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How well do climate models simulate regional atmospheric circulation over East Asia?

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19 Abstract

20 This study presents a comprehensive and quantitative evaluation of the mean state of
21 summer atmospheric circulation over East Asia. Attention is paid to the South Asian high
22 (SAH), western North Pacific subtropical high (WNPSH) and Indian low (IL) at the upper,
23 middle and lower troposphere, respectively. A total of 31 state-of-the-art climate models
24 from phase 5 of the Coupled Model Intercomparison Project (CMIP5) are used as examples
25 for the analysis. Most models can basically simulate the three closed-circulation systems
26 (CCSs), although there is a certain inter-model spread and an underestimation of their
27 intensity. In terms of geographic location, models demonstrated the best performance for
28 SAH and the poorest performance for WNPSH. The latter shows a generally south-
29 westward shift compared to the National Centers for Environmental Prediction (NCEP)
30 reanalysis. Five atmospheric fields (zonal and meridional wind at 850 hPa, geopotential
31 height at 500 and 100 hPa and sea level pressure) are inspected and generally well
32 reproduced in models, with Taylor-S indices all larger than 0.84 for 90% of the models.
33 The best performance is for the geopotential height of 500 hPa with an average Taylor-S
34 index of 0.98. Models' skill in simulating the sea level pressure is the lowest. However, a
35 significant positive correlation with models' resolution is observed. Almost all models
36 underestimate the 100 hPa geopotential height over East Asia, mainly due to the common
37 cold bias in the troposphere. As a whole, CCSM4, CNRM-CM5, CESM1-CAM5 and
38 NorESM1-M are identified as high-skill models for simulating the East Asian atmospheric
39 circulation. High-skill models also show better simulation of precipitations in East China,
40 with a 21.3% decrease of dry biases in Southeast China. The physical explanation for this

41 linkage is also reported to reside in the central position of the WNPSH, which determines
42 the quality of 850 hPa winds and water vapour transport in Southeast China.

43 **Key words** atmospheric circulation, closed-circulation systems, CMIP5 models, western
44 North Pacific subtropical high, Indian low, South Asian high, monsoon precipitation

45 **1 Introduction**

46 Atmospheric general circulation, allowing energy and water vapour to be redistributed
47 over the Earth, is the most important factor controlling climate variation at both the global
48 and regional scales. It contains a certain number of closed-circulation systems (CCSs) that
49 can be either permanent or temporary and can exert profound impacts on regional climate.
50 Many studies in the literature use this concept to investigate regional climate variability (e.g.,
51 Rossby, 1939; Akiyama, 1975; Khon and Mokhov, 2006; Han and Wang, 2007; Gamble et
52 al., 2008; Li et al., 2011; Hameed and Reimer, 2012; Wang et al., 2012; Seo et al., 2013; Sun
53 et al., 2017).

54 For East China, past studies demonstrated three dominant CCSs in summer. They are
55 the Indian low (IL), western North Pacific subtropical high (WNPSH) and South Asian high
56 (SAH). They have significant impacts on the regional precipitation. For example, moisture
57 from the tropical oceans is transported to East China through the southerly flow at the western
58 periphery of the WNPSH. Rainfall occurs at the north-western margin of the WNPSH, where
59 warm moisture and cold air from high latitudes converge (Meehl et al., 2005; Zhou and Yu,
60 2005; Han and Wang, 2007; Liu et al., 2014; Preethi et al., 2017). A stronger IL, accompanied

61 by stronger water vapour transport at low latitudes, leads to increased rainfall in North China
62 (Zhang, 2001; Liu and Ding, 2008; Ren et al., 2011).

63 Global climate models (GCMs) are primary tools for climate predictions and future
64 climate projections. Evaluating the performance of atmospheric circulation in GCMs can
65 increase our confidence in future projection. Much research directly considered atmospheric
66 fields when evaluating model performance for the Asian monsoon (e.g., Duan et al., 2013;
67 Gong et al., 2014; Jiang and Tian, 2013; Jiang et al., 2015; 2016; Li et al., 2018; Song and
68 Zhou, 2014a, 2014b; Sperber et al., 2013; Xu et al., 2017; Wei et al., 2014; Zhou et al., 2018a).
69 However, they rarely paid attention to model performance in terms of CCSs and their
70 consistency with the relevant atmospheric fields. For those studies focusing on the SAH and
71 the WNPSH (Liu et al., 2014; Qu and Huang, 2014; He and Hu, 2015; Tian et al., 2016; Xue
72 et al., 2016), there is a general lack of consideration of models' systematic cold biases, which
73 lower the geopotential height. It is worth noting that some recent studies used eddy
74 geopotential height to measure the WNPSH, which partially overcomes the issue of
75 geopotential height rise under global warming (He et al., 2015; Huang and Li, 2015; Huang
76 et al., 2015; Wu and Wang, 2015; He et al., 2018). However, all types of biases cannot be
77 corrected for using the concept of eddy geopotential height.

78 Wang et al. (2007, 2010) proposed an alternative algorithm dealing with a CCS, which
79 provides a unified definition of indices, including centre position and intensity, to suitably
80 describe CCSs. The algorithm, together with a few adaptations and ameliorations, is
81 described in next section.

82 The main objective of this study is twofold. First, we aimed to document CMIP5 model
83 performance in simulating the mean state of atmospheric fields and main CCSs over East
84 Asia and to study models consistency among different evaluated targets. Second, we wanted
85 to investigate how biases in atmospheric circulation exert impacts on biases in precipitation.

86 This paper is organized as follows: Section 2 shows the data and methodology. Section
87 3 presents a comprehensive assessment and consistency comparison of the atmospheric fields
88 and the major CCSs. Section 4 discusses the influence of simulated atmospheric fields and
89 CCSs on the simulated precipitation in eastern China. Section 5 presents final conclusions
90 for the whole work.

91 **2 Data and Methods**

92 2.1 Models, Simulations and Reference Data

93 Our study area covers a large zone in East Asia, 10–70°N, 60–160°E. The regional mean
94 state of atmospheric circulation is evaluated for 45 years, from 1961 to 2005. Variables from
95 31 CMIP5 models are used in this study, including monthly geopotential height at 100 hPa
96 (Z100) and 500 hPa (Z500), zonal (U850) and meridional (V850) wind at 850 hPa, sea level
97 pressure (SLP), atmospheric temperature and daily precipitation accumulation. Only one
98 historical run is chosen for each model (r1i1p1) to ensure that the evaluation is unbiased.
99 Table 1 shows the relevant basic information of these CMIP5 models. To facilitate the
100 comparison, a bilinear interpolation scheme was used to transform variables from their native
101 grids to a $2.5 \times 2.5^\circ$ common grid. The three CCSs evaluated in this study are listed in Table
102 2.

103 **Table 1** Acronyms, resolutions and institutions of the 31 CMIP5 Models. The first
 104 column shows models serial number in this paper, listed in alphabetic order. Expansions of
 105 model acronyms are available at <http://www.ametsoc.org/PubsAcronymList>

No.	Models name	LON. × LAT.	Modeling center or group
1	ACCESS1.0	1.875°×1.25°	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
2	ACCESS1.3	1.875°×1.25°	
3	BCC-CSM1.1	~2.8125°×2.8125°	Beijing Climate Center, China Meteorological Administration
4	BCC-CSM1.1(m)	~1.125°×1.125°	
5	BNU-ESM	~2.8°×2.8°	Beijing Normal University
6	CanESM2	~2.8125°×2.8125°	Canada Center for Climate Modeling and Analysis
7	CCSM4	0.9°×1.25°	US National Centre for Atmospheric Research
8	CESM1-CAM5	0.9°×1.25°	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
9	CMCC-CM	0.75°×0.75°	Centro Euro-Mediterraneo per I Cambiamenti Climatici
10	CMCC-CMS	1.875°×1.875°	
11	CNRM-CM5	~1.4°×1.4°	Centre National de Recherches Meteorologiques-CERFACS
12	EC-EARTH	~1.125°×1.125°	EC-EARTH consortium
13	FGOALS-g2	2.8125°×2.8125°	Institute of Atmospheric Physics, Tsinghua University
14	FGOALS-s2	2.81°×1.66°	Institute of Atmospheric Physics, Chinese Academy of Sciences
15	GFDL-CM3	~2.5°×2.0°	NOAA Geophysical Fluid Dynamics Laboratory
16	GFDL-ESM2G	~2.5°×2.0°	
17	GFDL-ESM2M	~2.5°×2.0°	
18	HadCM3	3.75°×2.5°	Met Office Hadley Centre
19	HadGEM2-CC	1.875°×1.25°	
20	HadGEM2-ES	1.875°×1.25°	
21	IPSL-CM5A-MR	1.25°×2.5°	Institut Pierre Simon Laplace
22	IPSL-CM5A-LR	1.5°×3.75°	
23	MIROC4h	0.5625°×0.5625°	University of Tokyo, National Institute for Environmental Studies Japan Agency for Marine - Earth Science and Technology
24	MIROC5	1.40625°×1.40625°	
25	MIROC-ESM	2.8125°×2.8125°	
26	MIROC-ESM-CHEM	2.8125°×2.8125°	
27	MPI-ESM-LR	~1.8°×1.8°	Max Plank Institute for Meteorology
28	MPI-ESM-MR	~1.8°×1.8°	
29	MPI-ESM-P	~1.8°×1.8°	
30	MRI-CGCM3	1.125°×1.125°	Meteorological Research Institute
31	NorESM1-M	2.5°×1.9°	Norwegian Climate Centre

106 **Table 2** Closed-circulation systems and their corresponding original fields from which they
 107 are deduced.

Acronyms	Closed-circulation systems	Original fields
IL	India Low	sea level pressure
WNPSH	western North Pacific subtropical high	500hPa geopotential height
SAH	South Asian High	100hPa geopotential height

108 In terms of observations used as a reference, we use reanalysis data from the National
 109 Centers for Environmental Prediction - National Center for Atmospheric Research
 110 (NCEP/NCAR), with a resolution of $2.5 \times 2.5^\circ$. For precipitation, a high - quality gridded
 111 dataset deduced from surface stations in China with a resolution of $0.5 \times 0.5^\circ$ is used as the
 112 reference (Chen et al., 2010).

113 2.2 Model Performance Metrics

114 2.2.1 Taylor Diagram

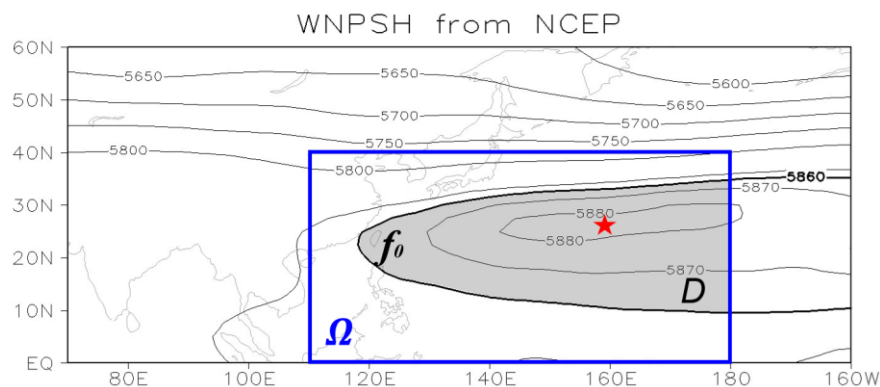
115 Taylor Diagram (Taylor, 2001) is designed to assess the matching degree of spatial
 116 pattern between models and the reference. It is a diagram summarizing the centered (spatial
 117 mean removed) root-mean square error (RMSE), correlation coefficient R and ratio σ_f of
 118 standard deviations (RSD) between models and the reference. Two of the three parameters
 119 are independent and the third one can be deduced. Taylor-S index (Taylor, 2001) uses the
 120 two independent parameters to form a combined indicator useful for quantitative evaluation:

$$121 \quad S = \frac{4(1+R)}{(\sigma_f + 1/\sigma_f)^2 (1+R_0)} \quad (1)$$

122 where R_0 is the maximum correlation attainable ($R_0 = 1$ in this study).

123 2.2.2 Indices for describing closed-circulation systems

124 A complete set of Closed-Circulation-System Indices (CCSI) proposed by Wang et al.
 125 (2007, 2010) is used to quantitatively describe closed-circulation systems, including center
 126 position (λ_c, θ_c) and intensity P . In previous studies using CCSI, the critical isobar (the
 127 largest closed iso-line) f_0 in the calculation of CCSI was generally determined by a
 128 predefined climatological value (e.g. Ren et al., 2011; Sun et al., 2013, 2017; Wang et al.,
 129 2012). In order to reduce the bias of f_0 selection, the most outside closed iso-line of the
 130 closed-circulation system is defined as the critical isobar f_0 in this study. Ω is the domain
 131 where the main body of the closed circulation system locates. Computational domain D is
 132 the common area of Ω and f_0 . Take the western North Pacific subtropical high from NCEP
 133 data as an example, the geopotential height at 500hPa is shown in Fig. 1. Ω is the blue box
 134 domain ($110\text{-}180^\circ \text{ E}$, $0\text{-}40^\circ \text{ N}$), critical isobar f_0 is the outer edge of the cyclone circulation
 135 (5860gpm shown here as bold black contour), and D is the shaded domain. For the South
 136 Asian high and the Indian low, the search domains Ω are ($110\text{-}180^\circ \text{ E}$, $10\text{-}50^\circ \text{ N}$) and (30-
 137 100° E , $10\text{-}40^\circ \text{ N}$) respectively.



138

139 Figure 1. WNPSH from NCEP represented by climatological geopotential height at 500hPa as
 140 example to show the critical isobar f_0 , search domain Ω , and computational domain D

141 By denoting \mathbf{r} as the positions vector for the grid (λ, θ) on the Earth sphere, $f(\mathbf{r})$
 142 represents the geopotential height at grid (λ, θ) , and f_0 represents the value of critical isobar.
 143 The intensity index P is the area integral of the values of geopotential height difference
 144 fields ($df = f(\mathbf{r}) - f_0$) in domain D. The center position index (λ_c, θ_c) is the barycenter of
 145 the difference fields df . The position vector for (λ_c, θ_c) is represented by \mathbf{r}_c . P and λ_c, θ_c can
 146 be calculated from the following equation:

$$147 \quad P = \left[\iint_D f(\lambda, \theta) - f_0 \right] ds \quad (2)$$

$$148 \quad \iint_D |f(\mathbf{r}) - f_0| (\mathbf{r} - \mathbf{r}_c) ds = 0 \quad (3)$$

149 The value of P is positive for high-pressure center, and negative for low-pressure center.
 150 For the high-pressure center, larger the value of P, stronger the closed-circulation system is,
 151 the low-pressure center converses. We define the radius of the earth as a unit radius, so unit
 152 of P is $\text{Pa} \cdot \text{rad}^2$ for the Indian Low and $\text{gpm} \cdot \text{rad}^2$ for the South Asian high and western North
 153 Pacific subtropical high. A square of 1 rad^2 corresponds to Earth surface area of 40.6 million
 154 km^2 at equator, and decreases with cosine of the latitude.

155 For the evaluated models, Ω is the same as in NCEP for each circulation system, but
 156 the critical isobar f_0 varies from one model to another. f_0 of each model shows its
 157 systematical bias. It can be considered as a comprehensive parameter of each individual
 158 model. By using the last closed iso-line of a closed-circulation system as its critical isobar,

159 we can easily deduce that the intensity parameter actually reveals the spatial gradient of the
160 closed-circulation system, an important measure for any geophysical flow. It is clear that
161 the proposed CCS indices can objectively represent the properties of any closed-circulation
162 systems in climate models.

163 2.2.3 Comprehensive Ranking Measure M_R

164 To assess model's performance and consistency among multiple properties and indices,
165 the comprehensive ranking measure M_R as defined in Radić and Clarke (2011) is used in this
166 study:

$$167 \quad M_R = 1 - \frac{1}{(n \times m)} \sum_{i=1}^m rank_i \quad (4)$$

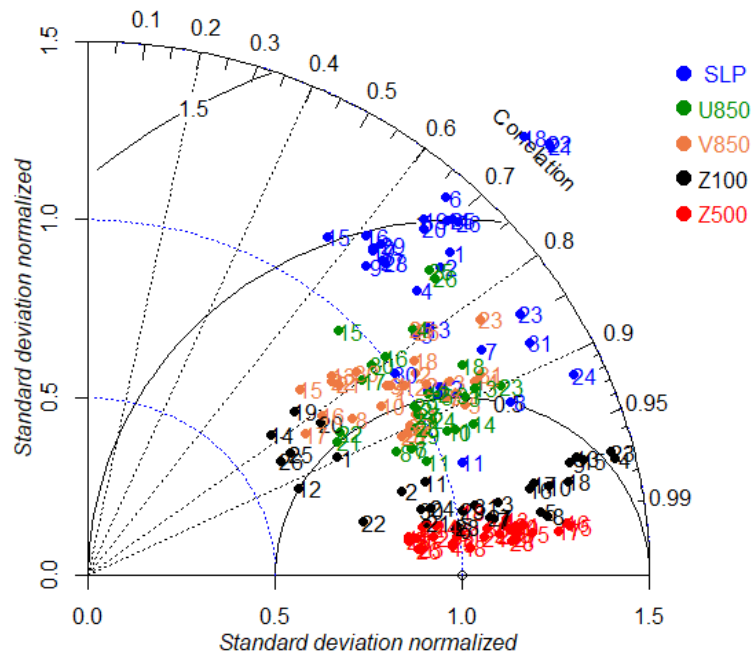
168 where m is the number of indices entering into the calculation, n is the number of
169 evaluated models. $rank_i$ is the model performance rank for the index i . The closer the value
170 of M_R to 1, the better the model comprehensive performance is (Chen et al., 2011; Jiang et
171 al., 2012, 2015; You et al., 2018).

172 **3 Models Performance in the Mean State of Atmospheric Circulation**

173 This section gives firstly models performance in simulating the mean state of five
174 atmospheric fields with the Taylor-S index. It pursues by a presentation of models
175 performance in simulating the mean state of three closed-circulation systems with CCS
176 indices. Finally, models consistency and comprehensive capabilities are evaluated with M_R
177 index.

178 3.1 Evaluation of Atmospheric Fields

179 Figure 2 displays the Taylor diagram showing the performance of models in simulating five
 180 atmospheric fields with NCEP data as reference. The number next to each point corresponds
 181 to models order listed in Table 1. We can see that the five atmospheric fields are well
 182 reproduced, with correlation coefficients all larger than 0.6. Models have the best skill in
 183 simulating the geopotential height, especially the 500hPa geopotential height (Z500), for
 184 which models also show the smallest inter-model spread. Such a result is in agreement with
 185 previous studies (e.g. Belleflamme et al., 2013; Gong et al., 2014; Tian et al., 2016).

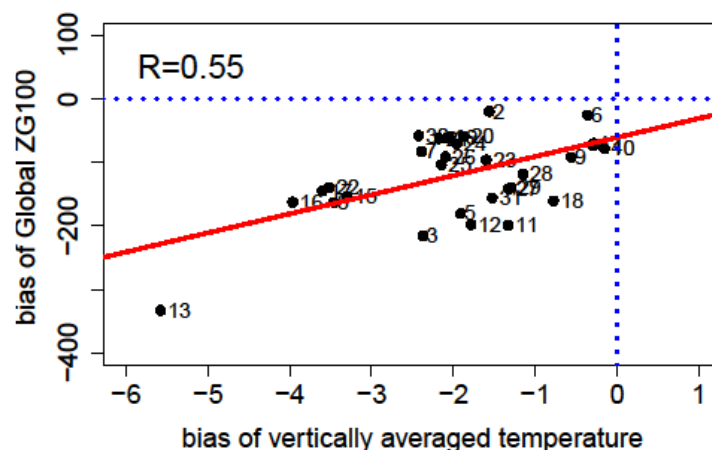


186

187 **Figure 2.** Taylor diagram obtained from five atmospheric fields, Sea Level Pressure (SLP), zonal
 188 (U850) and meridional wind (V850) at 850hPa, and geopotential height at 100hPa (Z100) and 500hPa
 189 (Z500), and from 31 CMIP5 models. Radial lines emanating from the origin (0.0, 0.0) display the
 190 spatial correlation coefficients between simulations and the reference NCEP, radial circles show

191 models standard deviations normalized by their counterpart from NCEP, and solid circles indicate the
192 root-mean square difference between models and NCEP field. The number next to each point
193 corresponds to the model number listed in Table 1.

194 The Taylor-S index for Z500 varies from 0.93 to 0.998, with the average value of 0.98.
195 For 100hPa geopotential height (Z100), the Taylor-S index ranges from 0.72 to 0.995 with
196 average value of 0.92. Most models have their spatial correlation coefficients with NCEP
197 larger than 0.9. However, there is a large inter-model spread for the spatial variance, with the
198 normalized standard deviations from 0.4 to 1.51. In addition, all models, except
199 CanESM2(6#), have negative bias (lower height) for Z100 compared with NCEP. The
200 underestimation of Z100 is not a local manifestation in East Asia, but occurs over the globe.
201 The vertically averaged temperature (VAT) between the surface and isobaric surface $p = 100$
202 hPa are calculated for NCEP data and CMIP5 models outputs. Results show that all models
203 have a globally-averaged cold bias. The inter-model correlation between the bias of VAT
204 and the bias of 100hPa geopotential height is 0.55, as shown in FIG. 3.



206 Figure 3. Scatter diagram showing the globally-averaged biases of tropospheric temperature
 207 (abscissa-axis) and the globally-averaged biases of 100hPa geopotential height (ordinate-axis) from
 208 the 31 models. R is the inter-model correlation coefficient between the two biases. The red solid line
 209 is the linear regression.

210 Models have the lowest skill in simulating sea level pressure (SLP), with average
 211 Taylor-S index of 0.79. There is a large inter-model spread and the correlation coefficients
 212 with NCEP vary from 0.6 to 0.95. Models performance in simulating SLP seems largely in
 213 connection with models resolution. The inter-model rank correlation coefficient between the
 214 Taylor-S index for SLP and models resolution is as high as 0.6. Another feature revealed by
 215 the Taylor diagram is that all models overestimate the spatial variance of SLP, since the
 216 normalized standard deviations (radial circles) against NCEP data are all above 1.0. Models
 217 can reasonably reproduce 850hPa zonal and meridional wind. Correlation coefficients with
 218 NCEP vary from 0.75 to 0.95. Models have a similar performance in zonal and meridional
 219 winds, their Taylor-S indices being of 0.89 and 0.88 respectively.

220 **Table 3** Spearman rank correlation coefficients for each pair of two rankings among the five
 221 atmospheric fields (SLP, U850, V850, ZG500 and ZG100) and the three closed-circulation
 222 systems. Bold figures show the statistical significance at $\alpha = 0.05$ level ($t_{\alpha,31} = 0.344$). The
 223 ranking for the atmospheric fields was based on their Taylor-S values, and the ranking for
 224 the closed-circulation systems was based on their absolute biases evaluated through the close-
 225 circulation-system indices.

SLP	U850	V850	ZG500	ZG100	WNPSH	SAH
-----	------	------	-------	-------	-------	-----

U850	0.37						
V850	0.43	0.73					
ZG500	0.24	0.38	0.35				
ZG100	0.27	0.31	0.43	0.26			
WNPSH	0.28	0.11	0.27	0.07	0.31		
SAH	0.27	0.26	0.43	0.34	0.53	0.44	
IL	0.44	0.01	0.13	0.27	0.09	0.08	0.24

226 To evaluate models consistency among the five atmospheric fields, inter-model rank
 227 correlation is calculated and shown in Table 3. Models rank was determined with the Taylor-
 228 S index, higher Taylor-S index corresponding to higher rank. We can see that models have
 229 the best consistency between zonal wind and meridional wind, with the rank correlation
 230 coefficient reaching 0.73. Moreover, models rank for 850hPa meridional wind has a good
 231 correlation with the rank from other fields. Although models rank can be divergent among
 232 different atmospheric fields, the high-skill models, such as CCSM4 (7#) and CNRM-CM5
 233 (11#), have an excellent behavior for almost all variables.

234 3.2 Evaluation of closed-circulation systems

235 Center location and intensity of the South Asian high (SAH), Indian low (IL) and western
 236 North Pacific subtropical high (WNPSH) simulated by CMIP5 models and from NCEP data
 237 can be assessed with the closed-circulation-system indices which allow the removal of
 238 models systematic but less-or-not-relevant biases such as too-low geopotential height in
 239 models. Results are shown in FIG. 4.

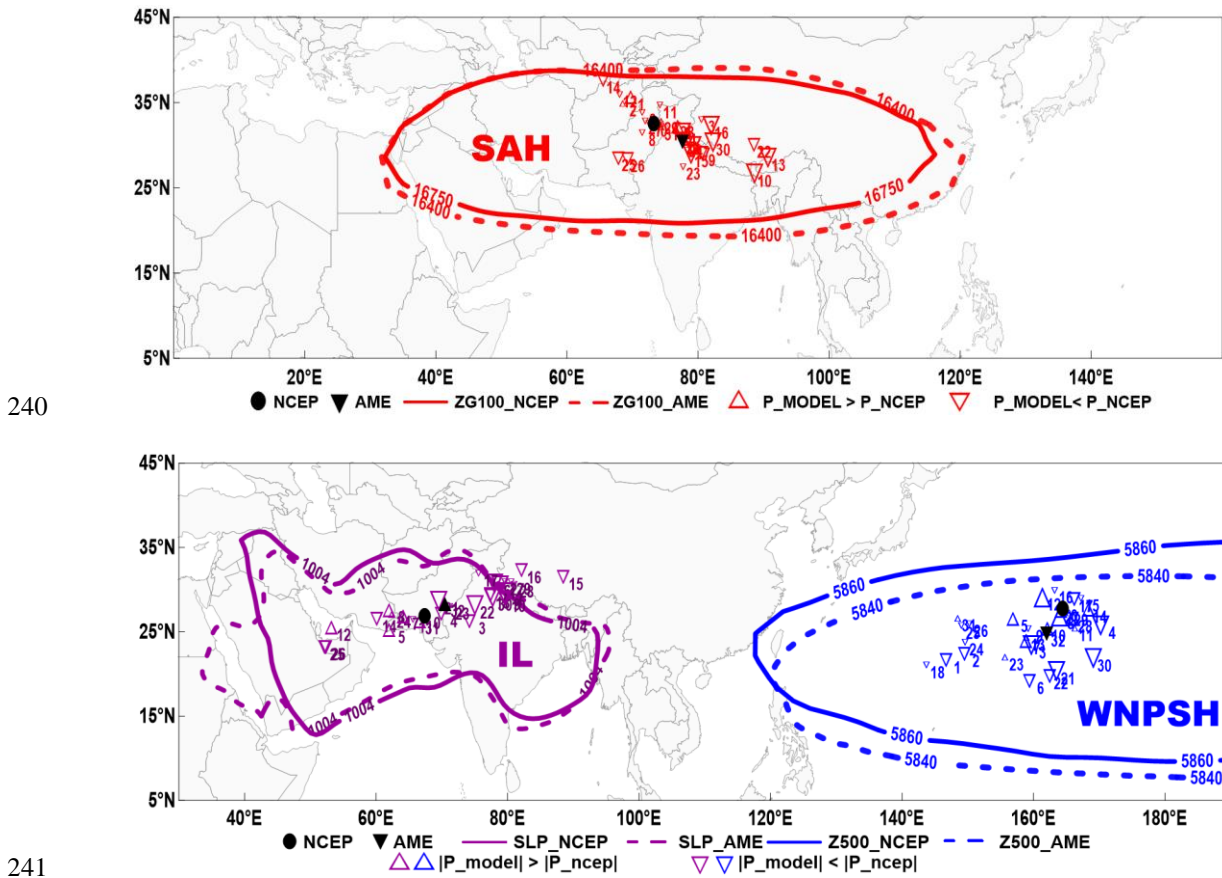


Figure 4. The three closed-circulation systems represented in the upper panel for the South Asian high (SAH) and in the lower panel for the Indian low (IL) and western North Pacific subtropical high (WNPSH). Solid contours show their limitation boundaries as depicted in NCEP reanalysis: the line 16750 gpm at 100 hPa for SAH, the line 1004 hPa at sea level for IL, and 5860 gpm at 500 hPa for WNPSH. Dashed contours are the counterpart from models as an ensemble mean. Center position and intensity for each CMIP5 individual model are plotted for the three closed-circulation systems respectively. Position is marked by either triangles or inverted triangles. Intensity is shown with the size and form of the symbols: an inverted triangle if $|P_{\text{model}}| < |P_{\text{ncep}}|$ and a triangle if $|P_{\text{model}}| > |P_{\text{ncep}}|$. The size of the symbols represents amplitude of the deviation. The position of the multi-model ensemble is marked by a solid and black inverted triangle, and the position of NCEP by a solid black circle.

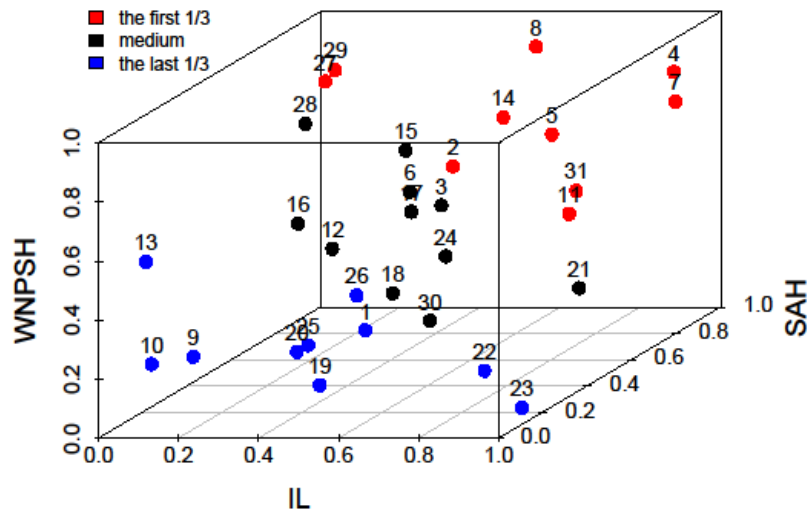
253 It can be seen that, although there is a large inter-model spread for the simulated center
 254 location, all models have the basic capability of simulating the three closed-circulation
 255 systems. Models have the best performance and the smallest inter-model spread in simulating
 256 the location of SAH, the average value and standard deviation of distances between models
 257 and NCEP being 599 km and 418 km respectively (Table 4). Most models simulate a
 258 southeast-shifted center of SAH compared with NCEP (FIG.4). The inter-model correlation
 259 coefficient between simulated bias in center latitude and longitude of SAH is -0.6. 71% of
 260 models underestimate the intensity of SAH. The inter-model rank correlation coefficient
 261 between the center position and intensity of SAH is 0.67. It indicates that, for SAH, models
 262 with high skill in simulating the center location usually have good performance for intensity.

263 **Table 4** Average distance of simulated closed-circulation system from their counterpart
 264 in NCEP, together with the standard deviation among models. Unites: km.

	Indian Low	South Asian high	western North Pacific subtropical high
Average distance	952	599	805
Standard deviation	505	418	586

265 There is a large inter-model spread for the location of IL. Two-thirds of the models
 266 simulate a northeast-ward shift compared with NCEP. Inter-model correlation coefficient
 267 between biases in center latitude and those in longitude is 0.89, which explains why models
 268 tend to be on a diagonal line from southwest to northeast. It is also interesting to note that
 269 those models situated in the northeast side of NCEP in Fig. 4b all underestimate the intensity.
 270 The largest inter-model spread for center position is from WNPSH (Table 4). Most models
 271 have a southwest-shifted center. Only 4 models simulate a north-shifted center of WNPSH

272 compared with NCEP. Nearly half of the models simulate a stronger WNPSH, but most of
 273 the positive deviations are small.



274

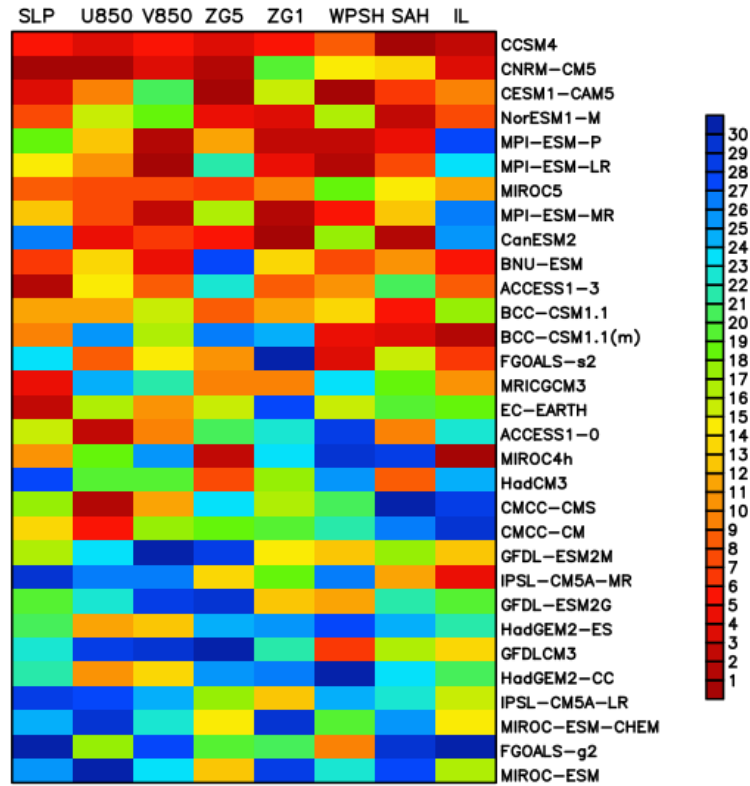
275 **Figure 5.** Three-dimensional scatterplot for the three comprehensive indices M_R from ranking
 276 performed on the three closed-circulation systems, Indian low (IL), South Asian high (SAH) and
 277 western North Pacific subtropical high (WNPSH) respectively. Numbers over each point are
 278 consistent with models serial number shown in Table 1. Following their comprehensive performance
 279 ranking, models in the top third are plotted in red color, while those in the bottom third are in blue.

280 Figure 5 shows the scatterplot of comprehensive indices M_R for the Indian low (IL),
 281 South Asian high (SAH) and western North Pacific subtropical high (WNPSH). The
 282 performance of models is quite divergent among the three closed-circulation systems. The
 283 rank correlation coefficient between WNPSH and IL is only 0.08 (Table 3) indicating almost
 284 no correlation at all. It is to be noted that, despite divergent performance for CMIP5 models
 285 in simulating the three closed circulation systems, top ranked models and bottom ranked
 286 models have good consistency respectively. For example, BCC-CSM1.1 (m) (4#) and

287 CCSM4 (7#) have an excellent performance for all the three closed circulation systems.
288 CMCC-CM (9#) and CMCC-CMS (10#) have the poorest performance for the circulation
289 systems.

290 3.3 Comprehensive Performance and Consistency

291 To evaluate models consistency among different variables, Figure 6 shows models rank for
292 each evaluated variable by color blocks. For atmospheric fields, models are ranked by their
293 Taylor-S index, with high value corresponding to good rank. For closed-circulation systems,
294 models are ranked according to their absolute biases of the relevant indices. In Fig. 6, models
295 rank is consistently indicated with colors as in the color bar. From top to bottom, models
296 comprehensive performance determined by multiple M_R goes from the best to the worst. It
297 can be seen that the rank of a model depends on the selection of assessment variables. This
298 result seems in agreement with a few previous studies (Gleckler et al., 2008; Jiang et al.,
299 2016; Ou et al., 2013; Radić et al., 2011; Sheffield et al., 2013a, 2013b; Su et al., 2013; Xu
300 et al., 2017). We can note, however, that top ranked models and bottom ranked models have
301 good consistency. Bad consistency is mainly manifested in the models at middle levels of the
302 ranking. Results shown in Fig. 6 can serve as guidance for selecting global models outputs
303 for regional climate downscaling, and can provide useful information for climate projection
304 within a framework of multi-model ensemble, models ranking being useful in assigning
305 weight for each model.

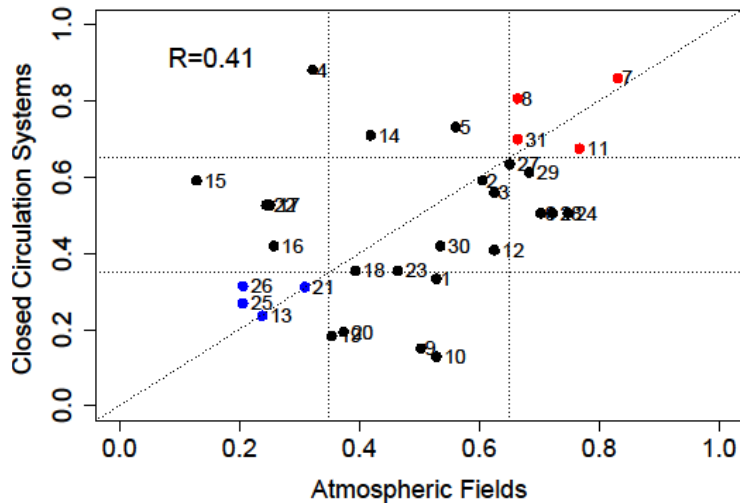


306

307 **Figure 6.** Portrait diagram with color blocks showing models ranking (as indicated by the color label
 308 bar) performed separately on the five atmospheric fields: sea level pressure (SLP), zonal (U850) and
 309 meridional (V850) wind at 850hPa, and geopotential height at 500hPa (ZG5) and 100hPa (ZG1); and
 310 on the three closed-circulation systems: western North Pacific subtropical high (WNP SH), South
 311 Asian high (SAH) and Indian low (IL). Models acronyms listed on the right follow their total record
 312 of ranking. From top to bottom, models go with decreasing performance.

313 Inter-model correlation between each pair of two rankings are calculated and shown in
 314 Table 3 which allows us to examine the consistency between closed-circulation systems and
 315 their original atmospheric fields from which they are deduced (listed in Table 2). The South
 316 Asian high has the best consistency with 100hPa geopotential height, the rank correlation
 317 coefficient being 0.53. The Indian low shows a rank correlation coefficient of 0.44 with the

318 sea level pressure. Finally, the western North Pacific subtropical high has the poorest
 319 correlation with 500hPa geopotential height, the rank correlation being only 0.07.



320

321 **Figure 7.** Scatter diagram for models comprehensive index from atmospheric fields (x axis: including
 322 sea level pressure, geopotential height at 100hPa and 500hPa, zonal wind and meridional wind at
 323 850hPa) and that from closed-circulation systems (y axis: Indian low, South Asian high and western
 324 North Pacific subtropical high). Number next to each point is consistent with models serial number
 325 shown in Table 1. R is the correlation coefficient between the two measures in X axis and Y axis.

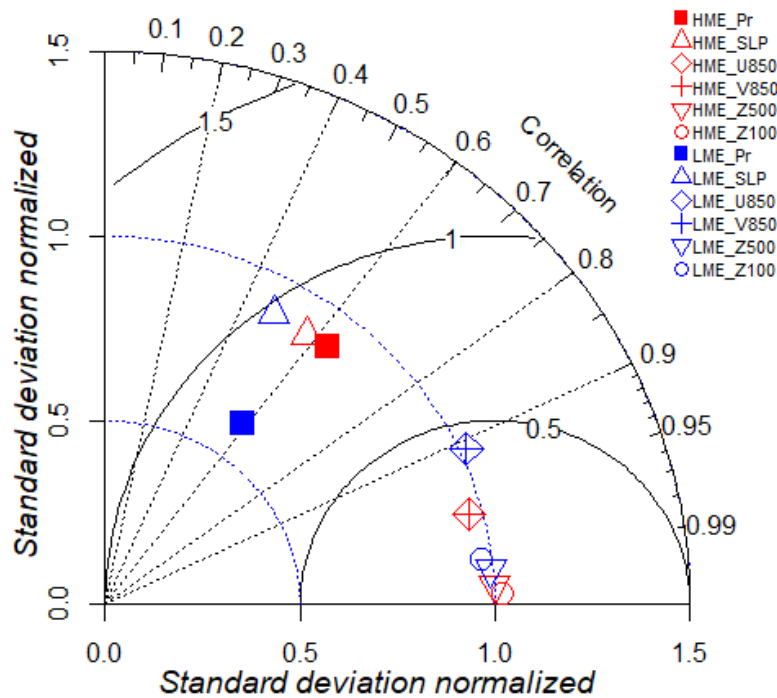
326 Let us now examine how the comprehensive index M_R from the closed-circulation
 327 systems is consistent with that from the corresponding atmospheric fields. The scatter
 328 diagram in Fig. 7 displays each model as a point with its ordering number, the x-axis being
 329 the comprehensive index M_R from all atmospheric fields, and the y-axis being that from all
 330 closed-circulation systems. Models situated in the upper right corner have the best
 331 performance in the two indices from both the closed-circulation systems and their
 332 corresponding atmospheric fields, while converse in the bottom left corner. There would be
 333 a perfect consistency between the models performance in simulating the two properties if all

334 dots in Fig. 7 were on the diagonal. The actual inter-model correlation coefficient between
335 the two is 0.41. It would be significantly increased (value =0.62) if models BCCCSM1.1(m)
336 (4#), CMCC-CMS (10#) and GFDL-CM3 (15#) (at the periphery of the collection of points)
337 were kicked off from the ensemble. Figure 7 can also allow us to select high-skill models
338 (red dots) and low-skill ones (blue dots) in a highly-synthetic way with consideration of M_R
339 from both atmospheric fields and closed-circulation systems. Red dots in Fig. 7 have M_R
340 values larger than 0.65. They are from CCSM4, CNRM-CM5, CESM1-CAM5 and
341 NorESM1-M respectively. They can be qualified as high-skill models within our evaluation.

342 **4 Influence of atmospheric circulation on precipitation at inter-model level**

343 In observation as well as in numerical models, East Asian monsoon precipitation is
344 closely related to atmospheric circulation in the region (He and Zhou, 2014; Song and Zhou,
345 2014; Zeng et al., 2012; Zhou et al., 2018b). For example, there is a significant correlation
346 between the low-level meridional wind jet and precipitation over East China. The western
347 North Pacific subtropical high largely determines the East Asian summer monsoon rainfall
348 band (He and Zhou, 2014; Song and Zhou, 2014). In this section, we want to check if similar
349 relations exist between rainfalls in East Asia and regional atmospheric circulation within the
350 framework of inter-model variability. In other words, we want to check if good models for
351 circulation are also good for rainfalls. Since monsoon precipitation is dependent on many
352 circulation factors, it is thus preferable to choose models following their comprehensive
353 performance. High-skill models and low-skill models, as selected in the previous section, can
354 be used to explore the impacts of atmospheric circulation biases on precipitation biases. As
355 shown earlier, four models (CCSM4, CNRM-CM5, CESM1-CAM5 and NorESM1-M) are

356 selected for the high-skill models ensemble (HME), and FGOALS-g2, MIROC-ESM,
 357 MIROC-ESM-CHEM and IPSL-CM5A-LR are included in the low-skill models ensemble
 358 (LME).

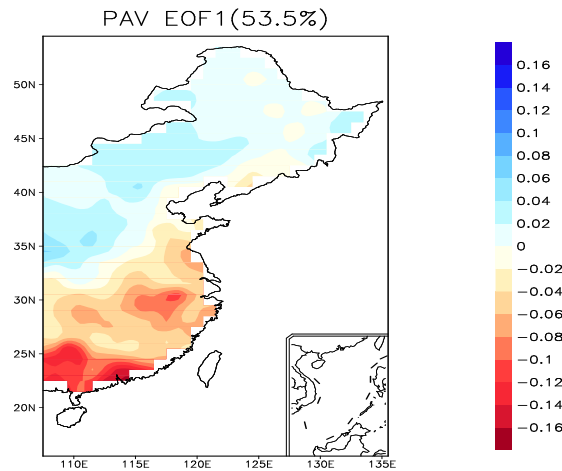


359
 360 **Figure 8.** Taylor diagram for the five atmospheric fields (AFs) over East Asia and the precipitation
 361 distribution in East China. The assessment was done for the high-skill models ensemble (HME, in
 362 red) and the low-skill models ensemble (LME, in blue) respectively. The reference for atmospheric
 363 fields was from NCEP, and that for precipitation from surface observation.

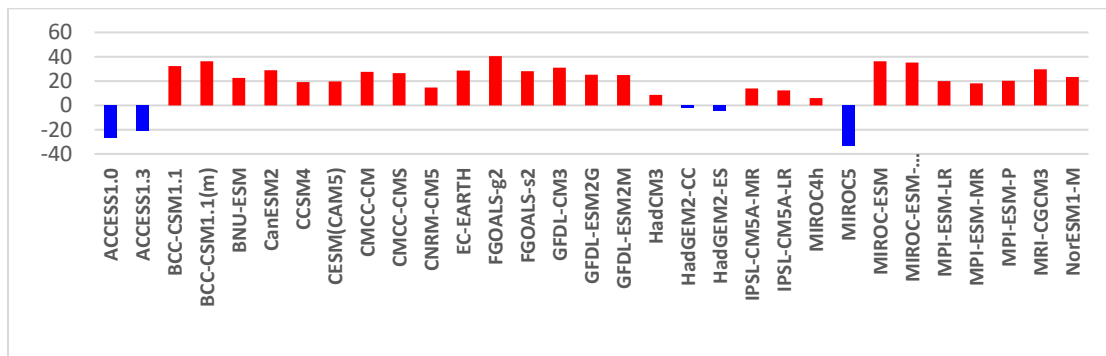
364 Figure 8 displays the Taylor diagram showing precipitation (solid symbols) in East
 365 China and atmospheric circulation fields (hollow symbols) over East Asia in HME (in red)
 366 and LME (in blue) respectively. For precipitation in East China, it is easy to see that HME
 367 remarkably reduces the deviation compared to LME, which obviously underestimates the
 368 spatial variability of precipitation. The standard deviation in HME is much closer to
 369 observation than in LME, their normalized standard deviations being 0.9 and 0.6 respectively.

370 In terms of geographic distribution of precipitations in East China, we perform an inter-
 371 model empirical orthogonal function (EOF) analysis on the precipitation biases of 31 models
 372 in East China, to analyze the dominant modes of inter-model variations in the average
 373 precipitation bias. Figure 9 shows the first inter-model EOF mode which accounts for most
 374 (53.5%) of the total inter-model variance. It is characterized by the “wet-north and dry-south”
 375 structure of precipitation biases for the most models. Such a result that dry biases in Southeast
 376 China and wet biases in Northeast China is in agreement with previous studies (Chen et al.,
 377 2014; Ou et al., 2013; Jiang et al., 2015). For PC1, all models from HME and LME have
 378 positive value. Such a situation is visible for both HME and LME as well, shown in Figure
 379 10. The dry biases in the south are smaller in HME than in LME by about 21.3%.

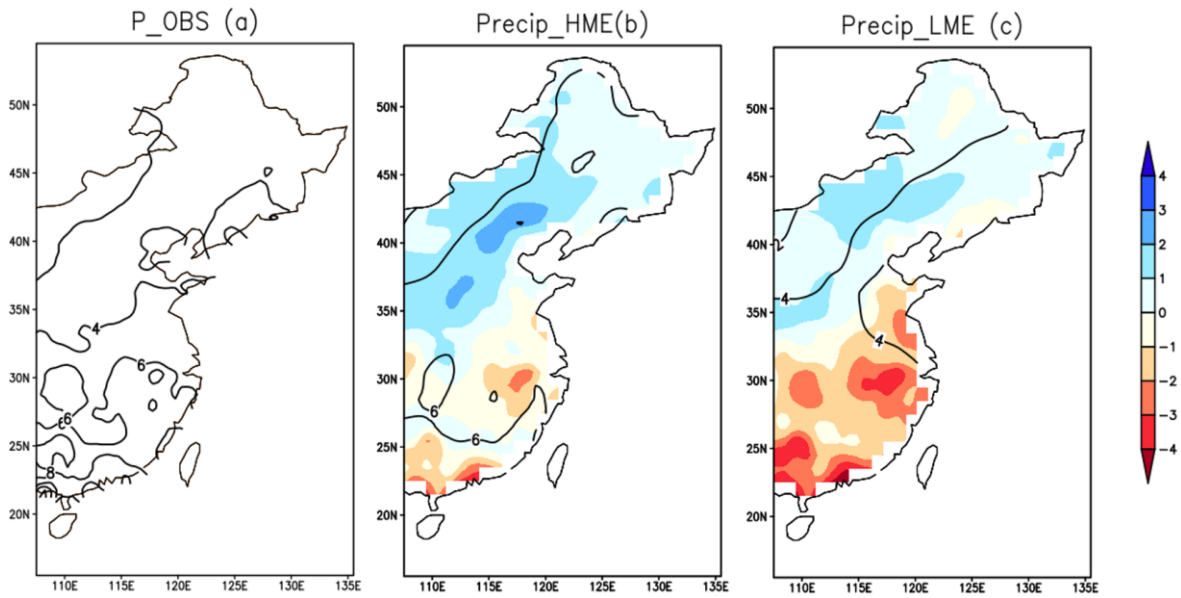
380



381



382 **Figure 9.** Upper panel shows the first EOF mode of the climatology precipitation bias in East China
 383 calculated by inter-model EOF from 31 models. Lower panel shows the corresponding PC, with red
 384 for positive value and blue for negative value.
 385



386

387 **Figure 10.** Distribution maps of average precipitation in summer in East China (contours, mm/day)
 388 from (a) observation, (b) high-skill models ensemble (HME) and (c) low-skill models ensemble
 389 (LME). Deviations from the observation are shown in shaded for HME and LME.

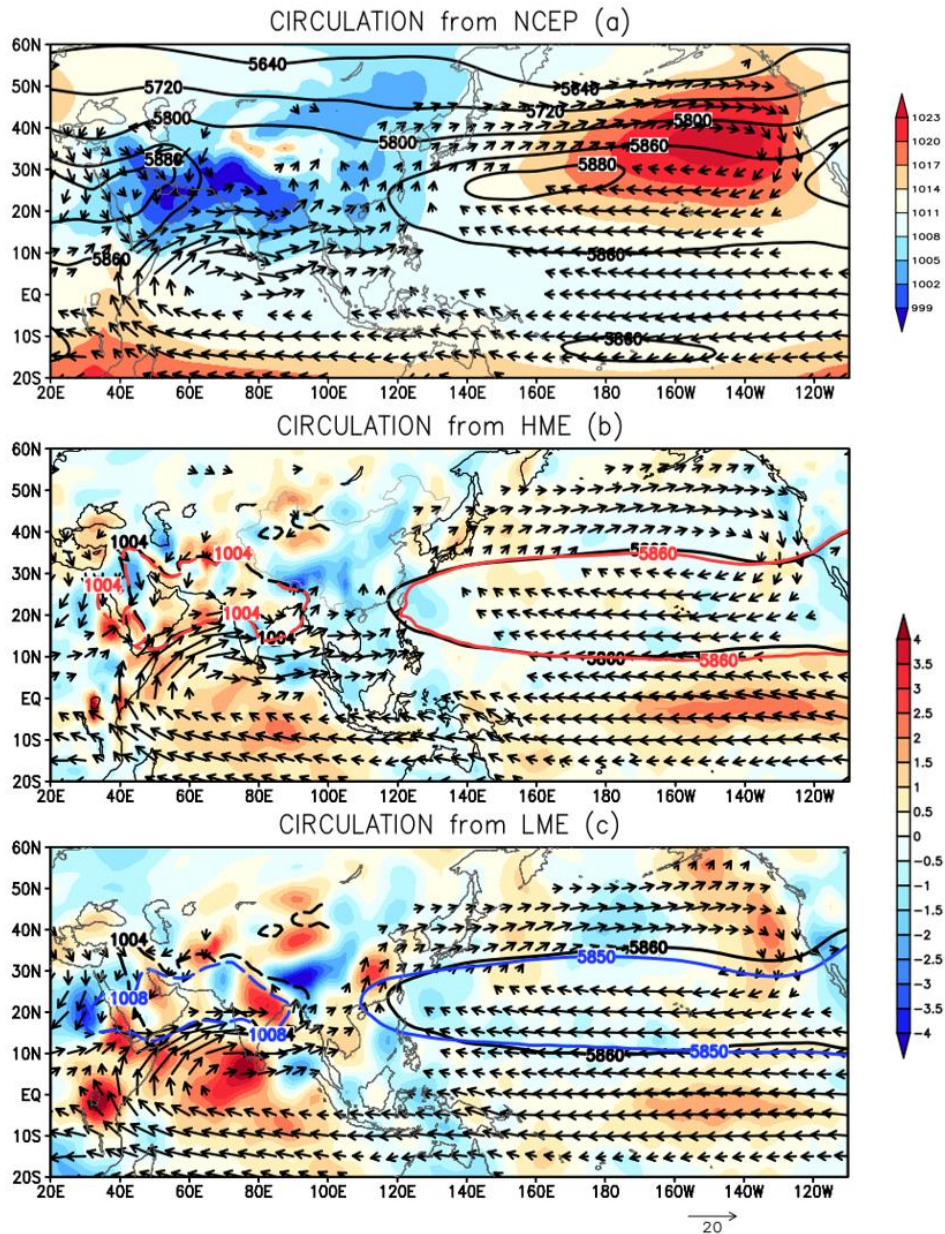
390 After exploring behaviors of the regional precipitation, we pursue our analyses on
 391 atmospheric fields and closed-circulation systems which can behave differently in HME and
 392 LME. Figure 8 shows clearly that there is a better performance for atmospheric fields in HME
 393 than in LME. The most obvious improvement is for 850hPa zonal and meridional wind
 394 (crosses and rhombuses). HME also has a better performance for all the three closed-
 395 circulation systems. In particular, it shows prominent advantages for intensity of the Indian
 396 low and position of the western North Pacific subtropical high (Table 5). Compared to NCEP,

397 LME shows a westward shift about 9 degrees in longitude for the center of the western North
 398 Pacific subtropical high. LME also has a weaker Indian low, as the difference of intensity
 399 with NCEP is $31.21 \text{ Pa}\cdot\text{rad}^2$ (for low-pressure system, the intensity index is smaller than zero).
 400 For the South Asian high, LME has only a little decrease of performance compared to HME.

401 **Table 5**

402 Center Coordinates, Intensity (P) and critical isobar (f_0) of the Indian low (IL), South Asian
 403 high (SAH) and western North Pacific subtropical high (WNPSH) from NCEP, and
 404 deviations from NCEP in HME and LME. Latitude is positive northward and longitude is
 405 positive eastward. Unites of P: $\text{Pa}\cdot\text{rad}^2$ for IL, $\text{gpm}\cdot\text{rad}^2$ for SAH and WNPSH.

	IL			SAH			WNPSH		
	center	P	f_0	center	P	f_0	center	P	f_0
NCEP	(66.1, 26.1)	-54.3	1004	(73.3,33.3)	15.3	16750	(164.5, 27.8)	4.1	5860
HME-NCEP	(-1.9, -0.3)	-5.2	0	(-0.1, -0.8)	-0.8	-150	(0.2, -1.8)	-1.1	0
LME-NCEP	(-6.7, -2.4)	31.21	4	(-2.3, -1.8)	-0.8	-1400	(-8.7, -1.8)	-3.6	-10



406

407 **Figure 11.** Upper panel (a) shows 850hPa wind vectors (ms^{-1}), 500hPa geopotential height (contours)
 408 and sea level pressure (shading) as depicted in NCEP reanalysis. Middle panel (b) shows 850hPa
 409 wind vectors (ms^{-1}), the critical lines f_0 to delimit the outside edge of the western North Pacific
 410 subtropical high (solid line in red) and the Indian low (dotted line in red) as depicted in HME (critical
 411 lines of NCEP reanalysis are also marked in black contours). Shading represents 850hPa meridional

412 wind deviation from NCEP (ms^{-1}). Lower panel (c) is the same as (b), but for LME (critical lines are
413 in blue instead of red). 850hPa wind vectors are omitted when smaller than 3 m/s in the three panels.

414 From the above analyses, we can see that HME, with an improvement of the
415 atmospheric circulation, does improve precipitations in East China. Similarly, LME with a
416 deterioration of the atmospheric circulation shows bad performance for the regional
417 precipitation. We want now to confirm this conclusion through compositing all models for
418 HME and LME. We also want to investigate the relevant physics behind this relationship, in
419 particular, how water vapor transport can influence wetness or dryness in the region. Figure
420 11(a) shows 850hPa wind fields representing the low-level water vapor paths over and
421 surrounding East Asia from NCEP data. It can be seen that, the main components of the water
422 vapor paths for East China include the southwesterly flows along the east coast of the Arabian
423 Peninsula, the southwesterly flows and westerlies extending from the Arabian Sea to the
424 Philippines, the southerlies from the South China Sea, and the southeasterly flows along west
425 flank of the Western North Pacific Subtropical High. Previous studies show that this water
426 vapor path from the Arabian Sea to East China exerts an important influence on the
427 precipitation in East China (Jiang et al., 2015; Simmonds et al., 1999; Tao and Chen, 1987;
428 Xu et al., 2008).

429 HME depicts well these water vapor paths. The southwesterly flows in East China are
430 well reproduced, especially for the meridional wind fields in Southeast China (shaded in FIG
431 11b), which are very close to what depicted in NCEP data. Moreover, HME has an excellent
432 performance for both intensity and location of the Indian low and the western North Pacific
433 subtropical high. The accurate simulation of the closed-circulation systems in the region can

434 certainly explain the good simulation of 850hPa wind fields. For LME, the western boundary
435 of the western North Pacific subtropical high locates westward to around 110°E, shifted
436 nearly 9 degrees in longitude compared with NCEP (FIG.11c). This situation, that is, under
437 control of the high-pressure system and with too-strong southwest flows, is not favorable to
438 generate precipitation in Southeast China. Hence, LME shows large dry biases in this region.
439 This result is in agreement with our expectation. An accurate simulation of the regional
440 closed-circulation systems, especially the western North Pacific subtropical high, is a
441 guarantee to produce good precipitations in East China.

442 **5 Conclusion**

443 In this paper we revisited the issue about CMIP5 models capability of simulating the
444 regional atmospheric general circulation in East Asia during summer when the summer
445 monsoon plays a dominant role. The particularity of our investigation resides in the
446 utilization of closed-circulation systems, a concept fully relevant and applicable in the region,
447 but insufficiently explored until now in evaluation of climate models. We paid attention on
448 three closed-circulation systems: the South Asian high (SAH), the western North Pacific
449 subtropical high (WNPSH) and the Indian low (IL) at upper, middle and lower troposphere.
450 All models can basically simulate the three closed-circulation systems, although there is a
451 certain inter-model spread and most models underestimate the intensity of the three closed-
452 circulation systems. For the center location, models have the best performance for the South
453 Asian high and the poorest performance for the western North Pacific subtropical high. The
454 latter shows a westward shift by about 6 degrees in longitude in multi-model ensemble
455 average, compared to NCEP reanalysis.

456 With a set of quantitative measures served as assessment tools, high-skill models which
457 have good comprehensive performance for atmospheric circulation and low-skill models
458 which have the opposite properties are identified respectively. The identification of models
459 capability of simulating the regional atmospheric general circulation has a very pragmatic
460 utility for climate downscaling, since it allows us to select driving models with an adequate
461 consideration for uncertainties in climate simulation. Although the ranking of models
462 depends on the actual measures used for assessment, both groups of high-skill models and
463 low-skill models show consistent behaviors and performances among models for all
464 measures. With our comprehensive and quantitative evaluation, CCSM4, CNRM-CM5,
465 CESM1-CAM5 and NorESM1-M are identified as the high-skill models for simulating the
466 East Asian atmospheric circulation.

467 The investigation presented here also constituted an occasion for us to check the
468 consistency between models biases in circulation and those in precipitation in East China.
469 This issue is not a trivial question and very few works in the literature investigated it. We
470 analyzed the atmospheric circulation and precipitation in East China from the high-skill
471 models ensemble (HME) and the low-skill models ensemble (LME). This analysis helps us
472 to confirm that biases in the atmospheric circulation impacts biases in precipitations. HME
473 (selected from models performance on atmospheric circulation over East Asia) shows a better
474 simulation of precipitations in East China as well, with 21.3% decrease of dry biases in
475 Southeast China. It was also shown that the physical explanation for this linkage resides in
476 the center position of the western North Pacific subtropical high which determines the quality
477 of 850hPa winds and water vapor transport in Southeast China.

478 Our quantitative evaluation also reveals some other findings as summarized in the
479 following. CMIP5 models that we examined in this work have generally a suitable capability
480 of simulating the mean state of atmospheric circulation over East Asia. Our five inspected
481 atmospheric fields are well reproduced as a whole. Their Taylor-S indices are larger than
482 0.84 for 90% of the models. The best performance is for the 500hPa geopotential height with
483 an average Taylor-S index of 0.98. Models skill in simulating the sea level pressure is the
484 lowest, with a Taylor-S index of 0.79. It shows however a significant positive correlation
485 with models resolution. Almost all models underestimate 100hPa geopotential height over
486 East Asia, mainly due to the quite common cold bias in the troposphere.

487 In terms of methodology, the algorithm that we used to determine indices for closed-
488 circulation systems has the advantage to be applicable for future global warming scenarios.
489 In fact, the critical value dynamically selected as the most outside closed iso-line allows us
490 to deal with models systematic errors in relation to cold biases of the troposphere, as well as
491 to deal with the rising trend of geopotential height in global warming scenarios. He et al.
492 (2018) showed that an 80% fraction of geopotential height rise is attributable to zonal
493 uniform warming through a calculation with the hypsometric equation. Our calculation of
494 closed-circulation-system indices shows very good properties, although an advanced
495 comparison with the algorithm using the concept of eddy geopotential height (He et al., 2018)
496 needs to be done in the future.

497 Finally, we look forward to applying our diagnostics to new CMIP6 simulations which
498 will be soon available. We believe that what we developed in this paper will provide a

499 quantitative measure in the assessment of forthcoming CMIP6 simulations, with a
500 meaningful comparison to CMIP5 simulations.

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