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The curious case of Indian Ocean warming

Mathew Koll ROXY¹, Kapoor RITIKA^{1,2}, Pascal TERRAY^{3,4} and Sébastien MASSON³

¹ *Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India*

² *Department of Environmental Sciences, Fergusson College, Pune, India*

³ *Sorbonne Universites (UPMC, Univ Paris 06)-CNRS-IRD-MNHN, LOCEAN Laboratory, 4 place Jussieu, F-75005 Paris, France*

⁴ *Indo-French Cell for Water Sciences, IISc-IITM-NIO-IRD Joint International Laboratory, IITM, Pune, India*

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Corresponding author address: Mathew Koll Roxy, Indian Institute of Tropical Meteorology, Pune 411008, India. E-mail: roxy@tropmet.res.in

1 **Abstract**

2 Recent studies have shown that the central Indian Ocean warm pool has been warming for the
3 past half-century, though the reasons behind this monotonous warming are still debated. The
4 results here reveal a larger picture—that the western tropical Indian Ocean has been warming
5 for more than a century, at a rate faster than any other region of the tropical oceans, and turns
6 out to be the largest contributor to the overall trend in the global mean sea surface
7 temperature (SST). During 1901-2012, the western Indian Ocean experienced anomalous
8 warming of 1.2°C in summer SSTs, while rest of the warm pool region went through an
9 increase of 0.7°C. The warming of the generally cool western Indian Ocean against the rest of
10 the tropical warm pool region displaces the zonal SST gradients, and has the potential to
11 change the Asian monsoon circulation and rainfall, as well as alter the marine food webs in
12 this biologically productive region. The current study using observations and global coupled
13 ocean-atmosphere model simulations gives compelling evidence that, besides direct
14 contribution from greenhouse warming, the long-term warming trend over the western Indian
15 Ocean during boreal summer is highly dependent on the asymmetry in the El Niño Southern
16 Oscillation (ENSO) teleconnection and the positive SST skewness associated with ENSO
17 during recent decades.

18

19 **Introduction**

20 A handful of studies have been devoted to the cause and effect of basin-wide Indian Ocean
21 warming (Alory et al. 2007; Chambers et al. 1999; Dong et al. 2014; Du and Xie 2008; Klein
22 et al. 1999; Rao et al. 2012; Swapna et al. 2013); yet the reasons behind the steady and
23 prominent warming remain ambiguous and are still debated. These studies have shown that
24 the whole Indian Ocean has been warming throughout the past half century. A close
25 examination of the sea surface temperatures (SSTs) over the Indian Ocean reveals a larger

26 story—that the western Indian Ocean has been warming for more than a century. Figure 1a
27 shows the SST trend during 1901-2012, during northern summer. A striking feature is the
28 absence of any trend in SST over the tropical Pacific, and the presence of a warming trend
29 ($>0.1^{\circ}\text{C}$ per decade) over the western tropical Indian Ocean. A similar evolution is found in
30 other seasons and other available SST datasets, though the trend is stronger during summer
31 (Fig.S1).

32 In comparison with the rest of the Indian Ocean, the western Indian Ocean generally
33 has cooler mean SSTs in summer, owing to the strong monsoon winds and the resultant
34 upwelling over the western Indian Ocean (Fig.2). This creates a zonal SST gradient, which
35 regulates the strength and flow of the moisture laden winds towards the South Asian
36 subcontinent (Izumo et al. 2008; Yang et al. 2007). In addition, the summer SSTs show that
37 western region has the largest interannual variability (Fig.1b). A warming trend in the mean
38 SSTs over this region can in turn modify the monsoon interannual variability (Yang et al.
39 2007). The western Indian Ocean is also one of the most biologically productive regions
40 during the summer due to the intense upwelling (Ryther and Menzel 1965). Hence a
41 significant change in the SSTs of this region can also alter marine food webs (Behrenfeld et
42 al. 2006). Besides localized responses, a warming in the Indian Ocean has remote influences
43 too. It has been suggested that a warm Indian Ocean has the potential to weaken the El Niño
44 during its developing and terminating phases (Annamalai et al. 2005; Kug and Kang 2006;
45 Luo et al. 2012).

46 Though earlier studies have investigated the sustained warming over the Indian
47 Ocean, the focus has been on the warm pool region (Dong et al. 2014; Du and Xie 2008; Rao
48 et al. 2012; Swapna et al. 2013). These studies have implied local ocean-atmosphere coupled
49 mechanisms for the continuous warming over the region, in addition to anthropogenic
50 forcing. However, there is large uncertainty among these studies, presenting a chicken-and-

51 egg problem on the cause and effect of the warming. Some of these studies argue that the
52 warming weakens the monsoon winds over the Indian Ocean which further enhance the
53 warming, while others suggest that weakened monsoon winds have accelerated the warming
54 (Rao et al. 2012; Swapna et al. 2013).

55 A few other studies have shown that the SSTs over Indian Ocean are warmer 3-4
56 months after the mature phase of El Niño (Du et al. 2009; Lau and Nath 2003; Xie et al.
57 2009). Though a connection between individual El Niños and warm Indian Ocean events has
58 been suggested (Cadet 1985; Murtugudde et al. 2000; Nicholson 1997; Tourre and White
59 1995; Xie et al. 2002; Yu and Rienecker 1999), no relationship has been demonstrated with
60 respect to the long-term warming trends over the Indian Ocean and hence, its association with
61 El Niño during summer is investigated here.

62

63 **Data, Model and Methods**

64 Long-term warming trend and correlations are estimated using SST data for the period 1901-
65 2012 obtained from the HadISST1 dataset, and robustness of these results are assessed using
66 ERSST and marine-nighttime SSTs from HadMAT (Rayner et al. 2003; Smith et al. 2008).
67 Data coverage in the tropical Indian Ocean is generally quite good since the late 19th century
68 (Compo and Sardeshmukh, 2010; Deser et al., 2010). In order to ascertain the role of
69 greenhouse warming on the Indian Ocean, SSTs from a suite of 25 climate models
70 participating in the Coupled Model Intercomparison Project (CMIP5, Taylor et al. 2012) are
71 used. For examining the atmospheric circulation, the wind and vertical velocity at different
72 levels for the years 1979-2012 are obtained from the ERA interim reanalysis (Dee et al.
73 2011).

74 For the numerical model experiments a global coupled ocean-atmosphere model, the
75 SINTEX-F2, which has a realistic simulation of the ENSO-monsoon variability is utilized

76 (Masson et al. 2012; Terray et al. 2011). The oceanic and atmospheric components have 0.5°
77 and 1.125° horizontal resolution respectively, with 31 levels in the vertical for both. The
78 coupled configuration of SINTEX-F2 is time integrated over a period of 300 years, and
79 utilized as the reference run. In addition, a model sensitivity run is performed over a period of
80 110 years, by suppressing the SST variability over the Pacific (100°E-70°W, 25°S-25°N) by a
81 nudging technique. For this experiment, we used the standard configuration of the coupled
82 model without any flux corrections, except in the Pacific where we applied a large feedback
83 value (-2400Wm⁻²K⁻¹) to the surface heat flux. This value corresponds to the 1-day relaxation
84 time for temperature in a 50-m mixed layer. The SST damping is applied towards a daily
85 climatology computed from the reference run. This large correction suppresses the SST
86 variability over the tropical Pacific. Difference between the control and sensitivity runs
87 renders the role of ENSO variability on global climate variability, including its effects on the
88 SST variability over the Indian Ocean.

89 The unbiased moment estimate of skewness is used to measure the asymmetry, and
90 also the frequency and intensity of ENSO events. This statistic may be computed as
91 Skewness = $n.M_3/[(n-1)(n-2).\sigma^3]$, where M_3 is $\sum(x_i - \bar{x})^3$, σ is the unbiased estimate of
92 standard deviation, and n is the number of observations.

93

94 **Results**

95 It is observed that the western Indian Ocean (Fig.1c, 50-65°E, 5°S-10°N) shows continuous
96 warming since the start of 20th century (which attains an increased rate post-1950s), while for
97 the rest of Indian Ocean including the warm pool (Fig.2, SST > 28.0°C) the warming is
98 prominent post-1950s only. At the beginning of the 20th century, the mean summer SST over
99 the western Indian Ocean was around 26.5°C, which is cooler in comparison to the rest of the
100 Indian Ocean at 27.2°C. The incessant warming for over a century has led to the western

101 Indian Ocean SSTs reaching the high SST values (28.0°C) observed over the warm pool
102 regions (Fig.1c). During 1901-2012, western Indian Ocean experienced anomalous warming
103 of up to 1.2°C, while the warm-pool warming was constrained to 0.7°C. This results in a
104 0.5°C difference in the warming, which is significant with respect to the Indian Ocean SSTs,
105 and in turn the monsoon dynamics (Izumo et al. 2008; Yang et al. 2007). Apart from
106 nullifying the zonal SST gradient and changing the monsoon circulation, an SST increase
107 from 26.5°C to 28.0°C will also drastically change the convective response from shallow to
108 deep convection (Gadgil et al. 1984; Roxy 2013; Roxy et al. 2012). The sustained warming
109 over the western Indian Ocean against that of the warm pool is also stronger in the annual
110 mean SSTs (Fig.1d).

111 Similar to other regions over the global oceans, anthropogenic forcing might be a
112 major contributor to the observed warming over the Indian Ocean. However, the historical
113 climate model simulations under CMIP5 using observed greenhouse gases forcing does not
114 reproduce the zonal SST gradient, or the pronounced warming over the western Indian Ocean
115 (Fig.1c). Instead, the western Indian Ocean warming trend in CMIP5 is similar to the warm
116 pool trend. This could mean that, apart from the direct radiative forcing due to increased
117 greenhouse gases, other unaccounted mechanisms in the simulations (e.g. modulation of
118 ENSO skewness and associated teleconnections) may also have a role in contributing to the
119 observed SST trends over the western Indian Ocean.

120 A simultaneous correlation analysis between east Pacific and global summer mean
121 SST anomalies, after removing the global warming trends, depicts significant positive
122 correlation over the western Indian Ocean (Fig.3a). Time series of these anomalies
123 constructed over the east Pacific (120-80°W, 5°S-5°N) and the western Indian Ocean yield a
124 high correlation ($r=0.6$), significant at 99% confidence level (Fig.3b). This indicates that

125 ENSO dominates the western tropical Indian Ocean variability during boreal summer through
126 fast atmospheric teleconnections.

127 It is striking to notice that the number and intensity of El Niño events have
128 significantly increased during the latter half of 20th century (12 events), in comparison with
129 the former half (7 events). During recent decades, SST skewness exhibits more positive
130 values in the eastern Pacific reflecting the fact that amplitude and frequency of El Niño
131 events have increased (Figs.3b and 4). The rate of Indian Ocean warming has also increased
132 during the last five decades, which saw some of the strongest El Niños during the past
133 century (Fig.3b). It is however noted that the Indian Ocean SST anomalies associated with
134 the La Niñas are relatively smaller in comparison with those associated with the El Niños.
135 One of the interesting facts is that, post-1950, a few warm events over the Indian Ocean have
136 attained the threshold value for El Niño ($1\sigma=0.77^{\circ}\text{C}$, Fig.3b). This places these warm events
137 almost on par with the El Niños in magnitude, although the peaks are not as high.

138 In order to ascertain whether the increasing number of warm events may contribute to
139 the long-term warming trend, the skewness of the east Pacific detrended SST anomalies is
140 contrasted along with the trend of the western Indian Ocean SST anomalies (Fig.4c). The
141 asymmetry between warm and cold events over east Pacific, with a skewness towards warm
142 events throughout the time period is evident. This positive skewness of eastern Pacific SSTs
143 is well correlated with the warming trend observed over the western Indian Ocean (Fig.4c,
144 $r=0.76$ for annual values, significant at 99% confidence level).

145 The asymmetry in ENSO forcing is substantiated by comparing the atmospheric
146 circulation over the tropics during El Niño and La Niña years against the climatological
147 walker circulation (Fig.5a). The El Niño composite shows an anomalous shift in the
148 circulation over the tropics, with the ascending cell over the east Pacific and subsidence over
149 the maritime continent, resulting in low-level easterly anomalies over the western Indian

150 Ocean (Fig.5b). These easterly anomalies weaken the mean westerlies over the Indian Ocean,
151 leading to the observed warming. On monthly timescale, the El Niño effect on warming
152 during summer is simultaneous. This is different from the Indian Ocean warming during
153 individual years, observed by other studies at 3-4 months lag (or more) after the mature phase
154 of El Niño in winter (Du et al. 2009; Lau and Nath 2003; Xie et al. 2009). The anomalous
155 circulation in the La Niña composite, meanwhile, does not show any significant change in the
156 low-level winds and the vertical velocity over the Indian Ocean (Fig.5c, 20-100°E, 5°S-
157 10°N). This might be a reason why the warm events over the western Indian Ocean are not
158 interspersed by any significant cooling events despite of the ENSO variability (Fig.3b). A
159 composite of the summer SST anomalies during El Niño and La Niña years further
160 demonstrates this asymmetry in forcing the Indian Ocean (Figs.4d and 4e). While the El Niño
161 composite exhibits significant warming over the western Indian Ocean, the La Niña
162 composite does not show any significant negative anomalies over the region.

163 The fact that the SST anomalies do not show any long-term significant trend over the
164 east Pacific, despite a globally warming environment and positive skewness in recent decades
165 is intriguing (Fig.1a). Tropical Pacific variability oscillating between the warm and cool
166 events might be a first reason. However, the fact that the Indian Ocean warming favors a
167 faster transition from El Niño to La Niña conditions in the Pacific may also contribute
168 significantly (Kug and Kang 2006; Luo et al. 2012). Also, a recent study shows that warming
169 trend over the Atlantic results in La Niña like conditions over the east Pacific, through a
170 modification of the Walker circulation (Kucharski et al. 2011). These negative feedbacks due
171 to enhanced warming over the Indian and Atlantic Oceans might explain why there are no
172 robust long-term trends over the east Pacific. It may however be noted that unlike the Indian
173 Ocean, data availability is relatively sparse over the Pacific, which makes it difficult for
174 robust assessment of long-term trends over this region (Deser et al. 2010).

175 So where does all the heat go to? The results here indicate that a large share of the
176 heat piles up in the Indian Ocean, consistent with earlier studies (Du et al. 2009; Xie et al.
177 2009). Figure 6a shows the SST difference between the post and pre-1950s, and demonstrates
178 the pronounced warming over the Indian Ocean in the recent decades. Apart from the direct
179 radiative forcing due to increasing greenhouse gases, El Niño appears as an event through
180 which the Pacific Ocean throws out its heat, which partially gets accumulated in the Indian
181 Ocean. Indeed, Compo and Sardeshmukh (2010) using a decomposition of ENSO-related and
182 ENSO-unrelated SST trends demonstrated that ENSO explains up to 40% of long-term
183 warming trends over the global oceans. Specifically, the following two factors might be
184 helpful in explaining the sustained warming of Indian Ocean SST anomalies. One is the
185 asymmetry in the ENSO teleconnection, due to which El Niño induces warming over the
186 western Indian Ocean, while the La Niña fails to induce any significant cooling. The second
187 factor is the positive skewness in ENSO forcing during recent decades, which aggravates the
188 warming in the recent period.

189 The hypothesis of ENSO forcing on the western Indian Ocean warming trend during
190 summer is tested with sensitivity experiments using a state-of-the-art global coupled ocean-
191 atmosphere model with a realistic ENSO variability (Fig.S2). Numerical simulations are
192 compared for a tropical Pacific in which ENSO variability is suppressed, against a Pacific
193 where ENSO variations are free to evolve. Figure 6b shows the SST anomalies over the
194 Indian Ocean due to ENSO variability in the simulations. During boreal summer, the SST
195 anomalies show a significant warming over the western Indian Ocean. Despite of the fact that
196 our coupled model has difficulties in representing the positive skewness associated with
197 ENSO (Fig.S3), it is found that El Niño events have a stronger impact in warming, than La
198 Niña events in cooling the Indian Ocean. The model experiment brings out an interesting
199 fact—that the long-term warming over the western Indian Ocean, though at magnitudes lower

200 than those observed, may exist even without increasing greenhouse gases, due to a decadal
201 modulation of the ENSO variability.

202 A consequence to the western Indian Ocean warming and ENSO is probably a
203 tendency towards more Indian Ocean Dipole (IOD) events during recent decades. IOD events
204 manifest as patterns of anomalously warm SST in the western Indian Ocean, along with cool
205 SST in the southeast Indian Ocean (Murtugudde et al. 1998; Saji et al. 1999; Webster et al.
206 1999). These dipole events tend to develop during the months of June-August and peak
207 during September-November. Positive IOD events generally coincide with El Niños or El
208 Niño-like events (Roxy et al. 2011). In fact, the SST anomalies over the Indian Ocean in
209 Figure 3a is indicative of an IOD like response to the ENSO at the interannual time scale, but
210 our trend analysis of the observations and model simulations do not corroborate the
211 hypothesis that the western Indian Ocean warming is tightly linked to IOD frequency changes
212 (Fig.6). Besides ENSO, other drivers such as the Asian monsoon variability can also trigger
213 IOD events (Ashok et al. 2003; Cai et al. 2013). The focus of the current study is not to
214 separate and examine the IOD events due to ENSO and other drivers, but to address whether
215 the increasing warm events and the long-term trend over the western Indian Ocean are a
216 consequence of the El Niños.

217

218 **Summary and Discussion**

219 Recent studies have pointed out an increased warming over the Indian Ocean warm pool,
220 during the past half century. The current study, using SST trends computed over the past
221 century indicates a long-term warming trend over the western Indian Ocean, which surpasses
222 that over the warm pool, in both magnitude and period (Fig.1c). The results from the study
223 point out the asymmetry in the ENSO teleconnection as one of the reasons, whereby El Niño
224 events induce anomalous warming over the western Indian Ocean and La Niña events fail to

225 do the inverse. A second, prominent reason is the positive SST skewness associated with
226 ENSO, as the frequency of El Niño events have increased during recent decades.

227 The IPCC Fifth Assessment Report (AR5) points out that 90% of the heat due to the
228 global warming during the last four decades has been accumulated in the oceans (IPCC
229 2013). The periodic occurrence of El Niño acts as a vent to exchange this heat from the ocean
230 to the atmosphere. It is this heat that is partially transferred to the Indian Ocean via a
231 modified Walker circulation, and is reflected in the warming trend over the region. It is
232 interesting to note that the warming trend over the Indian Ocean is a major contributor, and
233 largely in phase with the overall trend in the global mean SST (Fig.7). Though the frequency
234 of El Niño events has increased in the recent decades, a strong warm event has not been
235 recorded since 1997-98 (Fig.3b), and correspondingly the Pacific and Indian Ocean SST
236 anomalies show a slight dampening (Figs.1c). This could add up as a reason for the recent
237 hiatus in the global surface warming (Kosaka and Xie 2013). Again, the recent cool
238 conditions over the east Pacific might be due to the feedback from a warmer Indian Ocean,
239 bringing the sequence of events to a vicious cycle, which requires further extensive research.
240 As noted by several other studies (Kucharski et al. 2011; Kug and Kang 2006; Luo et al.
241 2012), the warming trends over the Indian and Atlantic Oceans lead to La Niña like
242 conditions over the Pacific.

243 In the recent decades, anomalous warm events, though of weaker amplitude, have
244 occasionally shown prominence over the central Pacific (El Niño Modoki; Ashok and
245 Yamagata 2009) and even the whole Pacific basin (Ashok et al. 2012), and the dynamics of
246 the Indian Ocean warming may reflect these changes as well. It was noted earlier that, post-
247 1950, the warm summer SSTs over the western Indian Ocean have occasionally attained the
248 El Niño threshold value (0.77°C). Supplementing the long-term persistence of these events,

249 the warming scenario over the Indian Ocean and related climate dynamics is a factor to be
250 vigilant of, while assessing long-term climate change and variability.

251

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258

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359 **Figure Captions**

360 Figure 1. **(a)** Observed trend in mean summer (June-Sept) SST ($^{\circ}\text{C}$ per year) over the global tropics
361 during 1901-2012. **(b)** Interannual standard deviation of SST ($^{\circ}\text{C}$) for the same domain and
362 time period. Time series of mean **(c)** summer and **(d)** annual SST ($^{\circ}\text{C}$) over the western Indian
363 Ocean (WIO, *red*, $50\text{-}65^{\circ}\text{E}$, $5^{\circ}\text{S}\text{-}10^{\circ}\text{N}$) and rest of the Indian Ocean (RIO, *black*, $70\text{-}100^{\circ}\text{E}$,
364 $20^{\circ}\text{S}\text{-}20^{\circ}\text{N}$). WIO and RIO are marked with dashed rectangles in **a**. The CMIP5 ensemble
365 means based on 25 climate models, averaged over the WIO (*light red*) and RIO (*light grey*),
366 are also displayed in **c**.

367 Figure 2. Observed mean summer (June-Sept) SST ($^{\circ}\text{C}$) over the Indian Ocean. Warm pool region in
368 the text refers to the highlighted region with SST $> 28^{\circ}\text{C}$.

369 Figure 3. **(a)** Observed correlation between mean summer (June-Sept) SSTs ($^{\circ}\text{C}$) over the east Pacific
370 ($120\text{-}80^{\circ}\text{W}$, $5^{\circ}\text{S}\text{-}5^{\circ}\text{N}$) and the global tropics during 1901-2012. Correlation coefficients have
371 been computed from detrended data. Contours denote regions significant at the 99%
372 confidence level. **(b)** Time series of mean summer SST anomalies ($^{\circ}\text{C}$) over the east Pacific
373 (*red*) and the western Indian Ocean (*green*). Both time series have been detrended. East
374 Pacific SST anomalies, which rise above 1 standard deviation (0.77°C , *horizontal dashed*
375 *line*) are considered as El Niño events.

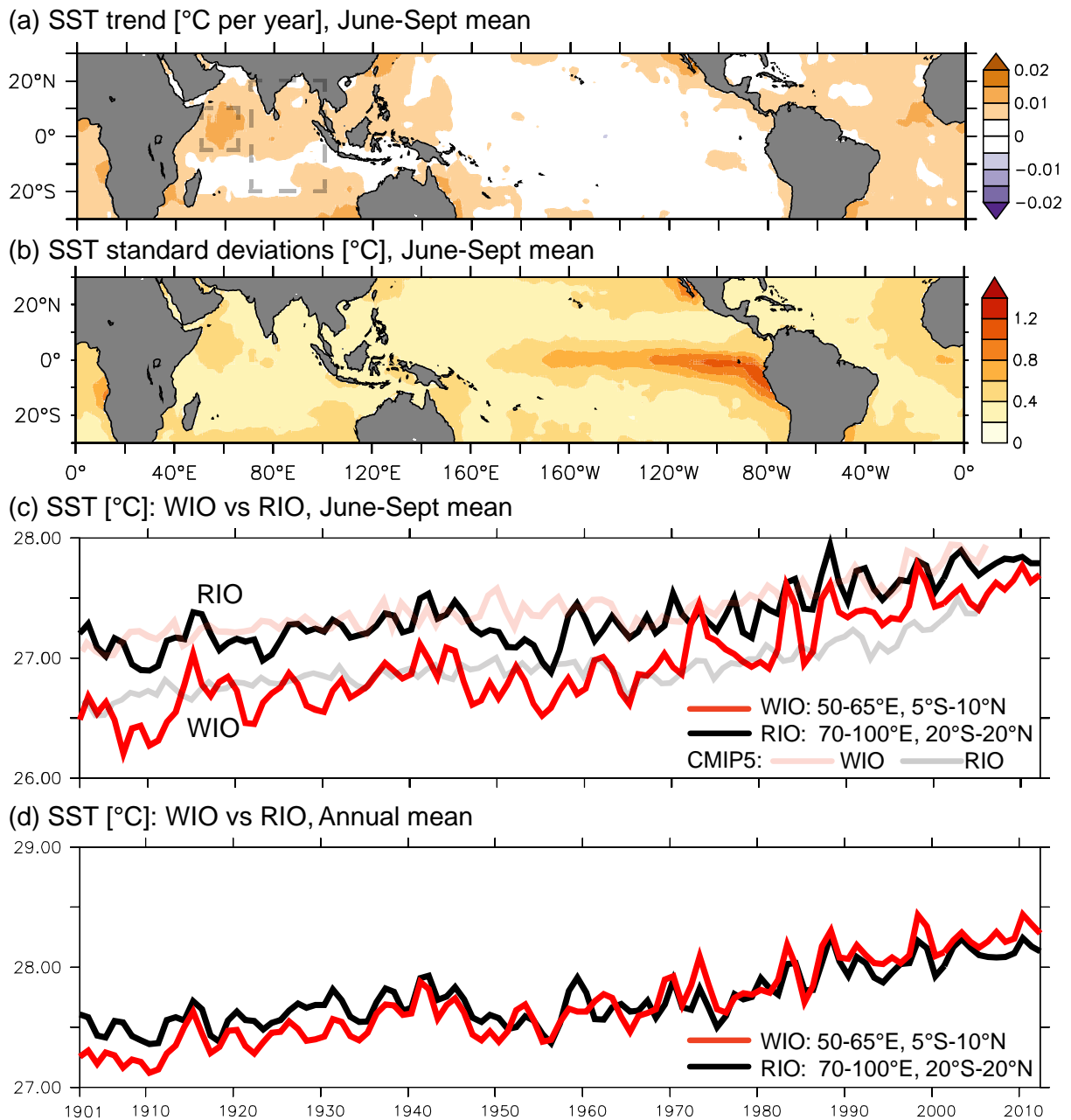
376 Figure 4. SST skewness estimated for detrended monthly SST anomalies during the periods **(a)** 1901-
377 1950 and **(b)** 1951-2012. Contours denote regions significant at the 99% confidence level. **(c)**
378 Time series of skewness computed from detrended SST anomalies over the east Pacific (*red*)
379 and of SST trend (*green*) over the WIO estimated over 31-year sliding periods, for the
380 northern summer. The two time series have also been smoothed with a 31-year moving
381 average for display only. The annual values of the two time series are significantly correlated
382 ($r=0.76$), at 99% confidence level.

383 Figure 5. Zonal atmospheric circulation for boreal summer over the equator ($5^{\circ}\text{S}\text{-}10^{\circ}\text{N}$) during **(a)**
384 climatological mean conditions, and anomalies during **(b)** El Niño years, and **(c)** La Niña
385 years. The winds (*vectors*, *unit* m s^{-1}) and the vertical velocity (*colors*, *unit* Pa s^{-1}) indicate the

386 zonal and vertical motion (positive upward) of air, respectively. Similarly, SST ($^{\circ}\text{C}$) during
387 (d) climatological mean conditions, and anomalies during (e) El Niño years, and (f) La Niña
388 years. The composites are estimated from detrended monthly SST anomalies.

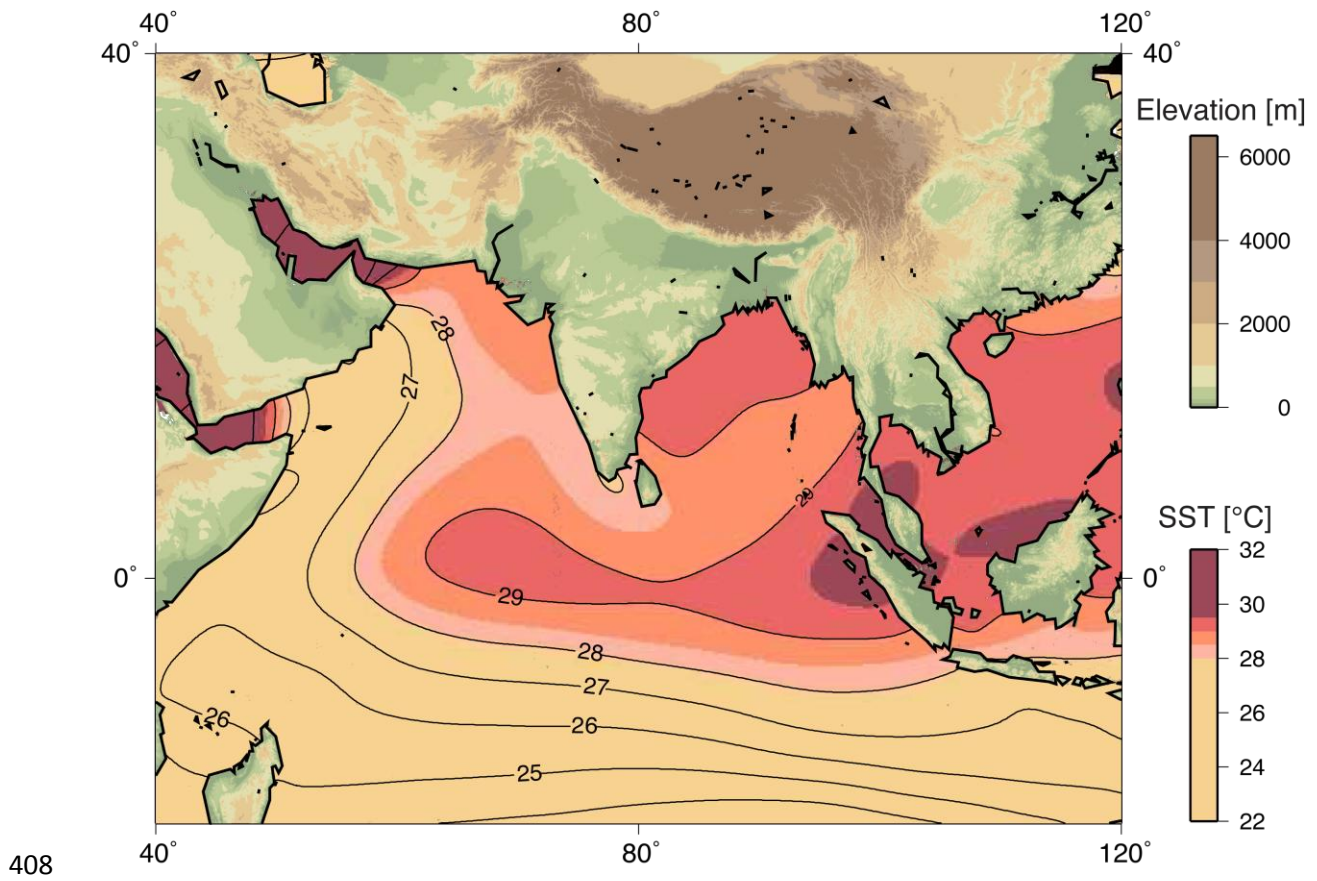
389 Figure 6. (a) Difference in the SST ($^{\circ}\text{C}$) over the Indian Ocean, for the periods 1951-2012 and 1901-
390 1950, for the northern summer. (b) Model simulated mean SST anomalies ($^{\circ}\text{C}$) during
391 northern summer, in response to ENSO variability in the model. The model simulated SST
392 variability due to ENSO is estimated from the SST anomalies in the control run (*ENSOvar*).
393 These SST anomalies are defined with respect to a monthly climatology computed from the
394 sensitivity experiment without ENSO variability (*noENSOvar*). *a* denotes the role of ENSO-
395 skewness and *b* that of ENSO-asymmetry, on the Indian Ocean. Contours denote regions
396 significant at the 99% confidence level estimated from a resampling method.

397 Figure 7. Observed correlation between annual global mean SST and the annual SST at each grid,
398 during 1901-2012. Color shading denotes correlation coefficients significant at the 99%
399 confidence.



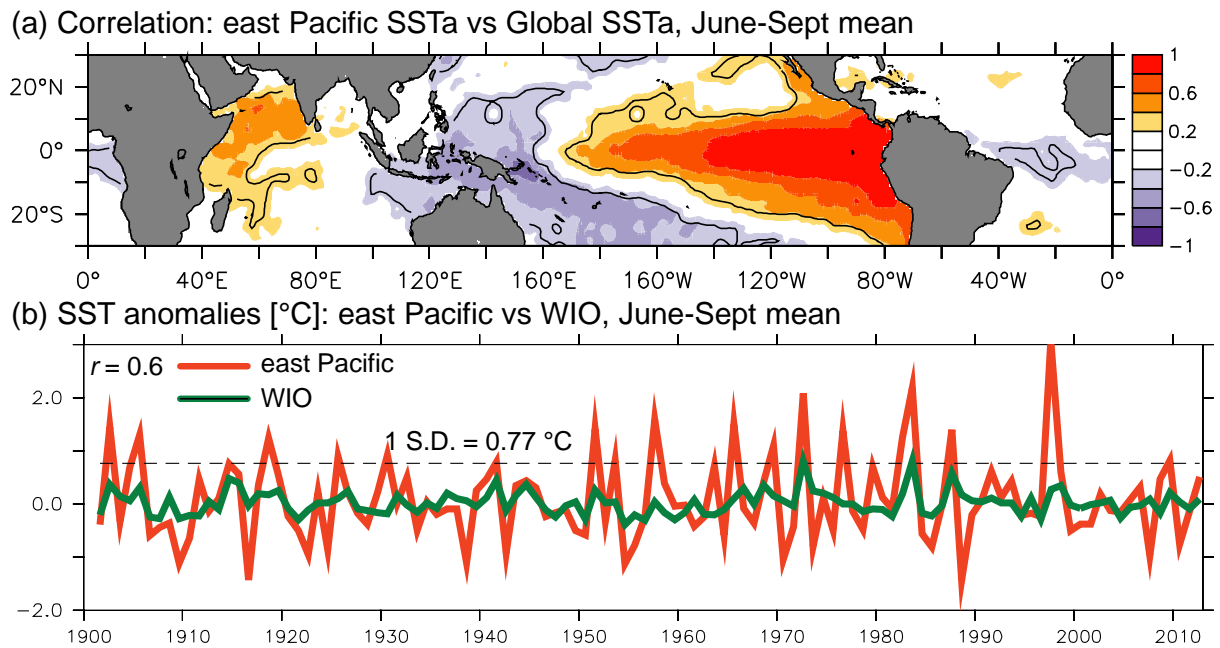
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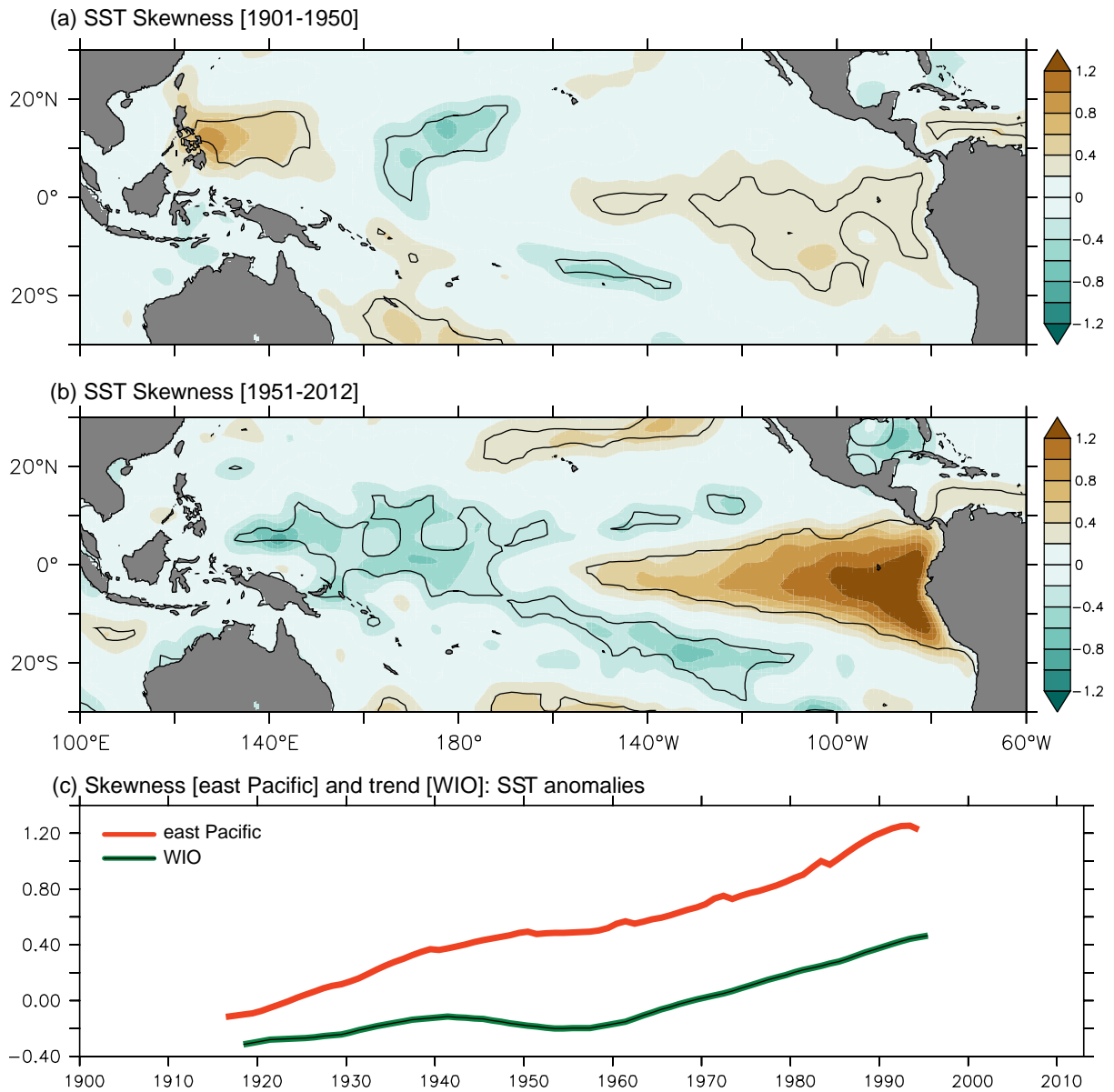


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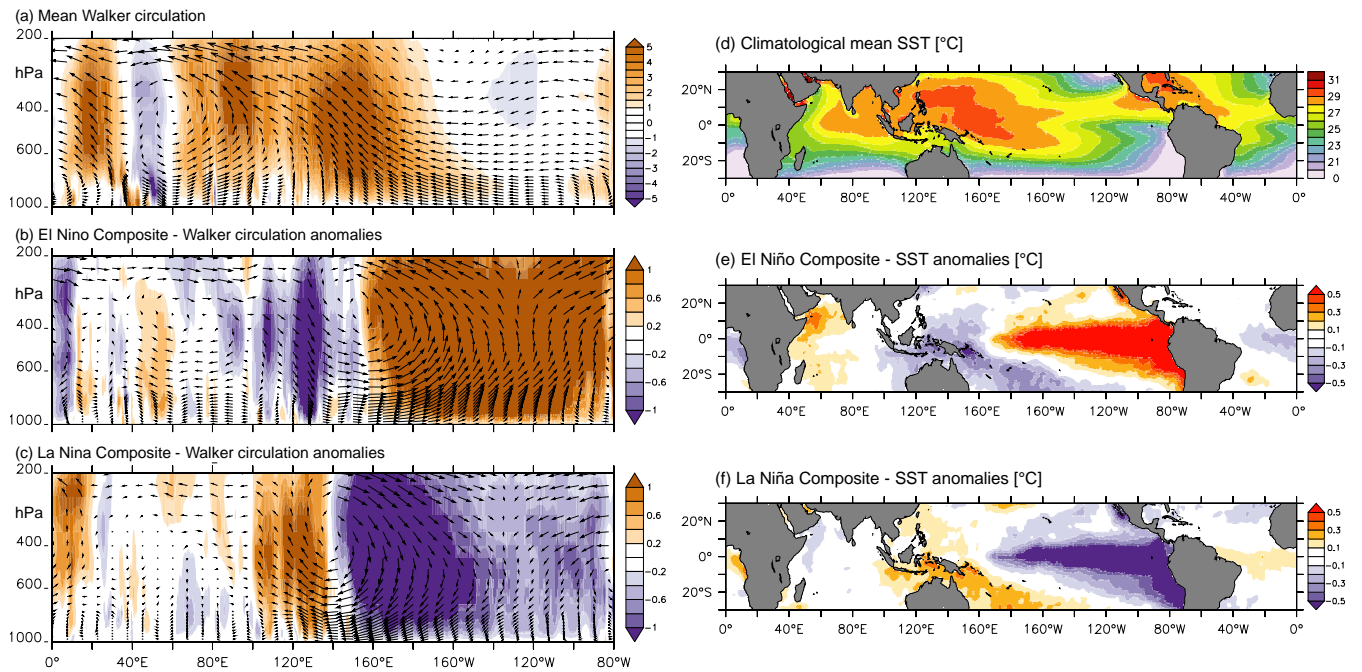


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 415 Time series of mean summer SST anomalies (°C) over the east Pacific (*red*) and the western Indian
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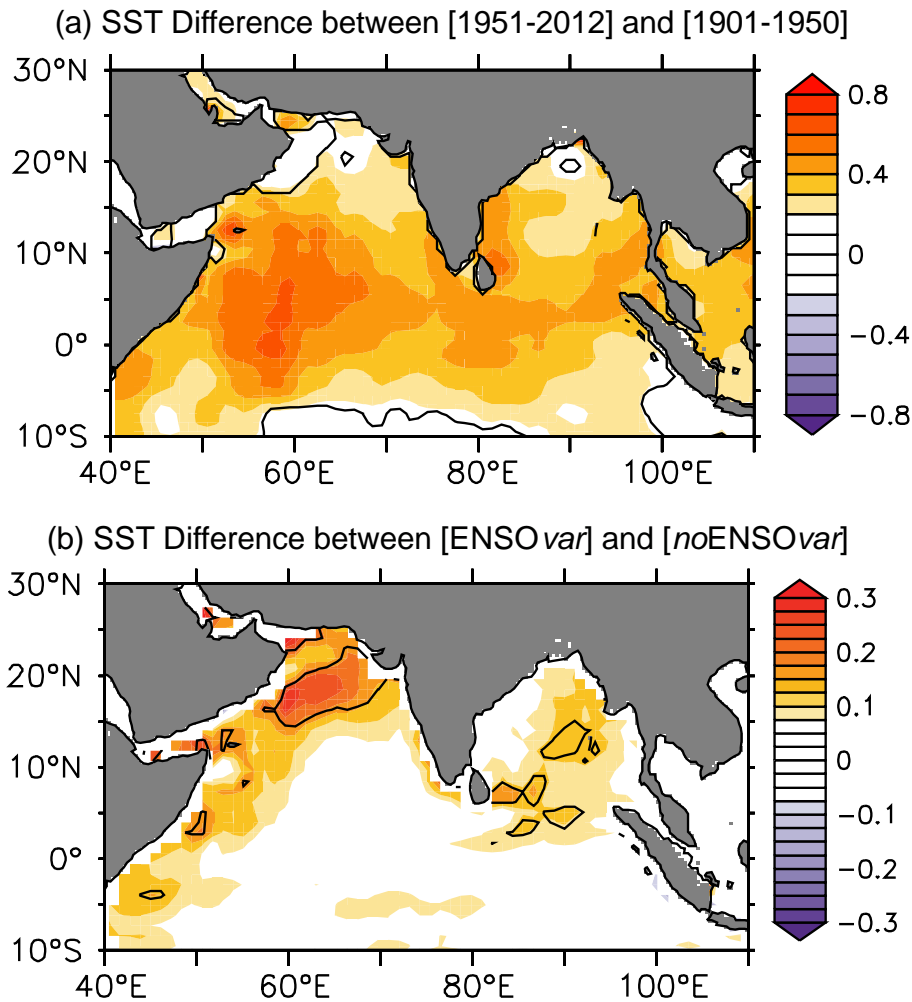
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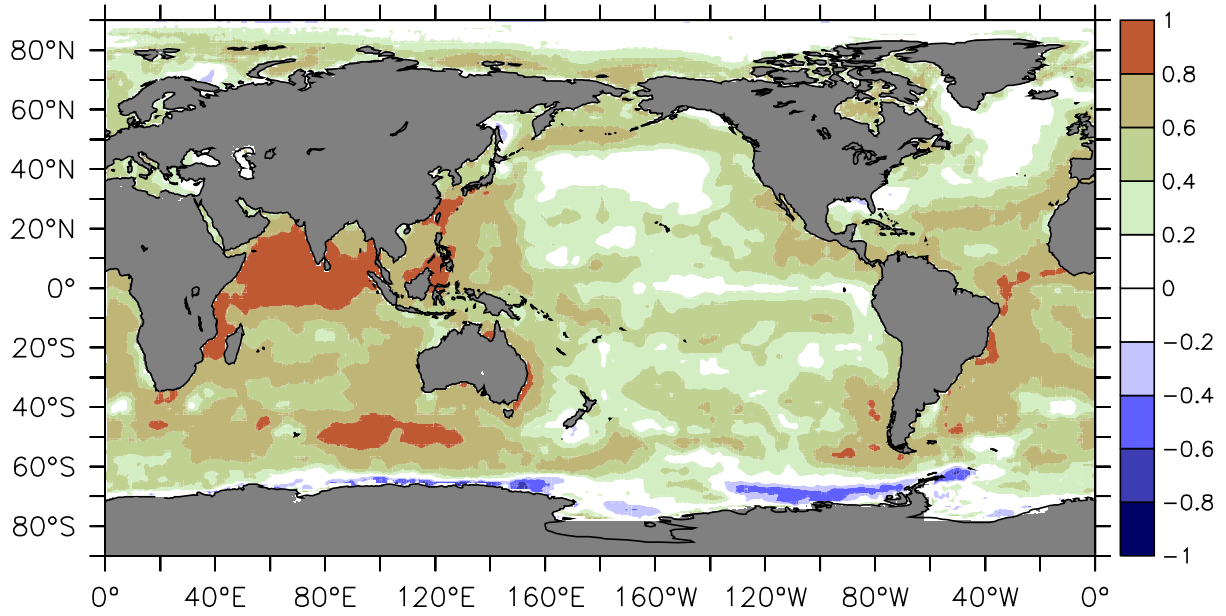
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432

433 Figure 6. (a) Difference in the SST ($^{\circ}\text{C}$) over the Indian Ocean, for the periods 1951-2012 and 1901-
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 440 estimated from a resampling method.

Correlation: Annual global mean SSTa vs annual SSTa



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442 Figure 7. Observed correlation between annual global mean SST and the annual SST at each grid,
443 during 1901-2012. Color shading denotes correlation coefficients significant at the 99% confidence
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