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Bimodality of the South Asia High Simulated by Coupled Models

ZHOU Ningfang*[1,2,3] (周宁芳), YU Yongqiang[2] (俞永强), and QIAN Yongfu[3] (钱永甫)

[1] *National Meteorological Center, China Meteorological Administration, Beijing* 100081

[2] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[3] *Department of Atmospheric Sciences, Nanjing University, Nanjing* 210093

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ABSTRACT

The observed South Asia High (SAH) center is characterized by two distinctive equilibrium modes during boreal midsummer, namely the center of SAH is located between 82.5°–92.5°E for the Tibetan Plateau mode and between 55°–65°E for the Iranian Plateau mode, respectively. The present study describes the ability of 15 coupled general circulation models (CGCM) used in the Intergovernmental Panel on Climate Change's (IPCC) 4th Assessment Report to reproduce the observed bimodality of the SAH. These models reveal a wide range of skill in simulating this bimodality. Nearly half of the models reproduced the bimodality, while the other half of the models did not simulate well these two modes whereas usually preferring one mode. The models that reproduced the bimodality of the SAH present similar horizontal and vertical circulations as those features from the NCEP reanalysis data. The results from these models identify the warm characteristics of the SAH and indicate that these two modes have different dynamic and thermodynamic properties.

Different characteristics of the simulated sensible heat and latent heat related to precipitation partly contribute to the difference in the simulations of the SAH bimodality. The majority of these models that prefer to simulate the Tibetan Plateau mode produce a small sensible heat flux difference between the Iranian Plateau and the Tibetan Plateau, and also generally simulate a very strong false precipitation center over the east of the Tibetan Plateau, which indicates strong latent release and thereby contributes to the preference of the SAH center on the Tibetan Plateau. Whereas, the models that reproduce the bimodality of the SAH tend to simulate large precipitation over the southern Himalayas and no obviously false precipitation is produced over the east of the Tibetan Plateau. In addition, the model's resolution may also have important impacts on the simulations of precipitation.

Key words: South Asian High, bimodality, coupled GCM

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1. Introduction

The Third Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) pointed out that one of the most important missions to improve climate modeling is to reduce the uncertainties as much as possible. Examination of model simulations, particularly intercomparison among various models, is very essential to point out the uncertainties in model simulations. Many modeling groups around the world have participated in an unprecedented set of coordinated 20th and 21st century climate change experiments for the IPCC Fourth Assessment Report (AR4) since 2004. The resulting multi-model dataset becomes a unique and valuable resource that enables international scientists to assess model performance, model sensitivity, and model response to a variety of forcings for the 20th and 21st century climates and climate change.

The South Asia High (SAH) is the strongest and

*Corresponding author: ZHOU Ningfang, zhounf@cma.gov.cn

steadiest circulation system at 100 hPa over the Northern Hemisphere besides the polar vortex. Suggested by Mason and Anderson (1958), Tao and Zhu (1964) did research and noticed the relationship between the variation of the SAH and the advance and retreat of the West Pacific Subtropical High. They found that the variation of the SAH location has a significant influence on weather over China. From that time on, especially after the first Tibetan Plateau science experiment carried out in 1979, the SAH has been widely investigated. As one of the leading components of the Asian summer monsoon, the SAH is closely related to the atmospheric circulation (Ye and Zhang, 1974; Zhu et al., 1980; Zhu and Song, 1981; Sun and Song, 1987; Zhang et al., 1988; Sun and Chen, 1988; Wu et al., 2000; Qian et al., 2002) and also has significant influences on summer rainfall anomalies in China (Li, 1996, 2000; Zhang et al., 2000; Zhang and Wu, 2001; Qian et al., 2004; Huang and Qian, 2003; Huang and Qian, 2004). At present, the activities of the SAH have been regarded as an important predictor for summertime weather and climate prediction in China. Due to the importance of the SAH, in the present study, we will analyze the multi-model simulation results used in the IPCC AR4 to examine the ability of these models to reproduce the observed spatial and temporal structure of the SAH.

One of the dominant climate characteristics of the SAH is the bimodality during midsummer, namely the Tibetan Plateau (TP) mode and the Iranian Plateau (IP) mode. These two modes have different influences on the climate anomaly over East Asia in the summer (Zhang et al., 2002), and correct simulation of these two modes is a precondition to obtain the correct prediction of weather over East Asia (Zhou et al., 2006). Thereby, the aim of this study is to examine the ability of 15 coupled models to simulate the two equilibrium modes of the SAH, and to enhance our understanding of the related dynamical processes.

2. Participating models and validation data

We compared the results from the 15 models listed in Table 1 in this study. The monthly mean geopotential height, horizontal wind components, vertical velocity, surface sensible heating flux and rainfall of the 20th century climate change experiment (20C3M) from these models are utilized. The detailed experimental design is available from http://www-pcmdi.llnl.gov. Each model has a 150-year integration, and the model output during the last 50 years (1950–1999) is used in this study.

In order to assess these modeling results, monthly mean reanalysis data from NCAR/NCEP (Kalnay et al., 1996) and observed precipitation (Xie and Arkin, 1996) are used to compare with the model results. All the observation-based data are from the same period as the model results, which is from January 1950 to December 1999.

3. Simulated bimodality of the South Asia High

3.1 *Statistical characteristics of the bimodality*

The SAH has strong zonal variations in spring and autumn, but is very steady longitudinally from July to August (Zhou et al., 2006), so the data for July and August over the period of 1950–1999 are analyzed in the present study. Monthly mean NCEP reanalysis data shows that the center of the SAH mainly lies over two longitude boxes, namely 55°–65°E and 82.5°–

Table 1. The models used in this study.

Model	Country	Resolution (Atmosphere)	Resolution (Ocean)	Reference
CGCM3.1 (t47)	Canada	T47L31	1.85°×1.85° L29	Flato and Boer (2001)
CGCM3.1 (t63)	Canada	T63L31	1.4° × 0.94° L29	Flato and Boer (2001)
CNRM-CM3	France	T63L45	2.0° × 0.5° L31	Deque and Piedelievre (1995)
GFDL_CM2.0	USA	2.5° × 2.0° L24	1.0° × 0.33° L50	Delworth et al. (2004)
GFDL_CM2.1	USA	2.5° × 2.0° L24	1.0° × 0.33° L50	Delworth et al. (2004)
FGOALS_g1.0	China	T42L26	1.0° × 1.0° L33	Yu et al. (2004)
INM-Cm3.0	Russia	5.0° × 4.0° L21	2.5° × 2.0° L33	Volodin and Diansky (2004)
IPSL_CM4	France	2.5° × 3.75° L19	2.0° × 0.5° L31	Goosse and Fichefet (1999)
MIROC3.2 (hires)	Japan	T106L56	0.28° × 0.19° L47	K-1 model developers (2004)
MIROC3.2 (medres)	Japan	T42L20	1.4° × 0.5° L43	K-1 model developers (2004)
ECHAM5	Germany	T63L31	1.5° × 0.5° L40	Roeckner et al. (2003)
MRI-CGCM2.3.2	Japan	T42L30	2.5° × 0.5° L23	Yukimoto et al. (2001)
CCSM3	USA	T85L26	1.125° × 0.27° L40	Kiehl and Gent (2004)
UKMO_HadCM3	UK	3.75° × 2.5° L19	1.25° × 1.25° L20	Gordon et al. (2000)
UKMO_HadGEM1	UK	1.87° × 1.25° L38	1.0° × 0.33° L40	Gordon et al. (2000)

Table 2. Frequency numbers (months) of the Tibetan Plateau mode and the Iranian Plateau mode and the corresponding mean location of the SAH center.

model	Tibetan Plateau mode			Iranian Plateau mode		
	Number	Lat (°N)	Lon (°E)	Number	Lat (°N)	Lon (°E)
NCEP	53	31	85	40	33	59
CCSM3	5	28	82	10	31	58
CGCM3.1 (t47)	24	31	82	24	35	59
CGCM3.1 (t63)	18	32	86	18	34	59
CNRM-CM3	16	34	84	2	36	61
ECHAM5/MPI-OM	23	31	85	28	33	60
FGOALS-g1.0	37	32	84	0		
GFDL-CM2.0	2	29	84	50	33	58
GFDL-CM2.1	29	32	88	18	33	60
INM-CM3.0	37	36	86	21	39	61
IPSL-CM4	11	28	88	1	29	63
MIROC3.2 (hires)	49	29	83	24	31	60
MIROC3.2 (medres)	27	28	86	4	32	56
MRI-CGCM2.3.2	56	29	84	1	34	56
UKMO-HadCM3	26	36	88	18	34	56
UKMO_HadGEM1	33	37	84	8	37	58

92.5°E corresponding to the Iranian Plateau mode and the Tibetan Plateau mode, respectively. It scarcely appears near 70°–80°E, which is consistent with the results from pentads mean data (Zhang et al., 2002). Table 2 lists the numbers (months) of the Tibetan Plateau mode, the Iranian Plateau mode and the corresponding mean location of the SAH center. Among the total 100 months there are 53 months that the SAH is in the Tibetan Plateau mode (82.5°–92.5°E) and 40 months in the Iranian Plateau mode (55°–65°E).

The 15 models show a wide range of ability in reproducing the bimodality of the SAH. All models simulate a high frequency in 70°–80°E that is different from the NCEP data. Seven models [i.e., CGCM3.1 (t47), CGCM3.1 (t63), GFDL-CM2.1, INM-CM3.0, MIROC3.2 (hires), ECHAM5 and UKMO_HadCM3] basically can simulate the bimodality of the SAH, with the frequency of the SAH longitude center appearing in the right range relatively high, there are more than 18 correct locations for each mode. Other models present obvious bias, such as in MRI-CGCM2.3.2, Fgoals-g1.0, MIROC3.2 (medres) and UKMO-HadGEM1, in which the SAH longitude center mainly locates in the range of the Tibetan Plateau mode, while it is in the range of the Iranian Plateau mode in the GFDL-CM2.0 simulation. The SAH center from the other three simulations scarcely appears in the range of either mode, but lies in the range of 95°E to the east, such as in CNRM-CM3 and IPSL-CM4, or in the range of 50°E to the west, such as in CCSM3. In addition, the simulated Iranian Plateau mode tends to be further northward than the Tibetan Plateau mode in most models similar to the results of the NCEP reanalysis data, whereas INM-CM3.0 and UKMO-HadGEM1 simulate the location of the SAH center is to the north of 36°N.

3.2 *Vertical circulation features of the bimodality of the SAH*

The Tibetan Plateau mode is closely related to the diabatic heating of the Tibetan Plateau, whereas the Iranian Plateau mode is rather associated with the adiabatic heating in the free atmosphere (Zhang et al., 2002). Figure 1 presents a pressure-longitude section of the mean and anomalous vertical circulation and temperature anomalies along the center latitude of the Tibetan Plateau mode and the Iranian Plateau mode for the NCEP reanalysis and models simulations. The mean circulation based on the NCEP reanalysis shows that the strong ascending motion dominates the whole troposphere and is up to 100-hPa over the Tibetan Plateau and the ascending motion over the Iranian Plateau is weaker obviously and limited to lower levels. Anomalous ascending over the Tibetan Plateau enhances the climatological mean ascending, which is accompanied with the anomalous warm column in the Tibetan Plateau mode. In the case of the Iranian Plateau mode, the ascending motion over the TP is reduced, but anomalous ascending over IP is strengthened, which alleviates the mean descending circulation, and is accompanied with the anomalous warm column.

The bimodality from 7-model simulations is compared, and MIROC3.2 (hires), GFDL-CM2.1 and ECHAM5 give the best performance in simulating the mean vertical circulation, which also reproduce the bimodality of the SAH. Vertical motions from the

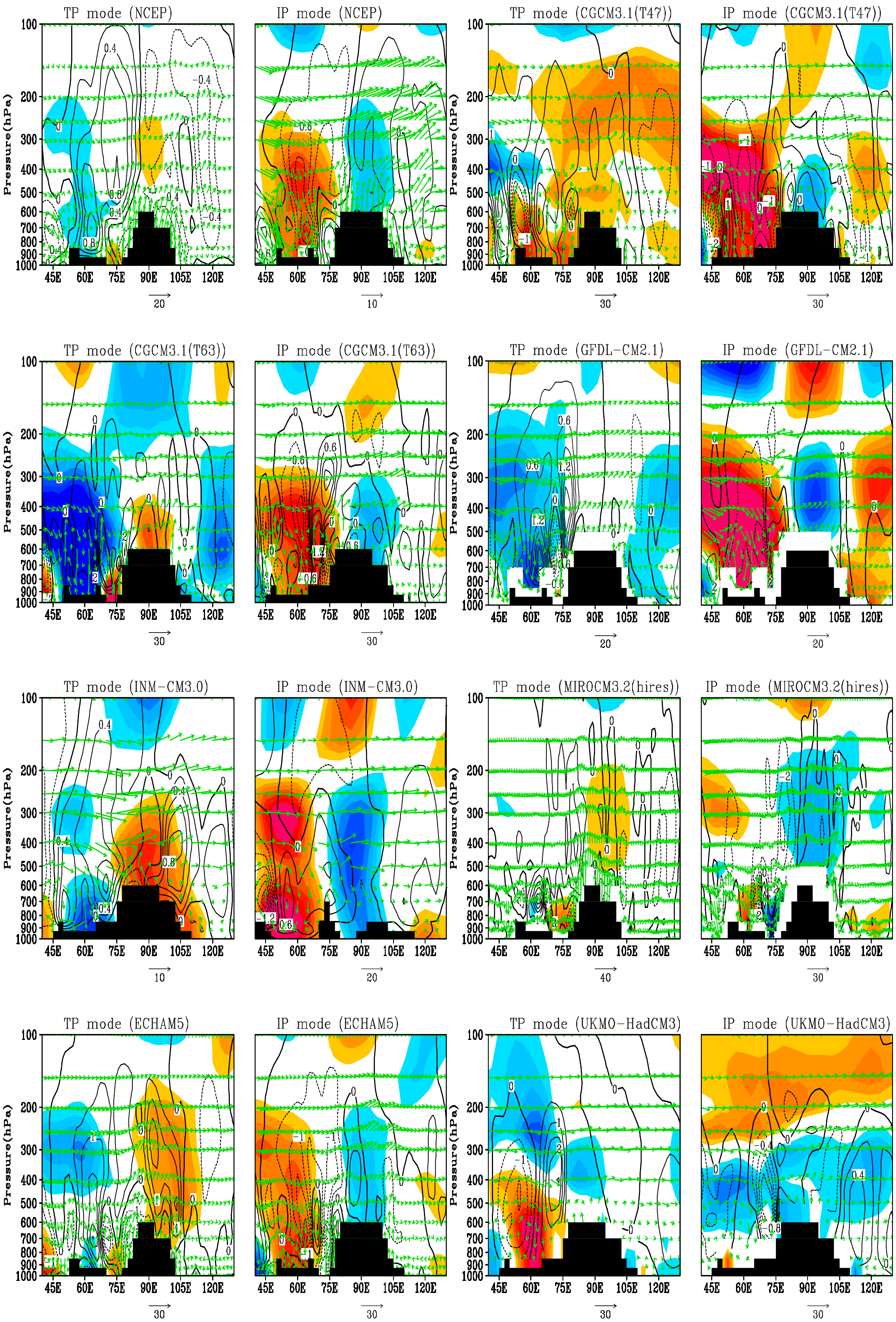

Fig. 1. The pressure-longitude section of the mean (vector) and anomalous vertical circulation (contour) and temperature anomalies (shaded, Units: K) for the Tibetan Plateau mode and the Iranian Plateau mode for the NCEP reanalysis and the models, along the latitudes of the corresponding mode center.

other models are only up to the middle-low troposphere (below the 300-hPa level), while the mean westerly wind dominates the upper troposphere for both modes. Almost all of the models except INM-CM3.0 basically reproduce the anomalous descending motion over both plateaus. Except the UKMO_HadCM3, the other models reproduce the warm (cold) column for both modes, and the SAH center prefers the warm anomalies.

4. Discussions

Besides the 7 models analyzed above, the other 8 models, i.e., MRI-CGCM2.3.2, FGOALS-g1.0, MIROC3.2 (medres), CNRM-CM3, IPSL-CM4, UKMO-HadGEM1, GFDL-CM2.0 and CCSM3, fail to simulate the bimodality of the SAH. Therefore, these simulation results need to be further investigated to enhance our understanding.

4.1 *Sensible heating*

Diabatic heating has been regarded as an important factor for the formation and maintenance of the SAH, so it may also contribute to the modeling bias. Figure 2 reveals the differences of the sensible heat flux between the Iranian Plateau (25°–35°N, 55°–75°E) and the Tibetan Plateau (25°–35°N, 75°–105°E). For the NCEP reanalysis this difference is about 67 W m^{-2}. Note that, for MRI-CGCM2.3.2, the difference is negative (about −0.85 W m^{-2}) indicating a larger sensible heat flux over the Tibetan Plateau than that over the Iranian Plateau, which is very unrealistic compared to the NCEP reanalysis. In other models, the sensible heat flux over the Iranian Plateau is larger than that over the Tibetan Plateau, similar to the NCEP reanalysis. Models that produce too small sensible heat flux difference between the Iranian Plateau and the Tibetan Plateau, i.e., FGOALS-g1.0，MRI-CGCM2.3.2, CNRM-CM3, IPSL-CM4 and UKMO-HadGEM1，also tend to simulate a higher frequency of the Tibetan Plateau mode (see Table 2). Small differences in the sensible heat flux between the Iranian Plateau and the Tibetan Plateau indicates the relatively lager sensible heat flux over the Tibetan Plateau, which maybe contribute, on some extent, to the preference of the SAH center lying over the Tibetan Plateau in these models.

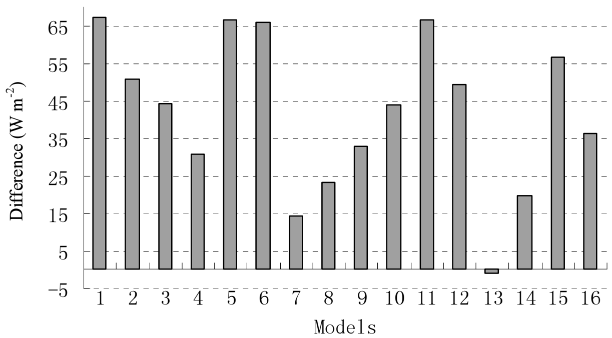

Fig. 2. Differences of the sensible heating fluxes between the Iranian Plateau (25°–35°N, 75°–105°E) and the Tibetan Plateau (25°–35°N, 75°–105°E) from NCEP reanalysis and participating models. (Units: W m^{-2}). 1. NCEP, 2. CGCM3.1 (t47), 3. CGCM3.1 (t63), 4. CNRM-CM3, 5. GFDL_CM2.0, 6. GFDL_CM2.1, 7. FGOALS-g1.0, 8. INM-CM3.0, 9. IPSL-CM4, 10. MIROC3.2 (hires), 11. MIROC3.2 (medres), 12. ECHAM5, 13. MRI-CGCM2.3.2, 14. CCSM3, 15. UKMO_HadCM3, 16. UKMO-HadGEM1.

4.2 *Mean precipitation*

Latent heat resulted from precipitation is also one of the important factors that influence the position of the SAH. Figure 3 shows the mean summer precipitation from CMAP and 15 models. In order to investigate the warm center of the upper troposphere that can reflect the location of the SAH center, the temperature at the 300 hPa level is also showed. The observations show that there is intense rainfall over South Asia with the center in the eastern Bengal Bay. The warm center at 300-hPa also lies over the northeastern part of the Bengal Bay. These results suggest that there is a close relationship between the precipitation and the warm center at the 300-hPa level.

There is a wide range of skills in simulating the precipitation from these models. For instance, CGCM3.1 (t47), CGCM3.1 (t63), GFDL_CM2.1, MIROC3.2 (hires), ECHAM5 and UKMO_HadCM3 that reproduce the bimodality of the SAH but also tend to simulate the largest precipitation center over the southern Himalayas, and false precipitation over the eastern TP. Some models (i.e., FGOALS-g1.0, MIROC3.2 (medres), CNRM-CM3, and IPSL-CM4), which tend to simulate one mode over the TP or to the east generally, produce a very strong false precipitation center over the eastern TP. The overestimated precipitation over the eastern TP indicates too large latent heat, which may contribute to the preference of the TP mode in these models. Comparing all 15 models, it reveals that the resolution of these models, to some extent, is responsible for the overestimated precipitation over the eastern TP. High resolution models, for instance, MIROC3.2 (hires), ECHAM5, CCSM3 and UKMO-HadGEM1, tend to simulate the largest precipitation center over the Bengal Bay, without overestimating precipitation to the east of the TP. However, GFDL-CM2.1 gives a better simulation of

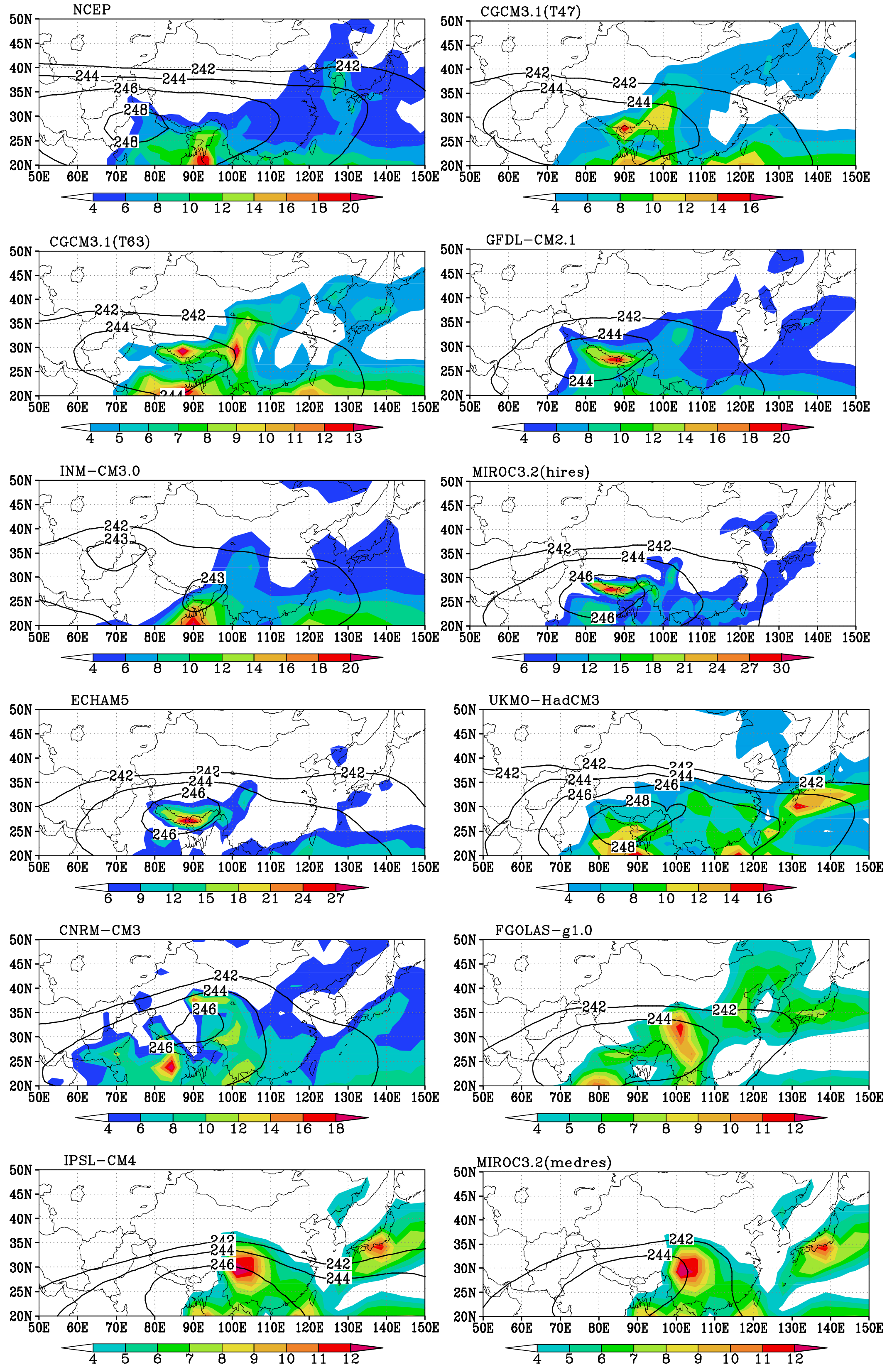

Fig. 3. Mean precipitation (mm d^{-1}; shaded) and temperature (K, contour)at 300 hPa for July–August from CMAP and participating models simulation.

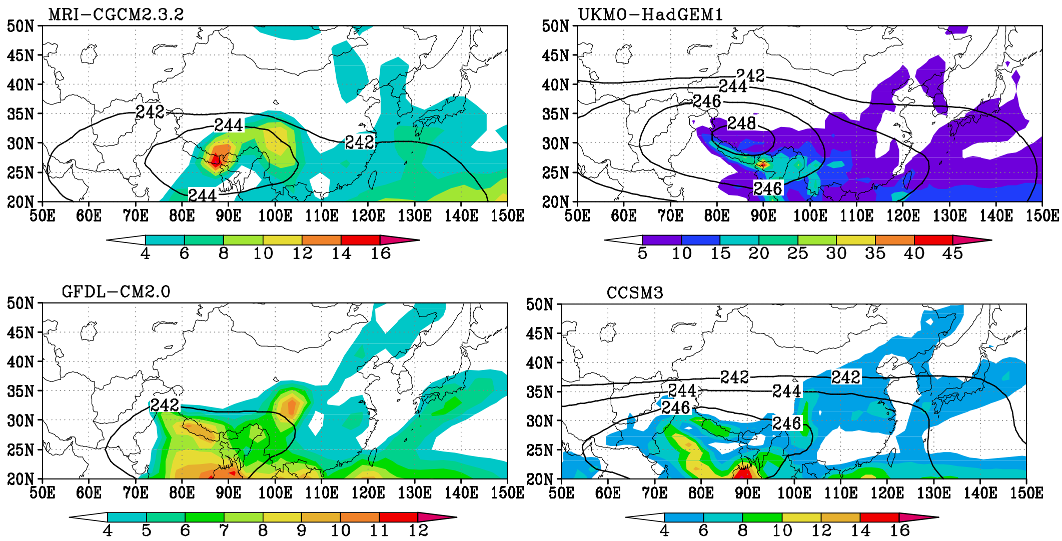

Fig. 3. (Continued).

precipitation than CM2.0 in spite of the identical horizontal resolution, which maybe because the finite difference is applied in the CM2.0 while the finite volume is applied in CM2.1.

5. Summary

Using the 20th century climate simulations for the 4th IPCC Assessment Report, the ability of 15-coupled models simulating the bimodality of the South Asia High is investigated through a detailed comparison with the NCEP reanalysis data. Observational data shows that, according to its preferable location, the SAH center has two equilibrium modes during midsummer, namely the Tibetan Plateau mode and the Iranian Plateau mode.

These models display a considerable wide range of skill in simulating the bimodality of SAH High. Nearly half of the models can simulate this most salient feature, although the longitudinal location of the simulated SAH center is too sparse relative to the NCEP reanalysis and there are cases when the SAH center appears near 70°–80°E where the SAH center is hardly observed in the NCEP reanalysis. The other half of the models fail to simulate the bimodality of the SAH and tend to have only one equilibrium mode. However, it is interesting in these models, the majority prefer to generate the Tibetan Plateau mode [i.e., FGOALS-g1.0, MIROC3.2 (medres), MRI-CGCM2.3.2, CNRM-CM3 and IPSL-CM4], except that the GFDL-CM2.0 and CCSM3 prefer to simulate the Iranian Plateau mode. The majority of the models that reproduce the bimodality of the SAH present similar horizontal and vertical circulations associated with the bimodality with the NCEP reanalysis. These model results also identify the feature of a warm preference of the SAH, which indicates that its two modes have different dynamic and thermodynamic properties, namely that the Tibetan Plateau mode is a thermal-induced high, related to the distributions of the diabetic heating over the Tibetan Plateau, while the Iranian Plateau mode is dynamically induced.

Many factors may be responsible for these different simulations of the bimodality. Further analyses focus on the sensible heat and precipitation related to latent heat. The NCEP sensible heat flux over the Iranian Plateau is much larger than that over the Tibetan Plateau. The majority of the models that prefer to simulate the Tibetan Plateau mode also produce too small a heat flux difference between the Iranian Plateau and the Tibetan Plateau, i.e., FGOALS-g1.0, MRI-CGCM2.3.2, CNRM-CM3, IPSL-CM4 and UKMO-HadGEM1.

Evaluation of the precipitation suggests that the related latent heat release may also contribute to the formation of the SAH. These participating models show a wide range of skill in simulating the precipitation. The models that reproduce the bimodality of the SAH also tend to simulate the large precipitation over the southern Himalayas without a false precipitation center over the eastern Tibetan Plateau. On the other hand, most models that prefer to simulate the Tibetan Plateau mode generally produce a very strong false precipitation center over the eastern Tibetan Plateau, which indicates strong latent release that thereby contributes to the preference of the SAH center on the Tibetan Plateau. The resolution of these models also has important impacts on simulations of the precipitation.

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