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Impacts of Systematic Precipitation Bias on Simulations of Water and Energy Balances in Northwest America

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ABSTRACT

At high latitudes and in mountainous areas, evaluation and validation of water and energy flux simulations are greatly affected by systematic precipitation errors. These errors mainly come from topographic effects and undercatch of precipitation gauges. In this study, the Land Dynamics (LaD) land surface model is used to investigate impacts of systematic precipitation bias from topography and wind-blowing on water and energy flux simulation in Northwest America. The results show that topographic and wind adjustment reduced bias of streamflow simulations when compared with observed streamflow at 14 basins. These systematic biases resulted in a −50%–100% bias for runoff simulations, a −20%–20% bias for evapotranspiration, and a −40%–40% bias for sensible heat flux, subject to different locations and adjustments, when compared with the control run. Uncertain gauge adjustment leads to a 25% uncertainty for precipitation, a 20%–100% uncertainty for runoff simulation, a less-than-10% uncertainty for evapotranspiration, and a less-than-20% uncertainty for sensible heat flux.

Key words: LaD model, bias adjustment, water and energy balance, Northwest America

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1. Introduction

The Land Dynamics (LaD) model has been used to study global land water and energy balances (Milly and Shmakin, 2002a,b) and to investigate its ability for runoff simulations using combined precipitation data developed by Milly and Dunne (2002a), the Climate Prediction Center Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997), and the ISLCP (International Satellite Land-Surface Climatology Project) precipitation data (Meeson et al., 1995). Results have shown that the LaD model is able to simulate global annual runoff.

Milly and Dunne (2002b) indicated that a 10%–20% error in precipitation may result in a 100% error in runoff. This is true at high latitudes and in mountainous areas. The recent North American Land Data Assimilation System (NLDAS; Mitchell et al., 2004) project also showed that all four land surface models underestimate the mean annual runoff in the northern Rocky Mountains. This underestimate varied from 20% to around 100%, subject to different models and basins. The main reason for this underestimation was considered to be systematic precipitation error (Lohmann et al., 2004).

Adam et al. (2006) indicated that systematic precipitation errors result from topographic effects and gauge error caused mainly by wind-blowing effects (Adam and Lettenmaier, 2003). It is very well known that rain gauges catch less precipitation than the true amount due to wind-blowing effects, especially for solid precipitation (Bogdanova et al., 2002). Even for rain at mid latitudes, it can also be reduced by 2%–10%. Meteorological measurements show that precipitation increases with elevation on scales ranging from hillsides up to entire mountain belts because of oro-

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*Corresponding author: Youlong XIA, youlong.xia@noaa.gov graphic lifting. Usually, rain gauge locations are in or near population centers, which tend to lie at low elevations relative to the surrounding terrain. Therefore, measured precipitation tends to be largely underestimated. This underestimation results in systematic precipitation error in mountainous areas. However, neither orographic errors nor gauge measurement errors are adjusted in the NLDAS retrospective precipitation dataset (Cosgrove et al., 2003). This unadjusted precipitation dataset hinders development, calibration and validation of land surface models.

It is acknowledged that errors of regional water and energy flux simulations originate not only from precipitation errors, but also from intrinsic errors in the model formulation, errors in the model parameters, and errors in the other forcing data, such as downward shortwave and longwave radiation. However, as indicated by Milly and Shmakin (2002b), precipitation error is currently the "bottleneck" for rigorous testing and development of land surface models.

To investigate the impacts of systematic precipitation error on the LaD simulations for water and energy fluxes in Northwest America, the LaD model is run using different precipitation datasets, such as the default NLDAS retrospective precipitation dataset, the NLDAS retrospective precipitation dataset adjusted by wind-blowing effects (Xia, 2006), the NLDAS retrospective precipitation dataset adjusted by topographic effects, and the NLDAS precipitation dataset adjusted by both wind-blowing and topographic effects. The simulated streamflow and observational streamflow are compared at 14 U. S. Geological Survey (USGS) sites (Fig. 1) in Northwest America. The impacts of different adjustments on streamflow simulations, precipitation, evapotranspiration, sensible heat fluxes, and soil moisture are discussed. In this study, annual mean water and energy flux are analyzed as did by Milly and Shmakin (2002a,b).

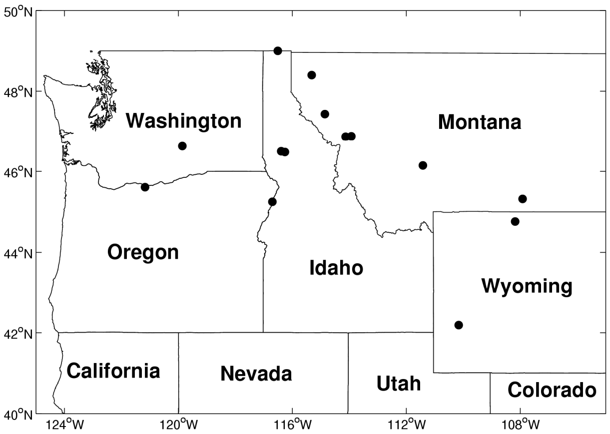

Fig. 1. The 14 USGS streamflow gauges in Northwest America used in this study.

2. Model, data and experiment design

2.1 *LaD model*

The details of the LaD model have previously been described by Milly and Shmakin (2002a). Land characteristic contributions to spatial variability and interannual variability of global water and energy balances were discussed in Milly and Shmakin (2002b). The following is a brief summary only.

The LaD model is a revised version of Manabe (1969) model of land water and energy balances at large scales by adding a non-water-stressed stomatal resistance to control evaporation processes; a ground heat storage process; a groundwater storage process; and varying land characteristics, such as vegetation root depth, vegetation roughness length, and soil and vegetation albedo. Like other land surface models, the LaD model partitions precipitation into evapotranspiration, runoff and soil storage, and partitions net radiation into sensible heat flux, latent heat flux and ground heat storage. Water is stored in snow, glacier ice, root-zone soil water moisture, and groundwater storage. Heat is stored as latent heat of fusion of snow and glacier ice, and as sensible heat in the ground. Runoff is generated when root-zone soil water storage exceeds a water holding capacity. All runoff passes through a groundwater reservoir of specified residence time and a river discharge is calculated by summing all grid cells of a basin according to a river routing network (Oki et al., 1999). A bulk stomatal resistance and an aerodynamic resistance control the land surface evapotranspiration process. It should be noted that there is no precipitation interception process in the LaD model. Nine parameters are used in the LaD model, and these are: effective depth of the root zone; available water ability; bulk heat capacity of the ground; thermal conductivity of the ground; surface roughness length; non-water-stressed bulk stomatal resistance; groundwater residence time; snow-free surface albedo; and snow-masking depth.

2.2 *Data*

Model parameter data and atmospheric forcing data are used to run the LaD model. The model parameters are dependant on soil and vegetation types. Vegetation and soil types are taken from GSWP2 (Global Soil Wetness Project phase 2; see http://www.iges.org/gswp/) and Matthews (1983), respectively. A look-up table for nine parameters can be obtained from Milly and Shmakin (2002a).

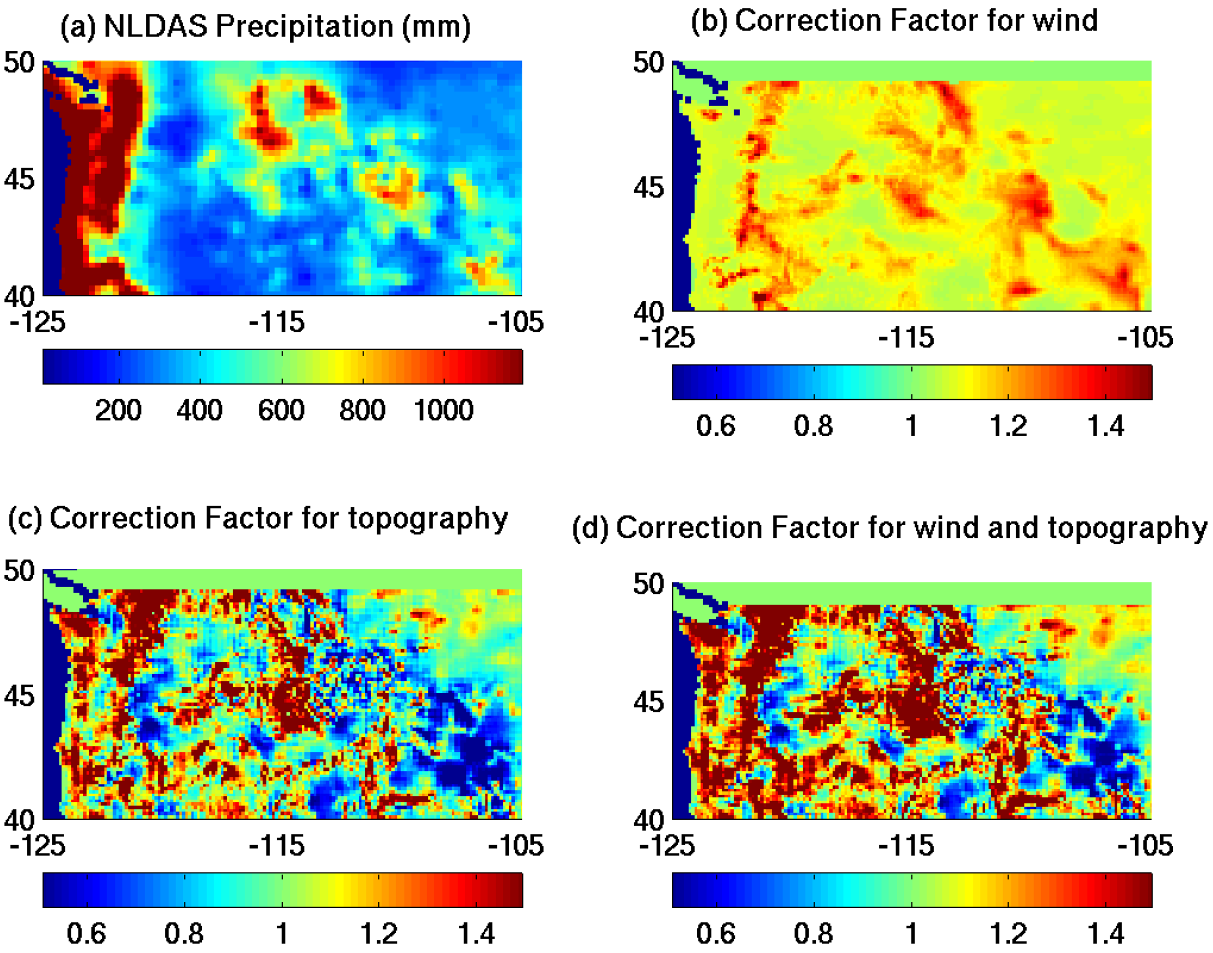

Fig. 2. Five-year (1998–2002) averaged (a) NLDAS precipitation, (b) correction factor for wind, (c) correction factor for topography, and (d) correction factor for both wind and topography.

A six-year (1997–2002) NLDAS retrospective dataset is used as the atmospheric forcing dataset. This dataset features a 0.125° spatial resolution. It includes surface air temperature at a height of 2 m, surface specific humidity at a height of 2 m, meridional and zonal wind speed at a height of 10 m, downward longwave radiation, and surface precipitation combined with gauge precipitation, satellite precipitation and radar precipitation. In order to correct orographic effects for NLDAS precipitation, monthly PRISM (Parameter-elevation Regressions on Independent Slopes Model, Daly et al., 1994) climate precipitation data from Oregon State University (http://www.ocs.oregonstate.edu/prism/) are used for the same period.

A five-year (1998–2002) discharge dataset at 14 USGS sites in western America are used to evaluate the performance of the LaD model for streamflow simulations. These sites were selected because they are located in the orographic effect area as indicated by Adam et al. (2006). The daily discharge data can be taken from http://water.usgs.gov/waterwatch/, and then monthly mean discharges are calculated.

2.3 *Experiment design*

To study the impact of systematic precipitation errors on simulation of land water and energy balances in Northwest America, six experiments were designed: (1) “Control” is a control experiment using the NLDAS retrospective precipitation data. (2) “Topo” is a topographic effect experiment using scaled NLDAS retrospective precipitation data with monthly PRISM precipitation data. The purpose of “Topo” is to discuss orographic effects on water and energy flux simulation by comparing “Topo” with “Control”. (3) “Winda” is a wind effect experiment using the adjusted NLDAS retrospective precipitation data with the optimal World Meteorological Organization (WMO) regression models (Xia, 2006). The goal of this experiment is to discuss the impacts of gauge error on land water and energy flux simulations by comparing “Winda” with “Control”. (4) “Combination”

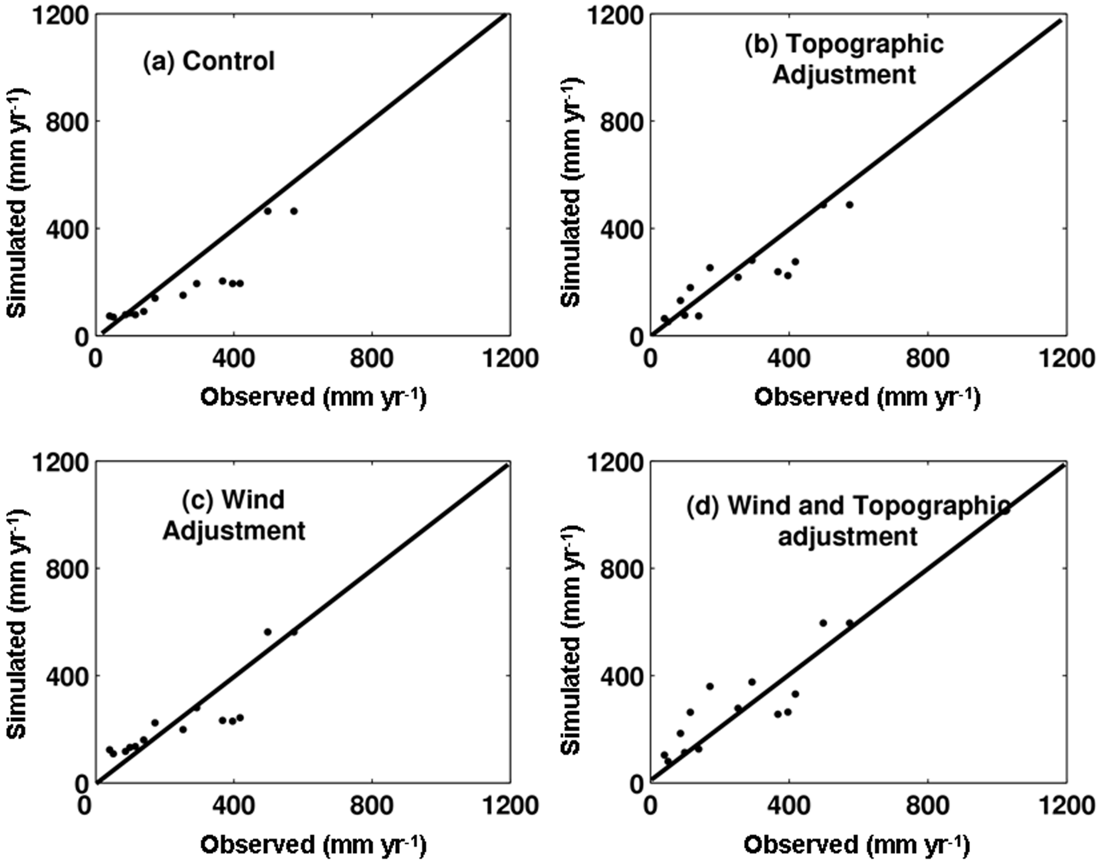

Fig. 3. Five-year (1998–2002) averaged annual streamflow for (a) control run, (b) topographic adjustment, (c) wind adjustment, and (d) topographic and wind adjustment.

is a combined experiment using the adjusted NLDAS retrospective precipitation data with wind and topography. The purpose here is to discuss the impacts of orographic error and gauge error on land water and energy flux simulations. In addition, two precipitation datasets containing levels of uncertainty of the WMO regression models at the 95% confidence level (Xia, 2006) are used to make the experiments (5) "Lowr" and (6) "Highr", respectively. The purpose of these experiments is to discuss the impacts of uncertain WMO regression models on the uncertainties of water and energy flux simulations.

For all analyses, forcing data from the year 1997 are used for a spin-up period. As indicated by Milly and Shmakin (2002a), one-year spin-up is enough for the LaD model. Therefore, only forcing and simulated data for the years 1998–2002 are used to analyze these results. Relative bias is used to assess impacts of systematic precipitation bias on water and energy flux simulations. It is defined as a ratio, that is, the difference between 5-year (1998–2002) mean values for one adjustment experiment and the control experiment is divided by 5-year averaged annual values for the control experiment.

3. Results

3.1 *Analysis of systematic precipitation bias*

Figure 2a shows the spatial distribution of 5-year averaged precipitation in Northwest America. Two strong precipitation bands appear on the west coast of America, where the amount of precipitation is over 2000 mm per year. The other strong precipitation centers are located in isolated mountainous areas, as shown in Fig. 2a.

Wind adjustment leads to a 20%–40% precipitation increase in the Rocky Mountains area and other areas of strong precipitation (Fig. 2b). Most of this increase is because of wind adjustment for snowfalls, as shown in Xia (2006). Wind adjustment results in a 13.2% increase for Northwest America (Table 1). This value is comparable with Legates' (1987) value of 13.7%.

Topographic adjustment generates a 11.8% increase for Northwest America. On the west coast, topographic adjustment increases precipitation by over 40% in two strong precipitation bands, rather than just one—because topography has large impacts on not only snowfall, but also rainfall. However, wind adjustment only increases precipitation in the Rocky

Table 1. Mean (1998–2002) annual precipitation (P), runoff (R), and evapotranspiration (E), and their percentage increase in Northwest America.

Test	P (mm)	E (mm)	R (mm)
Control	567.9	343.6	216.7
Wind	642.8 (13.2%)	355.2 (3.4%)	275.4 (27.2%)
Topo	635.1 (11.8%)	331.6 (−3.5%)	296.0 (36.6%)
Wind+Topo	722.9 (27.3%)	342.5 (−0.3%)	368.3 (70.0%)

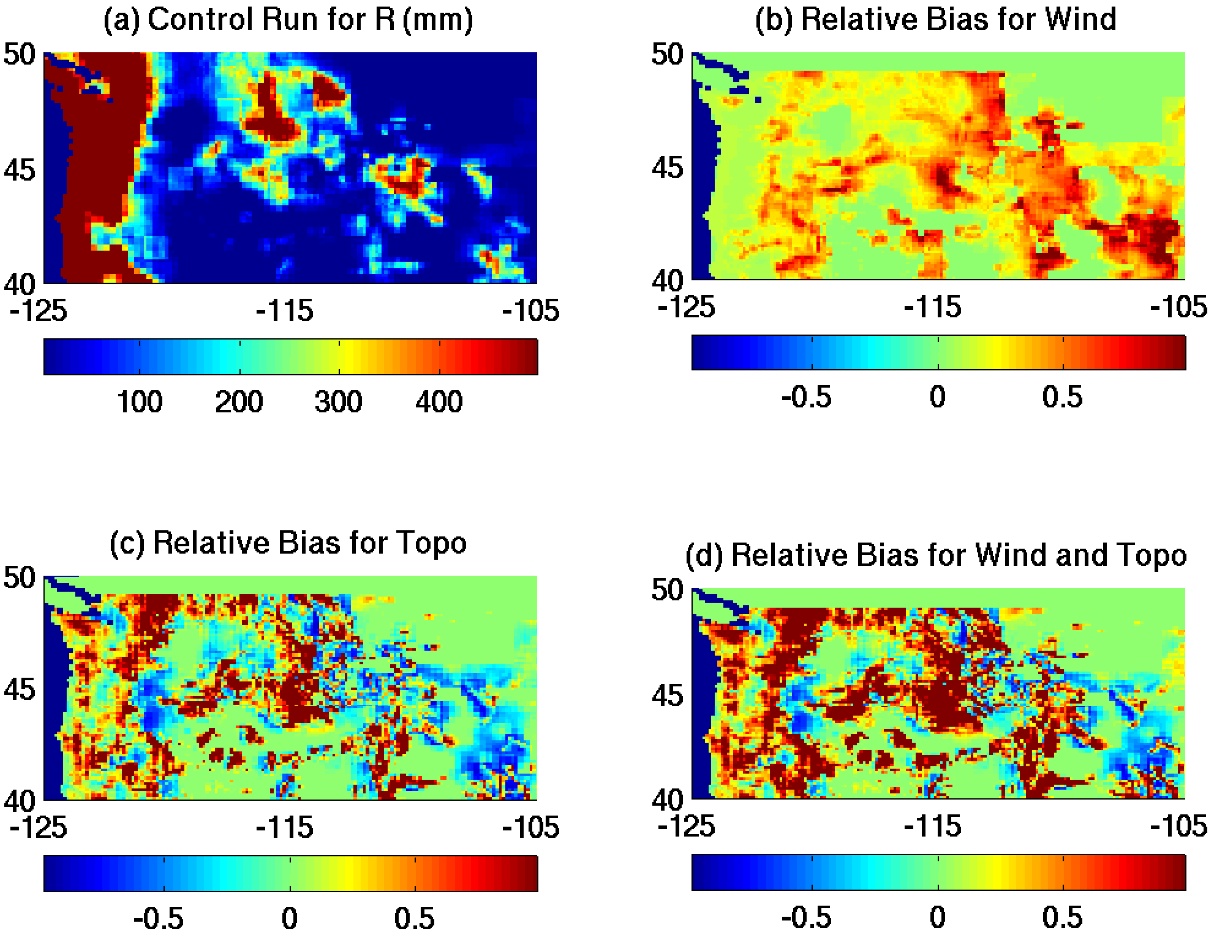

Fig. 4. Five-year (1998–2002) averaged annual runoff for (a) control run, (b) relative bias when wind adjustment is used, (c) relative bias when topographic adjustment is used, and (d) relative bias when both wind and topographic adjustment is used.

Mountains area because wind adjustment is small for rainfall and because there is little snowfall in coastal areas. Another area with a large precipitation increase is in mid Northwest America (Fig. 2c).

A surprising result is that precipitation is largely reduced in some areas. The reason for this decrease may be due to use of different data sources: monthly PRISM climate precipitation data are derived from gauge stations only, whereas NLDAS precipitation data are derived from gauge measurements, satellite precipitation, radar precipitation, and some mesoscle numerical model simulated precipitation data (to fill missing values). Satellite precipitation, radar precipitation and model precipitation may not be accurate (Cosgrove et al., 2003), and may result in larger precipitation than gauge precipitation. Therefore, within these areas the correction factor has large negative values.

Figure 2d shows a combination adjustment with wind and topography. Wind adjustment modifies the precipitation adjusted by topographic effects. This combination adjustment causes a 27.3% increase for

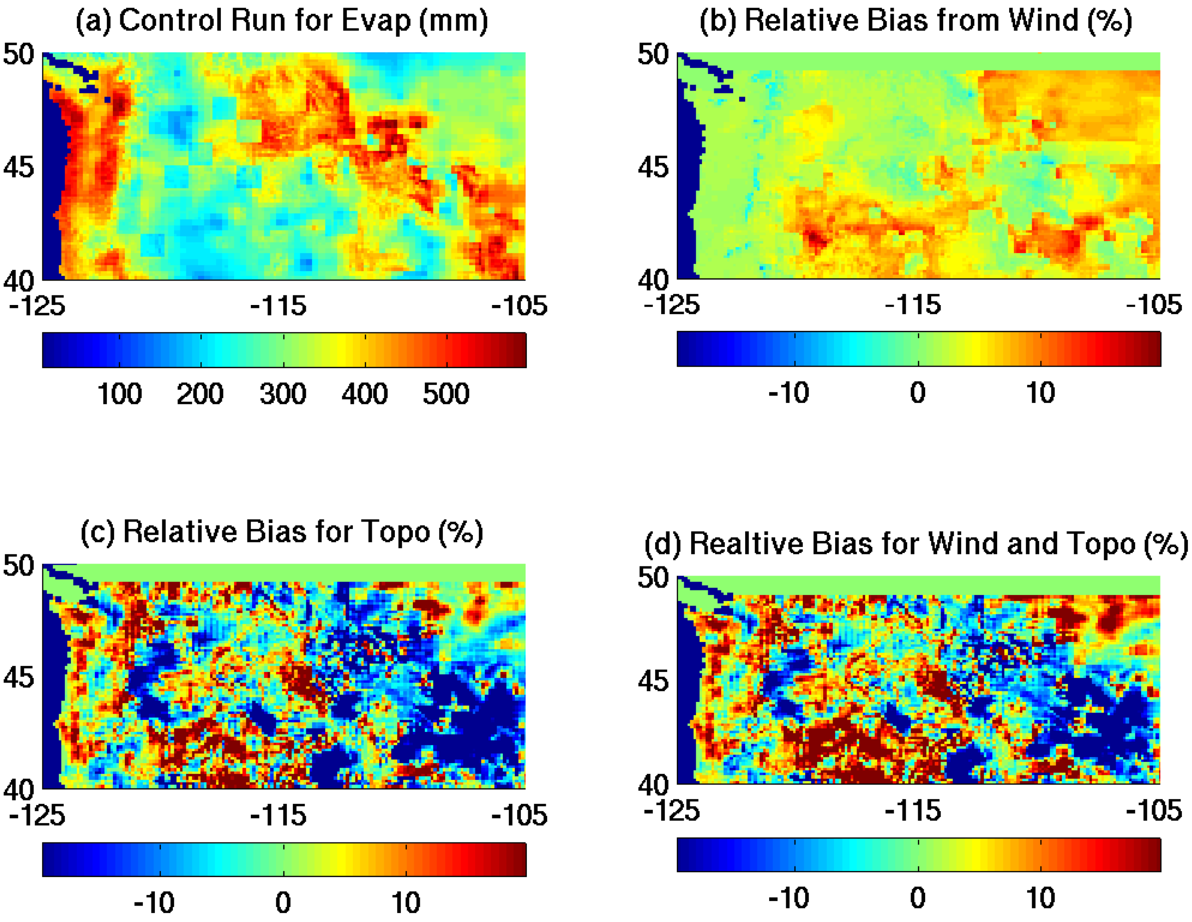

Fig. 5. Same as Fig. 4 but for evapotranspiration (Evap).

Northwest America when compared with the NLDAS retrospective precipitation data (Table 1).

3.2 *Impact of systematic precipitation bias on water fluxes*

Figure 3 shows observed and simulated annual streamflow at 14 basins in Northwest America for four of the experiments: "Control", "Topo", "Winda", and "Combination". The NLDAS precipitation data results in underestimates of simulated streamflow at most of the 14 basins when compared with observed streamflow. Some of the basins are underestimated by over 50% (Fig. 3a). Mean relative bias is −29.2% for all 14 basins. This underestimate is thought to be due to systematic precipitation bias, as indicated by Lohmann et al. (2004). Topographic adjustment reduces the mean relative bias from −29.2% to −12.8% (Fig. 3b), and wind adjustment reduces the mean relative bias from −29.2% to −5.2% (Fig. 3c). Combination adjustment leads to a 12.2% overestimate when compared with the control run (Fig. 3d). However, the absolute value of this relative bias is still comparable with the topographic adjustment case. Overall, wind and topographic adjustment reduces the relative bias of simulated streamflow at these 14 basins when compared with observed values.

Figures 4 and 5 show the spatial distribution of the mean annual runoff and evapotranspiration for the period 1998–2002, and relative biases resulting from wind and topographic adjustment. The model shows large runoff and evapotranspiration along the coast and in mountainous areas of Northwest America (Figs. 4a and 5a). The spatial pattern of runoff and evapotranspiration is mainly dominated by the precipitation spatial distribution (Fig. 2a). Wind adjustment (Fig. 4b), topographic adjustment (Fig. 4c), and combination adjustment (Fig. 4d) result in large runoff increases along the coast and in mountainous areas of Northwest America, which is consistent with the precipitation increase in this areas. This increase varies from 25% to over 100%, subject to location. A 20%–40% bias in precipitation can easily become a 100% bias in runoff. This result is in good agreement with the results of Milly and Dunne (2002a). For Northwest

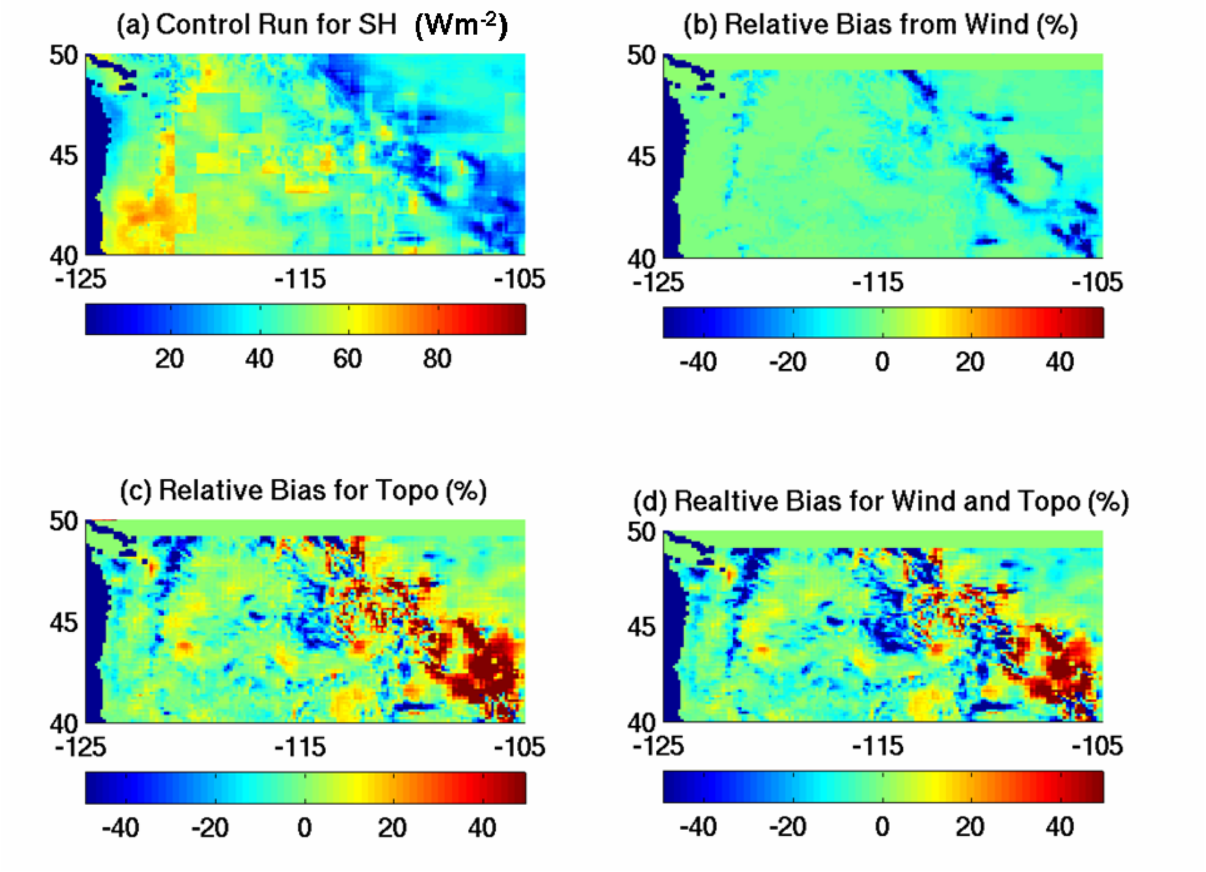

Fig. 6. Same as Fig. 5 but for mean annual sensible heat flux.

America, wind adjustment, topographic adjustment, and combination adjustment lead to a 27.2%, 36.6%, and 70% increase for annual mean runoff (Table 1), respectively.

Wind adjustment, topographic adjustment, and combination adjustment lead to a 3.4% increase, −3.5%, and −0.3% decrease in Northwest America for annual mean evapotranspiration, respectively. This increase or decrease is small in Northwest America. However, there is a large spatial variation from −20%–20%. Wind adjustment results in a 10%–20% evapotranspiration increase in the areas with low precipitation amount and a small runoff increase, and it results in a small evapotranpiration increase in the areas with a large precipitation increase (Fig. 5b). This is different from the runoff simulation case. The areas with a large precipitation increase usually occur at high evapotranspiration areas because they are wet. In contrast, the areas with a small precipitation increase usually appear at low evapotranspiration areas because they are dry. In wet areas, most of the precipitation increase is partitioned into runoff rather than evapotranspiration, and in dry areas most of the precipitation increase is partitioned into evapotranspiration rather than runoff. This process leads to different results for annual mean evapotranspiration and runoff simulations. Unlike wind adjustment, topographic adjustment leads to a large (over 20%) evapotranspiration increase or decrease, not only in dry areas but also in wet areas (i.e., two precipitation bands; Fig. 5c). Combination adjustment shows the combined effect of wind and topographic adjustment (Fig. 5d).

3.3 *Impacts of systematic precipitation error on energy fluxes*

Analysis of mean annual latent heat flux is the same as that of mean annual evapotranspiration, which has been discussed above. Figure 6 shows mean annual sensible heat flux for the period 1998–2002, and relative biases due to different adjustments. Large sensible heat flux appears in northern California, and small sensible heat flux appears along the western coast and in mountainous areas with high precipitation (Fig. 6a). Wind adjustment results in a 20%–40% relative bias for sensible heat flux in the Rocky Mountains area, and in other mountainous areas. This

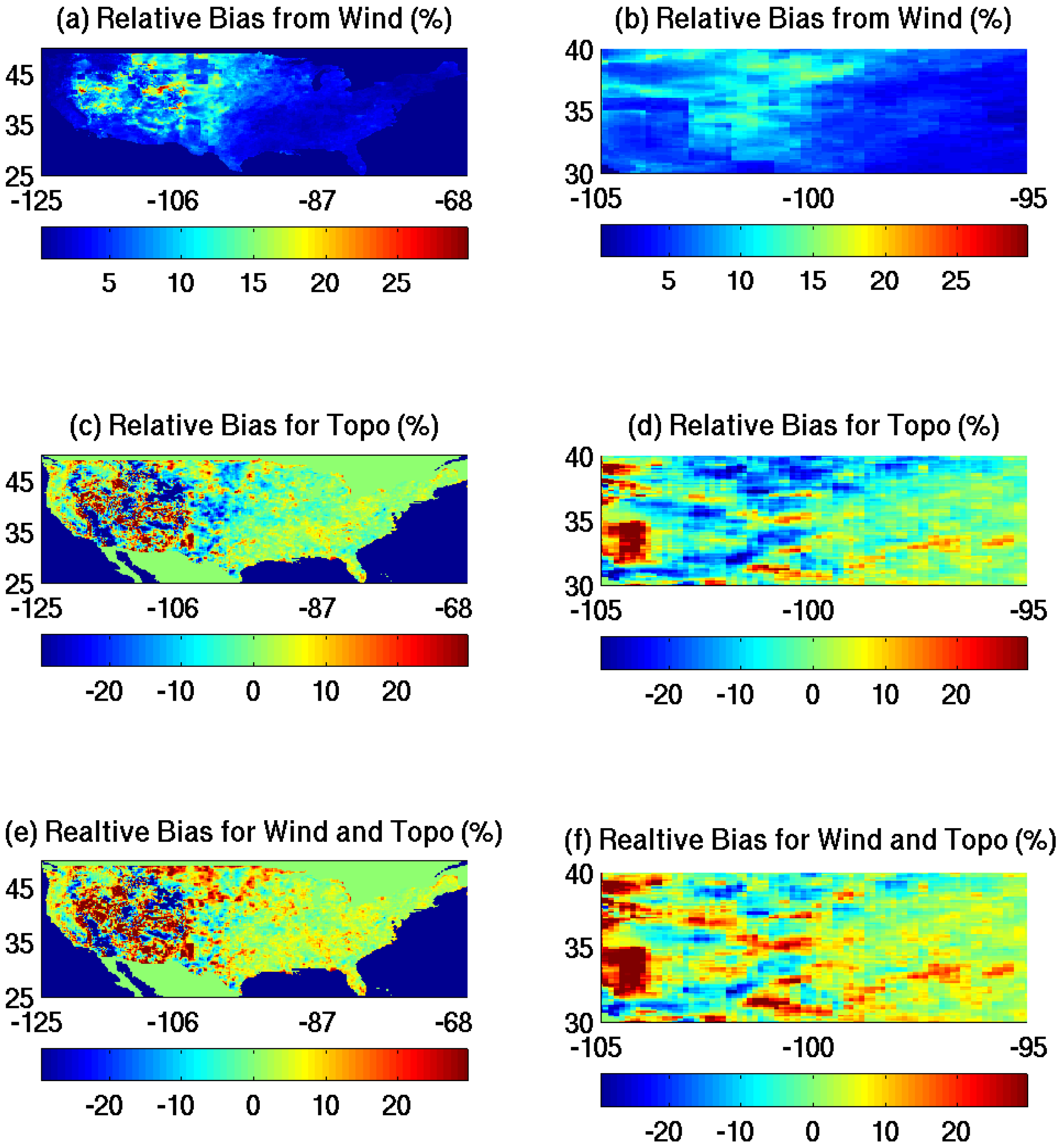

Fig. 7. Relative bias of mean annual soil moisture in the root zone caused by the wind and topographic adjustments for precipitation in continental America (left panels) and the Great Plains (right panels).

large relative bias is the result of a small sensible heat flux (Fig. 6b). Topographic (Fig. 6c) and combination (Fig. 6d) adjustment leads not only to a large relative bias along the western coast, in the Rocky Mountains area, and in other mountainous areas, but also in Wyoming state.

3.4 *Impacts of systematic precipitation bias on root-zone soil moisture simulations*

Soil moisture is an important variable that affects weather and climate simulation and prediction because its impact can persist for a long period. Usually, offline simulated soil moisture is used as an initial condition for coupled global climate models. As discussed above, systematic precipitation bias leads to large errors for water and energy flux simulations. It would also affect soil moisture simulation.

Figure 7 shows the relative bias for 5-year (1998–2002) mean soil moisture in the root zone when different adjustments are used. The left panel is an analysis for continental America, and the right panel for the American Great Plains. The reason for selecting the Great Plains is because Koster et al. (2004) showed that it is one of four "hot spots" which have a signifi-

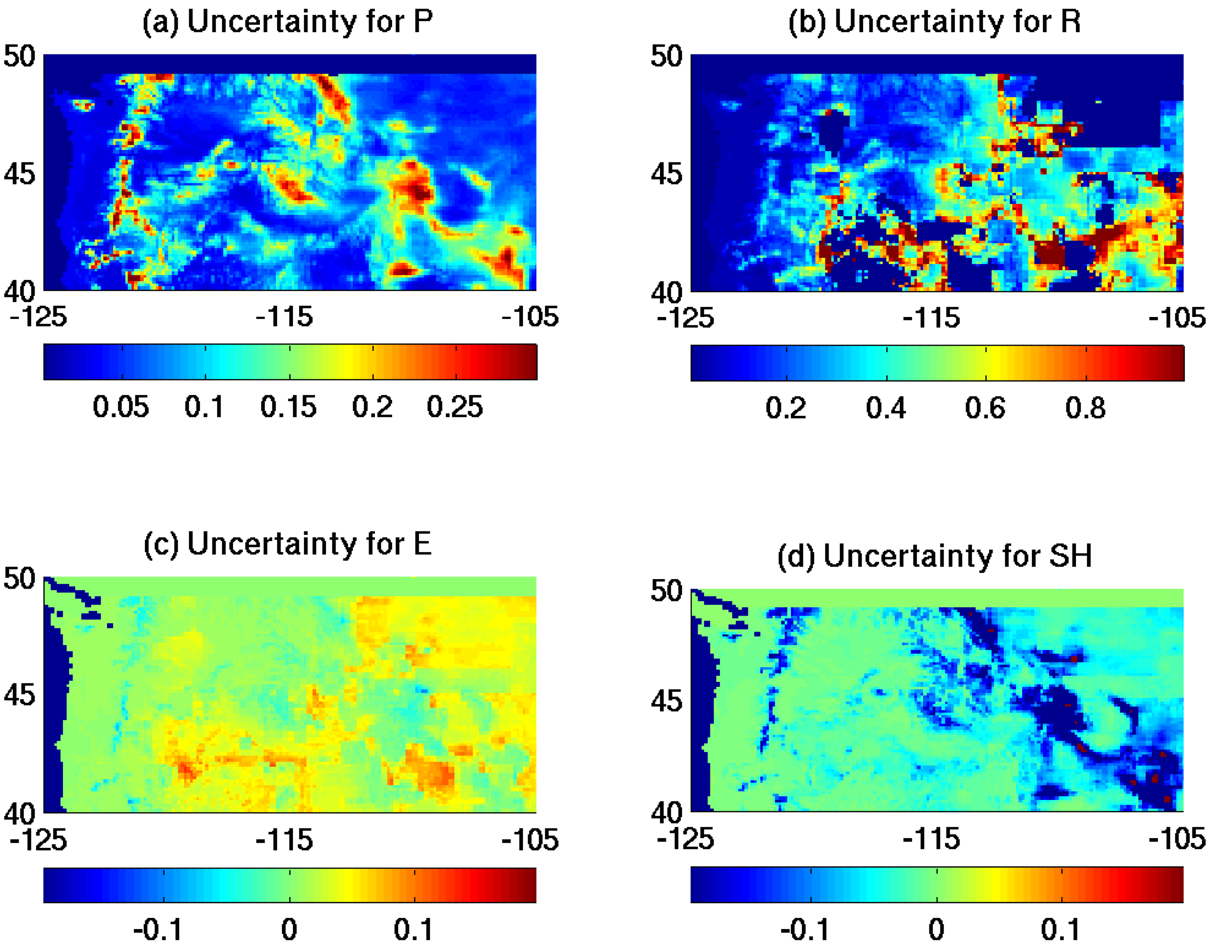

Fig. 8. Uncertainty estimates for mean annual (a) precipitation, (b) runoff, (c) evapotranspiration, and (d) sensible heat flux at the 95% confidence level.

cant effect on climate simulation. The results show that wind and topographic systematic bias adjustment for precipitation mainly affects soil moisture simulations in western America, with little impact on soil moisture simulations in eastern America. Wind adjustment for precipitation results in a 5%–25% relative bias (Fig. 7a), and topographic adjustment for precipitation results in a −25%–25% relative bias, subject to location (Fig. 7c). Combined adjustment for precipitation results in a pattern similar to the topographic adjustment case, except for a strong positive relative bias (Fig. 7e). Therefore, not only wind adjustment but also topographic adjustment affects the simulation of mean annual soil moisture in the United States, particularly in the west.

For the Great Plains, wind adjustment for precipitation leads to a small relative bias (Fig. 7b), and topographic adjustment for precipitation leads to an over 15% relative bias in many areas, as shown in Fig. 7d. Topographic and wind adjustment for precipitation leads to more areas with a 15% relative bias than either the wind adjustment case or the topographic adjustment case (Fig. 7f). A 15% relative bias is used as a limit because relative error larger than this limit has a significant effect on climate simulations (Koster et al., 2004). Overall, topographic adjustment leads to significant effects on soil moisture simulations, and wind adjustment intensifies the effect of topographic adjustment on soil moisture simulations in the Great Plains.

3.5 *Impacts of uncertain gauge adjustment on water and energy flux simulations*

Recently, the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) evaluated the relative biases of standard precipitation gauges using a rigorous method (Yang et al., 1998). It derived different regression models to correct undercatch of gauge precipitation when different gauge station types are used. Several gauge station types, such as Weighing Gauge, Tipping Bucket, Fischer and Porter, are used to measure American gauge precipi-

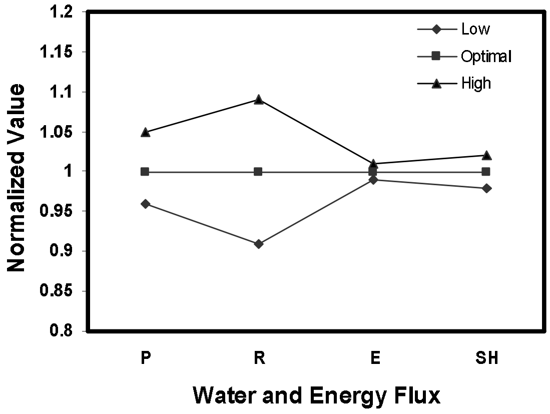

Fig. 9. Uncertainty estimates of mean annual precipitation, runoff, evapotranspiration and sensible heat flux when area-averaged values for Northwest America are used.

tation. These measured precipitation data are included in the NLDAS gauge precipitation dataset. In order to adjust these measured precipitation data, Xia (2006) developed a set of optimal WMO regression models by finding minimum error between simulated correction factors and the correction factors from Legates and Willmott (1990). This selection process brings uncertainties to optimal precipitation estimates, as discussed by Xia (2006). This uncertainty will result in uncertainty of simulated runoff, evapotranspiration and sensible heat flux. Figure 8 displays uncertainty (95% confidence level) of mean annual precipitation, mean annual runoff, mean annual evapotranspiration, and mean annual sensible heat flux during 1998 and 2002. Here, uncertainty is a ratio of uncertain range of the simulated variable to the simulated value from "Winda". The results present an uncertainty of 25% for precipitation in the Rocky Mountains area and other mountainous areas, which are related to the areas with large wind adjustment (Fig. 8a). The uncertainty of precipitation leads to an uncertainty of 40%–100% for runoff simulation (Fig. 8b). It results in an uncertainty of less than 10% for evapotranspiration (Fig. 8c) and −10%–20% in mountainous areas (Fig. 8d). For Northwest America, uncertainty is 10% for mean annual precipitation, 20% for mean annual runoff, 2% for mean annul evapotranspiration, and 4% for mean annual sensible heat flux (Fig. 9). Therefore, uncertain gauge adjustment results in large uncertainty for precipitation and runoff, and small uncertainty for evapotranspiration and sensible heat flux.

4. Discussion and conclusions

The primary goal of this study was to discuss the effects of systematic bias from topographic and wind adjustment on mean annual water and energy fluxes in Northwest America. The results have shown that wind and topographic adjustment results in a 13.2% and 11.8% increase of mean annual precipitation in Northwest America, respectively. The combination adjustment from wind and topography led to a 27.3% increase of mean annual precipitation. The results have shown significant spatial distributions: large adjustments appeared in mountainous areas and small adjustments in the valley and plains. For wind adjustment, the adjustment magnitudes in this study are comparable with those of Legates and Willmott (1990), and Adam and Lettenmaier (2003).

Systematic biases from wind and topography have significant impacts on water and energy flux simulations. As expected, topographic and wind adjustment reduced bias of streamflow simulations when compared with observed streamflow for 14 basins in Northwest America. These biases resulted in a −50%–100% bias for runoff simulations, a −20%–20% bias for evapotranspiration, and a −40%–40% bias for sensible heat flux, subject to location and different adjustments. Uncertain gauge adjustment led to a 25% uncertainty for precipitation, a 20%–100% uncertainty for runoff simulation, a less than 10% uncertainty for evapotranspiration, and a less than 20% uncertainty for sensible heat flux.

It should be noted that this analysis is based on the NLDAS dataset (e.g., precipitation, wind speed, and air temperature), and the LaD model. Although the LaD model has been carefully calibrated by observed annual streamflow, errors in model formulations (i.e. lack of interception evaporation and wet ground evaporation) and errors of forcing data still exist. These errors will affect streamflow simulations for the LaD model. Although Milly and Shmakin (2002b) indicated that errors in model formulations can be compensated for by model calibration processes, it should be noted that the results and conclusions in this study are still associated with the specific model and dataset.

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