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4 **The Resolution Sensitivity of the Asian Summer Monsoon and**
5 **its Inter-Model Comparison between MRI-AGCM and**
6 **MetUM**

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20 **Abstract**

21 In this study, we compare the resolution sensitivity of the Asian Summer
22 Monsoon (ASM) in two Atmospheric General Circulation Models (AGCMs): the
23 MRI-AGCM and the MetUM. We analyze the MetUM at three different resolutions,
24 N96 (approximately 200-km mesh on the equator), N216 (90-km mesh) and N512
25 (40-km mesh), and the MRI-AGCM at TL95 (approximately 180-km mesh on the
26 equator), TL319 (60-km mesh), and TL959 (20-km mesh). The MRI-AGCM and the
27 MetUM both show decreasing precipitation over the western Pacific with increasing
28 resolution, but their precipitation responses differ over the Indian Ocean. In
29 MRI-AGCM, a large precipitation increase appears off the equator (5-20°N). In MetUM,
30 this off-equatorial precipitation increase is less significant and precipitation decreases
31 over the equator. Moisture budget analysis demonstrates that a changing in moisture
32 flux convergence at higher resolution is related to the precipitation response.
33 Orographic effects, intra-seasonal variability and the representation of the meridional
34 thermal gradient are explored as possible causes of the resolution sensitivity. Both
35 high-resolution AGCMs (TL959 and N512) can represent steep topography, which
36 anchors the rainfall pattern over south Asia and the Maritime Continent. In MRI-AGCM,
37 representation of low pressure systems in TL959 also contributes to the rainfall pattern.
38 Furthermore, the seasonal evolution of the meridional thermal gradient appears to be
39 more accurate at higher resolution, particularly in the MRI-AGCM. These findings
40 emphasize that the impact of resolution is only robust across the two AGCMs for some
41 features of the ASM, and highlights the importance of multi-model studies of GCM

42 resolution sensitivity.

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44

45 **1. Introduction**

46 The Asian Summer Monsoon (ASM) is an important component of the global
47 monsoon. Its multi-scale variability, ranging from sub-seasonal to inter-decadal time
48 scales, impacts society through natural disasters and changes in water resources (e.g.
49 Chang et al. 2000, Lau and Kim 2012, He and Zhou 2015, Joseph et al. 2015, Cho et al.
50 2015). Recent advances in climate simulation have improved the fidelity of the ASM,
51 but large biases remain. Sperber et al. (2013) and Ogata et al. (2014) reported that there
52 is little improvement in Coupled Model Intercomparison Project Phase 5 (CMIP5)
53 General Circulation Models (GCM) seasonal climatology compared to CMIP3 GCMs
54 and there are still substantial biases in the ASM simulations. At inter-annual timescales,
55 the ENSO-Indian monsoon relationship (defined by all-India rainfall and Nino-3.4) is
56 too strong in individual CMIP5 models, while the ENSO-East Asian monsoon
57 relationship is too weak in multi-model mean. CMIP3 and CMIP5 GCMs also
58 commonly exhibit a late monsoon onset (Sperber et al., 2013). At sub-seasonal
59 timescales, CMIP5 GCMs depict a large inter-model spread in the reproducibility of the
60 Boreal Summer Intra-Seasonal Oscillation (BSISO) of about 20-60 day period (e.g.
61 Yasunari 1980, Jiang et al. 2004, Ajayamohan et al. 2009).

62 The most significant differences between CMIP3 and CMIP5 GCMs are the
63 improvement of physics schemes and the increase in horizontal and vertical resolutions.
64 CMIP results include the model-produced SST bias, which makes the detection of
65 causes of model bias in the ASM simulation difficult. Therefore, an intercomparison of
66 atmospheric GCMs (AGCM) in an “AMIP-style” (Atmospheric Model Intercomparison

67 Project) configuration, using observed SST and sea-ice boundary conditions, is often
68 more appropriate for diagnosing sources of bias or understanding the reason of response
69 changes in atmospheric models. In this paper, we focus on the effect of only increasing
70 horizontal resolution on the ASM simulation and perform an assessment with two
71 AGCMs.

72 Development in high-performance computing enables high-resolution AGCMs
73 that can resolve fine-scale orographic effect and synoptic-scale atmospheric variations.
74 Kitoh and Kusunoki (2008) investigated the ASM simulation in a 20-km resolution
75 AGCM and reported that increased resolution of steep orography improved the
76 precipitation climatology (Xie et al. 2006). Other resolution sensitivity studies have
77 shown that orographic precipitation over the Western Ghats and the Indochina peninsula
78 and the wind speed of Somali Jet are generally improved with increasing resolution
79 (Sperber et al. 1994, Jha et al. 2000, Kobayashi and Sugi 2004, Sabin et al. 2013).
80 However, resolution sensitivity of precipitation in other areas such as the western
81 equatorial Indian Ocean and Indian peninsula differs between studies (Sperber et al.
82 1994, Stephenson et al. 1998, Martin 1999, Sabin et al. 2013).

83 The 20-60 day BSISO, other intra-seasonal modes of 10-20 days (e.g.
84 Murakami 1976, Krishnamurti and Ardanuy 1980, Annamalai and Slingo 2001) and
85 synoptic 3-5 day Low Pressure Systems (LPS; e.g. Mak 1987, Goswami et al. 2003) all
86 interact on intra-seasonal time scales over the south Asia (Annamalai and Slingo 2001,
87 Goswami et al. 2003). These intra-seasonal variations and its multi-scale interactions
88 are considered as an important factor to the ASM reproducibility in GCMs (e.g. Liu et al.

89 2009, Sperber et al. 2013, Sabeerali et al. 2013), and it is believed that high-resolution
90 GCMs better simulate such multi-scale interactions (e.g. Roberts et al, 2015; Vellinga et
91 al, 2016). Increasing horizontal resolution is also key to improving simulations of
92 tropical cyclones (TC; e.g. Oouchi et al. 2006, Murakami and Sugi 2010) and has some
93 common effects including improvement of TC distribution and intensity, decrease of
94 weak TC and increase of strong TC in the future climate (Murakami et al. 2012, Roberts
95 et al. 2015).

96 Each resolution sensitivity study uses slightly different techniques and analyses
97 different aspects of resolution sensitivity. Moreover, it is also well known that a large
98 inter-model spread in the reproducibility of the ASM exists, even in AMIP-style
99 simulations. For example, on the south Asian monsoon, Kitoh and Kusunoki (2008)
100 exhibited that major precipitation maximum locates around 10-20°N in MRI-AGCM at
101 both low and high resolutions. In contrast, Johnson et al. (2016) showed that major
102 precipitation maximum locates over the equator and precipitation around 10-20°N is
103 rather weak in MetUM at both low and high resolutions. In order to understand what
104 aspects of resolution sensitivity are common among GCMs, it is important to conduct a
105 coordinated resolution sensitivity study of multiple AGCMs using the same analysis
106 techniques.

107 In this study, based on Johnson et al. (2016), we compare the resolution
108 sensitivity of the ASM in two state-of-the-art AGCMs (MRI-AGCM and MetUM). We
109 compare the MetUM integrations at N96 (200-km mesh on the equator), N216 (90-km
110 mesh) and N512 (40-km mesh) that were used by Johnson et al. (2016) with an

111 MRI-AGCM series at TL95 (180-km mesh on the equator), TL319 (60-km mesh), and
112 TL959 (20-km mesh) resolutions. Johnson et al. (2016) found that fine orography at
113 N512 improves orographic rainfall over the south Asian continent and the Somali Jet
114 wind speed is increased by the better resolution of the East African Highlands. Over the
115 Maritime Continent (MC), rainfall increases over land, while it decreases in the west
116 Pacific. Furthermore, Johnson et al. (2016) investigated the role of LPS on the rainfall
117 change over India and concluded that LPS contribute to slightly more rainfall over
118 northeast India at N512. In this paper, we compare this resolution sensitivity to the
119 sensitivity of the MRI-AGCM, and analyze similarities and differences. Section 2
120 describes the models used in this study. Section 3 shows the results of the seasonal
121 mean ASM and its resolution sensitivity. Section 4 presents the orographic effects and
122 intraseasonal variability. Upper tropospheric thickness and its seasonal evolution are
123 also investigated as a measurement of drivers of the ASM. Section 5 presents the
124 summary and a discussion of the results.

125

126 **2. Methodology**

127

128 *2.1. Experiments in MRI-AGCM and MetUM*

129 We make use of the MRI-AGCM3.2 model (Mizuta et al. 2012) developed at
130 20-km and 60-km horizontal resolutions, with 64 vertical levels (TL959L64 and
131 TL319L64). This model, in which an especially deep convective scheme was changed
132 from a relaxed Arakawa–Schubert scheme to a Tiedtke-like scheme proposed by

133 Yoshimura et al. (2015), is an improved version of MRI-AGCM3.1 (Mizuta et al. 2006).
134 Using the 20-km resolution AGCM (MRI-AGCM3.2S), Murakami et al. (2012)
135 reported that the simulated intensity of global TCs was significantly improved, as
136 compared with results of the previous version (MRI-AGCM3.1S). These 20-km and
137 60-km AGCMs are used for studies of TCs (Murakami et al. 2012), global monsoon
138 (Endo et al. 2012) and East Asian monsoon (Kusunoki and Mizuta 2013) in the future
139 climate. An additional simulation of MRI-AGCM3.2 at 180-km horizontal resolution
140 (TL95L64) was performed for resolution sensitivity studies. In MRI-AGCM, the lower
141 boundary conditions are prescribed by observed monthly-mean SST and sea ice
142 concentration of the Met Office Hadley Centre Sea Ice and Sea Surface Temperature
143 version 1 (HadISST1; Rayner et al. 2003) for the period 1979–2003. To focus on
144 resolution sensitivity, we only changed the horizontal resolution while other settings
145 (i.e. vertical resolution and physical package) remain the same.

146 The configuration of the MetUM used here is the Global Atmosphere 3.0
147 (Walters et al. 2011) configuration of the atmospheric component of the HadGEM3
148 family. We used integrations from the UPSCALE simulation campaign (Mizielinski et
149 al. 2014) at three horizontal resolutions: approximately 40-km, 90-km and 200-km, and
150 85 vertical levels (N512L85, N216L85, N96L85 respectively). The lower boundary
151 conditions are prescribed by the observed daily-mean SST and sea ice concentration of
152 the OSTIA product (Donlon et al. 2012) for the period 1985–2011. The UPSCALE
153 campaign simulations have previously been used for multiple resolution sensitivity
154 studies, such as the global and regional hydrological cycles (Demory et al. 2014;

155 Schiemann et al. 2014; Vellinga et al. 2016), ASM (Johnson et al. 2016) and TCs
156 (Roberts et al. 2015). Similar to MRI-AGCM, only horizontal resolution was changed
157 between integrations. A detailed description of the integrations and model settings is
158 given in Mizielinski et al. (2014).

159

160 *2.2. Observational datasets*

161 The Japanese 55-year reanalysis (JRA-55, Kobayashi et al. 2015, 1.25°
162 resolution) provided by Japan Meteorological Agency (JMA) and CPC Merged
163 Analysis of Precipitation (CMAP, Xie and Arkin 1997, 2.5° resolution) were used to
164 verify 1986-2003 in both AGCMs at all resolutions. Furthermore, we used Global
165 Precipitation Climatology Project version 1.2 (GPCP, Huffmann et al. 2001, 1°
166 resolution) in Section 4.2 to verify synoptic rainfall variability and Tropical Rainfall
167 Measuring Mission product 3B43v7 (TRMM, Huffman et al. 2007, 0.25° resolution) in
168 Section 4.1 to verify rainfall over orography. In these two observational datasets, due to
169 data coverage, different periods (1997-2012 in GPCP, and 1998-2012 in TRMM) were
170 analyzed. Except in Section 4.1, all datasets were re-gridded to N96 (approximately
171 200-km resolution).

172

173 *2.3. Analysis methods*

174 In Section 3, we used Taylor's skill scores to evaluate the model performance.
175 Using pattern correlation (R) and standard deviation ratio (SDR; GCM's value
176 normalized by observed value), Taylor (2001) proposed a skill score (S) to evaluate the

177 GCM reproducibility,

$$178 \quad S = \frac{4(1 + R)^4}{(SDR + 1/SDR)^2(1 + R_0)^4}, R_0 \rightarrow 1 \dots (1).$$

179 . Higher S means higher reproducibility and if a GCM's performance is perfect (SDR→
180 1 and R→1), S = 1.

181 In Section 4.2, to investigate the resolution sensitivity of the intra-seasonal
182 variability, we define the BSISO index (21-61 day rainfall variability over 12-22°N,
183 70-95°E) and calculate the lag covariance of intra-seasonal rainfall variability (21-61
184 day band-passed) onto the BSISO index (Ajayamohan et al. 2009) to assess the
185 characteristics of northward propagation of BSISO during boreal summer (Figure 10).

186

187 **3. Resolution sensitivity of the ASM seasonal mean**

188 First, in the ASM seasonal mean, we compare the June-July-August (JJA)
189 climatology of precipitation and 850 hPa circulation in MRI-AGCM and MetUM. TL95
190 MRI-AGCM and N96 MetUM (Figure 1a and 1c) shows similar clockwise ASM
191 circulation at 850 hPa. However, their JJA precipitation pattern is quite different. In
192 TL95 MRI-AGCM, the precipitation maximum is over the Indian subcontinent and
193 South Asia, while in N96 MetUM, precipitation peaks in the equatorial Indian Ocean.
194 The difference between the AGCM biases (defined as 'AGCM minus CMAP') in
195 MRI-AGCM and MetUM is shown in Fig. 1b and 1d. Over the tropical Indian Ocean,
196 dry (wet) bias exists near the equator while wet and cyclonic (dry and anticyclonic) bias
197 appears over the northern hemisphere in MRI-AGCM (MetUM). Over the western

198 Pacific, cyclonic bias appears south of Japan in both MRI-AGCM and MetUM.

199 Next, we investigate the resolution sensitivity of precipitation over the south
200 Asian monsoon domain. In MRI-AGCM, dry bias over the tropical Indian Ocean is
201 improved (Fig. 2a-2c). For example, mean bias over the tropical Indian Ocean
202 (20°S - 20°N , 40 - 100°E) is 0.62 mm day^{-1} in TL95 and $-0.19 \text{ mm day}^{-1}$ in TL959 (Fig.
203 3a). On the other hand, the root mean square error (RMSE) (2.6 mm day^{-1} in TL95 and
204 3.1 mm day^{-1} in TL959) and the pattern correlation (0.80 in TL95 and TL959) are not
205 improved (Fig. 3b and 3c). This is probably because some places show improvements,
206 but others do not and may even degrade, so the scores do not change. In MetUM, the
207 meridional dipole bias over the tropical Indian Ocean (wet bias on the equator and dry
208 bias around 10 - 20°N) is improved (Fig. 2d-2f). However, on the basin-wide average
209 (20°S - 20°N , 40 - 100°E), mean bias (0.12 mm day^{-1} in N96 and 0.08 mm day^{-1} in N512),
210 RMSE (3.9 mm day^{-1} in N96 and 3.6 mm day^{-1} in N512), and pattern correlation (0.60
211 in N96 and 0.62 in N512) are not substantially improved (Fig. 3a-3c). Taylor's skill
212 scores also show that the scores are not improved in both MRI-AGCM and MetUM (Fig.
213 4a). Consistent with Johnson et al. (2016)'s results, the resolution sensitivity decreases
214 as resolution increases, so the resolution sensitivity of precipitation and 850 hPa
215 circulation is larger from TL95 to TL319 in MRI-AGCM (N96 to N216 in MetUM),
216 than from TL319 to TL959 in MRI-AGCM (N216 to N512 in MetUM) (Fig. 2).
217 Resolution sensitivity of precipitation is different between MRI-AGCM and MetUM,
218 with a pattern correlation of 0.22 (0.21 - 0.24 in Jackknife method) over the Indian Ocean
219 (20°S - 20°N , 40 - 100°E). In MRI-AGCM, large off-equatorial precipitation increase

220 appears both north and south of the equator. Particularly, a large precipitation increase
221 can be seen over the west of the Western Ghats and a cyclonic anomaly appears over the
222 Arabian Sea (Fig. 2a-2c). Precipitation also increases with resolution over the northern
223 Indian subcontinent and southern Indian Ocean around 0-10°S. In MetUM, this
224 off-equatorial precipitation increase with resolution is less significant and a
225 precipitation decrease appears over the equator (Fig. 2d-2f).

226 MRI-AGCM and MetUM share a similar resolution sensitivity of precipitation
227 over the western Pacific (Fig. 2c and 2f), with a pattern correlation of 0.48 (0.41-0.53 in
228 Jackknife method) over the western Pacific (0-40°N, 120-180°E). At higher resolution,
229 precipitation decreases over the northwestern Pacific and northern MC, while it
230 increases over East Asia (around 20-40°N) and the southern MC., An anticyclonic
231 circulation change associated with the precipitation decrease also appears over the
232 northwestern Pacific. Such anticyclonic circulation transports moisture from the tropics
233 to the East Asia and reinforces the Baiu-Meiyu front, which is consistent with previous
234 studies showing that high-resolution AGCMs can reproduce a more realistic
235 Baiu-Meiyu rainband (Kitoh and Kusunoki 2008). Taylor's skill scores (Fig. 4c)
236 quantitatively show that the scores over the Baiu-Meiyu front (20-40°N, 120-150°E) are
237 improved in both MRI-AGCM (0.20 in TL95 and 0.50 in TL959) and MetUM (0.20 in
238 N96 and 0.27 in N512).

239 In order to investigate the resolution sensitivity of precipitation, we analyze the
240 moisture budget at different resolutions (Figures 5 through 7). Fig. 5a and 5e show JJA
241 climatology of TL95 MRI-AGCM and N96 MetUM moisture transport and

242 convergence. The clockwise moisture transport of ASM occurs in both models. On the
243 other hand, moisture convergence maximum over the Indian subcontinent appears in
244 MRI-AGCM, while convergence stays over the equatorial Indian Ocean in MetUM.
245 Over the southern MC, MetUM shows a large increase in moisture convergence (Fig.
246 5h), which is less significant in MRI-AGCM (Fig. 5d). Moisture budget analysis also
247 exhibits these features (Fig. 6d). Compared to the moisture convergence changes,
248 surface evaporation increases only slightly with resolution over the MC in MRI-AGCM,
249 while it does not change in MetUM (Fig. 6c). Over the northern Indian Ocean, similar
250 to the pattern of precipitation change (Fig. 2), a large moisture convergence increase
251 occurs over the west of the Western Ghats and Northern Indian Ocean in MRI-AGCM
252 (Fig. 5d), while this is less significant in the MetUM where increased divergence
253 appears over the equator (Fig. 5h). It should be noted that westward moisture flux
254 anomaly appears over the South China Sea and Bay of Bengal in both models, which is
255 probably related to the anticyclonic circulation anomaly seen in Fig. 2 and the decreased
256 diabatic heating in the west Pacific.

257 Johnson et al. (2016) showed in the MetUM that decreasing precipitation over
258 the northern Maritime Continent/west Pacific and increasing precipitation over the
259 southern Maritime Continent were related to changes in moisture flux convergence.
260 Following their study, we applied an area-integrated moisture budget analysis over their
261 Maritime Continent regions and show the results in Figure 6b-6d. In MRI-AGCM, the
262 precipitation decrease (and moisture convergence decrease) with resolution is consistent
263 with MetUM over the northern box. In MRI-AGCM (MetUM), precipitation decreases

264 from 9.67 mm day⁻¹ in TL95 (7.73 mm day⁻¹ in N96) to 8.73 mm day⁻¹ in TL959 (6.22
265 mm day⁻¹ in N512). Moisture convergence in MRI-AGCM (MetUM) also decreases
266 with increasing resolution: 5.05 mm day⁻¹ in TL95 (3.01 mm day⁻¹ in N96) to 4.11 mm
267 day⁻¹ in TL959 (1.85 mm day⁻¹ in N512). In contrast, precipitation and moisture
268 convergence tendencies in southern box are different between these AGCMs. In MetUM,
269 the precipitation increase from 5.5 mm day⁻¹ in N96 to 6.5 mm day⁻¹ in N512 is mainly
270 due to an increase in moisture convergence (0.5 mm day⁻¹ in N96 and 1.5 mm day⁻¹ in
271 N512). On the other hand, precipitation (5.2 mm day⁻¹ in TL95 and 5.3 mm day⁻¹ in
272 TL959) and moisture convergence (0.3 mm day⁻¹ in TL95 and TL959) are not sensitive
273 to resolution in MRI-AGCM.

274 To examine the difference in the resolution sensitivity of precipitation in the
275 Indian Ocean, we also perform a moisture budget analysis for the regions outlined in
276 Fig. 6a. Over the southern Indian Ocean (around 60-90°E, 0-10°S), the precipitation
277 increase is more significant in MRI-AGCM than in MetUM. Over the Northern Indian
278 Ocean (Fig. 6e-6g), increasing precipitation (and increasing moisture convergence) is
279 clear in MRI-AGCM. High-resolution MetUM also shows a slight precipitation and
280 moisture convergence increase in the northern box. However, there are large
281 inter-model differences in the low-resolution climatology in these two models. Moisture
282 converges (diverges) over the northern (southern) region in MRI-AGCM while the
283 opposite occurs in MetUM (Fig. 6e-6g).

284 To investigate the origin of the different behavior of moisture budget over the
285 southern MC, Figure 7 shows averaged moisture flux into and out of the

286 southern/northern MC and equatorial IO boxes (Fig. 7a). In MetUM, the increase of
287 moisture in finer-resolution over the southern MC is mainly caused by the decrease of
288 cross equatorial moisture flux (Fig. 7e-7g). On the other hand, in MRI-AGCM, change
289 of cross equatorial moisture flux is smaller than in MetUM (Fig. 7b-7d). Furthermore,
290 difference in the moisture supply across 160°E and moisture loss across 90°E seems
291 important. Across 160°E, moisture supply decreases (increases) in MRI-AGCM
292 (MetUM) with higher resolution, which partly contributes to the different resolution
293 sensitivity of moisture convergence between two AGCMs over the southern MC box.

294 This difference over the southern MC may be related to differences in the
295 southern IO. In MRI-AGCM, budget of southern equatorial IO box shows distinct
296 decrease of cross equatorial moisture flux, which causes increase of moisture
297 particularly from TL95 to TL319 (Fig. 7c). Moisture flux across 90°E increases
298 (decreases) moisture over the southern equatorial IO (southern MC).

299

300 **4. What contributes to the resolution sensitivity of the ASM seasonal mean?**

301 The previous section motivates a question: why is the resolution sensitivity of
302 precipitation similar over the MC and west Pacific, but different over the Indian Ocean
303 and India in the two models? To answer this, we examine possible mechanisms driving
304 the resolution sensitivity, including better resolution of orography, better resolution of
305 intraseasonal/synoptic variability and the resolution sensitivity of the meridional
306 temperature gradient that drives the monsoon.

307

308 *4.1. Orography*

309 High-resolution AGCMs are able to represent steep topography over south Asia
310 (Figure 8) and MC (Figure 9), which may affect the simulation of precipitation and
311 circulation. In both MRI-AGCM and MetUM, sharper rainfall peaks appear on the
312 western side of mountains at higher resolutions (Fig. 8b and 8d). The monsoon westerly
313 wind intersects the Western Ghats (75°E), Arakan Yoma (90-95°E), Bilauktang (100°E),
314 Annam Cordillera (110°E), and Cordillera Central (120°E). Precipitation is clearly
315 intensified around these mountains in TL959 and TL319 in MRI-AGCM (N512 and
316 N216 in MetUM), while TL95 MRI-AGCM and N96 MetUM cannot represent such
317 steep orography and the precipitation is smoothed (Fig. 8). Orography-induced
318 precipitation can be also seen in the MC. Fig. 9 shows that rainfall increases over the
319 mountains of New Guinea in the high-resolution AGCMs (around 5°S, Fig. 9b and 9d).
320 Although there is observation uncertainty, AGCMs are too wet over the land because of
321 the orography (Fig. 9b and 9d). The spatial distribution of precipitation over this area is
322 probably better at high resolution, but precipitation is more intense because of the
323 steepness of the mountains, causing a larger drag. High-resolution observation (TRMM)
324 also shows orography-induced rainfall, which can not be reproduced in
325 coarse-resolution AGCM (Fig. 8 and 9).

326 As mentioned in Section 3, in both models, rainfall decreases north of the
327 Maritime Continent. Johnson et al. (2016) hypothesized that increased resolution of the
328 orography of the Maritime Continent and Indochina created this precipitation decrease
329 through increasing moisture convergence over the orography, which reduces the

330 westerly and southerly moisture transport into the west Pacific. As mentioned in Section
331 3, the resolution sensitivity of westerly moisture flux into the northern Maritime
332 Continent is larger in the MRI-AGCM than the resolution sensitivity of southerly
333 moisture flux. In the MRI-AGCM, the change in westerly moisture flux could be related
334 to the increased rainfall in the Indian Ocean basin. The lack of a precipitation increase
335 over the southern Maritime Continent in MRI-AGCM is likely due to the increase in
336 moisture convergence over the southern Indian Ocean, which is not present in MetUM.
337 It is not clear whether the same mechanisms are leading to the decrease in precipitation
338 in the west Pacific in both GCMs, and this would be an interesting subject for future
339 sensitivity experiments.

340

341 *4.2. Synoptic and Intra-seasonal variations over India*

342 Intra-seasonal variability can be decomposed into three modes: BSISO (21-61
343 day; Yasunari 1980, Jiang et al. 2004, Ajayamohan et al. 2009), biweekly-mode (9-21
344 day; Murakami 1976, Krishnamurti and Ardanuy 1980, Annamalai and Slingo 2001),
345 and LPS (3-9 day; Mak 1987, Goswami et al. 2003). The lead-lag covariance of
346 precipitation over 70-95°E onto the BSISO index exhibits the characteristics of
347 northward propagation of BSISO during boreal summer (Figure 10). The northward
348 propagation with about 50-day period is clear in both MRI-AGCM and MetUM (Fig.
349 10a-10d), consistent with previous studies (Ajayamohan et al. 2009). In MetUM, there
350 is little difference in the BSISO propagation between N96 (Fig. 10c) and N512 (Fig.
351 10d). In MRI-AGCM, BSISO rainfall in TL959 (Fig. 10b) shifts slightly northward

352 (around 20°N) compared to TL95 (Fig. 10a), but there is little change in amplitude.
353 Therefore, the BSISO activity has very little resolution sensitivity in either GCM.

354 Another possible driver of the resolution sensitivity of rainfall and circulation is
355 synoptic variability. For example, high-resolution AGCMs often improve the
356 representation of LPS over the northern Indian Ocean (Stowasser et al. 2009, Sabin et al.
357 2013, Johnson et al. 2016). Figure 11 shows the standard deviation of
358 synoptic-timescale (3-9 day band-passed) rainfall variability. The intra-seasonal
359 variability over central India increases substantially in the high-resolution (TL959)
360 MRI-AGCM (Fig. 11c). In N512 MetUM, synoptic timescale variability increases
361 (decreases) slightly over Bangladesh (ocean, e.g. Bay of Bengal), which is consistent
362 with the shift of the synoptic systems (Fig. 11f), shown using LPS tracking in Johnson
363 et al. (2016). The larger increase synoptic variability in MRI-AGCM than in MetUM
364 partly explains why the resolution sensitivity of precipitation is different in the two
365 GCMs over India and the Indian Ocean. An increase in LPS increases condensation
366 heating over India and the atmospheric response to this heating can increase the
367 moisture transport to the continent. These processes may act as a positive feedback to
368 enhance the precipitation. Observed daily precipitation (GPCP, 1997-2012) in Figure 12
369 shows that too much (little) synoptic rainfall variability appears over the southern
370 (northern) subcontinent in TL95 MRI-AGCM (Fig. 12b) while synoptic rainfall
371 variability is generally too small over India in N96 MetUM (Fig. 12c). The resolution
372 sensitivity of LPS (Fig. 11), has the opposite sign of the bias, particularly in the
373 MRI-AGCM, and consequently improves the bias of synoptic rainfall variability over

374 India.

375

376 *4.3. Upper tropospheric warming*

377 Meridional thermal gradient (MTG) in the upper troposphere is a major driver of
378 the south Asian monsoon (e.g. Li and Yanai 1996, Xavier et al. 2007). In boreal summer,
379 warming over the south Asian continent causes reversal of the MTG and can be used to
380 define a south Asian monsoon (SAM) onset date. To investigate the resolution
381 sensitivity of the upper tropospheric warming, the resolution sensitivity of the 200-600
382 hPa tropospheric thickness is shown in Figure 13. As resolution increases, tropospheric
383 cooling appears over the tropics (from 30°S to 30°N) in MRI-AGCM and over the
384 Indo-Pacific in MetUM. Over the northwestern Pacific (NWP) and South China Sea
385 (SCS) region (0-20°N, 105-180°E), 200-600 hPa thickness change is larger in
386 MRI-AGCM (-23.08 m in MRI-AGCM, while -5.02 m in MetUM, equal to 21.8% of
387 MRI-AGCM). Such cooling seems to originate from the NWP, consistent with rainfall
388 decrease and anti-cyclonic anomaly. Tropospheric cooling spreads into the entire tropics
389 zonally, and this enhances land-sea thermal contrast over the South Asian continent.
390 Such thermal contrast change is larger in MRI-AGCM (Fig. 13a-c) than in MetUM (Fig.
391 13d-f).

392 To diagnose whether the resolution sensitivity of heating over the NWP is
393 important for this tropospheric cooling response, we investigate the Matsuno-Gill like
394 response (Matsuno 1966, Gill 1980) to regional heating using a linear baroclinic model
395 (LBM), similar to Ogata (2013). LBMs are derived from the linearized atmospheric

396 primitive equation using a sigma coordinate system. The LBM used here has a rest
397 background state (i.e. zero background velocity), a zonally averaged equatorial thermal
398 structure (i.e. uniform stratification) derived from JRA-55, and a resolution of 2.5°
399 horizontally with 14 vertical levels. Heating was estimated for each model individually
400 from the precipitation pattern seen in Fig. 2c and 2f, and is shown in Figure 14 a and c.
401 To define the vertical profile, a heating maximum of 0.47 K day⁻¹ per 1 mm day⁻¹ is
402 assumed at 600 hPa and the heating reaches zero at 200 and 1000 hPa. Figure 14 shows
403 the response to the change in heating when resolution is increased in the MRI-AGCM
404 and MetUM. In MRI-AGCM and the MetUM, response to western Pacific forcing
405 (30°S-30°N, 120-180°E in Fig. 14a, c) contributes to tropospheric cooling on 200-600
406 hPa due to the rainfall decrease (Fig. 14b, d), but in the MetUM the response is much
407 weaker. It should be noted that key features of tropospheric cooling in Fig. 13 (e.g.
408 larger tropospheric cooling in MRI-AGCM) cannot be reproduced in this linear model
409 by the Indian Ocean forcing (not shown). Particularly the effect of warming by the
410 Indian Ocean forcing may be overestimated.

411 Figure 15 shows the seasonal evolution of MTG, as defined by Xavier et al.
412 (2007): the difference between the 200-600 hPa upper tropospheric thickness (units: m)
413 averaged over south Asia (5-35°N, 40-100°E) and the equatorial Indian ocean
414 (15°S-5°N, 40-100°E). In both MRI-AGCM and MetUM, the MTG changes sign from
415 negative to positive between May and June. During May-June, the MTG is stronger in
416 TL959 MRI-AGCM than in TL95 MRI-AGCM, and similarly MTG in N512 MetUM is
417 stronger than in N96 MetUM. Interestingly, resolution sensitivity is comparable in

418 magnitude to the inter-model difference (Fig. 15). During August-September, in contrast,
419 there is little resolution sensitivity and the inter-model difference is larger. In reanalysis
420 (JRA-55), sign reversal of MTG starts earlier and the MTG is larger throughout the
421 season. This means the higher-resolution GCMs are more accurate (Fig. 15) than the
422 low-resolution. The stronger MTG in the high-resolution MRI-AGCM is likely related
423 to the increasing SAM precipitation. MTG is also linked to the easterly vertical wind
424 shear between U850 and U200, which contributes to synoptic variability through an
425 internal instability condition (Charney and Stern 1962, Shukla 1978). The larger MTG
426 in the high-resolution MRI-AGCM may consequently be related to the increase in
427 synoptic variability seen in Fig. 11 and the associated with increased precipitation from
428 monsoon LPS.

429

430 **5. Summary and discussion**

431 In this study, the resolution sensitivity of the ASM in two AGCMs, MRI-AGCM
432 and MetUM, is investigated and compared. We compare the MetUM series at N96
433 (200-km mesh on the equator), N216 (90-km mesh) and N512 (40-km mesh), with the
434 MRI-AGCM series at TL95 (180-km mesh on the equator), TL319 (60-km mesh) and
435 TL959 (20-km mesh).

436 Both MRI-AGCM and MetUM share a similar precipitation decrease over the
437 western Pacific with increasing resolution. Associated with the precipitation decrease,
438 low-level anti-cyclonic circulation change appears over the northwestern Pacific. On the
439 other hand, over the Indian Ocean, the resolution sensitivity of precipitation is quite

440 different between the two AGCMs. In MRI-AGCM, a large precipitation increase
441 appears off the equator, while such off-equatorial precipitation increase is less
442 significant and precipitation decreases over the equator in MetUM. The resolution
443 sensitivity is not a clear improvement on the mean state in either GCM, and the
444 resolution sensitivity is not proportional to the GCM bias. To examine the difference in
445 the resolution sensitivity of precipitation, we also performed a moisture budget analysis.
446 Over the Indian Ocean, there are large inter-model differences in the low-resolution
447 climatology in these two models. Moisture converges (diverges) over the northern
448 (southern) region in MRI-AGCM while the opposite occurs in MetUM. Over the
449 Maritime Continent, decrease of cross equatorial moisture flux which is important for
450 precipitation in MetUM (Johnson et al. 2016) is small in MRI-AGCM.

451 As possible causes of the resolution sensitivity of the ASM, orographic effect,
452 intra-seasonal variability, and changes to the meridional temperature gradient have been
453 considered. Both high-resolution AGCMs (TL959 and N512) can represent steep
454 topography, which anchors rainfall pattern over south Asia and the Maritime Continent.
455 Furthermore, increase of synoptic rainfall variability by low pressure systems at TL959
456 and N512 seems to contribute to the rainfall increase over the land, but is much more
457 significant in the MRI-AGCM. Additionally, an upper-tropospheric cooling over the
458 tropics, linked to rainfall and diabatic heating changes over the west Pacific (Section
459 4.3), causes a stronger meridional thermal gradient at high resolution, particularly in
460 MRI-AGCM, and improves the seasonal evolution of the MTG. The larger resolution
461 sensitivity of LPS and the MTG in the MRI-AGCM than the MetUM may be related,

462 and likely contribute to the larger resolution sensitivity of Indian precipitation in the
463 MRI-AGCM.

464 There are, however, large differences in circulation and precipitation over the
465 Indian Ocean between MRI-AGCM and MetUM. On the equatorial Indian Ocean, there
466 is a negative rainfall anomaly in MRI-AGCM. In contrast, a positive rainfall anomaly
467 appears around 10-20°N (Figure 16). These results suggest that the anti-symmetric
468 meridional dipole anomaly over the Indian Ocean generates a clockwise circulation and,
469 in presence of a positive feedback, the westerly response to the diabatic heating around
470 10-20°N further generates a condensation heating through moisture supply over south
471 Asia. Such mean state difference in the Indian monsoon between MRI-AGCM and
472 MetUM may cause the different resolution sensitivity through the interaction with
473 topography (e.g. larger rainfall increase in MRI-AGCM than in MetUM on the western
474 side of the mountains; Fig. 2 and 8), and synoptic intra-seasonal variability by moist
475 instability (e.g. different patterns in synoptic rainfall variability between MRI-AGCM
476 and MetUM; Fig. 11). It should be noted that the inter-model difference becomes
477 smaller at high resolution over the equatorial Indian Ocean (Fig. 16b and 16c).

478 In Section 4.1 and 4.2, we discussed orographic and non-orographic effects on
479 resolution sensitivity. However, quantitative evaluation of their effect is still unclear.
480 Sensitivity experiments would help quantify the relative importance of orographic and
481 non-orographic effects. In MetUM, for example, previous study has reported that annual
482 mean precipitation over the MC is sensitive to the representation of coastal lines
483 through mean circulation change (Schiemann et al. 2014).

484 Our findings have highlighted some common features in the resolution
485 sensitivity of the ASM simulation between the MetUM and the MRI-AGCM. However,
486 we have also highlighted some major differences, which are likely due to the differences
487 in the model physics schemes, which also cause different model mean biases. These
488 results highlight the necessity of multi-model assessments regarding the role of
489 resolution in climate simulations, such as the upcoming EU Horizon 2020
490 PRIMAVERA (PRocess-based climate sIMulation: AdVances in high-resolution
491 modelling and European climate Risk Assessment) project.

492

493

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514

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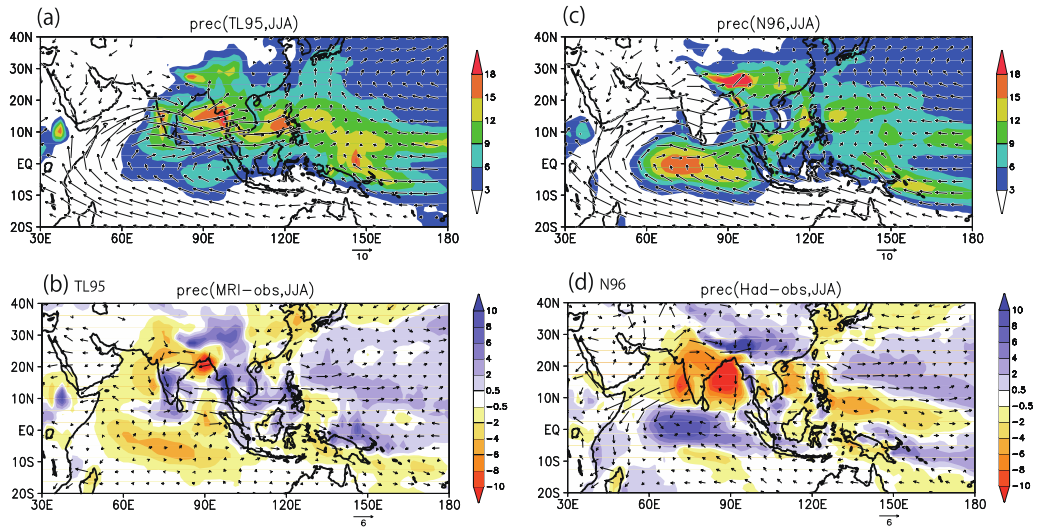
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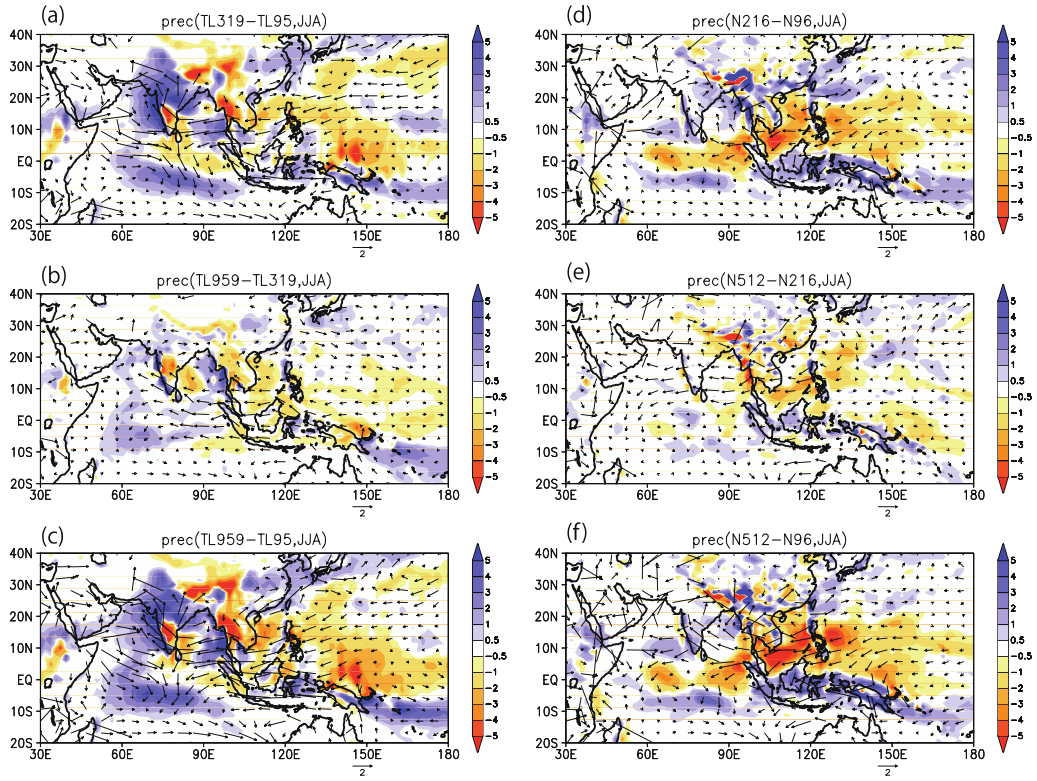
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1
 2 Figure 1: JJA precipitation (shaded, units: mm day⁻¹) and horizontal 850 hPa wind
 3 (vector, units: m s⁻¹) in (a) TL95 MRI-AGCM and (c) N96 MetUM. Difference between
 4 (b) TL95 MRI-AGCM, (d) N96 MetUM and CMAP observed precipitation / JRA-55
 5 reanalysis wind.

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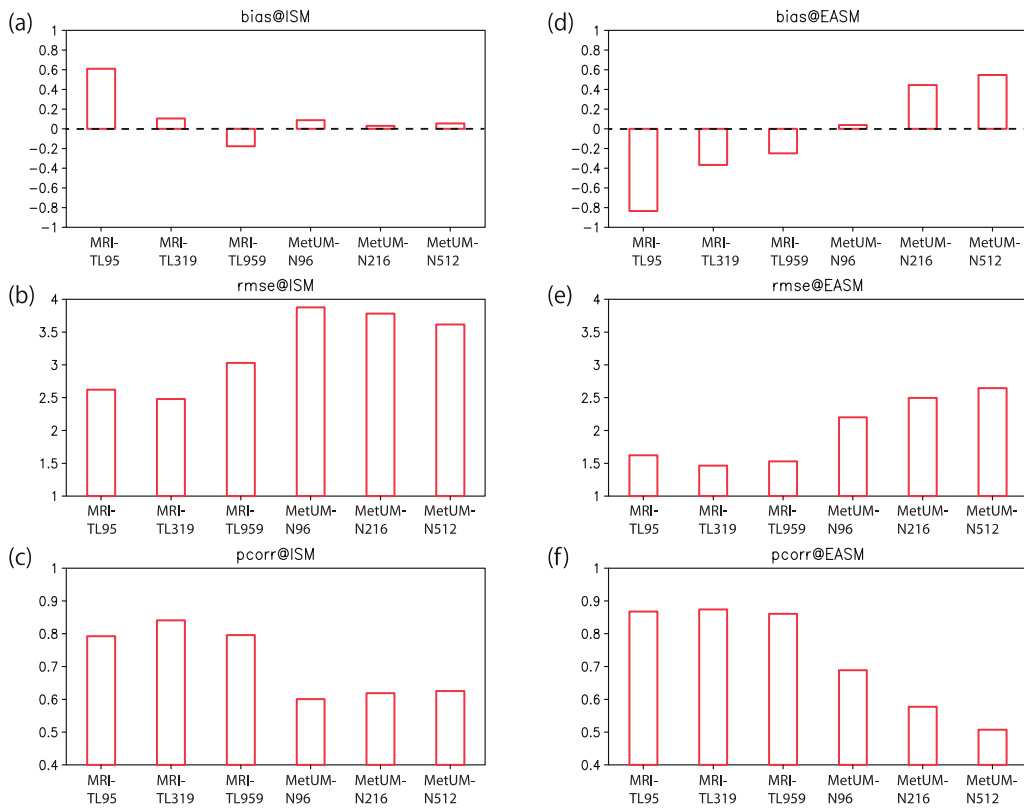


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11 Figure 2: Resolution sensitivity of JJA precipitation (shaded, units: mm day^{-1}) and
 12 horizontal 850 hPa wind (vector, units: m s^{-1}) : (a) TL319-TL95, (b) TL959-TL319, and
 13 (d) TL959-TL95 MRI-AGCM. Right panels are same as (a)-(c) but for (d) N216-N96,
 14 (e) N512-N216, and (f) N512-N96 MetUM.

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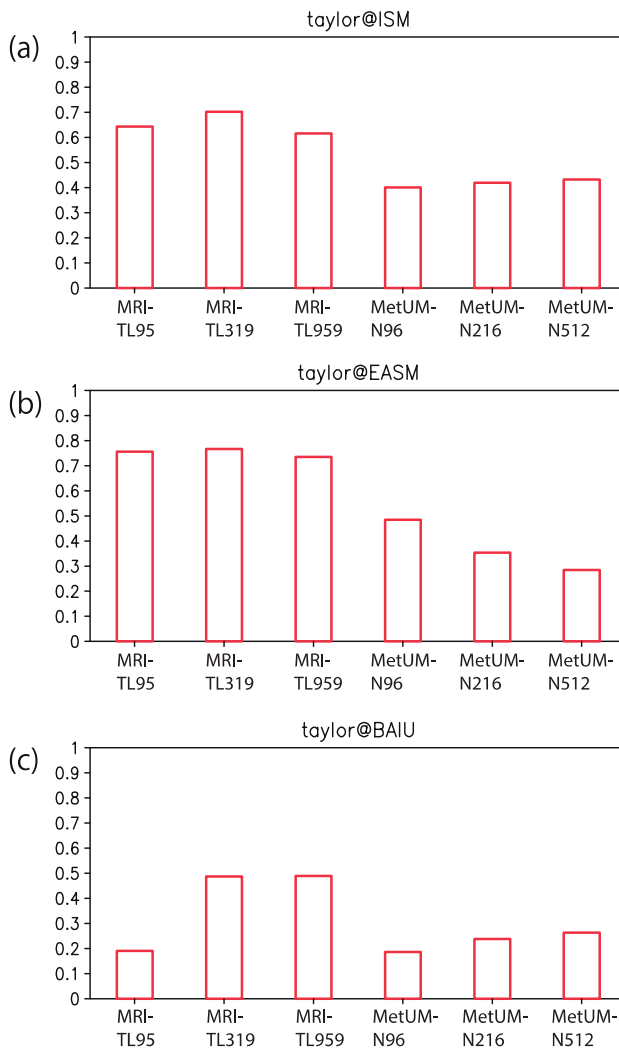


17

18 Figure 3: Area average over the tropical Indian Ocean (20°S-20°N, 40-100°E) of (a)
 19 mean JJA precipitation bias (units: mm day⁻¹), (b) RMSE, and (c) pattern correlation.
 20 (d)-(f) are same as (a)-(c) but for the western Pacific (0-40°N, 120-180°E). All datasets
 21 are re-gridded to CMAP resolution (2.5 degree). In (c) and (f), p-value at R=0.4 is p <
 22 0.00001.

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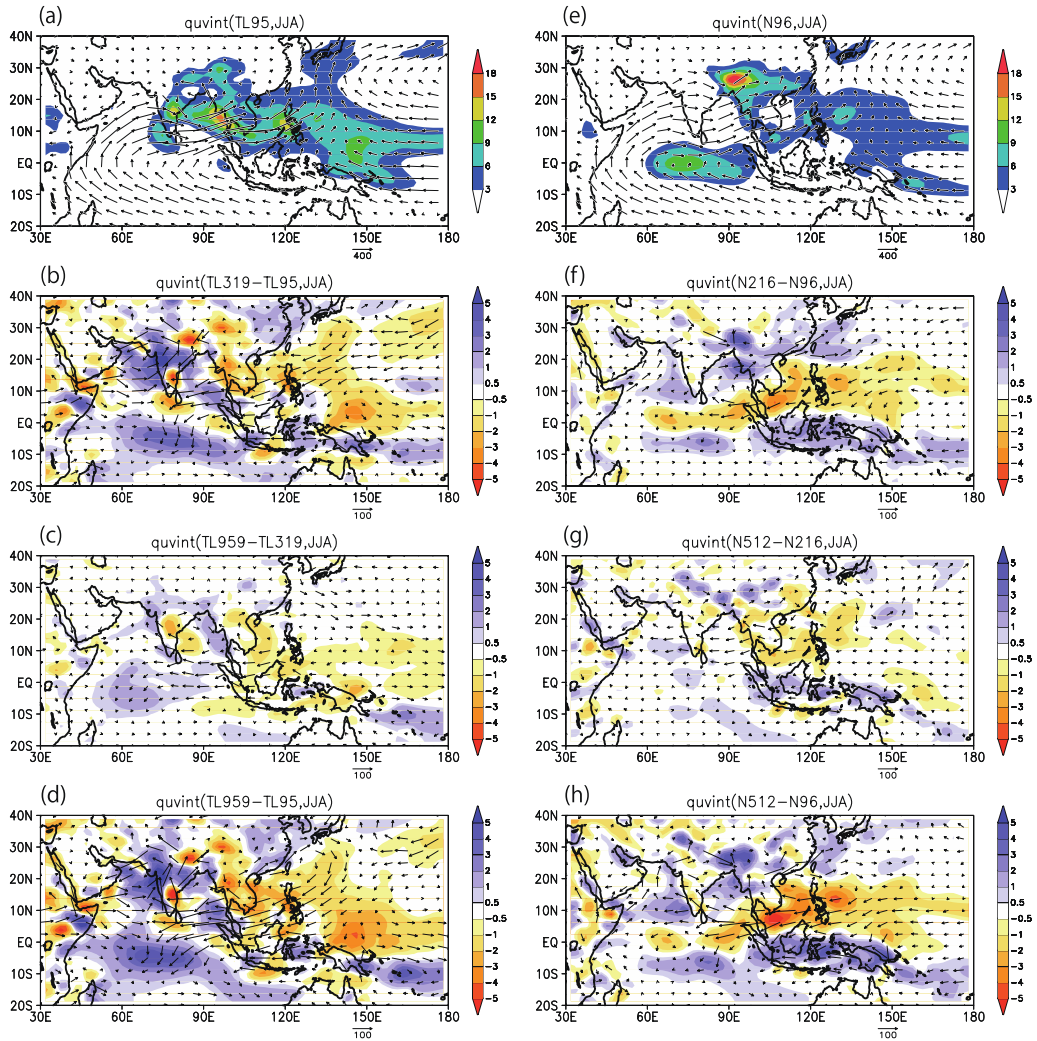


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26 Figure 4: Taylor's skill scores (Taylor 2001) of JJA precipitation over (a) the tropical
 27 Indian Ocean (20°S-20°N, 40-100°E), and (b) the western Pacific (0-40°N, 120-180°E),
 28 and (c) Baiu-Meiyu front (20-40°N, 120-150°E). All datasets are re-gridded to CMAP
 29 resolution (2.5 degree).

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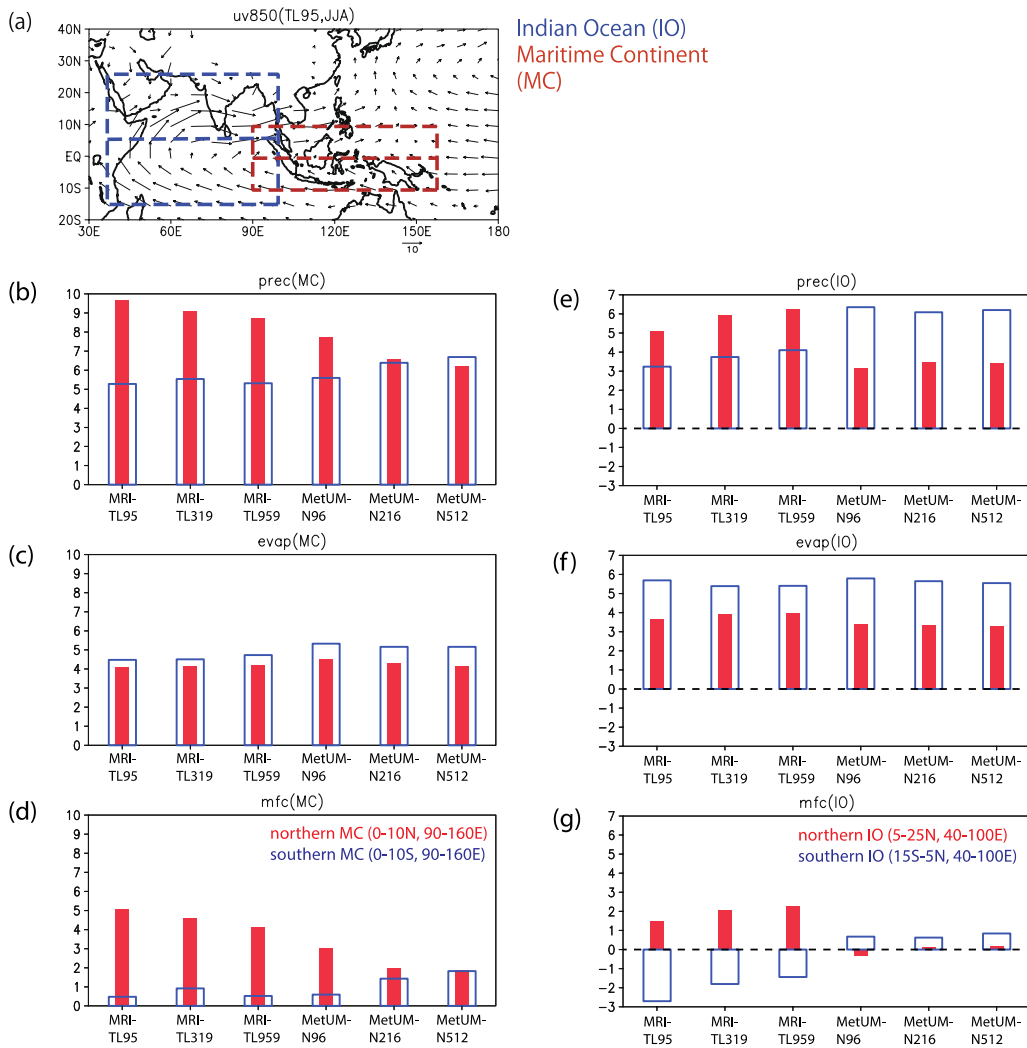


32

33 Figure 5: JJA vertical-integrated moisture flux (vector, units: $\text{kg m}^{-1}\text{s}^{-1}$) and its
 34 convergence (shaded, units: mm day^{-1}) in (a) TL95 MRI-AGCM, (b) TL319-TL95, (c)
 35 TL959-TL319, and (d) TL959-TL95. (e)-(h) are same as (a)-(d) but for (e) N96 MetUM,
 36 (f) N216-N96, (g) N512-N216, and (d) N512-N96.

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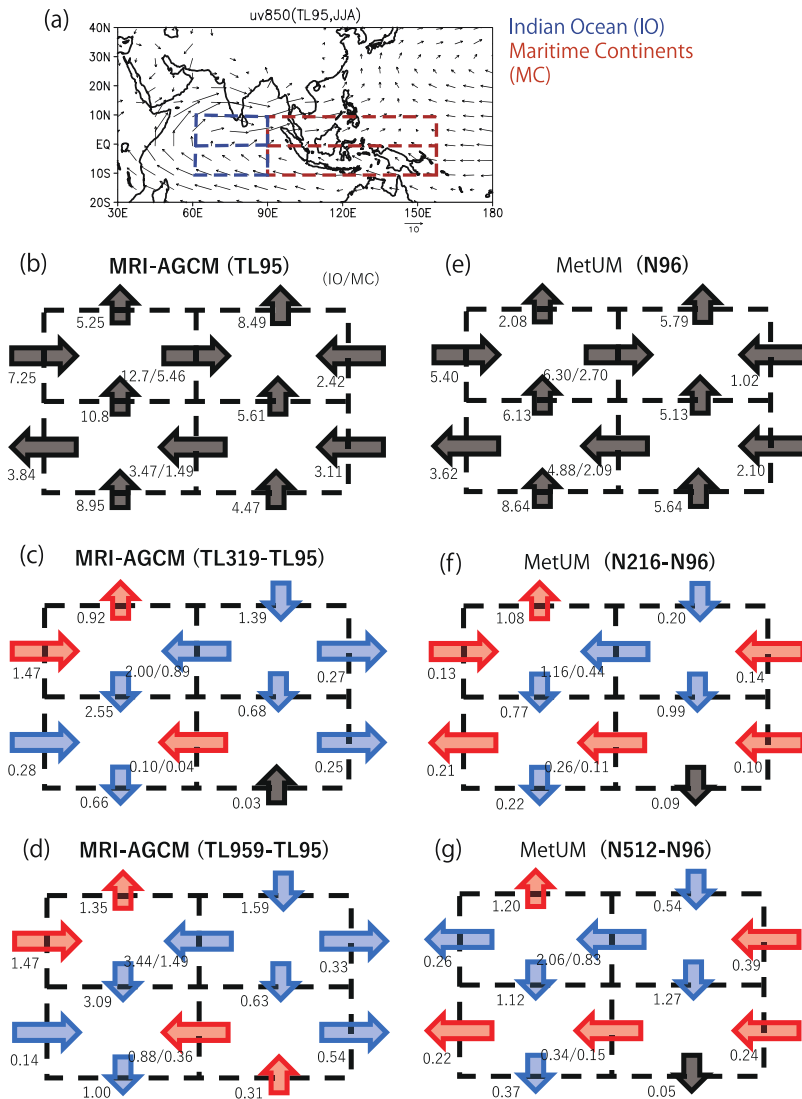
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39

40 Figure 6: Resolution sensitivity of the JJA moisture budget over the regions outlined in
 41 (a) (units: mm day^{-1}): (b) precipitation, (c) surface evaporation, and (d) moisture flux
 42 convergence. Red and blue bars correspond to the northern ($0-10^{\circ}\text{N}$, $90-160^{\circ}\text{E}$) and
 43 southern ($0-10^{\circ}\text{S}$, $90-160^{\circ}\text{E}$) MC box regions, respectively. (e)-(g) are same as (b)-(d)
 44 for the Indian Ocean (IO) box region. Red and blue bars correspond to the northern
 45 ($5-25^{\circ}\text{N}$, $40-100^{\circ}\text{E}$) and southern ($15^{\circ}\text{S}-5^{\circ}\text{N}$, $40-100^{\circ}\text{E}$) IO box regions, respectively.

46



47

48 Figure 7: Resolution sensitivity of the JJA moisture flux across the borders shown in (a)

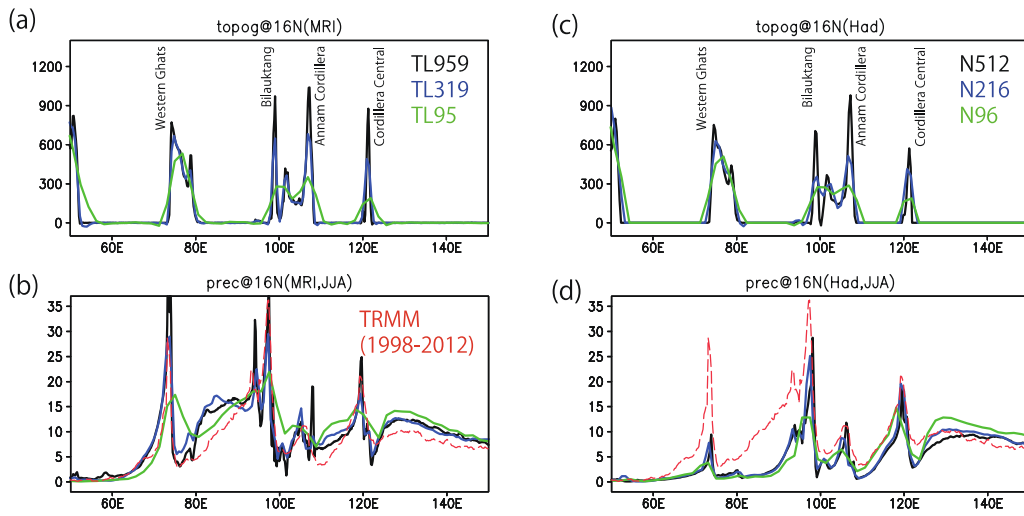
49 (units: mm day^{-1}). Since this is an area average quantity there are two values at the

50 borders between the Indian Ocean regions and Maritime Continent regions.: (b) TL95,

51 (c) TL319-TL95, and (d) TL959-TL95 MRI-AGCM. (e) N96, (f) N216-N96, and (g)

52 N512-N96 MetUM. Red (blue) arrows shows increase (decrease) of moisture flux.

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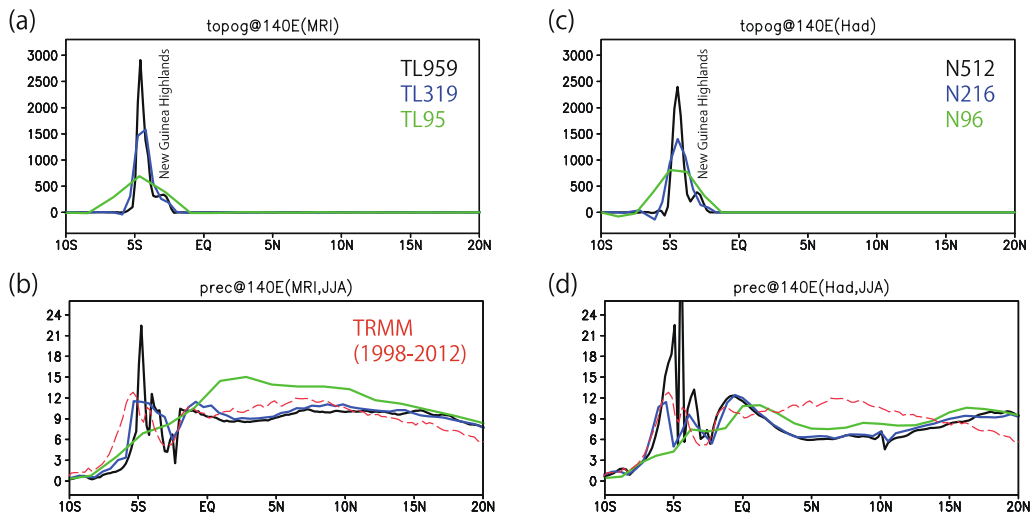


54

55 Figure 8: Zonal section at 16°N showing the resolution sensitivity of topography (units:
 56 m) in MRI-AGCM (a) and MetUM (c), and JJA precipitation (units: mm day⁻¹) in
 57 MRI-AGCM (b) and MetUM (d).

58

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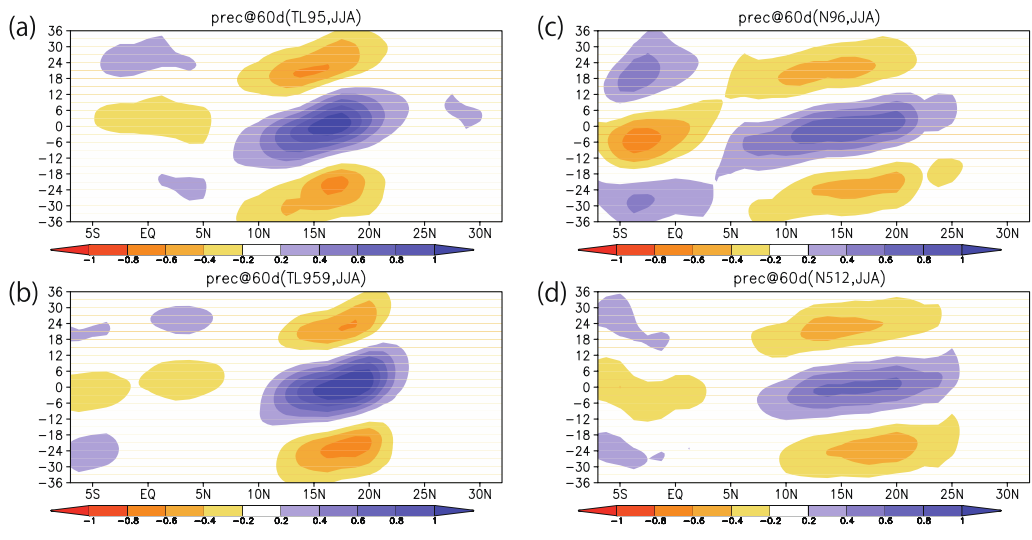


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61 Figure 9: Same as Fig. 8, for a meridional section at 140°E.

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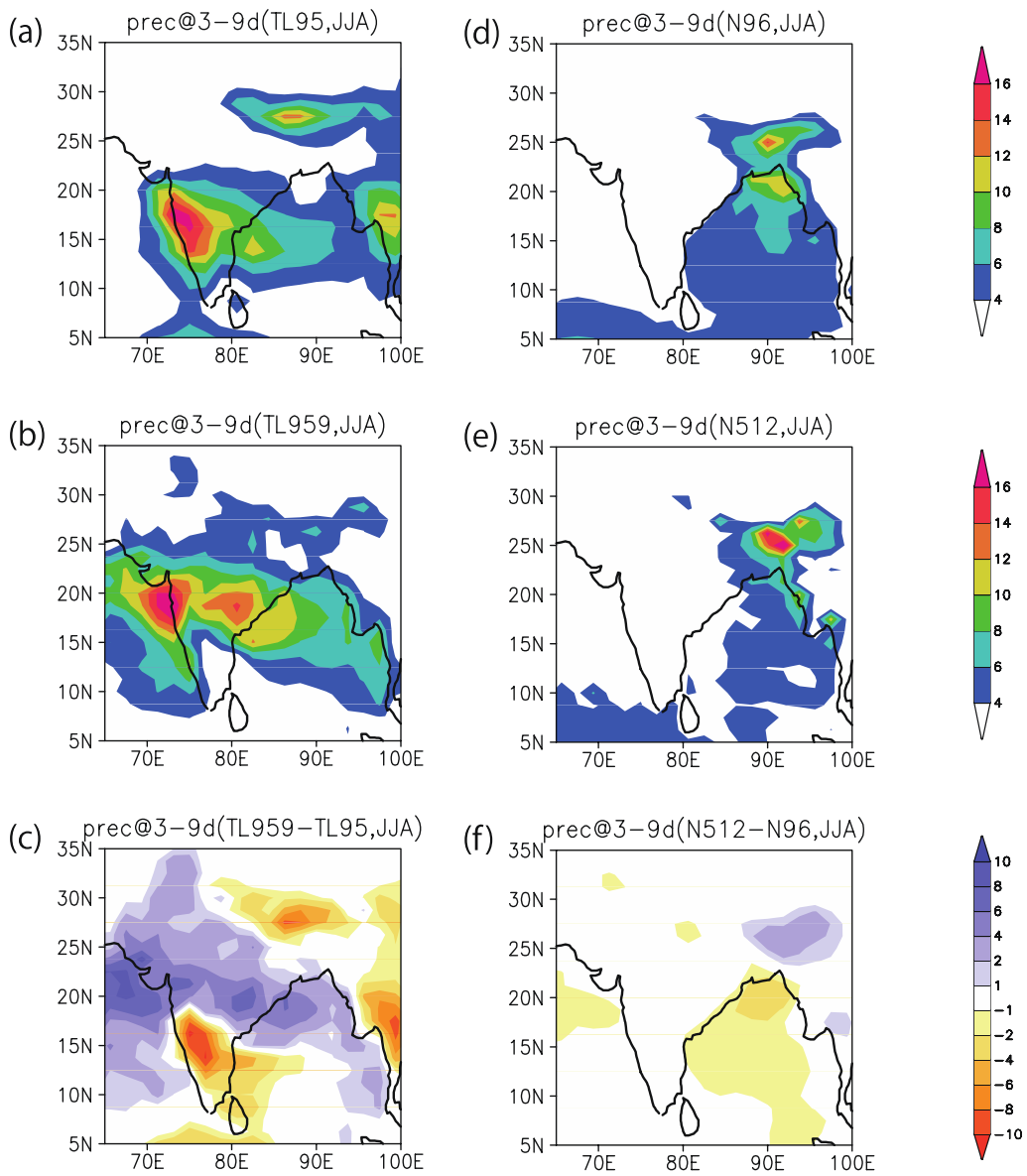


64

65 Figure 10: Latitude-time sections of lag covariance of intra-seasonal rainfall variability
 66 onto BSISO index (21-61 day rainfall variability over 12-22°N, 70-95°E during
 67 June-August) in (a) TL95 MRI-AGCM3, (b) TL959 MRI-AGCM3, (c) N96 MetUM,
 68 and (d) N512 MetUM. Units are mm day⁻¹. The covariance fields were normalized by
 69 the standard deviation of BSISO index.

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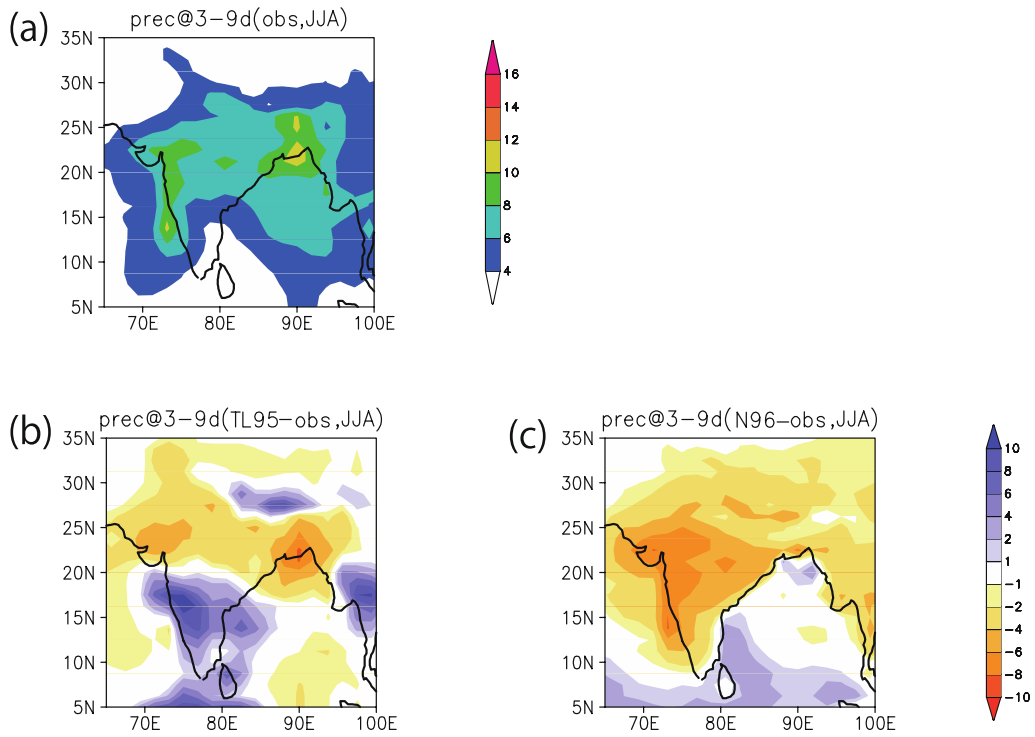
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73 Figure 11: (a) Standard deviation of synoptic-scale (3-9 day band-passed) rainfall
 74 variability during JJA (shaded, units: mm day⁻¹) in (a) TL95, (b) TL959, and (c) its
 75 difference (TL959-TL95). (d)-(f) is same as (a)-(c) but for MetUM: (d) N96, (e) N512,
 76 and (f) its difference (N512-N96).

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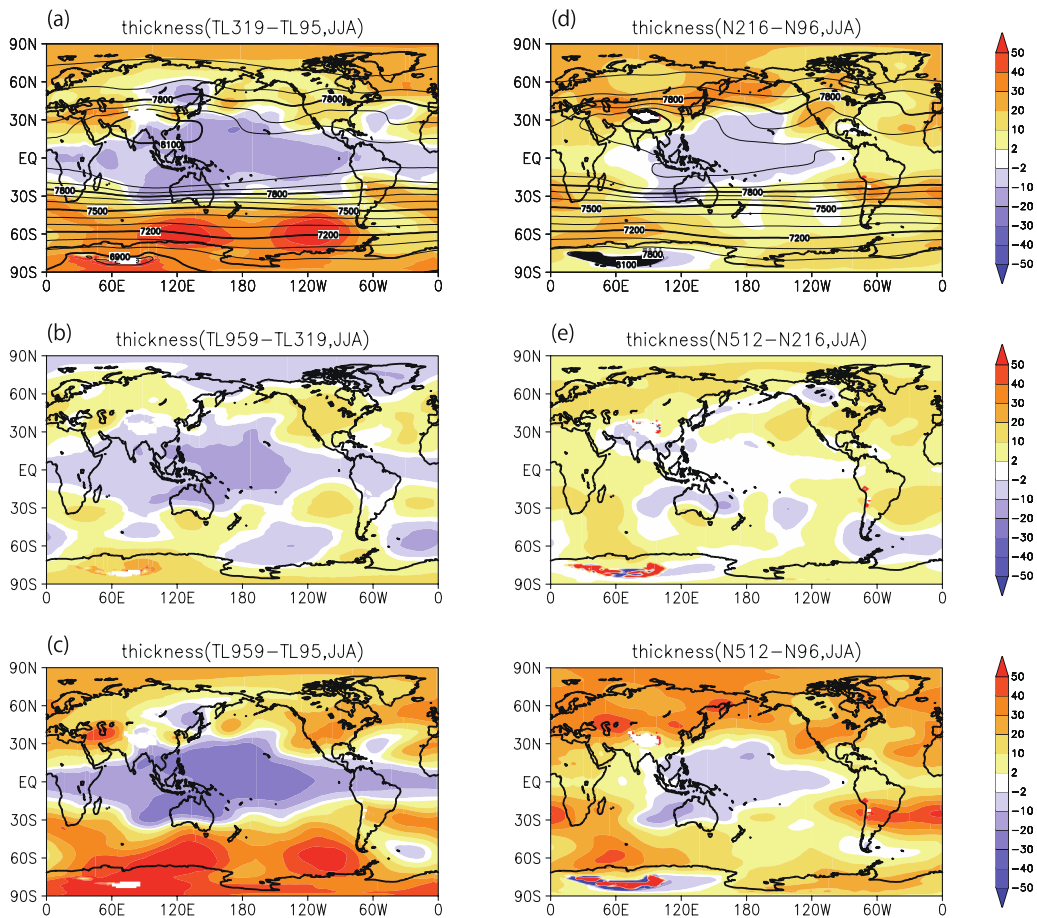
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79 Figure 12: Same as Fig. 11 but for (a) GPCP daily observation (1997-2012), (b) TL95

80 MRI-AGCM minus GPCP, and (c) N96 MetUM minus GPCP.

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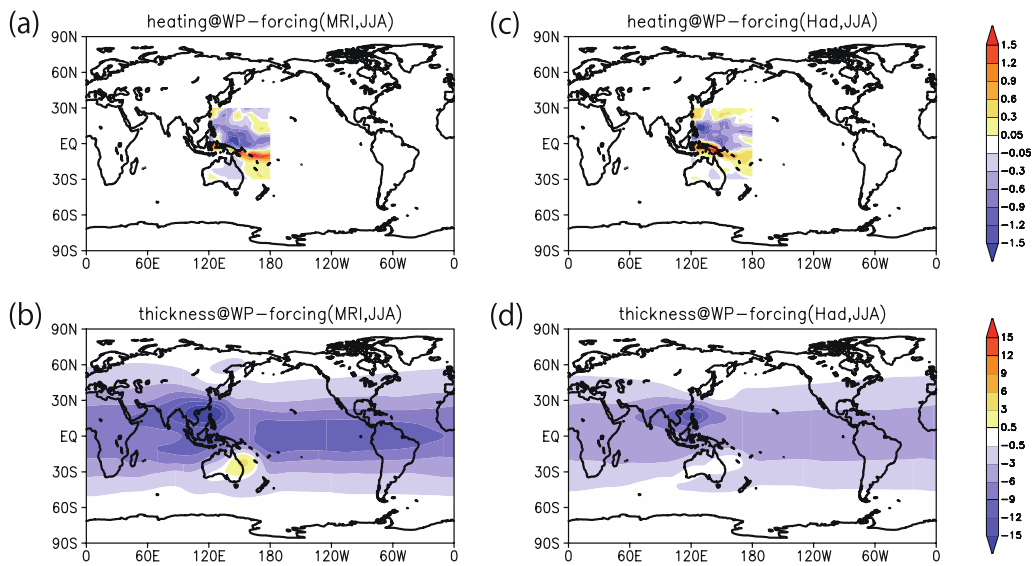


83

84 Figure 13: Differences in JJA 200-600 hPa upper tropospheric thickness (shaded, units:
 85 m): (a) TL319-TL95, (b) TL959-TL319, and (c) TL959-TL95 in MRI-AGCM. (d)-(f)
 86 are same as (a)-(c) but for (d) N216-N96, (e) N512-N216, and (f) N512-N96 in MetUM.
 87 Contours in (a) show upper tropospheric thickness in TL95 MRI-AGCM (units: m), and
 88 contours in (d) are for N96 MetUM.

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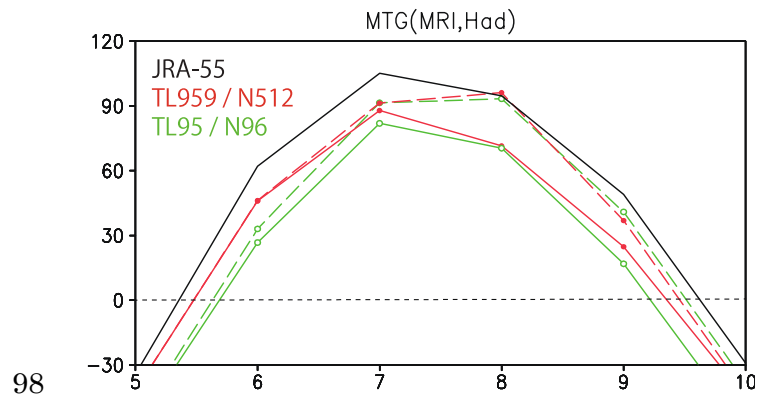


91

92 Figure 14: Responses (200-600 hPa thickness) to individual heating in MRI-AGCM and
 93 MetUM in a linear model. (a) Heating distribution (100-1000 hPa averaged, units: K
 94 day^{-1}) of western Pacific forcing (30°S - 30°N , 120 - 180°E) and (b) response to the
 95 forcing (units: m) in MRI-AGCM. (c)-(d) are same as (a)-(b) but for MetUM.

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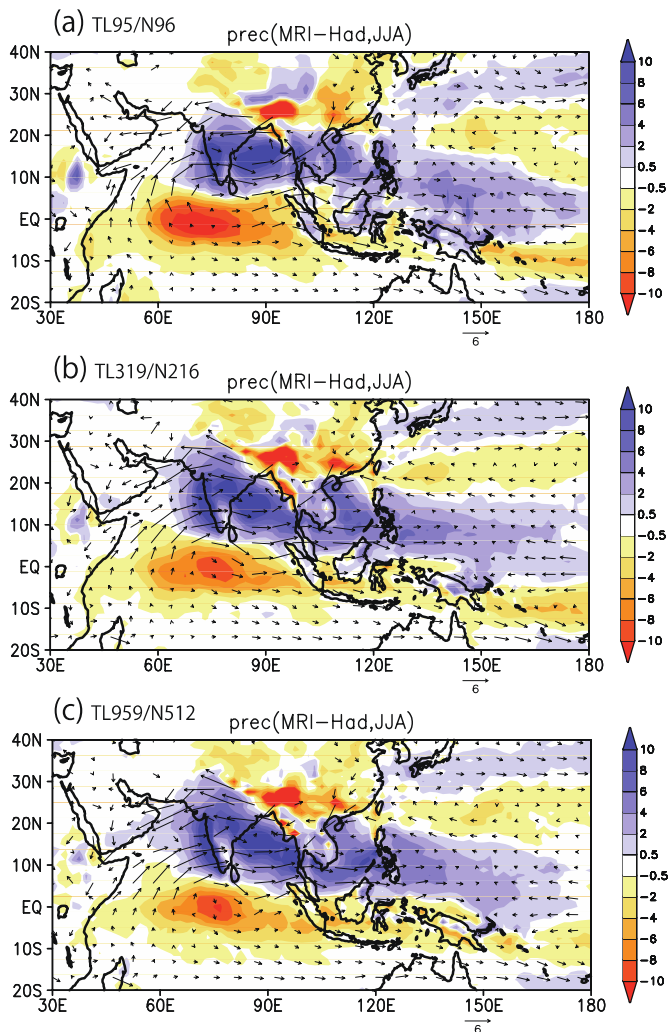
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 99 Figure 15: Seasonal evolution of monsoon temperature gradient (MTG, units: m) in
 100 Reanalysis (JRA-55, black solid line), MRI-AGCM (solid coloured lines) and MetUM
 101 (dash coloured lines). Higher resolution models are shown in red and lower resolution
 102 GCMs are shown in green.

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106 Figure 16: Difference in JJA precipitation (shaded, units: mm day⁻¹) and horizontal 850

107 hPa wind (vector, units: m s⁻¹) between the two GCMs compared in this study: (a)TL95

108 MRI-AGCM minus N96 MetUM, (b) TL319 MRI-AGCM minus N216 MetUM, and (c)

109 TL959 MRI-AGCM minus N512 MetUM.

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