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Climate effects of the Three Gorges Reservoir as simulated by a high resolution double nested regional climate model

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ABSTRACT

High resolution multi-annual regional climate model (RegCM3) experiments were performed to simulate the effects of the Three Gorges Reservoir (TGR) on the climate of the surrounding areas. The model was run in double nested mode. Firstly a 50 km resolution simulation was conducted over the China domain driven by the coarse resolution NCEP/NCAR re-analysis. Then the output of the simulation was used to drive the model over the Three Gorges Area (TGA) at a resolution of 10 km. SUB-BATS scheme was employed in the 10 km simulation to represent the land surface at 2 km. Two 10 km simulation, one with and the other without the inland water in TGR were conducted. Comparison of the simulations against observation were firstly carried out to validation the model performances over TGA. The 10 km sensitivity experiments with and without the TGR showed that little or negligible effects can be found except directly over the TGR. Most of the simulated effects are noisy and not statistically significant, except for cooling over the TGR water body in both June–July–August (JJA) and December–January–February (DJF). The cooling leads to an/a insignificant decrease/slight decrease of precipitation over the TGR and nearby grid points, respectively. The cooling is larger in JJA compared to DJF. As a typical river-like reservoir, the width and coverage of the TGR does not have significant influence on the local climate over the area.

1. Introduction

The Three Gorges Dam (TGD) which spans the Yangtze River in China is the largest hydroelectric project and the Three Gorges Reservoir (TGR) is the largest artificial water body (reservoir) in the world. Construction of the TGD was started in 1994 and the impoundment began in 2003. In 2010, the designed highest water level of 175 m was reached for the first time. Located in southwest China, the TGR extends for 660 km from Yichang (111.3°E, 30.7°N) to Chongqing (106.5°E, 29.5°N) along the waterway of the Yangtze River (Fig. 1) with an areal coverage of 1040 km^2. Being a typical river-type reservoir, the TGR is narrow, having a width of ~1.1 km. Increasing studies have been devoted to the TGR effects on local climate and environment (e.g., Li and Zhang, 2003; Liao et al., 2007).

Changes in land use and land cover can influence local and regional climates and such effects can be studied with high resolution regional climate models (RCMs) (e.g., Gao et al., 2003a, 2007; J.Y. Zhang et al., 2005). More specifically, Zhang et al. (2004) simulated the impact of the TGR on local climate by using of a simplified model, showing that the influence of the TGR on climate are limited to tens of kilometers from it. By using the Penn State/NCAR MM5, Miller et al. (2005) conducted multiple nested experiments down to 10 km resolution of 8 weeks duration to simulate the effects of the TGR. They showed that as a potential evaporating surface, the TGR cooled the surrounding area. However, no effects on precipitation were found. Conversely, the MM5 simulations of Wu et al. (2006), which reached a resolution of 3 km, found an effect on precipitation at the regional scale (~100 km) rather than on the local scale, using the same model of MM5 as Miller et al. (2005). The duration of their integration was still relatively short, 1 month.

The Chuanyu area, encompassing the eastern reach of the Sichuan Province and Chongqing Municipal City where the TGR are

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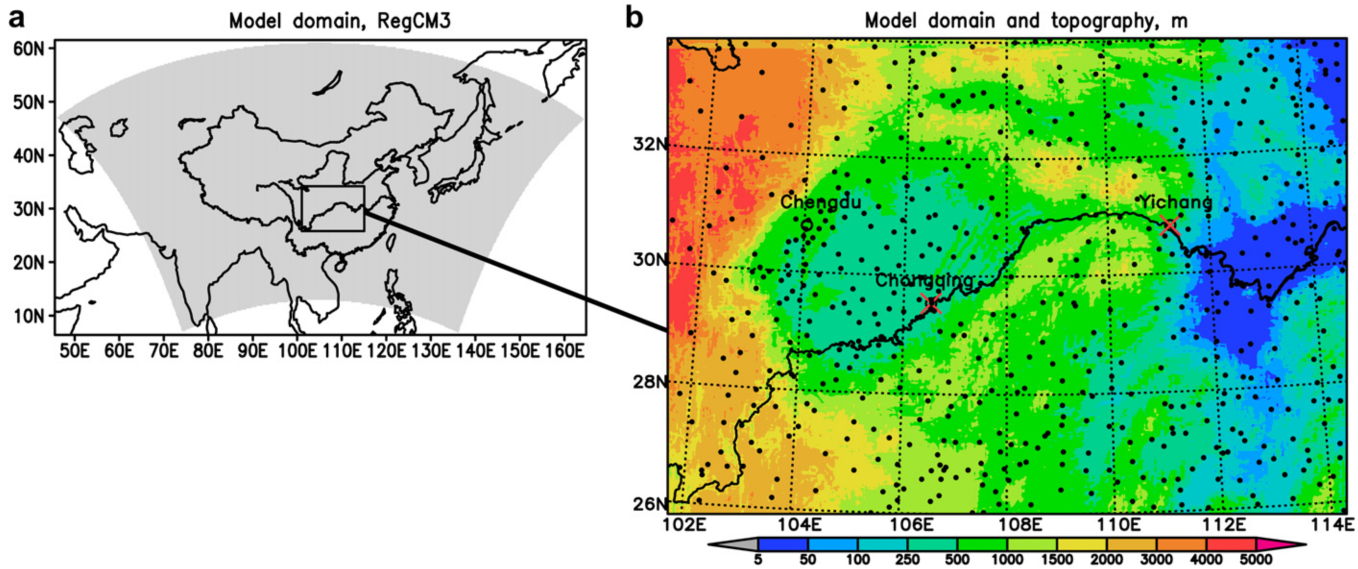

Fig. 1. Model domain of the 50 km (Exp. 1) (a, shaded area) and 10 km resolution simulations (Exp. 2 and Exp. 3) with topography (b, m). TGR is located between the two "×" along the Yangtze River.

located, experienced an extreme hot spell and drought during the summer (June–July–August, JJA) of 2006. It was a record breaking event in several meteorological elements, and led to a severe water shortage for local people and cattle, a strong reduction in crop production and an estimated economical loss of nearly 3 billion US dollars (Zou and Gao, 2007). The event drew wide attention in the media during the time and, although studies showed that it was mostly caused by large-scale circulation anomalies reinforced by

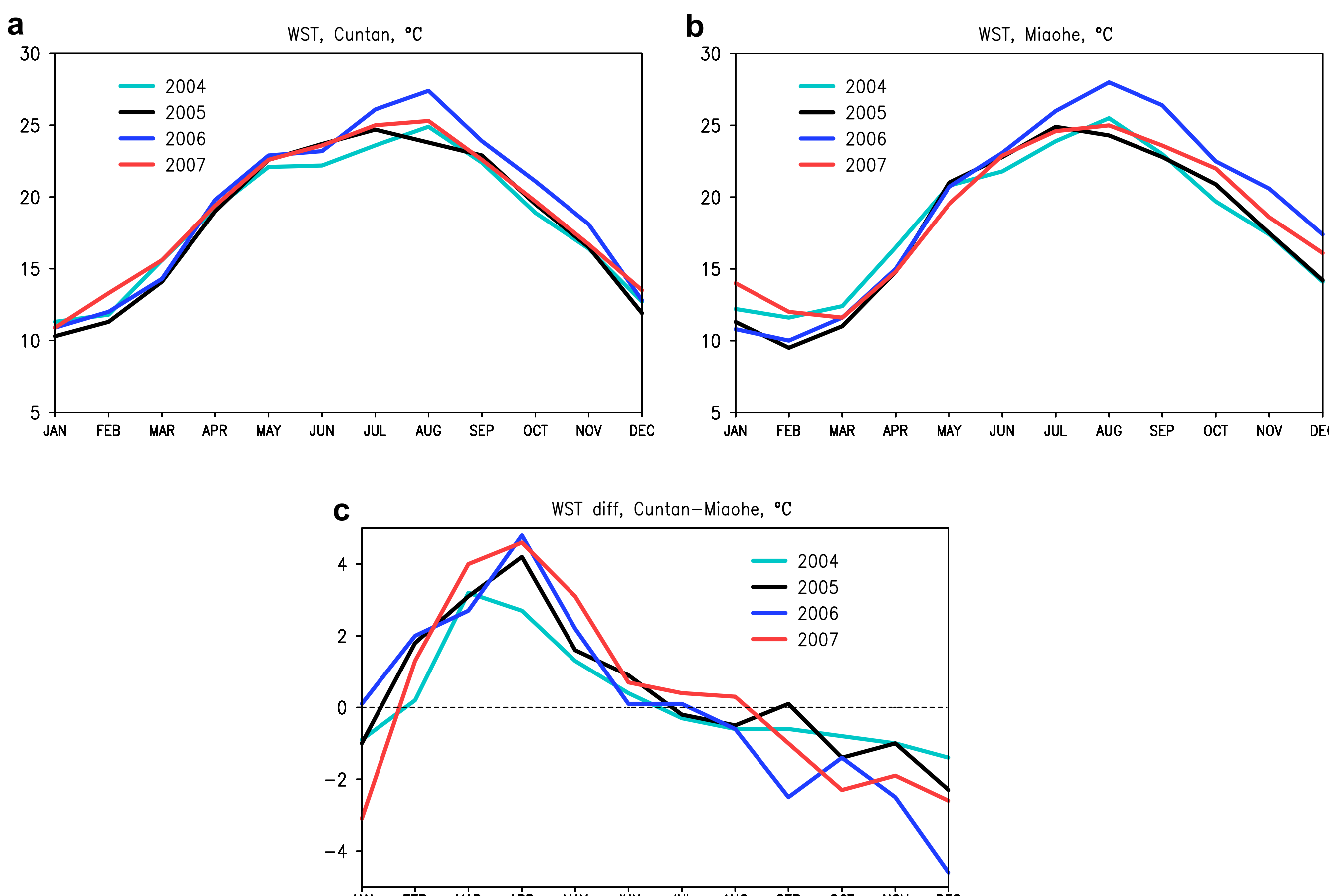

Fig. 2. Surface water temperature (WST) from the hydrological stations (°C). (a) in Cuntan; (b) in Miaohe; (c) the differences of WST between Cuntan and Miaohe.

global warming conditions (Q. Zhang et al., 2007; Zou and Gao, 2007), arguments arose attributing it to the construction of the TGD resulting in the TGR.

To investigate the possible role of the event, a set of multi-seasonal double nested RCM experiments over the area was conducted (Wu et al., 2011). The Abdus Salam International Center for Theoretical Physics (ICTP) Regional Climate Model (RegCM3) was used in the experiments, at a final model resolution of 10 km. The land surface was represented through the SUB-BATS scheme to represent the land surface at a resolution of 2 × 2 km in the experiments. Results showed that the 2006 event can be mostly attributed to the large-scale circulation rather than to a local forcing, while the contribution of the TGR to it is negligible.

However, further analysis of this topic is still needed, in particular by performing much longer simulations in order to better examine the statistical significance of the TGR effects in view of the internal variability and soil moisture spin up time present in RCM simulations (Giorgi and Bi, 2000). Thus, this paper examines the issue of the regional and local climatic effects of the TGR using the high resolution RegCM3 but with much extend simulation period (12 years). In addition, the observed water surface temperature (WST) in TGR was introduced in the simulation to obtain a more reliable scientific knowledge on the effects.

The paper is organized as follows. Model, data and experimental design are described in the next Section 2, model validation in Section 3, and the simulated impacts of the TGR on regional and local climate discussed in Section 4. Section 5 presents the major summary considerations.

2. Model, data and experimental design

As Wu et al. (2011) did, the model employed in the study is the ICTP RegCM3 (Pal et al., 2007) developed from its previous version RegCM2 (Giorgi et al., 1993a, 1993b). The dynamical core of the RegCM3 is based on the hydrostatic version of the Penn State/NCAR mesoscale model MM5 (Grell et al., 1994). The atmospheric radiative transfer is computed using the radiation package from the NCAR Community Climate Model CCM3 (Kiehl et al., 1996). Surface processes were carried out with the Biosphere–Atmosphere Transfer Scheme (BATS, Dickinson et al., 1993) while the ocean flux parameterization follows Zeng (Zeng et al., 1998). The planetary boundary layer computations employ the non-local formulation of Holtslag et al. (1990). Resolvable scale precipitation is

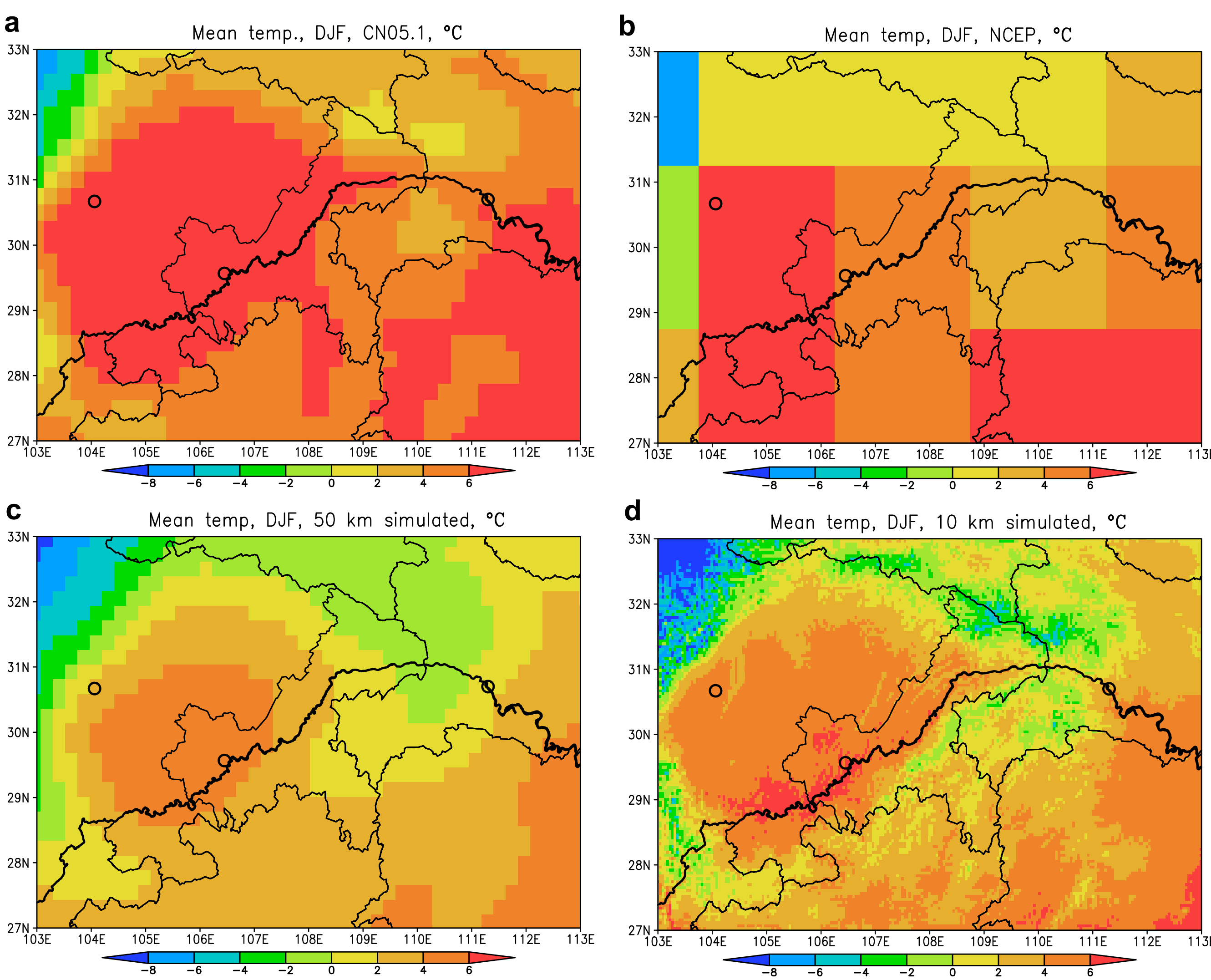

Fig. 3. Multi-annual mean temperature in DJF over TGA (°C). (a) observation; (b) NCEP re-analysis; (c) model simulation from Exp. 1; (d) model simulation from Exp. 2.

represented via the scheme of Pal et al. (2000) while convective precipitation is represented using the mass flux scheme of Grell (1993) based on Fritsch–Chappell closure assumption. The series of RegCM have been applied for climate simulations over East Asia for a number of years and showed a good performance in simulating regional climate, especially during the summer season (e.g., Gao et al., 2001, 2008, 2012; Ju and Wang, 2006; Ju et al., 2007; D.F. Zhang et al., 2007).

The model was run at its standard configuration of 18 vertical sigma layers and model top at 10 hPa. Three experiments were conducted for the same period of 1 January, 1995 to 1 January, 2007, for a total of 12 years. The first year was used as model spin up time and is thus not included in the analysis.

The first experiment (Exp. 1) used a domain encompassing continental China and adjacent areas at a horizontal resolution of 50 km (Fig. 1a), similar to that used by Gao et al. (2008). The land cover data were derived from the satellite-based Global Land Cover Characterization (GLCC) by the United States Geological Survey (USGS). The initial and time-evolving meteorological lateral boundary conditions were derived from the NCEP/NCAR re-analysis at a resolution of 2.5° × 2.5° latitude-longitude (Kalnay et al., 1996), updated every 6 h. Sea surface temperatures were obtained from the weekly dataset of National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) Sea Surface Temperature.

In the second experiment (Exp. 2), the model domain covers the TGR and the surrounding area as shown in Fig. 1b at a horizontal resolution of 10 km (the domain hereinafter referred to as the Three Gorges Area, TGA). The SUB-BATS scheme described by Giorgi et al. (2003) was employed to represent the land surface at a resolution of 2 × 2 km (i.e. 25 land sub-grid points for each model grid box). The lateral boundary conditions were derived from the 50 km run of Exp. 1 and no TGR was accounted for. Fig. 1b shows that the fine structure of the topography is well described in this high resolution model domain.

In the third experiment (Exp. 3) the model configuration was exactly as in Exp. 2 but description of the TGR was introduced by replacing the land surface with inland water along the Yangtze River from the TGD (close to Yichang) to Chongqing (Fig. 1b). In total, 267 grid points were replaced, accounting to 0.1% of the total grid point number in the domain.

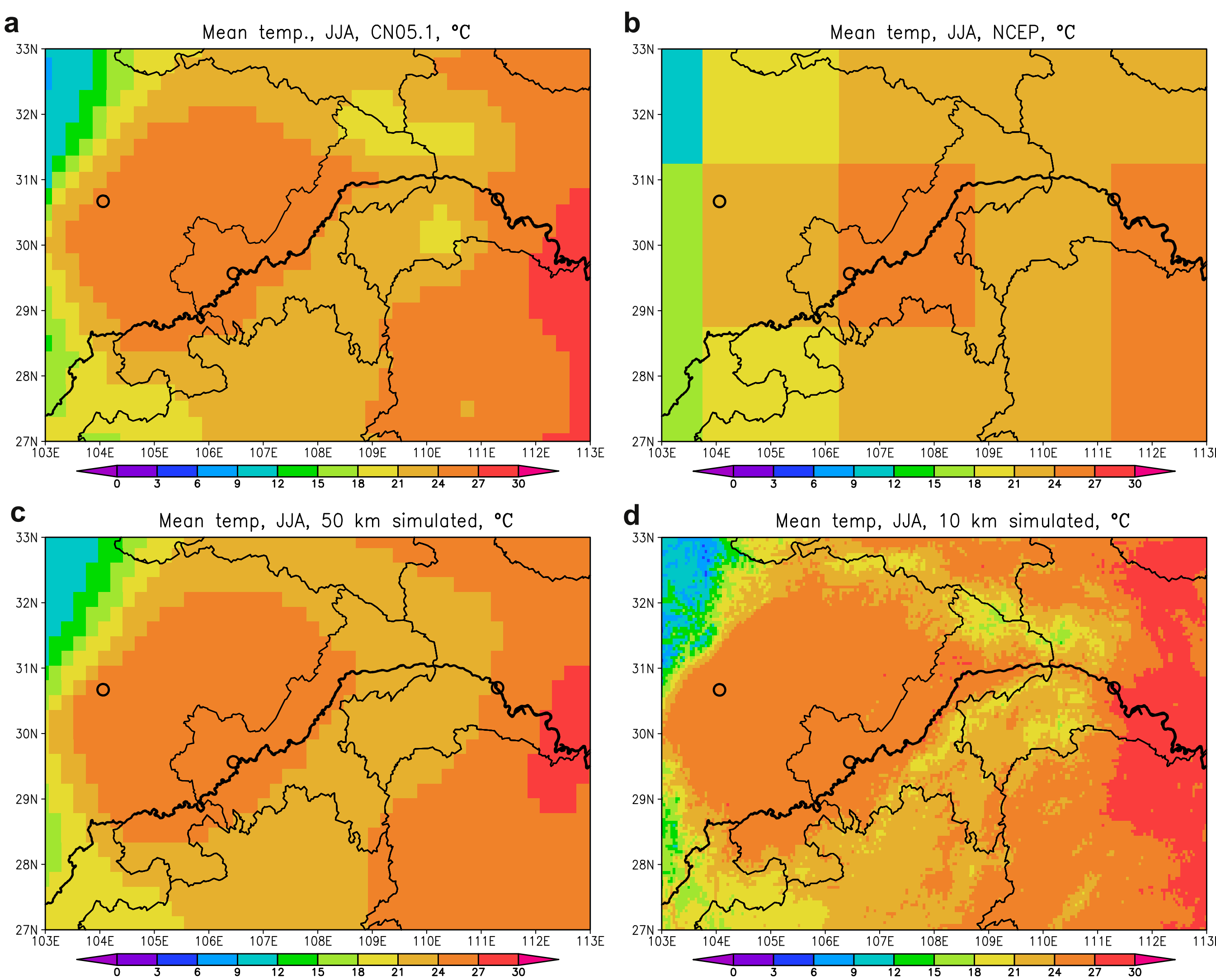

Fig. 4. Same as Fig. 3 but for JJA.

It is a common practice to use climatological sea surface temperature as surface boundary conditions over ocean in the global atmospheric model simulations (e.g., Gao et al., 2003b; Oouchi et al., 2006). Similarly, a climatological WST over TGR was used to force RegCM3 in Exp. 3. This was done also partly due to the limited WST observations available. Daily observed WST data in Cuntan (close to Chongqing in upstream of the TGR) and Miaohe (close to Yichang in the downstream of the TGR) hydrological stations during 2004–2007 were collected and firstly averaged over each day of the 4 years over the 2 stations to obtain a daily climatology of WST. Then the daily WST were linearly interpolated to the 267 inland water grid points in Exp. 3.

WST in Cuntan and Miaohe are presented in Fig. 2a and b, respectively. WST show a strong annual cycle with the maxima found in the summer season of JJA and minimum in the winter season of December–January–February (DJF). The inter-annual differences are relatively small over both stations, with the exception of a greater than normal value in later half of the year 2006, corresponding to the hot drought event during the time. The WST was warmer in the first half of the year in Cuntan located in the upstream, and cooler in later half of the year compared to that in Miaohe in the downstream. The differences of WST between the two stations are in general less than 1–2 °C except in the spring time (March–April–May) when the values can be up to 4 °C (Fig. 2c).

Exp. 1 was primarily used to provide the initial and boundary conditions for the 10 km resolution simulations of Exp. 2 and Exp. 3. Optimally, ratio of the resolutions between the driving field and RCM should be in the range of 3–5, and certainly less than 10. Thus, the NCEP re-analysis cannot be used to drive the 10 km model directly. The differences between Exp. 3 and Exp. 2 are considered as the effects of the TGR on local climate.

A brief comparison of the RegCM3 simulation against observation over China in Exp. 1 shows similar results as previous studies (e.g., D.F. Zhang et al., 2007; Ji et al., 2010). The model can in general reproduce the overall spatial distribution and amount of both temperature and precipitation well over the region, with a cold and wet bias over some areas. For brevity, analysis was focused over TGA (Fig. 1b) and in the season of DJF and JJA in the present study. To validate the model performances, the dataset of CN05.1 consist of both surface air temperature and precipitation in daily scale developed by Wu and Gao (in press) was employed. CN05.1 is based on over 2400 station observations over China

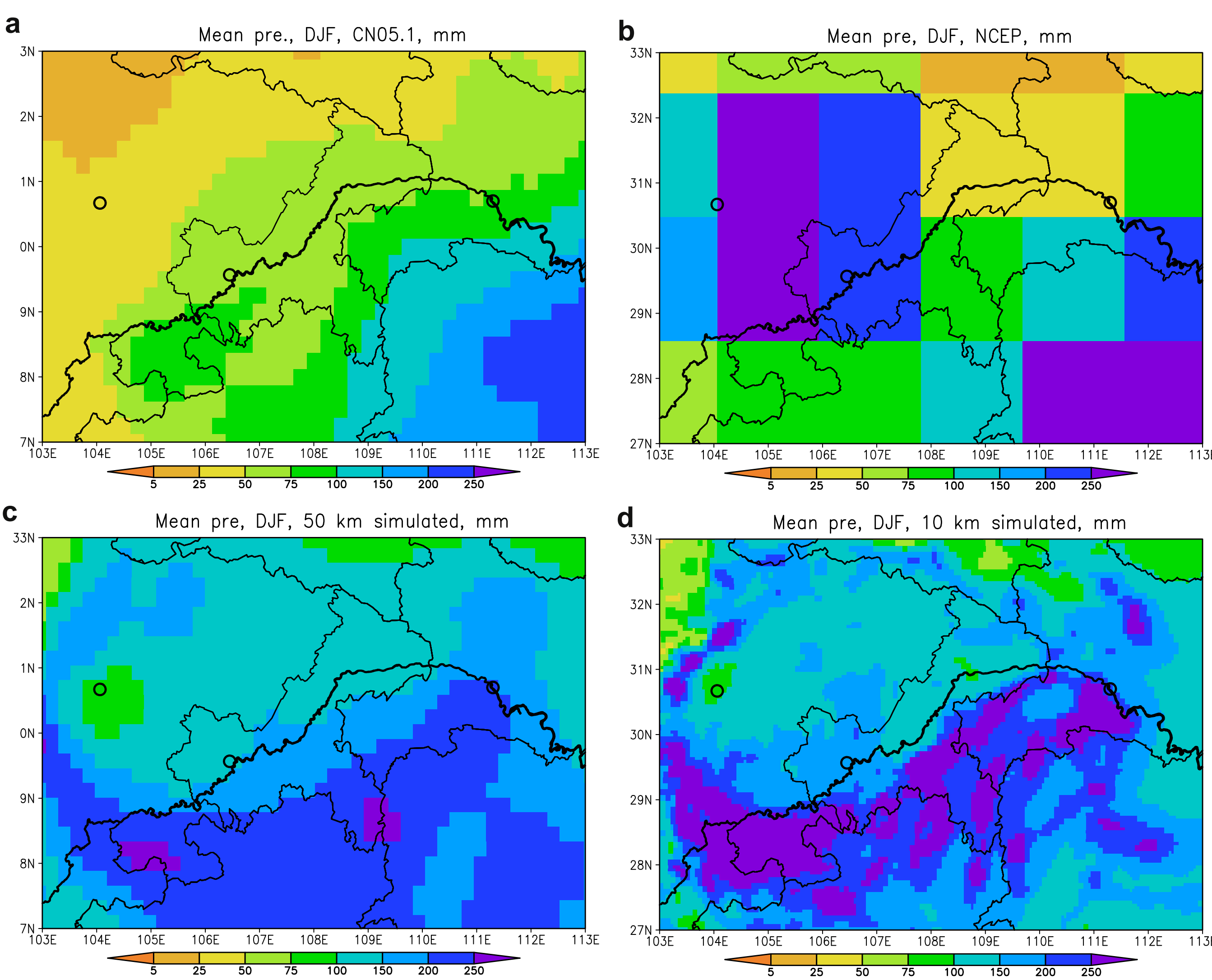

Fig. 5. Multi-annual mean precipitation in DJF over TGA (mm). (a) observation; (b) NCEP re-analysis; (c) model simulation from Exp. 1; (d) model simulation from Exp. 2.

with a resolution of 0.25° × 0.25° latitude–longitude. The interpolation follows the “anomaly approach” used by New et al. (2002) and Xu et al. (2009) when developing the CRU (Climatic Research Unit) and CN05 observation dataset, respectively. There are about 500 stations over the area of interest.

3. Validation of the model performances over TGA

3.1. Surface air temperature

The observed and simulated multi-annual mean (1996–2007) temperature in DJF, as well as that from NCEP re-analysis, are presented in Fig. 3. As shown in Fig. 3a, the temperature distribution from observation follows the local topography well, characterized by the warm over Sichuan Basin and the plain in the east, and cold over the mountains in the west of the domain (edge of the Tibetan Plateau). Lower temperature can also be found in the mountains along the north (Daba) and south both banks of the Yangtze River west of the TGD. The above structure can hardly be observed in the NCEP re-analysis except the lower temperature in the edge of the Tibetan Plateau (Fig. 3b). In Exp. 1, the 50 km model captures the general pattern (Fig. 3c) of the observed temperature although with a cold bias of a few degrees. The bias is usually larger over mountains than the lowlands, with an average of −3.4 °C over the area.

Compare Fig. 3c to d, the 50 km and 10 km simulations show similarities in the general patterns of this variable while the 10 km model provides with much more regional details. For example, the relatively lower temperature over the mountains south of the Yangtze River ranging from 108°E to 110°E, and warmer temperature west of Chongqing along the river sides are evident in Exp. 2 but not in Exp. 1. The finer scale effect of topography on the temperature patterns in Exp. 2 is also evident, particularly as forced by the sub-grid land scheme (Giorgi et al., 2003). The mean bias of Exp. 2 over the area keeps the magnitude as Exp. 1 with a value of −3.0 °C.

Fig. 4a–d present the temperature from observation, NCEP re-analysis and the simulations in JJA, respectively. The spatial distributions show similar structures as in DJF but with much larger values due to the distinct seasonal evolution. The simulation in Exp. 1 in JJA agrees much better in magnitude against observation compared to DJF, with the bias in the range of

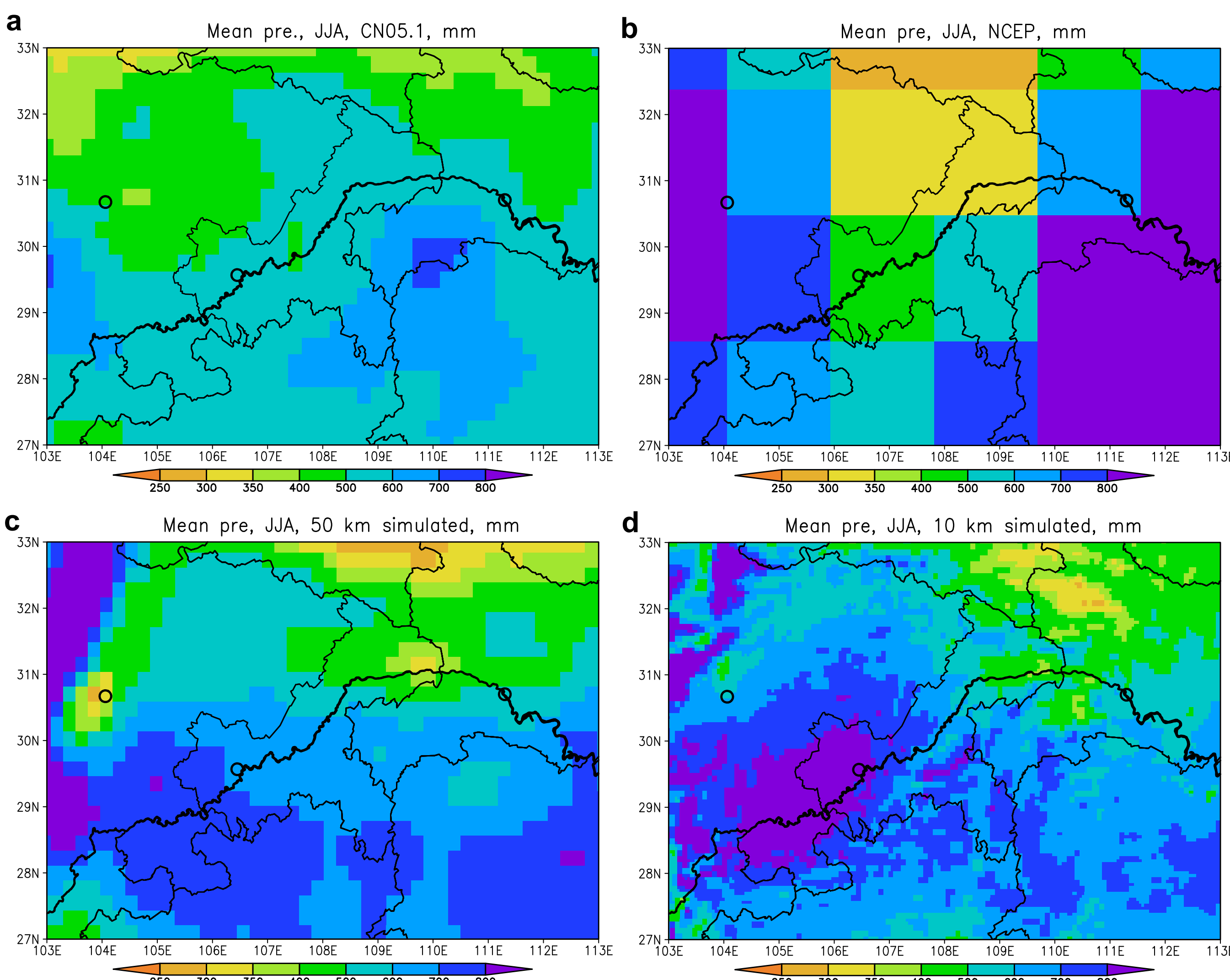

Fig. 6. Same as Fig. 5 but for JJA.

−1 to 1 °C over the domain. More spatial details are simulated in Exp. 2 corresponding to its higher resolution. In addition, the lower temperature zones over Daba and a few other mountain peaks are well simulated in Exp. 2 but not in Exp. 1. The regional mean biases are of 0.4 °C and 0.5 °C in Exp. 1 and Exp. 2, respectively.

3.2. Precipitation

Mean precipitation in DJF from observation, NCEP re-analysis and simulations of Exp. 1 and Exp. 2 are shown in Fig. 5. In the observation, a greater precipitation is found in the southeast and it decreases towards the northwest in the area (Fig. 5a). This spatial distribution basically cannot be found in the NCEP re-analysis (Fig. 5b). With slightly better agreements, a considerable overestimation of precipitation exists in the Exp. 1 and Exp. 2 simulations (Fig. 5c and d). The magnitudes of the overestimation are usually in the range from one to over two times except in the southwest part. The regional mean difference from observation of Exp. 1 and Exp. 2 are of 1.8 and 2.1 times, respectively.

Concerning the bias, at least part of the overestimation can be attributed to the driving NCEP re-analysis field in which doubled area-averaged precipitation compare to that observed can be found. In the mean time, Exp. 1 uses a large domain and the size of TGA is in a rather local scale compare to it. This makes it difficult to reproduce the precipitation pattern in the area well, while the amount and spatial pattern of precipitation in Exp. 2 in general are as in Exp. 1.

As found in previous simulations (e.g., D.F. Zhang et al., 2005; Gao et al., 2008), RegCM3 tends to simulate more precipitation over the mountains. A clear rain belt can be found in Exp. 1 (Fig. 5c) along the south/east slope of the mountains south/west of the Sichuan Basin following the prevailing wind circulation in the season (not shown). The topographic effects are more evident in Exp. 2 (Fig. 5d). However, uncertainty may exist in the observation data employed in the study to validate the model performances. The observation stations are usually located in the valleys and low elevation places thus may miss the greater precipitation over the mountains. Underestimation of precipitation due to the wind-induced gauge undercatch of solid precipitation in the mountainous areas in the cold seasons (may be up to 20%, e.g., Adam and Lettenmaier, 2003) can also contribute to the uncertainties.

In general, there are no systematic spatial structure of precipitation can be found in JJA in either the observation or the simulations (Fig. 6). Compared to DJF, the amounts of the precipitation are better simulated in both Exp. 1 and Exp. 2. The differences between simulations and observation are usually within ±25% except a greater than 50% overestimation along the Yangtze River west of

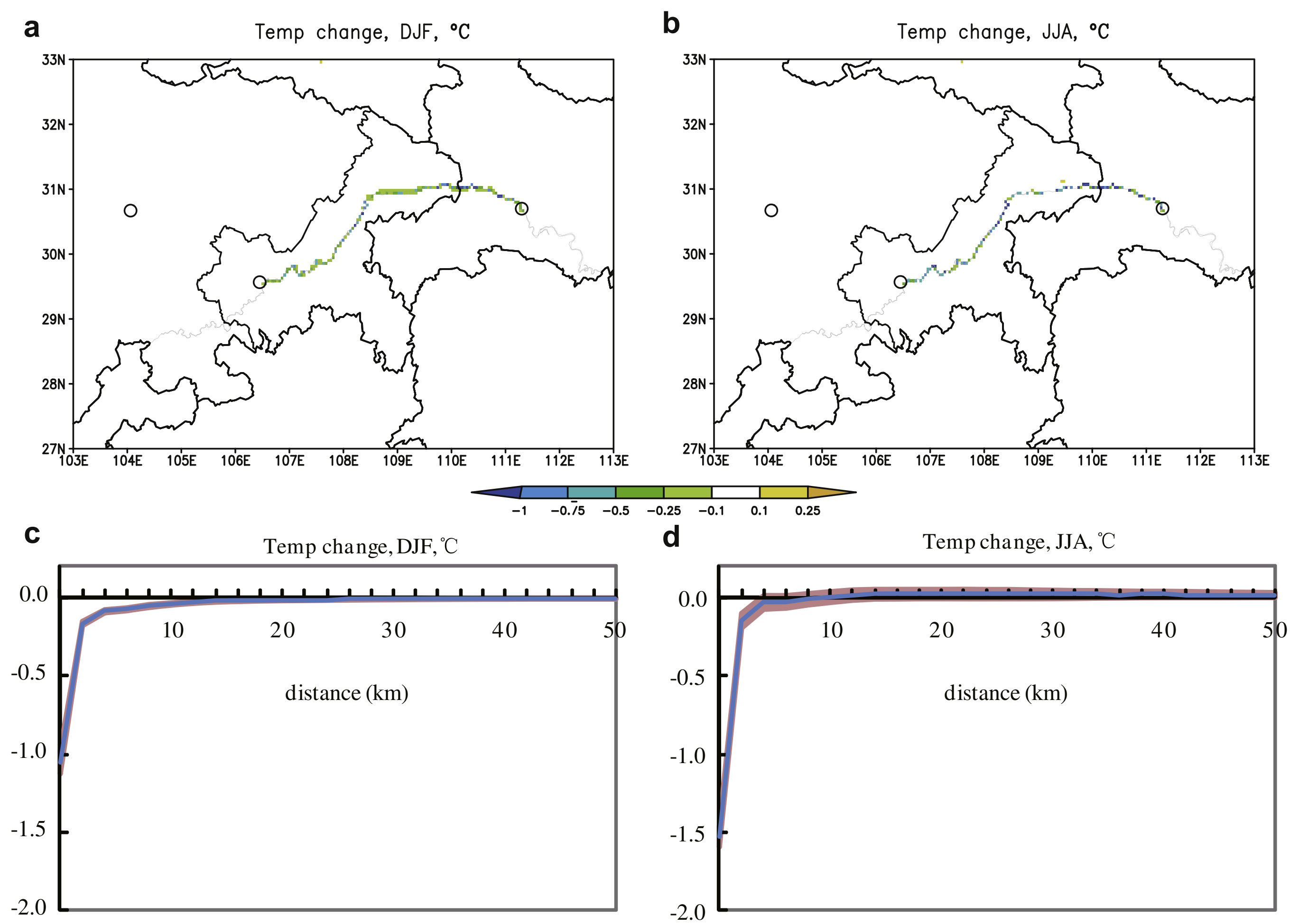

Fig. 7. Effects of TGR on temperature over TGA (°C). (a) spatial distribution in DJF; (b) spatial distribution in JJA; (c) in different distances to TGR in DJF; (d) in different distances to TGR in JJA. The solid lines in (c) and (d) show the multi-year mean and shaded areas denote ±1 standard deviation.

Chongqing in Exp. 2. The regional mean bias in NCEP re-analysis, Exp. 1 and Exp. 2 are of 30%, 20%, and 26%, respectively.

4. Impacts of the TGR on regional and local climate

4.1. Surface air temperature

The changes of temperature in DJF and JJA due to the TGR (Exp. 3–Exp. 2) are presented in Fig. 7. Cooling greater than 1 °C was found only over the TGR itself, as a result of the presence of inland water there. Most of the changes are statistically significant at the 95% confidence level over TGR, but not elsewhere. The cooling is mostly associated to the greater evaporation on the surface of inland water compared to the original land. Averaged over the area, the temperature differences between Exp. 3 and Exp. 2 are in the order of ~0.00 °C in both DJF and JJA.

As shown in Fig. 7c and d, the temperature effect quickly decreases away from the TGR. In fact, it drops to less than −0.2 °C in the nearest land grid points. The cooling over the water body was greater in JJA (~1.5 °C) compared to DJF (~1 °C). Decreased temperature is simulated in both DJF and JJA in the experiments. The hypothesis of winter warming may be more reasonable in a colder area, but not in TGA where the climate is in general moderate throughout the year. The inter-annual differences of the effects are small, although a minor warming can be found in JJA in some years.

4.2. Precipitation

Climate effects of TGR on precipitation are shown in Fig. 8. Besides the decrease over the TGR in JJA, there are very noisy fields in the spatial distribution of the effects, most likely tied to the internal model variability rather than resulting from the TGR forcing (Fig. 8a and b). Only at very few grid points in JJA over the TGR are the changes statistically significant at the 95% confidence level. The area-averaged changes are in a very small magnitude and not statistically significant, with the values of −0.08% and 0.25% in DJF and JJA, respectively.

A larger spread of the TGR effects on precipitation can be observed in Fig. 8c and d, compared to that of temperature. Averaged change of precipitation in DJF is a decrease of 1.6% over TGR with the range from 1% to 2% in different years. The minor decrease dropped slowly moving away from the TGR and the value in the 50 km distance is of ~0.5%. The effect of TGR on precipitation is larger in JJA compared to DJF. The averaged decrease is about 10% over TGR but dropped quickly to 3% and less than 1% at 10 km and 20 km away, respectively. Larger spread of the effects, in the range of 8%–12%, can also be found in JJA. The multi-year average of the effect is a decrease in JJA. But different from a uniformed decrease in different distances and years in DJF, an increase in precipitation is simulated in some years away from the TGR. The decreases of precipitation over TGR are mostly due to the decreased temperature corresponding to the excessive evaporation over the

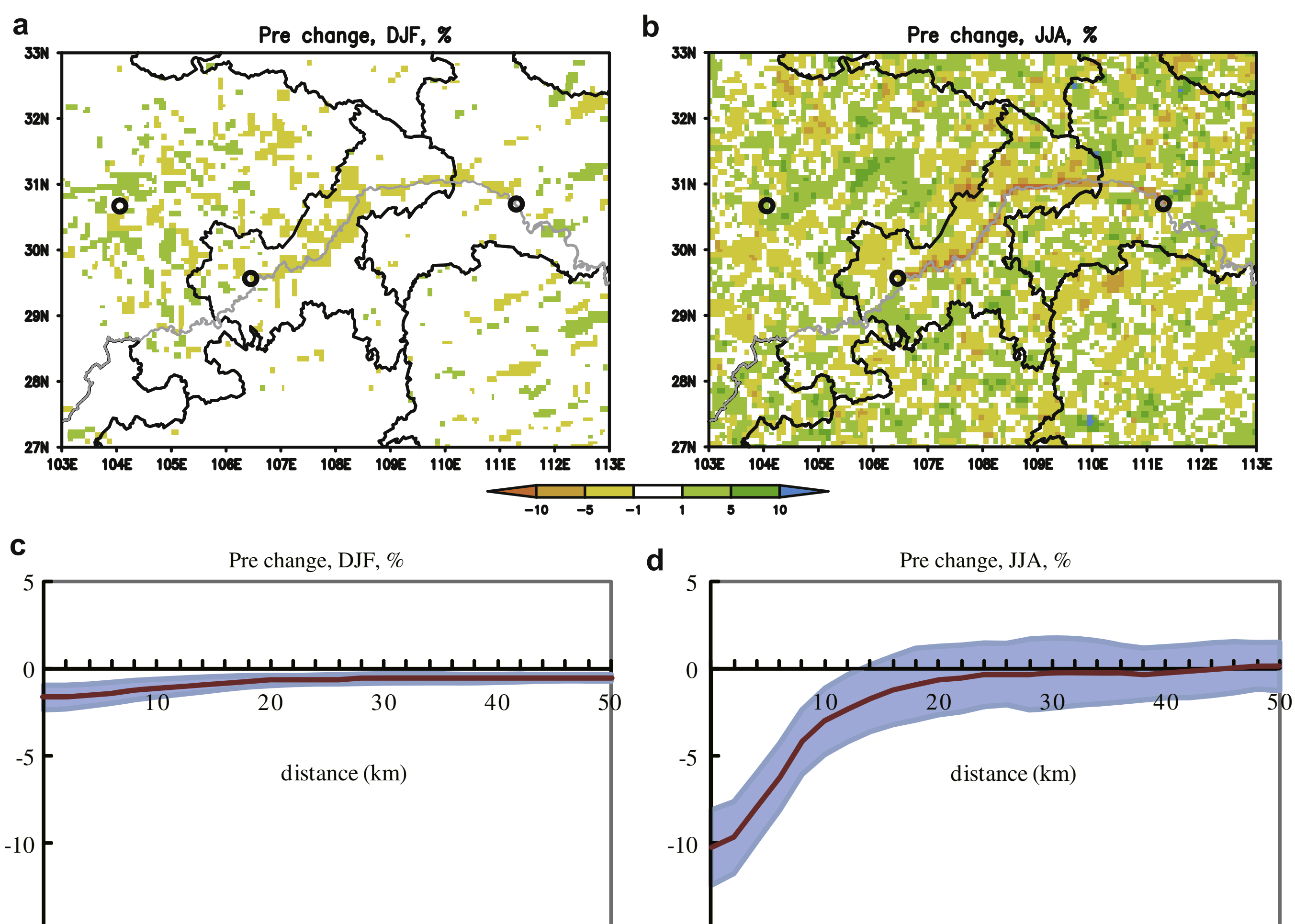

Fig. 8. Same as Fig. 7 but for precipitation (%).

inland water, which lead to a more stable vertical structure in the upper-air.

5. Summary and discussion

The effects of TGR over local and regional climate are investigated through multi-annual long simulations with RegCM3. A double nested method was employed in the study to reach a final resolution of 10 km with 2 km land surface representation by the SUB-BATS scheme. Validation of the model was firstly performed by comparing the simulations against observation. Results show that the model captures well the spatial distribution of temperature, although with a general cold bias of a few degrees in DJF. Simulation of the precipitation is not as good as temperature. The model tends to overestimate the precipitation over the area, particularly in DJF.

Concerning the climate effects of TGR, a statistically significant decrease of temperature and a decrease of precipitation over the TGR are simulated. The effects are larger in JJA compared to DJF. However, other than locally on the TGR surface, the TGR does not have significant effects on the climate of the surrounding region. Note the width of 2 km in these experiments is almost double the real width of TGR. Even so, the simulations indicate that being a typical river-like reservoir, the width and coverage of the TGR is not large enough to influence the regional climate. This further confirms the findings by Wu et al. (2011), and agrees with the observation evidence that the variation of precipitation around TGR in the late decades is part of the natural inter-annual oscillation and the TGR does not significantly influence the changes of precipitation around the TGR (Xiao et al., 2010).

Limitations of the study, and the future work plan, include:

1) Due to coarse resolution re-analysis data employed in the study, a 50 km simulation was firstly conducted to downscale it to provide the initial and boundary conditions for the 10 km resolution simulations. While the 50 km simulation captures well the general pattern and amount of the variables in its domain, discrepancies can be found in the rather local area of TGA. The discrepancies in the spatial pattern and amount of both temperature and precipitation in the 50 km simulations were then introduced and kept in the 10 km simulations. Further employment of re-analysis data with a better quality and higher resolution (e.g., ERA-interim, Uppala et al., 2008) to drive RegCM3 directly over TGA with further improvement, tuning and selection of model physics (e.g., different convection schemes), to better reproduce the local climate will help to add the robustness of the conclusions.
2) As discussed in the paper, uncertainties exist in the observation data used to validate the model performances. Further collection of station observations, correction of the bias in the original station observation data, and to develop a higher resolution gridded dataset matching the model resolution are needed in the future work.
3) Although the simulations show that the TGR does not have significant effects at the regional scale, it may still have some local effects in the areas directly adjacent to the water surface. However RegCM3 is a hydrostatic model so far which limits the further increase of its resolution beyond ∼10 km. If computer capabilities are available, multi-year simulations with the use of non-hydrostatic climate models at a horizontal resolution of a few hundred meters to 1 km, are likely needed to better address such local scale effects.

Acknowledgments

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