspec-

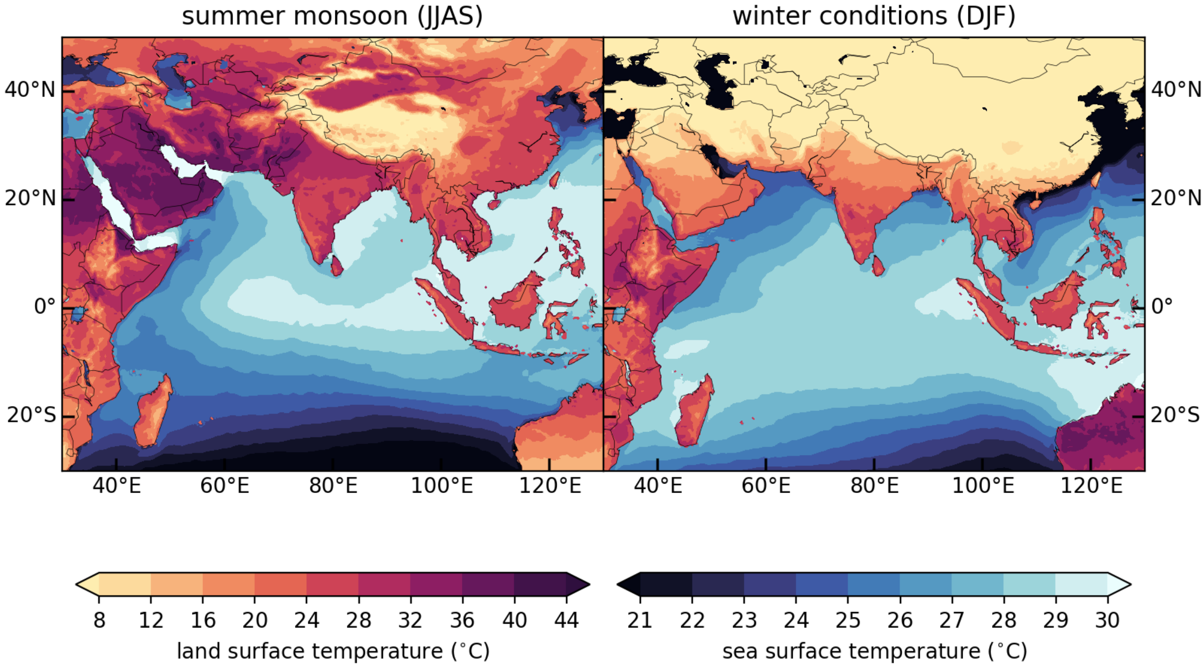

Figure 2: Land surface temperature (warm colours, °C) and sea surface temperature (cool colours, °C), for the Indian summer monsoon (June–September) and winter (December–February). Produced from ERA5 reanalysis data (Copernicus Climate Change Service, 2017), averaged over years 1988–2017.

tive, it is difficult to capture the Indian monsoon's response to both fast and slow-acting processes. Continuing research allows for increased understanding of how the components interact with each other and the monsoon system as a whole, enabling improved representation in weather and climate models.

On short timescales, of hours to days, processes that influence the monsoon variability include convection, presence and uptake of moisture, and synoptic disturbances such as easterly waves or low-pressure systems. Changes to the large-scale circulation and intensity of convection on a local scale can affect the spatial distribution of rainfall. The relationship between precipitation and total column water vapour is well documented (Neelin et al., 2009; Schiro and Neelin, 2019). An increase in moisture uptake, from surface evaporation or via advection over the ocean, can hasten monsoon onset and trigger precipitation. Low-pressure systems and monsoon depressions typically bring intense, localised bursts of rain over a short time, which can have a significant impact, particularly with regards to flood risk. It is important to quantify changes to the frequency of occurrence and intensity of these low-pressure systems in a warming climate.

Changes to oceanic properties such as temperature and salinity, and changes to the land surface such as the amount of snow cover and vegetation, affect the heat and moisture fluxes. These changes can occur over weeks–months. Differences in the heat and moisture fluxes close to the ocean/land surface impacts the monsoon response. Other phenomena, acting over years–decades, can also affect oceanic prop-

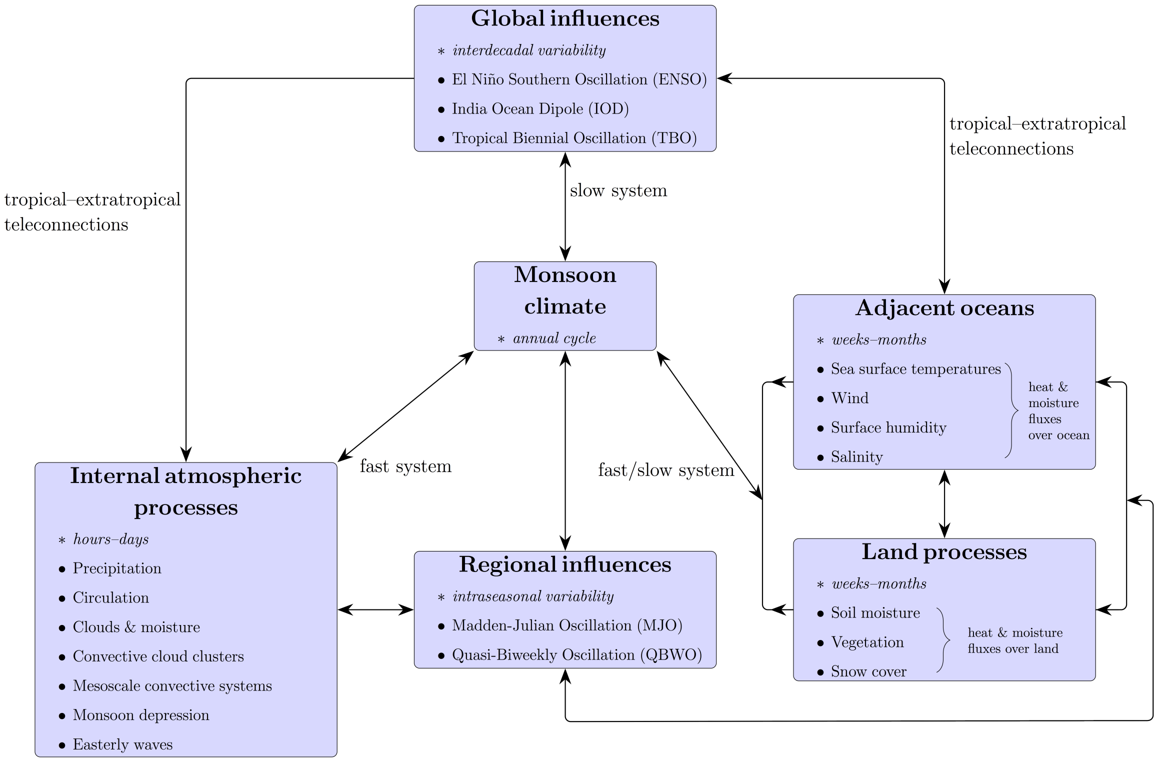

Figure 3: Schematic adapted from Lau et al. (2000) showing the various components and their contributions to a monsoon climate and its variability.

erties like sea surface temperature. Regional-scale phenomena include the Madden-Julian Oscillation (MJO) and the Quasi-Biweekly Oscillation (QBO). On a global scale there is ENSO, the Indian Ocean Dipole (IOD) and the Tropical Biennial Oscillation (TBO). El Niño years (positive ENSO phase) are linked with a weaker monsoon and La Niña years (negative ENSO phase) are linked with a stronger monsoon. Similarly, a positive IOD is correlated with an increase in monsoon rainfall, whilst a negative IOD is correlated with a decrease in monsoon rainfall. Teleconnections from other ocean basins, for example, the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation, have been linked to the intensity of the monsoon and the total summer rainfall (e.g. Krishnan and Sugi (2003); Hrudya et al. (2020); Naidu et al. (2020)). Such phenomena account for the majority of the interannual variability of the Indian monsoon.

There is more skill in predicting the interannual variability than the intraseasonal variability; however, the intraseasonal variability has a greater impact on the monsoon rainfall. There is value in understanding the relationships between the Indian monsoon and various external forcing factors, as it is likely that robust relationships are maintained in future climate scenarios.

Present-day trends

The location, intensity and timing of rainfall are the most key aspects of the monsoon to forecast accurately. In the future climate, changes to rainfall patterns will have the greatest impact. Figure 4 shows the present-day climatology of daily rainfall for the summer monsoon, compared to the winter. Areas receiving the highest rainfall totals are along the west coast, the Himalayan foothills and northeast India/Bangladesh.

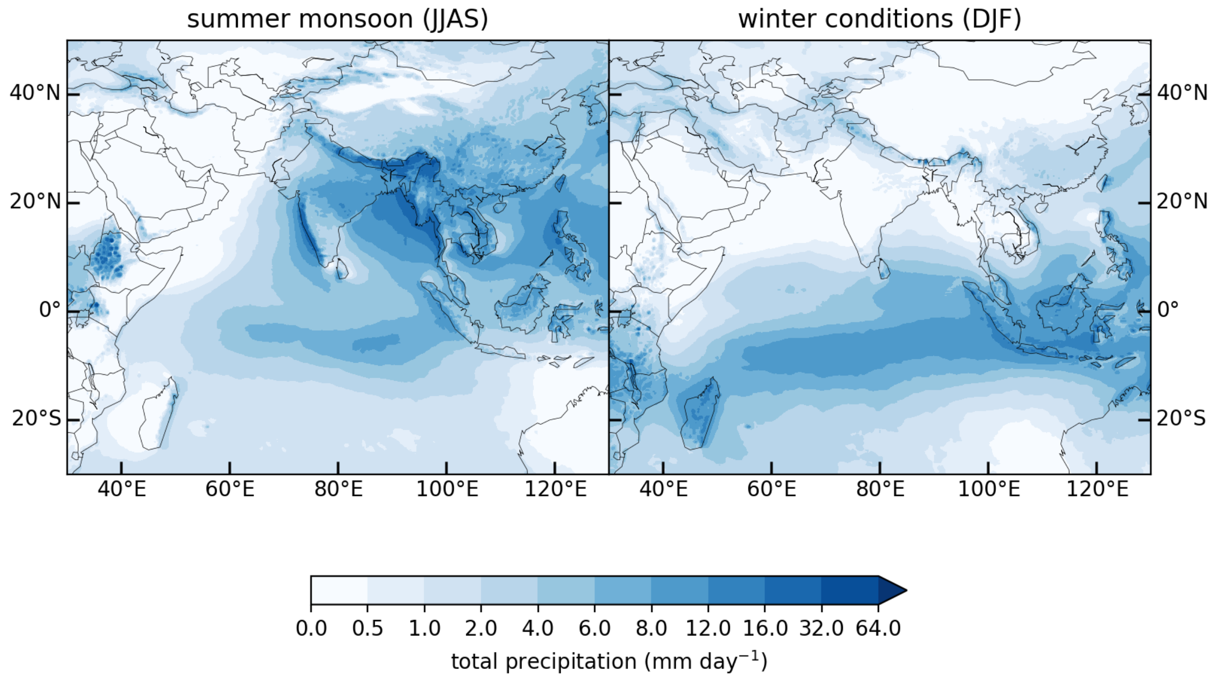

Figure 4: Total daily precipitation (shading, mm/day), for the Indian summer monsoon (June–September) and winter (December–February). Produced from ERA5 reanalysis data (Copernicus Climate Change Service, 2017), averaged over years 1988–2017.

Globally, precipitation is expected to increase with warming surface temperatures. Extreme precipitation events are likely to be more intense and more frequent (Collins et al., 2013; Intergovermental Panel on Climate Change (IPCC), 2013). Over India, there is a decreasing number of monsoon depressions being observed (Dash et al., 2004; Ajayamohan et al., 2010), but an increasing number of weak low-pressure systems (Pattanaik, 2007; Ajayamohan et al., 2010). A “normal” monsoon year is becoming more rare, whilst weaker or stronger monsoon years are becoming more common. The monsoon onset is typically delayed, with the monsoon season peaking in late August/September, rather than July (Turner and Annamalai, 2012). There has also been a spatial shift in the precipitation peak, from east to west, with increased rainfall over the tropical western Pacific and decreased rainfall over south Asia (Annamalai et al., 2013). Despite most models predicting an increase in the total monsoon rainfall over India, observations show a slight negative trend in rainfall from 1950–present day (Figure 5). The negative trend is explained by a dominance of aerosol forcing over greenhouse gases, leading to a drying effect (Bollasina et al., 2011; Kitoh, 2017). The presence of aerosols has an impact on the radiation budget as it causes, by and large, to anomalous heating in the mid troposphere. This leads to an increase in the static stability, which favours the weakening the monsoon circulation, giving a dynamic change of reduced mean moisture convergence (Li et al., 2015). Further work is required to constrain the uncertainty regarding monsoonal rainfall in future climate scenarios.

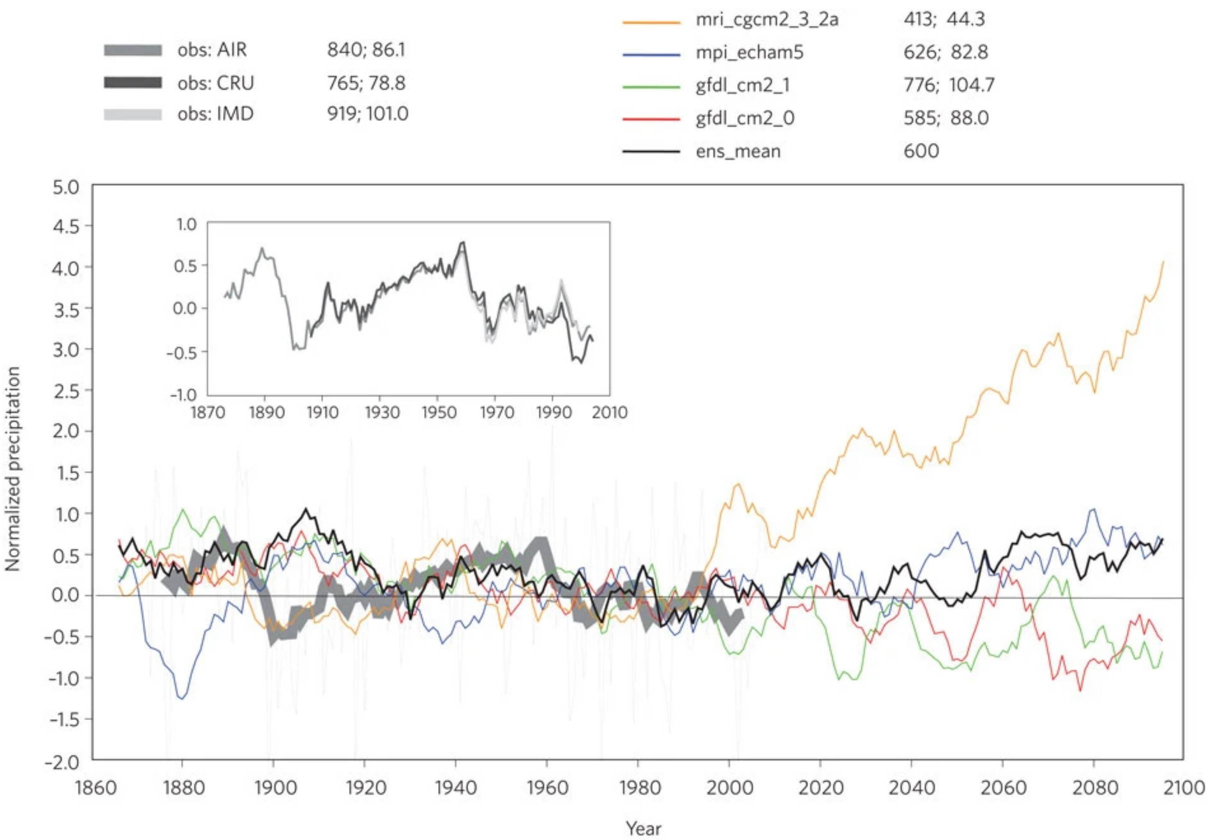

Figure 5: Historical (1861–1999) and future (2000-2100) projection of South Asian monsoon rainfall under 'balanced' A1B IPCC emission scenario. Time series of mean summer (June–September) precipitation averaged over land points within 60–90° E, 7–27° N. Only four models from the CMIP3 experiment, shown to have a reasonable simulation of the spatial pattern, seasonal cycle and interannual variability of monsoon rainfall, are depicted; the black curve shows their ensemble mean. Observations from the all-India rainfall (AIR) index based on gauge information are also shown for the 1871–2008 period as a proxy for South Asia rainfall. All curves are first normalized by their mean and standard deviation measured over 1961–1999 and are passed through an 11-year moving window. The faint black curve shows the observations without this smoothing. The inset compares the AIR with area-mean averages over the same domain as above from 1951–2004 India Meteorological Department (IMD) daily gridded data and 1901–2009 monthly gridded Climatic Research Unit (CRU) data. The values listed in the legend are for June–September mean rainfall and interannual standard deviation, in mm. Reproduced with permission from Turner and Annamalai (2012).

Future climate predictions

Looking ahead to the future 50–100 years, the summer monsoon rainfall is expected to increase (Douville et al., 2000; Cherchi et al., 2011; Turner and Annamalai, 2012; Kitoh, 2017; Krishnan et al., 2020; Intergovermental Panel on Climate Change (IPCC), 2013, 2021). Despite a weakening of the global circulation, the higher atmospheric moisture content due to warmer surface temperatures dominates, leading to a net increase in precipitation (Intergovermental Panel on Climate Change (IPCC), 2021, 2013; Ueda et al., 2006). The inability of models to capture the observed negative rainfall trend in the period 1950–2000 (Saha et al., 2014) reduces confidence in future climate predictions. On the other hand, the substantial number of different climate models predicting an increase in precipitation adds robustness. Complete failure of the Indian monsoon is unlikely (Intergovermental Panel on Climate Change (IPCC), 2013), but lower rainfall years are projected to become more frequent (Schewe and Levermann, 2012; Krishnan et al., 2020). This is in agreement with Turner and Annamalai (2012), in respect to the expectation of monsoon years becoming more severe and less “normal”. There remains considerable uncertainty regarding how much the precipitation will increase by, changes to the timing of monsoon phases and effects on a regional scale.

Regional trends

There are significant regional differences in projected rainfall in South Asia, which can be lost when considering the net change for all of the sub-continent (Hrudya et al., 2020). Over the southern peninsula, there is general agreement on an increasing rainfall trend (Turner and Annamalai, 2012; Das et al., 2014). There is considerable disagreement over central India and far northeast India. Turner and Annamalai (2012) suggests little change in precipitation over central India; Lau and Kim (2010); Das et al. (2014) suggest a decreasing trend, and Roxy et al. (2017) suggests an increasing trend. Although Das et al. (2014) note a decreasing rainfall trend in the northeast, future projections of tropical rainfall generally follow the pattern of wet-gets-wetter. This means that areas such as Assam, Meghalaya and the Himalayan foothills, which already receive significant amounts of rainfall during the monsoon season, are expected to become wetter Lau and Kim (2010). Similarly, it is anticipated that arid/desert regions, for example Rajasthan, get less rainfall (Turner and Annamalai, 2012; Das et al., 2014). Along the Western Ghats mountain range, decreasing precipitation trends are reported (Das et al., 2014; Varghese et al., 2020). A more detailed study specifically focusing on the Western Ghats region found that whilst rainfall is expected to decrease around the southern end of the Western Ghats range, it increases slightly in the north end of the Western Ghats range. It is important to note that the lack of a comprehensive definition for regions of India makes it difficult to compare regional rainfall trends.

Extreme weather events

Over India, there is expected to be a decrease in moderate rainfall events, but an increase in extreme rainfall events (Turner and Annamalai, 2012), in agreement with the global-scale prediction of more intense and frequent precipitation events occurring (Collins et al., 2013). As noted previously, there is a trend towards fewer monsoon depressions, but instead, a higher number of weaker, low-pressure systems. Supporting this observation, Sandeep et al. (2018) notes a weakening and a poleward shift of low pressure systems originating in the Bay of Bengal. Correspondingly, the frequency of extreme precipitation events over northern India, linked with the low pressure systems, is expected to increase. A rise in severe rain events is also predicted over central India (Srivastava et al., 2016; Roxy et al., 2017).

Response to external forcings

The response of the Indian monsoon to anthropogenic forcing is expected to change in the future climate. Historically, aerosol forcing has dominated, explaining the negative trend in precipitation (Dong et al., 2019). Going forward, greenhouse gas forcing is expected to dominate, with the associated thermodynamic effects leading to a more intense monsoon and higher rainfall totals (Ueda et al., 2006; Li et al., 2015; Kitoh, 2017). The cooling effect from sulphate aerosols (Sherman et al., 2021) is generally outweighed by the warming effect from increasing amounts of absorbing aerosols, particularly black carbon. Zhao et al. (2019) additionally links the reduced role of aerosol forcing in a future climate to an increase in extreme precipitation events. Future changes to the distribution of aerosols over the Tibetan Plateau, which plays a key role in monsoon dynamics, are likely to have a significant effect on the monsoonal rainfall, but the response is debated. Further observational and modelling studies are required to understand the relationship between aerosols and the Indian monsoon, as well as to quantify the effects of aerosol-cloud-precipitation interactions (Sanap and Pandithurai, 2015).

The inverse relationship between the Indian monsoon and ENSO has already been noted in a previous section. Future climate simulations suggest more frequent El Niño events, which could trigger more drought or break phases during the monsoon season (Azad and Rajeevan, 2016). Relationships between the Indian monsoon and other oscillations and/or oceanic phenomena are expected to persist in a future climate scenario, but changes to the occurrence and intensity of such phenomena are uncertain. For example, there is little confidence in the future projection of the MJO, and thus the subseasonal monsoon variability, which is linked to the MJO (Intergovernmental Panel on Climate Change (IPCC), 2013).

Modelling: CMIP6 vs CMIP5

In terms of modelling the Indian monsoon, there has been improvements since the Coupled Model Intercomparison Project Phase 5 (CMIP5), associated with the IPCC Fifth Assessment Report (2013). However, certain biases remain in the current phase, CMIP6, regarding accurate representation of the spatial pattern and intensity of rainfall.

Performance of CMIP5

A common issue across CMIP5 models is simulating the timing of the monsoon onset. Typically, onset is late in the simulations compared with observations (Ul Hasson et al., 2016). Typically, the monsoon withdrawal is better captured than the onset (Sperber et al., 2013). Many models feature a dry bias over (northern) India, which is linked with a weaker monsoon circulation and an underestimation of the rainfall in the region (Goswami and Goswami, 2017; Wang et al., 2018). The persistence of this dry bias across different models implies a lack of understanding of the physical processes and/or limitations of parameterisation schemes. In contrast, rainfall is often overestimated over the Indian Ocean and East Asia/China. The proportion of large-scale to convective rainfall is often incorrect, with models favouring convective rainfall, whereas it is the large-scale component that dominates in observations (Jain et al., 2019). The air temperature is better simulated than the precipitation (Jain et al., 2019). Sperber et al. (2013) suggests that improving the representation of the 850 hPa winds will improve the distribution of precipitation, and vice versa. Developments in computing may help overcome the challenge of capturing spatial patterns of rainfall, enabling higher resolution model runs which have been shown to reduce the dry bias over India and South Asia (Turner and Annamalai, 2012; Goswami and Goswami, 2017; Chen et al., 2020; Varghese et al., 2020).

Perhaps the most important factor determining accurate simulation of the Indian monsoon is the ability to represent ocean processes and teleconnections (Wang et al., 2018). Annamalai et al. (2017) show that accurate representation of coupled equatorial Indian Ocean processes is key to simulating the monsoon. Wang et al. (2014) highlight the importance of sea surface temperatures in the Atlantic and Pacific Oceans, linking biases in the oceans with biases in monsoonal rainfall. Similarly, the ability of models to reproduce the phases of ENSO is relevant. Unfortunately, CMIP5 models do a poor job of simulating the location and intensity associated with ENSO heating (Sperber et al., 2013). Generally, the multi-model mean of CMIP5 models outperforms any individual model. It is worth noting that CMIP5 models outperform CMIP3 models in all diagnostics (Sperber et al., 2013), showing that our ability to simulate the Indian monsoon is improving.

Performance of CMIP6

The Coupled Model Intercomparison Project Phase 6 (CMIP6) predicts a higher rise in precipitation than CMIP5, with CMIP6 models showing a greater sensitivity to greenhouse gas concentrations (Almazroui et al., 2020). There is some agreement between models in CMIP6 regarding changes to regional rainfall totals for the mid–far future, but little agreement for the near-future (Almazroui et al., 2020). Typical biases from CMIP5, such as a dry bias over South Asia and moist biases over the Indian Ocean & East Asia, remain in CMIP6, although the magnitude of these biases has been reduced (McKenna et al., 2020; Chen et al., 2020). Generally, CMIP6 captures the spatial pattern of rainfall better than CMIP5, particularly over northern and central India, likely due the higher horizontal and vertical resolutions and improved parameterisations of convective and microphysical processes (Gusain et al., 2020). Additionally, orographic precipitation over the Western Ghats and Himalayan foothills is better represented (Gusain et al., 2020). Aspects to be improved include the timing of monsoon onset, number of active/break spells (Gusain et al., 2020), and effects from oceanic phenomena including ENSO, IOD, MJO (see McKenna et al. (2020)). Further work is needed to represent the intensity of different phases of these oscillations and the changes to sea surface temperatures, which impact on the Indian monsoon.

Results & discussion

The main goal is to understand the impact of aerosol forcing on the regions of India, Southeast Asia and East China, in terms of significant reducing precipitation and weakening the large-scale circulation. We aim to find the level of forcing required to cause the monsoon system to collapse. Additionally, we wish to explore the interaction of regional aerosol forcing with globally increased carbon dioxide concentration.

Here, we describe the experiment design and subsequent simulation results for investigating the response of the Indian monsoon to regional forcing scenarios. Firstly, the model set up and performance is presented, then we show the results from applying an absorbing aerosol-style forcing over Asia. Next, we consider the effect on the monsoons of doubling carbon dioxide levels in combination with absorbing aerosol-style forcing. Finally, the linearity of the system is evaluated.

Model description

The Planet Simulator (PlaSim) model von Hardenberg (2020); Lunkeit et al. (2011); Fraedrich et al. (2005) is an intermediate complexity climate model, with a dynamical core, parameterised physical processes and a large-scale geostrophic ocean component. It includes parameterisation schemes for land-surface interactions, radiation and convection. There are 10 vertical levels. We use the T42 horizontal resolution, which is approximately 2.8°. For climate science, where the focus is on large-scale features over long timescales, the PlaSim model is an invaluable tool for investigating various future scenarios, at a low computational cost.

There is a precedent for using both the PlaSim model and other models of a similar complexity for climate simulations regarding the Asian monsoons (Wang et al., 2016; Thomson et al., 2021; Herbert et al., 2022). In terms of lower complexity models, Zickfeld et al. (2005) use a box model of the tropical atmosphere to investigate the stability of the Indian monsoon to changes in planetary albedo and carbon dioxide concentration. For higher complexity models, there is an abundance of literature where CMIP5 and CMIP6 standard models are used to explore the response of the Indian monsoon to future climate scenarios (Menon et al., 2013; Li et al., 2015; Kitoh, 2017; Swapna et al., 2018; Varghese et al., 2020; Krishnan et al., 2020; Almazroui et al., 2020; Chen et al., 2020; Moon and Ha, 2020; Wang et al., 2020, 2021; Swaminathan et al., 2022; Intergovermental Panel on Climate Change (IPCC), 2013, 2021). We use a combination of our own simulations with the PlaSim model and results from existing literature that use a hierarchy of models to quantify the Indian monsoon response to a range of future climate scenarios.

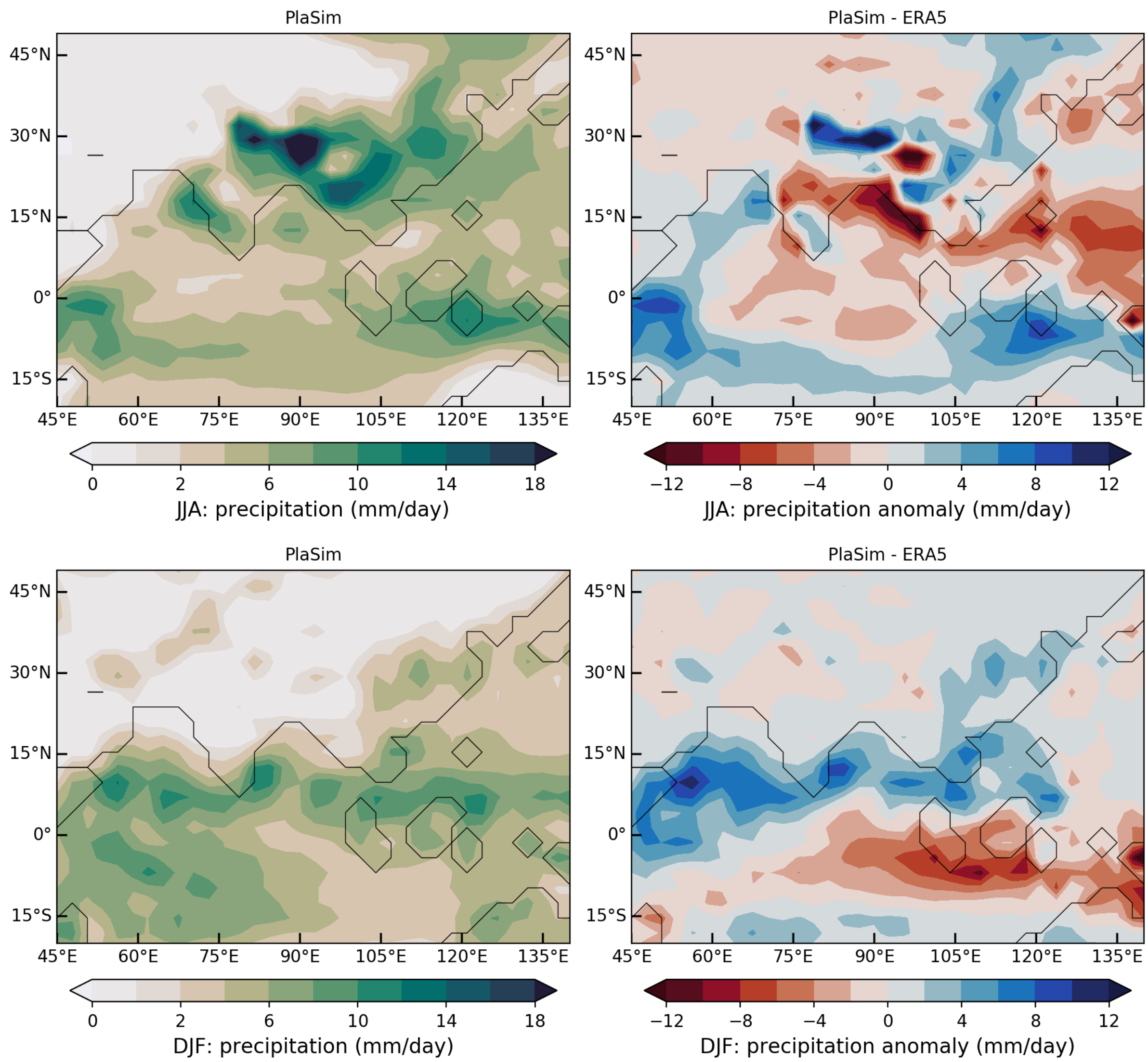

Figure 6: Precipitation (left column) and precipitation anomaly (right column) compared to ERA5 reanalysis data for June-July-August (top row) and December-January-February (bottom row).

Model validation

A brief evaluation of the PlaSim model is conducted, in order to show that the PlaSim model is capable of reproduces the seasonality of the Indian monsoon to a sufficient degree of accuracy for our purposes. Similar versions of the PlaSim model has shown to perform well in climate simulations (Holden et al., 2016; Platov et al., 2017). Figures 6–8 show the performance of a control simulation with the PlaSim model, compared to ERA5 reanalysis data (Copernicus Climate Change Service, 2017). The PlaSim simulation has been seasonally averaged over a 50 year period, and the ERA5 data has been seasonally averaged over the period 1988–2017. For the following figures, the left columns show the 50-year average of the PlaSim model simulation, and the right columns show the difference between the PlaSim model simulations and the ERA5 data (PlaSim - ERA5).

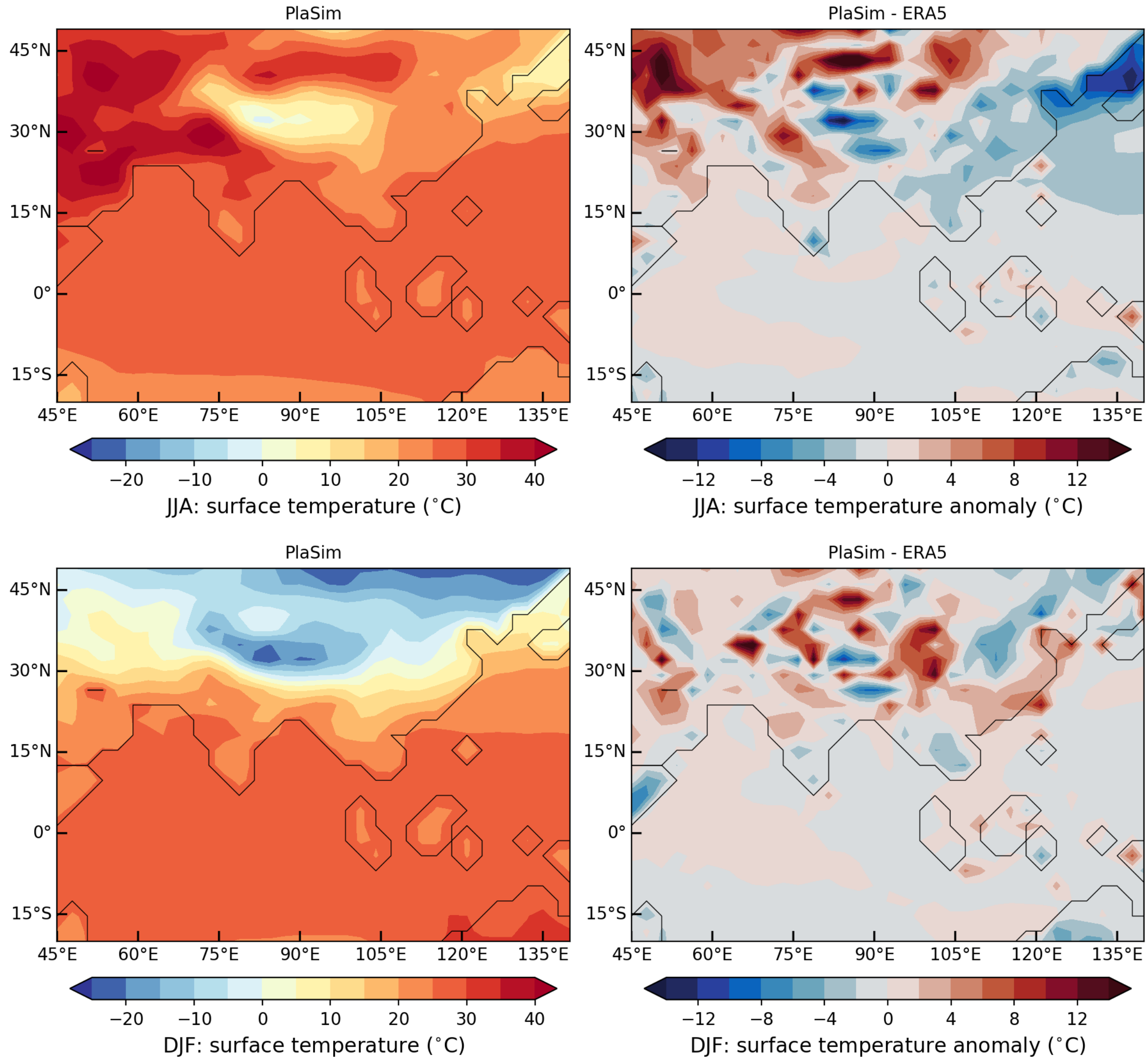

Figure 7: Surface temperature (left column) and surface temperature anomaly (right column) compared to ERA5 reanalysis data for June-July-August (top row) and December-January-February (bottom row).

There is a clear difference between summer and winter in the PlaSim model simulations, with summer bringing increased precipitation over India and showing the formation of strong low-level southwesterly winds over the Arabian Sea. The PlaSim model underestimates summer precipitation over North India and around the eastern coast of Bay of Bengal, but slightly overestimates precipitation over the Indian Ocean. There is good agreement between the PlaSim model and ERA5 reanalysis data for surface temperature in the region of interest. The low-level southwesterly monsoon flow is stronger in the PlaSim model than in ERA5 data, indicating some inconsistencies in the large-scale circulation. For the purposes of a parametric climate study, it is concluded that the PlaSim model is a sufficiently accurate tool.

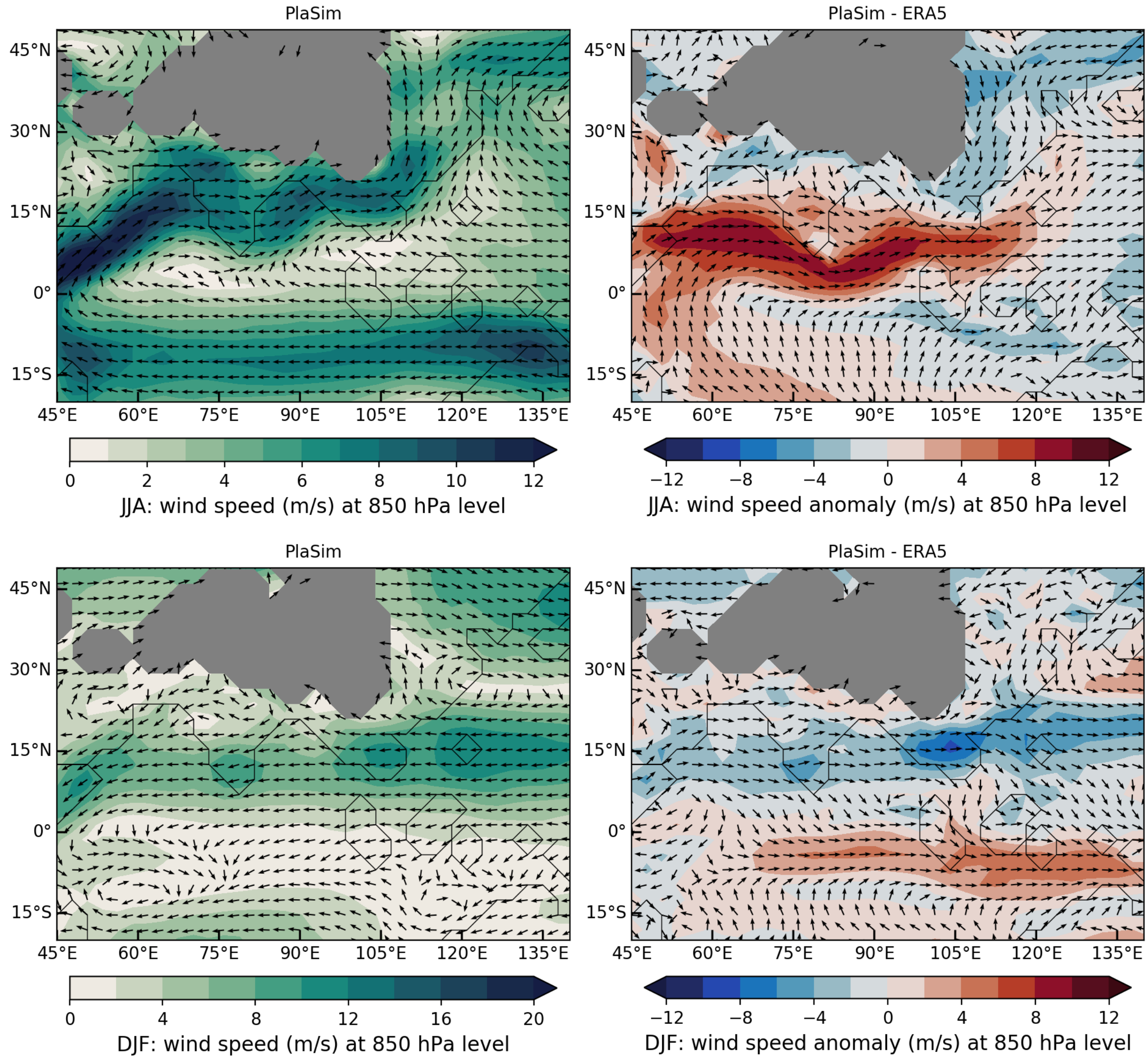

Figure 8: Wind speed & direction (left column) and wind speed & direction anomaly (right column) at the 850 hPa level compared to ERA5 reanalysis data for June-July-August (top row) and December-January-February (bottom row).

Experiment design

To analyse the roles of absorbing aerosols and greenhouse gases, which have contrasting effects, on the Indian monsoon, we implement two forcing scenarios with the PlaSim model: *heat only* and *heat with 2xCO$_2$*. The *heat only* simulation features increasing absorbing aerosol forcing, whilst the *heat with 2xCO$_2$* simulation features doubled carbon dioxide levels to represent higher levels of greenhouse gases, as well as increasing absorbing aerosol forcing. This is a simplified version of IPCC 6 forcing scenario SSP3-7.0 (Intergovermental Panel on Climate Change (IPCC), 2021).

The PlaSim model has no explicit treatment of aerosol interactions, so we use mid-level tropospheric heating as a proxy for absorbing aerosols, similarly to Chakraborty et al. (2004). This heating is applied over three vertical levels, approximately corresponding to 550–750 hPa. The heat forcing is applied simultaneously over three regions: India, Southeast Asia and East China, as per Figure 9. We consider the impact of forcing each of these regions in turn, in Section “Sensitivity to area of applied forcing”. To maintain radiative balance, the surface is cooled by the same value as the heat forcing.

For both simulations, the heat forcing, used as a proxy for absorbing aerosols, is gradually increased from 0W to 150W, and then decreased back to 0W. This is done over a simulation length of 900 years, giving the rate of applied heating as $\pm$0.33W/year. We consider 30W to be low forcing, 60W medium forcing and 90W high forcing. These values are within observed ranges of radiative forcings (Kumar and Devara, 2012; Vaishya et al., 2018). Heat forcing much above 100W is considered unrealistic in real-world terms, but we want to ensure that we capture the breakdown of the monsoon system.

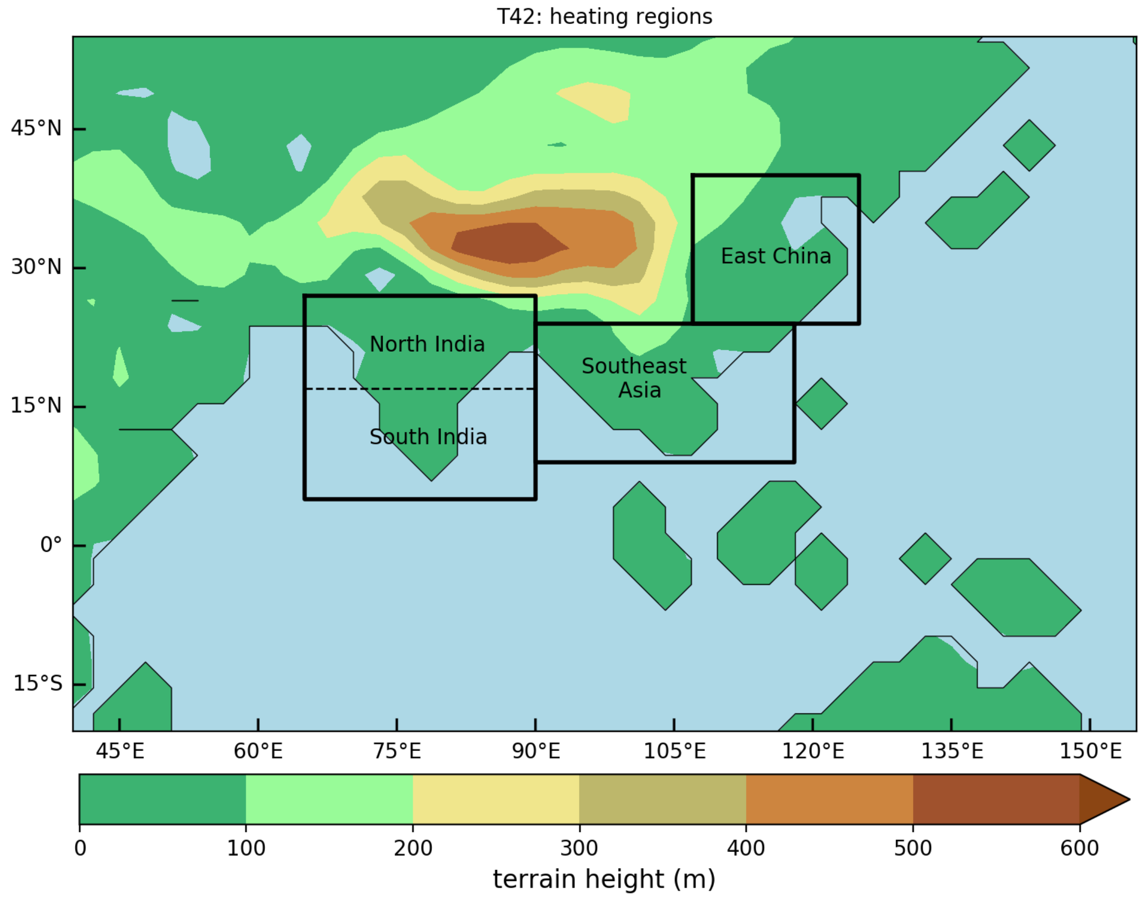

Figure 9: Regions showing where mid-tropospheric heating has been applied. Shading indicates terrain height (m).

Response to absorbing aerosol forcing

The added heat forcing, a proxy for absorbing aerosols, causes the surface to cool in the regions where the forcing is applied, whilst also causing a warm anomaly around 700 hPa. The increased stratification of the atmosphere suppresses precipitation and weakens the large-scale circulation. As the heat forcing is increased, the response of the monsoons become more pronounced.

Figure format

The figures in this section are presented as 2 x 6 panels, with the top left panel showing the state of the system at approximately 30W of heating. The remaining five panels show the anomaly with respect to the control simulation (*heat only* - control) at forcings of approximately 30, 60, 90, 120 and 150W. There is no significant hysteresis in the simulations and so and an average is taken of the ascending branch with forcing 0→150W and the descending branch with forcing 150→0W. With the exception of 150W, each panel in the figures is produced using the average of the two 10-year means centred around the respective forcing values. The panel for 150W represents the single 10-year period centred on 150W. All means refer only to the summer months - June, July, August. Areas of high orography will be masked in grey for certain pressure levels.

Precipitation

Increased heat forcing corresponds with a reduction in precipitation, illustrated by Figure 10 (top two rows). The East China and Southeast Asia regions are the most affected. With the exception of the west coast and northeastern states, areas of higher orography, the majority of India does not follow the trend of declining rainfall. Partly, this is due to the low-level wind, which brings a large influx of moisture from over the Arabian Sea. In contrast, eastern Siberia experiences a reduction in precipitation, despite being outside the heat-forced area. The relationship between aerosol-like forcing and precipitation is complex, with significant regional effects.

Precipitable water

Figure 10 (bottom two rows), showing the change in precipitable water with heat forcing, highlights a moist anomaly over the Middle East, and to a lesser extent, the Indian Ocean. Advection of moisture from East to West helps explain why precipitation over India is not reduced as much as over Southeast Asia and East China. It is notable that the precipitable water does not decrease at as fast a rate as the rainfall decreases. Significant reductions in the precipitable water only occur at high rates of forcing, over 90W. Therefore, the decline in rainfall is primarily attributed to a reduction in precipitation efficiency, rather than a scarcity of moisture availability.

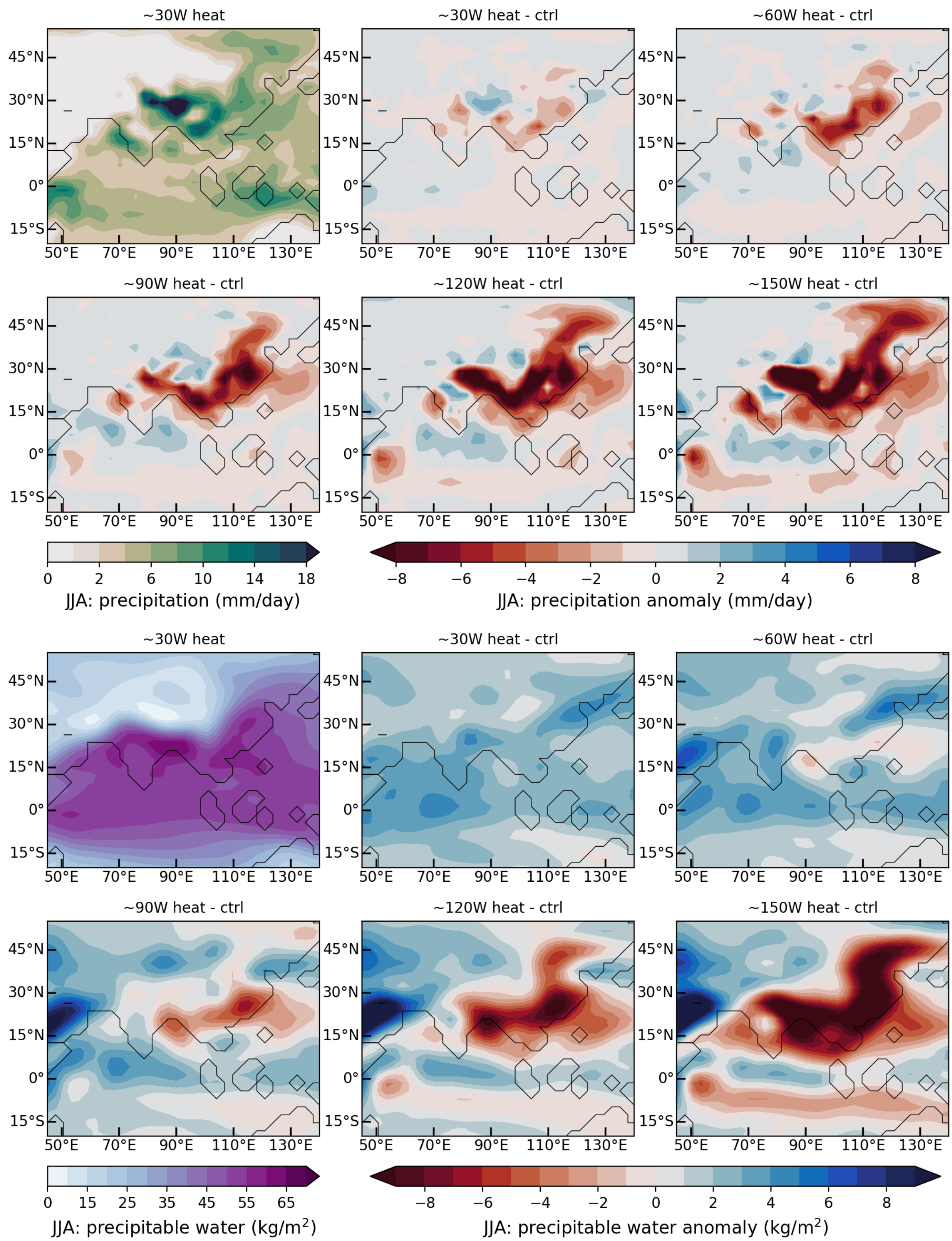

Figure 10: Heat only simulation. Contours showing mean decadal June-July-August precipitation (first column, top row) & precipitable water (first column, third row), and mean decadal June-July-August precipitation anomaly (top two rows) & precipitable water anomaly (bottom two rows) compared to the control run, for a range of heat forcing values.

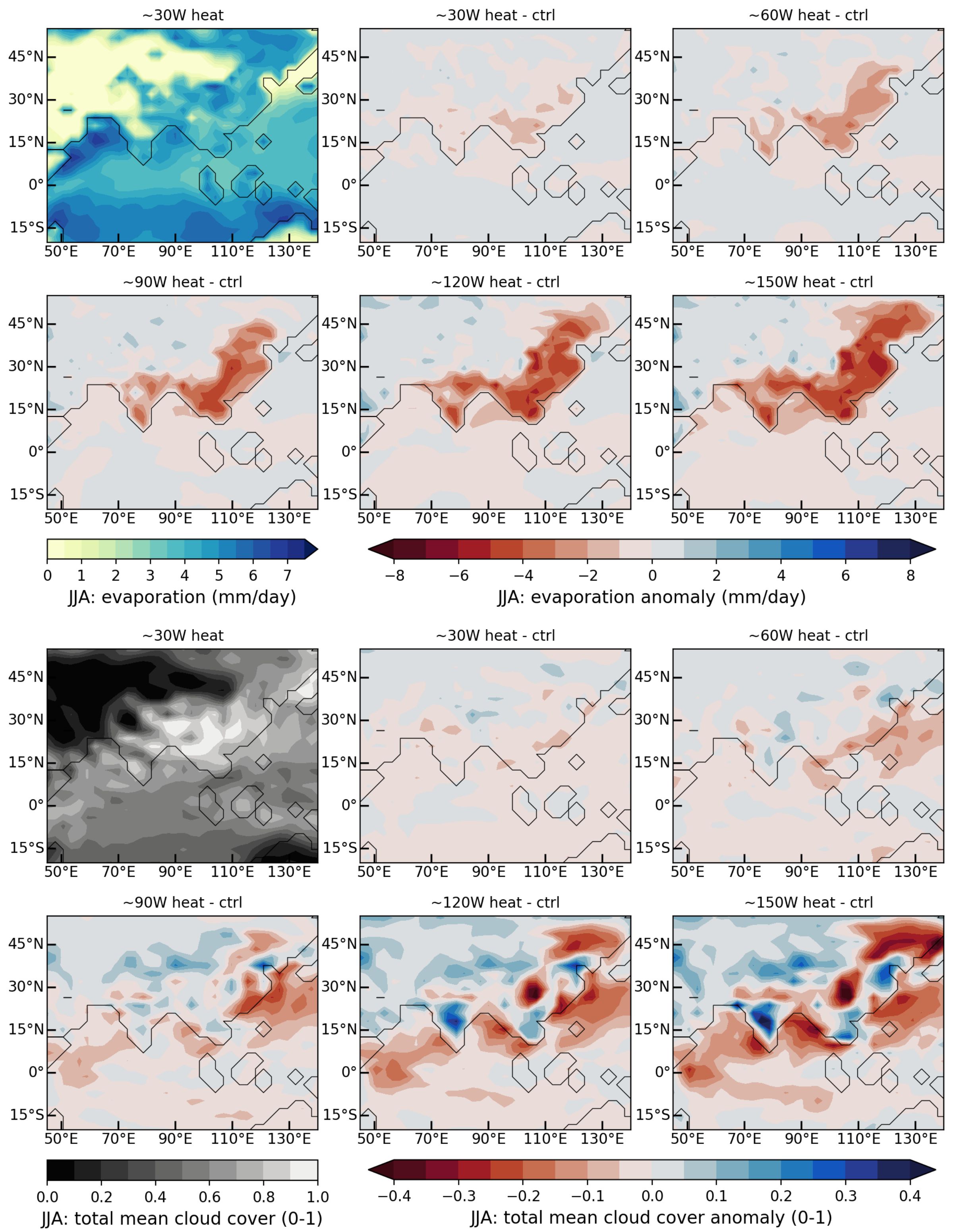

Figure 11: *Heat only* simulation. Contours showing mean decadal June-July-August evaporation (first column, top row) & total mean cloud cover (first column, third row), and mean decadal June-July-August evaporation anomaly (top two rows) & total mean cloud cover anomaly (bottom two rows) compared to the control run, for a range of heat forcing values.

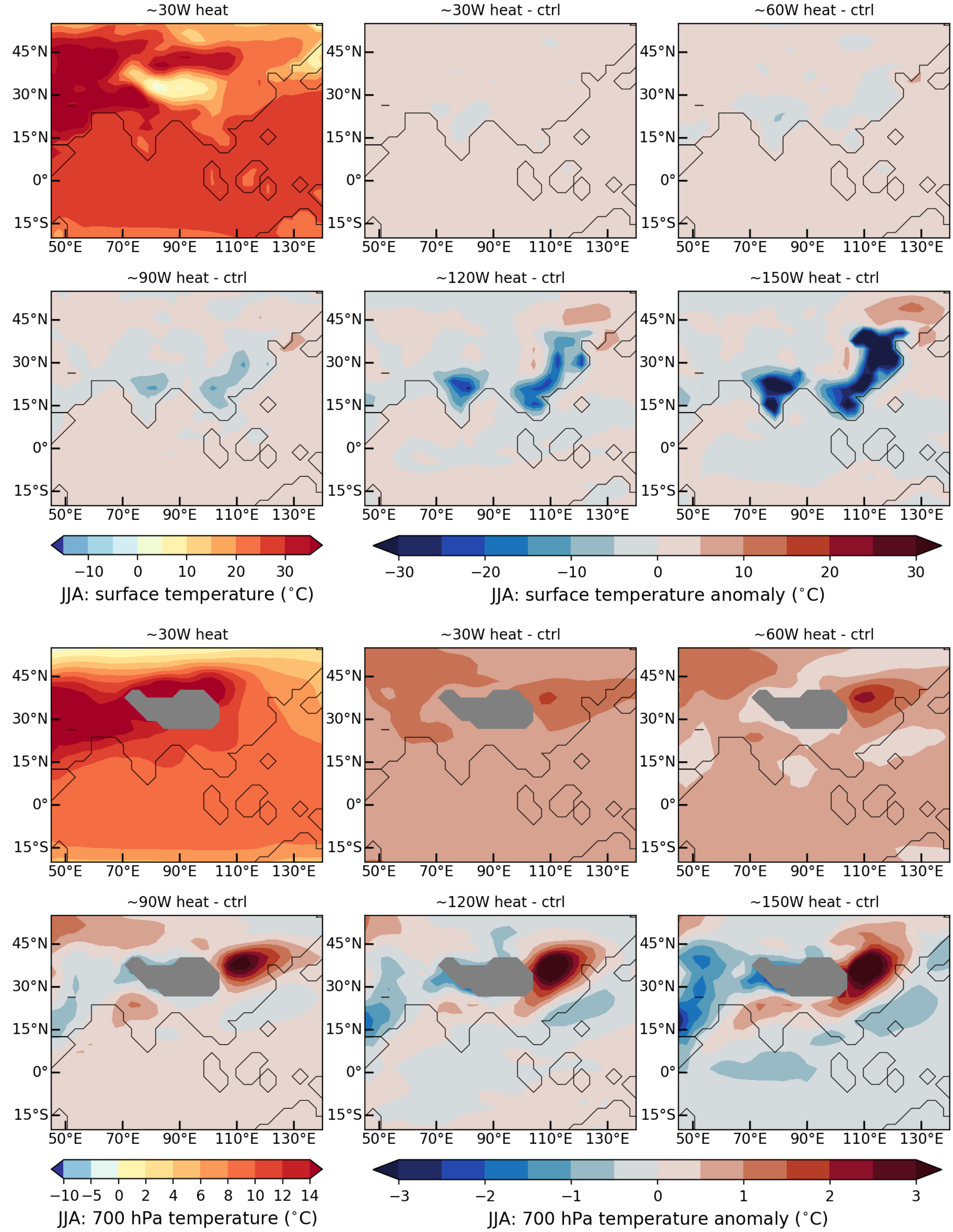

Figure 12: *Heat only* simulation. Contours showing mean decadal June-July-August temperature and mean decadal June-July-August temperature anomaly compared to the control run, for a range of heat forcing values. The top two rows are at the surface and the bottom two rows at 700 hPa. Areas of high orography are masked in grey.

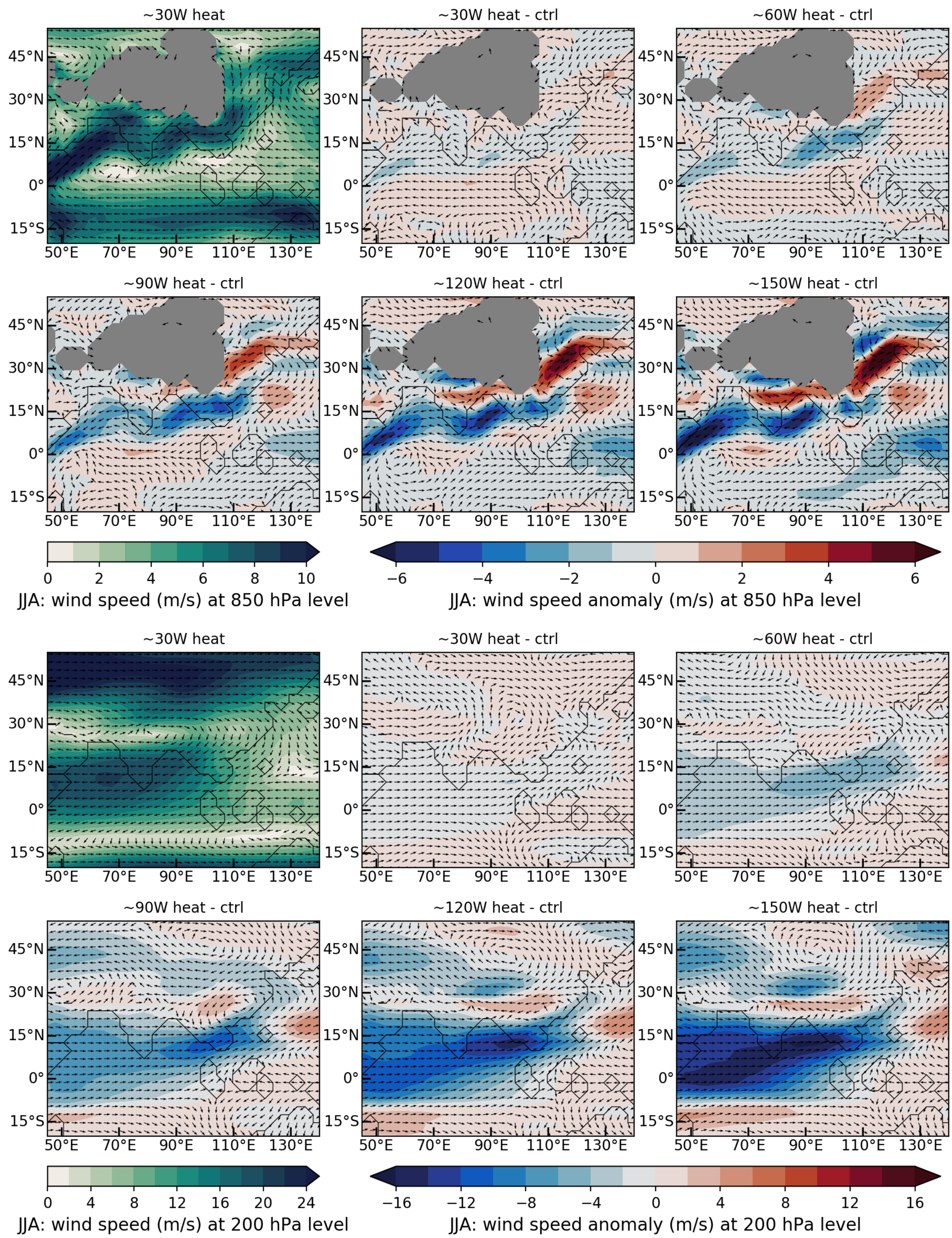

Figure 13: *Heat only* simulation. Contours showing mean decadal June-July-August wind speed & direction (shading & vectors) and mean decadal June-July-August wind speed & direction anomaly (shading & vectors) compared to the control run, for a range of heat forcing values. The top two rows are at 850 hPa and the bottom two rows at 200 hPa. Areas of high orography are masked in grey.

Evaporation

The evaporation rate (Figure 11, bottom two rows) decreases with increasing heat forcing, following a similar spatial pattern to the precipitation. However, the decline in evaporation is lesser than the decline in precipitation, meaning that the reduction in rainfall is not solely due to a lack of moisture in the atmosphere. In addition, although the evaporation rate reduces over India, this does not correspond with a reduction in precipitation. Thus, there is a mechanism of moisture being advected to India, likely from the surrounding oceans.

Clouds & radiation

In Figure 11, it can be seen that cloud cover over India increases as the forcing increases, further supporting the supposition that the precipitation decline is due to a loss in efficiency, and not a lack of moisture. Generally, cloud cover decreases around coastlines and over ocean, but increases slightly inland to the north and west of India, spatially coherent with the precipitable water. Outgoing longwave radiation (not shown) increases over the Arabian Sea, Southeast Asia and East China, as forcing increases, consistent with the reduction the cloud cover.

Temperature

Considering Figure 12 (top two rows), a surface cooling of several degrees is immediately evident over India for approximately 30W of heating. By around 90W of heat forcing, some areas of India and South East Asia have cooled by 10°C. Above 90W, the surface temperature drops more rapidly and becomes unrealistically cool at -15°C in parts of East China when the forcing is close to 150W. At the 700 hPa level (Figure 12, bottom two rows), a warm anomaly develops over East China, which becomes warmer as the forcing increases. There is also a slight warming at 700 hPa over North India. Despite the same forcing being applied over Southeast Asia, there is no corresponding warming at the 700 hPa level. When the heat forcing is greater than 90W, a cold anomaly forms over the Middle East, creating an East-West temperature dipole. There is some hysteresis evident at 700 hPa, with the entire plot region being warmer at the end of the simulation than at the start. The temperature variation at the surface is greater than at the 700 hPa level. In general, the combination of surface cooling and mid-level warming leads to a strong temperature inversion, increasing the static stability of the atmosphere and suppressing moist convective processes.

Circulation

The addition of heat forcing, representing absorbing aerosols, weakens the large-scale circulation. At low levels (Figure 13, top two rows), there is a reduction in strength of the southwesterly wind, which is a key driver of both the Indian and East Asian monsoons. With approximately 60W of heating, the wind speed is reduced by 2-3 ms^{-1}, and with 90W heating, there is a 4-5 ms^{-1} reduction in wind speed. When the maximum forcing is applied, the speed of the southwesterly monsoon wind becomes close to zero. There is a strengthening of the southwesterly wind in East China, causing dry air to be advected towards East Siberia and corresponding to a reduction of precipitation in the region. The mid-level wind field (not shown) experiences changes of a similar magnitude to the low-level wind field. Several regions, including North India, Bangladesh and East China, have increased wind speeds, which are associated with the formation of atmospheric highs. At high levels (Figure 13, bottom two rows), there is a significant reduction in the speed of the Tropical Easterly Jet, from Southeast Asia to the east coast of Somali. Higher heat forcing corresponds with greater declines in easterly wind speeds. Additionally, there is a slight weakening of the westerly subtropical jet, located north of India, at high forcing rates (>90W).

Pressure

Several areas - Northwest India, Bangladesh and East China - show increasing height of the 500 hPa level as the forcing increases (Figure 14). The greatest positive geopotential height anomaly, over East China, indicates a region of persistent high pressure. The assertion of an atmospheric high over East China is supported by the mid-level wind field, warmer 700 hPa temperatures and reduced precipitation.

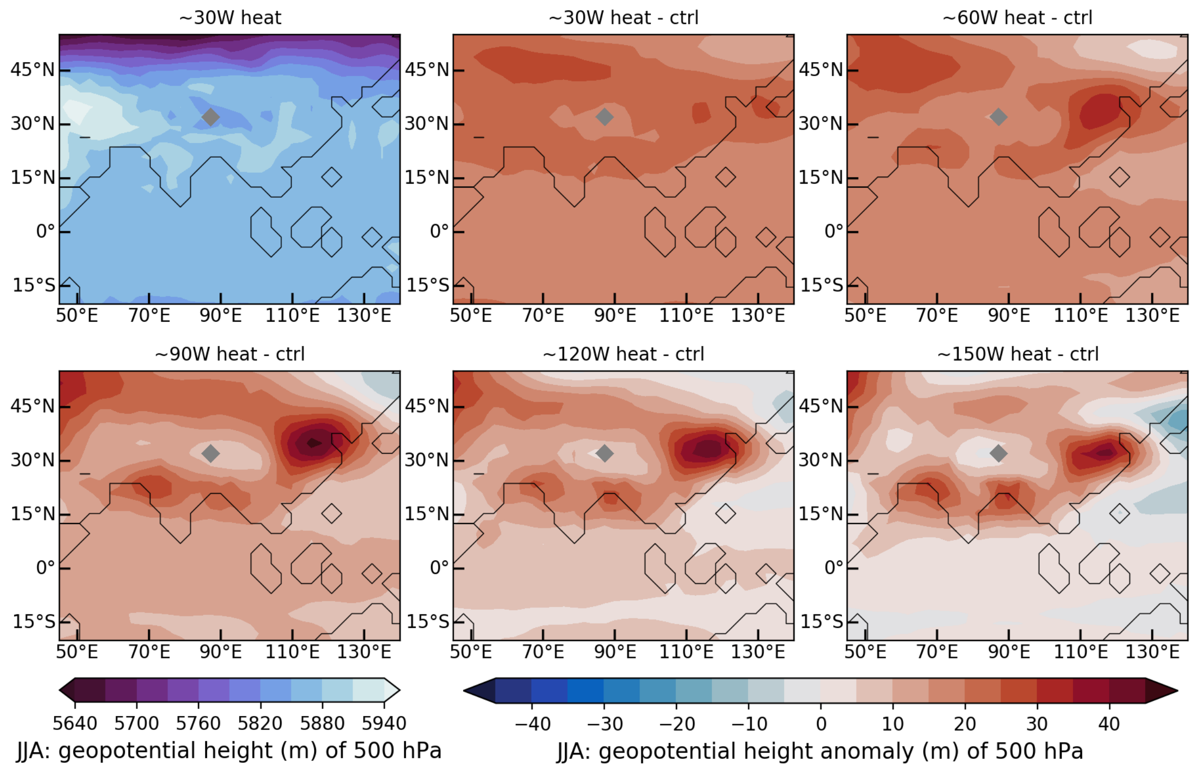

Figure 14: *Heat only* simulation. Contours showing mean decadal June-July-August 500 hPa geopotential height (top left) and mean decadal June-July-August 500 hPa geopotential height anomaly compared to the control run, for a range of heat forcing values. Areas of high orography are masked in grey.

Summary & discussion

Increasing mid-tropospheric heating, a proxy for absorbing aerosols, over southern Asia, cools the surface, suppresses precipitation and weakens the large-scale circulation in the region. Areas of high pressure form, most prominently over East China. Some effects, such as the reduction in precipitation, extend to eastern Siberia. There is a much greater decline in precipitation over Southeast Asia and East China, than over India. The weakening of both the Indian and East Asian monsoons in response to absorbing aerosol forcing has been observed and modelled (e.g. Lau and Kim (2010); Bollasina et al. (2011); Ganguly et al. (2012); Song et al. (2014); Dong et al. (2019)). Our simulation results are in agreement with the results of CMIP5 and CMIP6 standard models (Song et al., 2014), in particular with Ayantika et al. (2021) and their historic simulations with the IITM Earth System Model (version 2).

Response to combined absorbing aerosol and greenhouse gas forcing

Generally, enhanced carbon dioxide levels leads to higher surface temperatures, higher humidity levels and weakening of the large-scale circulation. The response of the monsoons to greenhouse gas forcing can be contradictory to the response to aerosol forcing. In our experiments, we find that doubling carbon dioxide levels slightly moderates the effect of the aerosol-style heat forcing. For key variables such as precipitation and surface temperature, the decline is lesser for the combination of greenhouse gas and absorbing aerosol forcing than for the absorbing aerosol forcing alone.

Figure format

The figures in this section are presented as 2 x 6 panels, with the top row showing the anomaly with respect to the control simulation and the bottom row the anomaly with respect to the *heat only* simulation. The three columns represent the forcing at approximately 30W, 60W and 90W. Given that there is almost no hysteresis, we take the average of the two halves of the dataset; the ascending branch of forcing 0→150W and the descending branch of forcing 150→0W. Thus, each panel in the figures is produced using the average of the two 10-year means centred around the forcing values of 30, 60 and 90W. All means refer only to the summer months - June, July, August.

Precipitation & evaporation

There is a significant decline in precipitation over Southeast Asia and East China as the heat forcing increases, following the pattern of the *heat only* simulation (Figure 15, top two rows). South India and areas of higher orography also see a reduction in rainfall. In contrast, there is a slight increase in precipitation over North India compared to both the control and the *heat only* simulations. Within the forced regions, evaporation rates decline with heat forcing, although at a lesser rate than for the *heat only* simulation. Over the ocean, evaporation is greater for the *heat with* $2xCO_2$ run, compared with the other simulations.

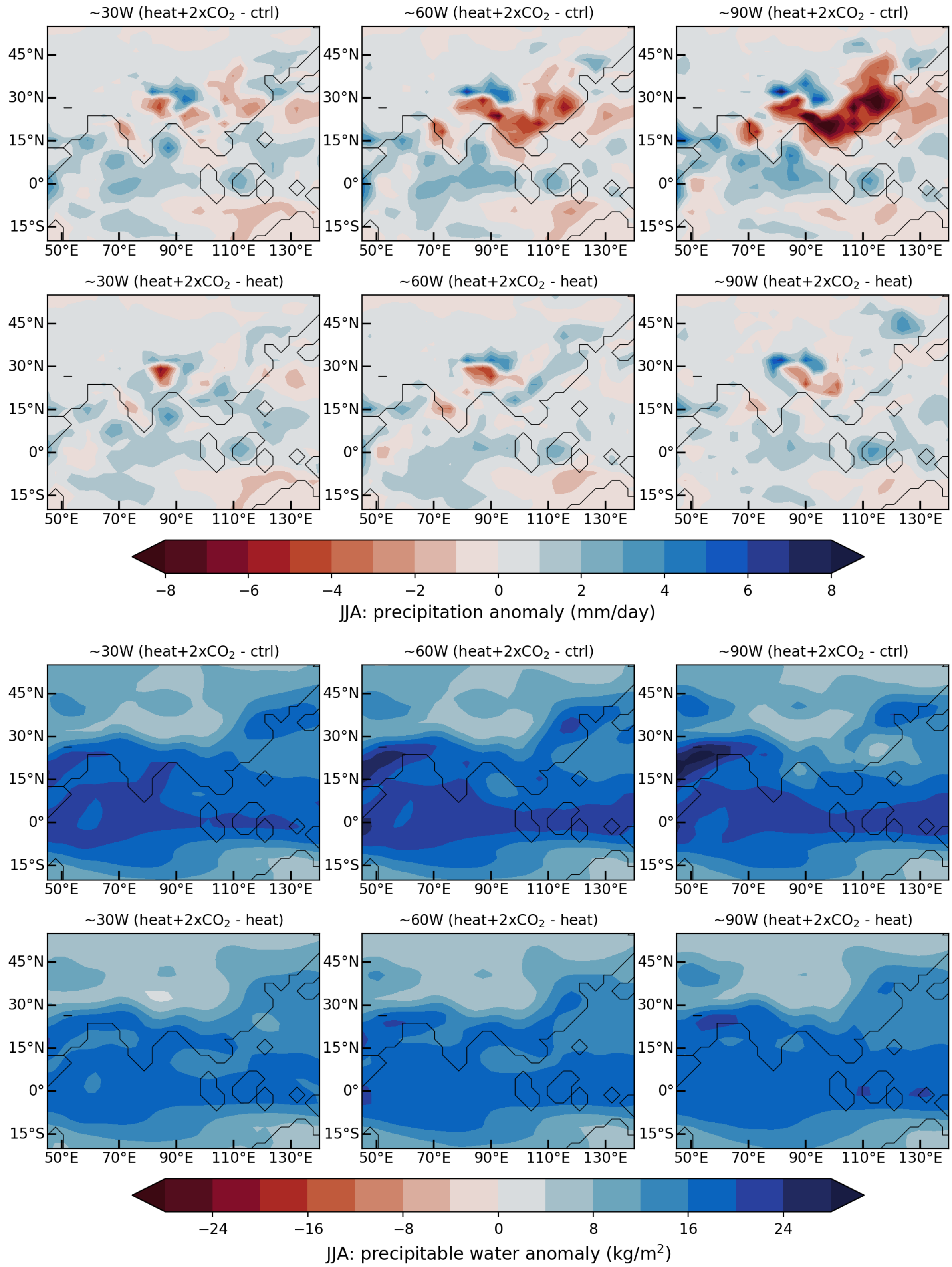

Figure 15: *Heat with $2xCO_2$* simulation. Contours showing mean decadal June-July-August precipitation anomaly (top two rows) & precipitable water anomaly (bottom two rows), for a range of heat forcing values. The top & third rows are the anomaly compared to the control run (*heat with $2xCO_2$* - control), and the second & bottom rows are the anomaly compared to *heat only* run (*heat with $2xCO_2$* - *heat only*).

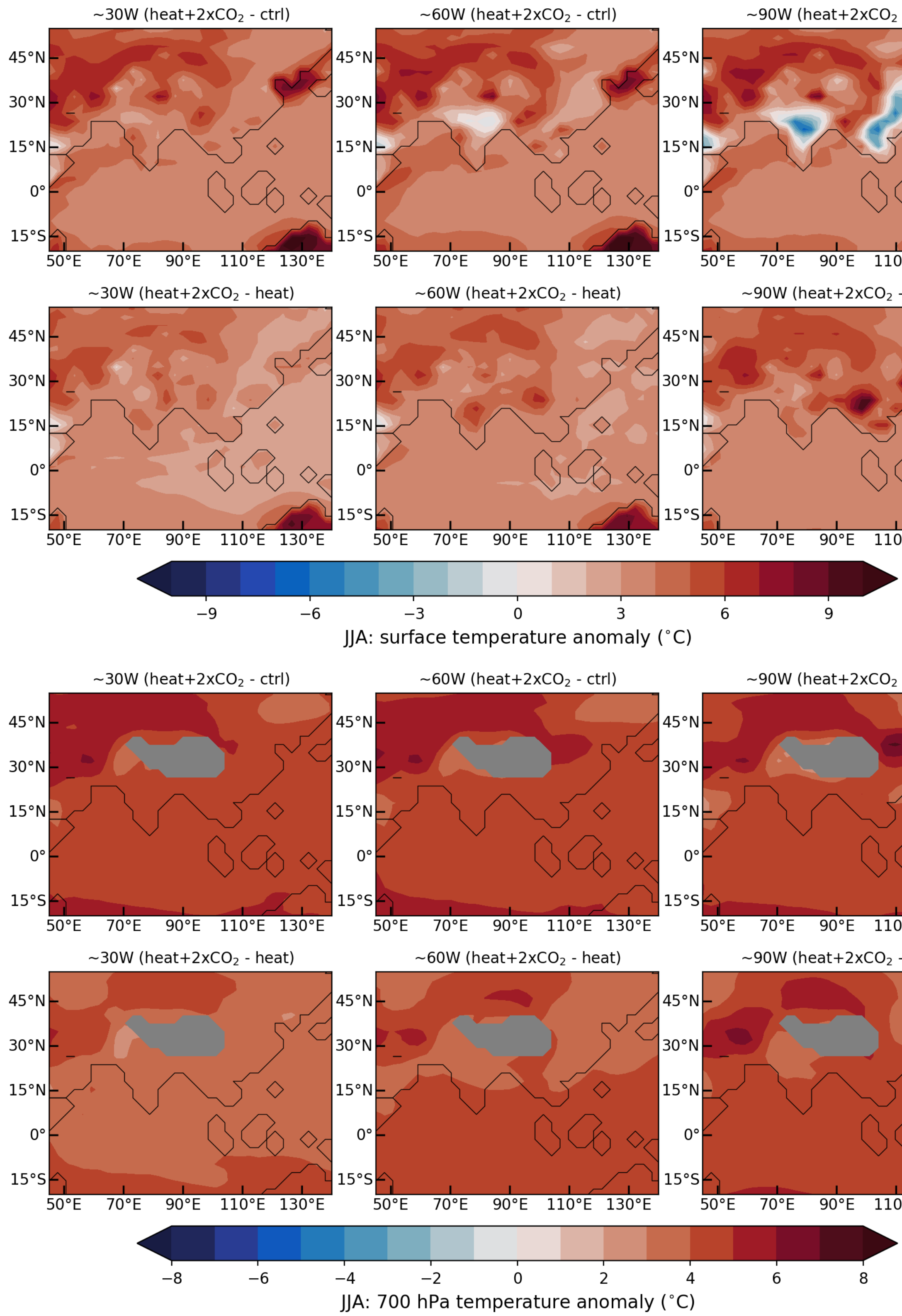

Figure 16: *Heat with 2xCO_2* simulation. Contours showing mean decadal June-July-August surface/700 hPa temperature anomaly (top/bottom rows), for a range of heat forcing values. The top & third rows are the anomaly compared to the control run (*heat with 2xCO_2* - control), and the second & bottom rows are the anomaly compared to *heat only* run (*heat with 2xCO_2* - *heat only*). Areas of high orography are masked in grey.

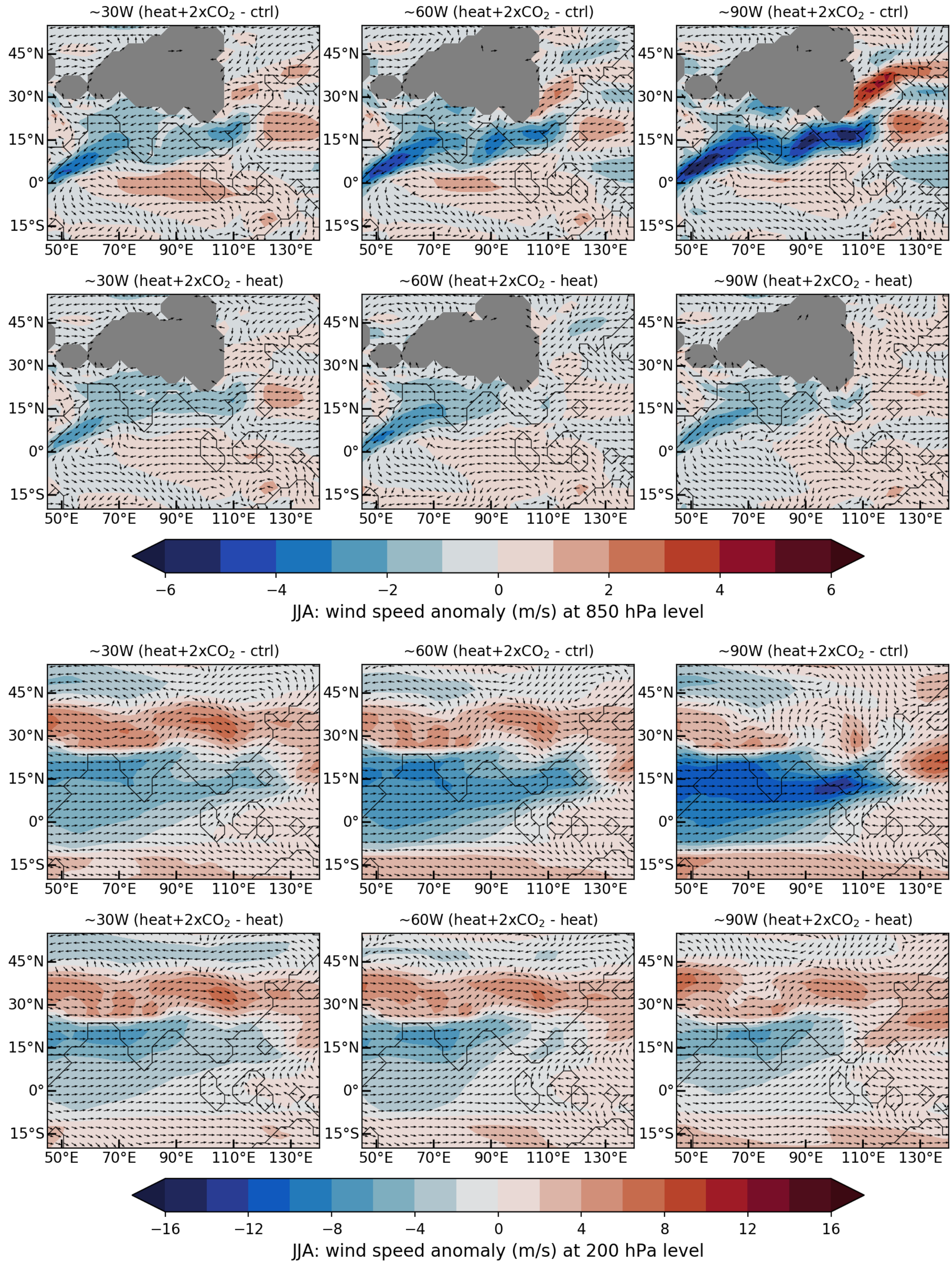

Figure 17: *Heat with 2xCO_2* simulation. Contours showing mean decadal June-July-August 850/200 hPa wind speed & direction anomaly (top/bottom two rows), for a range of heat forcing values. The top & third rows are the anomaly compared to the control run (*heat with 2xCO_2* - control), and the second & bottom rows are the anomaly compared to *heat only* run (*heat with 2xCO_2* - *heat only*). Areas of high orography are masked in grey.

Precipitable water

Doubling the carbon dioxide enables greater moisture uptake, thus it is expected that the precipitable water will be higher, as shown by Figure 15 (bottom two rows). Note that the higher levels of precipitable present in the *heat with 2x*CO_2 run do not correspond with a significance difference in rainfall between the two heat-forced runs.

Temperature

The areas where the heat forcing is applied experience a cooling of the surface, although the surface temperature is 10-15°C warmer in the *heat with 2x*CO_2 simulation than in the *heat only* simulation. Elsewhere, for the *heat with 2x*CO_2 run, both surface and 700 hPa temperatures are around 5°C higher than either the control or the *heat only* runs (Figure 16).

Circulation

The large-scale circulation weakens in a similar way to the *heat only* run. At low levels (Figure 17, top two rows), the southwesterly monsoon wind speed decreases in relation to the *heat only* simulation by a further 2-3 ms^{-1}. At mid-levels, the anti-cyclonic wind over the Middle East is stronger in the *heat with 2x*CO_2 simulation than the control or the *heat only* simulations. As in the *heat only* run, the 500 hPa geopotential height (not shown) indicates areas of high pressure in North India, Bangladesh and East China. Generally, the 500 hPa geopotential height is greater everywhere in the *heat with 2x*CO_2 simulation. Considering Figure 17 (bottom two rows), showing the high level wind field, a further weakening of the Tropical Easterly Jet can be seen compared to the *heat only* run. In contrast, there is a strengthening of the westerly Subtropical Jet (30-45°N). The strengthening of the jet is likely related to the warmer mid-tropospheric temperatures in the *heat with 2x*CO_2 simulation, analogous to the mechanism described by Rotstayn et al. (2013) for the subtropical jet in the Southern Hemisphere.

Consistency of response

The difference between the *heat with 2x*CO_2 and the *heat only* simulation remains similar, regardless of the forcing intensity. Looking at the second and bottom rows in Figures 15 to 17, the panels for 30W, 60W and 90W forcing are comparable, indicating linearity in the system.

Summary & discussion

In general, greenhouse gases act to warm the surface temperature, enabling greater moisture uptake of the atmosphere and leading to enhanced rainfall (e.g. Douville et al. (2000); Ueda et al. (2006); Cherchi et al. (2011); Samset et al. (2018)), whilst aerosols are responsible for cooling and drying trends (Monerie et al., 2022). We find that enhanced carbon dioxide levels act to partially mitigate the effect of imposed aerosol-style forcing. Compared to the *heat only* simulation, the *heat with 2xCO_2* simulation is warmer at the surface and aloft, has higher levels of precipitable water and precipitation, weaker low-level winds but a stronger subtropical jet. Although doubling the carbon dioxide has a significant impact on the Indian monsoon, here we find that the aerosol forcing dominates. The competition between aerosol and greenhouse gas forcing with respect to the Indian monsoon has been explored in a range of modelling experiments (Samset et al., 2018; Wilcox et al., 2020; Ayantika et al., 2021; Swaminathan et al., 2022), yet the uncertainty in the forcing itself limits the degree to which the response can be constrained. Our results suggest that in the future, the anticipated reduction in aerosol concentration will have a greater impact on monsoonal precipitation in India than the increase in greenhouse gases.

Sensitivity to area of applied forcing

The location of the applied heat forcing is varied, to investigate both the local regional response and any remote connections. Referring back to Figure 9, a heat forcing of 60W is applied in turn to each of the black-outlined regions - India, Southeast Asia and East China. Figure 18 shows the precipitation and surface temperature anomalies, with respect to the control run, for the three simulations. The data is seasonally averaged over a 50-year period, and we show the summer months: June, July and August.

In general, East China exhibits the greatest response to local forcing, in agreement with the results presented in Section “Response to absorbing aerosol forcing”. When either India or Southeast Asia is heat-forced, the spatial response of the region is mostly in accordance with the area of applied forcing. Forcing applied to East China is responsible for the remote connection in Siberia. Furthermore, forcing East China has nearly as great an effect on India as forcing India itself. In particular, it is the forcing over the East China region that is responsible for the increased moisture and cloud cover over India, which is linked with the lesser decline of precipitation over India, compared to the other regions (Figure 18, top row).

Considering the surface temperature anomaly (Figure 18, second row), forcing East China causes the surface temperature to drop in both East China and India. However, forcing Southeast Asia has the opposite effect on India, with a remote link to India leading to surface warming. The contrasting effects on surface temperature in India from forcing East China and Southeast Asia cancel out when the regions are forced simultaneously.

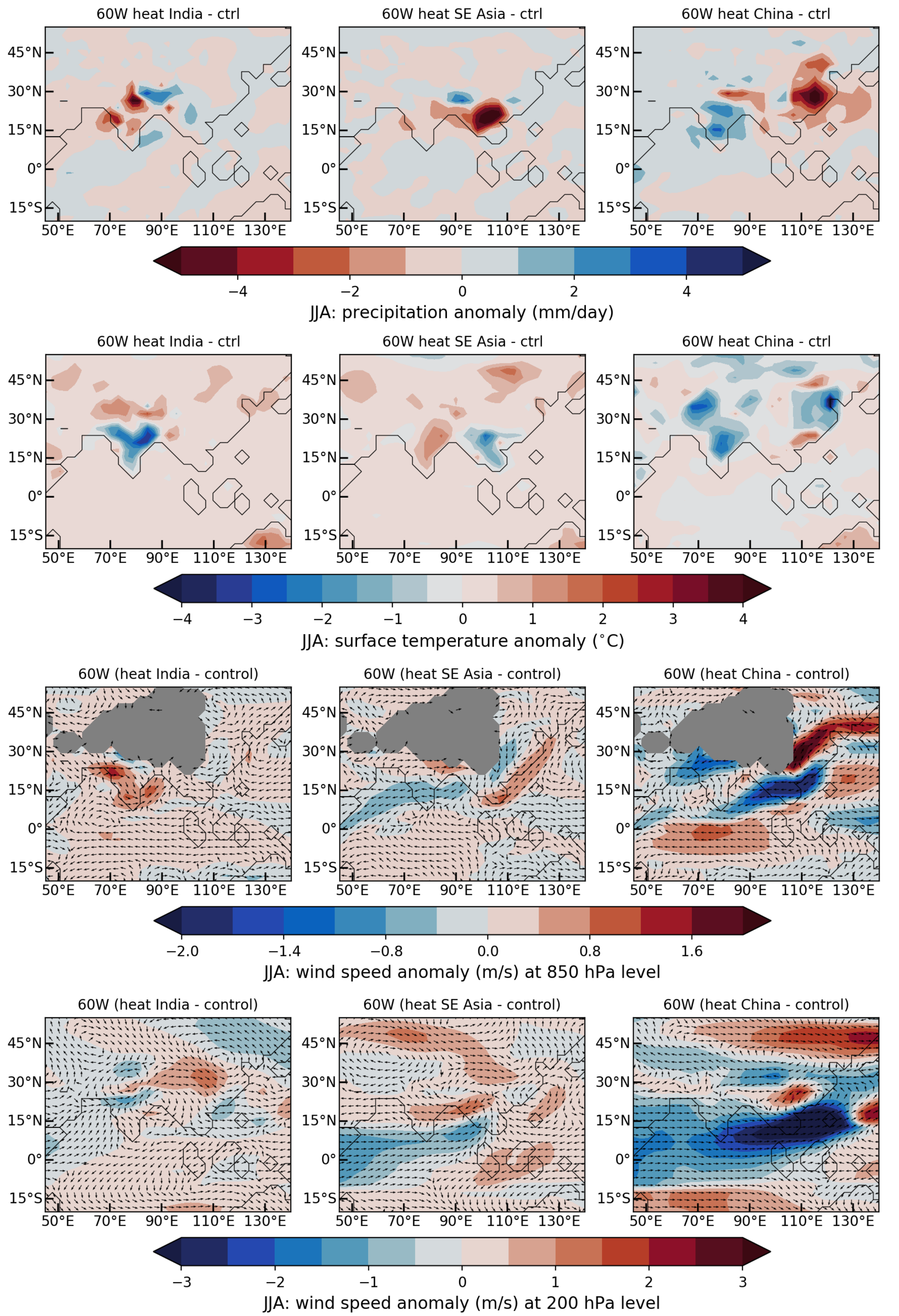

Figure 18: Applying 60W heat forcing in turn to regions of India, Southeast Asia and East China. 50-year June-July-August mean anomaly of labelled variables, compared to the control run. Areas of high orography are masked in grey.

In terms of the circulation, the majority of the changes are attributed to forcing East China (Figure 18, bottom two rows). These changes include a reduction in the low-level southwesterly monsoon flow, increased advection from East China to Siberia at low-mid levels, and a decrease in speed of the Tropical Easterly Jet at high levels. Forcing Southeast Asia also contributes to slowing down the low-level southwesterly wind, which brings moisture from over the Arabian Sea to India. Despite the reduction of moisture influx to India from the southwest, more moisture is retained over India because of the lower rates of advection toward Southeast Asia. This mechanism is primarily attributed to forcing East China.

These results compliment the findings of Herbert et al. (2022), in that varying the aerosol forcing over East China has a greater effect on the surrounding regions than varying forcing over India. Similarly, Guo et al. (2016) find that the biggest contributors to precipitation changes over India are from remote sources.

Quantifying the linearity of the response

Combining the separately forced regions of India, Southeast Asia and East China, (Section) and comparing to the *heat only* simulation at a 60W snapshot, where all the regions are forced simultaneously, we find some linearity in response. Looking at Figure 19, the left and right columns are qualitatively similar. This is in contrast to Herbert et al. (2022), who found a non-linear response when North India and East China were forced separately, compared to being forced simultaneously. The discrepancy is likely due to the use of different models and forcing strategy.

From the earlier figures and sections, it is difficult to quantify the relationship between key variables and the applied forcing. To investigate further, quantities such as precipitation and precipitable water are averaged over several regions and compared to the varying forcing. The linearity of the relationship between the variable and the forcing is considered for the regions of North India, South India, Southeast Asia and East China (as per the black outlined boxes in Figure 9). India is divided into North and South regions because of the variance in response. Figure 20 illustrates the results. Note that each line represents an average of the ascending (forcing 0→150W) and the descending (forcing 150→0W) halves of the dataset, due to the lack of hysteresis.

Relationship between precipitation and forcing

Looking firstly at the precipitation (Figure 20, top), we can see that the convective component dominates. As the forcing increases, the convective precipitation reduces; however, the large-scale precipitation slightly increases. The *heat with 2x*CO_2 show higher amounts of convective precipitation for each of the regions. There is significant variation in convective precipitation response between the regions, with East China showing the most abrupt decline and South India being the least impacted. The response of South India to the applied forcing, which causes a cooling and drying effect, is partially mitigated by advection of moisture from the surrounding oceans. For North India, there is a near-linear decline in convective precipitation as the forcing increases. As noted above, East China experiences an abrupt decline at approximately 60W forcing, after which the convective precipitation drops to almost zero. The behaviour of the

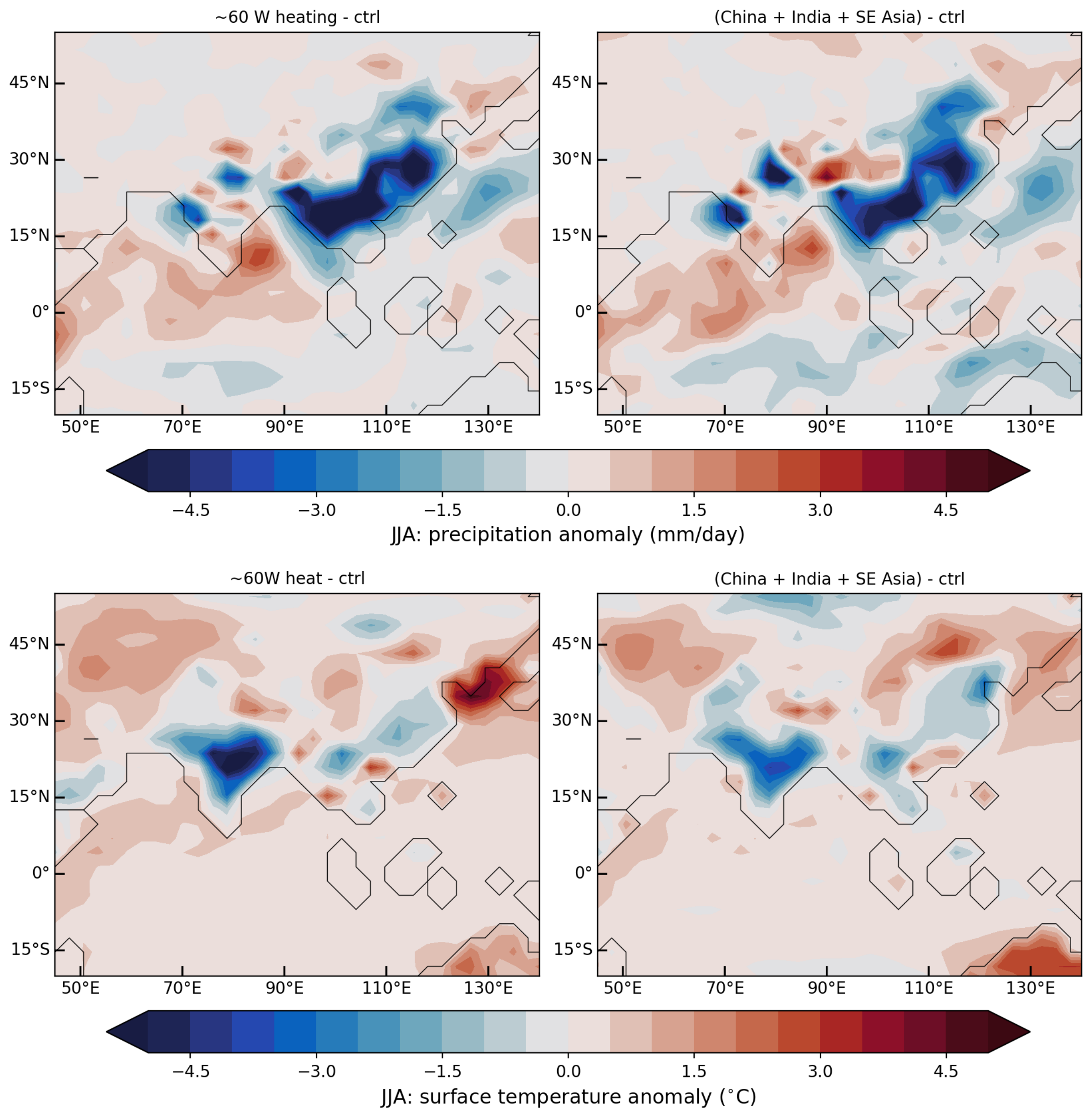

Figure 19: Precipitation (top) and surface temperature (bottom). Left column: 10-year June-July-August mean anomaly (*heat only* - control) that approximately corresponds to 60W forcing. Right column: sum of anomalies from regionally forced runs (India/East China/SE Asia - control), taken as 50-year June-July-August average.

convective precipitation in Southeast Asia is somewhere between that of East China and North India: it decreases more sharply than North India, but without the abrupt transition at around 60W.

Relationship between precipitable water and forcing

The regional variation of area-averaged precipitable water is less than that of precipitation. Rather, the more striking difference is the higher levels of precipitable water in the *heat with CO_2* runs, compared to the *heat only* runs. The much greater amount of precipitable water in the *heat with CO_2* runs doesn't correspond to much greater precipitation. Another key difference between the behaviour of precipitation and precipitable water is that while the precipitation decreases as the forcing increases from 0 to 60W, the *heat only* precipitable water remains constant and the *heat with CO_2* actually increases slightly. At 60W, there is a clear transition in the precipitable water for all regions, after which the precipitable water declines with further increases in forcing. The reduction in convective precipitation between 0 and 60W forcing is explained by a decrease in precipitation efficiency, and is not due to scarcity of moisture.

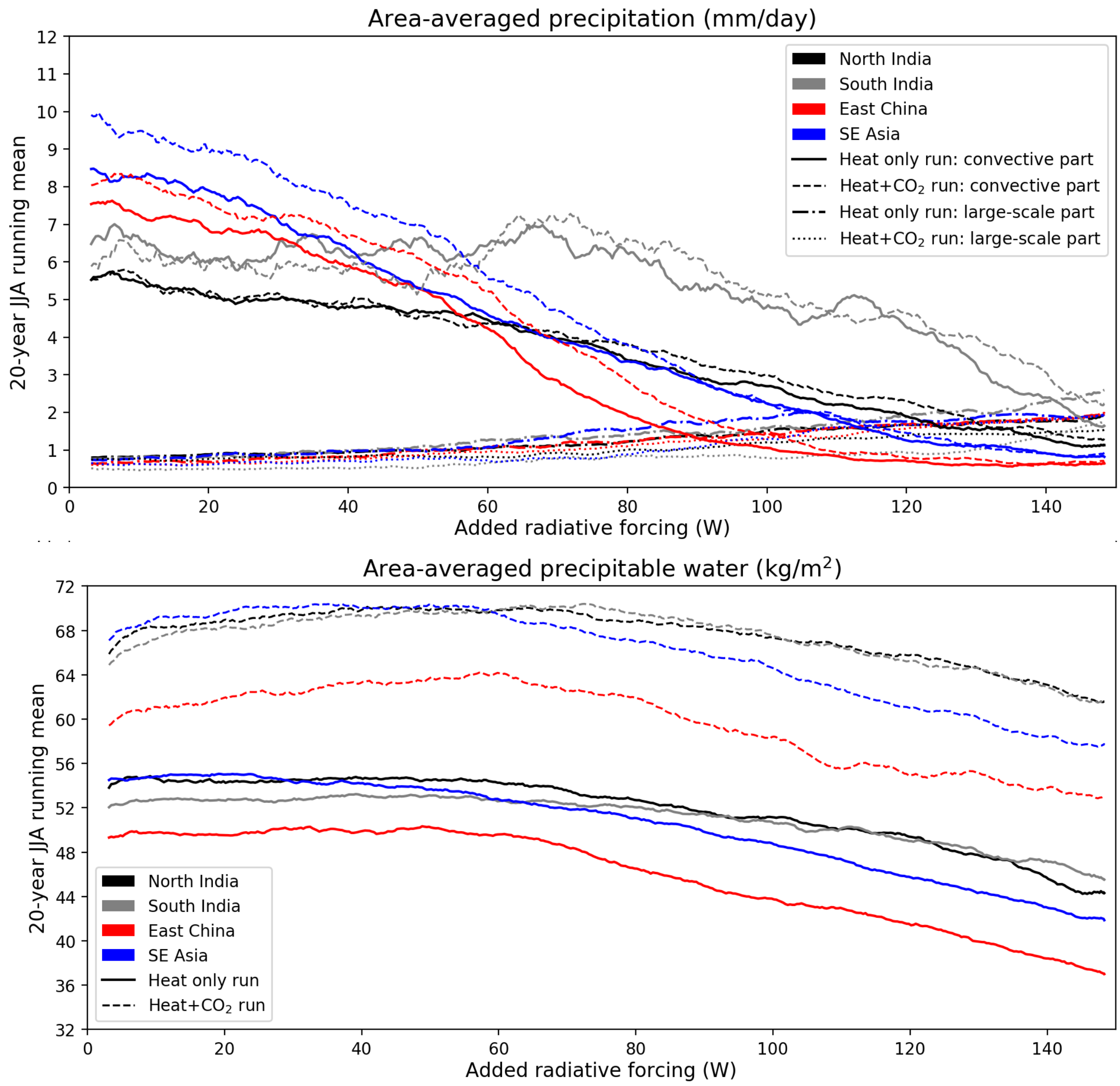

Figure 20: Precipitation (top) and precipitable water (bottom), averaged over the regions indicated (following the marked boxes in Figure 9), for *heat only* and *heat with 2xCO_2* runs, against the heat forcing. Precipitation is separated into convective and large-scale components. Variables taken as a running 20-year June-July-August mean.

Main results achieved

We have conducted a parametric study with an intermediate complexity climate model, to assess the roles of absorbing aerosol and greenhouse gas forcing on the Indian monsoon. In addition, we have identified the level of regional forcing at which the monsoon breaks down, in terms of a significant reduction in precipitation.

Absorbing aerosol forcing, which we apply through mid-tropospheric heating in our model, causes surface cooling, mid-level warming, weakening circulation and a reduction in (convective) precipitation. Surprisingly, as the forcing increases, the precipitation declines much faster than the precipitable water, indicating that it is a lack of precipitation efficiency, rather than a lack of moisture. Advection of dry air from East China leads to a reduction in precipitation in eastern Siberia, which is outside of the area being forced. Doubling carbon dioxide concentration partially mitigates the effects of the aerosol forcing, through warmer surface temperatures enabling greater moisture take-up, but further weakens the large-scale circulation. On removal of the heat forcing, we find that the monsoon system recovers fully, indicating that there is no hysteresis in our model simulations.

The strongest regional responses, particularly in regards to the circulation, are attributed to aerosol loading over East China. Although the precipitation decline for each region directly corresponds to applying forcing to that region, there is a remote connection between East China and India. Forcing applied to East China leads to an increase in precipitation over India, which is in contrast to the response when forcing is applied to India. When both regions are forced simultaneously, there is a reduction in precipitation over India, but the reduction is much than for Southeast Asia or East China. Comparing simulations where the regions have been forced separately to the simulation where the regions have been forced simultaneously, the results are qualitatively similar, indicating linearity in the response.

We have characterised regional behavioural regimes in terms of area-averaged precipitation and precipitable water. India is separated into North and South regions, due to the significant variance in their responses. South India is the least affected region, likely due to its peninsula nature. North India shows an approximately linear decrease in precipitation in relation to the heat forcing. For East China, there is an sharp transition at around 60W to a regime where the precipitation is close to zero. The precipitation response of Southeast Asia is somewhere between the other regions, with precipitation declining at a faster rate than North India but without the abrupt transition of East China. In terms of the precipitable water, it remains relatively constant for all regions until 60W; thereafter the precipitable water linearly declines with further increases in forcing.

We note the importance of aerosol loading over East China and the competition between aerosol loading over India, in determining the response of the India monsoon to future climate scenarios. A tipping point at approximately 60W of heat forcing causes a shift to a low precipitation regime for the East China region, whilst Southeast Asia and South India show a more linear decline in precipitation with increasing forcing. There is a compensating effect from East China aerosol forcing on precipitation over India. For area-averaged precipitable water, there is a clear transition at 60W for all regions from near-constant to decreasing levels. To maintain a safe operating space for the India monsoon, it is suggested to keep the absorbing aerosol forcing below 60W, through air quality policies and collaboration between Asian countries.

Progress beyond the state of the art

With this report we progress beyond the state of the art by using an intermediate complexity climate model to conduct a parametric study regarding the Indian monsoon response to regional and global forcings. There remains considerable uncertainty in the regional response to aerosol forcing over Asia, despite extensive modelling studies. Few studies use intermediate complexity climate models, although they have been shown to perform comparably to CMIP5 and CMIP6 standard models in long climate simulations. To our knowledge, no similar hysteresis-style experiment has been conducted. Furthermore, finding and modelling the breakdown of the Indian monsoon system under regional forcing, in a climate model, is relatively novel.

Impact

The Indian monsoon is a key meteorological event, bringing around 80% of India's rainfall during the summer months. Accurate prediction of the Indian monsoon is of great significance for Indian agriculture, industry and the economy. Delayed onset, periods of drought and extreme rainfall events have an impact on millions of people. It is important to understand how the Indian monsoon system will change in an evolving climate. This report reviews the state of the art research on the possible changes to the Indian monsoon system in a future climate, which helps support major scientific assessments such as the IPCC. Our work complements and builds on the existing literature, adding confidence to the results. It is expected that in the future, as greenhouse gases dominate over aerosol forcing, the Indian monsoon will bring more rainfall, despite a weakening in the large-scale circulation. We identify a tipping point in terms of aerosol forcing, beyond which the Indian monsoon breaks down and precipitation drastically declines. We also note the importance of aerosols over East China in their impact on the Indian monsoon. Both of these points have implications for air quality policies.

Regionally, there remains disagreement in the response to future climate scenarios, with the dynamic and thermodynamic reactions disputed. Further work is necessary to address shortcomings and biases in global climate models, which will increase confidence in future projections of the Indian monsoon. An outcome of this report is that it will help guide future modelling strategies of the project partners. It will also contribute to maintaining strong interdisciplinary collaborations across Europe, sustaining leadership and innovation in European climate science.

Lessons learned and links built

This report is the first of its kind in terms of assessing a suitable research direction for studying safe operating spaces of the Indian monsoon. We consider the Indian monsoon in a broader geographical and meteorological context, and identify the importance of regional aerosol forcing which can distinct non-local effects. The literature review presented will be of use to many in the scientific community, specifically experts in tropical meteorology and climate modelling groups active in CMIP. The report will also form the basis of a new publication, Recchia et al. (2022). Our simulations with an intermediate complexity climate model can be used to inform detailed modelling studies with advanced climate models, such as the UK Earth System Model (UKESM).

During the project, links have been built and strengthened with the University of Hamburg, specifically the Institute of Geography (S. Ul Hasson) and Institute of Meteorology (F. Lunkeit), through collaboration regarding modelling studies and technical advice. Within the TiPES community, we have strengthened the collaboration to WP3 (including M. Montoya, Universidad Complutense Madrid), by active discussions of the delivery during the weekly online meetings (Gathertown) and 6-monthly updates.

To highlight the importance and implications of this research, we have presented at the European Geosciences Union General Assembly 2022 (see “Dissemination activities”) and we plan to present at the American Geophysical Union Fall Meeting 2022.

Contribution to the top level objectives of TiPES

Objective 1-Identify tipping elements (TEs) and their interactions in models and data

The Indian monsoon has been identified as a possible tipping element. This report considers the representation of the Indian monsoon system and its dynamical interactions in state of the art climate models. A tipping point is found at 60W of absorbing aerosol style forcing for the East China region, after which the monsoonal precipitation declines to almost zero. The other regions, India and Southeast Asia, show a more linear decrease in precipitation as forcing increases. We also see a transition at 60W from constant to declining precipitable water, for India, Southeast Asia and East China. On removal of the applied forcing, the system fully recovers.

Objective 3-Characterise climate response in the presence of Tipping Points (TPs)

The response of the Indian monsoon to future climate forcings has been evaluated. Systematic biases in models which contribute to uncertainty in future predictions, have also been noted. A regime shift in the Indian monsoon from high to low precipitation has been discovered when aerosol forcing is applied to the Asian region. Aerosol loading over East China is found to be important for the response of the Indian monsoon.

Objective 4-Define and identify safe operating spaces

Having identified a transition at 60W of absorbing aerosol forcing, it is suggested to keep the equivalent aerosol loading under this value in order to maintain a safe operating space. For India, it is important to consider both local and remote aerosol forcing, which can have contrasting effects on the monsoon. Note that increasing levels of carbon dioxide partially negate the negative precipitation impact of aerosol forcing.

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Dissemination and exploitation of TiPES results

Dissemination activities

Type of dissemination activity	Name of the scientist (institution), title of the presentation, event	Place and date of the event	Estimated budget	Type of audience	Estimated number of persons reached	Link to Zenodo upload
Communication in the host institution & social media engagement	Department of Mathematics and Statistics, Centre for the Mathematics of Planet Earth, University of Reading	ongoing	N/A	Scientific community (higher education, research)	150	N/A
EGU presentation	Lucy Recchia (UR), "Effect of varying aerosol forcing on the Indian summer monsoon in an intermediate complexity climate model"	online, 24/05/22	£160	Scientific community (research)	200	https://meetingorganizer.c 12436.html
TiPES presentation	Lucy Recchia (UR), " Investigating the response of the Indian & East Asian monsoons to varying anthropogenic aerosol forcing, in accordance with future climate scenarios"	online, 22/04/22	N/A	TiPES project	50	N/A
TiPES presentation	Lucy Recchia (UR), WP3 update	online, Jan 22	N/A	TiPES project	30	N/A
TiPES presentation	Lucy Recchia (UR), WP3 update	online, Jun 21	N/A	TiPES project	30	N/A
TiPES presentation	Lucy Recchia (UR), WP3 update	online, Sep 21	N/A	TiPES project	30	N/A

Peer reviewed articles

Title	Authors	Publication	DOI	Is TiPES correctly acknowledged?	How much did you pay for the publication?	Status?	Open access granted	Comment on the embargo imposed by the publisher	If in Green OA, provide the link where this publication can be found
Controls on propagation of the Indian monsoon onset in an idealised model	L.G. Recchia, S.D. Griffiths, D.J. Parker	Quarterly Journal of the Royal Meteorological Society	10.1002/qj.4165	Yes		Published	Yes	None	N/A
Effect of varying aerosol forcing on the Indian summer monsoon in an intermediate complexity climate model	L.G. Recchia, V. Lucarini, F. Lunkeit, S. ul Hasson	Earth System Dynamics	N/A	Yes	N/A	In prep.	N/A	N/A	N/A
Seasonal prediction of Indian summer monsoon onset with echo state networks	T. Mitsui, N. Boers	Environmental Research Letters	10.1088/1748-9326/ac0acb	Yes		Published	Yes	None	N/A
Holocene climate forcings and lacustrine regime shifts in the Indian summer monsoon realm	S. Prasad, N. Marwan, D. Eroglu, B. Goswami, P.K. Mishra, B. Gaye, A. Anoop, N. Basavaiah, M. Stebich, A. Jehangir	Earth Surface Processes and Landforms	10.1002/esp.5004	Yes		Published	Yes	None	N/A

Other publications

https://www.tipes.dk/improved-prediction-of-indian-summer-monsoon-onset-three-months-in-advance-using-machine-learning/

Uptake by targeted audiences

As indicated in the Description of the Action, the audience for this deliverable is:

X	The general public (PU) and is made available to the world via https://cordis.europa.eu/.
	The project partners, including the Commission services (PP).
	A group specified by the consortium, including the Commission services (RE).
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