Impact of Asian aerosols on the summer monsoon strongly modulated by regional precipitation biases

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Abstract. Reliable attribution of Asian summer monsoon variations to aerosol forcing is critical to reducing uncertainties in future projections of regional water availability, which is of utmost importance for risk management and adaptation planning in this densely populated region. Yet, simulating the monsoon remains a challenge for climate models that suffer from long-standing biases, undermining their reliability in attributing anthropogenically-forced changes. We analyse a suite of climate model experiments to identify a link between model biases and monsoon responses to Asian aerosols, and associated physical mechanisms, including the role of large-scale circulation changes. The aerosol impact on monsoon precipitation and circulation is strongly influenced by a model's ability to simulate the spatiotemporal variability of the climatological monsoon winds, clouds, and precipitation across Asia, which modulates the magnitude and efficacy of aerosol-cloud-precipitation interactions, an important component of the total aerosol response. There is a strong interplay between South and East Asia monsoon precipitation biases and their relative predominance in driving the overall monsoon response. We found a striking contrast between the early and late summer aerosol-driven changes ascribable to opposite signs and seasonal evolution of the biases in the two regions. A realistic simulation of the evolution of the large-scale atmospheric circulation is crucial to realise the full extent of the aerosol impact over Asia. These findings provide important implications to better understand and constrain the diversity and inconsistencies of model responses to aerosol changes over Asia in historical simulations and future projections.

1 Introduction

The Asian summer monsoon is one of the key components of the global atmospheric circulation, providing critical water resources to more than 60% of the world's population. Because of this reliance, even small changes in the spatio-temporal characteristics of the monsoon represent a significant hurdle for the local population. Yet, despite considerable efforts, simulating the monsoon remains a long-standing challenge for climate models as some biases have persisted for decades, such as the deficient rainfall over central India and excess wetting over eastern China (Sperber et al., 2013; Liu et al., 2021). The existence of these large and widespread biases not only decreases the confidence in the modelled monsoon and associated physical mechanisms (Yang et al., 2019; Jiang et al., 2020; Rajendran et al., 2022; Liu et al., 2022) but also represents a major cause of the large inter-model spread in historical monsoon evolution (Zhou et al., 2019; Guilbert et al., 2023). Moreover, these biases are likely to hinder reliable monsoon projections with critical implications for water management and planning across Asia and subsequent impacts on agriculture and economy (Zhou et al., 2019; Cao et al., 2020; Wang et al., 2020; Pillai et al., 2021). In particular, model biases introduce large uncertainties in our ability to separate externally-forced from internally-generated monsoon variability, preventing robust attribution to specific drivers, including the extent to which recent and near-future trends of temperature and precipitation over East Asia are driven by anthropogenic aerosols (Wilcox et al., 2015; Dai et al., 2022).

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50 Anthropogenic aerosols represent the largest uncertainty in quantifying the total anthropogenic forcing on climate since

51 the pre-industrial era (Andrews and Forster, 2020). Aerosols exert an overall cooling effect on climate by modulating

52 solar radiation via absorption and scattering, as well as by acting as cloud condensation and ice nuclei, and thus altering

53 cloud albedo, lifetime, and precipitation processes (Boucher et al., 2013). Asia has the largest present-day anthropogenic

54 aerosol burden as rapid urbanization and economic development have drastically increased aerosol emissions and loading

55 since the 1950s (Lin et al., 2016a). China has recently implemented strong pollution control policies, which has

56 substantially reduced aerosol emissions since 2013 (e.g., 59% for sulfur dioxide and 28% for black carbon during 2013–

57 2017; Zheng et al., 2018). Yet, Asia will still experience the highest aerosol loading in the world over the coming decades

58 as projected by the different future socioeconomic pathways used in the Coupled Model Inter-comparison Project Phase

59 6 (Lund et al., 2019).

60

61 Aerosols have been found to play a key role in driving the observed decreasing trend in Indian summer rainfall (Chung

62 and Ramanathan, 2006; Lau and Kim, 2010; Bollasina et al., 2011; Guo et al., 2015) and the southern-flood-northern-

63 drought (SFND) pattern over East Asia (Menon et al., 2002a; Guo et al., 2013; Song et al., 2014a; Yu et al., 2016; Tian

64 et al., 2018) during the late 20th century. Studies that have separately investigated the impact of regional (Asian) and

65 remote (outside Asia) emissions have found the former to be fundamental to explaining the observed monsoon changes,

66 but with the latter also providing an important contribution (Cowan and Cai, 2011; Ganguly et al., 2012; Bollasina et al.,

67 2014; Dong et al., 2016). In particular, either South or East Asian aerosols can separately exert a strong influence on both

68 the South and East Asian monsoons, with contrasting, if not opposite, changes as well as strong non-linear interactions

69 between the responses to individual emission sources (Singh et al., 2019; Sherman et al., 2021; Herbert et al., 2022; Liu

70 et al., 2023).

71

72 At larger scale, the Asian monsoon progression is linked to the evolution of semi-permanent features of the tropical and

73 extratropical atmospheric circulation, such as the western Pacific subtropical high (Zhang et al., 2005) and the Mascarene

74 high in the southern Indian Ocean (Vidya et al., 2020). The monsoon and the large-scale circulation are affected by

75 anthropogenic aerosol forcing, resulting in complex and intertwined interactions between externally and internally forced

76 variability (Deser et al., 2012; Huang et al., 2020a; Zha et al., 2022). Understanding the interplay between the Asian

77 monsoon and the large-scale circulation outside Asia and the extent to which concurrent changes in the large-scale

78 circulation modulate the monsoon response to regional aerosol changes is thus beneficial to achieve better monsoon

79 simulations and more robust projections (An et al., 2012; Liu et al., 2021).

80

81   One approach that has provided valuable insights into the mechanisms of aerosol-monsoon interactions is the

82   decomposition of the response into two complementary components: a fast response involving atmospheric and land

83   surface adjustments but fixed sea surface temperature (SST), acting on a short time scale (few years), and a slow response

84   scaling with SST changes (Samset et al., 2016; Li et al., 2020; Zhang et al., 2021). The fast and slow components over

85   and around Asia show similar features under global and regional (Asian only) aerosol forcing. In the case of sulfate

86   aerosols, the total response over Asia and downwind Pacific regions shows substantial precipitation decreases, with the

87   fast component featuring negative anomalies over land and positive ones over the adjoining ocean. While the monsoon is

88   a fully atmosphere-ocean coupled system, recent studies have found rapid adjustments to be of fundamental importance

89   in explaining inter-model differences in the response to aerosols (Fläschner et al., 2016; Liu et al., 2018; Zanis et al.,

90   2020).

91

92   Building on the above considerations, this study aims to identify a link between model biases and monsoon response to

93   Asian aerosols, and the underpinning physical mechanism, including the role of large-scale circulation changes outside

94   Asia and SST changes. The rest of the manuscript is organized as follows: Details of model experiments and analysis

95   methods are provided in Section 2. Section 3 examines the influence of precipitation biases on the climate response to

96   Asian aerosol perturbations and describes the underlying mechanism. Discussion and Conclusions follow in Section 4

97   and 5, respectively.

98   **2 Data and methods**

99   The primary dataset analysed consists of simulations conducted with the Met Office Unified Model (MetUM) HadGEM3-

100   Global Atmosphere version 7.1 (GA7.1) at N96 horizontal resolution (1.875° × 1.25°) and with 85 vertical levels

101   extending up to 85 km (Walters et al., 2019). The Global Model of Aerosol Processes (GLOMAP) modal aerosol scheme

102   is used to represent aerosol processes, including a representation of both aerosol-radiation and aerosol-cloud interactions

103   (see Mann et al., (2010) and Bellouin et al. (2013) for more details). GA7.1 was used as the atmospheric component of

104   the climate model participating in CMIP6, which reduces the overly negative global-mean anthropogenic aerosol effective

105   radiative forcing in the previous model version, GA7.0 (Walters et al., 2019). A single-moment microphysics is used

106   based on Wilson and Ballard (1999), with extensive improvement of the warm rain scheme (Boutle et al., 2014a, b). To

107   account for aerosol-cloud interactions, the cloud droplet number concentration is calculated using prognostic aerosol

108   concentration according to the UK Chemistry and Aerosol (UKCA)-Activate scheme (West et al., 2014). The atmospheric

109   boundary layer and convection schemes are based on Lock et al. (2000) and Gregory and Rowntree (1990), respectively.

110   A detailed description of the HadGEM3-GA7.1 physics provided by Walters et al. (2019).

111

112 A set of four experiments (see Table 1) is performed with HadGEM3-GA7.1 for the period December 1991 to December
113 2012 with prescribed daily observed SST from the European Centre for Medium-Range Weather Forecasts (ECMWF)
114 Interim Re-Analysis (ERA-I; Dee et al., 2011). The reference experiment (CONT) is driven by monthly-varying historical
115 emissions of anthropogenic aerosols and precursors following CMIP6 (Hoesly et al., 2018). CONTfA is identical to
116 CONT except for having anthropogenic aerosol emissions of sulfur dioxide (SO_2), black carbon, organic carbon, and
117 biomass burning emissions fixed at the year 1991 over Asia (10°–45°N, 60°–125°E, the purple box in Fig. 2c). The
118 difference between CONT and CONTfA represents the fast response to changes in Asian anthropogenic aerosols.
119
120 To separate regional and remote circulation adjustments to aerosol forcing, dynamical nudging (also known as Newtonian
121 relaxation) is applied by constraining horizontal winds towards ERA-I (Kooperman et al., 2012; Liu et al., 2021). We
122 conducted another pair of experiments (NUDG and NUDGfA, respectively) identical to CONT and CONTfA except for
123 nudging horizontal winds to ERA-I outside Asia (the region outlined in Fig. 2c). The difference, NUDG minus NUDGfA,
124 represents the local response to Asian aerosols in the absence of concurrent changes in the large-scale atmospheric
125 circulation outside Asia. Nudging is only applied above the planetary boundary layer (model level 12, or approximately
126 850 hPa) so that low-level winds can adapt to surface conditions (e.g., different topography with respect to ERA-I; (Liu
127 et al., 2021)). Comparing the differences between the free-running experiments (i.e., CONT – CONTfA) and the nudged
128 runs (i.e., NUDG – NUDGfA) enables us to determine the extent to which simultaneous adjustments in the large-scale
129 atmospheric circulation outside the region modulate the Asian monsoon response to changes in regional anthropogenic
130 aerosols.
131
132 To account for the role of internal variability, all experiments consist of three ensemble members initialized from different
133 atmospheric conditions. Only the last 10 years of each experiment are analysed (i.e., 2003 – 2012) when Asian aerosol
134 emissions are at the maximum (Fig. 2a). The results are however largely unchanged if a longer analysis window is chosen
135 (e.g., 15-year averages) as anomalies display similar large-scale features, albeit of slightly smaller magnitude (not shown).
136 The statistical significance of ensemble-mean differences relative to model internal variability is estimated using a 35-
137 year HadGEM3-GA7.1 experiment where all forcing factors are set at pre-industrial (1850) levels. After splitting the
138 output from this simulation into 26 overlapping 10-year segments, the probability distribution of the unforced 10-year
139 means for a 3-member ensemble is computed by randomly selecting three of these segments without repetition, for a total
140 of 2600 samples. In turn, the probability distribution of the 10-year ensemble-mean differences is calculated by randomly
141 selecting 2 of the 2600 samples a total of 10000 times (e.g., Efron and Tibshirani, 1993), and the 90% confidence interval
142 is estimated as the range in which 90% of the samples fall.
143

144 Data from the Precipitation Driver Response Model Intercomparison Project (PDRMIP; Samset et al., 2016) is also
145 utilized to corroborate our findings from a multi-model perspective. Two experiments are considered (Table 1) the
146 baseline simulation forced by present-day (year 2000) levels in aerosols and greenhouse gases emissions/concentrations,
147 and one identical to the baseline run except for having a ten-fold increase in sulfate aerosol emissions/concentrations over
148 Asia (10°–50°N, 60°–140°E; SULASIA). The geographical distribution of the baseline sulfate burden in the PDRMIP
149 ensemble (Myhre et al., 2017) is very close to that in the CONT–CONTfA difference (Fig. 2b) over Asia, with the latter
150 also showing an approximately 10-fold increase in SO_2 emissions since the early 1990s (Fig. 2a), which ensures a sound
151 comparison between the different simulations. The PDRMIP experiments were run for 15 years with fixed present-day
152 SSTs and for 100 years in coupled mode (Liu et al., 2018). The response to Asian aerosols is identified as the difference
153 between the perturbed and baseline simulation averaged over the years 6–15 for both fixed SST and coupled simulations.
154 In the case of fixed SST, this choice is consistent with previous studies (Samset et al., 2016; Myhre et al., 2017) and
155 accounts for the adjustment time to the step change in emissions from the baseline simulation. We chose the same
156 averaging period also for the coupled experiments for consistency with the nature of the transient response to time-
157 evolving emissions examined in this study. In this sense, the coupled experiments allow us to ascertain whether the
158 findings are sensitive to "fast" oceanic-mediated responses (i.e., air-sea interactions), thus excluding the contribution
159 brought about by slow oceanic adjustments pertaining to a fully equilibrated atmosphere-ocean climate system.
160
161 We also analyse the transient historical simulations with the MetUM HadGEM3-GC2 coupled model described in Wilcox
162 et al. (2019). These consist of four-member ensemble runs with all historical forcings, and a companion experiment in
163 which aerosols over Asia (5°–47.5°N, 67.5°–145°E) are fixed at their 1971–1980 mean levels (Table 1). The difference
164 between the two ensemble means across two 10-year periods (i.e., 1999–2008 and 1971–1980) is interpreted as the total
165 transient response to Asian aerosol changes. We choose the later period 1999–2008 when aerosol emission differences
166 maximize (see Fig. 1 in Wilcox et al., 2019) and are at a comparable magnitude to our HadGEM3-GA7.1 simulations.
167 These experiments allow us to ascertain the consistency between uncoupled and coupled transient settings.
168
169 In light of the strong seasonality of the precipitation response to aerosol changes and the partial compensation between
170 the monsoon response in the early and late summer (Bollasina et al., 2013), we examine monthly precipitation and
171 circulation changes in addition to the June–September seasonal means. The simulated climatological precipitation and
172 circulation are evaluated against the arithmetic mean of the Climate Prediction Center Merged Analysis of Precipitation
173 (Xie and Arkin, 1997) and the Global Precipitation Climatology Project (GPCP) version 2 (Adler et al., 2003)
174 precipitation observations (Wang et al., 2014) and the ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2020) sea-level
175 pressure and 850-hPa winds for the period 1981–2010, respectively. These datasets are also used to provide a broader
176 interpretation of the aerosol-driven simulated changes in the context of recent observed trends.

3 Results

3.1 Model evaluation

Fig. 1 compares the 1993-2012 June–September average precipitation and 850-hPa winds in the control simulation to observations (GPCP and CMAP average for precipitation, ERA5 for wind). The model reproduces the broad characteristics of the observed rainfall and circulation patterns (pattern correlation of 0.80 for precipitation, which is significant at the 99.9% confidence level). The difference panel indicates that the model underestimates the rainfall amount by 60% over India and the Bay of Bengal due to a weaker southwesterly monsoon flow. To the east, there are wet biases ranging from 20 to 60% of the observed climatology over southwestern China, and even up to 80% over the northwestern subtropical Pacific, associated with enhanced cyclonic flow. Note that this bias pattern is common across CMIP6 models, although the magnitude of the anomalies varies from model to model (Wilcox et al., 2020), and is also consistent with that in the historical simulations of the CMIP6 Met Office model (Rajendran et al., 2022). A thorough discussion of the model bias and its linkage to regional and remote circulation can be found in Liu et al. (2021).

3.2 Monsoon response to Asian aerosols in HadGEM3-GA7.1

3.2.1 Seasonal mean changes in Asian aerosols

The temporal evolution of the seasonal-mean differences in aerosol emissions and total aerosol optical depth (AOD) between CONT and CONTfA averaged over Asia (the area enclosed by the purple box in Fig. 2c) is displayed in Fig. 2a. The rapid rise of AOD after 2002 is mostly due to the increase in SO_2 emissions as the similarity between the respective time-series indicates. BC and OC emissions exhibit a comparatively minor increasing trend, while biomass burning emissions show negligible changes. The spatial distribution of changes in column-integrated sulfate burden closely resembles that of emission changes and is characterized by large increases over eastern China and northern India (Fig. 2b). The pattern of the seasonal AOD change follows that of sulfate loading, further indicating the primary contribution of SO_2 emissions to the total aerosol amounts over the region. Positive AOD anomalies also extend eastward from China to the northwestern Pacific, reflecting atmospheric transport of aerosols by climatological southwesterly winds. Seasonal mean aerosol changes across Asia are thus dominated by sulfate aerosols, consistently with longer-term trends since the 1950s (Lund et al., 2019), which hints at a predominant role of SO_2 emissions in driving the response discussed below.

3.2.2 Seasonal mean response to Asian aerosols

Fig. 3a shows the aerosol-driven summer precipitation changes. A band of excess rainfall stretches from southeastern China and the South China Sea (SCS) to northern Indochina and the northern the Bay of Bengal (BOB), associated with

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205 a negative sea-level pressure anomaly and anomalous cyclonic flow centered over the northern BOB (Fig. 3b). The
206 enhanced cross-equatorial southwesterly flow over the western tropical Indian Ocean and subsequent northeastward
207 moisture transport and precipitation increases across the basin indicate an intensified monsoon circulation (Fig. 3b and
208 3c). The anomalous wind then turns anticlockwise, bringing abundant moisture across the BOB to northern India,
209 Indochina, and southern China (Fig. 3c). Concurrently, anomalous dry westerlies over central India lead to precipitation
210 decrease, resulting in an approximately southwest to northeast oriented wet/dry rainfall dipole (Fig. 3a).

211

212 Over China, the widespread wetting to the south, together with the drying to the north, form a meridional dipole. The
213 dipole is accompanied by a marked anomalous anticyclone centered over the western subtropical Pacific and extending
214 further inland, suggesting a strong dynamical link with the rainfall anomalies via modulation of the climatological western
215 Pacific subtropical high (WPSH; Fig. 3a and 3b). On the southwestern flank of the anticyclone, anomalous southeasterlies
216 blow from the sub-tropical western Pacific across SCS and bring moisture to southern China (Fig. 3c). Here the flow
217 converges with the southwesterly winds from the Indian Ocean mentioned above, resulting in the abundant precipitation
218 increase. Moist southerlies further extend over eastern China and result in a positive, albeit of weak magnitude, moisture
219 convergence anomaly. This contrasts with the local precipitation deficit which, given also the modest evaporation
220 anomaly (not shown), appears to be associated with moisture divergence due to transient eddies whose contribution to
221 the total moisture flux convergence is relevant for the region (e.g., Seager et al., 2010; Li et al., 2018).

222

223 Examining these changes in a broader context, the aerosol-driven rainfall difference pattern displays, in its large-scale
224 features, a remarkable similarity, but opposite sign, to observations (Fig. 3a and 3d). In particular, model and observations
225 feature key rainfall action centers of comparable magnitude and in similar geographical locations while of opposite
226 polarity. For example, observed changes show drying from northern India across the northern BOB to southeastern China,
227 with wetting over central and western India, northern China, and the western subtropical Pacific (Fig. 3d), in stark contrast
228 to the simulated anomalies shown in Fig. 3a. These precipitation anomalies over East Asia are associated with an
229 anomalous cyclone over the western subtropical Pacific (Fig. 3g; compared to the anomalous anticyclone in Fig. 3b),
230 leading to oceanic moisture advection over northern China and dry northeasterlies over southern and eastern China.
231 Anomalous anticyclonic anomalies are seen over the northern BOB in contrast to a low over the Arabian Sea, which leads
232 to excess rainfall over central and western India and a deficit to the northeast and the northern BOB (Fig. 3g; opposite to
233 the simulated dipole in Fig. 3b). Interestingly, the consistency between observed and simulated (sign-reversed)
234 precipitation and sea-level pressure patterns is also evident in CONT (Fig. 3e and 3h), albeit with some dissimilarities
235 over land, while it is less obvious when aerosol emissions are not evolving (Fig. 3f and 3i), particularly around the Indian
236 subcontinent and eastern China, resulting in an overall mixed signal. While this suggests a possible important role of

aerosols in driving the model anomalies, the opposite polarity of the aerosol-induced patterns compared to observations is puzzling and warrants further investigation into the underpinning cause and physical mechanism.

3.2.3 Subseasonal response to Asian aerosols

Inspection of monthly precipitation and low-level circulation changes reveals a stark contrast over the Indian subcontinent and adjacent ocean between the early and late monsoon season (Fig. 4). In June, there is increased precipitation and anomalous cyclonic flow over the BOB, consistent with the seasonal mean (Fig. 4a and 4e). On the contrary, decreased precipitation and anomalous anticyclonic winds are seen over India in September (Fig. 4d and 4h). Rainfall and circulation anomalies in July display similarities to those in June (Fig. 4b and 4f), while August shows a mixed pattern, with more spatially confined and smaller magnitude anomalies (Fig. 4c and 4g). Over East Asia, the June-July precipitation anomalies, closely resembling the seasonal-mean changes, feature a zonal-elongated meridional dipole, with wetting stretching from Indochina and southern China to the South China Sea, and drying to the north across central and eastern China (Fig. 4a and 4b). Interestingly, the dipole reverses sign in September, accompanied by a southward displacement (i.e., the dipole nodal line moves from around 30°N to about 20°N), with widespread drying over southern Indochina and most of the western subtropical Pacific and wetting to the north over northern Indochina and most of China (Fig. 4d). Consistently with the comparison for the seasonal means, the sub-seasonal aerosol-driven simulated response patterns bear a strong similarity, with opposite signs, to those observed (not shown).

These contrasting changes in the simulated aerosol-induced responses between the early and late summer, despite negligible monthly variations in magnitude and spatial distribution of aerosol emissions across Asia, especially for SO_2 (Fig. S2b and S2f), and the consistently reversed polarity of their key centres compared to observations, suggest that different mechanisms may underpin the responses throughout the season. This also suggests a possible link between long-term changes and the underlying mean seasonal cycle, and the possibility of discrepancies between simulated and observed characteristics in the latter to be the cause of the differences in the former. From a more general perspective, this also highlights the importance of investigating and interpreting seasonal monsoon changes accounting for the pronounced sub-seasonal variability in the response – an aspect usually overlooked in aerosol-monsoon research but particularly relevant for attribution studies.

3.3 A mechanism linking model climatology to response

3.3.1 Subseasonal monsoon biases

The accuracy of the simulated regional climate change signal and its attribution to anthropogenic drivers has been suggested to be strongly dependent on the model performance in reproducing the corresponding mean climatological conditions, which represent the baseline state on top of which changes occur (Matsueda and Palmer, 2011; Christidis et al., 2013). Examining the sub-seasonal evolution of the model bias could therefore provide insights into the simulated aerosol-induced monsoon response described above, a topic that has been insufficiently addressed and possibly underappreciated so far.

Fig. 5a and 5b show the model precipitation bias relative to the mean of CMAP and GPCP in June and September, respectively. In June, there is a clear anomalous meridional dipole over the Indian sector with rainfall excess over the equatorial Indian Ocean and deficit over India and surrounding oceanic areas, including the BOB (Fig. 5a). This dipole pattern is similar to that of the seasonal-mean bias commonly presented in both uncoupled and coupled models (Song and Zhou, 2014; He et al., 2022; Rajendran et al., 2022). Particularly, the magnitude of the June dry bias over the Indian subcontinent (–2.8 mm day^{-1}) is about 60% of the observed climatological amount (4.7 mm day^{-1}). The model is excessively wet to the east over northern Indochina and most of China, particularly to the south, with predominant dry anomalies over the China Sea. Interestingly, this bias pattern over continental Asia, and particularly the contrasting dipole between (dry) India and (wet) northern Indochina/China, bears a close resemblance, with opposite sign, to the June aerosol-induced simulated precipitation distribution discussed above (wetting over India and drying over northern Indochina/China; Fig. 5b). Is there a mechanistic link between bias and aerosol-driven response?

3.3.2 Monsoon bias and response in the pre-monsoon season

Aerosol-cloud interactions have been found to play a fundamental role in modulating the Asian summer monsoon response to anthropogenic aerosols, both in uncoupled and coupled experiments (Guo et al., 2015; Li et al., 2018). Hydrophilic aerosols (e.g., sulfate) activated at a given supersaturation level can serve as cloud condensation nuclei and increase the cloud droplet number concentration (CDNC). At constant cloud liquid water content, the increases in CDNC reduce the cloud effective radius and enhance the cloud albedo (Twomey, 1974), exerting a cooling effect at the surface. Meanwhile, the smaller cloud droplets reduce the collision/coalescence probability of droplets and thus weaken the precipitation efficiency (Albrecht, 1989). Cloud effective radius, the critical variable linking aerosol emission changes to cloud and precipitation variations, is proportional to the liquid water content at a given CDNC (Menon et al., 2002b). While column water content also changes in response to aerosol variations (Sato et al., 2018; Wang et al., 2022), and thus cause and effect are tightly intertwined at short time scales, the above hints at the possibility of baseline conditions to

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294 modulate aerosol-cloud interactions and the subsequent monsoon response to aerosol changes, especially in the presence
295 of large model discrepancies in simulating the climatological distribution of atmospheric moisture (John and Soden, 2007;
296 Bastin et al., 2019; Han et al., 2022). The marked and abrupt shift in the atmospheric state accompanying the monsoon
297 onset and subsequent establishment across Asia is also by nature substantially affected and pre-conditioned by the
298 presence of anomalous conditions in the preceding spring months. In view of this and to better identify possible precursor
299 conditions leading to the marked aerosol-induced response in June, we examine the model anomalies in late spring.

301 It is worth noting that while the band of excess climatological rainfall over southern and eastern China is present for most
302 of the year, the magnitude of the bias undergoes a rapid increase from April until the peak in June and then decays from
303 July to September (Fig. 6). Also, the wet bias over eastern China is particularly spatially extensive in the spring (up to
304 50% of the climatology), while a weak, dry anomaly appears in the summer over the lower reaches of the Yangtze River.
305 Importantly, the widespread wet anomaly over China in April–May is largely collocated with the largest aerosol emission
306 sources, particularly SO_2 (Fig. 7a). The excess climatological moisture available over China provides favourable
307 conditions for the aerosol impact via aerosol-cloud interactions in addition to changes in radiation. In fact, the CONT–
308 CONTfA difference shows reduced shortwave clear-sky radiation at the surface, a simultaneous increase in cloud droplet
309 number concentration, and a decrease of the cloud-top effective radius (Fig. 7b–d). An anomalous anticyclone situated
310 over southeastern China (Fig. 7h), consistent with the pattern of aerosol forcing, leads to a meridional dipole in the water
311 content and precipitation response, with large and widespread wet anomalies over Indochina and the SCS, and drying
312 over eastern China (Fig. 7e and 7f).

314 Conversely, the model underestimates the observed rainfall over the already dry pre-monsoon Indian subcontinent, with
315 a substantial dry bias over eastern India and the BOB (Fig. 6a and 6b). In response to the aerosol increase, there is a clear
316 reduction in clear-sky shortwave radiation over India, albeit secondary to that over China due to the smaller emission
317 changes, and a minor increase (decrease) in cloud droplet number concentration (cloud top effective radius) (Fig. 7b–d).
318 This indicates overall weak aerosol-radiation and aerosol-cloud interactions, resulting in negative, although very weak,
319 precipitation anomalies and associated mixed lower-tropospheric circulation response (Fig. 7f and 7h). It is worth noting
320 that the upper-level divergent outflow from the rainfall maximum anomaly over Indochina converges over northeastern
321 India where it subsides and generates a near-surface return flow, forming a system of closed and interacting cells (Fig. 7g
322 and 7h).

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3.3.3 Contrasting bias and response between early and late summer

With the arrival and establishment of the monsoon over Asia in June, the simulated climatological precipitation increases considerably over northern Indochina and southern China but only marginally over India (Fig. S1), resulting in a substantial zonal precipitation dipole in the model bias across Asia, with marked dry anomalies over and around India, and wet conditions over Southeast Asia and southern China (Fig. 5a). There is also a dry anomaly over eastern China, resulting from weak southwesterlies and stagnation of the monsoon front to the south (Liu et al., 2021). As in the spring, the patterns of the precipitation bias and associated water content anomalies are important to understand the corresponding aerosol-driven response. The anticyclonic circulation anomaly over eastern China strengthens and widens compared to the earlier months from both aerosol-radiation and aerosol-cloud interactions (Fig. 5c and 7h), manifested in the considerable reduction in surface clear-sky shortwave radiation (Fig. S2c), overall increased cloud droplet number concentration, and decreased cloud effective radius over central and eastern China (Fig. 8a and 8b). Note the latter displays positive anomalies over southern China, where enhanced easterlies along the southern flank of the anticyclone bring moist-laden air from the western Pacific towards South Asia (Fig. 5c), leading to increased water availability and the large precipitation excess there. Over India, the substantial climatological atmospheric water content deficit, seeing in the ensuing large dry bias (Fig. 5a), strongly limits local aerosols to exert a sizable impact by markedly weakening the magnitude of regional aerosol-cloud interactions (e.g., modest changes in could top effective radius in Fig. 8b). Regional anomalies in the aerosol response are thus interpreted as remotely-induced by the large-scale circulation adjustment to aerosol changes over China. Local aerosols and ensuing circulation and precipitation response are therefore tightly coupled over Asia and linked by positive feedbacks, whereby an initial aerosol-induced anomaly in precipitation subsequently acts to reinforce the anomalous pattern by regional circulation adjustments. For example, the deep ascent and upper tropospheric divergent outflow associated with the excess precipitation over the BOB and Indochina bifurcates with the primary branch converging and subsiding over northeastern China (reinforcing the local anticyclone) and the secondary branch over the southeastern Philippines Sea where dry anomalies are found and are part of the northwestward rainfall shift (Fig. 9a–c).

As summer progresses, the simulated climatological precipitation reaches its peak over India, while it retreats markedly over China (Fig. S2a and S2b). This, together with the anomalies set up as part of the aerosol response in the earlier part of the season (Fig. 5b), leads to enhanced moisture availability over South Asia compared to the earlier months, while also partially alleviating the reduced, but persisting, model dry bias there (Fig. 5e). Conversely, over China, the moisture deficit from the aerosol-weakened monsoon circulation (Fig. 5b), as well as the rapid monsoon demise in the simulated climatology (Fig. S2e), contribute to lessening the degree of interaction between aerosols and clouds and precipitation. As a result, aerosol-cloud interactions over South Asia are more effective compared to the early summer, and the

355 continental-scale simulated response is predominantly driven by aerosol-induced anomalies over South Asia. Associated

356 with a decrease in cloud top effective radius (Fig. 8f), negative precipitation anomalies appear over South Asia from

357 August (Fig. 4c), with maximum peak in September (Fig. 4d). Correspondingly, the lower-tropospheric circulation

358 features an anomalous anticyclone, with westerly winds over northern India and the BOB (Fig. 5g). The flow turns

359 southwesterly over northern Indochina, bringing more moisture to eastern China (leading to increased could top effective

360 radius in Fig. 8f) and increasing precipitation which forms a zonal dipole with the rainfall decrease over the north-

361 equatorial western Pacific (Fig. 5f and 5h). The associated anomalous western Pacific anticyclone weakens and shifts

362 eastward (Fig. 5g). The large-scale anomalous circulation pattern is characterized by the mid-tropospheric vertical motion

363 and divergent outflow over southern China, and upper-level convergence and subsidence over South Asia and the north-

364 equatorial western Pacific (Fig. 9d–f), which further attests for the strong coupling across the region.

3.4 Response in nudged simulations

366 The Asian monsoon response to aerosol changes discussed above entails large-scale atmospheric circulation adjustments

367 extending beyond the Asian region. It is therefore interesting to understand whether the extent to which they contribute

368 to driving the regional response. Constraining the large-scale circulation outside Asia to observations allows us to isolate

369 the effect of remote (i.e., outside Asia) circulation changes in generating the monsoon response to Asian aerosols.

370

371 The AOD differences between the pair of nudged simulations (Fig. S3) resemble those shown in Fig. 2 despite the

372 considerably different circulation and precipitation anomalies (see Fig. 5c, 5g, 10c, 10g), indicating that the AOD

373 distribution is predominantly influenced by emissions changes rather than by aerosol transport and removal processes.

374 The spatial patterns of both the June and September precipitation biases in NUDG, where horizontal winds outside Asia

375 are nudged to ERA-I, are overall very similar to those in the control simulation (cf. Fig. 10a and 10e). Sub-regional

376 differences in the magnitude of the bias between the two sets of experiments are however noticeable (e.g., the dry bias is

377 markedly reduced over India, whereas southeastern China is wetter, compared to CONT), indicating that an improved

378 representation of the remote circulation can potentially reduce the precipitation bias in some areas but not necessarily

379 across the entire domain (Liu et al., 2021).

380 The June precipitation response to aerosol changes features an approximately meridional dipole, with widespread drying

381 from north-eastern India to southern China and wet anomalies over central India, the BOB, and parts of the South China

382 Sea (Fig. 10b). Compared to the free-running simulations, precipitation anomalies are of much smaller magnitude and

383 mostly confined within Asia and the neighbouring oceanic areas, without a significant aerosol signature downstream (e.g.,

384 over the equatorial Indian Ocean and the subtropical Pacific). This is expected as the atmospheric circulation above the

385   planetary boundary layer is nudged outside Asia, and attests to the key role of large-scale circulation adjustments in

386   realizing the aerosol impact. Consistently with the link between rainfall bias and response to aerosol forcing found in the

387   free-running simulations, wetter climatological conditions over China and a reduced dry bias over India translate into

388   more efficient aerosol-cloud interactions over both regions (Fig. 10a). As a result, the ensuing precipitation response,

389   while bearing similarities with that in Fig. 5, and thus on the driving role of Chinese aerosol emissions, also shows

390   noticeable differences: the drying over China is more spatially extensive, particularly to the south, while the wetting over

391   the Indian sector is mainly confined to the northern BOB (Fig. 10b). While sign and pattern of the aerosol-induced

392   response are consistent with the bias pattern, the generally weak anomalies are a result of the unchanged large-scale

393   circulation outside Asia in the nudged experiments. For example, Fig. 10c shows a pattern of sea level pressure anomalies

394   which resembles that shown in Fig. 5c, but with much smaller gradients and mostly confined to Asia only. In particular,

395   there is only a very weak westerly flow across the north-equatorial Indian Ocean, with reduced moisture supply towards

396   Indochina and southern China, in contrast to the vigorous cross-equatorial moisture-laden flow from the western Indian

397   Ocean in the free-running experiments. These anomalies, manifestation of a local aerosol effect, are indicative of the

398   predominant role of large-scale circulation adjustments and two-way interactions with local anomalies in realising the

399   full extent of the aerosol impact over Asia. Nudging the circulation outside Asia thus proves to be a strong constraint on

400   the model response to aerosols over Asia, despite unchanged emissions compared to the free running simulations.

401

402   In September, the dry bias over India is reduced compared to June (Fig. 10e) as in the free-running simulation. The wet

403   bias over China also reduces overall in magnitude compared to June, although NUDG is wetter than CONT (Fig. 2b),

404   which may be conducive to enhanced aerosol-cloud interactions. In fact, CDNC increases across Asia (Fig. S4c) but cloud

405   top effective radius decreases mainly over central and eastern China, with conversely muted changes over India (Fig.

406   S4d). As a result, precipitation decreases over most of central and eastern China, accompanied by positive sea-level

407   pressure anomalies and anomalous low-tropospheric anticyclonic circulation (Fig. 10f and 10g). The anomalous easterly

408   flow over northern Indochina and northern India draws anomalous southwesterly moisture transport across India, which

409   features widespread wetting. As during June, the lack of circulation adjustments outside Asia appears to play an important

410   role in determining magnitude and sign of the aerosol response: the marked anomalous anticyclone over the subtropical

411   western Pacific in the free-running simulations contributes to the strong southerly moisture advection toward southern

412   and eastern China, and thus to the generation of the precipitation increase (Fig. 5g and 5f). These features are of very

413   weak magnitude in the nudged experiments due to the fixed circulation, leading to prevalently dry conditions over China

414   (as opposed to wet anomalies). This, in turn, contributes to weakening, or even opposing, the anomalous westerly wind

415   across India and Indochina seen in CONT, with these regions now displaying prevalently wet (as opposed to dry)

416   anomalies. These findings highlight a competing role and complex interplay between sub-regional precipitation biases in

417   modulating the response to aerosols.

14

3.5 Response in the fixed SST PDRMIP simulations

To ascertain whether the link between climatological biases and aerosol response found above for HadGEM3-GA7.1 is common to other models, we analyse the PDRMIP multi-model experiments forced by fixed SST. In particular, models are composited based on the sign of the June precipitation bias over central India (the area 73°–85°E, 20°–28°N, approximately corresponding to the core monsoon region), given its key role in determining the seasonality of the aerosol imprint discussed above. Given the key role of aerosol-cloud interactions in realising the aerosol impact, the CESM1-CAM4 and GISS models are excluded from the analysis as they include only a parameterization of aerosol-radiation interactions (Liu et al., 2018). In fact, these two models display very weak monthly precipitation variations over India and China induced by aerosol changes (not shown). Of the five remaining models, two (i.e., HadGEM3 and IPSL-CM) display precipitation deficit while the other three (i.e., MIROC-SPRINTARS, NorESM1and CESM1-CAM5) present excessive rainfall over India in June (hereafter DRY and WET ensembles, respectively; Fig. S5). Biases and responses for individual models are shown in Fig. S5.

DRY features a dipole pattern in the June precipitation bias over Asia with drying across India and most of Indochina, and wetting over China, particularly to the south and east (Fig. 11a). Based on the mechanism described above, this pattern provides favourable conditions for aerosol-cloud interactions to come into play over China, leading to anomalous low-tropospheric anticyclonic flow over China (Fig. 12a), thereby reducing precipitation there and shifting it southward (Fig. 11c). This leads to compensating precipitation increases over northern India, the BOB and the SCS. Key features of both the bias and response patterns are common, in sign and magnitude, to both HadGEM3 and IPSL-CM (Fig. S5), and overall bear marked similarly to those in HadGEM3-GA7.1 (Fig. 5). One notable difference compared to HadGEM3-GA7.1 is that DRY shows an evident meridional land-ocean contrast in the precipitation distribution over the western Pacific, with the wetting predominantly confined to the ocean, and drier Indochina and southeastern China. This feature is recognizable in both HadGEM3 and IPSL-CM, with the former model close to the one employed in this study, which suggests the shift to be related to the differing prescribed SST patterns.

In order to account for model differences and to more clearly highlight the spatio-temporal changes between early and late summer, Fig. 11b and 11f show incremental variations (i.e., September minus June differences) rather than absolute anomalies. The DRY bias features a relative precipitation excess over India, the northern BOB, and most of Indochina, and a deficit over eastern China. Correspondingly, the aerosol-induced response shows easterly flow (Fig. 12b) and widespread decreased precipitation across the Indian subcontinent in September with respect to June (Fig. 11d), associated with an anticyclonic anomalous flow over the SCS (Fig. 12b), contributing to precipitation increases over southern and

449 eastern China. There is again marked similarity between these patterns and those for the HadGEM3-GA7.1. As noted for
450 the June response, there is a strong land-ocean contrast in the WET precipitation distribution over the East Asian sector.
451

452 Turning to the analysis of the WET ensemble, the June bias features precipitation excess over most of India and central
453 and northern China, while deficient precipitation is seen over eastern and southern China (Fig. 11e). This pattern, with
454 opposite anomalies over India and reversed meridional dipole over China compared to DRY, is conducive to strong
455 aerosol-cloud interactions over India and relatively weaker signals over eastern China (compared to DRY). As a result,
456 the WET response displays northeasterly flow and widespread drying over India and a cyclonic anomaly over the tropical
457 western Pacific, leading to dry northeasterlies over central and eastern China and wet anomalies over the SCS (Fig. 11g
458 and 12c). The June-to-September incremental bias features an approximately opposite pattern to that in June, and so does
459 the precipitation response (Fig. 11f and 11h). Overall, the reversed polarity of bias and responses in WET compared to
460 DRY and the consistency of the key features of the patterns among the individual models further corroborate the
461 robustness of the physical mechanism proposed above.

462 **3.6 Response in coupled simulations**

463 One may wonder whether the findings above, based on the analysis of atmospheric-only models, still hold in fully coupled
464 models and how much they are modulated by including two-way air-sea interactions. First, we analyse the PDRMIP
465 coupled model experiments. For consistency with the analysis of the fixed SST experiments, as well as to include the
466 contribution of air-sea coupling but not the full long-term response of the ocean, which presumably has not adjusted to
467 the time-varying emissions in the transient experiments, the analysis was restricted to the first 6–15 years of the
468 simulations. All five chosen models display a dry bias over India in June (Fig. S6) and thus Fig. 13 only shows the DRY
469 multi-model ensemble. In common with the experiments investigated above, the June bias features dry anomalies over
470 South Asia and wet anomalies over southern China (Fig. 13a). A noticeable difference compared to HadGEM3-GC2 is
471 the large-scale drying over the SCS and western subtropical Pacific, showing a meridional dipole (Fig. S6 and Fig. 14a).
472 This dipole is obvious in most individual models except for HadGEM3 (mostly zonal; Fig. S6). In September, the dry
473 bias over the Indian sector and western subtropical Pacific undergoes a marked reduction, while the wetting over China
474 is restricted to the central regions. Correspondingly, both the June and September responses follow the shapes of bias
475 patterns (Fig. 13c and 13d), further attesting to the pervasiveness and consistency of the link between bias and aerosol
476 response across different models.
477

478 To further examine the robustness of the results, we also analyse the HadGEM3-GC2 coupled transient simulations, which
479 are a close counterpart to the simulations discussed in Section 3.2 and 3.3. The bias pattern and magnitude in the coupled

480 experiment bear a close similarity to that of the HadGEM3-GA7.1 model during both June and September (Fig. 14a and
481 14b), including the dipole between India and central-southeastern China and its sign reversal between early and late
482 summer. This suggests the underlying cause to be rooted in the atmospheric component (Bollasina and Nigam, 2009;
483 Song and Zhou, 2014). The June precipitation response features widespread wetting over India and a large southwest to
484 northeast oriented dipole over China, with excess precipitation over the western Pacific and drying from northern
485 Indochina across southeastern China to Japan (Fig. 14b). These two main features, of comparable magnitude, are also
486 evident in Fig. 5. The main difference is that the dipole is slightly shifted southeastward in the coupled model, associated
487 with the anticyclonic circulation extending over the SCS due to aerosol-induced oceanic cooling (not shown), with
488 consequent opposite sign precipitation anomalies over southeastern China. Also, in agreement with the atmospheric-only
489 simulations, the September response shows extensive drying across South Asia and wetting over southeastern China. As
490 in June, oceanic coupling appears to lead to some differences over southeastern China and the SCS, where the precipitation
491 anomalies, modulated by the slower oceanic response, are slightly shifted over the ocean compared to the uncoupled
492 simulations.

493 **4 Discussion**

494 While numerous studies have emphasised the key role of anthropogenic aerosols in driving seasonal-mean changes in the
495 Asian monsoon, only very few of them have focused on the aerosol impact at sub-seasonal (e.g., monthly) time scale (e.g.,
496 Lau and Kim, 2006; Bollasina et al., 2013; Fang et al., 2023). Yet, the onset and withdrawal phases of the monsoon are
497 of key importance for the regional economy and water resources as they herald the arrival and demise of the monsoon
498 rains, which provide up to 75% of the total annual rainfall for large areas of Asia. For example, a delayed monsoon onset
499 as well as an early monsoon retreat, or long-term trends in their timings induced by anthropogenic aerosols, can lead to
500 severe consequences for the region. Equally important, inter-model discrepancies in the simulated aerosol-induced
501 monsoon changes at sub-seasonal scale may help to explain the diversity of the seasonal-mean responses.
502
503 A link between model bias and corresponding response has been shown to hold, for example, in the case of summer
504 precipitation over Asia (Wilcox et al., 2015), global SST patterns and overlying rainfall changes (He and Soden, 2016),
505 tropical rainfall (Chadwick, 2016) and circulation (Zhou and Xie, 2015), extratropical stationary eddies and their influence
506 on tropical convection (Chen et al., 2018), and Arctic Ocean temperature (Park and Lee, 2021). Given that state-of-the-
507 art climate models still suffer from large and persistent biases in simulating magnitude and distribution of the monsoon
508 precipitation and circulation across Asia (Wilcox et al., 2020; Rajendran et al., 2022; Tong et al., 2022), it is certainly
509 plausible for these biases to exert a sizeable control on the aerosol-induced monsoon changes. Climatological biases in

510 climate models could lead to unrealistic projections of anthropogenic climate change and add further uncertainties, for

511 example due to their possible non-stationarity (Krinner and Flanner, 2018).

512

513 One important implication of the link between model climatological bias and response pattern found here is the possibility

514 of better understanding and constraining the diversity and inconsistencies of model responses to aerosol changes over

515 Asia in historical and future projections by accounting for model deficiencies in simulating the climatological monsoon

516 seasonal cycle compared to observations. These biases critically modulate the magnitude and efficacy of aerosol-cloud-

517 precipitation interactions, an important component of the total aerosol-driven response (e.g., Li et al., 2018; Dong et al.,

518 2019). This finding will help in further narrowing the uncertainties associated with aerosol-cloud interactions, given their

519 important role in driving the monsoon changes. For example, the clear contrast in the monthly response to aerosols

520 between the PDRMIP DRY and WET composites calls for caution in the interpretation of the aerosol-induced signal

521 without proper consideration of the model baseline performance. This will translate into more robust assessments of sub-

522 regional scale monsoon variations. In fact, despite an overall similarity in the seasonal mean monsoon responses between

523 the DRY and WET ensembles, it is interesting to notice that the difference pattern in precipitation (e.g., DRY minus WET)

524 bears a striking similarity to the observational pattern (Fig. S8f and Fig. 3d).

525

526 One may wonder whether the linkage between monsoon bias and aerosol-induced monsoon responses still works in fully

527 coupled models, particularly at longer time scale when SST changes occur. Response patterns between uncoupled and

528 coupled models indeed differ in both magnitude and sign over the surrounding oceanic regions. However, the coupled

529 model response pattern displays an overall minor sensitivity to changes in the averaging period (see Fig. S7 and Fig. 13),

530 with the key anomalies, particularly over land, appearing already in the first decades of the simulation. This indicates that,

531 while air-sea interactions contribute to realising the aerosol impact, the full oceanic response plays a secondary role

532 compared to the predominant action of the atmospheric circulation (Soden and Chung, 2017). This topic, and particularly

533 the analysis of the time scales required to set-up the equilibrium response, has been mostly overlooked in literature, which

534 often compared the fast to the slow response, the latter taken after 50 or more simulated years (e.g., Samset et al., 2016).

535

536 Differences exist between the observed monsoon changes during the recent decades shown above (Jin and Wang, 2017;

537 Monerie et al., 2022) and those over a longer period (e.g., late 20th century) documented in previous literature and

538 attributed to the dominating regional aerosol forcing, and sulfate aerosols in particular. For example, the increase in

539 anthropogenic aerosol emissions over Asia in the second half of the 20th century has been found to play a key role in

540 driving the observed southern flood-northern dry rainfall dipole over East Asia (Gong and Ho, 2002; Song et al., 2014b;

541 Dong et al., 2016), as well as the South Asian monsoon decline (Gu et al., 2006; Bartlett et al., 2018; Dong et al., 2016;

542 Jiang et al., 2013). A combination of factors, including internal climate variability, may have contributed to these recent

543 trends (Huang et al., 2020b; Monerie et al., 2022) or to set background (oceanic) conditions on top of which aerosols

544 acted (Lin et al., 2016b). While the findings of our study on the possible role of aerosols are necessarily not conclusive,

545 the model bias is found to be equally important to explain model discrepancies. A careful examination of these biases

546 could help reconcile the generally poor performance of state-of-the-art climate models in reproducing recently observed

547 trends (Huang et al., 2020b; Monerie et al., 2022).

548

549 It is also worth emphasizing that the analysis carried out above focuses on the impact of sulfate aerosol emission changes,

550 either because of their marked dominance over other aerosol components (e.g., BC and OC) in the historical period

551 investigated with the HadGEM3-GA7.1 and HadGEM3-GC2 experiments or because of experimental design in the

552 PDRMIP simulations. While sulfate aerosol emissions underwent the largest changes across Asia throughout the historical

553 period (e.g., Lund et al., 2019), the imprint of BC aerosols, although of comparatively weaker magnitude (e.g., Liu et al.,

554 2018; Westervelt et al., 2018), needs also to be accounted to interpret the full extent of the simulated monsoon response

555 to historical aerosol changes and its inter-model inconsistencies given, for example, their different physical mechanisms

556 and responses of opposite sign compared to those due to sulfate aerosols (e.g., Xie at al., 2020).

557

558 The competition between South Asia and East Asia in generating the continental-scale monsoon response and the

559 underpinning modulation by the bias pattern is very relevant in the context of interpreting near-future monsoon projections

560 and related uncertainties, including for regional attribution studies, given the present-day and near-future dipole pattern

561 of emission changes between the two regions (Lund et al., 2019; Samset et al., 2019). For example, it is conceivable to

562 expect that a reduced model bias over South Asia, particularly in early summer, would further promote the importance of

563 Indian aerosol emissions compared to those over China. This also highlights the potential key role of non-local aerosols

564 in driving the simulated response across Asia, which is again crucial in interpreting future projections.

565 **5 Summary and conclusions**

566 Based on the analysis of several climate models and aerosol forcing experiments, we find the sub-seasonal variability of

567 the Asian summer monsoon response to regional anthropogenic aerosol changes to be significantly affected by the spatial

568 pattern and seasonality of the model bias across Asia. The aerosol impact on monsoon precipitation and circulation is

569 strongly influenced by the model ability to simulate the spatial distribution and temporal variability of the climatological

570 monsoon clouds and precipitation, as well as the underlying atmospheric dynamical action centres. The amount of

571 available water vapour in the model baseline climatological state exerts a strong control on the extent to which aerosols

572 can interact with clouds and precipitation processes (i.e., via reduced cloud effective radius) and thus modulate the

573 aerosol-induced monsoon response. This involves a strong interplay between South and East Asia and their relative

574 predominance in driving the overall monsoon response, with a striking contrast between the early and late summer
575 aerosol-driven changes ascribable to the seasonal evolution of the biases between the two regions. Our results and
576 proposed mechanism, firstly based on a detailed analysis of atmospheric-only experiments with the HadGEM3-GA7.1
577 model, are corroborated by the analysis of other atmospheric and coupled models for which sensitivity experiments to
578 Asian aerosol changes are also available.
579
580 In summary, during the onset month (June), models that feature a dry bias over India display corresponding wet anomalies
581 over eastern China. As the monsoon season progresses and approaches the end (September), the absolute bias decreases,
582 or even reverses, such that incremental changes show wetter conditions over India and drier over eastern China compared
583 to June. Similar variations, but of opposite sign, occur for the models that display a wet June bias over India (and
584 corresponding deficient rainfall over China). These patterns and their sub-seasonal evolution, together with the
585 corresponding atmospheric circulation anomalies, indicate the existence of a strong internal coupling between the South
586 and East Asian monsoon systems, whereby the two components fluctuate and oppose each other at short (monthly or
587 below) time scales. As a result, the aerosol influence on the monsoon, modulated by aerosol-cloud interactions, also
588 features a dipole and oscillating pattern between South and East Asia, with the key driving region varying during the
589 season and depending on the evolution of the model climatological state. For example, while the direct aerosol imprint is
590 predominant over East Asia in early summer, it is dominating over South Asia towards the end of the season in the DRY
591 composites. The continental-scale aerosol response, particularly the inter-monsoon interaction, involves an ensuing large-
592 scale atmospheric circulation response, which is pivotal to extending the aerosol impact downstream of the dominating
593 aerosol-forcing region by modulation of the associated moisture transport towards the rest of the domain. The analysis of
594 the nudged experiments further supports the crucial role of non-regional atmospheric circulation adjustments: while
595 keeping the circulation outside Asia close to observations reduces the model bias over Asia, the lack of adjustments under
596 varying Asian aerosol emissions dampens and modifies the pattern and evolution of the regional precipitation response,
597 leading to unrealistic changes (e.g., seasonal mean wetting over South Asia). This suggests that climatological large-scale
598 circulation features, such as the western Pacific subtropical high, are not only modulated by aerosol forcing over Asia but
599 are also active contributors to generating the aerosol impact itself over Asia.
600
601 The consistency of our findings across different models suggests that the mechanism is robust with respect to the specific
602 model structure and physics, including details of the aerosol module, as long as aerosol-cloud interactions are
603 parameterized. Biases and responses are markedly similar between atmosphere-only and coupled models over land (e.g.,
604 South and East Asia), where the largest aerosol loading is also located and thus the largest forcing is exerted via aerosol-
605 cloud-precipitation interactions. Furthermore, compared with the fixed SST experiments, the fully coupled settings may

606 affect the magnitude and sign of oceanic responses but the anomalies over land keep follows the bias pattern, further

607 attesting the robustness of the proposed physical mechanisms.

608

609 We acknowledge some limitations of this study. Only a few models are available in each of the DRY and WET composites

610 as aerosol-cloud interactions are not parameterised in some of the PDRMIP models. There are also inter-model differences

611 in the aerosol setups (i.e., prescribed concentrations or emissions) the implications of which are difficult to ascertain given

612 the limited model sample. Including more models and conducting coordinated perturbed aerosol experiments to Asian

613 aerosols would further increase the robustness of our study. It would be interesting to extend this analysis to a longer

614 period and examine, for example, the 20th-century monsoon changes. Internal climate variability may also play an

615 important role and partially mask or offset externally-driven changes, especially given the relatively short time period

616 examined here.

617

618

628

629 **Author contribution.** MAB and ZL designed the study. ZL ran the model simulations. ZL and MAB carried out the

630 analysis, visualized the results and discussed the results. All authors edited the paper.

631

632 **Competing interests.** At least one of the (co-)authors is a member of the editorial board of Atmospheric Chemistry and

633 Physics. The authors also have no other competing interests to declare.

634

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Table 1. Model simulations used in this study. For the HadGEM3-GA7.1 simulations, the Asia domain (10°–45°N, 60°–125°E) is enclosed by the purple box in Fig. 2c. Note wind nudging is applied only above the planetary boundary layer (model level 12, or approximately 850 hPa). Years 2003 –2012 are used for analysis. The PRRMIP experiments include both fixed-SST (15 years) and coupled (100 years) model configurations. The experiment details of HadGEM3-GC2 and PDRMIP are documented in Wilcox et al (2019) and Samset et al (2016), respectively.

Model/Project	Experiment	Description
HadGEM3-GA7.1	CONT	Transient Asian aerosols during 1991–2012 and without nudging
	CONTfA	Asian aerosols fixed at their 1991 values and without nudging
	NUDG	Same as CONT except for wind nudging outside Asia
	NUDGfA	Same as CONTfA except for wind nudging outside Asia
HadGEM3-GC2	Historical	Transient aerosol forcing simulation during 1959–2012
	Fixed Asia	Fixed Asian aerosol experiment at 1971–1980 mean values
PDRMIP	BASE	Present-day (year 2000) aerosol emissions/concentrations
	SULASIA	Sulfate over Asia increased by 10 times
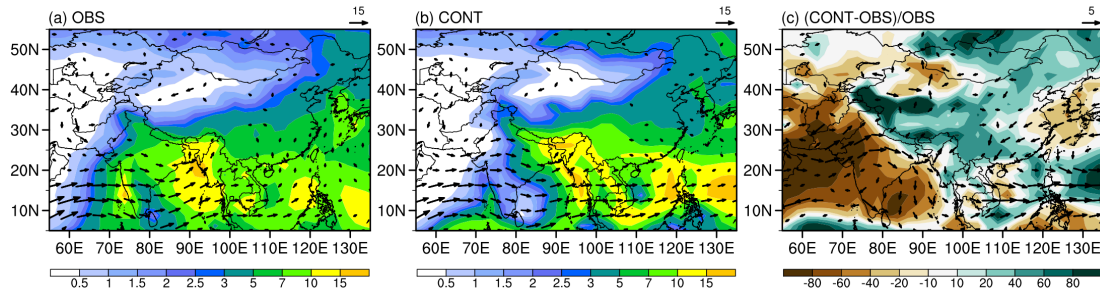
Fig. 1. June–September average precipitation (mm day^{-1}) and 850-hPa wind (m s^{-1}) for the observations (GPCP and CMAP average for precipitation, ERA5 for wind), the control simulation, and their differences (precipitation differences in percentage and wind differences in absolute values) during the period 1993 to 2012.

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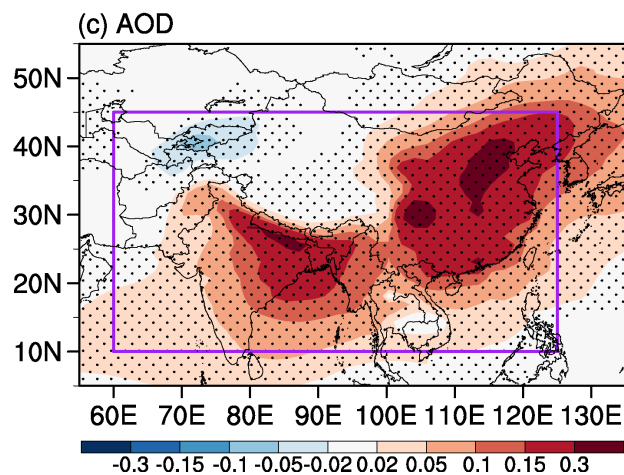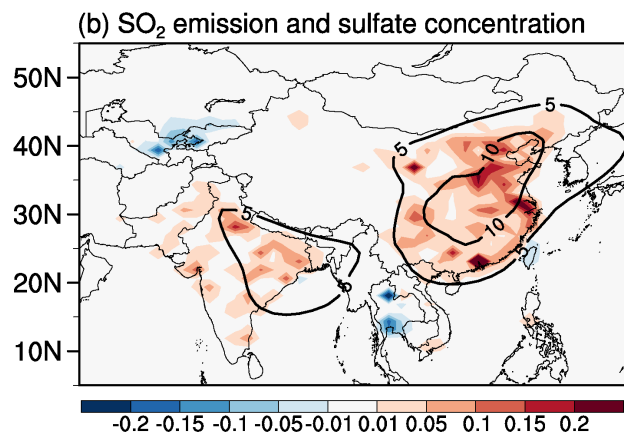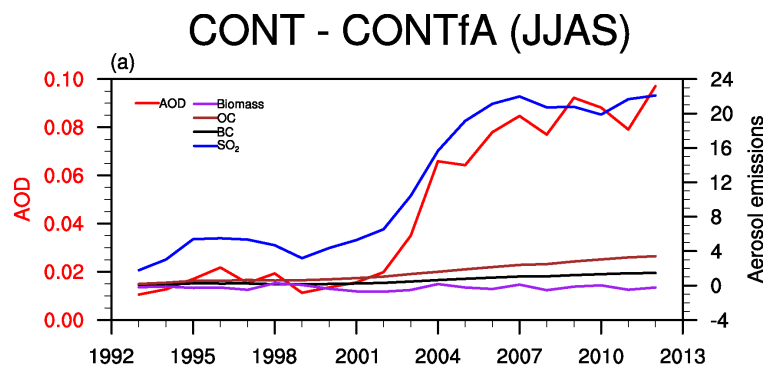
Fig. 2. (a) Differences of annual time series of summer AOD (unitless; red), total SO_2 emissions (Tg yr^{-1}; blue), total BC emissions (Tg yr^{-1}; black), total OC emissions (Tg yr^{-1}; brown), and total biomass burning emissions (Tg yr^{-1}; purple) over Asia between CONT and CONTfA. Spatial distribution of changes in (b) SO_2 emissions (shading; Tg yr^{-1}) and sulfate column burden (contour; mg m^{-2}) and (c) AOD changes (difference between CONT and CONTfA averaged for the period 2003–2012). The purple box in (c) denotes the Asia region (10°–45°N, 60°–125°E). Black dots in (c) mark grid-points for which the difference is significant at the 90% confidence level.
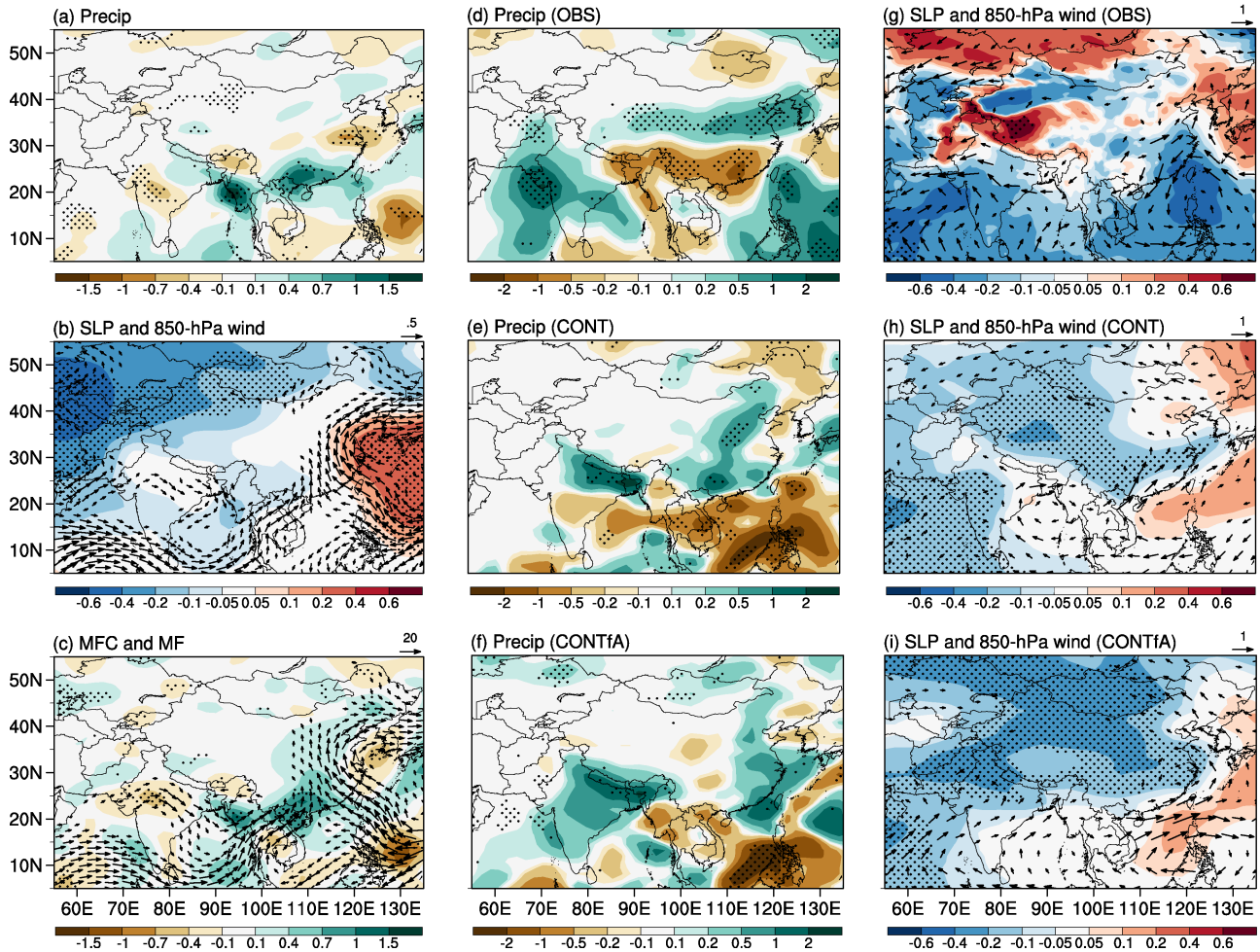
Fig. 3. JJAS response to Asian anthropogenic aerosols (difference between CONT and CONTfA averaged during 2003-2012) for (a) precipitation (mm day^{-1}), (b) sea-level pressure (hPa; shades) and 850-hPa winds (m s^{-1}), and (c) 1000–300 hPa vertically integrated moisture flux convergence (mm day^{-1}, shades) and moisture flux (kg m^{-1} s^{-1}). Black dots mark grid-points for which the difference is significant at the 90% confidence level. JJAS precipitation differences (mm day^{-1}) between (2003–2012) and (1993–2002) in (d) the mean of GPCP and CMAP, (e) CONT, and (f) CONTfA. (g, h, i) Same as (d, e, f) but for SLP (hPa) and 850-hPa wind (m s^{-1}) in ERA5 reanalysis and model simulations.

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CONT - CONTfA

(a) Precip (Jun)
(b) Precip (Jul)
(c) Precip (Aug)
(d) Precip (Sep)
(e) SLP and 850-hPa wind (Jun)
(f) SLP and 850-hPa wind (Jul)
(g) SLP and 850-hPa wind (Aug)
(h) SLP and 850-hPa wind (Sep)
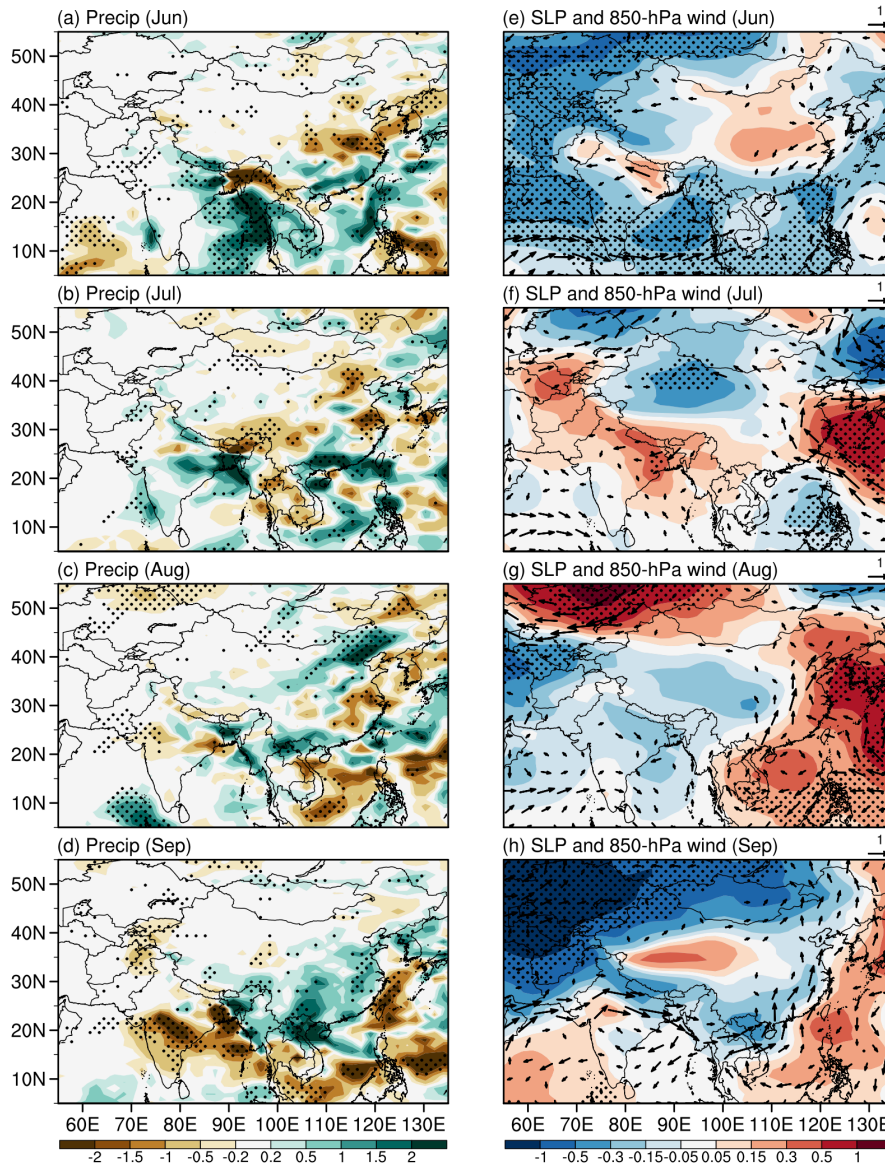
Fig. 4. Monthly differences in precipitation (mm day^{-1}) between CONT and CONTfA in (a) June, (b) July, (c) August, and (d) September for the period 2003–2012. (e–h) Same as (a–d) but for sea-level pressure (hPa, shades) and 850-hPa winds (m s^{-1}). Black dots mark grid-points for which the difference is significant at the 90% confidence level.
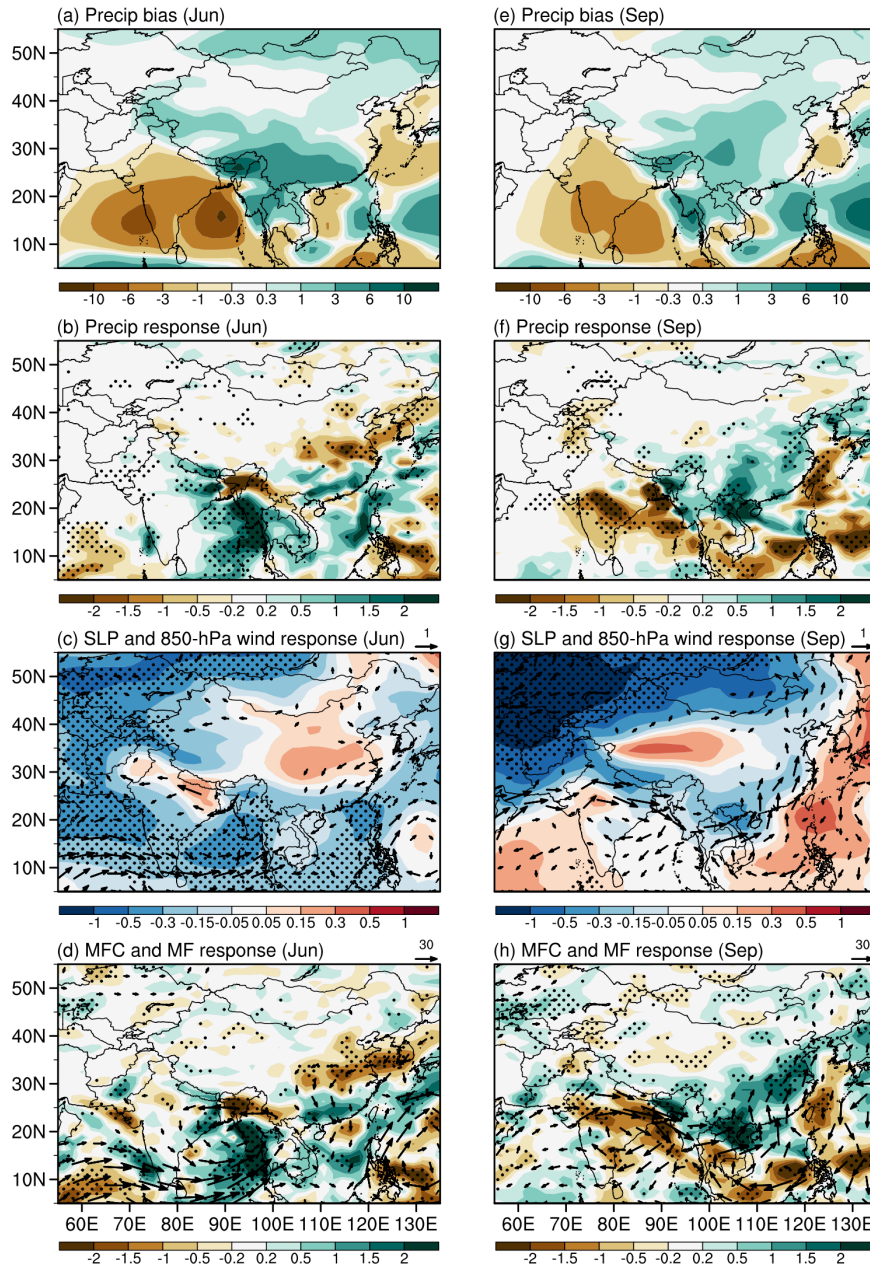
Fig. 5. (a) June precipitation bias (mm day^{-1}) in CONT with respect to the mean of GPCP and CMAP. Model data is averaged over 2003–2012, observations are averaged over 1981–2010. June response to Asian anthropogenic aerosols (difference between CONT and CONTfA averaged during 2003–2012) for (b) precipitation (mm day^{-1}), (c) sea-level pressure (hPa, shades) and 850-hPa wind (m s^{-1}), and (d) 1000–300 hPa vertically integrated moisture flux convergence (mm day^{-1}, shades) and moisture flux (kg m^{-1} s^{-1}). (e–h) Same as (a–d) but for September. Black dots in (b–d) and (f–h) mark grid-points for which the difference is significant at the 90% confidence level.

Precip bias (CONT-(GPCP+CMAP)/2)
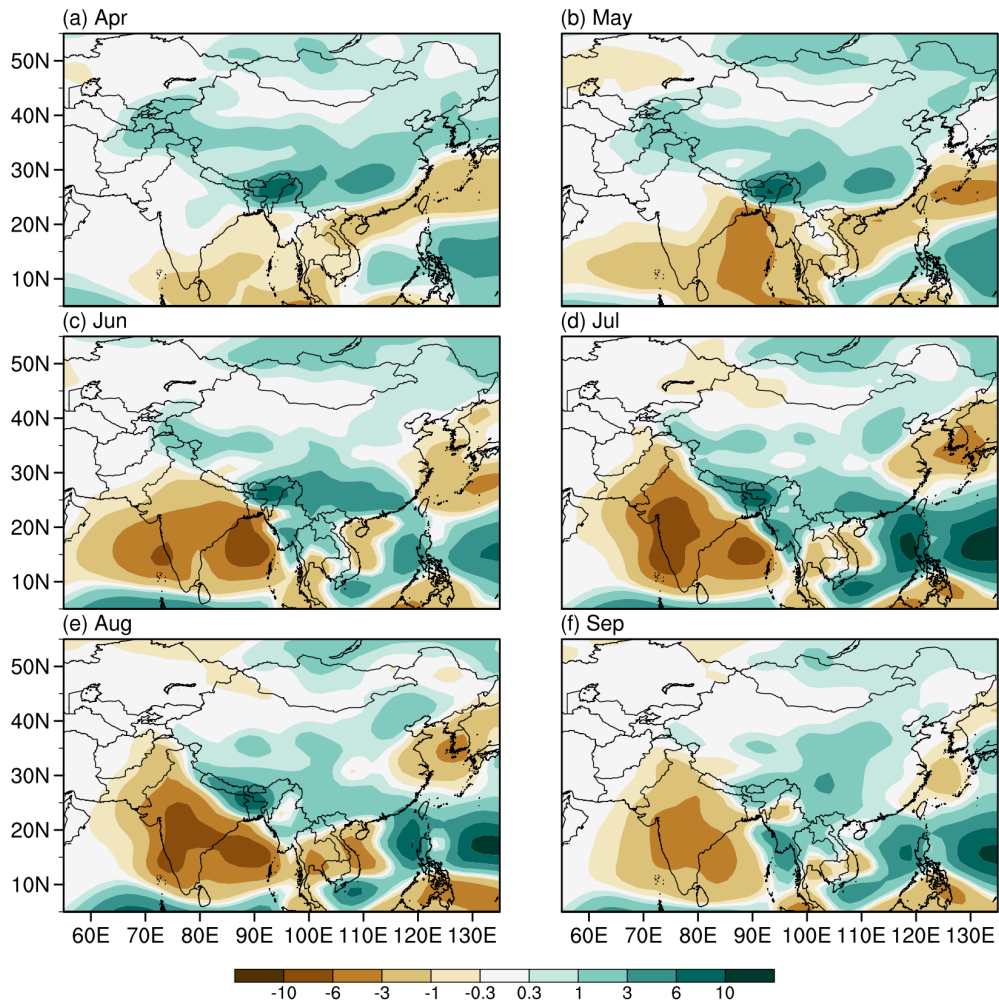
Fig. 6. Monthly precipitation bias (mm day^{-1}) in CONT with respect to the mean of GPCP and CMAP for (a) April, (b) May, (c) June, (d) July, (e) August, and (f) September.
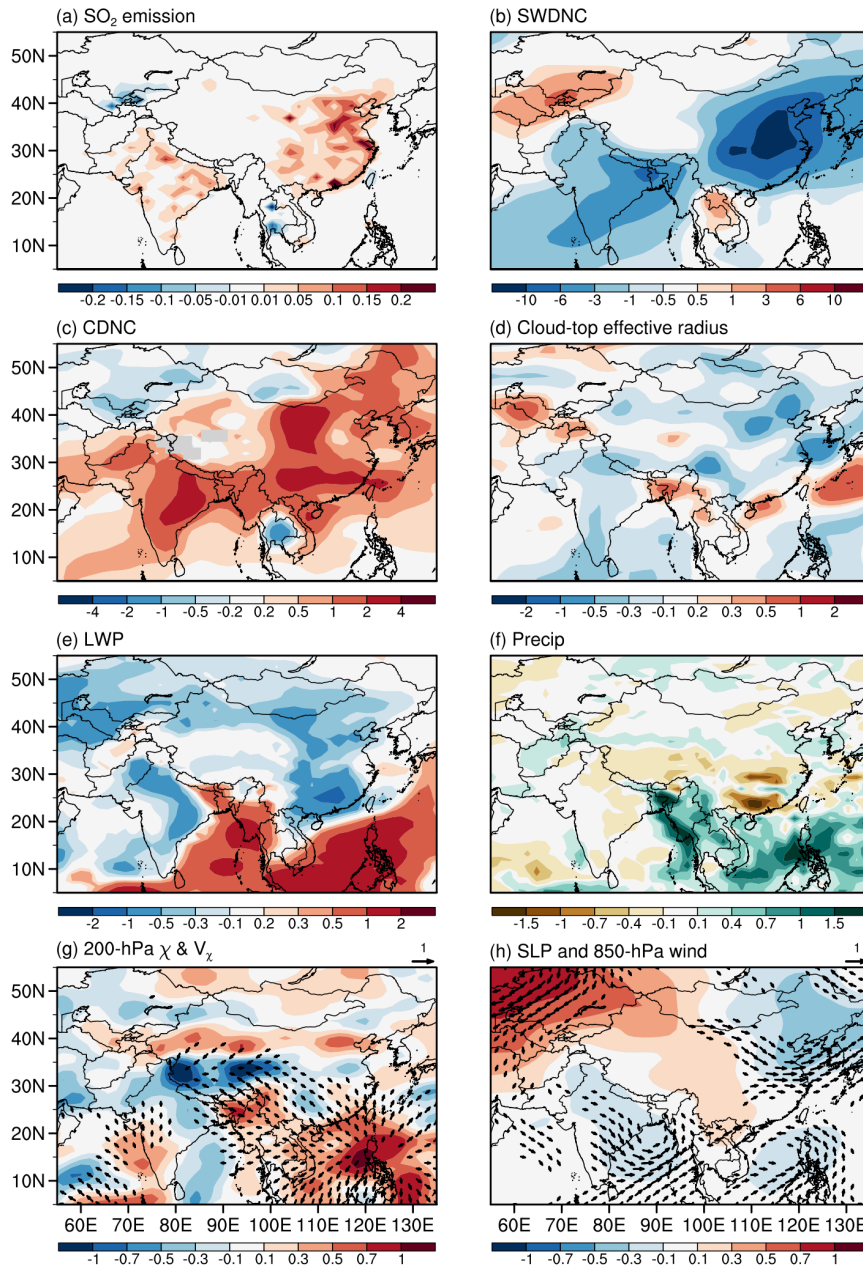
Fig. 7. April-May average differences in (a) SO_2 emissions (Tg yr^{-1}), (b) clear-sky downward shortwave radiation (W m^{-2}), (c) cloud droplet number concentration (10^{10} m^{-2}), (d) cloud-top effective radius (μm), (e) liquid water path (g m^{-2}), (f) precipitation (mm day^{-1}), (g) 200-hPa divergence (10^6 s^{-1}, shades) and divergent wind (m s^{-1}), and (h) sea-level pressure (hPa) and 850-hPa winds (m s^{-1}) between CONT and CONTfA.
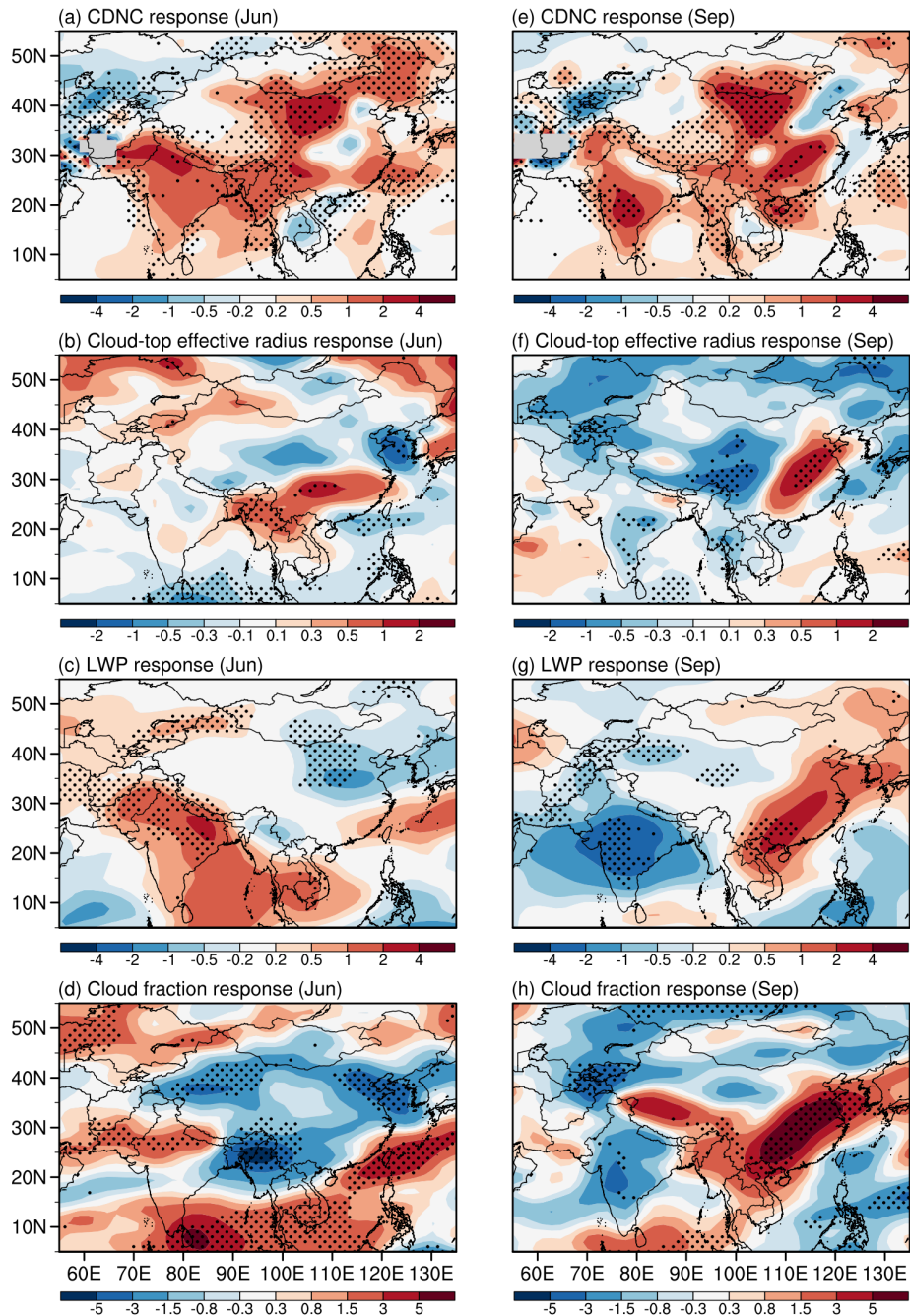
Fig. 8. June response to Asian anthropogenic aerosols (difference between CONT and CONTfA averaged during 2003-2012) for (a) cloud droplet number concentration (10^{10} m^{-2}), (b) cloud-top effective radius (μm), (c) liquid water path (g m^{-2}), and (d) cloud fraction (%). (e–h) Same as (a–d) but for September. Black dots mark grid-points for which the difference is significant at the 90% confidence level.
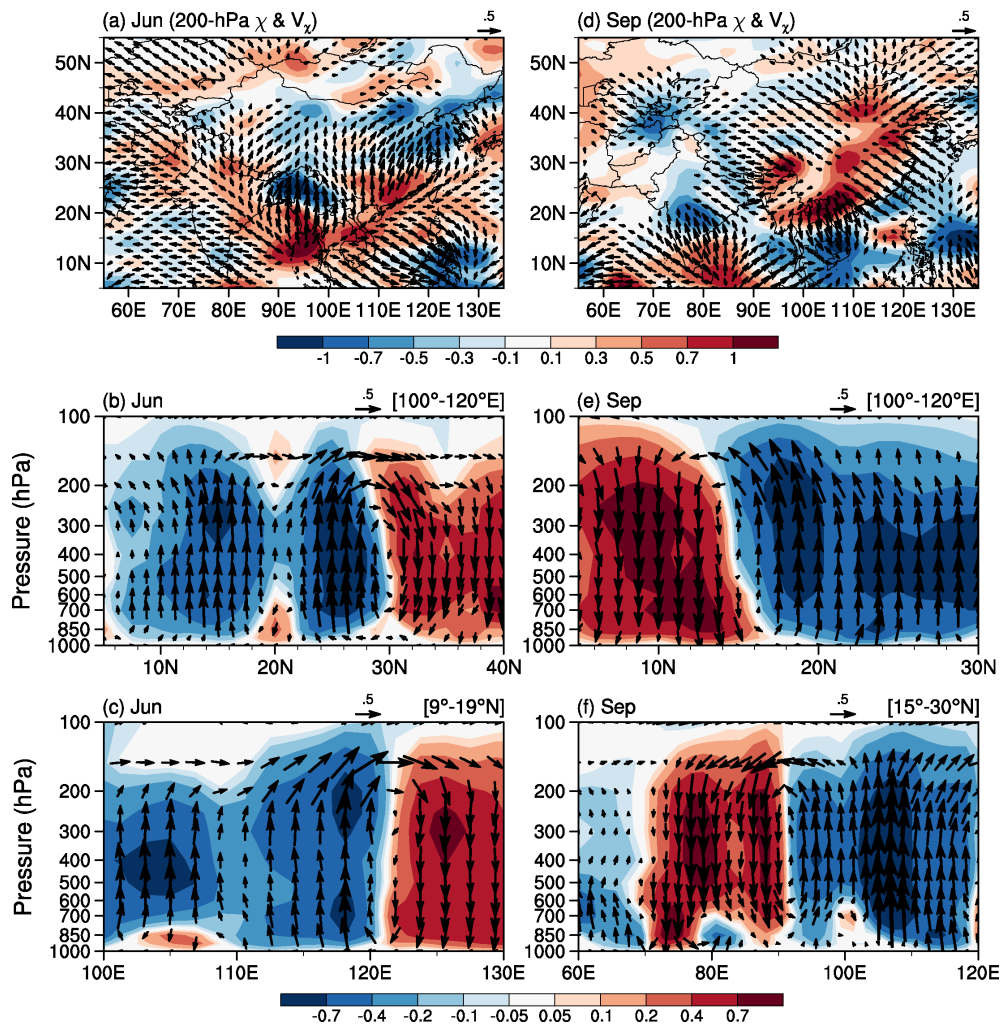
Fig. 9. June differences in (a) 200-hPa divergence (10^6 s^{-1}, shading) and divergent wind (mm day^{-1}), (b) vertical cross-section of vertical velocity (10^{-2} Pa s^{-1}) and divergent circulation averaged over 100°–120°E, and (c) over 9°–19°N. (d–f) Same as (a–c) but for September.
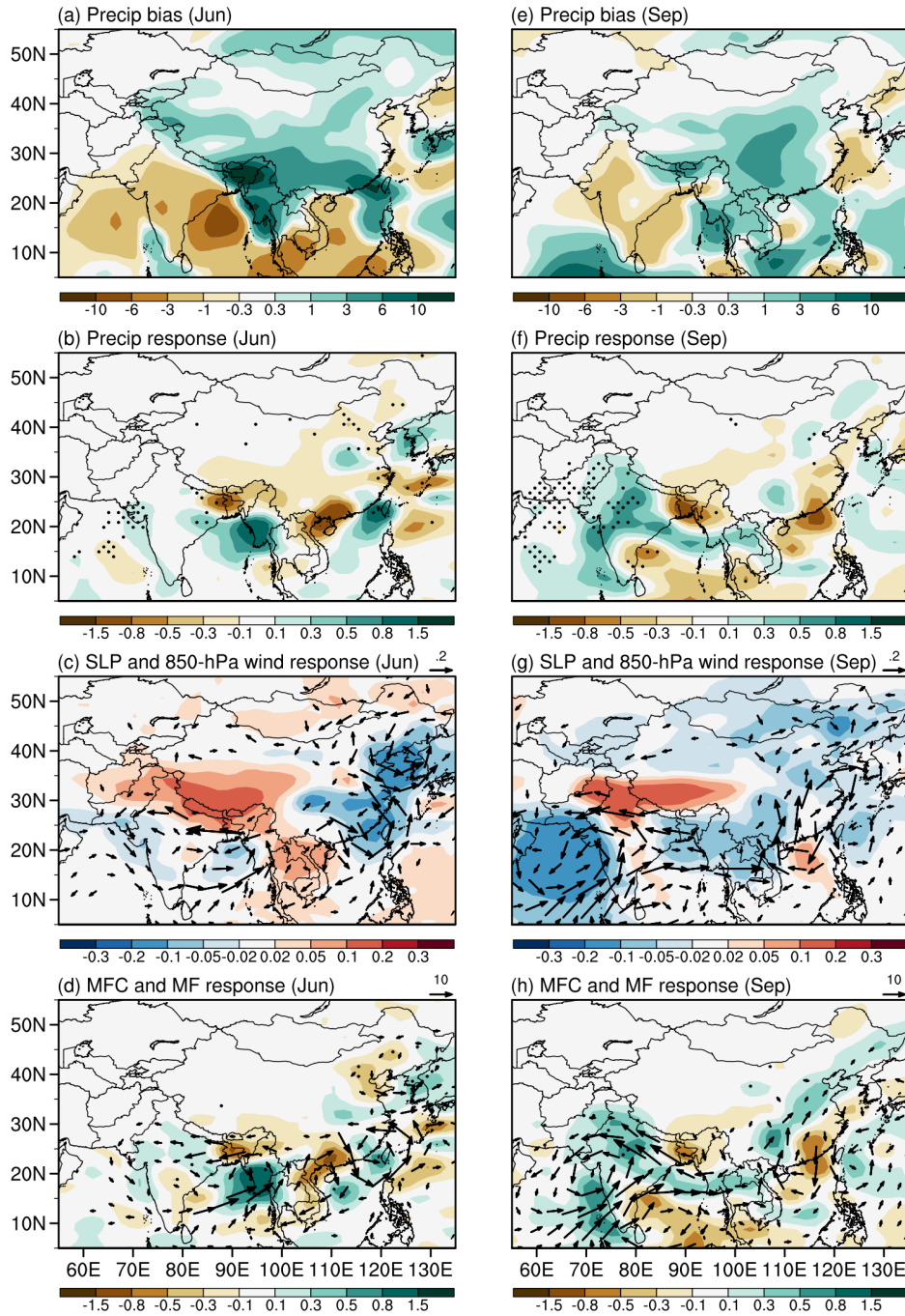
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984 Fig. 10. Same as Fig. 5 but for the difference between the corresponding nudged simulations (i.e., NUDG–NUDGfA).
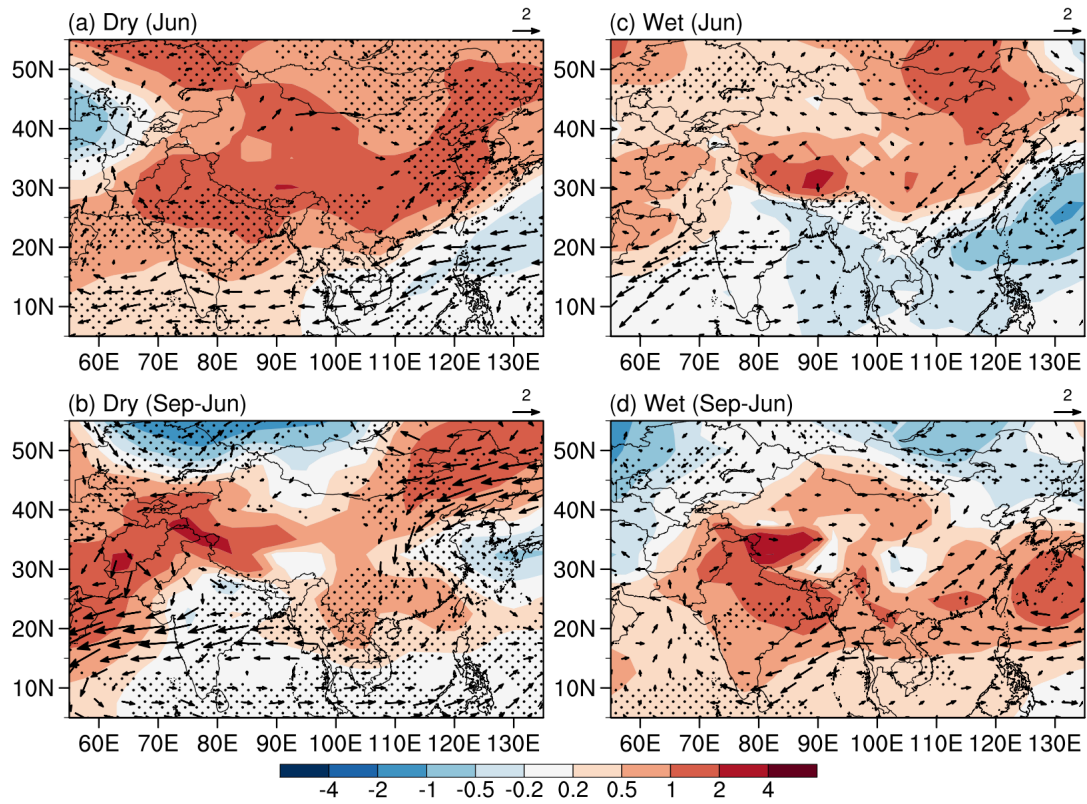
Precip bias
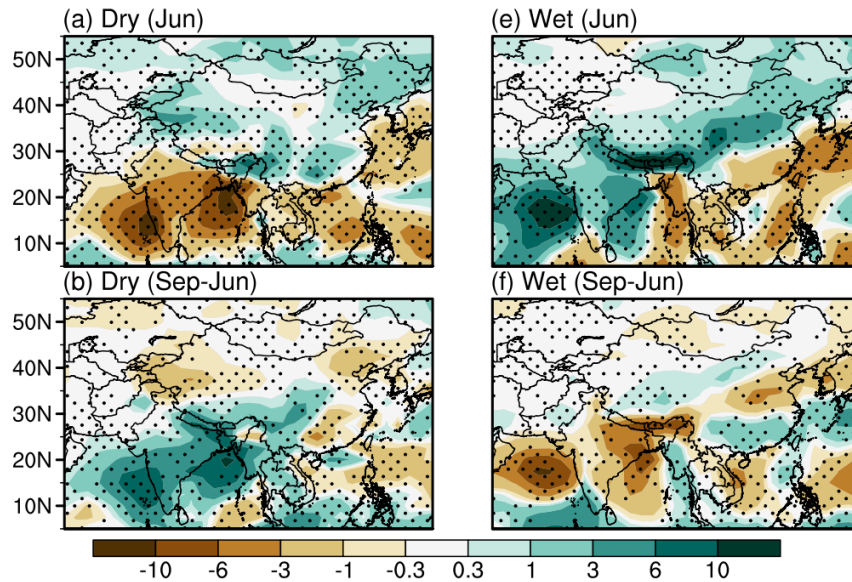
Precip response
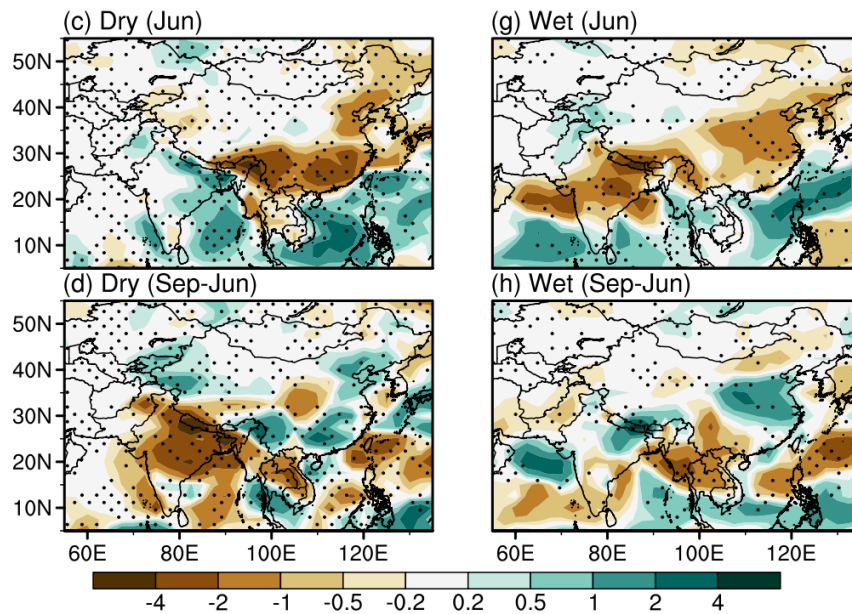
Fig. 11. DRY PDRMIP model composites in (a) June precipitation bias (mm day^{-1}), (b) September minus June difference in precipitation bias, (c) June precipitation response to increased Asian sulfate aerosols (i.e., the difference between 10× sulfate and baseline simulations), and (d) September minus June difference in the precipitation response to increased Asian sulfate aerosols. (e–h) Same as (a–d) but for WET PDRMIP model composites. Black dots mark grid-points for which all models agree on the sign of the precipitation differences.

SLP and 850-hPa wind response
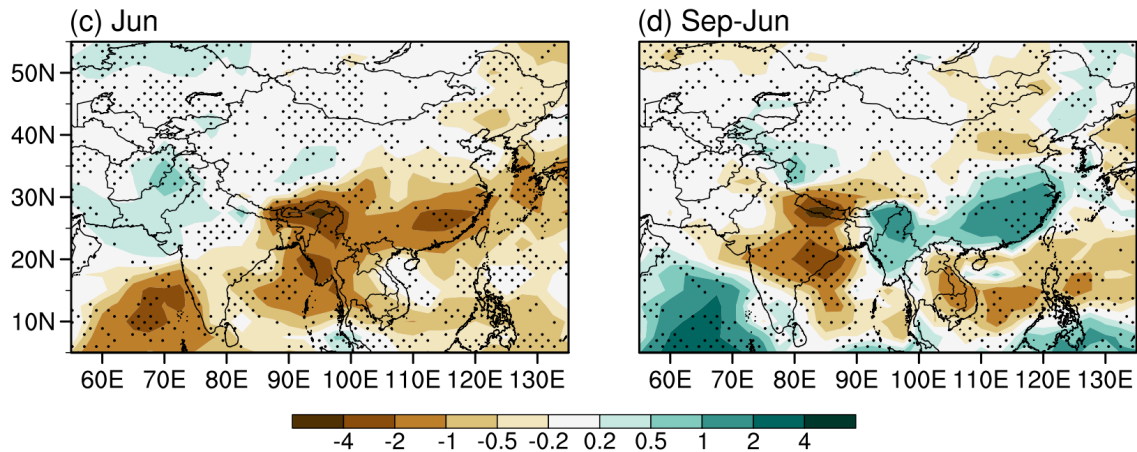

Fig. 12. Sea-level pressure (hPa, shades) and 850-hPa wind (m s^{-1}) responses to increased Asian sulfate aerosols in the (left column) DRY and (right column) WET PDRMIP model composites. (a) and (c): June, (b) and (d): September minus June differences. Black dots mark grid-points for which all models agree on the sign of the precipitation differences.
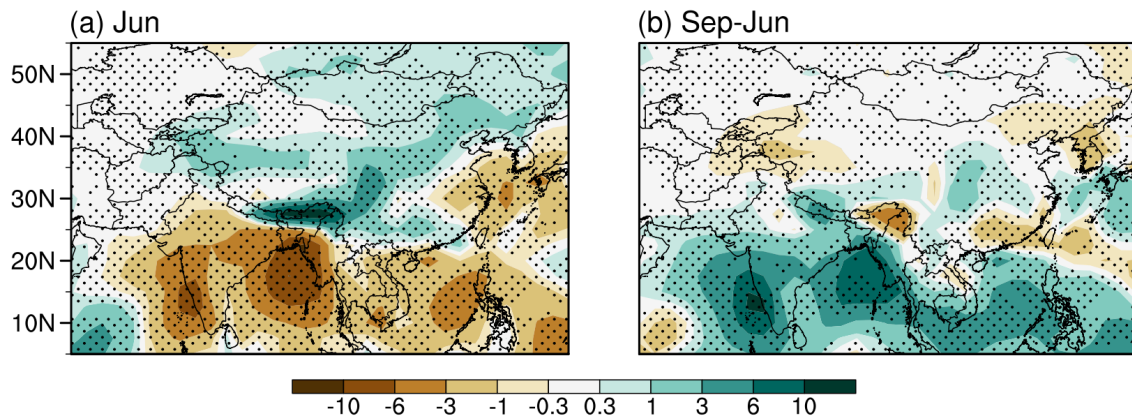
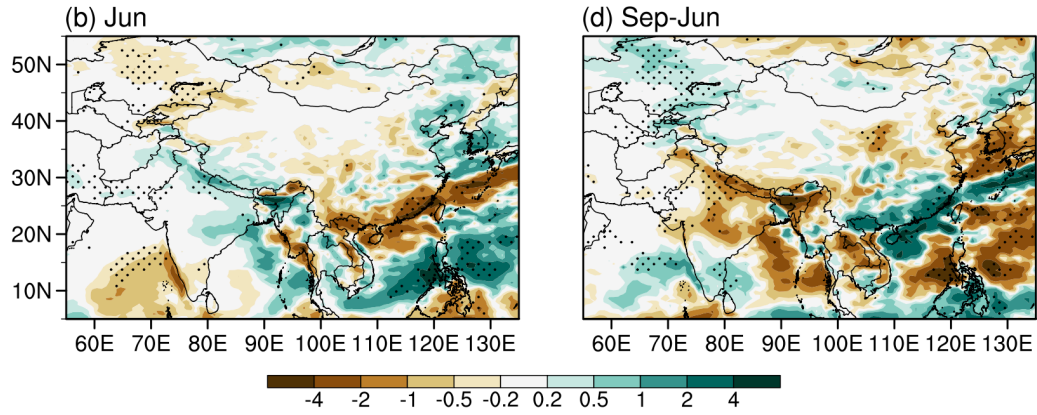Fig. 13. PDRMIP coupled model composites in (a) June precipitation bias (mm day^{-1}), and (b) June precipitation response to increased Asian sulfate aerosols (i.e., the difference between 10× sulfate and baseline simulations). (c) and (d): Same as (a) and (b) but for the September minus June differences. Black dots mark grid-points for which at least four out of the five models agree on the sign of the precipitation differences.
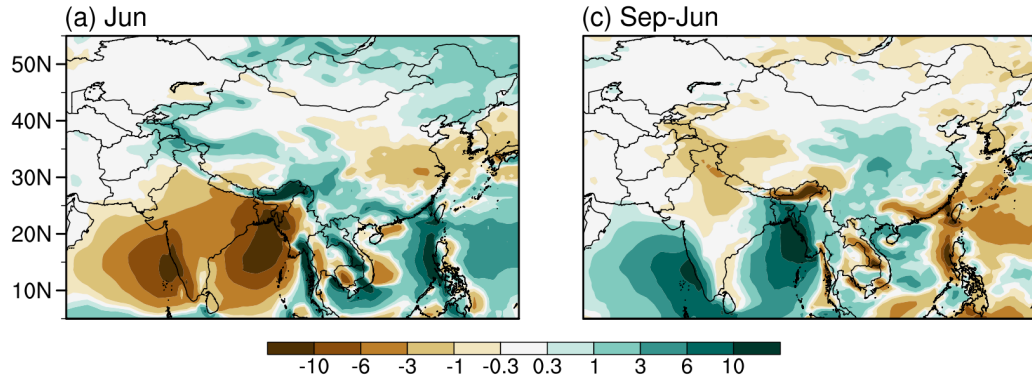
Fig. 14. (a) June precipitation bias (mm day^{-1}) in HadGEM3-GC2 coupled simulations, (b) precipitation bias difference between September and June, (c) June precipitation response to Asian aerosol changes, (d) difference in the precipitation response to Asian aerosols between September and June. Black dots in (b) and (d) mark grid-points for which the difference is significant at the 90% confidence level.