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Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient.

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1 **Abstract**

2 There are large uncertainties looming over the status and fate of the South Asian summer
3 monsoon, with several studies debating whether the monsoon is weakening or strengthening in
4 a changing climate. Our analysis using multiple observed datasets demonstrates a significant
5 weakening trend in summer rainfall during 1901-2012 over central South Asia, extending from
6 south of Pakistan through central India to Bangladesh, with up to 10-20% reduction over
7 central-eastern India. Earlier studies have suggested an increase in moisture availability and
8 land-sea thermal contrast in the tropics due anthropogenic warming, favoring an increase in
9 tropical rainfall. In contrast, we notice a weakened land-sea thermal contrast due to rapid
10 warming in the Indian Ocean, along with a relatively subdued warming over the subcontinent.
11 Using long-term observations and coupled model experiments, we provide compelling
12 evidence that the enhanced Indian Ocean warming, especially that over the western region,
13 potentially weakens the land-sea thermal contrast, dampens the summer monsoon Hadley
14 circulation, and thereby reduces the rainfall over South Asia.

15

16 **Introduction**

17 The South Asian summer monsoon rainfall during June to September plays a significantly large
18 role in the *roti and dal** of roughly one-half of the world population¹. The variability of the
19 monsoon makes the region one of the most susceptible areas around the world to the impacts
20 of climate-related natural disasters such as droughts and floods. Through observations and
21 modeling, the scientific community has advanced its understanding of the past and future
22 changes in the monsoons. With regard to the northern summer monsoon, some studies suggest
23 that the monsoon circulation and rainfall have intensified in a changing climate². Wang et al.²
24 show that the rainfall over the northern hemisphere summer monsoon domain, as well as the

* *bread and butter* in south Asian nomenclature

25 Hadley and Walker circulations have all undergone substantial intensification during the last
26 three decades (1979-2011), with a striking increase of monsoon rainfall by 9.5% per degree of
27 global warming. A few recent studies have also pointed out the increasing frequency of extreme
28 rainfall events over the south Asian monsoon domain, due to a warming climate³. However,
29 quite a few other studies indicate that the monsoon rainfall^{4, 5, 6} and the Hadley and Walker
30 circulations^{7, 8, 9} are weakening over the South Asian domain during the past half century (since
31 1950s). Some of these studies suggest that, though the extreme rainfall events have increased
32 over some regions³, the frequency of moderate-to-heavy rainfall events has decreased over the
33 subcontinent⁸. In addition, several recent studies based on the Coupled Model Inter-comparison
34 Project phase 5 (CMIP5) indicate a significant weakening of the large-scale Asian summer
35 monsoon circulation, especially in the middle to upper atmosphere^{10, 11, 12}. Monsoonal changes
36 are found to be different when the region and time-periods considered are different—and so are
37 the implications¹³. In fact, a recent study¹⁴ using proxy records for the Asian monsoon over the
38 past two millennia suggests that the monsoon is currently in the decreasing phase of a multi-
39 decadal oscillation. This study also cautions that monsoonal changes due to anthropogenic
40 forcing will be difficult to detect against a backdrop of large natural variability. The
41 Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) is also
42 suggestive of the uncertainties looming over the status and fate of the monsoons^{15, 16}.
43 Considering these uncertainties, there is an urgent need to provide robust information through
44 the use of long-term observed datasets and climate models that could resolve the spatial and
45 temporal lacuna associated with the monsoon variability in a changing climate.

46 Climate models consistently show that, under increasing greenhouse gas forcing, the
47 land-sea temperature contrast increases, possibly due to enhanced evaporation (latent heat loss)
48 over the ocean¹⁷. An increase in the land-sea thermal contrast should ideally increase the
49 strength of the monsoon^{18, 19, 20}. Also, the sea surface temperatures (SST) over the Indian Ocean

50 have shown a warming trend over the last several decades^{21, 22, 23}, potentially enhancing the
51 supply of moisture to the monsoon regions and increasing the rainfall amounts²⁴. In a recent
52 review of climate change and the South Asian monsoon, Turner and Annamalai¹³ point out that
53 though the land-sea contrast and the increased moisture availability should favor an increased
54 monsoon rainfall, the observations do not provide any convincing evidence for such a positive
55 trend. On the contrary, the South Asian monsoon rainfall has decreased significantly during the
56 past several decades and this time evolution is not well reproduced by the CMIP5 models used
57 in the IPCC AR5^{4, 11, 12, 25, 26, 27}. This is indeed intriguing, and escalates the uncertainty
58 associated with the monsoon in a changing climate.

59 In this study, we find that the summer monsoon rainfall during 1901-2012 shows a
60 significant weakening trend over central South Asia, especially over the central-eastern parts
61 of India where agriculture is still mostly rain-fed. Using observations and climate model
62 experiments, we demonstrate that this reduction in rainfall is linked to the rapid warming of
63 the Indian Ocean, especially its western part, during the past century. The Indian Ocean
64 warming, along with a relatively subdued warming of the Indian subcontinent, has played a
65 key role in weakening the land-sea thermal contrast, which is a major driver of the South Asian
66 monsoon. The weakened land-sea thermal contrast dampens the summer monsoon Hadley
67 circulation, reducing the rainfall over South Asia.

68

69 **Results**

70 **Rainfall trends during the past century**

71 Figures 1a and 1b show the trend in precipitation over the South Asian region, during summer
72 monsoon for the years 1901-2012, using gridded datasets from the India Meteorological
73 Department (IMD) and the Climate Research Unit (CRU). The trends are similar in both the
74 datasets, with a weakening trend over the central and northeast Indian subcontinent, and south

75 of the Western Ghats region. The CRU dataset shows that the negative trend over the central
76 subcontinent extends west to east, from south of Pakistan to central-eastern India, with a
77 prominent horseshoe pattern with one of its arms placed on the foothills of the Himalayas, and
78 the other obliquely along the central east coast of India. The reduction in summer rainfall over
79 central-eastern India during the past century is about 10-20%. This could have socio-economic
80 consequences since the agriculture in this region is still largely rain-fed. Significant positive
81 trends in precipitation are consistently observed to the north of the Western Ghats region, in
82 both the datasets. However, the positive rainfall trends are confined to a small domain along
83 the west coast.

84

85 **Indian Ocean warming and its association with the rainfall trends**

86 Previous studies using atmospheric general circulation models (AGCM) forced by observed
87 SST variations suggest that a decrease in global land monsoon rainfall can be caused by
88 warming trends over the tropical oceans, especially the central-eastern Pacific and the western
89 Indian Ocean²⁸. Among these tropical oceans, the Pacific SST anomalies do not show any long-
90 term significant trend, while the western Indian Ocean exhibited rapid warming throughout the
91 past century²⁹ (Fig. 2). In comparison with the rest of the Indian Ocean, the WIO generally has
92 cooler mean SSTs in summer, owing to the strong monsoon winds and the resultant upwelling
93 over the west. Meanwhile, the central-east Indian Ocean is characterized by a warm pool with
94 SSTs greater than 28.0°C. Though previous studies demonstrate a basin-wide warming in the
95 Indian Ocean during the past half century^{22, 23}, our analysis using long-term SST datasets show
96 that over an extended period of 112 years, the western Indian Ocean (WIO, 50-65°E, 5°S-10°N)
97 has experienced anomalous warming of 1.2°C (Fig. 2), which is 0.5°C greater than the warming
98 over the warm pool region²⁹. Even though a warming trend over the Indian Ocean may result
99 in an increased supply of moisture locally over the ocean, it is not necessary that the surplus

100 moisture is carried on to the peninsula³⁰. The sustained Indian Ocean warming in the west has
101 led to a greater westward extension of this Indian Ocean warm pool in recent decades^{22, 29}. The
102 expansion of the Indian Ocean warm pool can in turn modify the land-sea thermal gradient,
103 which could modulate the strength and flow of the monsoon circulation and the moisture laden
104 winds towards the South Asian subcontinent. Hence, deciphering the relationship between the
105 Indian Ocean warming and the monsoon precipitation might give a clue to the cause and effect
106 of the observed rainfall trends over the region.

107 In order to evaluate the association of the nearly monotonic warming over the WIO on
108 the observed monsoon trends over the subcontinent, we carried out a correlation analysis
109 between SST and precipitation anomalies over the two regions. Figures 3a and 3b show the
110 correlation between the WIO SST anomalies and precipitation anomalies over the South Asian
111 region, using multiple datasets. The spatial distribution of the correlation coefficients is
112 consistent among the different datasets. The fascinating aspect is that, the correlation of
113 precipitation anomalies with the Indian Ocean SST anomalies, and the trend in these
114 precipitation anomalies are strikingly similar. A pattern correlation computed between the
115 trends in Fig.1b and the correlation coefficients in Fig.3b (for the region 60°-100°E, 5°-35°N
116 at 0.5° horizontal grid resolution) indicates that they are strongly correlated ($r=0.73$, significant
117 at 95% confidence level). The most robust common feature among the trend and correlation
118 patterns is a horseshoe pattern over central India. Apart from this, a dipolar pattern in the
119 rainfall trends, with positive in the north and negative in the south is also visible along the
120 Western Ghats of the Indian subcontinent (Fig. 1). A recent study³¹ suggests that enhanced
121 warming to the north of WIO in recent decades has also led to a poleward shift of the core of
122 low level monsoon winds, increasing the precipitation to the north of the Western Ghats, while
123 weakening it over the south. This dipolar rainfall pattern between the south and north of the

124 Western Ghats is also found to be associated with the WIO warming at both the interannual
125 and low frequency (e.g. trend) time scales (Fig.3).

126 For a time series analysis, we consider the precipitation over the central South Asia
127 (60°-100°E, 20°-30°N, inset box in Fig. 3b) along with the WIO SST anomalies (Fig. 3c). The
128 rainfall region under consideration is chosen because the decreasing trend in rainfall is
129 significant over this region, and also consistent with other studies utilizing station-wise analysis
130 of rain gauge data⁶. Indeed, the SST and precipitation time series in Figure 3c are negatively
131 correlated ($r = -0.35$ at $df = 110$, for the unsmoothed time series), significant at 95% confidence
132 level. Analysis using detrended time series data also shows significant negative correlation
133 over the same region (Supplementary Fig. 1). This means that similar processes may operate
134 at interannual and lower frequency timescales to generate a secular downward monsoon rainfall
135 trend in response to the warming of the WIO, or alternatively, that a part of the Indian Ocean
136 warming is due to the weakening of the monsoon²³. The negative correlation is not observed
137 during the first half of the 20th century, but becomes statistically significant post-1950s,
138 probably due to the accelerated warming observed during the latter half. This implies that the
139 relationship between a warm ocean and a weak monsoon is not linear. Since the ocean warming
140 is a slow process, the heat has to build up over several decades to make a substantial difference
141 and reach the warm pool SST values (28.0°C)^{22, 29}. The sustained WIO warming has led to a
142 greater spatial extension of the Indian Ocean warm pool in the recent decades only²².

143

144 **Changing land-sea thermal contrast**

145 As pointed out earlier, changes in the land-sea thermal contrast impact the strength of the
146 monsoon^{17, 18, 19, 20}. Studies show that over the northern hemisphere, the surface temperatures
147 over land increase more rapidly than over sea, under increasing greenhouse gases²⁰. Ideally,
148 such a scenario should strengthen the South Asian monsoon^{17, 18, 19, 20}. Figures 4a and 4b show

149 the climatological mean and trends of surface temperatures over the Indian Ocean and the south
150 Asian monsoon domain, during summer. Obviously, the monotonic warming trend over the
151 Indian Ocean is prominent, with the strongest warming over the west. At the same time the
152 Indian subcontinent exhibits suppressed warming during the past century. In fact, the surface
153 temperatures in the northern Indian peninsula show a cooling trend. This implies a weakening
154 meridional thermal gradient over the South Asian domain, in contrast with earlier studies,
155 which suggest a strengthening of the thermal gradient under a globally warming scenario. The
156 weakening land-sea thermal gradient is reproduced in other datasets also, indicating the
157 robustness of the trend (Supplementary Fig. 2).

158 The land-sea contrast in surface temperatures, though important, may not provide a
159 comprehensive picture of the factors modulating the strength of the monsoon circulation. Once
160 the monsoon rains set in on the South Asian subcontinent, the land surface cools down
161 considerably. However, the troposphere above the land remains warm due to the latent heat
162 release from the convective activity, keeping the thermal contrast functional³². This means that
163 the tropospheric temperature is an ideal parameter for examining the thermodynamic forcing
164 related to the monsoon³². However, unlike the surface temperature, robust records of air
165 temperature at different levels of the troposphere are not available prior to the 1950s, which
166 makes it difficult to examine the role of long-term tropospheric temperature trends on the
167 monsoon. Nevertheless, to confirm that our results are valid for the recent decades also, we
168 analyze the tropospheric temperatures over the monsoon domain. The trend in the thermal
169 contrast is well reflected in the upper tropospheric (200 hPa) temperature anomalies also, as
170 demonstrated in Figure 4c. Along with a cooling trend over the larger Indo-Tibetan landmass,
171 increasing positive temperature anomalies are observed over the WIO, indicating its potential
172 role in weakening the monsoon flow towards the Indian peninsula. The warming of the upper
173 troposphere over the Indian Ocean (Fig. 4c) is co-located with that over the sea surface (Fig.

174 4b). This may be attributed to the fact that the tropical Indian Ocean is a highly convective
175 region during the northern summer, as the mean SSTs are above the minimum convective
176 threshold (26°C) and the southwesterly monsoon winds are conducive for enhanced moisture
177 convergence³³. Further warming of the Indian Ocean enhances the convection²⁴, transferring
178 surplus heat to the upper troposphere^{34, 35, 36}.

179 To evaluate the trends observed in land-sea thermal contrast in Figs. 4b and 4c, we
180 analyze the difference between the summer tropospheric temperatures over WIO and the Indian
181 subcontinent, at 850 and 200 hPa levels (Fig. 4d). The surface temperature gradient (T_{surf}) shows
182 a sharp decline throughout the past century, largely contributed by an increased warming over
183 the WIO. The tropospheric temperature gradient (T_{trop}) post-1950s also indicates a trend similar
184 to that in the surface temperatures. This is suggestive of a warm Indian Ocean having a strong
185 hold on the whole troposphere, from the surface to the top, possibly due to enhanced convective
186 mixing over the ocean^{34, 35, 36}. Indeed, a separate analysis of the trend at each of these levels
187 gave consistent results of a warming troposphere over the Indian Ocean, and a weakening
188 thermal contrast between the subcontinent and the ocean. All these results indicate a reduced
189 land-sea thermal contrast during the past century, partly due to increased warming over the
190 Indian Ocean, especially over the western region, and partly due to a relatively weaker warming
191 over the Indian peninsula.

192

193 **Weakening of the summer monsoon Hadley circulation**

194 Many studies have shown that warm SST anomalies are accompanied by large variations in the
195 lower and upper troposphere due to enhanced latent heating aloft from convection over the
196 ocean^{34, 35, 36}. Furthermore, these changes are highly correlated with the strength of the
197 monsoon circulation^{32, 35}. A more recent study using a coupled model framework also points
198 out that a spatial extension of Indian Ocean warm pool could enhance the convection over the

199 ocean while introducing a dry bias over land, by modulating the meridional Hadley
200 circulation³⁷. It is therefore likely that the impact of the Indian Ocean warming on the monsoon
201 has become more prominent in recent decades. Consistently, an examination of the vertical
202 wind velocity over the South Asian domain (50-100°E) during the years 1948-2012 indicates
203 large scale upward motion over the equatorial ocean (10°S-10°N), extending up to the upper
204 troposphere and favoring intense local convection (Fig. 5a). Furthermore, this enhanced
205 upward motion over the ocean is compensated by subsidence of air over the subcontinent (10-
206 20°N), inhibiting convection over the landmass and drying the region, through a modulation of
207 the local Hadley cell (Fig. 5a). This suggests that though the warming ocean engenders
208 enhanced local rainfall due to increased moisture availability, it weakens the monsoon Hadley
209 circulation and reduces the rainfall over the land, ultimately building up a competition among
210 the land and ocean rainfall in the south Asian monsoon domain.

211

212 **Climate model response to Indian Ocean warming**

213 Attribution of the decreasing monsoon rainfall to the Indian Ocean warming from observations
214 alone is very difficult and probably impossible. Thus, to delineate and examine the role of the
215 Indian Ocean warming on the monsoon circulation and rainfall, model sensitivity experiments
216 using an ocean-atmosphere coupled climate model were carried out. In the sensitivity
217 experiment, positive SST anomalies similar to those in the observations were added to the WIO
218 region (Supplementary Fig. 3). Figure 5b shows the model response in the summer monsoon
219 Hadley circulation, and features a weakening of the local Hadley cell, much similar to the
220 observed trends. The fact that the warming has resulted in enhanced convection over the ocean
221 and subsidence over the landmass serves as the evidence that the observed warming trend in
222 the Indian Ocean has the potential to weaken the monsoon circulation.

223 Figure 6 compares the observed trends in precipitation and surface winds with the
224 model-simulated anomalies in response to warming over the WIO. The interesting, robust
225 element in the model simulations (Fig. 6b) is the horseshoe pattern in the negative precipitation
226 anomalies, with one arm placed over the Himalayan foothills and the other over the central
227 Indian landmass, similar to the one in the precipitation trends (Figs. 1, 6a) and the correlation
228 pattern with WIO SST anomalies (Figs. 3a,3b). Consistent with the reduced precipitation, the
229 surface winds also suggest weakened mean southwesterly winds. The trend analysis (Fig. 6a)
230 shows a Rossby wave-like response³⁸ to the Indian Ocean warming, with northeasterly wind
231 anomalies over most of the Arabian Sea, converging towards the central Indian Ocean. The
232 model simulation (Fig. 6b) also shows similar results, with respect to the Rossby wave response
233 near the subcontinent and over the Arabian Sea. However, the zonal direction of the wind
234 anomalies near the equator appears different in the observations and the model. This is not an
235 unexpected result as the periods under consideration and the model simulations are different,
236 since the observed winds are available only for 1948-2012—a period during which the Indian
237 Ocean experienced a basin-wide warming^{22, 23}. In fact previous studies using AGCM
238 experiments driven by recent basin-wide warming in the tropical Indian Ocean reproduced the
239 observed zonal wind changes in the recent decades³⁹. In the model sensitivity experiment,
240 however, the positive SST offset is prescribed only over the WIO region, where the long-term
241 warming trend is observed in the SST records during 1901-2012. This suggests that while WIO
242 warming plays a significant role in the long-term change in winds, basin-wide warming over
243 the tropical Indian Ocean has emerged as a co-conspirator in the change in land-sea thermal
244 contrast and winds in recent decades.

245 A further comparison of the model response to the warming is provided in
246 Supplementary Fig. 4. The thermal response (surface and upper troposphere) is similar to those
247 in the observed trends over the ocean, but exhibit some discrepancies over land. More

248 specifically, for the model response in temperature at 200 hPa, the results reproduce the upper
249 tropospheric warming over the ocean, but do not replicate the cooling over the Indo-Tibetan
250 landmass. This is possibly because of the role of other processes on the upper tropospheric
251 temperatures, such as aerosol forcing^{40, 41} and stratosphere-troposphere interactions⁴², which
252 are not included in the model experiment. It may also be noted that previous studies⁴² have
253 suggested that the NCEP upper tropospheric data overestimates the cooling trend over the Indo-
254 Tibetan landmass. Nevertheless, the similarity between the rainfall and local Hadley responses
255 between the model experiments and observed fields clearly demonstrates the importance of
256 WIO warming in determining the observed monsoon response.

257

258 **Discussion**

259 The above analysis using observations and climate model sensitivity experiments indicates the
260 potential role of the Indian Ocean warming in weakening the monsoon circulation and rainfall
261 over central South Asia. The Indian Ocean and monsoon exhibit a coupled relationship^{33, 43, 44},
262 and it is also possible that a feedback from a weak monsoon accelerates the warming in the
263 Indian Ocean²³. Some studies have suggested a role for anthropogenic aerosols in weakening
264 the monsoon circulation during the recent decades^{41, 45, 46, 47, 48, 49}. It is possible that such a
265 weakened circulation amplifies the SST warming due to a decreased evaporation. In contrast,
266 recent studies show that the anthropogenic aerosols tend to have a cooling effect and compete
267 with the greenhouse warming over the Indian Ocean^{50, 51}. Despite the fact that aerosols are a
268 competing factor, the observed SST trends do not show any change during the post-1980s
269 where aerosols have increased (Fig.3c). In fact, a study⁵¹ points out that a large share of the
270 CMIP5 models with aerosol forcing are not able to reproduce the observed SST warming over
271 the Indian Ocean. They attribute this issue to the large uncertainties in representing the direct
272 and indirect effects of aerosols in these models. Meanwhile, a recent study demonstrates that

273 apart from the warming due to greenhouse gas forcing⁵², the long-term warming trend in the
274 western Indian Ocean is significantly associated with the asymmetry in the ENSO forcing²⁹.
275 That is, while the quasi-periodic El Niño events induce a warming over the Indian Ocean via
276 the Walker circulation, the La Niña events fail to do the inverse. Along with this, an increase
277 in the magnitude and frequency of El Niños in the recent decades has accelerated this
278 warming²⁹. The heat pile-up due to this ENSO forcing⁵³ persists in the land-locked Indian
279 Ocean which has a restricted thermohaline circulation, sustained by a feedback from the local
280 air-sea interaction^{54, 55} and ocean dynamics^{56, 57}. Considering the strong seasonal variability in
281 this region and short-term persistence in atmospheric changes, it is rather self-evident that, on
282 longer time scales, the warmer ocean plays a larger role in weakening the monsoon than vice-
283 versa.

284 Though the observed increase in anthropogenic aerosols may not have a direct effect in
285 warming the Indian Ocean, they may have a potential role in suppressing (or even cooling) the
286 surface warming over the South Asian domain in the recent decades^{40, 41}. Aerosols could be
287 considered as the perfect partner in reducing the land-sea thermal contrast, along with a
288 warming Indian Ocean. An evaluation of the CMIP5 models⁴¹ suggest that aerosols could
289 potentially reduce the incoming solar radiation over the Indo-Gangetic plain, thereby cooling
290 the surface. However, it may be pointed out that majority of these models could not simulate
291 the spatial distribution of aerosols or related processes over the South Asian subcontinent⁴¹.
292 Also, ambiguity still remains on the extent of cooling (or warming) induced by different types
293 of aerosols^{46, 47, 48}. Meanwhile, other studies link the upper tropospheric cooling over the larger
294 Indo-Tibetan landmass during summer to stratospheric temperature changes which are
295 channeled through stratosphere-troposphere interactions⁴². Further research is required to
296 differentiate the individual contributions of these components on the observed trends in surface
297 and upper tropospheric temperatures over land.

298 The current study discusses the role of Indian Ocean warming in weakening of the
299 monsoon, but does not rule out the possibility that similar impacts may also arise due to SST
300 changes in the tropical Pacific and the Atlantic^{9, 55, 58, 59, 60, 61, 62}. Recent studies show that the
301 Pacific warming trend during the past century is not prominent as compared to the Indian Ocean
302 warming while the tropical and extratropical Atlantic show strong warming trends²⁹. However,
303 Prodhomme et al.⁶² pointed out that a warming in the tropical Atlantic does not change the
304 tropospheric temperature gradient between the Indian Ocean and the subcontinent as the
305 temperature changes due to the teleconnection are uniform over this domain. Meanwhile,
306 Goswami et al.⁶⁰ suggest that a North Atlantic warming should ideally strengthen the Asian
307 monsoon by increasing the tropospheric temperatures over northern India and southern Eurasia.
308 However, temperature and rainfall trends during recent decades suggest that any such role of
309 the Atlantic is offset by the tropospheric temperature trends induced by a warming Indian
310 Ocean. Deconvolving the non-stationary relations between the monsoon and the warming over
311 these remote regions is beyond the scope of this study. But considering the robustness of the
312 Indian Ocean warming and its direct role in monsoon dynamics in comparison with the other
313 tropical oceans, it is justified to say that the Indian Ocean SST trends play a relatively larger
314 role on the observed rainfall trends in the South Asian domain.

315 A recent study comparing present observations and future regional climate model
316 projections of the summer monsoon suggests a further weakening of the monsoon circulation
317 and peninsular rainfall in the future⁶³. Meanwhile, the CMIP5 future projections suggest an
318 increase in rainfall over the central Indian subcontinent²⁸, though one must note the ongoing
319 debate about whether CMIP5 models are in fact capturing the historic monsoon trends
320 accurately^{4, 11, 12, 25} and whether the monsoon projections are reliable in these models²⁶. The
321 overall weakening trend of monsoon rainfall over South Asia is a matter of grave concern since
322 the socio-economic livelihood in this region, including agriculture, water resources and power

323 generation are irrevocably dependent on it. The role of Indian Ocean warming might not be
324 solely limited to weakening the Asian monsoon. Research based on climate proxy records and
325 models point out that the climate signals forced by warm SST anomalies over the tropical
326 Indian and western Pacific oceans synergistically contribute to widespread drying over south
327 Asia and mid-latitudes, an ideal scenario for a large-scale drought^{64, 65}. In addition, a recent
328 study points out that the Indian Ocean warming may also be playing an important role in
329 modulating the Pacific climate change in recent decades—by favoring stronger trade winds in
330 the Pacific, thereby contributing to the recent global warming hiatus⁶⁶. Hence, the critical role
331 of the warm Indian Ocean deserves special attention not only for its decisive effect on the food
332 security of a large fraction of the world's population, but also due to its disproportionately large
333 role as a partner to the warm pool Pacific in inducing a drought, as well as its potential role in
334 the global warming pause.

335

336 **Methods**

337 **Rainfall and SST historical data analysis**

338 Two long-term precipitation datasets for the northern summer during the period 1901-2012,
339 obtained from the India Meteorological Department (IMD) and Climate Research Unit (CRU)
340 are used in this study. The recent IMD precipitation data uses daily rainfall data from all the
341 rain gauge stations over India, gridded at 0.25° horizontal resolution⁶⁷. This includes rainfall
342 records from 6,955 stations, which is the highest number of stations used by any gridded
343 datasets currently available. The data density varies from year to year from about 1,500 in the
344 first couple of years to about 4,000 by the end of the century. The trend in precipitation over
345 the central Indian region under consideration, is compared with studies utilizing station wise
346 analysis of rain gauge data⁶. SST data for the same period is obtained from the HadISST1
347 dataset provided by the Met Office Hadley Centre, and also the Extended Reconstructed Sea

348 Surface Temperature (ERSST) provided by NOAA. In order to examine the role of land-sea
349 temperature gradient, surface temperatures from HadCRUT (1901-2012) and tropospheric
350 temperature values from NCEP reanalysis (1948-2012) are used. Observed trends in the
351 monsoon southwesterlies are inferred from the wind data based on NCEP reanalysis during
352 1948-2012. The significance of the trends and correlations is examined using standard two-
353 tailed student's t-tests. The correlation analysis in Fig.3c has also been tested using Kendall's
354 rank correlation which is non-parametric and therefore makes no assumptions about the
355 distribution and at the same time determine the direction and significance of the relation
356 between the two variables⁶⁸. The correlated variables are said to be concordant if their ranks
357 vary together (-1) and discordant if they vary differently (+1). The significance of the rainfall
358 and SST linear trend values are further assessed with Mann-Kendall tests⁶⁹ with block bootstrap
359 to improve the significance test when a time series shows auto-correlation.

360

361 **Model and experimental design**

362 For the numerical model experiments, we use the standard configuration of a global coupled
363 ocean-atmosphere model, the Climate Forecast System version 2 (CFSv2). The CFSv2 model
364 simulates the mean monsoon and its interannual variability reasonably well, and hence used in
365 this study⁴³. The oceanic component has a 0.25-0.5° horizontal resolution, 40 vertical levels
366 and includes an ice model. The atmospheric component is at T126 (~0.9°) horizontal resolution,
367 and 64 sigma-pressure hybrid levels. The atmosphere and ocean exchange quantities such as
368 heat and momentum fluxes every half an hour, with no flux adjustment or correction. See Saha
369 et al.⁷⁰ for further details on the model and its components. The coupled configuration of CFSv2
370 is time integrated over a period of 100 years, and utilized as the reference run (CFSv2_{CTL}). In
371 order to examine the role of a warming Indian Ocean, a sensitivity experiment (CFSv2_{WIO})
372 using ensembles (20 members) of short integrations for the summer monsoon season during

373 June-September were performed by adding temperature anomalies to the SSTs passed over the
374 WIO, to the atmosphere. Positive anomalies of the order of 1.5°C were added over the region,
375 in such a way that it tapers out by the limits of the domain (50-65°E, 5°S-10°N). The positive
376 offset added to the simulated SSTs over WIO in the sensitivity experiments is similar to the
377 amplitude of the observed trends (Fig. 2, Supplementary Fig. 3). The difference between
378 CFSv2_{WIO} and CFSv2_{CTL} is taken as the model response to the summer warming over the WIO.

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384

385 **Author Contributions**

386 M.K.R. designed the study and the model experiment. M.K.R. and K.R. performed the model
387 sensitivity experiments and the analysis. All authors contributed ideas in developing the
388 research, discussed the results and wrote the paper.

389

390 **Competing financial interests**

391 The authors declare no competing financial interests.

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567 **Figure Legends**

568 Figure 1. Observed trend in precipitation ($\text{mm day}^{-1} \text{ 112 year}^{-1}$) in **(a)** IMD and **(b)** CRU
569 datasets, during June-September, for the years 1901-2012. Contours denote regions
570 significant at the 95% confidence level.

571 Figure 2. Observed trend in mean summer (June–September) SST ($^{\circ}\text{C 112 yr}^{-1}$) over the global
572 tropics during 1901–2012.

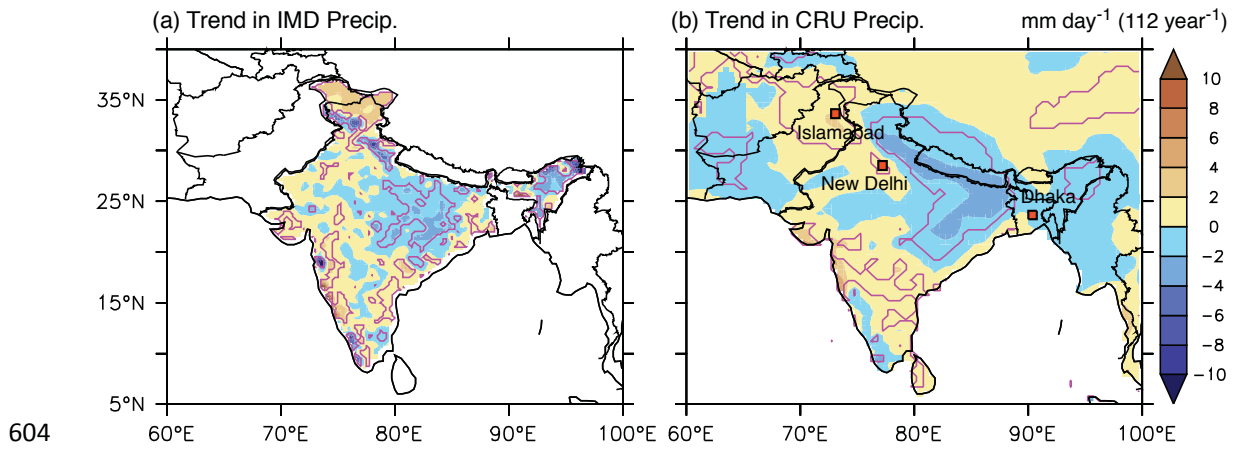
573 Figure 3. Correlation between SST over the western Indian Ocean (WIO, $50\text{-}65^{\circ}\text{E}$, $5^{\circ}\text{S}\text{-}10^{\circ}\text{N}$)
574 and precipitation over the South Asian subcontinent, for **(a)** HadISST and IMD
575 precipitation, and **(b)** ERSST and CRU precipitation, for June-September 1901-2012.
576 Contours denote regions significant at the 95% confidence level. **(c)** Time series of SST
577 anomalies ($^{\circ}\text{C}$, *red*) over WIO along with CRU (*blue*) precipitation (mm day^{-1}) over
578 central South Asia ($60\text{-}100^{\circ}\text{E}$, $20\text{-}30^{\circ}\text{N}$, inset box in **b**), smoothed with a 10 year moving
579 average. Note that the correlation coefficient ($r = -0.34$) between HadISST and CRU
580 precipitation is estimated using non-smoothed time series. Kendall's rank correlation
581 test for the two variables provided a tau coefficient of -0.3 ($P < 0.01$, two tailed). Mann-
582 Kendall test for the trend in the time series provided a tau coefficient of 0.6 for SST
583 and -0.2 for precipitation, both significant at 95% confidence level.

584 Figure 4. Observed **(a)** mean ($^{\circ}\text{C}$) and **(b)** trend ($^{\circ}\text{C 112 year}^{-1}$) of surface temperatures during
585 June-September, 1901-2012. For the trend, the color shades represent regions
586 significant at the 95% confidence level. **(c)** Observed trend ($^{\circ}\text{C 65 year}^{-1}$) of upper
587 tropospheric (200 hPa) temperatures during June-September, 1948-2012. **(d)** Time
588 series of the trend in land-sea contrast in the surface (T_{surf}) and tropospheric (T_{surf} , 850-
589 200hPa average) temperatures ($^{\circ}\text{C}$). The land-sea contrast is estimated as the difference
590 in the values between the boxes over the South Asian subcontinent ($70\text{-}85^{\circ}\text{E}$, $10\text{-}30^{\circ}\text{N}$)
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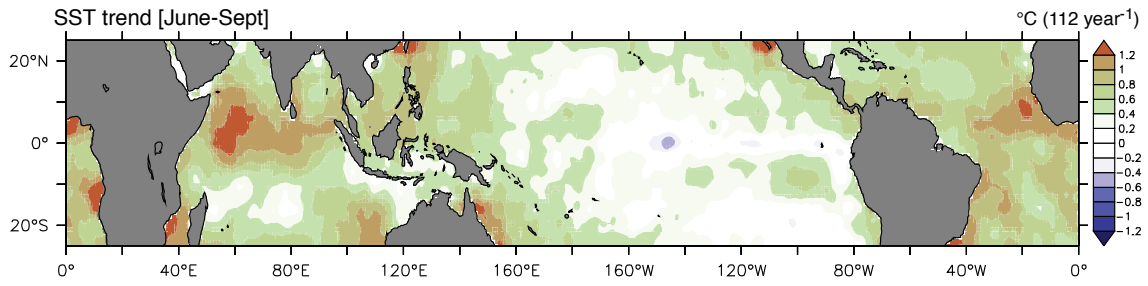
592 The land surface temperature is from HadCRUT, SST from HadISST, and tropospheric
593 temperature from NCEP reanalysis.

594 Figure 5. **(a)** Trend from NCEP re-analysis ($\text{Pa s}^{-1} \text{ year}^{-1}$) and **(b)** model simulated response
595 (Pa s^{-1}) to WIO warming in vertical velocity (ω) during northern summer (June-
596 Sept) along the South Asian domain ($50\text{-}100^\circ\text{E}$). Positive (red) values indicate upward
597 motion.

598 Figure 6. **(a)** Observed trend in precipitation (CRU data, 1901-2012, mm day^{-1}) and near-
599 surface winds (NCEP, 1948-2012, m s^{-1}), for June-September. **(b)** Model simulated
600 mean precipitation (mm day^{-1}) and wind (10m) anomalies (m s^{-1}) in response to
601 warming over the WIO. The model simulated anomalies are estimated from the
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603 (CFSv2_{WIO}), with respect to a model control run (CFSv2_{CTL}).

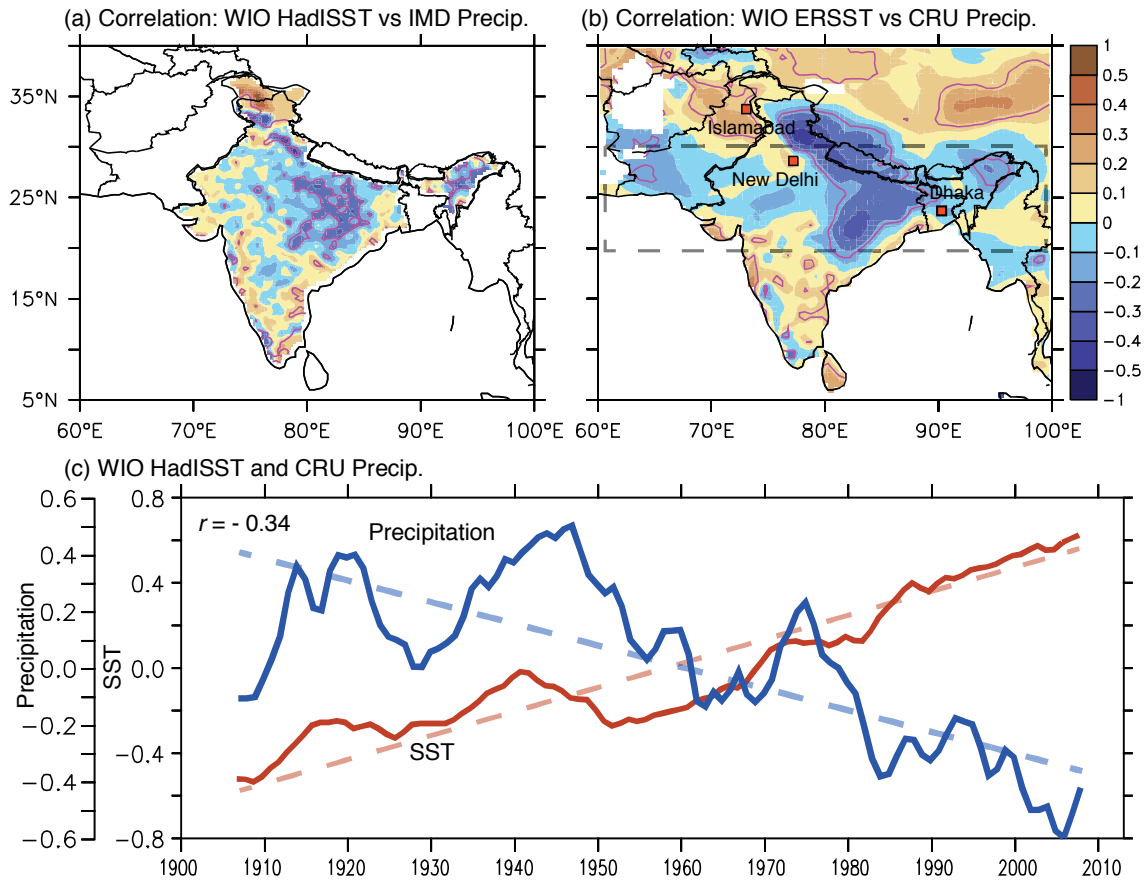


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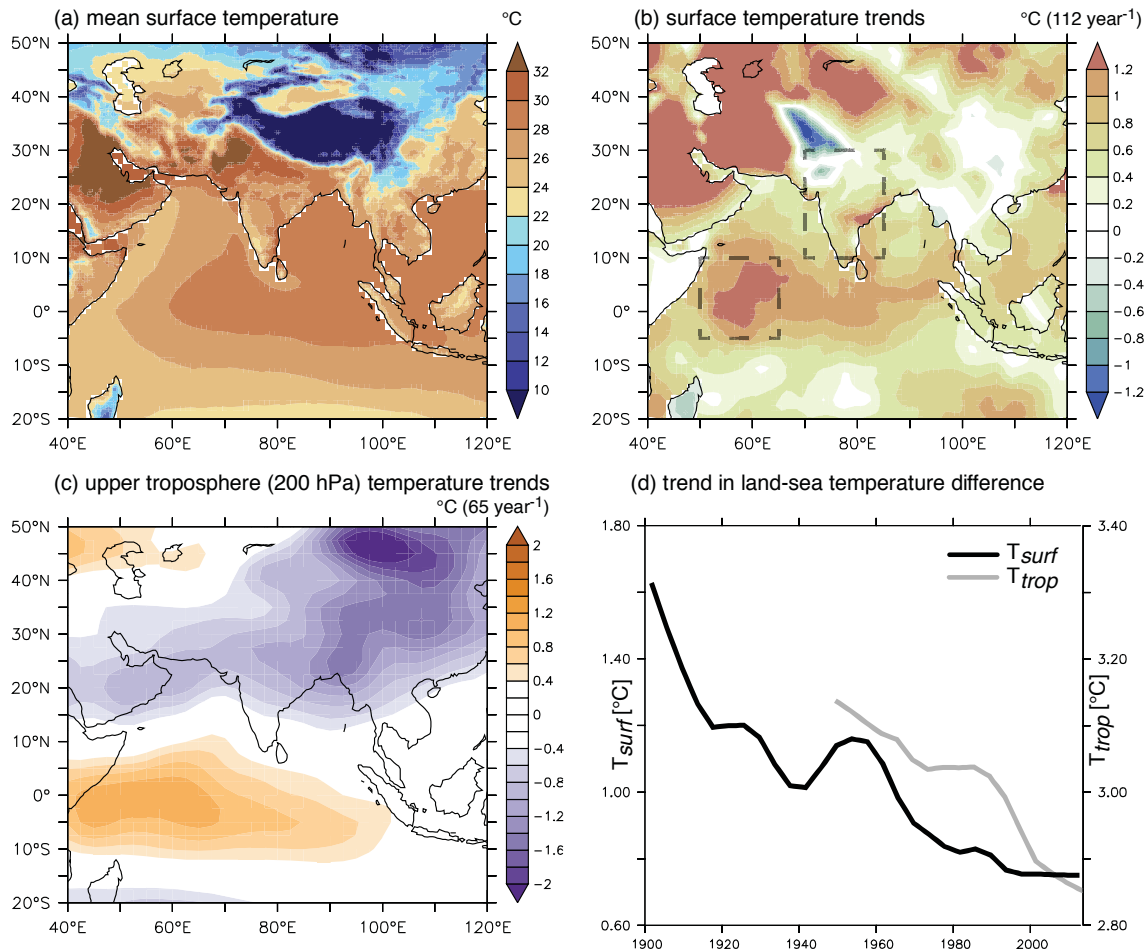
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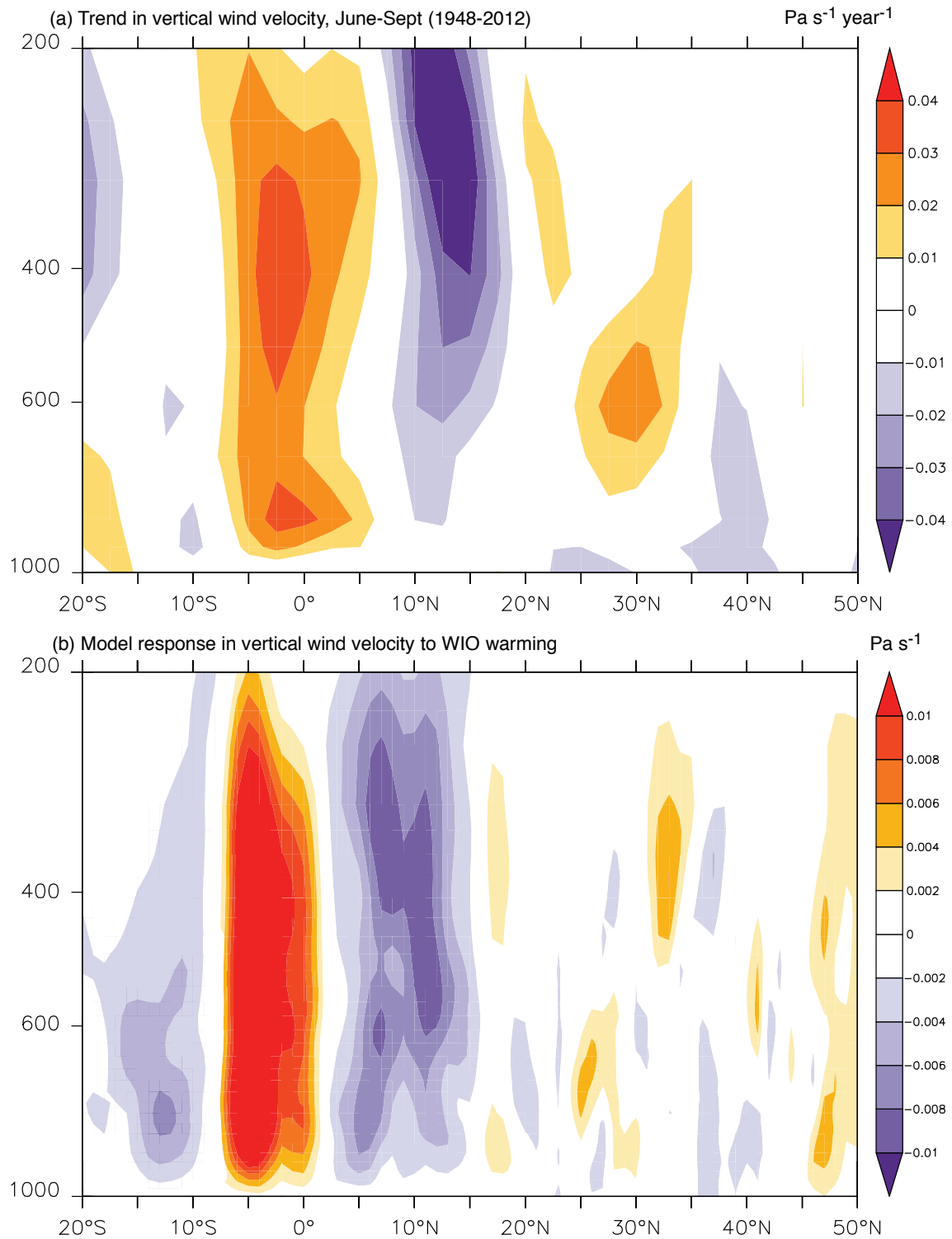
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612 Figure 3. Correlation between SST over the western Indian Ocean (WIO, 50-65°E, 5°S-10°N) and
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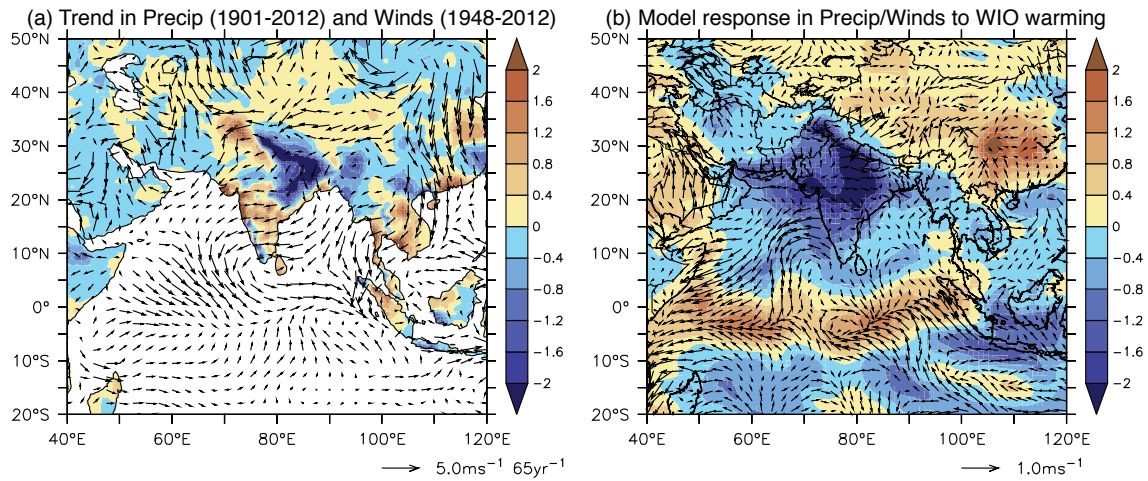
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