

Interdecadal changes on the seasonal prediction of the western North Pacific summer climate around the late 1970s and early 1990s

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1 **Interdecadal changes on the seasonal prediction of the western North Pacific**
2 **summer climate around the late 1970s and early 1990s**

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29 Identifying predictability and the corresponding sources for the western North Pacific
30 (WNP) summer climate in the case of non-stationary teleconnections during recent
31 decades benefits for further improvements of long-range prediction on the WNP and
32 East Asian summers. In the past few decades, pronounced increases on the summer
33 sea surface temperature (SST) and associated interannual variability are observed over
34 the tropical Indian Ocean and eastern Pacific around the late 1970s and over the
35 Maritime Continent and western-central Pacific around the early 1990s. These
36 increases are associated with significant enhancements of the interannual variability
37 for the lower-tropospheric wind over the WNP. In this study, we further assess
38 interdecadal changes on the seasonal prediction of the WNP summer anomalies, using
39 May-start retrospective forecasts from the ENSEMBLES multi-model project in the
40 period 1960 to 2005. It is found that prediction of the WNP summer anomalies
41 exhibits an interdecadal shift with higher prediction skills since the late 1970s,
42 particularly after the early 1990s. Improvements of the prediction skills for SSTs after
43 the late 1970s are mainly found around tropical Indian Ocean and the WNP. The
44 better prediction of the WNP after the late 1970s may arise mainly from the
45 improvement of the SST prediction around the tropical eastern Indian Ocean. The
46 close teleconnections between the tropical eastern Indian Ocean and WNP summer
47 variability work both in the model predictions and observations. After the early 1990s,
48 on the other hand, the improvements are detected mainly around the South China Sea
49 and Philippines for the lower-tropospheric zonal wind and precipitation anomalies,

50 associating with a better description of the SST anomalies around the Maritime
51 Continent. A dipole SST pattern over the Maritime Continent and the central
52 equatorial Pacific Ocean is closely related to the WNP summer anomalies after the
53 early 1990s. This teleconnection mode is quite predictable, which is realistically
54 reproduced by the models, presenting more predictable signals to the WNP summer
55 climate after the early 1990s.

56

57 **Key words:** Western North Pacific, Seasonal forecast, Interdecadal change, Air-sea
58 interaction, ENSEMBLES

59

60 **1. Introduction**

61 Large year-to-year variability of the summer climate is displayed over the western
62 North Pacific (WNP) and East Asia, resulting in disastrous floods and droughts over
63 East Asia. This variability will be enhanced under the background of global warming
64 (Lu and Fu 2009). Interannual variation of the WNP summer climate, which has
65 pronounced impacts on the climate over East Asia (e.g., Huang and Sun 1992; Wang
66 et al. 2000; Lu and Dong 2001), acts as a basis for identifying the variation and
67 long-range prediction of East Asian summer climate. Thus, understanding the
68 predictability of the WNP summer climate under different backgrounds of the
69 changing climate is of particular importance.

70 Current coupled models exhibit a somewhat reliable capability in predicting
71 seasonal anomalies of precipitation and circulation over the WNP (Lee et al. 2011; Li
72 et al. 2012; Kosaka et al. 2013). This reliability arises mainly from its teleconnections
73 with El Niño–Southern Oscillation (ENSO) forcing and monsoon-ocean interactions
74 in the tropical Indian Ocean (e.g., Chowdary et al. 2009; Wang et al. 2009). Using
75 five state-of-the-art coupled models from ENSEMBLES forecast system, Li et al.
76 (2012) presented a comprehensive assessment on the predictability of the WNP
77 summer climate and suggested a skillful prediction on the atmospheric anomalies and
78 a good representation on the associated atmosphere-ocean interactions over the
79 tropical Indian and Pacific Ocean. In addition, good predictions of the WNP summer
80 anomalies are found even during the years when there are no significant
81 ENSO-related SST anomalies (Li et al. 2014). It suggests that the local

82 atmosphere-ocean interactions act as another important role in the predictability of the
83 WNP summer climate. Kosaka et al. (2013) proposed a coupled mode arising from
84 interactions between the tropical Indian Ocean sea surface temperature (SST) and
85 Pacific-Japan teleconnection pattern during boreal summer, as the origin of seasonal
86 predictability for the WNP summer climate. They pointed out that this Pacific-Japan
87 and Indian Ocean coupled mode is quite predictable and can exist without ENSO.

88 However, it should be noticed that interannual variation of the WNP summer
89 climate and associated tropical SSTs displays remarkable interdecadal changes during
90 the past few decades (e.g., Kwon et al. 2005; Wang et al. 2008; Park et al. 2010; Xie
91 et al. 2010). Around the late 1970s, the WNP subtropical high shows an increase on
92 its interannual variability with an enhanced relative vorticity at the middle and lower
93 troposphere over the WNP and more water vapor transport from Indian summer
94 monsoon (e.g., Huang et al. 2015). The SST in the tropical Indian Ocean and
95 equatorial eastern Pacific has been noticed to have remarkable local or remote effects
96 on these changes (Wang et al. 2008; Huang et al. 2010; Xie et al. 2010). Remarkable
97 warming with an enhanced variability for these two major tropical SST variations is
98 shown after the late 1970s, resulting in strengthened teleconnections with the WNP
99 summer monsoon. It has been documented that fluctuations of the WNP summer
100 climate can be affected by remote tropical SST anomalies. The tropical Indian Ocean
101 SST anomalies, for instance, can excite a tropospheric Kelvin wave and induce robust
102 atmospheric and precipitation anomalies over the WNP, particularly during the ENSO
103 decaying summers (Terao and Kubota 2005; Yang et al. 2007; Li et al. 2008; Xie et al.

104 2009).

105 Around the early 1990s, on the other hand, a clear interdecadal change on the
106 WNP summer climate is also detected with a strengthened anomalous low-level
107 anticyclone (Wu et al. 2010). It is associated with an enhanced teleconnection
108 between the WNP and East Asian summer monsoon after the early 1990s (Kwon et al.
109 2005; Park et al. 2010). This may result from enhanced fluctuations of precipitation
110 and associated latent heat forcing over the WNP domain after the early 1990s, which
111 is reflected by the interdecadal change of the dominant modes for the precipitation
112 anomalies in the WNP and East Asian region (Kwon et al. 2005; Yim et al. 2008; Lee
113 et al. 2014). It is different to that before the early 1990s, in which ENSO and related
114 Indian Ocean warming dominate the interannual variation of the summer precipitation
115 over the WNP and East Asian region (Wang et al. 2008). Lee et al. (2014) suggested
116 that the WNP summer monsoon variability is significantly related to the SST
117 anomalies over the central Pacific since the early 1990s rather than canonical
118 ENSO-related forcing during 1979–1993. Some recent studies pointed out that the
119 periodicity of the WNP subtropical high and the relative role of tropical SST forcing
120 in the WNP subtropical high demonstrated significant decadal changes in the early
121 1990s and suggested that SST anomalies around the Maritime Continent and central
122 Pacific contribute more to the WNP subtropical high after the early 1990s (e.g., Sui et
123 al. 2007; He and Zhou 2015).

124 In view of the interdecadal changes of the WNP summer climate and associated
125 tropical air-sea interactions in observations, whether the seasonal predictability for the

126 WNP summer climate is changed on similar timescale? If so, what are the possible
127 mechanisms for the changes of the prediction skills and sources of reliability? The
128 above questions remain unclear and will be examined in the present study. To achieve
129 this, the retrospective forecasts from ENSEMBLES multi-model project are used,
130 which cover a long period from 1960 to 2005.

131 The remainder of this paper is organized as follows. Section 2 describes the
132 models, datasets and methods used in this study. The interdecadal changes on the
133 mean state and interannual variability are shown in Section 3. Section 4 presents the
134 interdecadal changes in the prediction skill of the WNP summer climate, followed in
135 Section 5 by an interpretation of possible reasons for the interdecadal changes in the
136 predictability. And finally, the summary and discussion are given in Section 6.

137 **2. Models, datasets and methods**

138 The models used in this study are five fully coupled atmosphere-ocean prediction
139 systems from ENSEMBLES multi-model project, including the UK Met Office
140 (UKMO), Météo-France (MF), the European Centre for Medium-Range Weather
141 Forecasts (ECMWF), the Leibniz Institute of Marine Sciences at Kiel University
142 (IFM-GEOMAR) and the Euro-Mediterranean Center for Climate Change
143 (CMCC-INGV). All models include major radiative forcing and have no flux
144 adjustments. The atmosphere and ocean were initialized using realistic estimation of
145 their observed states. Each model was run from an ensemble of nine initial conditions.
146 Further details on the ENSEMBLES multi-model project, the main model
147 components and the initial condition perturbations are referred to Doblas-Reyes et al.

148 (2010), Weisheimer et al. (2009) and van der Linden and Mitchell (2009).

149 The retrospective forecasts were carried out for a 46-year period of 1960–2005 on
150 the above-described five models. For each year, the forecasts were initialized in 1st of
151 May and performed seven-month long hindcasts. The multi-model-ensemble (MME)
152 results were calculated through a simple composite by applying equal weight to all the
153 five models.

154 The observed datasets for validating the model simulation include monthly mean
155 National Centers for Environmental Prediction/National Center for Atmospheric
156 Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996) and NOAA Extended
157 Reconstructed monthly mean SST V3 dataset (Smith and Reynolds 2004), with the
158 time period from 1960 to 2005. The observational monthly precipitation data are
159 obtained from Global Precipitation Climatology Project (GPCP) during 1979–2005
160 (Adler et al. 2003).

161 **3. Mean state and interannual variability**

162 Figure 1 shows the climatology of JJA-mean (June, July and August) SST during
163 the period 1960–1978, 1979–1993 and 1994–2005. It is found that significant
164 warming of the tropical ocean has been taking place in recent decades. In observations,
165 compared to the period 1960–1978, warmer SST is found over the Indian Ocean and
166 tropical central and eastern Pacific during 1979–1993. Maximum of the averaged SST
167 differences between these two periods are higher than 0.5°C over the ENSO regions.
168 This SST warming pattern for the period 1979–1993 relative to the early period
169 1960–1978 is due to the climate shift around 1976/1977 (e.g., Trenberth and Hurrell

170 1994; Deser et al. 2004). Relatively, the warming pattern after the early 1990s
171 exhibits significant difference to previous period. It is observed mainly over the
172 Indo-Pacific warm pool and indicates a notable enlargement on its size. A recent
173 study by Dong et al. (2014) suggested that internal variability, greenhouse gases and
174 aerosols are driving factors for the decadal fluctuation of SSTs over the Pacific
175 domain. The warming pattern after the early 1990s relative to the early period might
176 be the combination of all these forcing factors. The above interdecadal changes are
177 well reproduced by the models, suggesting the models shows similar bias on the mean
178 state during these three periods.

179 For the SST interannual variability, significant interdecadal changes are also
180 found after the late 1970s and early 1990s (Fig. 2). ENSO, which has been
181 extensively reported for its influence on the WNP and East Asian summer climate
182 (e.g., Wang et al. 2000; Li et al. 2007; Ding et al. 2014, 2015), is associated with
183 larger standard deviation over the tropical central and eastern Pacific. During
184 1979–1993, significant increase on the variability is found over the tropical eastern
185 Pacific and Indian Ocean, suggesting stronger air-sea interactions over these two
186 regions than the previous period, as described in Huang et al. (2010) and Wang et al.
187 (2008). The increase of tropical Indian Ocean SST variability in observations would
188 strengthen its influence on the WNP climate. After the early 1990s, on the other hand,
189 SST anomalies around the Maritime Continent and central Pacific show stronger
190 interannual variability than the previous period. Increase of SST interannual
191 variability in the equatorial Pacific, which shows an interdecadal change during the

192 1990s, has been previously documented (e.g., Latif et al. 1997; Keenlyside et. al. 2007;
193 Yu et al. 2010; Lee and McPhaden 2010), but not for the SST variability around the
194 Maritime Continent. This change around the early 1990s is different to the
195 interdecadal change around the late 1970s, with a weak decrease of the interannual
196 variability over most of the Indian Ocean. Understanding the causes of enhanced SST
197 interannual variability around the Maritime Continent around the early 1990s is an
198 important research area and it needs further investigation. Additionally, for the model
199 results, the stronger variability over the ENSO region after the late 1970s and around
200 the Maritime Continent after the early 1990s is well simulated by the models. The
201 large interannual variability over the Indian Ocean after the late 1970s and over the
202 central Pacific after the early 1990s is also reproduced by the models. But the models
203 overestimate the variability over the Indian Ocean during 1960–1978 and over the
204 central and western Pacific during 1979–1993. This gives rise to the discrepancy over
205 these two regions between models and observations in Figs. 2d and 2f.

206 Associated with the interdecadal changes of SST and interannual SST variability,
207 significant increases of the interannual variability for the 850-hPa zonal wind are also
208 found around the late 1970s and early 1990s (Fig. 3). After the late 1970s, prominent
209 increases are found around the WNP, especially for the subtropical WNP, where the
210 interannual variability of the 850-hPa zonal wind is more than 2.2 m s^{-1} . On the other
211 hand, the variability enhances significantly over the tropical WNP after the early
212 1990s. The intensity is larger than 3 m s^{-1} around the Philippine Sea. Additionally, the
213 models simulate well the variability during 1979–1993 and 1994–2005, but show

214 larger variability around the WNP during 1960–1978 than observations. In general,
215 the above significant interdecadal changes on the mean state and interannual
216 variability around the late 1970s and early 1990s provide backgrounds to the changes
217 of air-sea interactions related to the WNP summer climate and seasonal predictions.

218 **4. Interdecadal changes of the WNP summer prediction**

219 The WNP summer monsoon index (WNPMI), which is defined as the difference
220 of the JJA-mean 850-hPa zonal wind anomalies between (5° – 15° N, 100° – 130° E) and
221 (20° – 30° N, 110° – 140° E), is used to measure the intensity of the interannual variation
222 of the WNP lower-tropospheric circulation following Wang and Fan (1999). A
223 positive (negative) index means an anomalous cyclonic (anticyclonic) circulation. The
224 anomalous cyclone/anticyclone over the WNP, which is well described by the
225 WNPMI, is the dominant mode of the lower-tropospheric wind anomalies over the
226 WNP and plays a key role in the relationship between ENSO and the WNP/East Asian
227 climate anomalies (e.g., Wang et al. 2000; Li et al. 2007). Models from the
228 ENSEMBLES show considerable capability in capturing the interannual variation of
229 the WNPMI during the hindcast period (Li et al. 2012).

230 Figure 4 shows the time series of the WNPMI for observations and the MME
231 predictions and the 9-year running correlation of them. It is found that the
232 predictability of the WNPMI exhibits an interdecadal change with higher
233 predictability since the late 1970s, particularly after the early 1990s. The prediction
234 skill is relatively low before the late 1970s. The models demonstrate certain inability
235 in capturing the WNPMI in most years during this period, especially from the late

236 1960s to late 1970s with the running correlation not exceeding the 95% confidence
237 level. The correlation coefficient between the observed and MME-predicted WNP
238 is only 0.4 during 1960–1978 (Table 1), in spite of that the WNP is well predicted
239 in the early 1960s. After the late 1970s, the prediction skill increases evidently. The
240 9-yr running correlations are at the 95% confidence level during almost all the years.
241 The corresponding correlation coefficient is 0.67 during 1979–1993 (Table 1).

242 Furthermore, more significant increase of the WNP prediction skill is found
243 after the early 1990s. The running correlation coefficients remain to be higher than
244 0.8 and the MME predictions well reproduce the observed WNP in all the years
245 except the negative anomaly in 1996. The bad prediction in 1996 might be caused by
246 the frequent tropical cyclones, which are difficult for the models in describing them
247 (Chan 2005; Li et al. 2014). The stable and high prediction skill after 1993/1994 acts
248 as one of the most important reasons for selecting it as the separating point.
249 Additionally, this separating point consists well with many previous works (e.g.,
250 Kwon et al. 2005; Lee et al. 2014; He and Zhou 2015), in which significant
251 interdecadal changes of monsoon system are found around the early 1990s. The above
252 considerable reinforcement of the predictability is also reflected by the different skill
253 before and after 1993/94 (Table 1). The correlation coefficient between the observed
254 and MME-predicted WNP reaches up to 0.9 during 1994–2005. The above decadal
255 changes can be evidently detected from all the five models (Table 1). The correlations
256 shown by the five models correspond well to the MME prediction, in which most of
257 them exceed the 95% confidence level during 1979–1993, and become much larger

258 after 1994. The ECMWF, which shows the highest prediction correlation among the
259 models during 1979–1993, displays relatively weak increase of the prediction skill
260 after 1994. The consistency between the models confirms that the prediction skill of
261 the WNP summer monsoon exhibits significant interdecadal changes around the late
262 1970s and early 1990s.

263 Pronounced interdecadal changes of the WNPMI interannual variability are also
264 found with higher standard deviation (SD) since the late 1970s and after the early
265 1990s (Table 2), corresponding to the decadal changes of the prediction skill. The
266 observed SD increases from 1.39 m s^{-1} in 1960–1978 to 2.45 m s^{-1} in 1979–2005. It
267 arises mainly from the subtropical WNP as shown in Fig. 3c. After the early 1990s,
268 interannual variability of the observed WNPMI also strengthens significantly,
269 corresponding well to that shown in Fig. 3e. Actually, the variability of the WNPMI is
270 to some extent positively correlated with the predictability of the summer anomalies
271 over the WNP and East Asian sector (Sun and Wang 2013). The larger interannual
272 variability after the late 1970s and early 1990s might help better prediction of the
273 WNPMI. In addition, the models reproduce the strengthened interannual variability
274 after the late 1970s and early 1990s, but overestimate its intensity before 1979.

275 Figure 5 shows the temporal correlation coefficient (TCC) of the 850-hPa zonal
276 wind and SST anomalies during 1960–1978 and 1979–1993. Before the late 1970s,
277 high skills of the lower-tropospheric zonal wind are mainly confined to the warm pool
278 regions (Fig. 5a). This connects to the good prediction of the SST anomalies over the
279 tropical Pacific (Fig. 5d). But the skills of the SSTs over the tropical Indian Ocean are

280 low with the coefficient over most of the regions not exceeding the 95% confidence
281 level, especially over its eastern part. Low skills are also found over the subtropical
282 WNP, both for the SST and wind anomalies, suggesting the model's deficiency in
283 well describing local air-sea interaction over the subtropical WNP during 1960–1978.
284 This corresponds well to the low prediction correlation of the WNPMI shown in Fig.
285 4. After the late 1970s, significant improvements on the WNP summer prediction are
286 shown by the models, especially over the subtropical WNP (Figs. 5b and 5d). The
287 regions with the TCC of lower-tropospheric zonal winds exceeding the 95%
288 confidence level extend north to 40°N, which is associated with local high SST skills.
289 Improvement of the prediction skill after the late 1970s is also found over the tropical
290 Indian Ocean, where the TCC skills for SST anomalies over most of this region are
291 larger than 0.7. The above improvements on the summer prediction after the late
292 1970s are better described by the differences of TCC between these two periods (Figs.
293 5c and 5f). To be mentioned, the most profound increase of the SST prediction skill
294 over the tropical Indian Ocean after the late 1970s are mainly found in its eastern part.
295 This increase, associating with those of the subtropical WNP anomalies, may suggest
296 a physical consistency between this SST and lower-tropospheric wind anomalies over
297 these regions. Meanwhile, good predictions on the WNP anticyclone/cyclone and the
298 SST anomalies over the tropical Indian Ocean are related to the improvement on the
299 prediction skills of lower-tropospheric zonal wind from the Maritime Continent to the
300 tropical Indian Ocean, which act as a linkage between the tropical Indian Ocean and
301 the WNP (e.g., Yang et al. 2007; Li et al. 2008; Xie et al. 2009).

302 Interdecadal change of the WNP summer prediction around the early 1990s shows
303 different characteristics relative to that around the late 1970s, as shown in Fig. 6.
304 During 1994–2005, the models show better capability in predicting the anomalies
305 mainly around the WNP and Maritime Continent. Compared with those during
306 1979–1993 (Figs. 5b and 5e), the high skills of the lower-tropospheric zonal winds
307 extend more westward and cover most regions of the South China Sea, Indo-China
308 Peninsula and Bay of Bengal (Fig. 6a). This is associated with the good prediction of
309 precipitation around the Maritime Continent, east of the Philippines and the tropical
310 eastern Indian Ocean (Fig. 6d), where the prediction skills are relatively low for the
311 previous period (Fig. 5b). These improvements correspond well to the good prediction
312 of the WNPMI after the early 1990s (Fig. 4). Relatively, the SST anomalies over most
313 tropical Indian Ocean are not well predicted after the early 1990s with the TCCs not
314 exceeding the 95% confidence level over most regions (Fig. 6c), suggesting an
315 independence of the improvement on the WNP prediction to the remote forcing of
316 tropical Indian Ocean SST. The prediction correlations of SST anomalies are high
317 around the Maritime Continent and east edge of the tropical Indian Ocean. The above
318 decadal changes around the early 1990s are further confirmed by the differences of
319 TCC between 1994–2005 and 1979–1993 (Figs. 6b, 6d and 6f), indicating that a
320 different but particular prediction pattern appears after the early 1990s. These TCC
321 differences indicate a better prediction over the South China Sea, Indo-China
322 Peninsula and Bay of Bengal for the 850-hPa zonal winds after the early 1990s,
323 associating with significant improvements for the SSTs over the Maritime Continent

324 and precipitation anomalies around the Philippines and tropical eastern Indian ocean,
325 but with lower prediction skills for the SSTs over the tropical western Indian Ocean.

326 **5. Possible reasons related to the interdecadal changes**

327 5.1 Around the late 1970s

328 In observations, the summer anomalies related to the interannual variation of the
329 WNPMI show significant interdecadal change around the late 1970s and are
330 illustrated in Fig. 7. During 1960–1978, associated with a positive WNPMI is a
331 remarkable wave-like pattern of the lower-tropospheric circulation, with an
332 anomalous cyclonic circulation along 20°N of the WNP and an anomalous
333 anticyclonic circulation along 40°N of North Pacific (Fig. 7a). These anomalies are
334 not just confined over the WNP but also extend eastward and occupy almost the
335 whole North Pacific. The corresponding SST anomalies exhibit a significant belt
336 seesaw pattern in the meridional direction over North Pacific (Fig. 7c), which is well
337 consistent with the lower-tropospheric circulation. The cyclonic (anticyclonic)
338 circulation anomaly along 20°N (40°N) induces upwelling (downwelling) and favors
339 the negative (positive) SST anomalies. In the tropics, there are negative SST
340 anomalies in the eastern Indian Ocean and the South China Sea, and positive
341 anomalies in the eastern Pacific. However, these SST anomalies are weak and
342 essentially insignificant. During 1979–1993, a significant wave-like pattern of the
343 lower-tropospheric circulation in the meridional direction is also found over the WNP,
344 but shows different features (Fig. 7b). The anomalies locate mainly over the WNP,

345 not extending eastward over North Pacific as the previous period. Furthermore, the
346 cyclonic circulation over the WNP is associated with a stronger intensity,
347 corresponding to the enhancement of the interannual variability of the WNPMI after
348 the late 1970s (Table 2). Related to a positive WNPMI, negative SST anomalies are
349 found over the tropical Indian Ocean and with significant anomalies around the north
350 Indian Ocean and around the Philippines (Fig. 7d), suggesting a Pacific-Japan and
351 Indian Ocean coupled mode as in Kosaka et al. (2013).

352 In the ENSEMBLES MME prediction, the Pacific-Japan and Indian Ocean
353 coupled mode is well reproduced in both the periods (Fig. 8). The cyclonic anomaly
354 over the WNP is closely related to the westerly anomaly over the northern Indian
355 Ocean (Figs. 8a and 8b). This coupled mode is associated with the significant
356 negative SST anomalies in the eastern Indian Ocean and the South China Sea (Figs.
357 8c and 8d), and associated with the positive precipitation anomaly in the Philippine
358 Sea and negative anomaly in the eastern Indian Ocean and the Maritime Continent
359 (Figs. 8e and 8f).

360 However, there are some discrepancies between prediction and observations. The
361 extra-tropical anomalies associated with the WNPMI in observations are not
362 reproduced in the prediction. In addition, the models tend to overestimate the negative
363 SST and precipitation anomalies in the eastern Indian Ocean during 1960–1978 in
364 comparison with the period 1979–1993.

365 The Pacific-Japan and Indian Ocean coupled mode in the ENSEMBLES MME
366 prediction is significantly related to the SST anomalies in the eastern Indian Ocean.

367 This result is in agreement with many previous studies (e.g., Xie et al. 2009; Huang et
368 al. 2010; Li et al. 2012). In these studies, the WNPMI-related SST anomalies appear
369 in the entire tropical Indian Ocean. Xie et al. (2009) used an atmospheric general
370 circulation model (AGCM) to investigate the contributions of north and south Indian
371 Ocean to the WNP climate variability, and suggested the north Indian Ocean plays an
372 important role in the teleconnections between the tropical Indian Ocean and WNP.
373 However, the present results of prediction suggest that the SST anomalies in the
374 eastern Indian Ocean, rather than the north Indian Ocean, play a dominant role.
375 Actually, the local SST-Precipitation relationship is significantly positive over the
376 tropical eastern Indian Ocean, but weak or even negative over the other regions of
377 tropical Indian Ocean (e.g., Ding et al. 2014; Kumar et al. 2013; Lu and Lu 2014).
378 Therefore, the ocean variability drives the atmosphere in the tropical eastern Indian
379 Ocean, and provides more prediction signals to the models.

380 The eastern Indian Ocean-WNP coupled mode exists during the both periods in
381 the predictions. Therefore, the reproducibility of this mode cannot be used to interpret
382 the difference in predictability of WNPMI between these two periods. The reason for
383 the difference in predictability may lie in the difference of predictability of eastern
384 Indian Ocean SSTs. This hypothesis can be supported by the increase of SST TCC in
385 the eastern Indian Ocean (Fig. 5f). The TCC of SST anomalies averaged over the
386 eastern Indian Ocean (20°S–20°N, 80°–100°E) is 0.37 during 1960–1978, and
387 increases to 0.84 during 1979–1993. Therefore, it can be concluded that the models
388 capture the eastern Indian Ocean-WNP coupled mode during both the periods, and

389 higher predictability of the eastern Indian Ocean during the later period leads to
390 higher predictability of the WNPMI.

391 5.2 Around the early 1990s

392 Figure 9 shows the summer anomalies related to the interannual variation of the
393 WNPMI after the early 1990s. In observations, a remarkable wave-like pattern of the
394 lower-tropospheric circulation is also found over the WNP, but the related air-sea
395 interactions are quite different to the previous period. A dipole SST pattern, with
396 significant negative anomalies around the Maritime Continent and positive anomalies
397 over the equatorial central Pacific, is associated with a positive WNPMI. The
398 correlation coefficient between the WNPMI and the dipole SST pattern, which is
399 defined as the SST differences between (10°S – 10°N , 100° – 150°E) and (5°S – 5°N ,
400 170°E – 130°W) (according to Fig. 9c), is 0.70 in observations. This east-west dipole
401 SST pattern with cold SST over the Maritime Continent and warm SST over the
402 central equatorial Pacific Ocean favors strong westerly anomalies via atmospheric
403 heating, induces convergence by the Ekman friction, further enhances the convection
404 around the Philippine Sea and thus contributes to the WNP lower-tropospheric
405 cyclonic anomaly (Fig.9) (Lu 2001; Terao and Kubota 2005; Xie et al. 2009; He and
406 Zhou 2015). This pattern is coupled with a stronger precipitation anomaly around the
407 Philippine Sea, Maritime Continent and equatorial western Pacific.

408 This east-west dipole SST pattern over the Maritime Continent and the central
409 equatorial Pacific Ocean are reproduced quite well by the models (Fig. 9d). The

410 correlation coefficient between this dipole SST pattern and WNPMI is 0.70 in the
411 MME prediction, quite close to that in observations. The positive precipitation
412 anomalies in the Philippine Sea are also well captured by the models (Fig. 9f). Higher
413 predictability of the WNP summer climate is brought by this pattern after the early
414 1990s. The SST anomalies related to the WNPMI in the model predictions are apt to
415 display a dipole pattern over the tropical regions, in all periods, as shown in Figs. 8c,
416 8d and 9d. The dipole SST anomalies are not clearly appeared in observations during
417 the first two periods before the early 1990s, but quite similar to observations during
418 1994–2005. These changes on the dipole SST anomalies in observations after the
419 early 1990s correspond well to those for the SST interannual variability (Fig. 2e).

420 The ensemble-mean predictions are apt to display strong variability over the
421 regions where the local SST-Precipitation relationship is positive, including the
422 tropical eastern Indian Ocean, the Maritime Continent and the central Pacific Ocean
423 (e.g., Ding et al. 2014; Kumar et al. 2013; Lu and Lu 2014) and providing more
424 prediction reliability to the models. The dipole SST pattern over the Maritime
425 Continent and central equatorial Pacific dominates the variation of the WNP summer
426 climate after the early 1990s, both in observations and the model predictions (Fig. 9),
427 acting as the primary sources for the predictability. This dipole SST forcing becomes
428 stronger after the early 1990s in observations, reflecting by a higher correlation
429 coefficient between the WNPMI and dipole SST in observations (-0.70 after the early
430 1990s, -0.12 before that time). The tropical eastern Indian Ocean SST anomalies are
431 also shown related to the WNPMI after the early 1990s, but are relatively weaker in

432 observations (Figs. 9c and 9d). In general, the dipole SST pattern provides more
433 prediction reliability to the WNP summer climate and dominates the WNP summer
434 predictability after the early 1990s.

435 **6. Summary and discussion**

436 It has been found that pronounced interdecadal changes for the summer SST and
437 associated interannual variability take place around the late 1970s and early 1990s.
438 Significant warming and stronger variability over the tropical Indian Ocean and
439 eastern Pacific are shown after the late 1970s. But the pattern is changed after the
440 early 1990s, with the warming SST and stronger variability over the Maritime
441 Continent and western Pacific. These changes are associated with the interdecadal
442 changes on the predictability of the WNP summer climate, and have been well
443 examined in this study. The ENSEMBLES May-start seasonal predictions during a
444 46-year period from 1960 to 2005, which comprises five state-of-the-art
445 atmosphere-ocean coupled models, are used here. The primary measurement for the
446 prediction skill is the temporal correlation coefficient between observations and
447 models' hindcast.

448 Our analyses reveal that seasonal prediction for the WNP summer anomalies
449 exhibits a significant interdecadal shift with higher prediction skills since the late
450 1970s, particularly after the early 1990s. The prediction correlation of the WNP
451 increases from 0.40 during 1960–1978 to 0.67 during 1979–1993, displaying a
452 projected enhancement on the predictability of the WNP climate after the late 1970s.
453 This enhancement is associated with significant improvements of the prediction skill

454 over the subtropical WNP and tropical Indian Ocean, both for the lower-tropospheric
455 wind and SST anomalies. The prediction correlation of the WNPMI becomes further
456 higher and reaches to 0.90 after the early 1990s (1994–2005). It is different to the
457 changes around the late 1970s, with higher prediction skills around the South China
458 Sea and the Philippines for the lower-tropospheric zonal wind and precipitation
459 anomalies, and around the Maritime Continent for the SST anomalies. In addition, the
460 interannual variability of the WNPMI increases significantly after the late 1970s,
461 particularly after the early 1990s.

462 Higher predictability of tropical eastern Indian Ocean after the late 1970s gives
463 rise to the improvement on prediction skill of the WNP anomalies. The corresponding
464 TCC skill for the tropical eastern Indian Ocean SST increases to 0.84 during
465 1979–1993, which is only 0.37 during 1960–1978. A close relationship between the
466 tropical eastern Indian Ocean SST and the WNP summer anomalies is found in the
467 model predictions during both the periods. It corresponds well to that in observations,
468 especially during 1979–1993. These SST anomalies are relatively weak and
469 essentially insignificant during the previous period.

470 The predictable pattern related to the WNP climate is also changed around the
471 early 1990s. During 1994–2005, the WNP anomalies are coupled with an east-west
472 dipole SST pattern between the Maritime Continent and equatorial central Pacific in
473 observations. It favors the convection around the Philippine Sea and the WNP
474 lower-tropospheric circulation via atmospheric adjustment. For the model predictions,
475 the SST anomalies related to the WNP summer climate tend to display a dipole SST

476 pattern over the tropical region, with warm SSTs over the central Pacific Ocean and
477 cold SSTs around the Maritime Continent and tropical eastern Indian Ocean (Figs. 8c,
478 8d and 9d). Thus, the teleconnections between the tropical dipole SST pattern and
479 WNP summer climate work in both the model predictions and observations during
480 1994–2005. It would give rise to the higher predictability for the WNP summer
481 climate after the early 1990s.

482 This work suggests that SST forcing from the tropical eastern Indian Ocean plays
483 an important role in the WNP summer prediction. The corresponding physical
484 mechanisms are not discussed in this study. In view of the positive SST-Precipitation
485 relationship over there, it would be possible to be revealed by an AGCM SST
486 experiment and will be investigated in our future study.

487 Furthermore, the present results interpret predictability and the corresponding
488 sources for the WNP summer climate in the case of non-stationary teleconnections
489 during recent decades. It implies a sensitivity of the prediction skills for the WNP
490 summer anomalies to different coupled modes over the tropics. High prediction skills
491 with more predictable signals are found in recent two decades over the WNP,
492 presenting a basis in further investigation on seasonal prediction for the East Asian
493 summer rainfall. Rainfall over the central China, for instance, is better captured by the
494 models after the early 1990s (Fig. 6e). Nevertheless, this improvement seems modest,
495 especially over the other regions of East Asia (Fig. 6f). Skillful prediction on
496 year-to-year fluctuations of the East Asian summer rainfall remains a challenge.

497

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504

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640

641 **Table Captions**

642 **Table 1** Correlation coefficients of the WNPMI between the observations and models.

643 The values underlined and in bold represent statistical significance of the
644 correlation coefficients at 95% and 99% confidence level, respectively

645 **Table 2** Standard deviation (SD) of the observed and predicted WNPMI (Unit: m s^{-1}).

646 The predicted SD is calculated as the averaged SD for each ensemble member

647

648 **Figure Captions**

649 **Figure 1** Climatology of JJA-mean SST for observations (left) and the ENSEMBLES

650 MME prediction (right) during 1960–1978 (upper), 1979–1993 (middle) and
651 1994–2005 (lower). Unit: $^{\circ}\text{C}$. The shading represents differences of SST to the
652 previous period

653 **Figure 2** Similar to Fig. 1, but for the interannual variability of the JJA-mean SST

654 **Figure 3** Interannual variability of 850-hPa zonal wind for observations (*left*) and the
655 ENSEMBLES MME prediction (*right*). Unit: m s^{-1} . The contours represent
656 where differences of SD to previous period are larger (smaller) than 0.4 (-0.4)
657 m s^{-1}

658 **Figure 4 a** Time series of the normalized WNP summer monsoon index (WNPMI)

659 for observations (*solid black line*), the MME predictions (*dashed red line*) and **b**
660 the 9-year running correlation of the WNPMI between the observations and
661 MME predictions. The dashed lines in **b** represent statistical significance of

662 the correlation coefficients at 95% and 99% confidence levels, respectively

663 **Figure 5** Temporal correlation coefficients (TCC) of JJA-mean 850-hPa zonal wind
664 (*upper*) and SST anomalies (*lower*) between the observations and MME
665 predictions during 1960–1978 (*left*), 1979–1993 (*middle*) and the differences
666 between these two periods (*right*). The contours represent statistically
667 significance of the correlation coefficients at 95% and 99% confidence levels,
668 respectively

669 **Figure 6** Same as Fig.5, but for the TCC of JJA-mean 850-hPa zonal wind (*upper*),
670 SST (*middle*) and precipitation (*lower*) anomalies during 1994–2005 (*left*) and
671 the differences (*right*) to that during 1979–1993

672 **Figure 7** Regression of the 850-hPa winds (*upper*) and SST (*lower*) anomalies onto
673 the normalized WNPMI in observations during 1960–1978 (*left*) and
674 1979–1993 (*right*). The shading indicates the regions where the anomalies
675 exceed the 95% confidence level. Interval of the SST anomaly is 0.1°C

676 **Figure 8** Same as Fig. 7, but for the 850-hPa zonal wind (*upper*), SST (*middle*) and
677 precipitation (*lower*) anomalies in the ENSEMBLES MME prediction. Interval
678 of the precipitation anomaly is 0.4 mm day⁻¹

679 **Figure 9** Regression of the 850-hPa zonal wind (*upper*), SST (*middle*) and
680 precipitation (*lower*) anomalies onto the normalized WNPMI in observations
681 (*left*) and the ENSEMBLES MME prediction (*right*) during 1994–2005.
682 Intervals of the SST and precipitation anomalies are 0.1°C and 0.4 mm day⁻¹,
683 respectively

684

685 **Table 1** Correlation coefficients of the WNPMI between the observations and models.

686 The values underlined and in bold represent statistically significance of the

687 correlation coefficients at 95% and 99% confidence level, respectively

688

Corr. OBS	1960–1978	1979–1993	1994–2005
MME	0.40	0.67	0.90
ECMWF	0.42	0.73	0.79
IFM-GEOMAR	0.33	<u>0.62</u>	0.90
MF	0.17	<u>0.63</u>	0.78
UKMO	<u>0.47</u>	0.46	0.80
CMCC-INGV	0.26	<u>0.63</u>	0.82

689

690

691 **Table 2** Standard deviation (SD) of the observed and predicted WNPMI (Unit: m s^{-1}).

692 The predicted SD is calculated as the averaged SD for each ensemble members

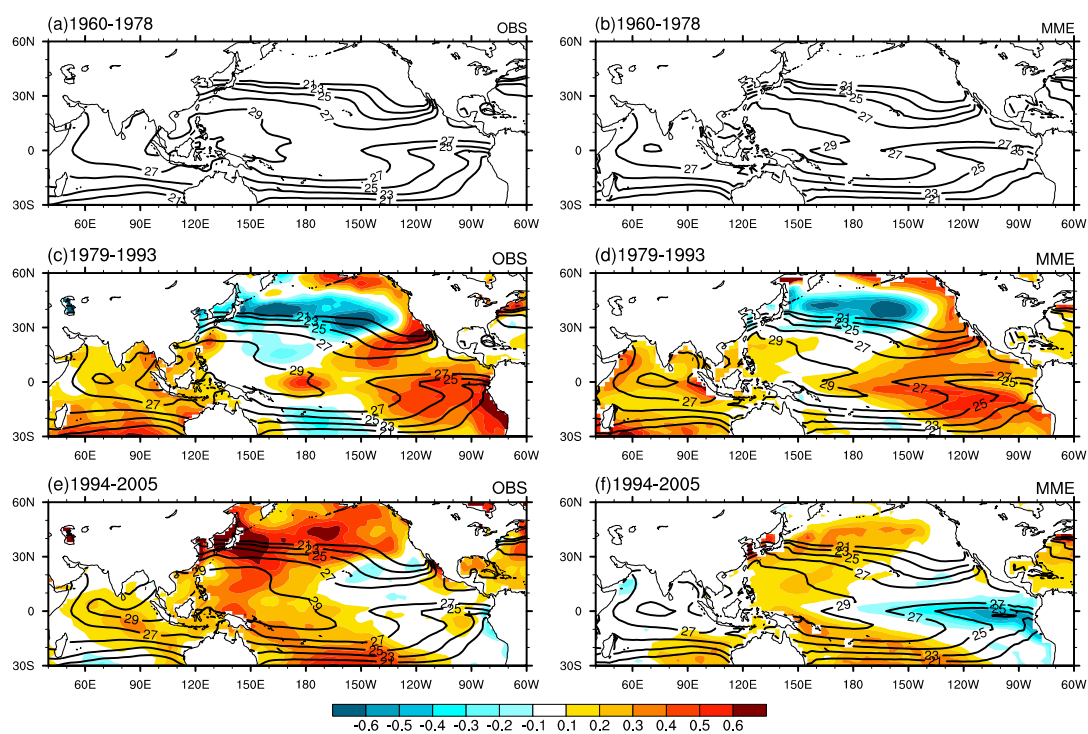
693

SD of the WNPMI	1960–1978	1979–1993	1994–2005
OBS	1.39	2.14	2.87
MME	2.0	2.28	2.71
ECMWF	1.91	2.36	2.61
IFM-GEOMAR	2.15	2.73	2.91
MF	1.55	2.12	2.33
UKMO	2.18	2.13	2.80
CMCC-INGV	2.23	2.00	2.91

694

695

JJA SST



696

697 **Figure 1** Climatology of JJA-mean SST for observations (*left*) and the ENSEMBLES

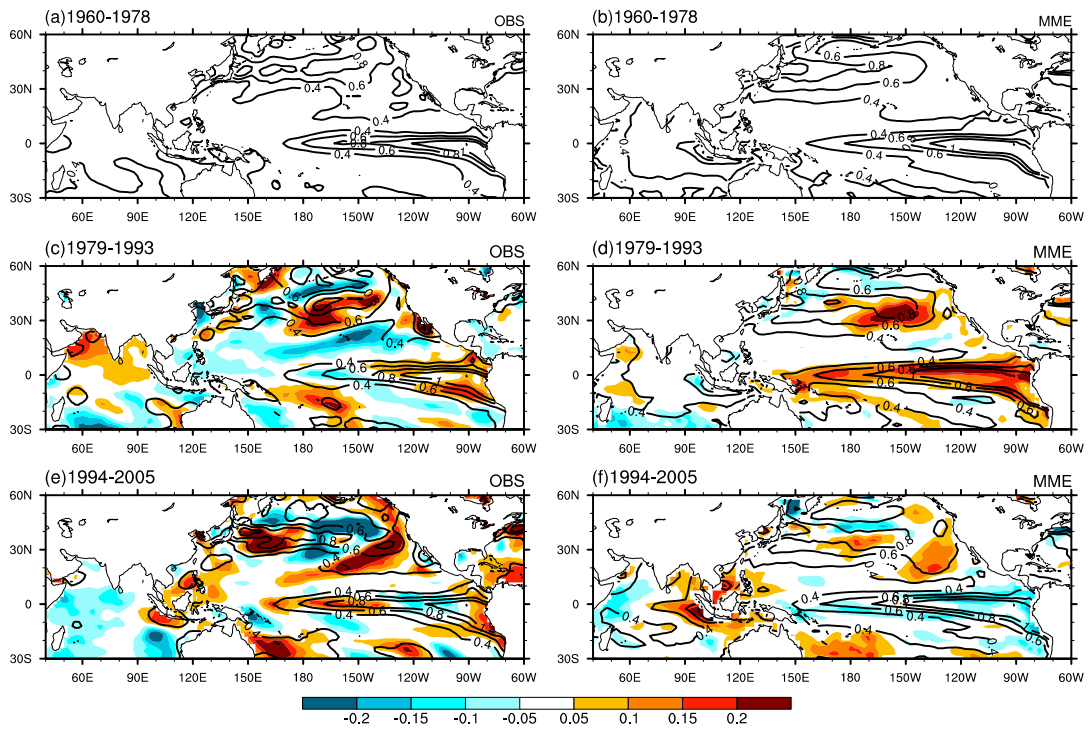
698 MME prediction (*right*) during 1960–1978 (*upper*), 1979–1993 (*middle*) and

699 1994–2005 (*lower*). Unit: °C. The shading represents differences of SST to the

700 previous period

701

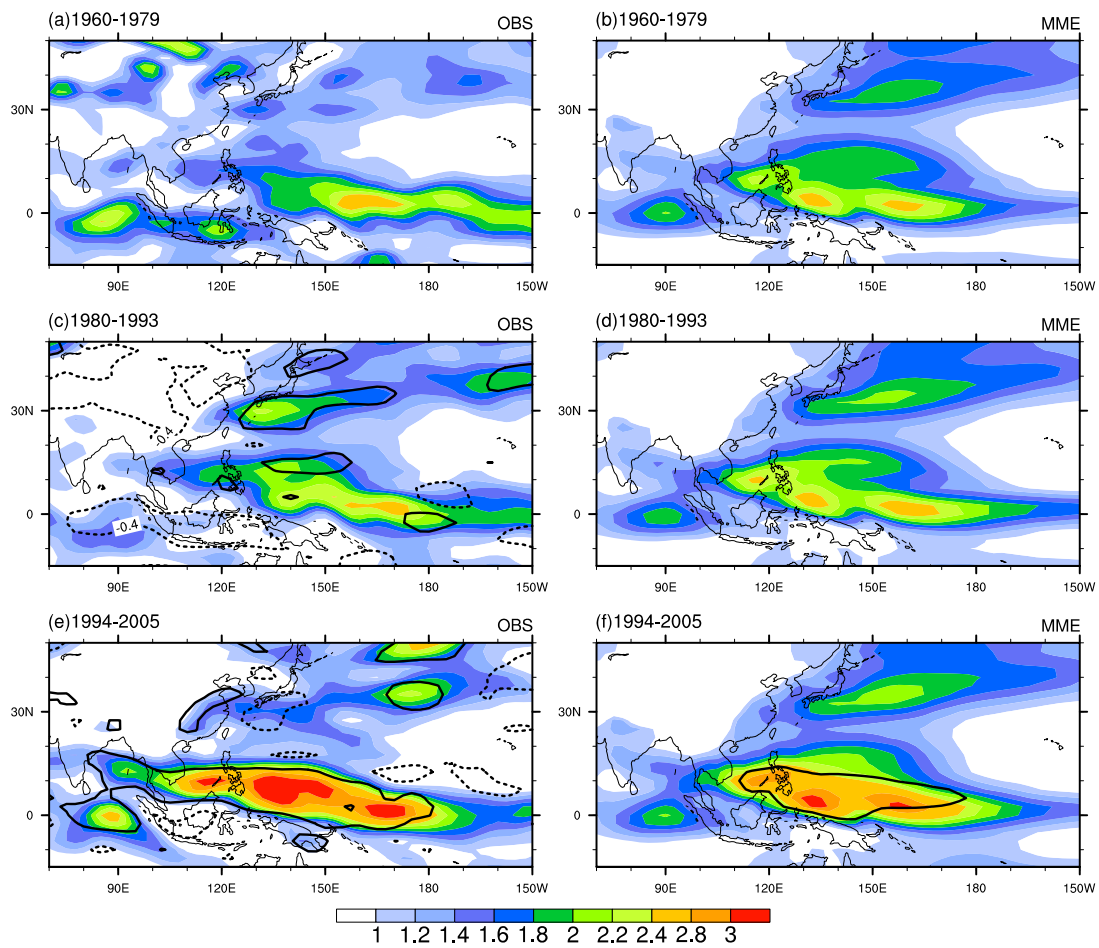
SD of JJA SST



702

703 **Figure 2** Similar to Fig. 1, but for the interannual variability of the JJA-mean SST

SD of JJA U850



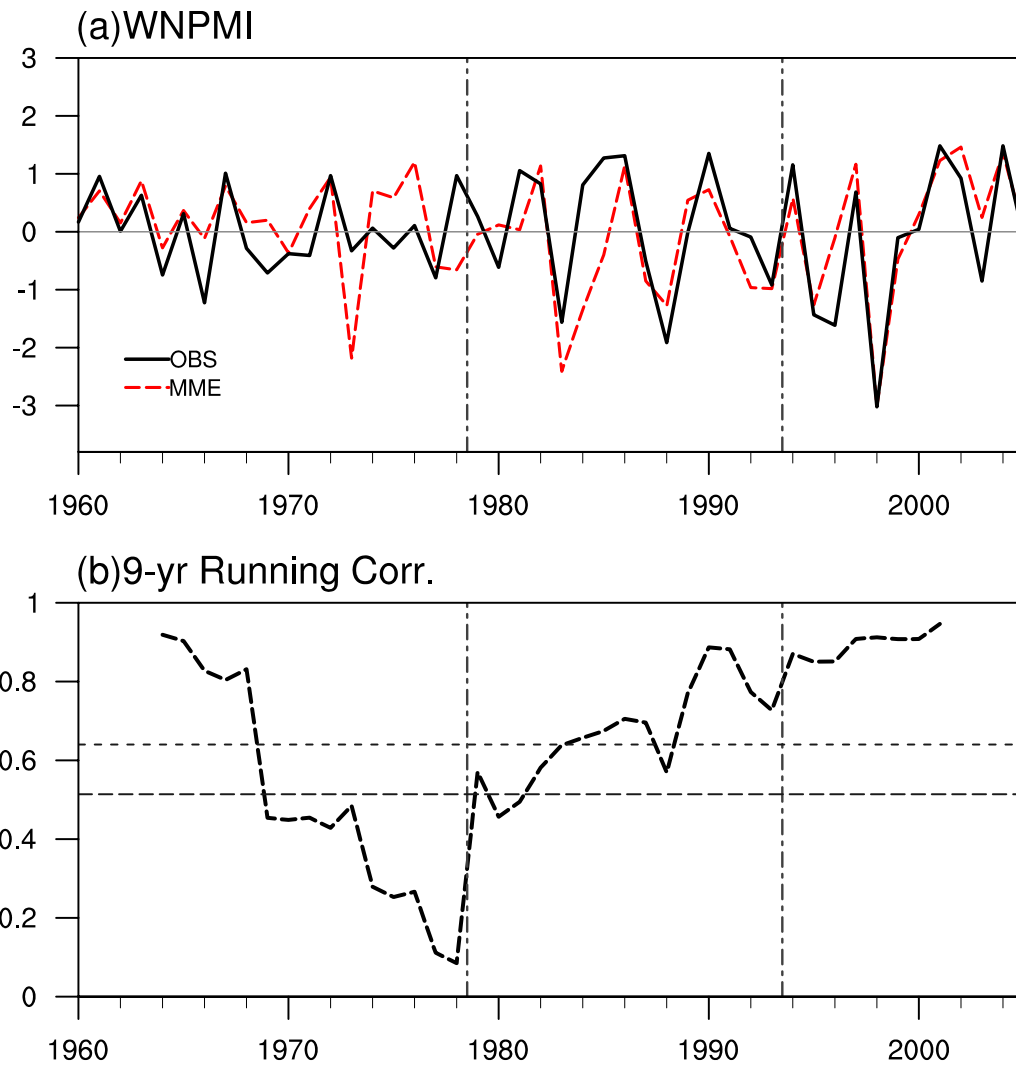
704

705 **Figure 3** Interannual variability of 850-hPa zonal wind for observations (*left*) and the

706 ENSEMBLES MME prediction (*right*). Unit: m s^{-1} . The contours represent

707 where differences of SD to previous period are larger (smaller) than 0.4 (-0.4)

708 m s^{-1}



709

710 **Figure 4 a** Time series of the normalized WNP summer monsoon index (WNPMI)

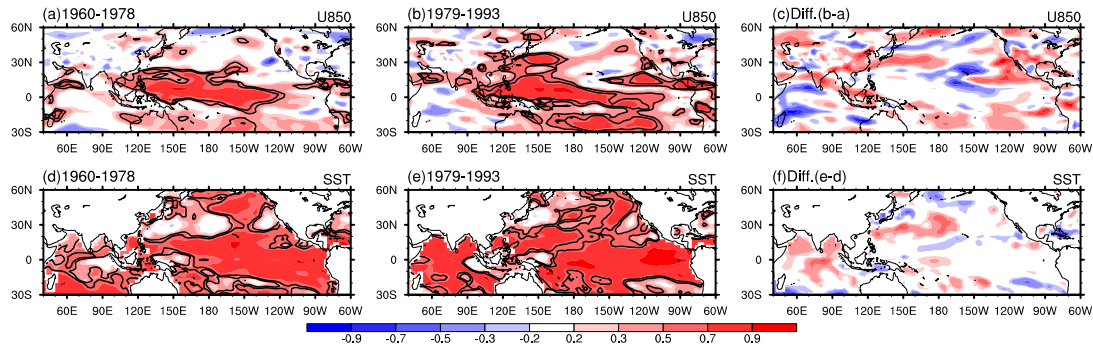
711 for observations (*solid black line*), the MME predictions (*dashed red line*) and

712 **b** the 9-year running correlation of the WNPMI between the observations and

713 MME predictions. The dashed lines in **b** represent statistically significance of

714 the correlation coefficients at 95% and 99% confidence levels, respectively

715



716

717 **Figure 5** Temporal correlation coefficients (TCC) of JJA-mean 850-hPa zonal wind

718 (*upper*) and SST anomalies (*lower*) between the observations and MME

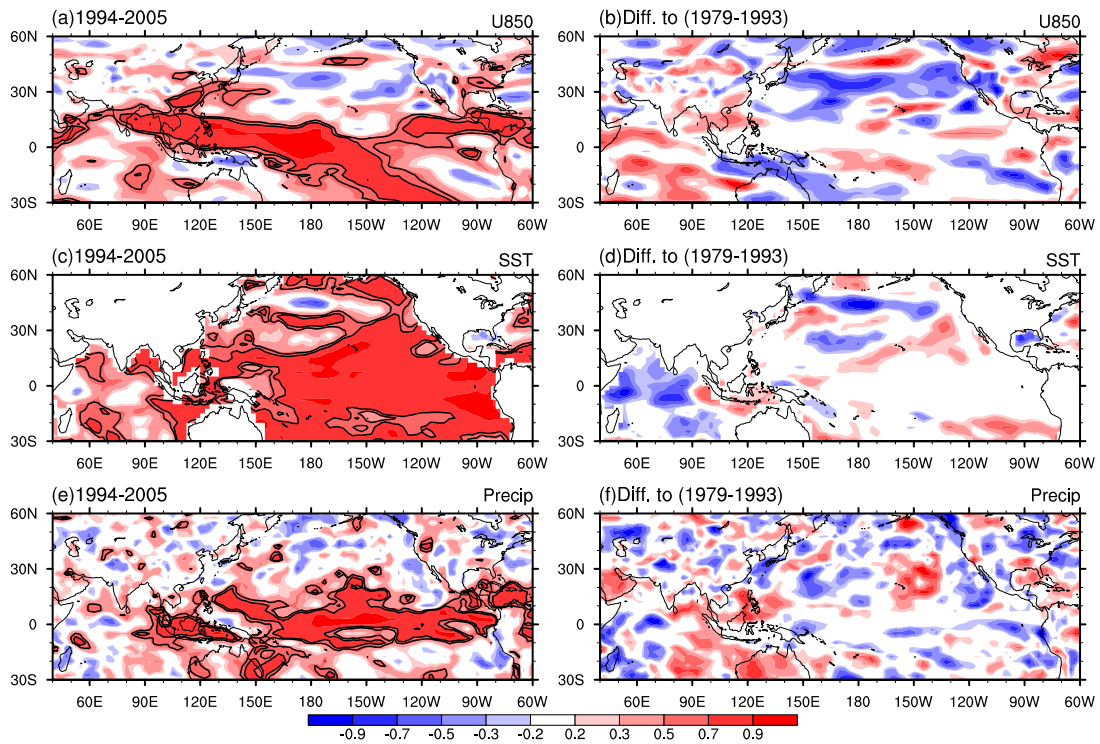
719 predictions during 1960–1978 (*left*), 1979–1993 (*middle*) and the differences

720 between these two periods (*right*). The contours represent statistically

721 significance of the correlation coefficients at 95% and 99% confidence levels,

722 respectively

723



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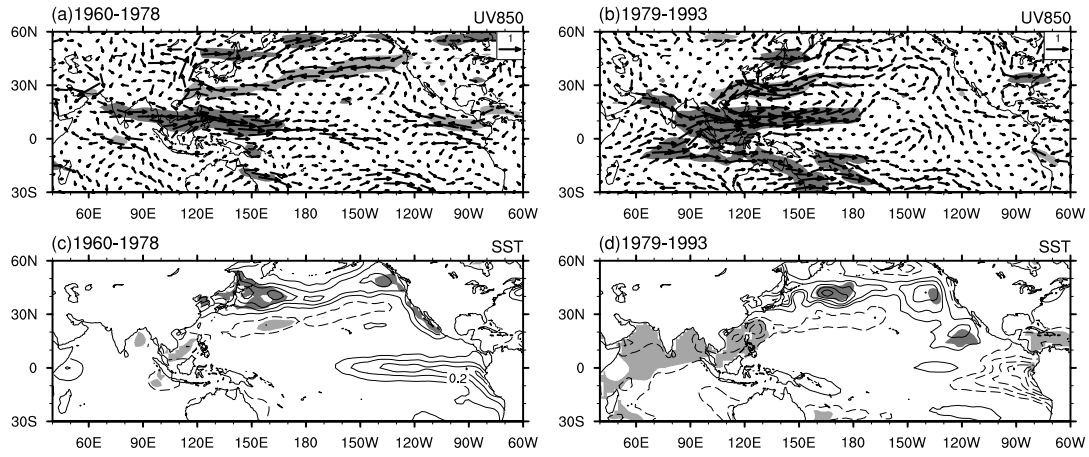
725 **Figure 6** Same as Fig.5, but for the TCC of JJA-mean 850-hPa zonal wind (*upper*),

726 SST (*middle*) and precipitation (*lower*) anomalies during 1994–2005 (*left*) and

727 the differences (*right*) to that during 1979–1993

728

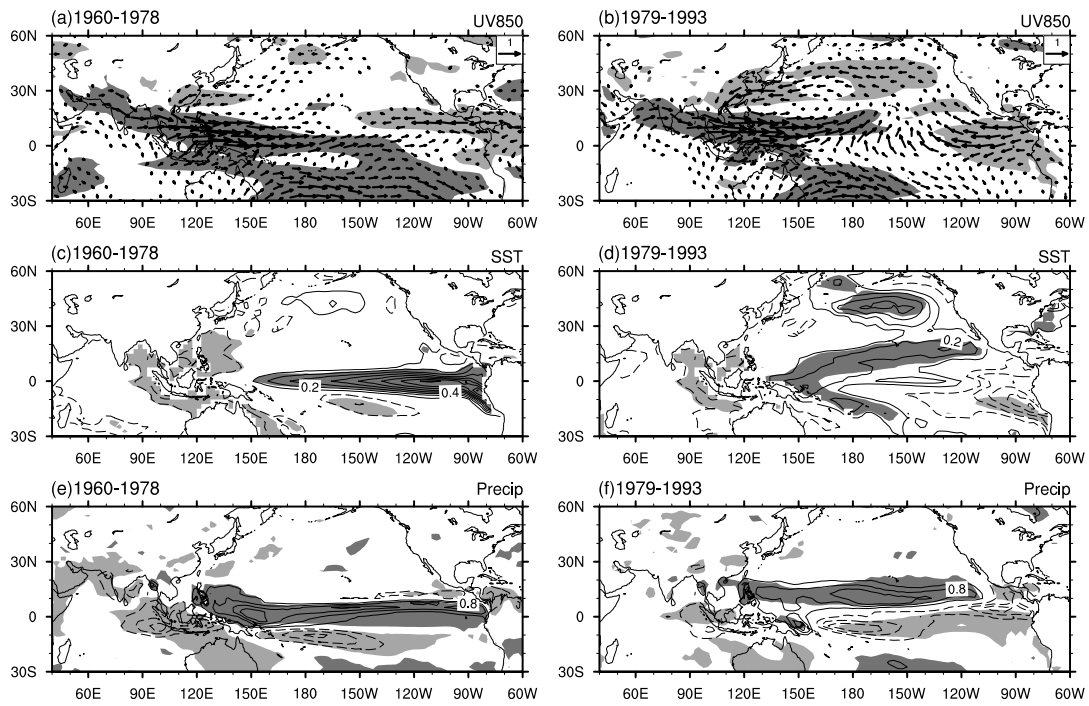
729



730

731 **Figure 7** Regression of the 850-hPa winds (*upper*) and SST (*lower*) anomalies onto
 732 the normalized WNPPI in observations during 1960–1978 (*left*) and
 733 1979–1993 (*right*). The shading indicates the regions where the anomalies
 734 exceed the 95% confidence level. Interval of the SST anomaly is 0.1°C

735



736

737 **Figure 8** Same as Fig. 7, but for the 850-hPa zonal wind (*upper*), SST (*middle*) and

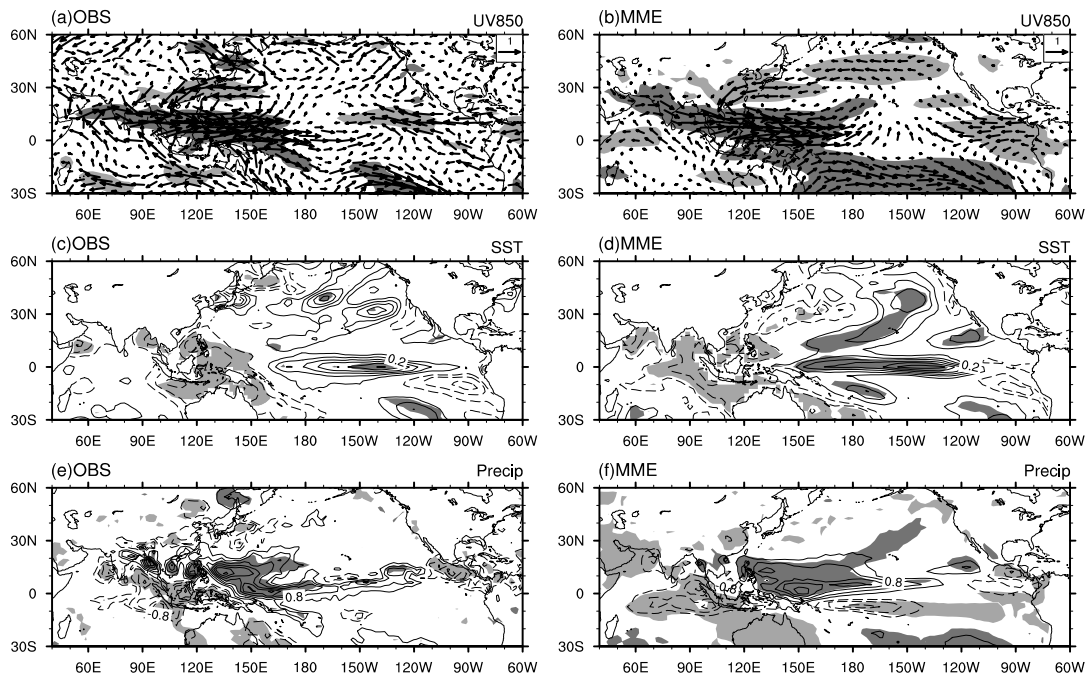
738 precipitation (*lower*) anomalies in the ENSEMBLES MME prediction. Interval

739 of the precipitation anomaly is 0.4 mm day^{-1}

740

741

Regg. onto WNPMI (1994-2005)



742

743 **Figure 9** Regression of the 850-hPa zonal wind (*upper*), SST (*middle*) and
744 precipitation (*lower*) anomalies onto the normalized WNPMI in observations
745 (*left*) and the ENSEMBLES MME prediction (*right*) during 1994–2005.

746 Intervals of the SST and precipitation anomalies are 0.1°C and 0.4 mm day^{-1} ,

747 respectively