Changes in Moisture Flux over the Tibetan Plateau during 1979–2011: Insights from a High-Resolution Simulation

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ABSTRACT

Net precipitation [precipitation minus evapotranspiration ($P - E$)] changes between 1979 and 2011 from a high-resolution regional climate simulation and its reanalysis forcing are analyzed over the Tibetan Plateau (TP) and compared to the Global Land Data Assimilation System (GLDAS) product. The high-resolution simulation better resolves precipitation changes than its coarse-resolution forcing, which contributes dominantly to the improved $P - E$ change in the regional simulation compared to the global reanalysis. Hence, the former may provide better insights about the drivers of $P - E$ changes. The mechanism behind the $P - E$ changes is explored by decomposing the column integrated moisture flux convergence into thermodynamic, dynamic, and transient eddy components. High-resolution climate simulation improves the spatial pattern of $P - E$ changes over the best available global reanalysis. High-resolution climate simulation also facilitates new and substantial findings regarding the role of thermodynamics and transient eddies in $P - E$ changes reflected in observed changes in major river basins fed by runoff from the TP. The analysis reveals the contrasting convergence/divergence changes between the northwestern and southeastern TP and feedback through latent heat release as an important mechanism leading to the mean $P - E$ changes in the TP.

1. Introduction

In the past three decades, the Tibetan Plateau (TP) has been warming at a faster pace than the global average temperature (Wu et al. 2007; Kang et al. 2010). The warming has already exerted great impacts on the cryosphere and water cycle in the TP (Solomon et al. 2007; Krause et al. 2010; Moore 2012; Gao et al. 2014) that feed major rivers supporting the large population and economic development in Asia. Complex topography has a dominating influence on the TP climatology (Xu et al. 2008; Wu et al. 2013), but observations are sparse in the expansive plateau due to the harsh conditions. With observation sites predominantly located in the eastern mountain valley with accessibility, the vast northwestern TP is mostly devoid of observations. Therefore, climate change analysis is severely limited by poorly gauged or ungauged conditions. Although global reanalyses are appropriate tools for assessing past climate change, they have limited value in the TP because global...
models are not well constrained by observations and they lack sufficient spatial resolution to represent the large spatial heterogeneity associated with topography (Fig. 1a), land cover (Fig. 1b), and soil that influence atmospheric and land processes. Land cover in the TP is dominated by grassland, shrubland, and sparse vegetation or barren ground, denoted as land cover types 7, 9, and 19 respectively in Fig. 1b. These land copy types are distributed from the southeast to the northwest, with a corresponding decrease in leaf area index (LAI; Fig. 1c).

Observations and global reanalyses of the net precipitation \( P - E \) revealed a trend toward drier and wetter conditions over the humid southeastern TP and the vast arid northwestern TP, respectively (Yang et al. 2011; Yin et al. 2012; Gao et al. 2014). Among four global reanalysis products analyzed, Gao et al. (2014) found that ERA-Interim (ERA-Int) best captured the general moistening in the northwestern TP and drying in the southeastern TP in the past three decades, but a large discrepancy is still notable. For example, ERA-Int does not capture the decrease of \( P - E \) in the Yellow River headwater and the Rouergai plateau located in the east. Also the contrast in \( P - E \) changes between the northwestern and southeastern TP is not well replicated. None of the global reanalyses yields a statistically significant pattern correlation with the observed changes at the 70% confidence level. Since the headwater of major rivers originating from the TP is widely distributed across the eastern and central plateau, uncertainty in estimating the spatial distribution of \( P - E \) changes limits the usefulness of the global reanalysis products in understanding the mechanisms responsible for historical changes across the broad Asian region.

Regional climate models (RCMs) are useful for a host of climate change applications that require finer-scale information. They have been widely used to study historical and projected regional climate changes (Mearns et al. 2009; Nikulin et al. 2012; Déqué et al. 2005; Duffy et al. 2006; Giorgi et al. 1992; Kim et al. 2002; Leung et al. 2003a,b; Plummer et al. 2006; Zhang et al. 2009; Laprise et al. 1998) and are generally shown to provide useful skill in simulating surface air temperature, precipitation, and water resources in East Asia (Gao et al. 2008, 2011; X. Gao et al. 2012; Xu and Gao 2014). A recent 33-yr-long regional climate simulation has been conducted over East Asia and comparisons with observations show that the high-resolution simulation not only improves the pattern correlations but also reproduces finer-scale changes in the surface air temperature in the wet season over the TP compared to the global reanalyses (Gao et al. 2015). This study analyzes the precipitation \( P \), evapotranspiration \( E \), and net precipitation \( P - E \) changes from the regional simulation between 1979 and 2011. Differences between the high-resolution simulation and the coarse-resolution reanalysis that provided meteorological forcing are investigated to explore the mechanisms behind the regional-scale \( P - E \) changes. Section 2 introduces the methods and data used. Results are presented in section 3, with conclusions and discussion provided in section 4.

2. Data and methods

The Weather Research and Forecasting (WRF) Model (http://www.wrf-model.org/index.php; Skamarock et al. 2005) was used in the high-resolution regional climate simulation. WRF is a nonhydrostatic model with various choices of physics parameterizations suitable for applications across a wide range of scales. The simulation was performed at 30-km horizontal grid resolution with 159 × 196 grids cells covering East Asia for 1 January 1979 to 31 December 2011 using lateral boundary
The ensemble mean of the multiland model products is used as the reference $E$ in this study.

Observed annual surface air temperature and precipitation averaged across the TP showed abrupt changes around 1998 (Fig. 2 in Gao et al. 2014). Following Gao et al. (2014), 1998 is used as the pivotal year to study changes in $P - E$ from 1979 to 2011, using the definition difference as

$$\delta(\cdot) = (\cdot)_{\text{post}} - (\cdot)_{\text{pre}},$$

where the subscripts “pre” and “post” represent the average in 1979–97 (prephase) and 1998–2011 (postphase), respectively. Terrestrial $P$, $E$, and $P - E$ changes are compared with GLDAS. For the mechanism behind the $P - E$ changes, we analyze the column integrated moisture flux convergence. To reduce uncertainty in post-processing, vertical integration of the moisture budget terms is performed at the original model levels assuming a piecewise linear profile from the surface to the top level of the datasets to give a second-order approximation (Y. Gao et al. 2012). Changes of $P - E$ in the postphase relative to the prephase can be decomposed into mean moisture flux convergence and transient eddy moisture convergence:

$$\rho_w g \delta(P - E) = - \int_0^{P_{\text{post}}} \nabla \cdot (\nabla \theta) \, dp - \int_0^{P_{\text{pre}}} \nabla \cdot (\nabla \theta') \, dp - \delta S,$$

where $\delta S = \delta(q_s \nabla \cdot \nabla p_s)$ represents the changes in surface contributions; $P_0$ is the surface pressure, $q_s$ is the surface specific humidity, and $V_s$ is the wind vector. Since the surface contributions are a few times smaller than the other terms in Eq. (2) [for details, please see Seager et al. (2010) and Gao et al. (2014)], they are neglected in subsequent analysis.

The mean moisture flux convergence change is further separated into the thermodynamic contributor (TH) due to changes in mean specific humidity ($\theta$) and the dynamic contributor due to changes in mean circulation ($\nabla$). Consequently, $P - E$ changes are attributed to a combination of changes in thermodynamics (TH), dynamics (MCD), and transient eddy (TE) components as denoted in Gao et al. (2014):

$$\rho_w g \delta(P - E) \approx \delta \text{TH} + \delta \text{MCD} + \delta \text{TE},$$

$\delta \text{TH} = - \int_0^{P_{\text{post}}} \nabla \cdot (\nabla p_{\text{pre}} \delta \theta) \, dp,$

$\delta \text{MCD} = - \int_0^{P_{\text{post}}} \nabla \cdot (\delta \nabla \theta) p_{\text{pre}} \, dp,$

$\delta \text{TE} = - \int_0^{P_{\text{post}}} \nabla \cdot (\delta \nabla q_{\text{pre}}') \, dp.$

Most importantly, the GLDAS product replicates the observed contrast in $P - E$ changes between the northwestern and southeastern TP (Gao et al. 2014).
3. Results

a. $P - E$ changes

For comparison, $P - E$ changes from GLDAS and ERA-Int are presented alongside those from WRF and the results are shown in Fig. 2. The difference $P - E$ exhibits general increases in the vast northwestern TP and decreases in the southeastern TP in all three datasets. However, the pattern of $P - E$ changes in the WRF simulation (Fig. 2h) resembles GLDAS (Fig. 2g) more than ERA-Int (Fig. 2i) does. The pattern correlation of $P - E$ changes between GLDAS and WRF is 0.17 (Table 1), which passes the statistical significance $t$ test at a 98% confidence level. In testing the statistical significance of the pattern correlation, we estimated the degree of freedom based on the autocorrelation length of the dataset following Leith (1973). In contrast, the correlation (0.04) between GLDAS and ERA-Int does not pass statistical significance even at 70% confidence level, although ERA-Int is already reproducing the observed $P - E$ climatology and trend in the TP better than other popular reanalyses (Gao et al. 2014). Most notably, the WRF simulation captures the larger increase in the Qiangtang plateau over the northwest comparable to GLDAS, but ERA-Int shows increases that are more evenly distributed over the TP and a slight positive gradient from the northwestern to southeastern TP (Fig. 2i). Furthermore, the decrease in the southeastern TP has smaller values and spreads across the lower reaches of the Upper Brahmaputra River basin in WRF (Fig. 2h) compared to the larger, more concentrated decreases in ERA-Int (Fig. 2i). Interestingly, the pattern correlation coefficients between $P - E$ in GLDAS with HGT and MODIS annual mean LAI averaged from 2001

![Fig. 2. Changes in (a)–(c) $P$, (d)–(f) $E$, and (g)–(i) $P - E$ (unit: mm day$^{-1}$) of 1998–2011 compared to 1979–97 for OBS/GLDAS, WRF simulation, and ERA-Int, respectively, over the TP.](image)

<table>
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<th>GLDAS</th>
<th>ERA-Int</th>
<th>WRF</th>
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<tbody>
<tr>
<td>GLDAS</td>
<td>1</td>
<td>0.04</td>
<td>0.17*</td>
</tr>
<tr>
<td>HGT</td>
<td>0.20*</td>
<td>0.02</td>
<td>0.16*</td>
</tr>
<tr>
<td>LAI</td>
<td>−0.27*</td>
<td>0.01</td>
<td>−0.20*</td>
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to 2012 are 0.20 and −0.27, respectively. The positive correlation of the GLDAS $P - E$ change with topography indicates larger $P - E$ increase at higher elevation, while the negative correlation of the GLDAS $P - E$ change with LAI suggests that $P - E$ increases more over the dry land cover type (type 19) with smaller LAI in GLDAS. These relationships of $P - E$ changes in GLDAS with elevation and LAI are well captured by the WRF simulations showing high pattern correlations of $P - E$ with topography (Fig. 1a) and LAI (Fig. 1c). However none of these relationships is captured in ERA-Int (Table 1). This suggests a potential shift toward topography and vegetation distribution as a stronger driver of $P - E$ changes at regional scale, and further supports the importance of resolving topography and land cover using models with higher resolution to simulate regional changes in $P - E$.

Comparing the $P$ and $E$ changes with $P - E$ changes separately for GLDAS, WRF, and ERA-Int (Figs. 2a–f), $P$ changes significantly contribute to the $P - E$ change pattern in all three datasets (Table 2). Furthermore, Table 2 shows that the $P - E$ changes are explained much more by the $P$ changes than the $E$ changes in GLDAS and WRF, but in ERA-Int the $P - E$ changes explained by the $P$ and $E$ changes are more comparable. Like most GCMs, ERA-Int greatly overestimates $P$ in the TP (Fig. 2c) but the wet biases at high elevation are reduced in WRF at high resolution (Fig. 2b). Similar bias reduction is also found in $P - E$ in many subregions of the TP except QDB and QLB (Figs. 2h, 3, and 1a; regions are defined in Fig. 1). Larger improvements are most notable in the southern (Figs. 3a–d) rather than the northern TP (Figs. 3e–i), hinting that the WRF improvements may be related to better representation of the sharp topographic gradient associated with the Himalayas in the southern slope and its impacts on moisture transport and precipitation.

### Table 2. Pattern correlations between annual $P - E$ change with $P$ and $E$ changes in GLDAS and ERA-Int/WRF simulation in 1998–2011 compared to 1979–97. Correlation coefficients with an asterisk are statistically significant at 98% confidence level based on a two-tailed test, and the same applies in other tables.

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<thead>
<tr>
<th></th>
<th>$P$</th>
<th>$E$</th>
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<tr>
<td>GLDAS</td>
<td>0.81*</td>
<td>0.14</td>
</tr>
<tr>
<td>ERA-Int</td>
<td>0.74*</td>
<td>0.30*</td>
</tr>
<tr>
<td>WRF</td>
<td>0.66*</td>
<td>0.06</td>
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The WRF simulation presents the same predominant contribution of $\delta$MCD to $P - E$ changes (Figs. 4a,c), which explains 41% of the $P - E$ change pattern (Table 3). Unlike ERA-Int, however, changes in the thermodynamics ($\delta$TH) and the transient eddy ($\delta$TE) also contribute importantly to $P - E$ changes in the high-resolution simulation (Figs. 4e,g and Table 3 vs Figs. 4f,h). Pattern correlations between $\delta$TH and $\delta$TE with the $P - E$ changes are 0.40 and −0.26, respectively, both statistically significant at 99.9% confidence level (Table 3).

1. $\delta$TE

Having demonstrated important differences between ERA-Int and the regional simulation in their depiction of $P - E$ changes and the contributors to those changes, it would be interesting to contrast how moisture budget terms differ between regional models and their global counterparts in the TP and the Rocky Mountains, two important mountain ranges in the midlatitudes. Y. Gao et al. (2012) found a similar opposite contribution of transient eddy changes to $P - E$ changes in the high-resolution simulation over the Rocky Mountains region, which offsets the drying trend in the southwestern United States under climate change, but in the global models the transient eddy changes contribute to the drying trend, exacerbating the vulnerability of the southwestern United States to droughts in the global model projections. For the TP, in contrast, $\delta$TE in the regional simulation offsets the wetter trend in the northwestern TP and drier trend in the southeastern TP in the historical period, but it has almost no contribution to the $P - E$ changes in ERA-Int. Previous studies of extreme precipitation changes have reported an upward trend in the southern TP and a downward trend in the central TP (Wu et al. 2013; You et al. 2008). Since transient eddy changes are associated with changes in storms, similarities between the distributions of $\delta$TE changes in the WRF simulation with observed pattern of extreme precipitation changes suggest that the WRF simulated $\delta$TE changes may be more realistic than those of ERA-Int.

In the Rocky Mountains, the difference in the transient eddy changes dominates the difference in $P - E$ changes between the high- and coarse-resolution moisture budgets (Gao 2012a). However, in the TP, differences in the thermodynamic changes also contribute to differences in $P - E$ changes between the high-resolution simulation and the coarse-resolution forcing. In the narrower, north–south-oriented Rocky Mountains with prevailing westerly winds, higher resolution has important effects on a model’s ability to simulate orographic uplift and partitioning of precipitation between upwind and leeside along the winter storm tracks. Hence, it is not surprising that the primary difference between the high- and coarse-resolution moisture budgets is related to the transient eddy changes.
However, the TP is a massive highland with altitude above 5000 m across a vast mountaintop, with its annual water cycle changes dominated more by the warm season changes (Gao et al. 2014). Unlike the Rocky Mountains where the main difference between the regional and global simulations lies in the transient eddies changes, in the TP the regional simulation and ERA-Int differ in both changes in transient eddies and thermodynamic effects.

2) δMCD AND δTH

To provide further insights into the mechanisms of the projected hydrological changes and why the regional and global moisture budgets differ, we follow Seager et al. (2010) to further decompose the thermodynamic (δTH) and mean circulation dynamics contributions (δMCD) into terms due to advection of moisture (δTH$_A$ and δMCD$_A$) and convergence or divergence of moisture (δTH$_D$ and δMCD$_D$). The thermodynamic contribution can be written as

$$\delta \text{TH} = \delta \text{TH}_A + \delta \text{TH}_D,$$

$$\delta \text{TH}_A = - \int_0^{P_r} \left( \overline{U_{\text{pre}}} \cdot \nabla \delta q \right) \, dp,$$

$$\delta \text{TH}_D = - \int_0^{P_r} \left( \delta q \overline{V} \cdot \overline{U_{\text{pre}}} \right) \, dp,$$

in which $U_{\text{pre}}$ represents the wind components in 1979–97 (prephase), δq denotes the moisture change between postphase and prephase, and $P_r$ is the surface pressure.

Similarly, the dynamic contribution can be written as

$$\delta \text{MCD} = \delta \text{MCD}_A + \delta \text{MCD}_D,$$

$$\delta \text{MCD}_A = - \int_0^{P_r} \left( \delta \overline{U} \cdot \nabla \overline{q_{\text{pre}}} \right) \, dp,$$

$$\delta \text{MCD}_D = - \int_0^{P_r} \left( \overline{q_{\text{pre}}} \cdot \delta \overline{U} \right) \, dp,$$

Fitch 3. Time series of annual mean $P$, $E$, and $P - E$ (unit: mm day$^{-1}$) for nine subregions labeled in Fig. 1a corresponding mostly to the headwater of major rivers in Asia that originate from the TP.
in which \( q_{\text{pre}} \) represents the moisture in 1979–97 (prephase), 
\( \delta U \) denotes the changes in wind components between postphase and prephase, and \( P_s \) is the surface pressure.

Figure 5 shows the annual changes of the four terms and Table 4 summarizes the pattern correlation coefficients between the changes in mean circulation/thermodynamics \( (\delta MCD/\delta TH) \) and the contributions due to the advection terms \( (\delta MCD_A/\delta TH_A) \) and the convergence or divergence terms \( (\delta MCD_D/\delta TH_D) \), respectively. The correlation between \( \delta MCD \) and \( \delta MCD_A \) is negative (Table 4) so the changes in the advection of the mean circulation tend to offset the MCD changes. This is also
TABLE 3. Pattern correlations between annual $P - E$ changes and annual changes in mean circulation contribution ($\delta$MCD), thermodynamic contribution ($\delta$TH), and transient eddy contribution ($\delta$TE) in WRF simulation in 1998–2011 compared to 1979–97. Correlation coefficients with an asterisk are statistically significant at 95% confidence level based on a two-tailed t test, and the same applies in other tables.

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<th>$\delta$MCD</th>
<th>$\delta$TH</th>
<th>$\delta$TE</th>
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<tbody>
<tr>
<td>$\delta(P - E)$</td>
<td>0.64*</td>
<td>0.40*</td>
<td>-0.26*</td>
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As demonstrated in Gao et al. (2014), the circulation changes in the upper level are highly correlated to the thermal wind changes, which are triggered by the thermal gradient changes above. The circulation changes in the high-resolution simulation are constrained by the same mechanism related to the thermal changes as in ERA-Int. However, major differences are found and interpreted in the following discussion.

As mentioned above, a major difference between the WRF simulation and ERA-Int is the thermodynamic contribution. There is almost no contribution of thermodynamic change to $P - E$ changes in ERA-Int (Figs. 4b, 4f), but thermodynamic change contributes to $P - E$ changes in the WRF simulation, especially for the wetter trend in the Qiangtang plateau and Yangtze River headwater and the drying in the southeastern TP.

In recent decades, the largest and second largest inner river basin in the arid northern marginal TP, the Tarim basin and the Heihe River basin, experienced discharge increases (Figs. 2g, 3h,i) revealed by historical records (Wang and Meng 2008; Jiang and Xia 2007). In Figs. 4a,b and 5c.g, the $P - E$ increase over the upper reaches of the Tarim basin comes from the divergence change of the mean circulation (Fig. 6a) while the $P - E$ increase over the upper reaches of the Qilian Mountain stems from the moisture change indirectly driven by the convergence at low levels. The $P - E$ decrease in the Qaidam basin also comes from the moisture change.

Annual changes in MCD and TH are both more highly correlated with changes in the wet season than the dry season (Table 4; Gao et al. 2014). Therefore, changes in the wet season are further investigated. Changes in divergence at 500 and 100 mb, average vertical motion, moisture, and microphysics diabatic latent heat averaged between 500 and 200 mb are presented in Fig. 7. The patterns in Fig. 7 are all broadly similar to the $\delta$MCD (Fig. 4c) and $\delta$MCD$_A$ (Fig. 5c) patterns. More convergence and divergence are noted in the northwestern and southeastern TP, respectively (Fig. 7a). So moisture is advected to the northwestern TP from its surroundings and enhances moisture from the Qiangtang plateau to Qilian Mountain (Fig. 7d) as shown in Fig. 6a. Larger
convergence triggers upward motion (Fig. 7c), resulting in condensation and release of diabatic latent heat by cloud microphysics processes (Fig. 7e) that further heats the air masses over the northwestern TP and enhances divergence at upper levels (Fig. 7b). The patterns of column integrated moisture, divergence, vertical motion, and microphysics diabatic latent heat all match the $\delta MCD_D$ and $P - E$ changes patterns very well.

Comparing Figs. 7a and 7b herein to Figs. 11a and 11b in Gao et al. (2014), we see different divergence changes...
in the WRF simulation and ERA-Int, especially at low levels. Unlike the evenly increased convergence at low levels in ERA-Int, contrasting changes in divergence between the northwestern and southeastern TP are clear in the WRF simulation. This heterogeneity in divergence is likely related to heterogeneity in topography and overlaid vegetation captured by the finer-scale simulation but not the coarse forcing (Figs. 1, 2h, 2i). This uneven pattern is strengthened through feedback by the latent heat release associated with the convergence and condensation. Herein we identified the precipitation changes and subsequent changes in convergence (divergence) as an important mechanism leading to MCD increases (decreases) in the vast northwestern (southeastern) TP in the regional simulation (Fig. 2h). Furthermore, the larger convergence in the northwestern TP at low levels attracts more moisture to the Qiangtang plateau and Qilian Mountain from the surroundings, which enhances moisture in a swath extending from the Qiangtang plateau to Qilian Mountain, leading to TH changes in the TP (Fig. 4c). This mesoscale contrast in divergence at low levels is captured by the regional simulation but not coarse-resolution products like ERA-Int.

4. Conclusions

The \( P - E \) changes from a high-resolution regional climate simulation and the global reanalysis that provided boundary forcing are evaluated by comparing them to GLDAS in the TP. The high-resolution WRF climate simulation not only improves the pattern of \( P - E \) changes compared to GLDAS over the best available reanalysis, but it also provides new and substantial findings regarding the contributions of the thermodynamic and the transient eddy components of moisture flux convergence. Most notably, the WRF simulation better represents the observed positive (negative) changes in the vast northwestern (southeastern) TP than the coarse-resolution reanalysis forcing. The improved \( P - E \) change pattern is attributed to improved \( P \) changes and reduced \( P \) biases at high elevations in the high-resolution simulation. Furthermore, the WRF simulation captures the correlation between \( P - E \) changes with topography and LAI in the TP similar to that found in GLDAS. This demonstrates that over the TP with complex terrain, high-resolution climate simulations can provide important insights into regional water cycle changes.

Besides the predominant contribution of the mean circulation dynamic changes inherited from the large-scale forcing, thermodynamic and transient eddy changes also contribute importantly to \( P - E \) changes in the WRF simulation but not the reanalysis. Contrasting divergence changes at low levels between the northwestern and southeastern TP induced by land surface heterogeneity trigger stronger (weaker) upward motion in the vast northwestern (southeastern) TP, leading to \( P - E \) increases (decreases) by MCD changes. The larger convergence in the northwestern TP attracts more moisture to Qiangtang plateau and Qilian Mountain from the surroundings and strengthens \( P - E \) changes through diabatic latent heat released and TH change contribution.

![Figure 6](image-url)

**FIG. 6.** Distributions of changes in circulation (unit: m s\(^{-1}\)) at 200 mb in 1998–2011 compared to 1979–97 in (a) the WRF simulation and (b) ERA-Int.
Although the WRF simulation provided improved depictions of $P - E$ changes in the TP, the $P - E$ increase in the Yellow River basin and Rouergai plateau is still uncertain because the horizontal resolution of 30 km used in the WRF simulation is still not fine enough to resolve the complexity in land surface properties such as the wetland in the Rouergai plateau and land and atmospheric processes over the TP. Furthermore, many studies reported that the Yellow River basin has experienced large land cover/land use changes in recent decades (Li and Liu 2004; Dong et al. 2005; Cuo et al. 2013), which are not included in our simulation. Increasing model resolution (Jiménez and Dudhia 2012; Ikeda et al. 2010; Rasmussen et al. 2011) and including variable land characteristics/parameters (Gao et al. 2008; Meng et al. 2009) might provide additional realisms to better understand $P - E$ changes in the eastern TP.

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REFERENCES
Chen, F., and J. Dudhia, 2001: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling


