Reduction in the east–west contrast in water budget over the Tibetan Plateau under a future climate

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Abstract:

As the Tibetan Plateau (TP) is an important Asian water resource, future changes in precipitation over the TP are an essential part of climate change assessments for the TP and surrounding regions. Here we investigate the water budget over the TP with a global 20-km grid atmospheric general circulation model. Future simulations are performed using CMIP5 multi–model ensemble mean sea surface temperature changes at the end of the 21st century under the RCP8.5 scenario. In the present climate, an east–west contrast in the water budget is noted: over the eastern TP, both moisture flux convergence and local evaporation contribute to summertime precipitation with comparable magnitude; on the other hand, over the western TP, contribution from local evaporation dominates. Under the future climate, precipitation increases over the TP. Contribution from increasing evaporation dominates that from increasing moisture flux convergence into the TP. A prominent east–west contrast is also found in future surface water budget changes. Over the western TP, surface temperature increases are higher, an increasing rate of precipitation is greater, soil moisture becomes wetter, and runoff increases more than over the eastern TP. This suggests that the east–west contrast in surface climate over the TP could become smaller in the future.

KEYWORDS Tibetan Plateau; water budget; east–west contrast; climate change; GCM

INTRODUCTION

The Tibetan Plateau (TP) is one of the most important geographical features on the Earth and influences the weather and climate systems over Asia through distinct thermal and dynamic processes (Yanai and Wu, 2006; Wu et al., 2012). As the origin of major Asian rivers due to snow and runoff, the TP also plays the role of the “Asian water tower”, affecting the water sustainability for the Asian people (Qin et al., 2006; Immerzeel et al., 2010). In recent decades, climatic warming has been observed in the TP (Liu and Chen, 2000; Qin et al., 2009; You et al., 2016). Lake area expansion and water depth increase have also been observed (Lei et al., 2014) together with changes in regional water and energy cycles (Yang et al., 2014). Due to its high elevation, the TP is unique for atmospheric moisture distributions (Zhang et al., 2013; Zhou et al., 2013).

Therefore, future changes in the distribution and transport of water over the TP is an essential part of climate change assessment, not only for the TP itself but also for the surrounding regions. The models in the Coupled Model Intercomparison Project phase 5 (CMIP5) project overall increasing precipitation but decreasing soil moisture due to increasing evaporation over the TP, however, agreement among the models is low (Collins et al., 2013). In addition, those models highly overestimate the climatological annual mean precipitation in present-day simulations compared to observations (Su et al., 2013). Su et al. (2013) also showed that only half of the CMIP5 models investigated reproduce the observed seasonal pattern.

High-resolution models may be necessary to reasonably simulate regional climate and project future changes over and around mountainous regions with complex terrain (Arakawa and Kitoh, 2012). Here we use a 20-km mesh global atmospheric general circulation model to investigate possible future changes in water budget over the TP. The present-day climate experiment with this model reveals an elevation dependency in precipitation, which matches observations better than lower resolution models.

MODEL AND EXPERIMENT

We used a global 20-km mesh Meteorological Research Institute (MRI) atmospheric general circulation model (AGCM) version 3.2 (MRI-AGCM3.2, Mizuta et al., 2012). This model is superior to previous version in reproducing global climatology including monsoon precipitation and tropical cyclones. Using this model, Endo et al. (2012) showed an increase in extreme precipitation in South Asia and Southeast Asia under a future climate. Kitoh and Endo (2016) further investigated projected changes in regional precipitation extremes. They found an increase in regional precipitation extremes in all regional domains, even where mean precipitation decreased. South Asia was found to be the region with the largest extreme precipitation increase.

The present climate simulation used the observed monthly mean sea surface temperature (SST) during 1979–2003. For the future climate (2075–2099), the boundary SST data were prepared by superposing the future change in the multi-model ensemble mean of the SST projected by the CMIP5 models to the present-day observed SST. The 25-year annual mean global surface air temperature difference is 3.48°C in this experiment. Kitoh and Endo (2016) assessed the uncertainty by using four different SST patterns in the future climate projections. Based on their result, projected changes in the annual mean precipitation under the RCP8.5 scenario over Tibet (75°E–100°E, 30°N–50°N in their definition) are

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between +20.2% and +24.0%. As the uncertainty range is small, we analyzed one experiment with the multi-model mean SST in this paper.

**PRECIPITATION AND ITS FUTURE CHANGE**

Due to its high elevation, the TP is dry in terms of precipitation. Figure 1a shows the observed annual mean precipitation estimated with the Tropical Rainfall Measuring Mission (TRMM) 3B42 product version 6 (Huffman et al., 2007), which covers 1998–2013. The horizontal resolution of TRMM data is 0.25 degrees and is very close to the model resolution. Figure 1b shows the climatology simulated by the 20-km mesh MRI-AGCM3.2. We define grid points above 3,000 m elevation as the TP in this paper. Due to southerly summer monsoon circulation, strong precipitation exists to the south of the TP. Studies based on observed data show a double rainfall maxima, one along the foothills (500–1,000 m height) and the other along the southern slopes (4,000–4,500 m height) of the Himalayas (30–32°N, 75–80°E) (Yatagai et al., 2005; Bookhagen and Burbank, 2006). Yatagai et al. (2005) showed that the 20-km-mesh MRI-AGCM successfully reproduced these two rain bands.

Compared to low-elevation regions, it is relatively dry over the TP. There exists a clear gradient from the wetter south-eastern TP toward the drier northwestern TP. This gradient is also well reproduced by the model. It is driest in the Tarim Basin where annual mean precipitation is less than 0.25 mm d⁻¹.

Maussion et al. (2014) described the spatial pattern and seasonality of precipitation over the TP using the High Asia Reanalysis dataset (HAR). They observed a winter precipitation regime in the west, a spring precipitation regime in the northern and southern parts, and a summer precipitation regime elsewhere. On the central and northern TP, the spring precipitation constitutes a substantial part of the annual amount. By comparing the HAR with satellite-based precipitation estimates from TRMM, Maussion et al. (2014) suggested a severe underestimation of frozen precipitation in TRMM, which falls mainly over the western TP.

Bold solid lines in Figure 2 show the seasonal cycle of the monthly mean precipitation for the present-day simulation over the western Tibetan Plateau (west of 90°E, WTP) and the eastern Tibetan Plateau (east of 90°E, ETP), respectively. For precipitation in the WTP, observations are rare and satellite estimates not reliable. As a surrogate for observations, the HAR data is plotted in thin solid lines in Figure 2. There is a clear west–east contrast in the seasonal cycle in precipitation, not only in its shape but also in magnitude. The 20-km-mesh MRI-AGCM reasonably reproduces these characteristics. There is a single peak in summer over the ETP, while there are double peaks over the WTP, one in summer and the other in early spring. Note that the magnitude of precipitation over the WTP is about a half of that over the ETP. The precipitation peak in summer is brought...
about by southerly winds related to monsoonal circulations (Chen et al., 2012; Dong et al., 2016). The peak in early spring over the WTP is caused mainly by westerly mid-latitude cyclonic disturbances (Maussion et al., 2014). Considering an overestimation in precipitation over the TP and a poor representation in its seasonal pattern by CMIP5 models (Su et al., 2013), superiority of the high-resolution MRI-AGCM is clear, thus providing us a rationale for further investigation of climate change over the TP due to global warming.

Precipitation is projected to increase overall over the TP in a future warmer climate. The long dashed lines in Figure 2 show the monthly mean precipitation projected at the end of the 21st century under the RCP8.5 scenario. Some annual mean values averaged over the WTP and the ETP are shown in Table I. Over the ETP, the annual mean precipitation is projected to increase by about 22% from 2.15 mm d\(^{-1}\) to 2.61 mm d\(^{-1}\). This ratio is much less than the increase in precipitable water, which increases 50% from 4.87 mm to 7.31 mm. It has been well discussed that changes in the long-term and regionally averaged precipitation are more regulated by heat balance than local changes in moisture availability (e.g., Allen and Ingram, 2002). Here the change rate in precipitable water, about 10.9%/°C both over the WTP and the ETP, is larger than the Clausius-Clapeyron relationship. This may be partially explained by greater warming in the troposphere than at the surface, but the full reason is yet to be clarified. It is projected that an increase in spring to early summer will be more than that in late summer to fall (Figure 2).

Over the WTP, annual mean precipitation is projected to increase from 1.17 mm d\(^{-1}\) to 1.47 mm d\(^{-1}\), with a slightly greater ratio of about 25% than over the ETP (Table I). Precipitable water over the WTP increases 59% from 2.81 mm to 4.47 mm. Precipitation increases in summer are large, however changes in May are small, which is in contrast with changes in the ETP (Figure 2a). There are also greater increases in precipitation in March–April. The west–east contrast in changes in precipitable water and precipitation may be associated with changes in temperature. The annual mean surface air temperature over the WTP increases more than that over the ETP (5.42°C versus 4.59°C), probably reflecting higher elevation in the WTP (average elevation is 4,565 m in the model) than in the ETP (4,243 m) through snow–albedo feedback and/or larger atmospheric temperature increase at higher altitude in the troposphere under the global warming (Bony et al., 2006).

Table I. Annual mean water-related values over the western Tibetan Plateau (WTP; west of 90°E) and the eastern Tibetan Plateau (ETP; east of 90°E). Ratio (%) indicates percent change ratio between present and future

| variable                  | unit   | WTP          | ETP          |
|---------------------------|--------|--------------|--------------|
|                           | Present| Future       | Change       | Ratio (%) | Present| Future       | Change       | Ratio (%) |
| Surface Air Temperature   | K      | 264.98       | 270.39       | 5.42      | 269.55 | 274.14       | 4.59         |
| Precipitation             | mm d\(^{-1}\) | 1.17       | 1.47         | 0.29      | 25.0   | 2.15         | 2.61         | 0.47       | 21.6   |
| Evaporation               | mm d\(^{-1}\) | 0.53       | 0.75         | 0.22      | 41.8   | 1.22         | 1.55         | 0.33       | 27.5   |
| Runoff                    | mm d\(^{-1}\) | 0.45       | 0.70         | 0.25      | 53.9   | 0.93         | 1.07         | 0.15       | 15.8   |
| Moisture Flux Convergence | mm d\(^{-1}\) | 0.65       | 0.72         | 0.07      | 11.3   | 0.93         | 1.06         | 0.13       | 13.9   |
| Precipitable Water        | mm     | 2.81         | 4.47         | 1.67      | 59.4   | 4.87         | 7.31         | 2.40       | 50.1   |
| Snow Water Equivalent     | mm     | 1155.57      | 450.06       | –705.51   | –61.1  | 83.95        | 20.24        | –63.71     | –75.9  |
| Soil Moisture             | mm     | 140.08       | 146.81       | 6.72      | 4.8    | 326.57       | 309.30       | –17.27     | –5.3   |

WATER BUDGET

Here we investigate the water budget and its change, both in the atmosphere and at the surface. The atmospheric water budget equation can be written as

\[
\frac{\partial W}{\partial t} = -\text{div} \; Q + E - P
\]

where \( W \) is the total water vapor in the atmospheric column (precipitable water), \( t \) is the time, \( \text{div} \) is the divergence, \( Q \) is the moisture flux, \( E \) is the evaporation, and \( P \) is the precipitation.

Figures 3a and 3b show the seasonal cycle of atmospheric water budget over the WTP and the ETP, respectively. Changes in precipitable water in a month are negligibly smaller than the other three components. Over the ETP, local evaporation is larger than moisture flux convergence nearly all year round. Evaporation increases gradually from winter to summer associated with the seasonal evolution of temperature. On the other hand, moisture flux convergence over the ETP increases three times from May to June concurrent with the onset of the South Asian summer monsoon. Moisture flows into the ETP through the southern and eastern boundaries (not shown). Contribution of the moisture flux convergence becomes comparably large to that of the evaporation during June–September. Over the WTP, evaporation and moisture flux convergence have different contributions within a year. In summer, evaporation has a dominant role in the precipitation peak. The role of moisture flux convergence is small in the WTP, being different from the ETP. In winter, evaporation becomes smaller, and moisture flux convergence almost determines precipitation. Thus, the early spring precipitation peak in the WTP is mainly due to moisture flux convergence from the western side of the TP (not shown).

Figures 3c and 3d show the future changes in the seasonal cycle of atmospheric water budget over the WTP and ETP, respectively. Over the ETP, large precipitation increases are projected during April–July. The increase in evaporation mostly explains the precipitation increase in late spring (April–June), but a July peak in precipitation changes is due to increased moisture flux convergence. From August to October, local evaporation is the source of the precipitation increase. Over the WTP, evaporation changes almost explain the precipitation increases, except in March and July when the moisture flux convergence term is dominant. It is noted that the anomalous moisture flux term is negative, i.e. anomalous moisture flux divergence, in May, October and
November in the WTP.

Next we investigate the surface water budget over the TP. The surface water budget equation can be written as

$$\frac{\partial H}{\partial t} = P - E - R \tag{2}$$

where $H$ is the depth of liquid water storage at the surface, and $R$ is the runoff. $H$ consists of the soil moisture ($W$) and the snow water equivalent ($S$). The land surface model of the MRI-AGCM3.2 has different depths of three soil layers depending on the vegetation type from 50 cm in desert grids (bare soil) to 350 cm in forest grids (Yukimoto et al., 2012). The vegetation type in the ETP of the MRI-AGCM3.2 mainly consists of ground cover, while that in the WTP mainly consists of broadleaf shrubs with bare soil, with some grids of bare soil only and glacier at higher elevation grids. The maximum depth of the soil moisture of ground cover, broadleaf shrubs with bare soil, and bare soil is set to 62.58 cm, 64.84 cm, and 21.32 cm, respectively. There is no glacier model. At the glacier grids, when snow mass exceeds 10 m, the excess amount is assumed to enter the nearest ocean grid immediately. This results in an unbalanced surface water budget in Table I, especially in the present-day climate.

Figures 4a and 4b show the seasonal cycle of the surface water budget of the present-day climate over the WTP and the ETP, respectively. Over the ETP, about a half of precipitation runs off and the rest is evaporated back to the atmosphere. During the year, the runoff is large from May to October. Snow accumulates from October to March, during which period some grids of bare soil only and glacier at higher elevation grids may have an unbalanced surface water budget.

Figures 3 and 4c show the future changes in the seasonal cycle of surface water budget over the WTP and ETP, respectively. Over the ETP, evaporation increases throughout the year except during winter. Runoff increases in March–April due to earlier snow melt by warming. Precipitation increases throughout the year with the largest changes in April–June. An increase in precipitation during the latter half of a year is nearly balanced by that in evaporation. Over the WTP, a large decrease in snow mass occurs in spring (April–June), leading to large runoff. Evaporation dominates over runoff only after July when the precipitation increase is largest.

A large east-west contrast is projected in soil moisture between the WTP and the ETP: it becomes wetter over the WTP, while it becomes drier over the ETP (Table I). Wetting soil in the WTP may have resulted in a large increasing rate of evaporation and precipitation. This result can be compared with coarse resolution climate model projections by Immerzeel et al. (2010) who obtained a projected decrease in river flow over the Brahmaputra and Indus basins, and Su et al. (2016) who projected future increase in water availability in the Indus Basin. The poor skill of coarse resolution models in reproducing precipitation amounts, as well as
its seasonal cycle, over the TP warrants the use of high-resolution climate models for future changes in water cycle in this region and surroundings.

CONCLUDING REMARKS

This paper focused on future changes in the water-related variables over the TP and their contrast between the west and the east, projected by the global 20-km mesh MRI-AGCM3.2. The present climate simulation produces an east–west contrast in the water budget. Over the ETP, the moisture flux convergence and the local evaporation is comparable in magnitude for the summertime precipitation, while over the WTP, contribution from the local evaporation dominates. In the future climate under the RCP8.5 scenario at the end of the 21st century, the precipitation over the whole TP increases, for which the contribution from increasing evaporation dominates that from increasing moisture flux convergence into the TP. A prominent east–west contrast is found in the future surface water budget changes. Over the WTP, surface temperature increases more, the increasing rate of precipitation is greater, soil moisture becomes wetter, runoff increases more, and moisture recycling or precipitation efficiency becomes larger than over the ETP.

The WTP becomes wetter, while the ETP becomes drier in the 21st century under the scenario used. This implies that an east–west contrast in the present-day surface climate over the TP becomes smaller in the future climate. A wetting trend over the WTP would continue as long as snow melting contributes to the local water balance, although this modeling largely depends on the initial conditions of the experiment. Moreover, a drier land surface over the ETP would impact water resources in this region and lower reaches. Here we have only evaluated the surface runoff. Changes in river discharge should be investigated further with a glacier and river model (e.g., Su et al., 2016). Obviously, more research is needed for quantitative discussions by utilizing a large ensemble experiment of this model and/or output of various different models.

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