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Comparison of convective parameterizations in RegCM4 experiments over China with CLM as the land surface model

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Abstract

In the latest version of the International Centre for Theoretical Physics' regional climate model, RegCM4, CLM was introduced as a new land surface scheme. The performance over China of RegCM4-CLM with different convection schemes is analyzed in this study, based on a series of short-term experiments. The model is driven by ERA-Interim data at a grid spacing of 25 km. The convection schemes employed are: Emanuel; Grell; Emanuel over land and Grell over ocean; Grell over land and Emanuel over ocean; and Tietdke. The simulated mean surface air temperature and precipitation in December–February–January and June–July–August are compared against observation. In general, better performance of Emanuel is found both for temperature and precipitation, and in both seasons. Thus, the model physics of CLM and Emanuel for the land surface processes and convection, respectively, are recommended for further application of RegCM4 over the China region. The deficiencies that remain in the model are also outlined and discussed.

区域气候模式 RegCM 最新版中引入了新的陆面模式 CLM，为了考察在选用 CLM 时不同对流参数化方案在中国地区的表现，本文进行了五种不同对流参数化方案下—Grell、Emanuel、Tietdke，Mix（陆地上位 Emanuel 方案，海洋上为 Grell 方案）和 Mix2（陆地上为 Grell 方案，海洋上为 Emanuel 方案）的模拟试验。将模拟的冬、夏季平均气温和降水与观测进行了对比分析，结果表明，Emanuel 方案是综合模拟效果最好的。在使用 RegCM-CLM 进行中国区域模拟研究时，对流参数化方案推荐选为 Emanuel。

1. Introduction

Previous studies have shown that model resolution is very important in reproducing present climate in China more successfully, and high resolution RCMs in particular can improve the simulation of East Asian monsoon climate, compared with the driving GCM (Gao et al. 2006, 2012; Yu, Wang, and Sun 2010). In climate change projections, high resolution RCMs can introduce a fine-scale topography-induced structure in the climate change signal. In addition, they can also simulate different patterns of change compared with the driving GCM. The differences are mainly due to the stronger and more realistic topographic forcings in the RCM, and the resulting circulation and moisture flux changes (Gao et al. 2008). This further emphasizes the importance of using RCMs for climate change projections and to produce better impact assessments.

Of the various RCMs that have been applied over the China region, the RegCM series (Giorgi, Marinucci, and Bates 1993; Giorgi et al. 1993; Pal et al. 2007; Giorgi et al. 2012) is the most commonly used. As the first limited-area model developed for long-term regional climate simulation, its application over East Asia can be dated back to the early 1990s (e.g., Liu, Giorgi, and Washington 1994), and has since been widely used in a variety of studies (e.g., Zhang et al. 2015). As a community model, RegCM is a public, open source, and user-friendly tool, with portable code, that can be easily applied to any region of the world. It is also supported through the Regional Climate Research Network, or RegCNET, which is a widespread network of scientists coordinated by the Abdus Salam International Centre for Theoretical Physics (http://users.ictp.it/ RegCNET/).

Compared with the previous version (RegCM3; Pal et al. 2007), the latest release (RegCM4) has undergone substantial development both in terms of its software code and physical representations (Giorgi et al. 2012). One of the most important improvements in the model physics is the introduction of CLM (Dai et al. 2003; Oleson et al. 2008) as an option to describe land surface processes, i.e., in addition to BATS (Dickinson, Henderson-Sellers, and Kennedy 1993), which had been used solely for many years in the model. A brief introduction to BATS and CLM in RegCM4 can be found in Giorgi et al. (2012) and Halder, Dirmeyer, and Saha (2015).

Previous studies have shown that the model performs well when using BATS over the East Asia region (e.g., Gao et al. 2012). Furthermore, while CLM offers improvements in terms of land–atmosphere exchanges of moisture and energy and associated surface climate feedbacks compared with BATS (Steiner et al. 2009), its use may lead to a poorer performance of RegCM compared with the relatively simple land-surface model of BATS; for example, over India, as reported by Halder, Dirmeyer, and Saha (2015). Thus, the performance of RegCM4 when using CLM (RegCM4-CLM) needs to be evaluated before its further application in climate and climate change simulations.

Among the different physical processes in climate models, convective parameterization is usually considered the most important when simulating monsoon rainfall (Giorgi 1991; Leung et al. 2004; Im et al. 2008). Therefore, in the present study, based on a series of 1-yr long simulations, we examine the performance of RegCM4-CLM over East Asia when using different convection schemes, and try to identify the “best” option for future long-term climate change projections.

The paper is structured as follows: The model, experimental design, and datasets employed in the study are described in section 2; section 3 analyzes the model’s performance when using the different convection processes; and section 4 provides a brief summary and discussion.

2. Model, data, and experimental design

Since the release of RegCM4 (http://gforge.ictp.it/gf/project/regcm/), its physical representations have been subject to a continuous process of development and implementation. The version employed in the present study is RegCM4.4. The version of CLM in RegCM4.4 is CLM3.5 (Oleson et al. 2008), and the convection scheme options include a simplified version of the Kuo-type scheme of Anthes (Anthes, Hsie, and Kuo 1987), the Grell scheme (Grell 1993), the MIT-Emanuel scheme (Emanuel 1991), and the Tiedtke scheme (Tiedtke 1989). RegCM4.4 also has the option to run different convection schemes over land and ocean, referred to as ‘mixed convection’. More detailed information about the convection schemes employed can be found in Giorgi et al. (2012) and Im et al. (2008).

In the experiments, the Phase II East Asia domain of the Coordinated Regional Climate

Downscaling Experiment (CORDEX; Giorgi, Jones, and Asrar 2009) is used, which encompasses the whole of continental China and adjacent areas at a horizontal resolution of 25 km (http://www.cordex.org/index.php?option=com_content&view=article&id=88&Itemid=625). The model is run at its standard configuration of 18 vertical sigma layers, with the model top at 50 hPa. ERA-Interim data (Uppala et al. 2008) at a resolution of 1.5° latitude × 1.5° longitude are used to derive the initial and six-hourly updated lateral meteorological boundary conditions needed to drive the model.

Five experiments using the convection schemes of (1) Emanuel, (2) Grell, (3) Emanuel over land and Grell over ocean (Mix), (4) Grell over land and Emanuel over ocean (Mix2), and (5) Tiedtke (TDK), are conducted using RegCM4-CLM for the period 1 November 1999 to 30 November 2000. The first month is used for model spin-up and not included in the analysis. The simulations are compared against observation to select the “best” convection scheme for the model over the region. Based on previous experience, a 1-yr simulation is in general adequate to evaluate model performance, and the year 2000 has been randomly selected in this study.

Other model physics adopted in the experiments include PBL computations employing the non-local formulation of Holtslag, Bruijn, and Pan (1990), resolvable scale precipitation represented via the scheme of Pal, Small, and Eltahir (2000), and the atmospheric radiative transfer computed using the radiation package from CCM3 (Kiehl et al. 1998).

We focus our analysis on the mean surface air temperature and precipitation in the boreal winter of December–January–February (DJF) and summer of June–July–August (JJA) over mainland China. The observational dataset employed to validate the model simulations is CN05.1 (resolution: 0.25°×0.25°), developed by Wu and Gao (2013), which is an augmentation of CN05 (Xu et al. 2009). The model simulations are interpolated bilinearly to the same 0.25°×0.25° grids of CN05.1 to facilitate the comparisons.

3. Results

3.1 Temperature

We begin by validating the mean temperature in DJF simulated by RegCM4-CLM when using the different convection schemes (Figure 1). A distinct latitudinal distribution of the observed temperature is found in eastern China, with over 10°C in southern China and dropping to below −18°C in the northeast (Figure 1a). The temperature in western China shows a strong dependence on topography. Over the mountains in the northwest and the Tibetan Plateau, temperatures are lower than −18°C, but close to zero in the Tarim Basin.

In the model simulations, a dominant cold bias over most of China and a warm bias in the high latitude areas of Northeast and Northwest China are found (Figures 1b–f). The magnitude of the cold bias generally varies within the range 1°C–5°C, with the largest biases (exceeding 5°C) found mainly in the Tibetan Plateau. The above pattern of bias is broadly consistent to those reported for previous versions of RegCM over the same region (e.g., Zhang et al. 2008). It is noted that similar bias also exists in different generations of GCMs (e.g., Xu, Gao, and Giorgi 2010; Chen 2014; Jiang, Tian, and Lang 2015).

The mean temperature in JJA from observation and the bias in the simulations are provided in Figure 2. In JJA, the observed temperature shows a much weaker latitudinal distribution in eastern China, as compared to DJF. The temperature across the large area extending from the southern part of the northeast to the southern coast ranges from 24°C to 27°C, with more values of less than 30°C found in portions of North China, the middle and lower reaches of the Yangtze River, and Hua'nan along the southern coast. Temperatures warmer than 27°C are found in the basins in the northwest, and the lowest temperatures in the northern part of the Tibetan Plateau are found in western China.

The model bias in JJA is in general smaller than in DJF, and more sensitive to the choice of convection scheme, as can be expected (Figures 2b–f). Both the magnitude and distribution of bias show differences across the simulations. A mixture of warm and cold bias within ±2.5°C for Emanuel can be found, aside from the larger warm bias over the basins in the northwest where observations are lacking due to the sparse distribution of weather stations. The bias of Mix shows a similar pattern to that of Emanuel, but with larger values. A cold bias generally occurs over the region with Grell, reaching −2.5°C to −5.0°C in southern China and the Tibetan Plateau, and to a lesser extent in Mix2 also. The model produces results that are in general too warm when using TDK. An overall better performance when using the Emanuel scheme is evident in the figure.

The correlation coefficients between the model simulations and observation for temperature are high, at around 0.95 for DJF and 0.98 for JJA. For a better quantitative evaluation, the PDF distributions of the temperature bias in DJF and JJA are shown in Figure 3, and the percentages of grid points with bias within ±1°C over the region are summarized in Table 1. As shown in Figure 3a, a dominant cold bias in DJF is evident under the different convective schemes, with Emanuel and Mix showing lower magnitudes of bias compared to the others. For JJA, consistent with Figure 2, a large warm bias can be found for TDK, and a cold bias for Grell and Mix2 (Figure 3b). A normal mode type distribution of bias is apparent for the Emanuel and Mix experiments, indicative of relatively better performance. In terms of the bias within ±1°C (Table 1), generally more than double the amount of grid points are well simulated in JJA compared with DJF. The largest values in DJF are 26% (Emanuel) and 25% (Mix), while in JJA they are 55% (Emanuel) and 48% (Mix). Thus, the Emanuel scheme is further confirmed as the "best" with respect to temperature simulation.

3.2 Precipitation

The precipitation amounts in DJF from observation and the simulations are presented in Figure 4. In DJF, the winter monsoon brings cold and dry air to China from the polar regions, leading to very low precipitation over broad areas in the north, except the mountains. Precipitation greater than 50 mm is found along and south of the Yangtze River, with maxima of over 200 mm in the southeast (Figure 4a).

The model simulations in general capture the observed precipitation pattern, with an increasing gradient from the north to southeast (Figures 4b–f). However, substantial overestimation by up to a few factors are found over most of the northern areas, although the large values over the mountain chains may relate to uncertainties in the observational dataset (Wu et al. 2011). Conversely, the model underestimates the precipitation center in the southeast, both in magnitude and spread, except when employing TDK. The spatial correlation coefficients between the model simulations and observation are low, in the range of 0.16–0.27 (Table 1). Again, it is noted that these discrepancies have also been reported for previous versions of RegCM, using BATS, as well as in most GCM simulations (Zhang et al. 2008; Xu, Gao, and Giorgi 2010; Chen 2014; Jiang, Tian, and Lang 2015).

JJA is the monsoon season, with precipitation amounts of greater than 500 mm found in the south, and decreasing towards the north and northwest (Figure 5a). The pattern is in general simulated well by the model using the different convection schemes. The spatial detail in terms of the peak precipitation centers over smaller scale mountains versus the dryness in the nearby basins in the northwest are also reproduced well by the model.

A wetter than observed precipitation pattern in northern China is found when using Emanuel and Mix, while the model produces results that are too dry when using the Grell scheme. The TDK simulation shows considerable overestimation along the southern coast and over southwestern China, but underestimation in the northern part of the region. The largest values of spatial correlation coefficients for the simulations are found with Emanuel and Mix2, both at 0.64, followed by Mix at 0.60 (Table 1). Considering the good performance in the temperature simulation when employing Emanuel, we consider it to be the "best" convection scheme of RegCM4-CLM over the region.

Based on previous experience and studies, it is noted that use of the Emanuel convection scheme in RegCM3 and 4 tends to simulate too much precipitation when using BATS as the land surface scheme. This is mainly due to the fact that the Emanuel scheme responds quite strongly to heating from the surface and, once convection is triggered, it tends to become quite strong. BATS maximizes this response because, using a force–restore method with only two soil levels of depth up to some tens of centimeters, the surface temperatures respond quite strongly to the solar heating and thus the soil pumps sensible heat to the convection scheme. By contrast, CLM uses several soil layers down to a depth of several meters; therefore, the upper soil temperatures have more inertia and respond less strongly to the solar heating. In this way, the pumping of surface heat is lower and the Emanuel scheme is kept more stable, ultimately leading to a better performance in the combination of CLM with Emanuel. The combination of BATS with Grell also shows good performance; however, CLM tends to reduce the forcing of convection and this inhibits the triggering of the Grell scheme, which is less “reactive” than Emanuel to surface heating. Therefore, the precipitation amount is much reduced when using CLM, which is good for Emanuel but not good for Grell.

4. Summary and discussion

A series of experiments have been conducted by the newly released RegCM4 to evaluate its performance, when using CLM as the land surface process scheme, in simulating the present climatology over China. The sensitivity of the model to different convection schemes has also been tested and compared with observation. The main findings and conclusions can be summarized as follows:

(1) Compared with the previous version of RegCM, RegCM4-CLM also shows a general warm bias in the high latitudes and a cold bias elsewhere in the cold season of DJF. It tends to overestimate precipitation in the north and underestimate it in the southeast. These are also common features in many GCM simulations. The introduction of CLM does not significantly change the model’s behavior in this season. The Emanuel scheme shows generally better performance than the other schemes in RegCM4-CLM for DJF, in particular for temperature.

(2) For JJA, the Grell convection scheme, which also performs well in RegCM3 with BATS as the land surface scheme, exhibits a generally cold and dry bias in RegCM4-CLM (e.g. Gao et al. 2001, 2012; Gao, Wang, and Giorgi 2013). However, the model’s use of Emanuel with CLM agrees better with observed precipitation, as compared to the other schemes. Similar to RegCM3, better performance of RegCM4 over the region in JJA,

compared with DJF, is found both for temperature and precipitation.

(3) As a more advanced package compared to the previously used BATS, CLM can be considered as the primary land surface processes option in RegCM4. Therein, the use of the Emanuel convection scheme is recommended over the China region. We plan to use this configuration in long-term, multi-decadal simulations, to further evaluate the model’s capability in reproducing the mean climatology, as well as the variability and extremes over the region. Following this, we then intend to conduct climate change simulations under the CORDEX framework.

(4) It is important to note that climate models possess common deficiencies in their winter simulations for this region, characterized by a warm bias in high latitudes and underestimation of precipitation in the southeast. For RegCM4, a better performance in summer than in winter can be found. Substantial effort is needed in the future, including more extensive analysis of simulations, implementation, and testing of new physical processes in models, and more numerical experiments, to better understand and further improve climate models.

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Table 1. Percentages of grid points with a temperature bias of less than ±1°C, and spatial correlation coefficients between simulated and observed precipitation, in DJF and JJA, under the different convection schemes.

	Temperature (%)		Precipitation	
	DJF	JJA	DJF	JJA
Emanuel	26	55	0.21	0.64
Grell	14	32	0.16	0.44
Mix	25	48	0.19	0.60
Mix2	15	36	0.22	0.64
TDK	17	41	0.27	0.50

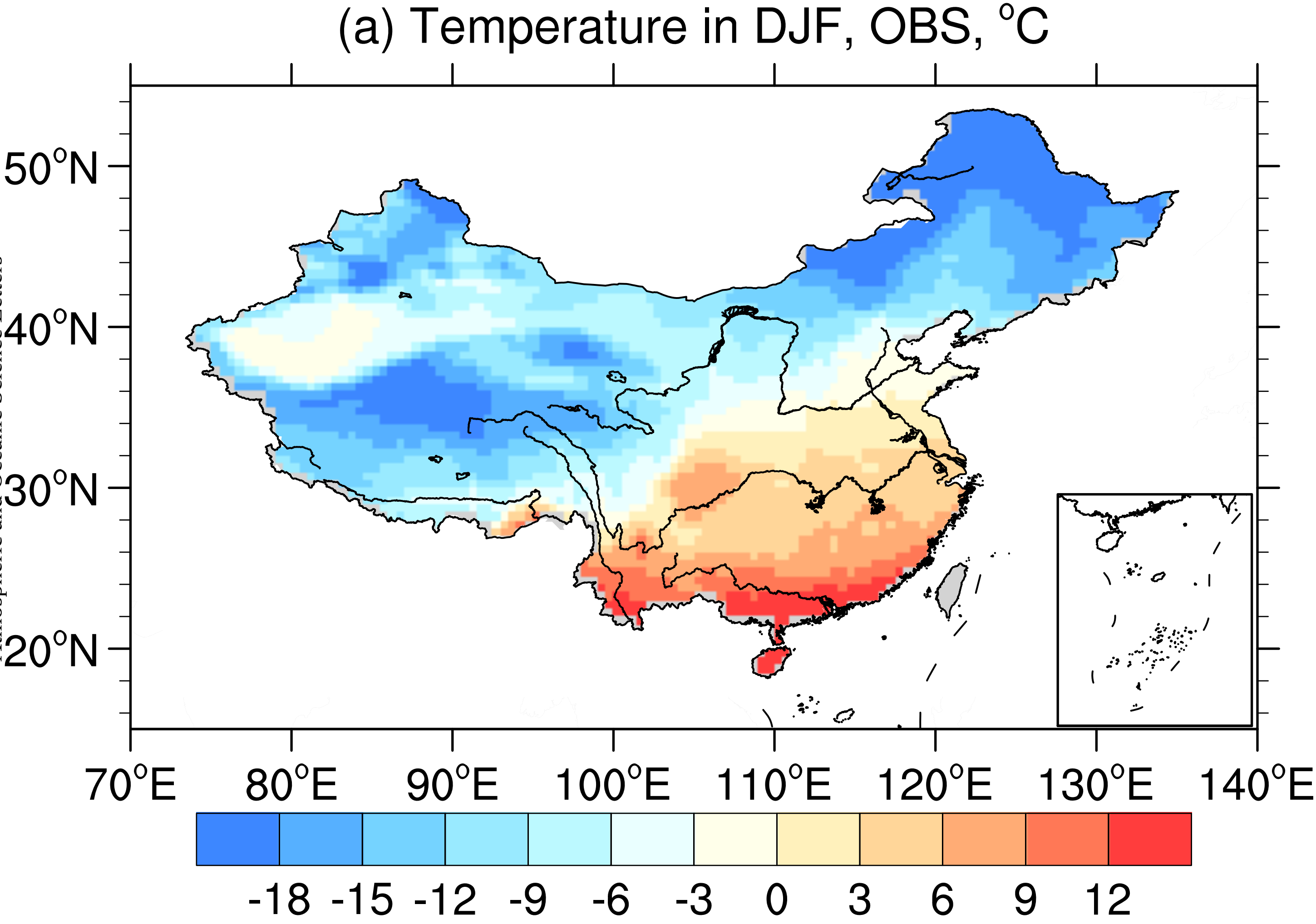
Figure 1. The (a) observed mean temperature in DJF, 1999–2000, over China, and (b–f) bias in the model when using different convection schemes (land only; units: °C): (b) Emanuel; (c) Grell; (d) Mix; (e) Mix2; (f) TDK.

Figure 2. The (a) observed mean temperature in JJA, 1999–2000, over China, and (b–f) bias in the model when using different convection schemes (land only; units: °C): (b) Emanuel; (c) Grell; (d) Mix; (e) Mix2; (f) TDK.

Figure 3. PDF distributions (%) of temperature bias in (a) DJF and (b) JJA, over China, derived from the model simulations using different convection schemes (land only; units: °C).

Figure 4. The (a) observed and (b–f) simulated mean precipitation in DJF, 1999–2000, over China (land only; units: mm): (b) Emanuel; (c) Grell; (d) Mix; (e) Mix2; (f) TDK.

Figure 5. The (a) observed and (b–f) simulated mean precipitation in JJA, 1999–2000, over China (land only; units: mm): (b) Emanuel; (c) Grell; (d) Mix; (e) Mix2; (f) TDK.


(a) Temperature in DJF, OBS, ^{o}C
50^{o}N
40^{o}N
30^{o}N
20^{o}N
70^{o}E
80^{o}E
90^{o}E
100^{o}E
110^{o}E
120^{o}E
130^{o}E
140^{o}E
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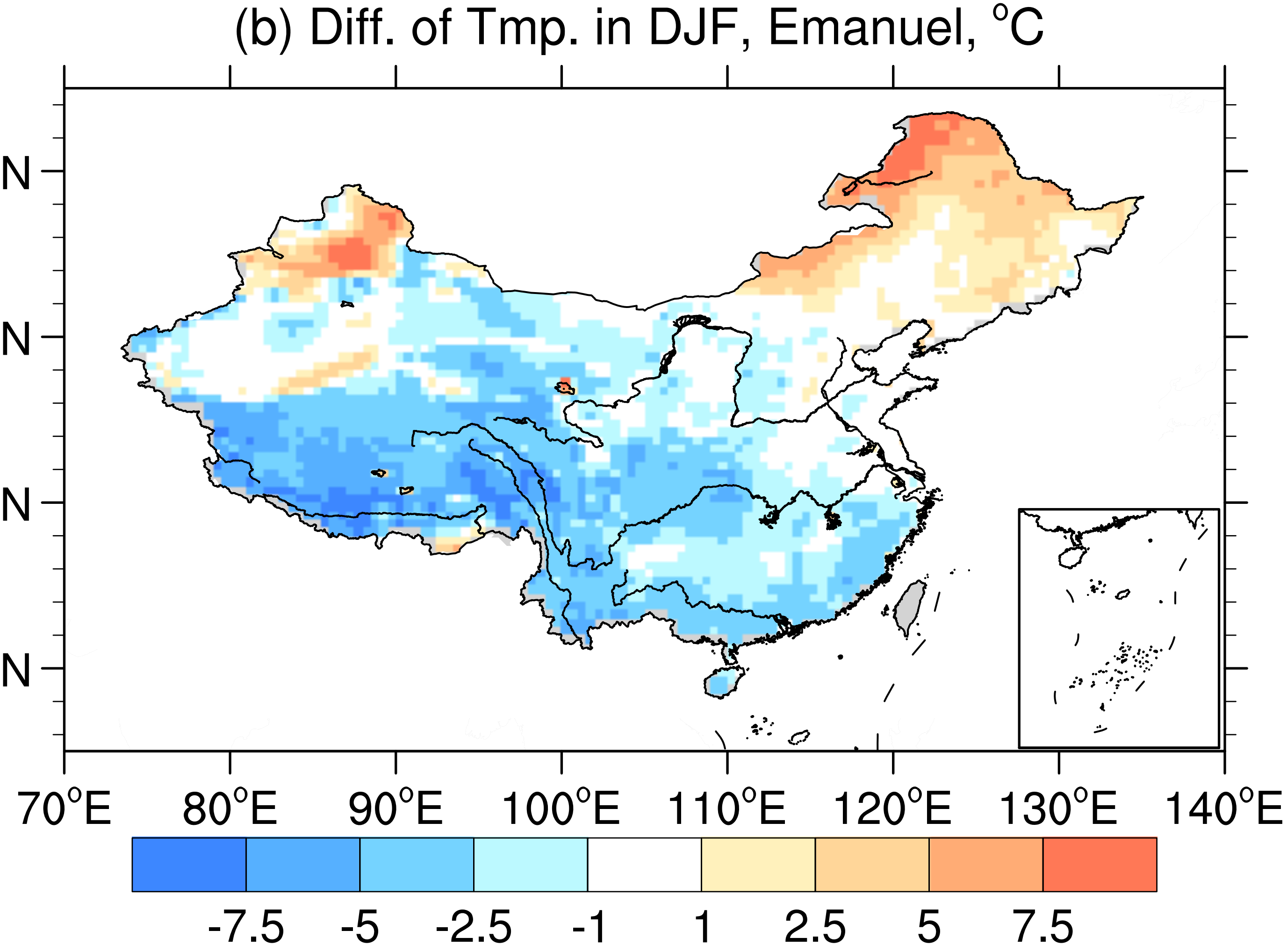
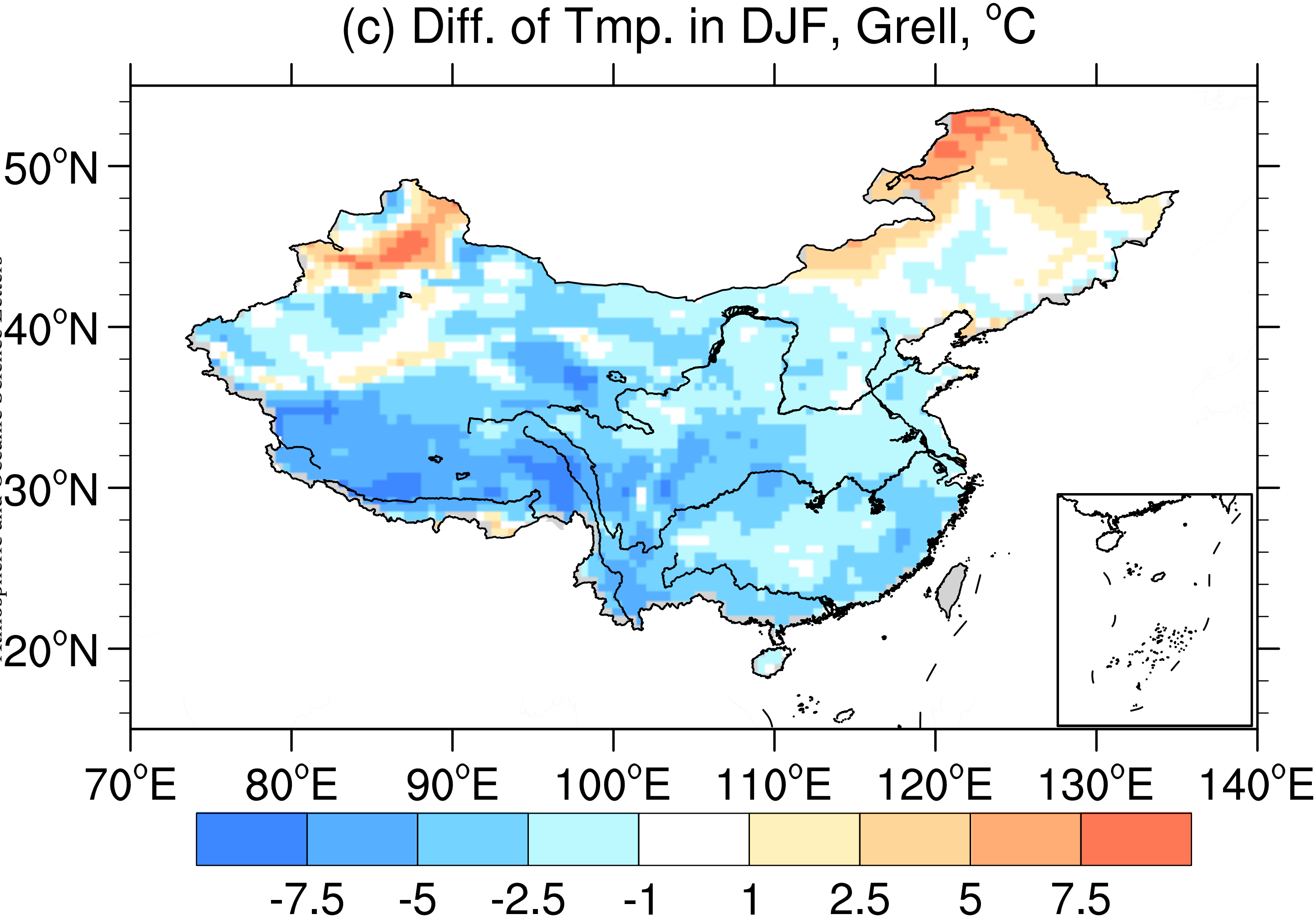
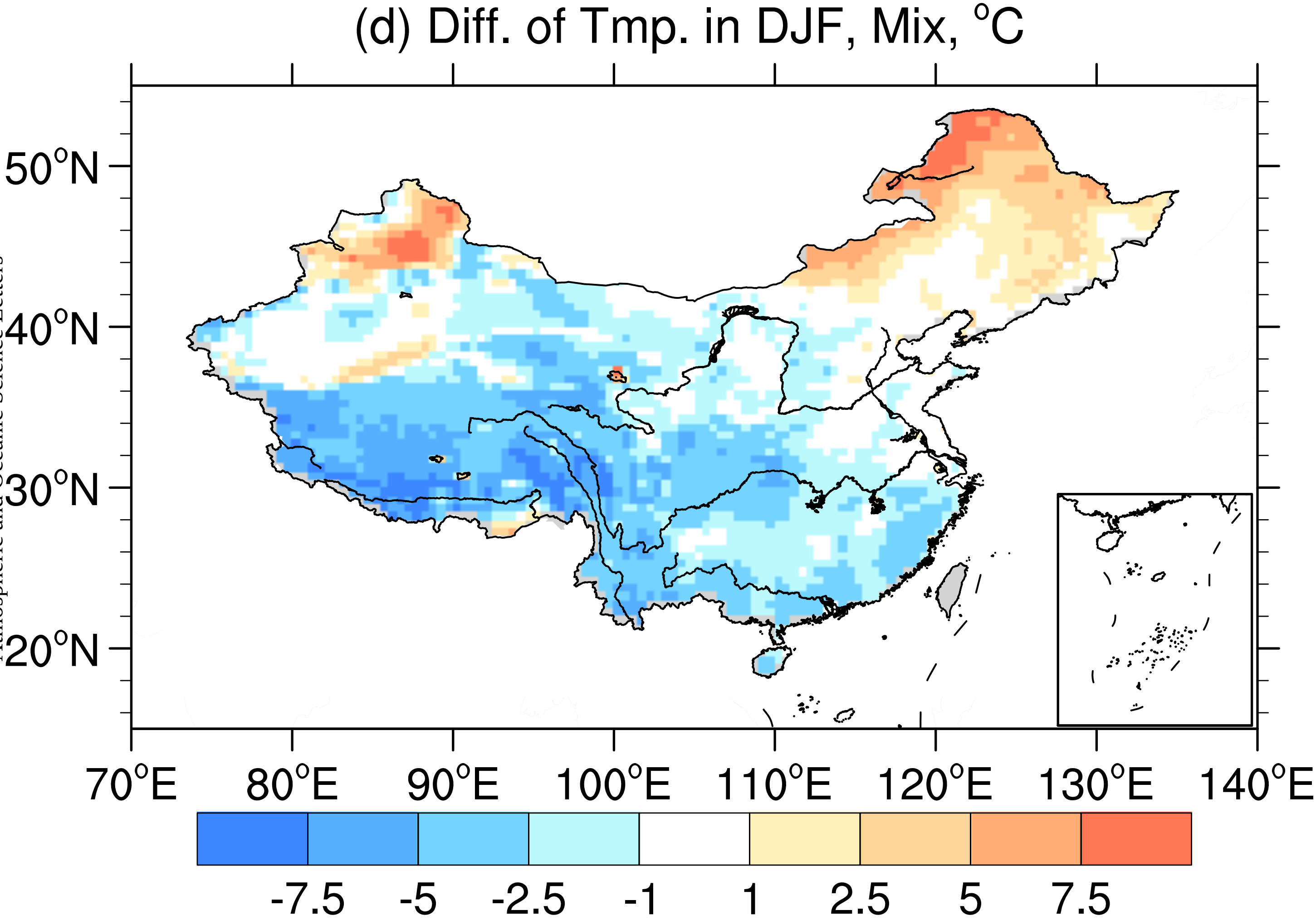
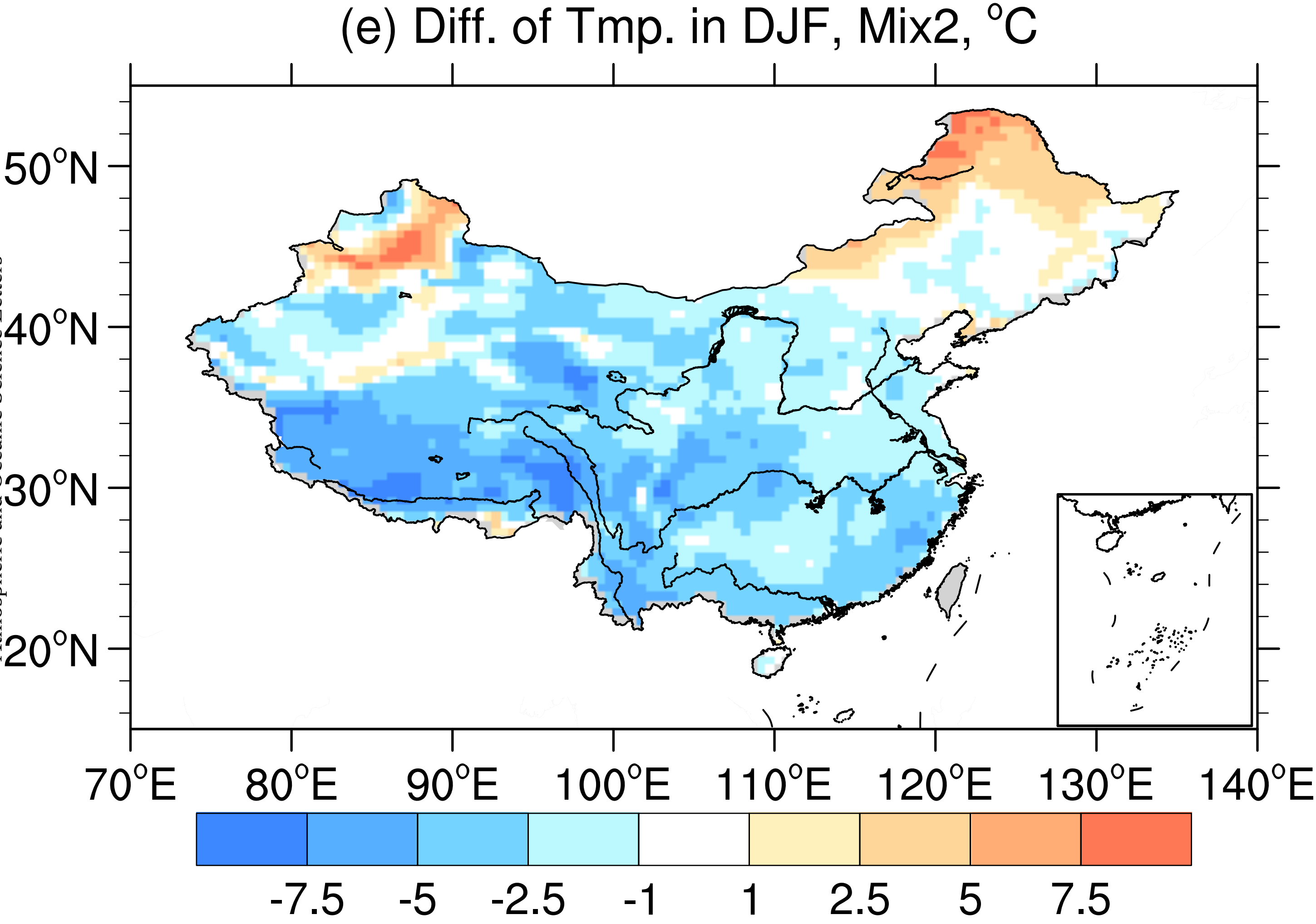
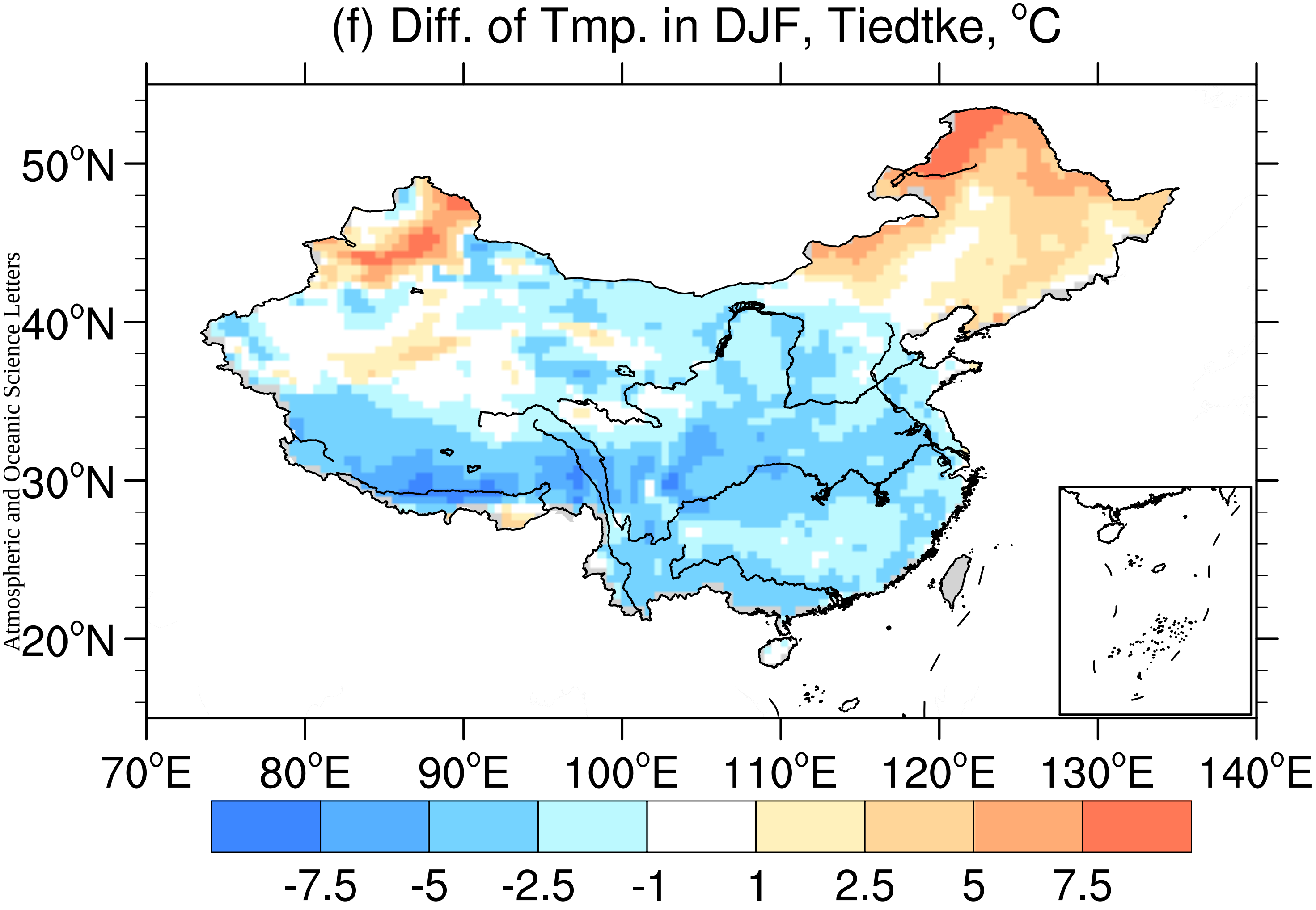
-6
-3
0
3
6
9
12

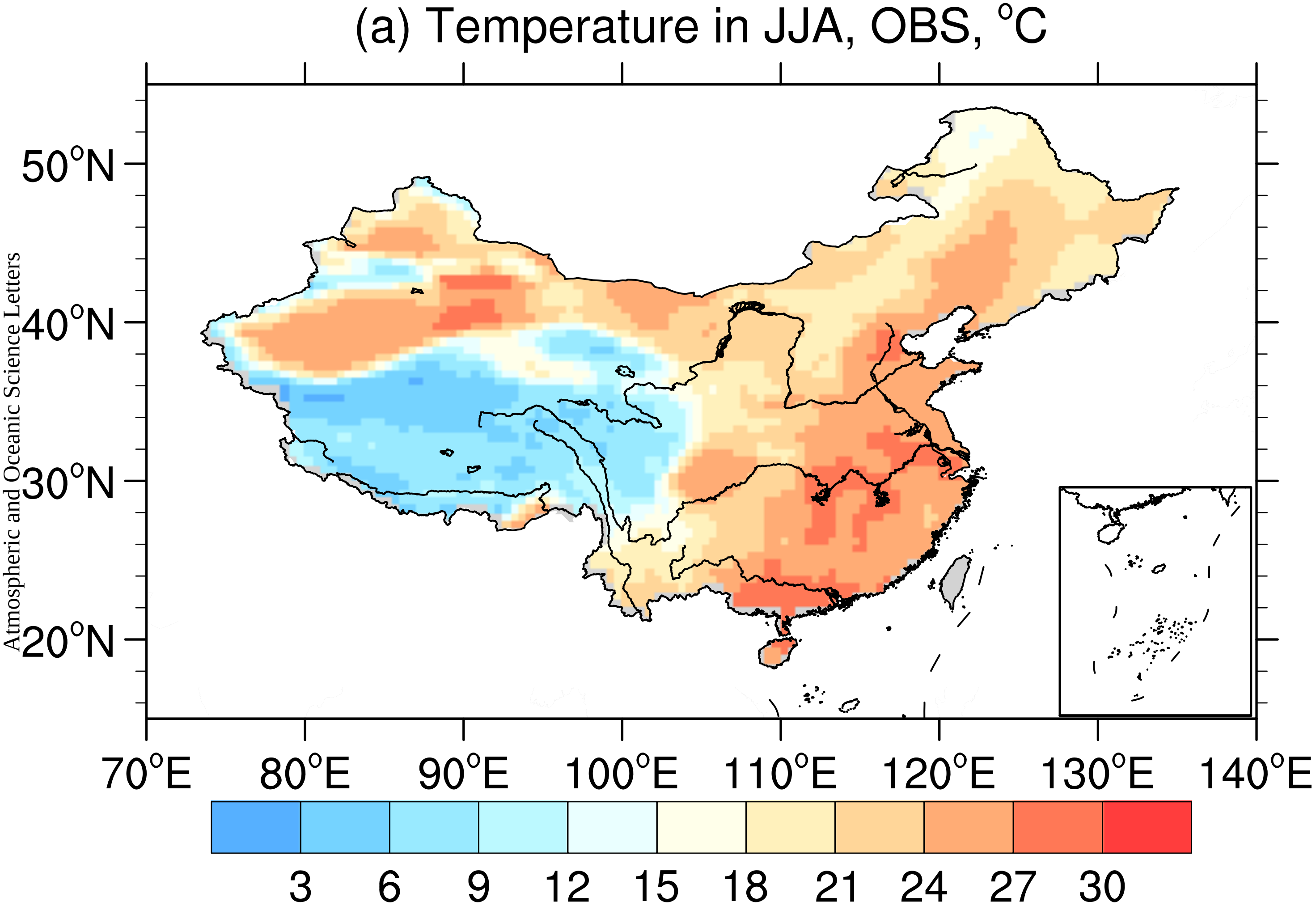

(b) Diff. of Tmp. in DJF, Emanuel, °C
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

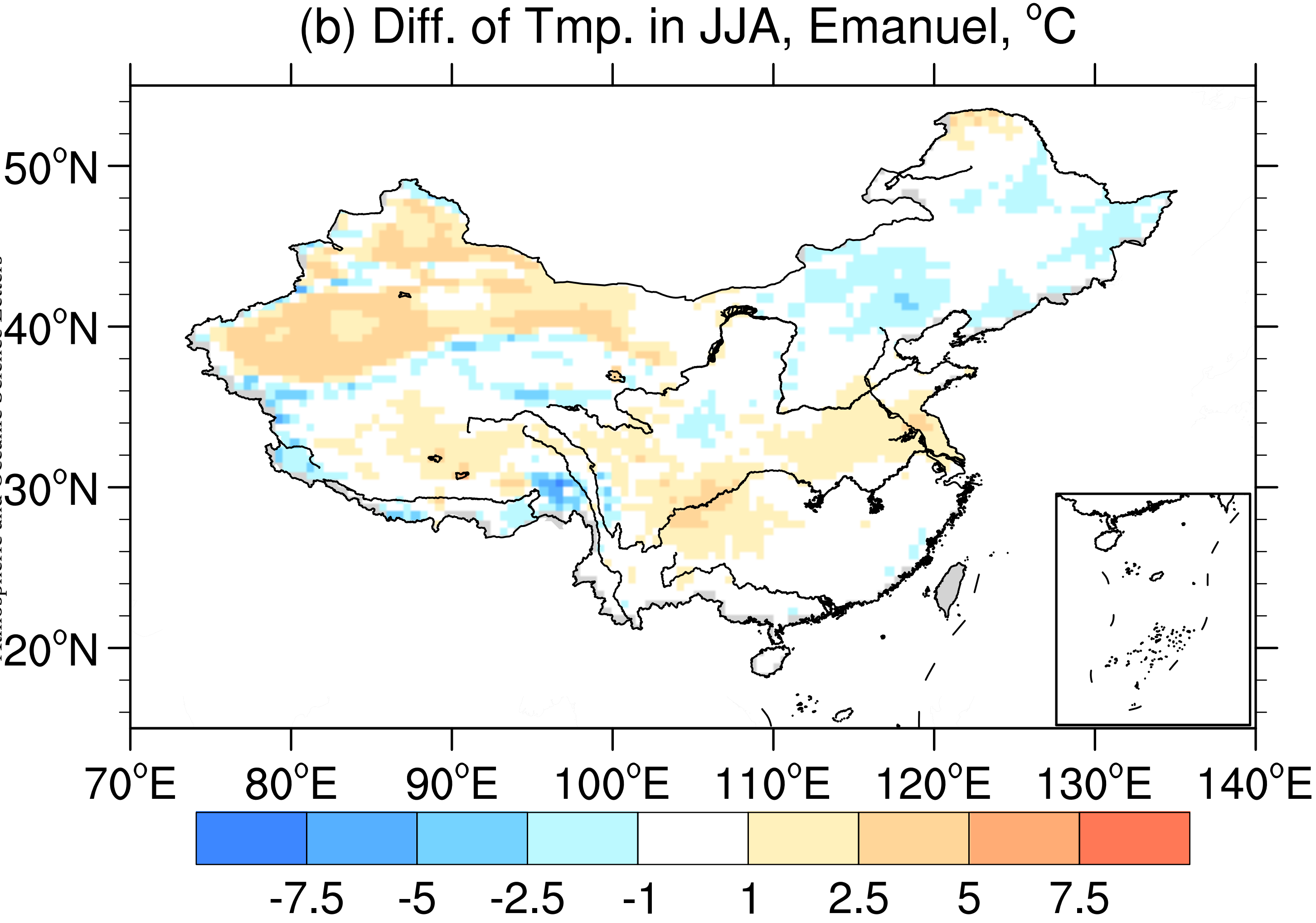

(c) Diff. of Tmp. in DJF, Grell, ^{o}C
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

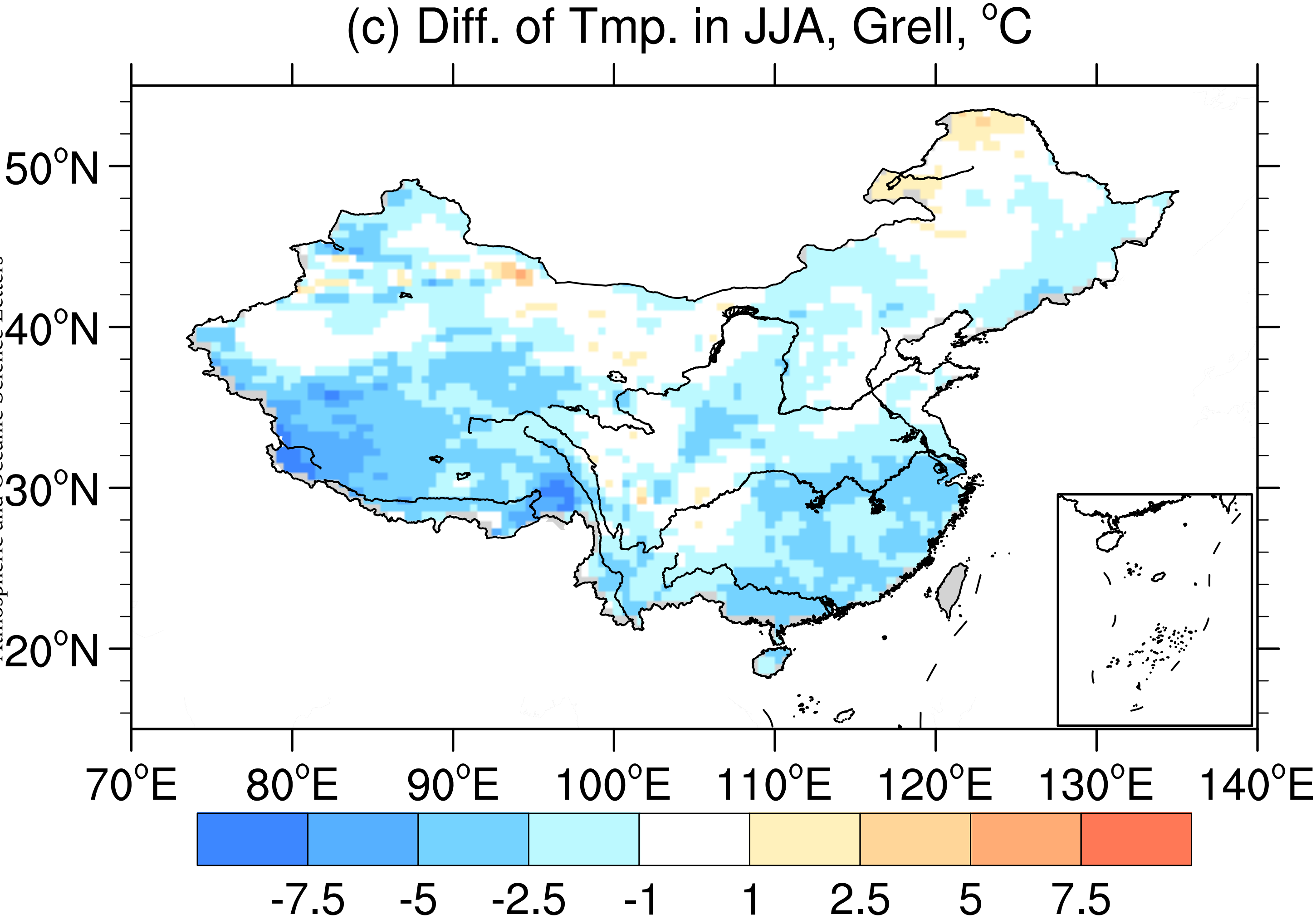

(d) Diff. of Tmp. in DJF, Mix, °C
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
-7.5
-5
-2.5
-1
1
2.5
5
7.5


(e) Diff. of Tmp. in DJF, Mix2, ^{o}C
50^{o}N
40^{o}N
30^{o}N
20^{o}N
70^{o}E
80^{o}E
90^{o}E
100^{o}E
110^{o}E
120^{o}E
130^{o}E
140^{o}E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

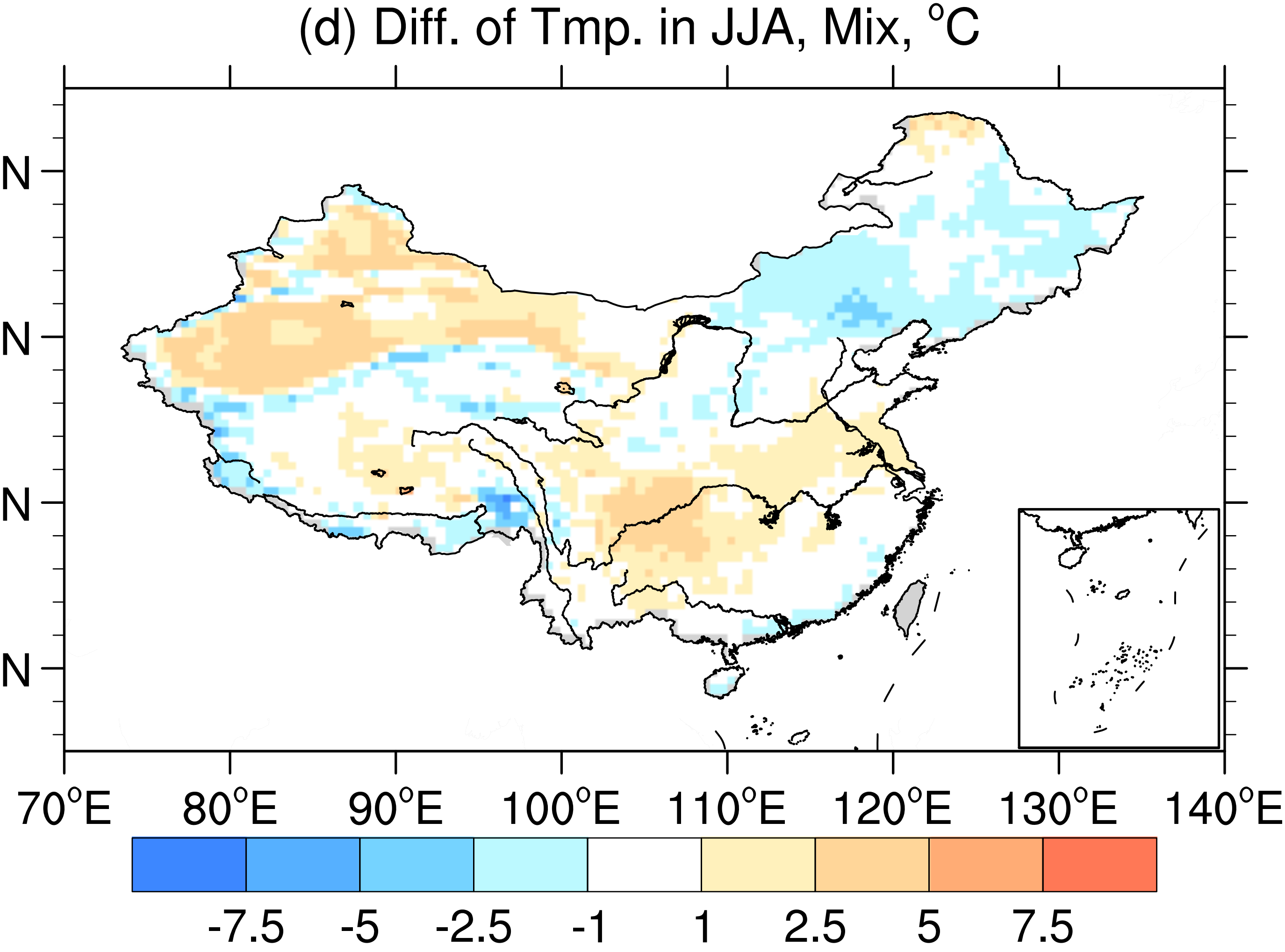

(f) Diff. of Tmp. in DJF, Tiedtke, °C
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

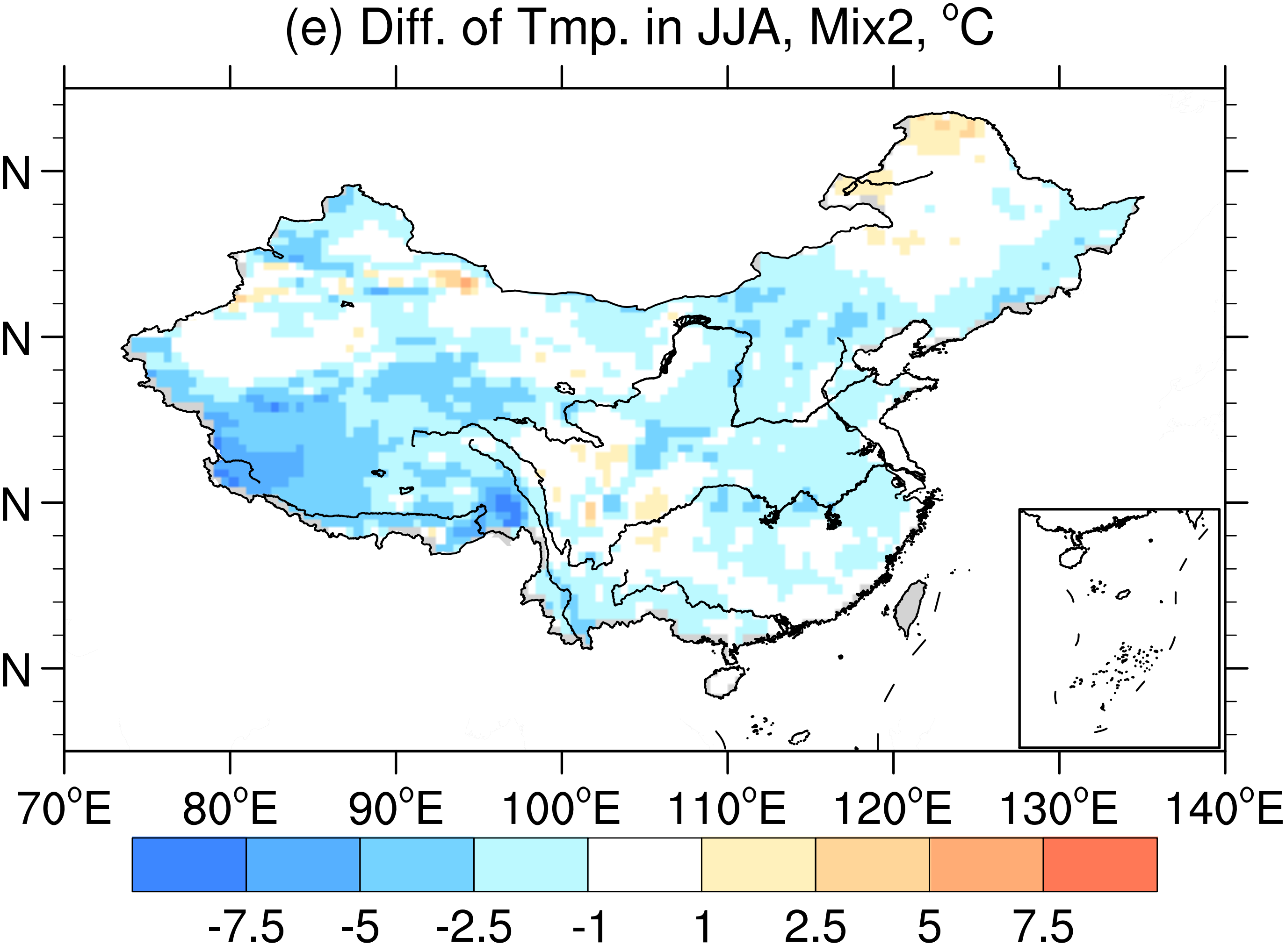

(a) Temperature in JJA, OBS, °C
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
3
6
9
12
15
18
21
24
27
30

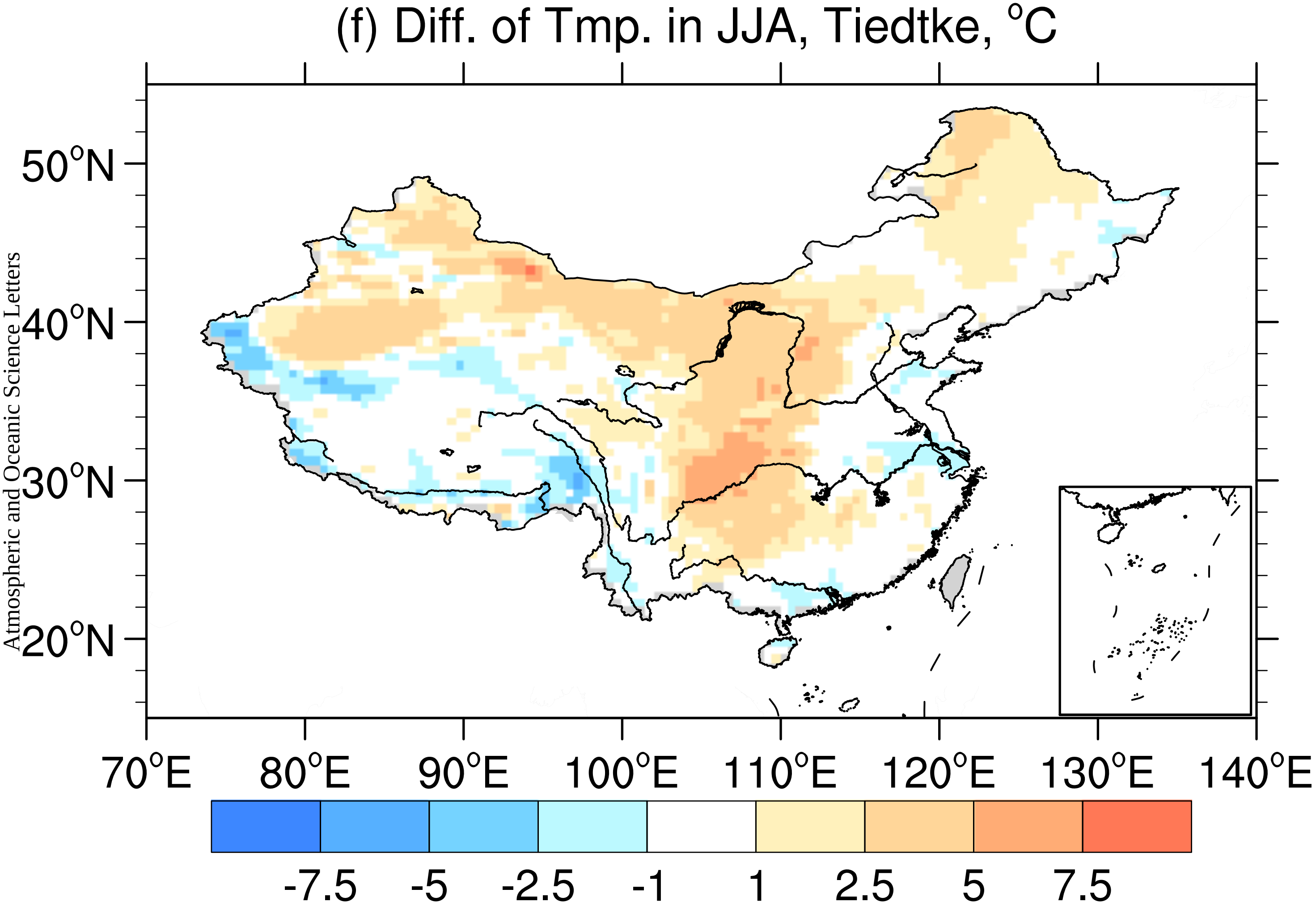

(b) Diff. of Tmp. in JJA, Emanuel, ^{o}C
50^{o}N
40^{o}N
30^{o}N
20^{o}N
70^{o}E
80^{o}E
90^{o}E
100^{o}E
110^{o}E
120^{o}E
130^{o}E
140^{o}E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

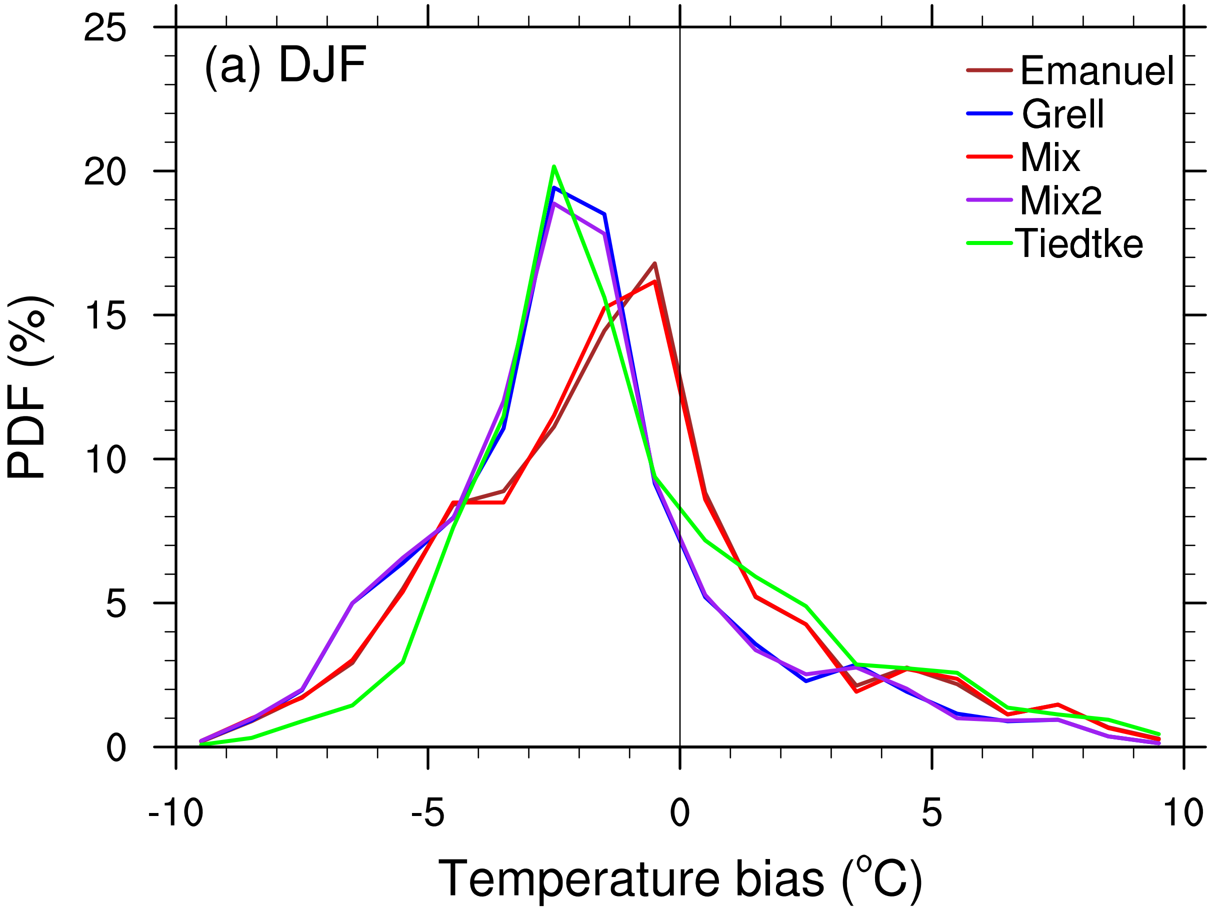


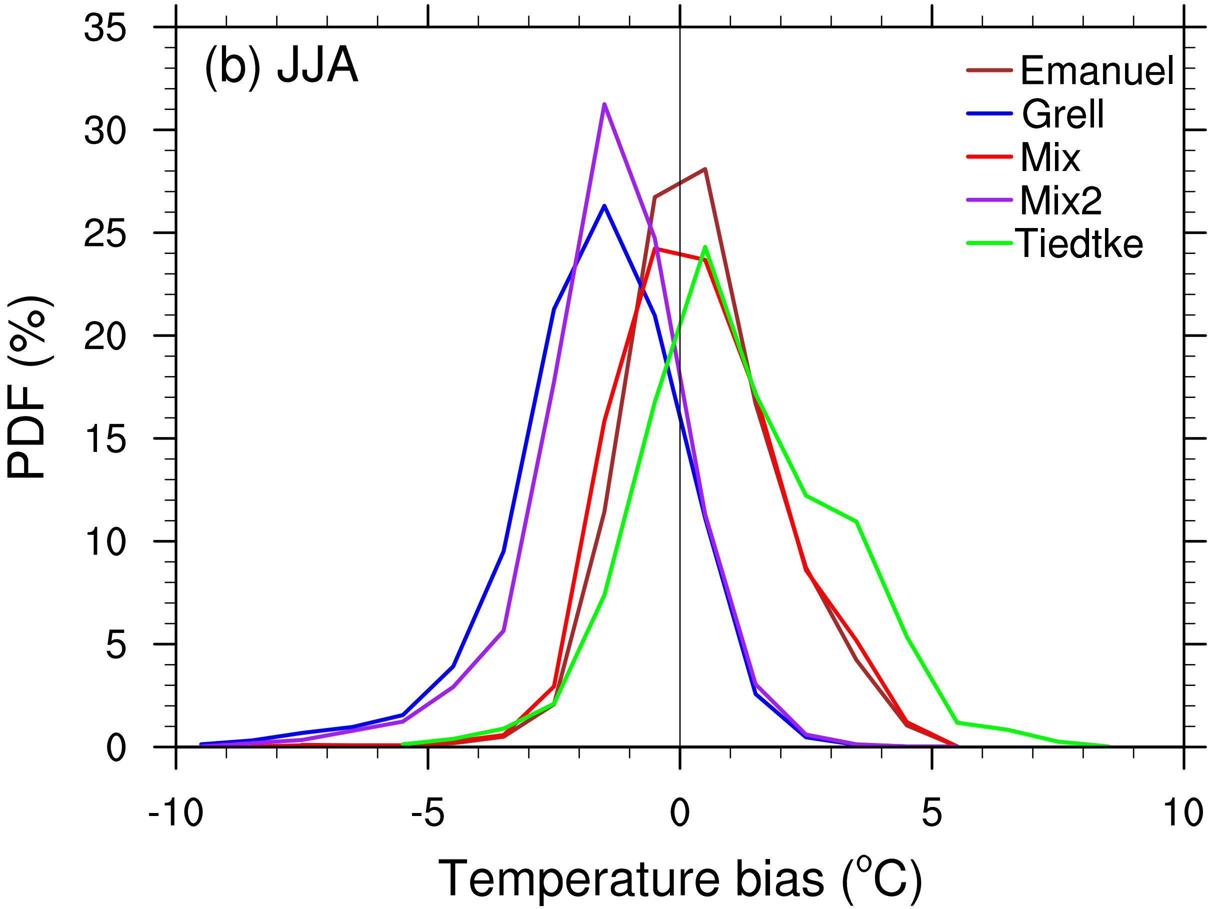
(c) Diff. of Tmp. in JJA, Grell, ^{o}C

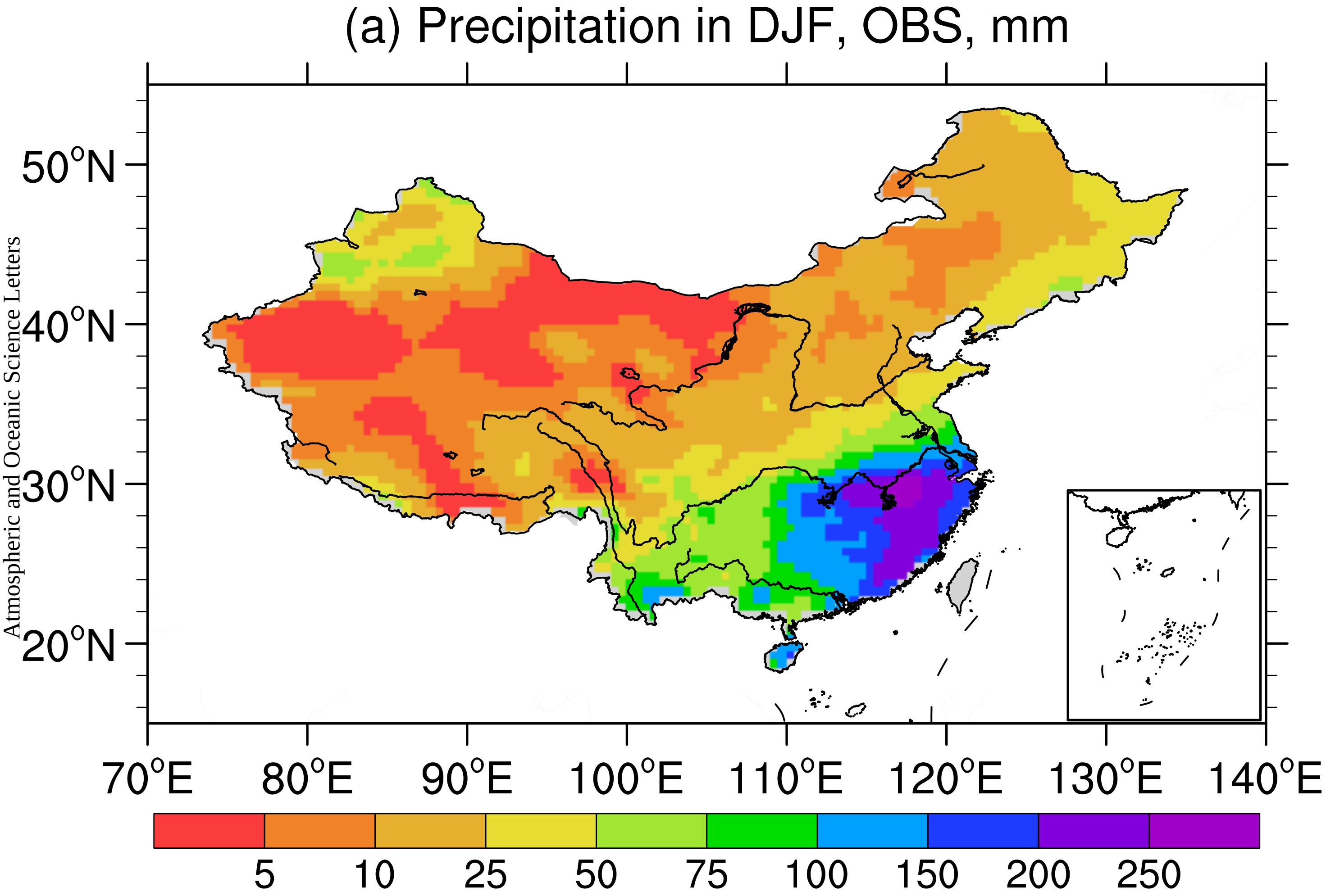

(d) Diff. of Tmp. in JJA, Mix, ^{o}C
50^{o}N
40^{o}N
30^{o}N
20^{o}N
70^{o}E
80^{o}E
90^{o}E
100^{o}E
110^{o}E
120^{o}E
130^{o}E
140^{o}E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

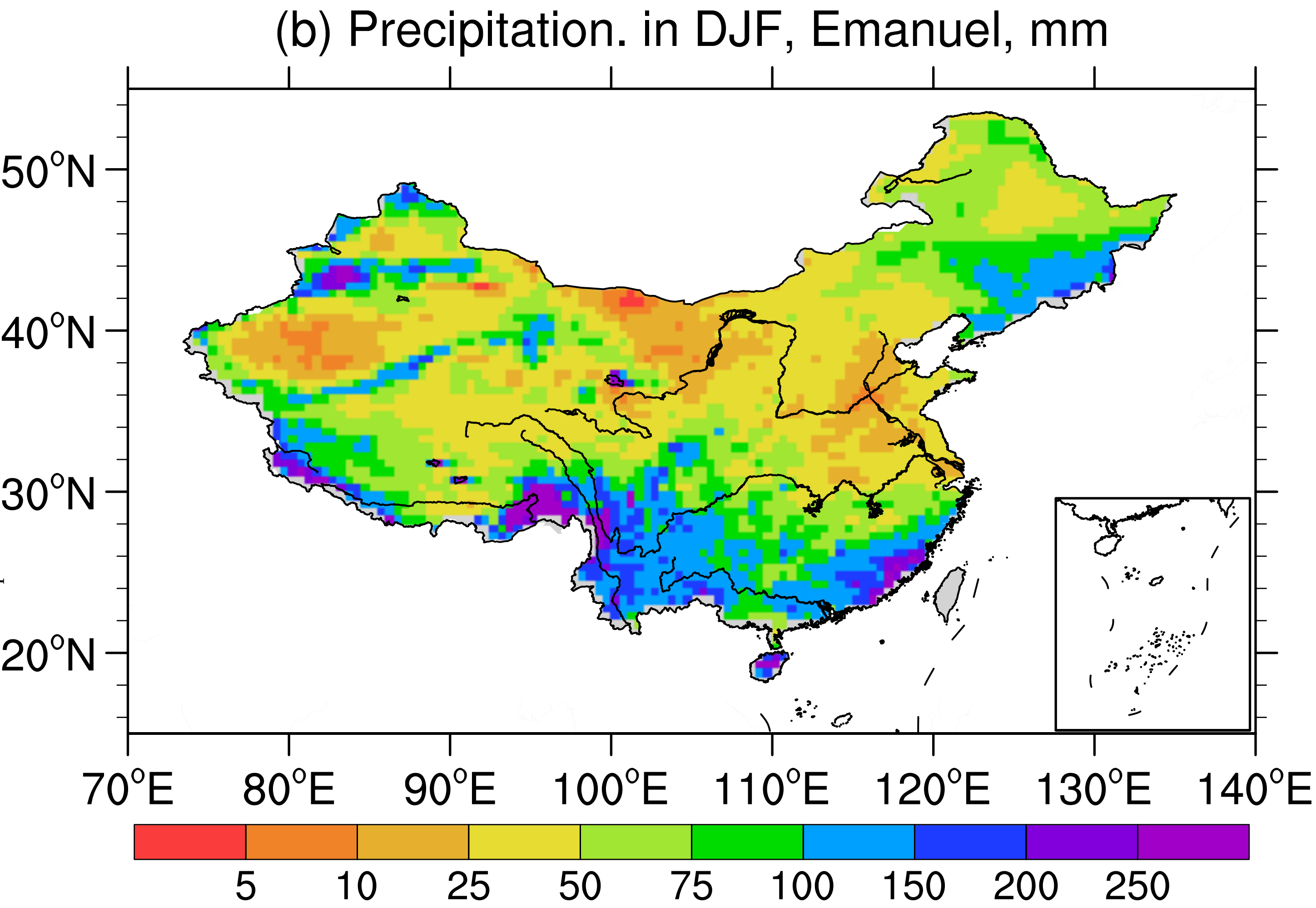

(e) Diff. of Tmp. in JJA, Mix2, ^{o}C
50^{o}N
40^{o}N
30^{o}N
20^{o}N
70^{o}E
80^{o}E
90^{o}E
100^{o}E
110^{o}E
120^{o}E
130^{o}E
140^{o}E
-7.5
-5
-2.5
-1
1
2.5
5
7.5


(f) Diff. of Tmp. in JJA, Tiedtke, °C
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
-7.5
-5
-2.5
-1
1
2.5
5
7.5

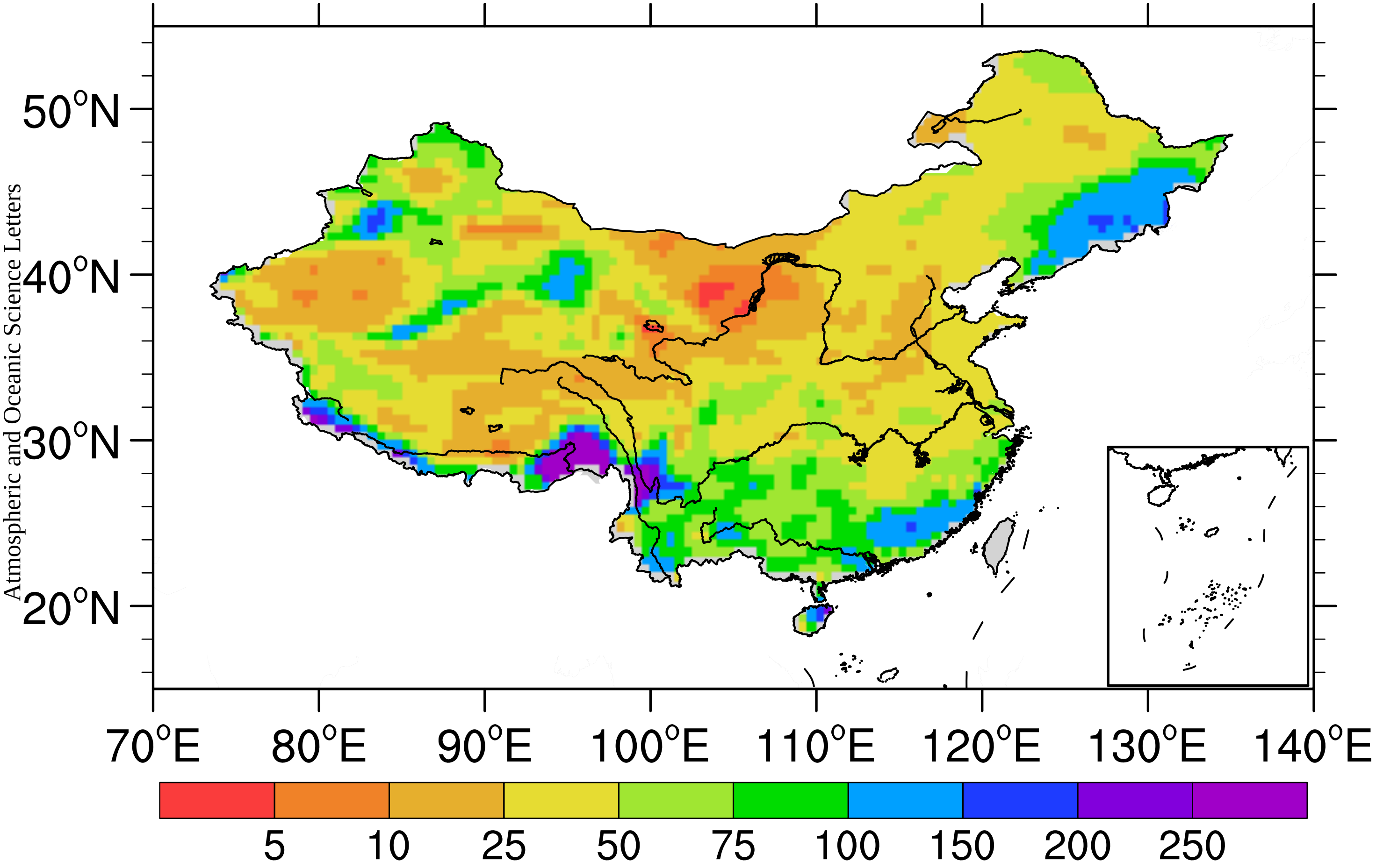

(a) DJF
Emanuel
Grell
Mix
Mix2
Tiedtke
PDF (%)
25
20
15
10
5
0
-10
-5
0
5
10
Temperature bias (°C)

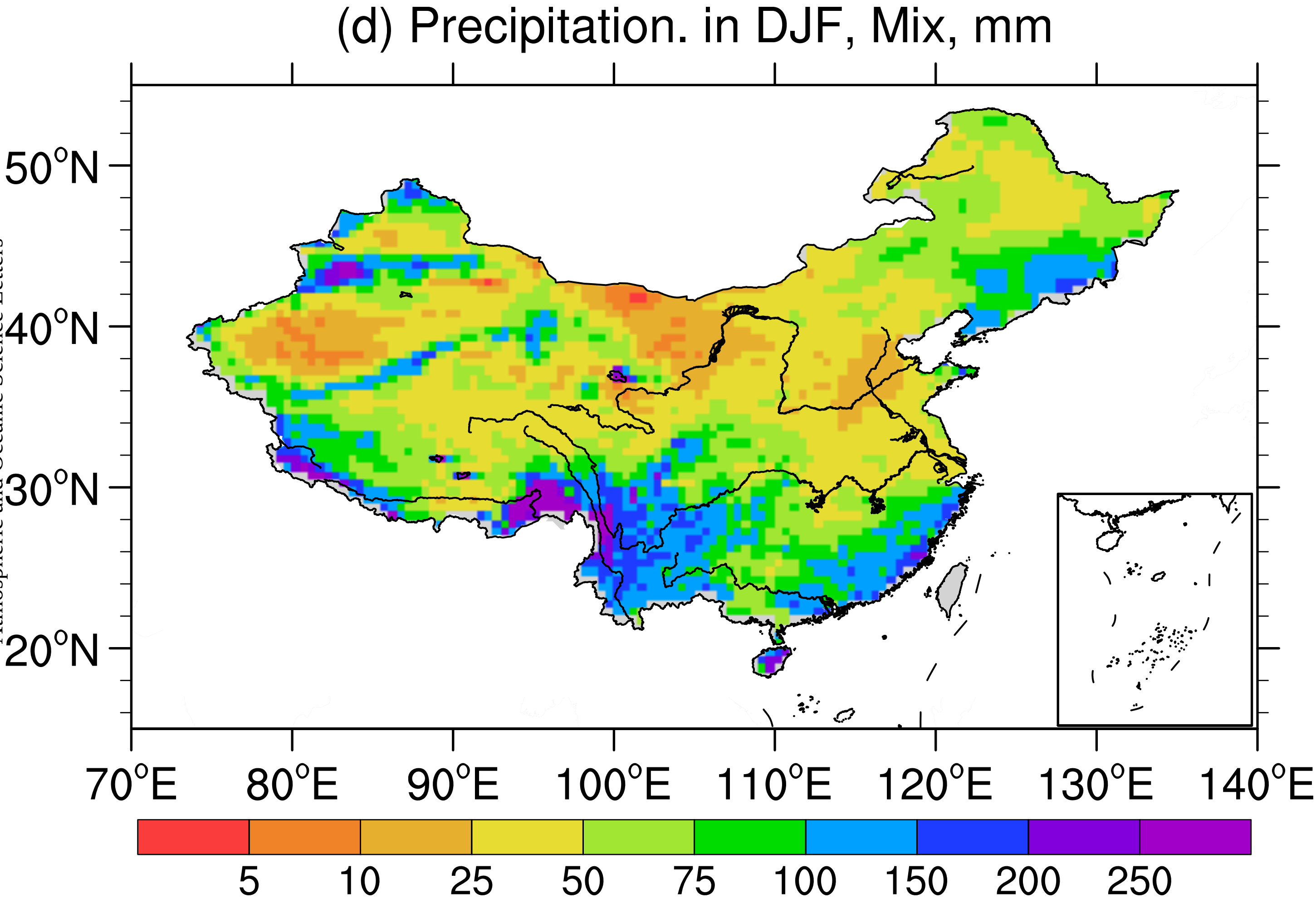

(b) JJA
Emanuel
Grell
Mix
Mix2
Tiedtke
PDF (%)
Temperature bias (^{o}C)
0
5
10
15
20
25
30
35
-10
-5
0
5
10

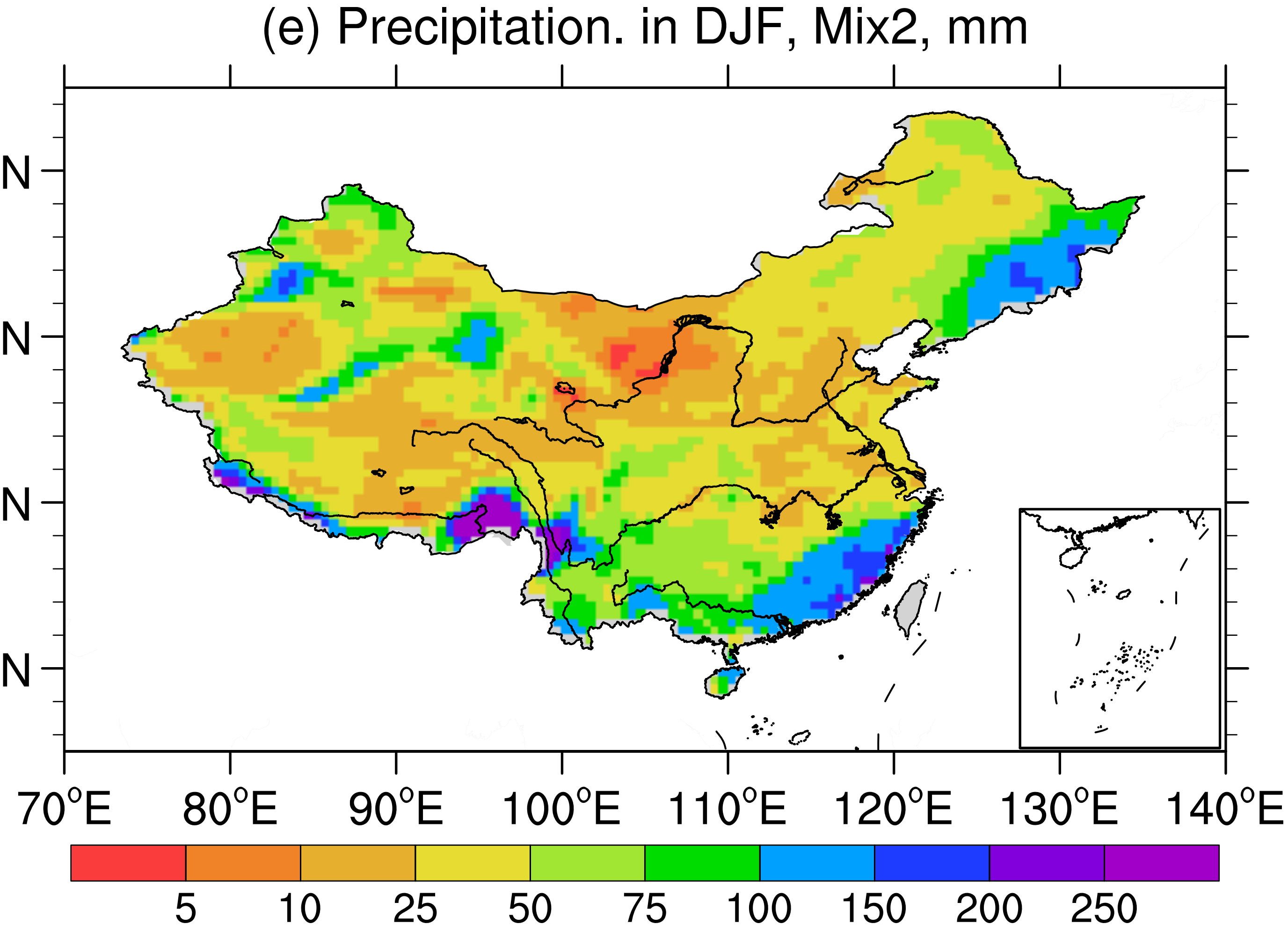

(a) Precipitation in DJF, OBS, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
5
10
25
50
75
100
150
200
250

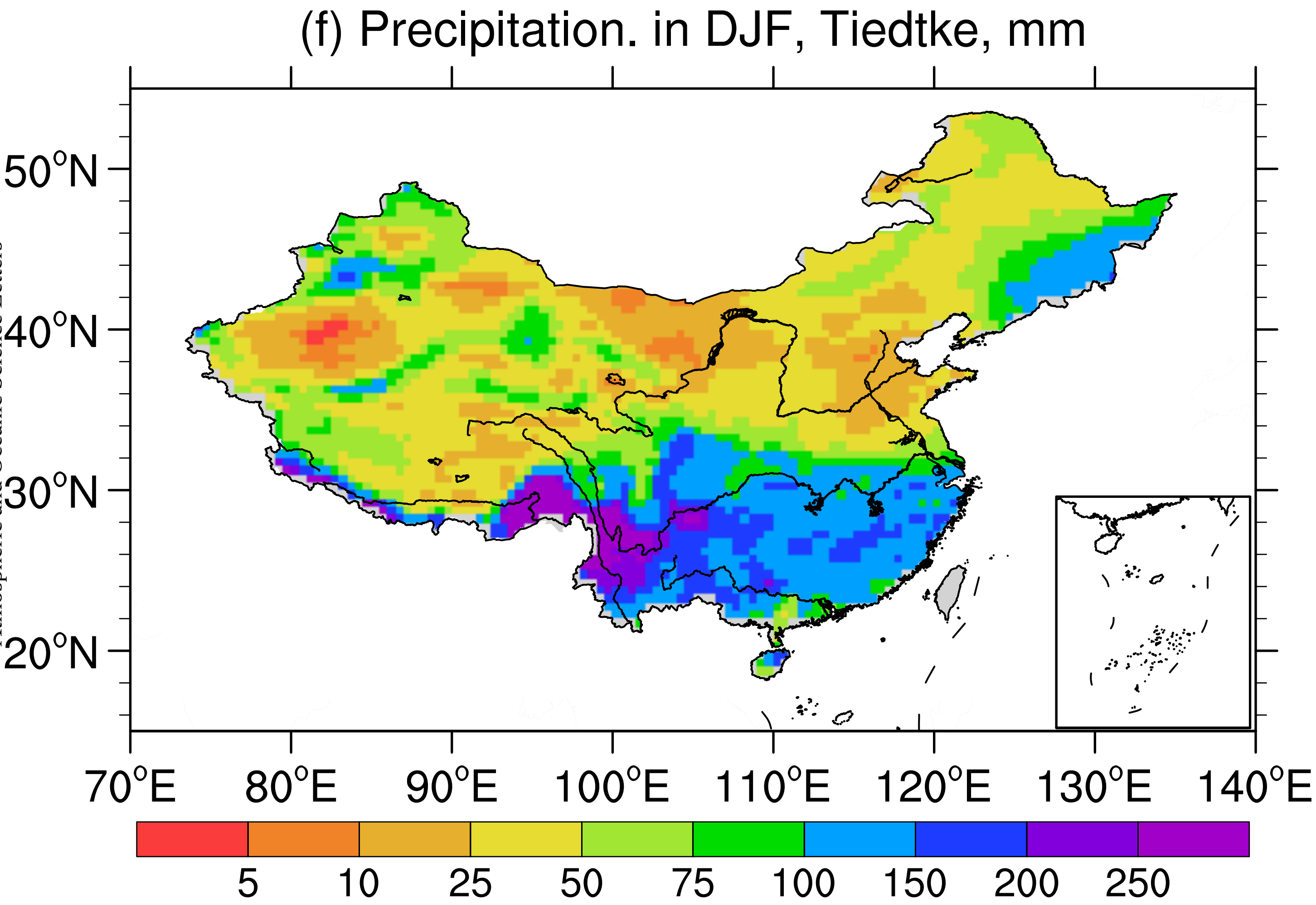

(b) Precipitation. in DJF, Emanuel, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
5
10
25
50
75
100
150
200
250

(c) Precipitation. in DJF, Grell, mm

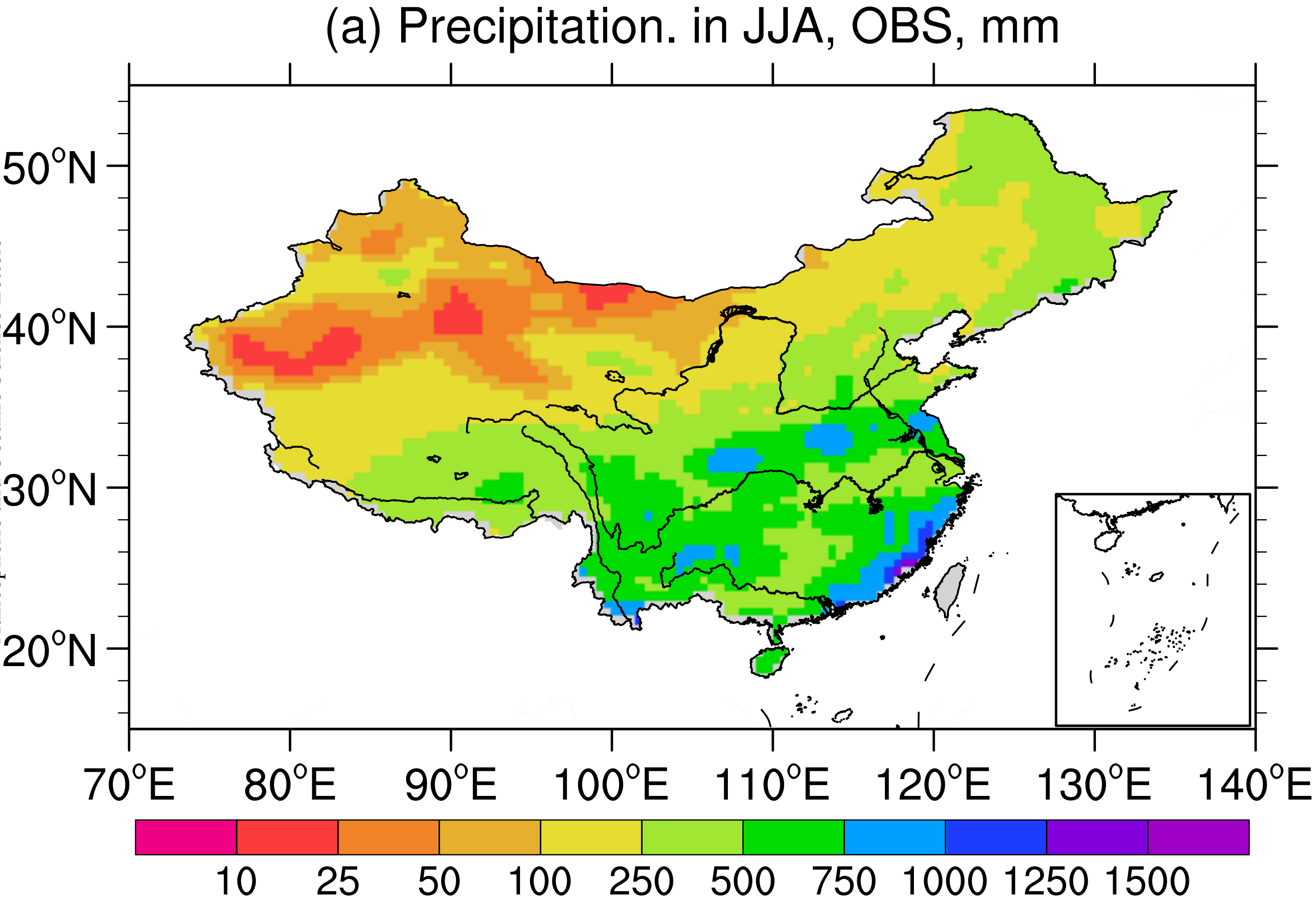


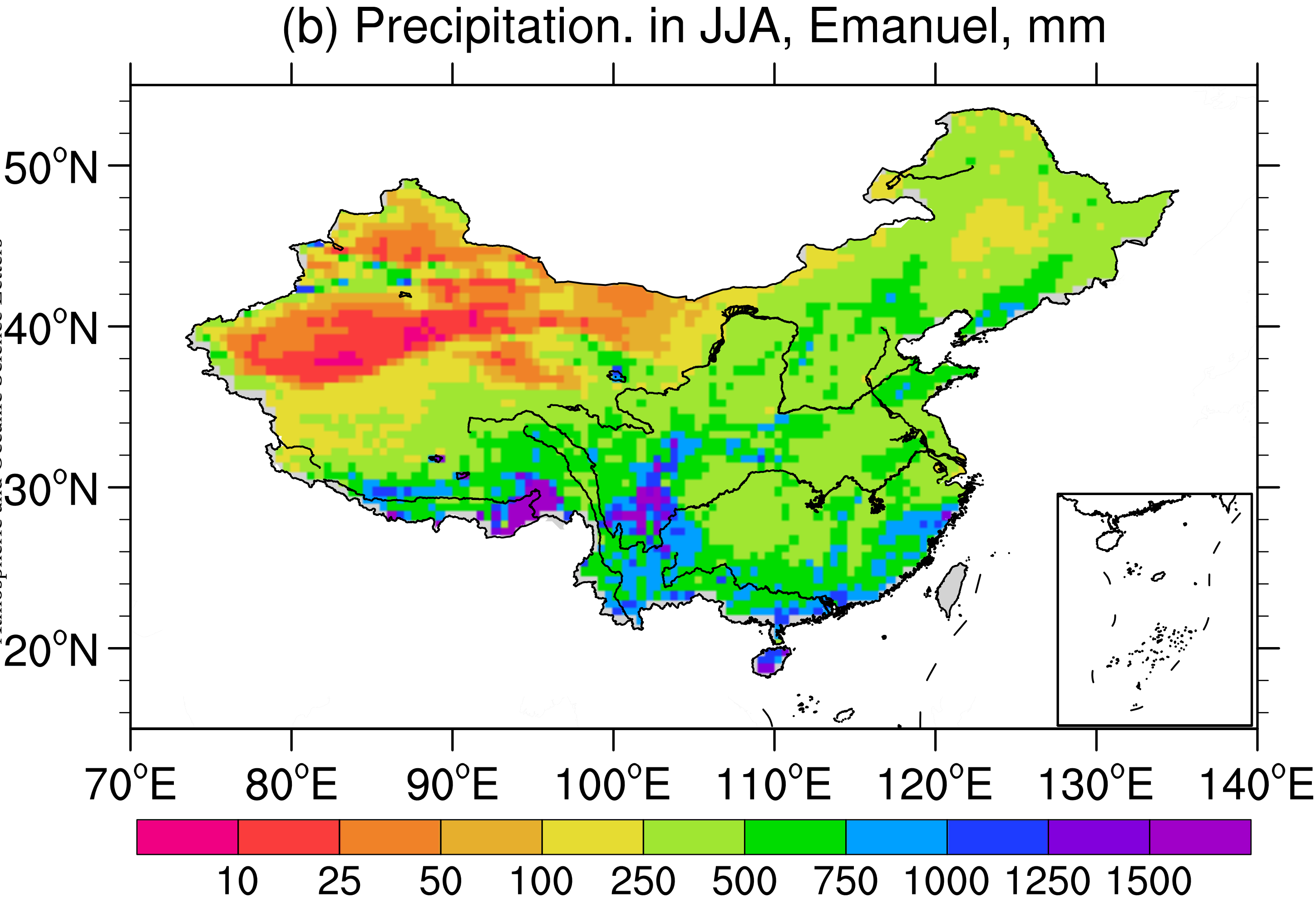

(d) Precipitation. in DJF, Mix, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
5
10
25
50
75
100
150
200
250

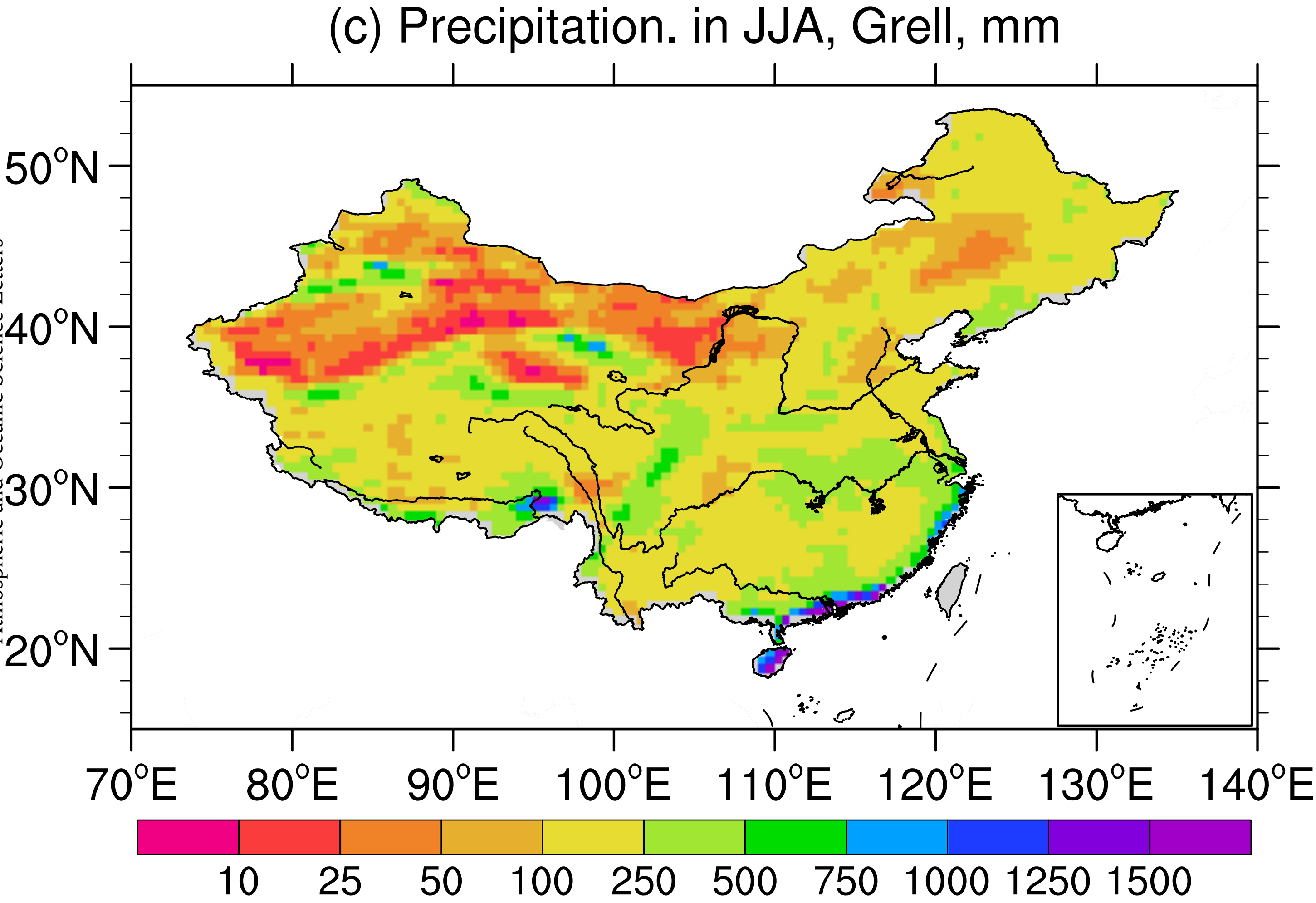

(e) Precipitation. in DJF, Mix2, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
5
10
25
50
75
100
150
200
250

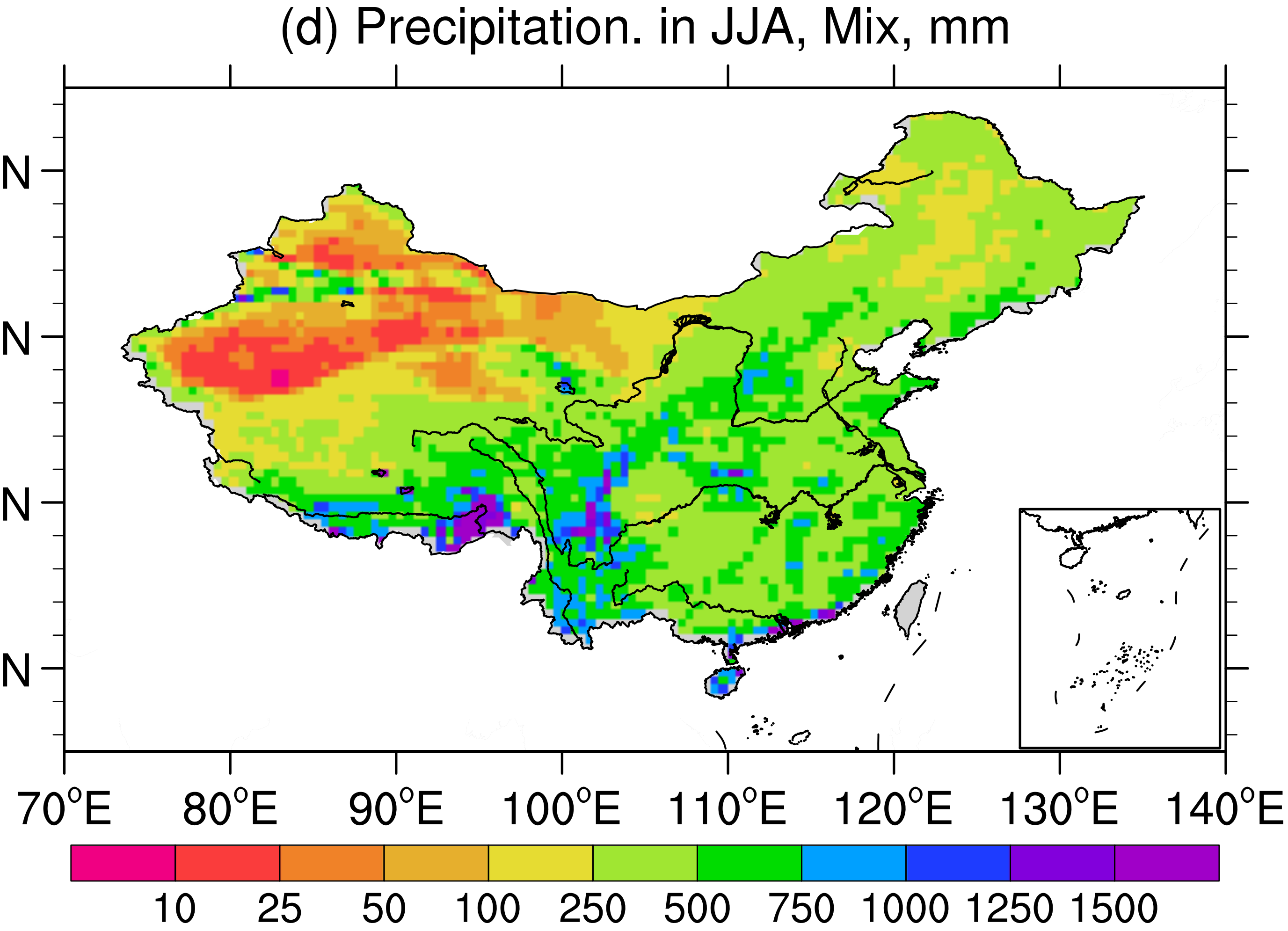


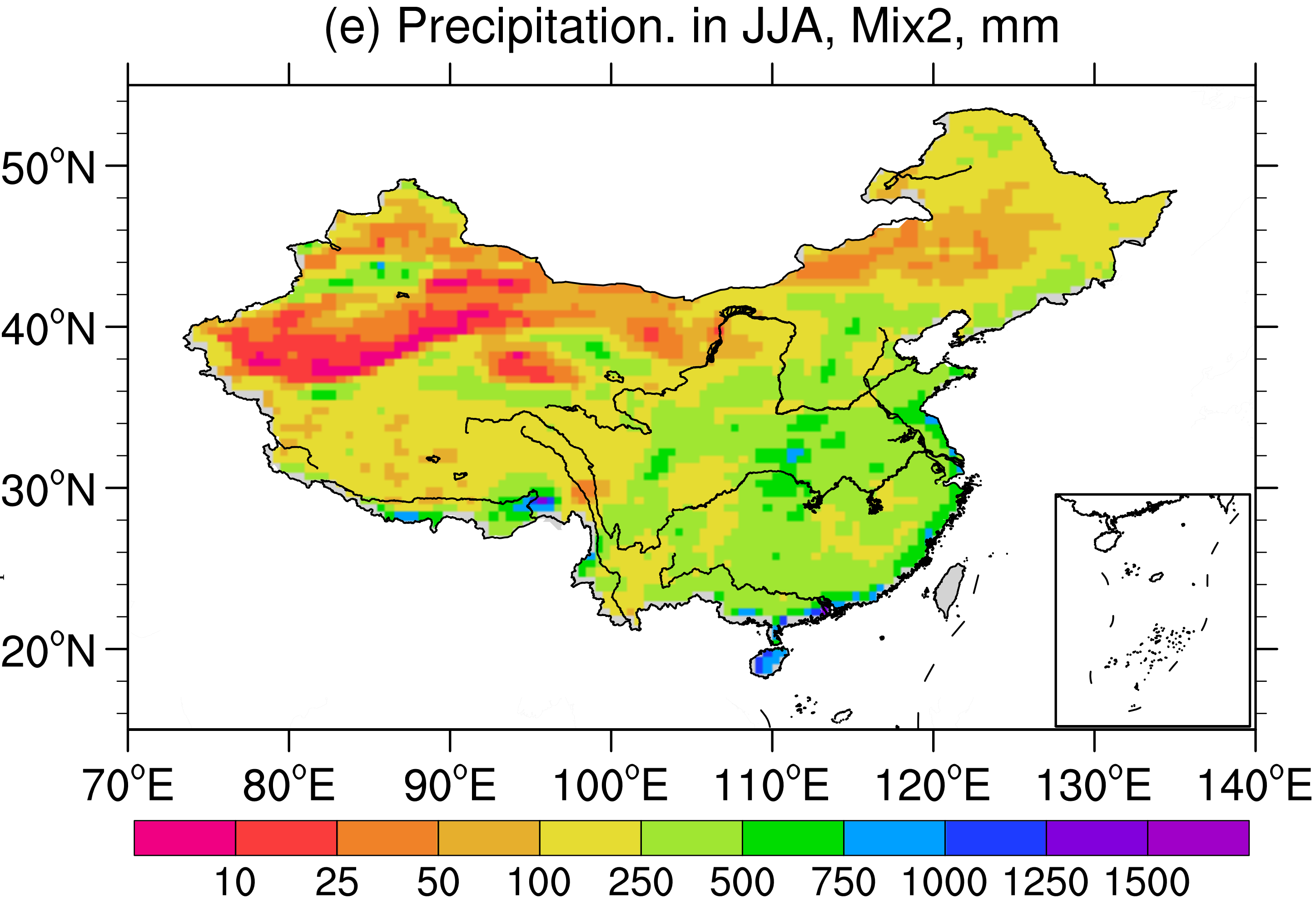
(f) Precipitation. in DJF, Tiedtke, mm


(a) Precipitation. in JJA, OBS, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
10
25
50
100
250
500
750
1000
1250
1500

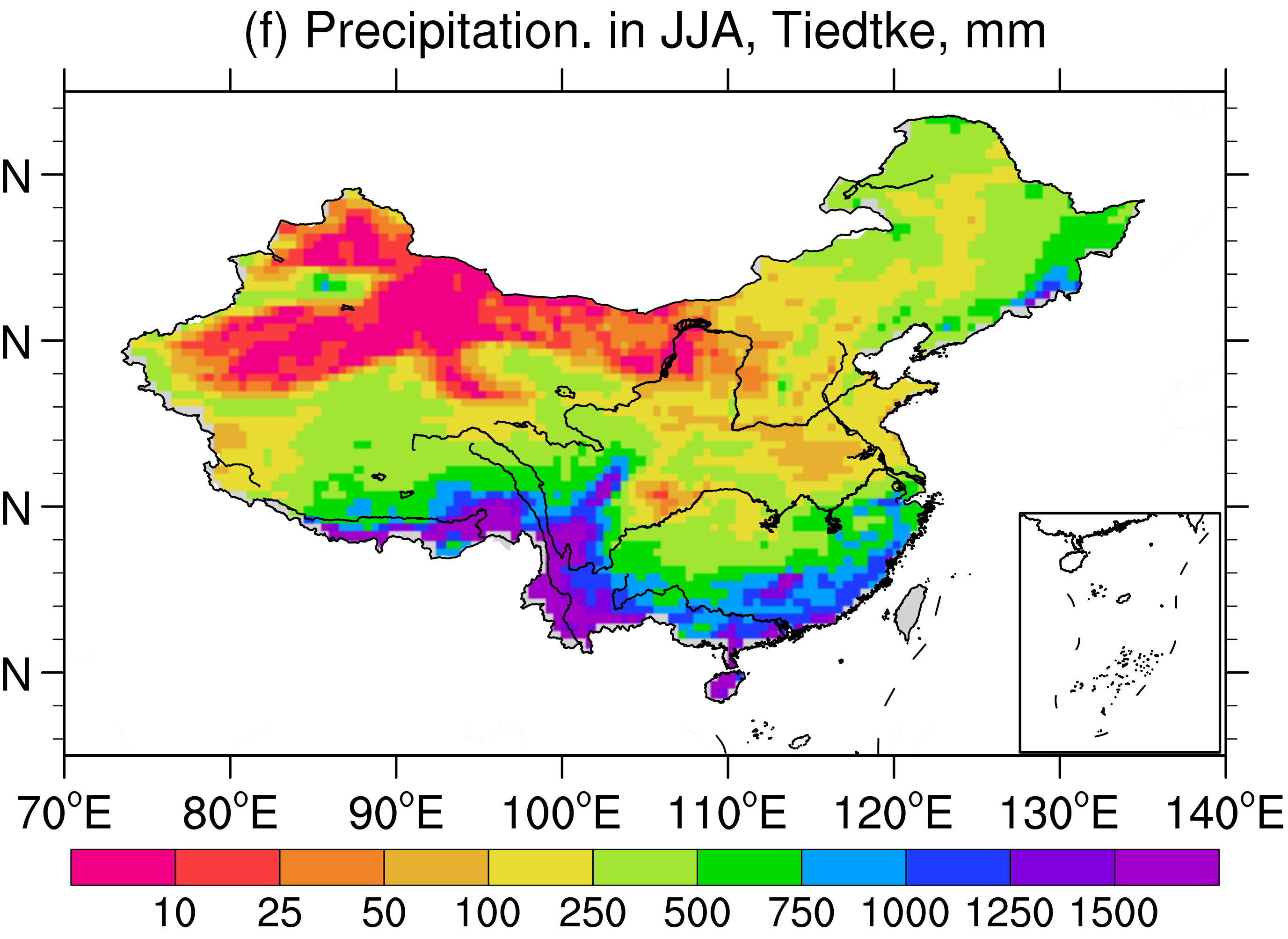

(b) Precipitation. in JJA, Emanuel, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
10
25
50
100
250
500
750
1000
1250
1500


(c) Precipitation. in JJA, Grell, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
10
25
50
100
250
500
750
1000
1250
1500


(d) Precipitation. in JJA, Mix, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
10
25
50
100
250
500
750
1000
1250
1500



(e) Precipitation. in JJA, Mix2, mm


(f) Precipitation. in JJA, Tiedtke, mm
50°N
40°N
30°N
20°N
70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
10
25
50
100
250
500
750
1000
1250
1500