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Effects of precipitation-bias corrections on surface hydrology over northern latitudes

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[1] Under-catch errors in precipitation gauge records can be as large as 50–100% during the cold season at high latitudes. To quantify the impacts of these errors on hydrometeorological fields, a comprehensive land surface model, namely the Community Land Model version 3 (CLM3), is run forced with (COF) and without (CON) precipitation-bias corrections and other identical atmospheric forcing from 1973 to 2004. It is found that the enhanced snowfall induced by the bias corrections increases snow accumulation on the ground (by 6–18 cm for December to February), which in turn increases May to July runoff by 0.4–0.6 mm day^{-1} and streamflow by 5–25% for most major rivers in the northern latitudes (north of 45°N). The precipitation-bias corrections also improve the model-simulated mean annual cycle and temporal variations of streamflow for the major northern rivers during 1973–2004. As a result, the simulation of the freshwater discharge into the Arctic Ocean is also improved. Only small and statistically insignificant changes are found in soil moisture content, surface evaporation, and sensible heat flux between the CON and COF runs. Nevertheless, the results still suggest that it is important to use bias-corrected precipitation in terrestrial water balance analyses and land surface modeling.

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1. Introduction

[2] Precipitation is a key component of the global water cycle and terrestrial hydrology. Accurate measurements of precipitation are needed in water balance analyses and other climate and hydrological applications, but they are notoriously difficult to obtain, especially over high latitudes in cold seasons [e.g., *Groisman et al.*, 1991]. Under-catch of solid precipitation [*Adam and Lettenmaier*, 2003; *Yang et al.*, 2005] and under-representation of precipitation at higher elevations [*Adam et al.*, 2006] by existing rain gauges are two major sources of systematic errors in various precipitation products derived from uncorrected rain gauge records, while satellite remote sensing still faces technical challenges to accurately measure precipitation at high latitudes [*Liu*, 2002]. As a result, substantial differences exist among current global precipitation climatologies, especially over the northern latitudes [*Legates*, 1995; *Fekete et al.*, 2004], where large under-catch biases are not corrected in most current precipitation data sets. These uncertainties have significant impacts on runoff and terrestrial water balance analyses, especially over relatively dry areas [*Fekete et al.*, 2004; *Nijssen and Lettenmaier*, 2004].

[3] Many efforts have been devoted to assess and correct the biases in rain gauge measurements [e.g., *Groisman et al.*, 1991, 1999; *Yang*, 1999; *Adam and Lettenmaier*, 2003; *Yang et al.*, 2005]. One of them is the Solid Precipitation Measurement Intercomparison Project initiated by the World Meteorological Organization (WMO) in 1985 [*Goodison et al.*, 1998]. Thirteen countries participated in this project and the experiments were conducted at 20 selected sites from 1986 to 1993. The WMO experiment has developed bias correction procedures for many precipitation gauges commonly used around the world. These bias correction methods were applied to gauge records over the high latitude regions, which resulted in significantly higher estimates of precipitation [*Yang*, 1999]. Based on regional applications of the WMO bias correction methods, *Yang et al.* [2005] developed a modified general model to correct daily precipitation-biases associated with wind-induced under-catch, wetting loss, evaporation loss, and trace events using daily meteorological data at 4802 stations over high-latitude regions (north of 45°N) from 1973 to 2004. The major advantage of their approach is the capability of examining the discontinuity of precipitation records across national borders. These corrections have increased monthly precipitation significantly by up to 22 mm during winter and slightly by about 5 mm in summer. Although these corrections do not account for spatial sampling errors [e.g., associated with orography, see *Adam et al.*, 2006], in regional estimates of precipitation, they represent a major

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effort to correct the biases in gauge records *at individual stations*.

[4] In this study, we employ a comprehensive land surface model, namely the Community Land Model version 3 (CLM3) [*Oleson et al.*, 2004; *Dickinson et al.*, 2006], to quantify the effects of the precipitation-bias corrections made by *Yang et al.* [2005] on surface hydrology over the northern latitudes. We ran the CLM3 from 1973 to 2004 with two different sets of atmospheric forcing: one with the precipitation-bias corrections and the other without them. By analyzing the differences in snow cover, soil water, evaporation, runoff, and streamflow between the two simulations, we show that the precipitation-bias corrections have considerable effects on high-latitude hydrology, especially on snow depth and late spring to early summer streamflow.

2. Data, Model, and Simulations

[5] *Yang et al.* [2005] modified the general model of *Sevruk and Hamon* [1984] to correct daily precipitation records for wind-induced under-catch, wetting loss, evaporation loss, and trace events. They derived a correction factor (CF, defined as the ratio of corrected vs. measured precipitation) using daily data of (measured) precipitation, air temperature, and wind speed at 4802 stations located north of 45°N with record length longer than 15 years during 1973–2004. The reader is referred to the work of Yang et al. for more details of the corrections. Here we used their mean values of CF for individual months from the 4802 stations and mapped the CF onto a 2.5° latitude × 2.5° longitude grid by arithmetically averaging the station CF values within each 2.5° box. A small fraction of the land boxes did not contain any stations and a bi-linear interpolation was used to estimate CF values for them using the CF values at nearby boxes. The gridded CF was used to multiply the precipitation from *Qian et al.* [2006], who did not correct for the under-catch biases, to produce the bias-corrected precipitation for driving the land surface model CLM3.

[6] The CLM3 is a comprehensive land surface model designed for use in coupled climate models but was used here in an offline mode. It is described in detail by *Oleson et al.* [2004] and *Dickinson et al.* [2006]. In the CLM3, spatial heterogeneity of land surface is represented as a nested sub-grid hierarchy in which grid cells are composed of multiple land units, snow/soil columns, and plant functional types (PFTs). Each grid cell can have a different number of land units, each land unit can have a different number of columns, and each column can have multiple PFTs. Biogeophysical processes are simulated for each sub-grid land unit, column, and PFT independently and each sub-grid land unit maintains its own prognostic variables. The grid-averaged atmospheric forcing is used to force all sub-grid units within a grid cell.

[7] In the standard CLM3 run (referred to as CON, same as the standard run in *Qian et al.* [2006] without the frequency adjustment), observation-based three hourly atmospheric forcing data (of precipitation, near-surface air temperature and pressure, specific humidity, wind speed, and surface downward solar radiation) from Qian et al. were used to drive the model from 1948 to 2004. The model was spun up for 220 years using the recycled forcing data and was run at a global, T42 (~2.8°) grid. Qian et al. created the forcing data by combining monthly data of temperature and precipitation derived from station records with intramonthly variations from the National Center for Environmental Predictions and National Center for Atmospheric Research (NCEP/NCAR) reanalysis. Historical records of cloud cover were also used to derive surface downward solar radiation. They showed that the CLM3, when forced with the forcing data, can simulate the observed broad patterns and interannual to longer-term variations in global surface runoff, streamflow, and soil water; although large mean biases exist in many of these fields. More details about the CLM simulation and forcing data are given in the work of *Qian et al.* [2006].

[8] In a separate CLM3 run (referred to as COF, starting from the condition of 1 January 1973 of the CON run), the (uncorrected) precipitation from *Qian et al.* [2006] was multiplied by the gridded monthly CF values, while the other forcing fields remained the same as in the standard run. Differences between the CON and COF runs were analyzed for a number of fields to examine the effects of the precipitation-bias corrections on land surface hydrology. The CLM3 runs are global; here we only focus on the northern latitudes (north of 45°N) where the precipitation-bias corrections were made. We recognize that the CLM3 still has deficiencies in representing land hydrology, especially for the high-latitudes [*Niu and Yang*, 2006]. Although the COF minus CON differing removes most of the CLM3 mean biases, the results reported here could still be model-dependent, especially in a quantitative sense.

3. Results

3.1. Effects of the Corrections on Precipitation

[9] *Yang et al.* [2005] show that the long-term mean CF for January is very large (≈1.6–2.0) along the Arctic coasts of Russia and Alaska and Greenland coasts, over eastern coastal regions of Asia and western Siberia, large (1.3–1.6) in eastern Europe, and moderate (1.1–1.3) in northern Canada, central Siberia, and western Europe. Winter CFs are relatively high (1.2–1.7) for northern US stations (including Alaska) but low over Canada due to use of gauges with varying catch efficiency. On the other hand, the CFs for July are usually less than 1.1 owing to high gauge catch efficiency for rainfall and large amounts of precipitation in summer.

[10] These CF patterns are reflected in the (forcing) precipitation difference between the CON and COF runs. The CLM3 partitions the total precipitation into liquid (rain) and solid (snow) precipitation based on concurrent air temperature. Figure 1 shows that the bias corrections increase 1973–2004 mean snowfall by 0.4–0.5 mm day^{-1} during winter over many coastal regions, while changes in rainfall during both winter and summer are small (0–0.2 mm day^{-1}, less than 10% for summer). This is expected since winter precipitation at northern latitudes consists of mostly snow, for which most gauges have low catch efficiency. For annual mean, large corrections (0.10–0.35 mm day^{-1}) for snowfall are seen over eastern coastal Canada, northern Russia, and along coasts of the Bering Strait, while corrections for rain are relatively uniform (0.02–0.08 mm day^{-1}) over most of the regions except

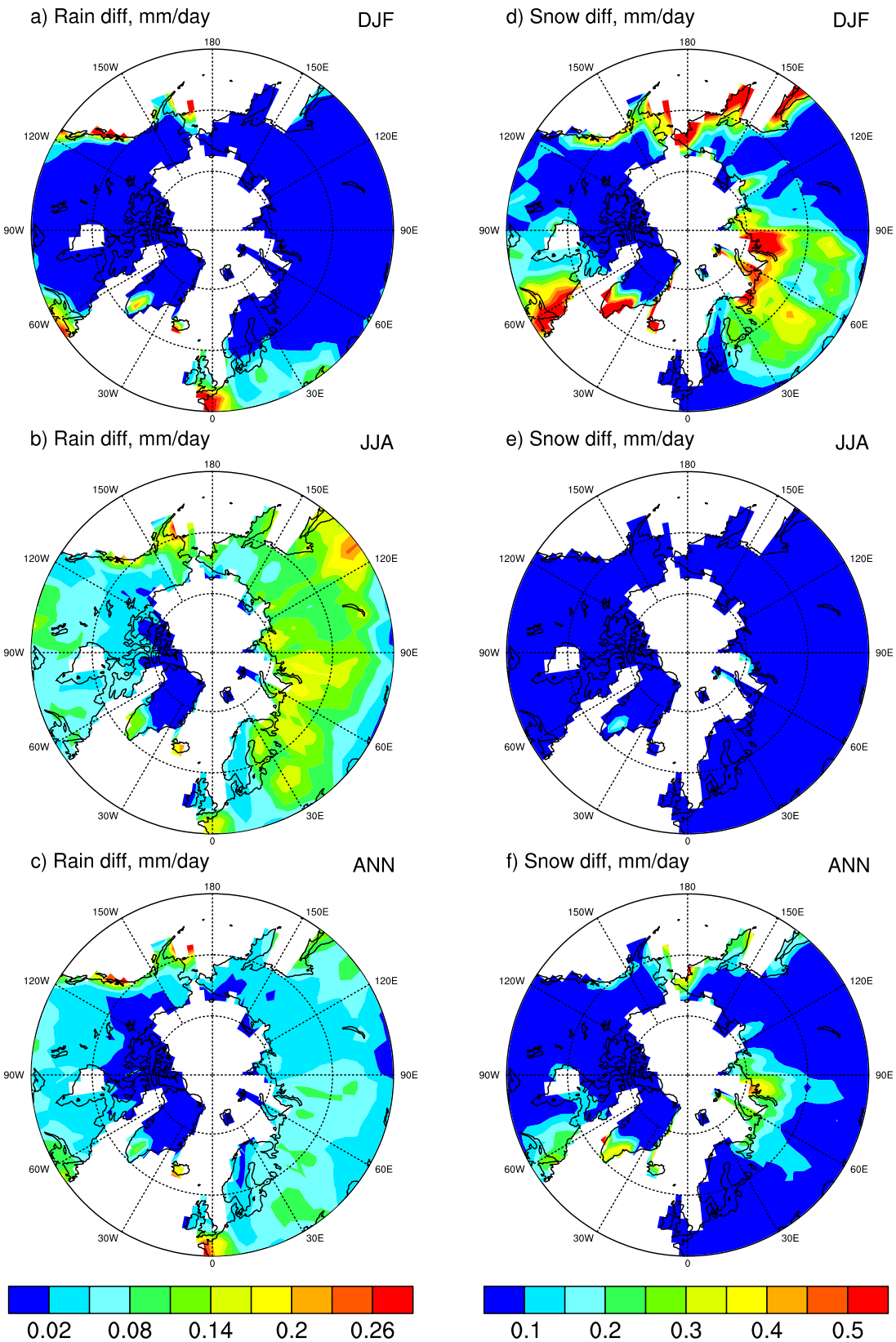

Figure 1. 1973–2004 mean differences (in mm day^{-1}, COF − CON) of rainfall (left column) and snowfall (right column) for DJF (top), JJA (middle) and annual mean (bottom) used to drive the CLM3 in the COF and CON runs.

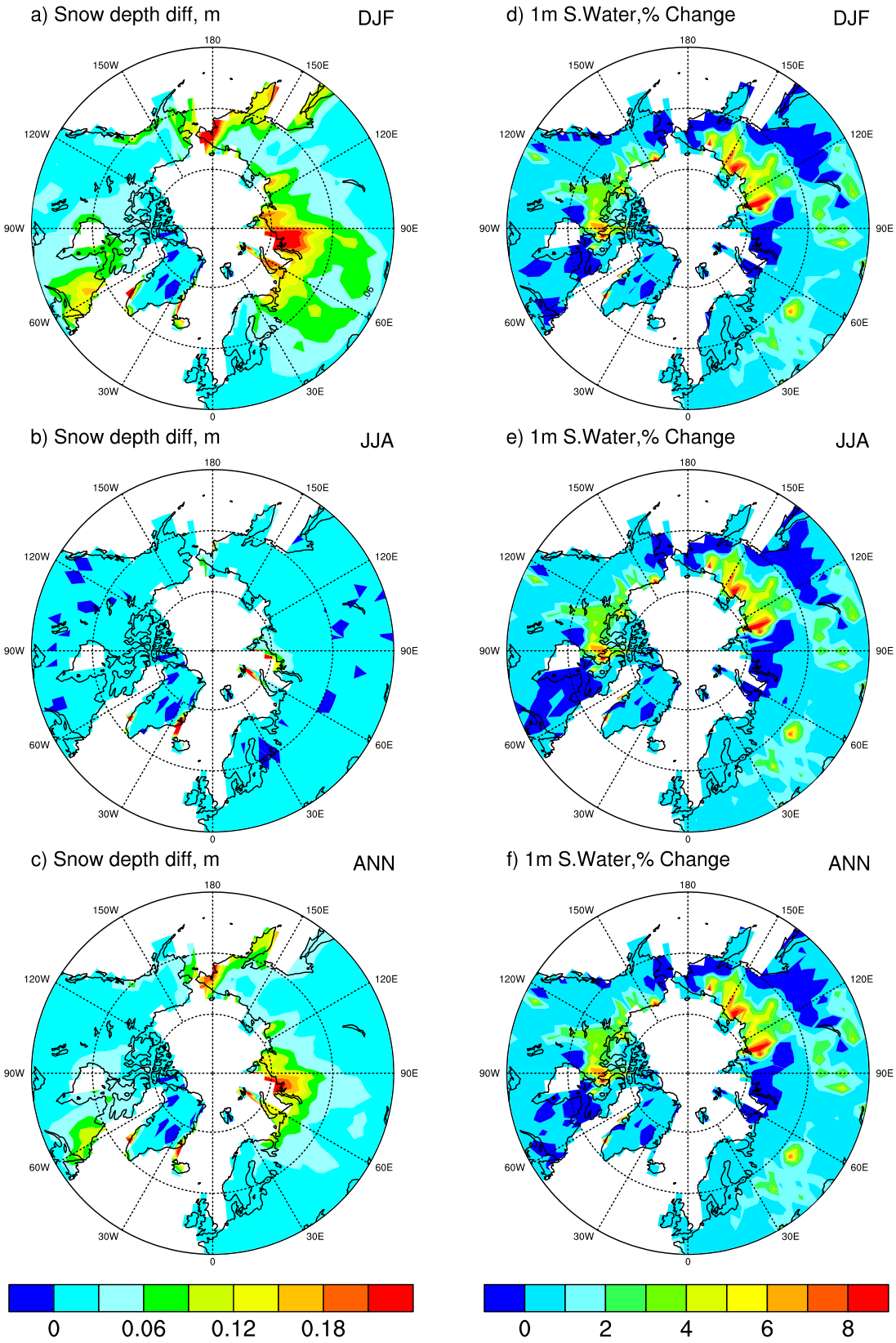

Figure 2. 1973–2004 mean differences (COF − CON) of CLM3-simulated ground snow height (m, left column) and total soil water within the top 1-m depth (in % change from CON, right column) between the COF and CON runs for DJF (top), JJA (middle) and annual mean (bottom).

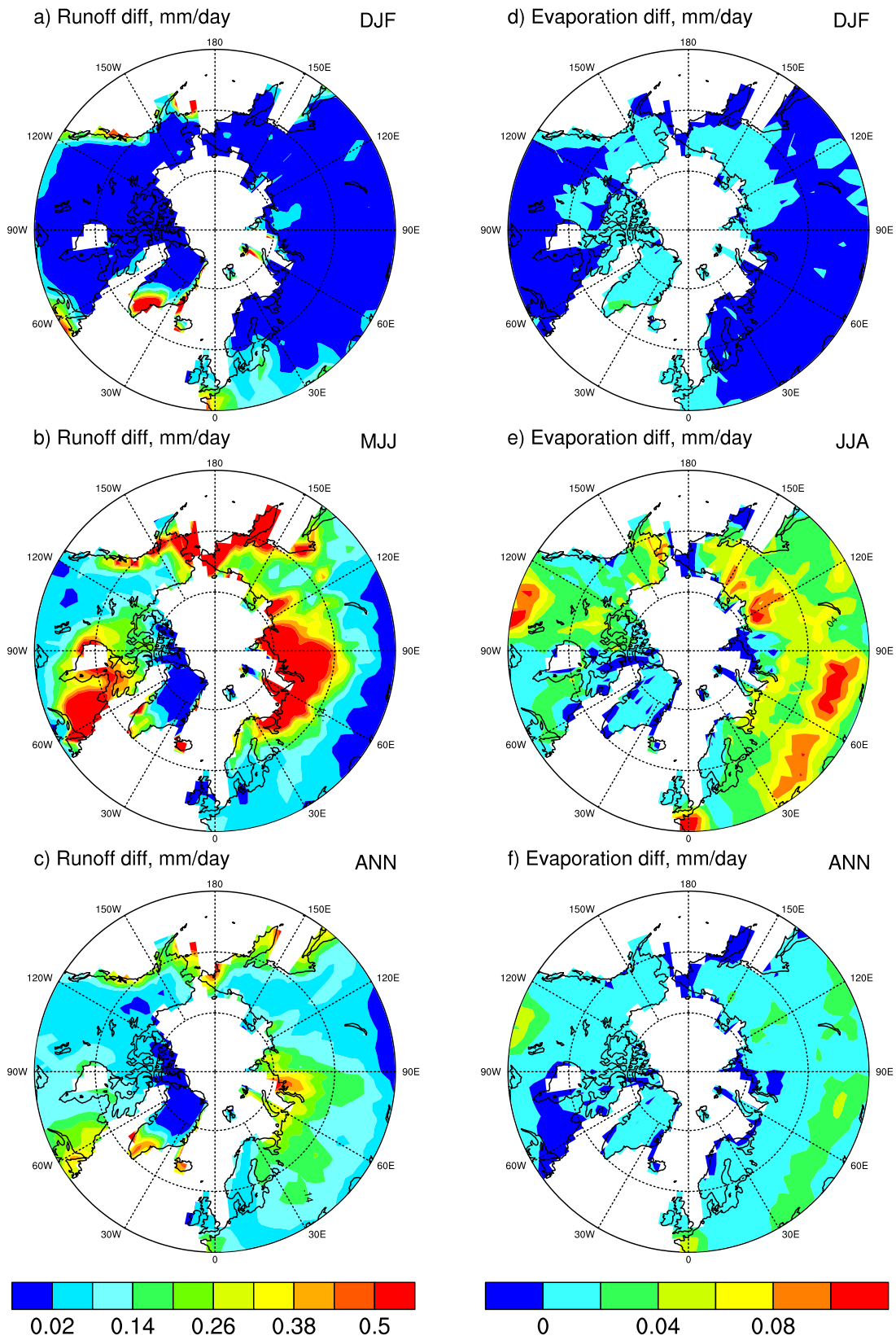

Figure 3. Same as Figure 2 but for CLM3-simulated runoff (mm day^{-1}, left column) and evaporation (mm day^{-1}, right column).

Arctic Canada and Greenland where the rainfall corrections are very small (Figure 1f, 1c).

3.2. Snow Depth and Soil Water

[11] Figure 2 shows the COF minus CON 1973–2004 mean difference of ground snow depth (left column) and top 1-m soil water content (right column, in % change from CON) for December to February (DJF), June to August (JJA) and annual (ANN) means. It is not surprising that large snow depth differences occur, especially for DJF (6–18 cm), over areas with large snowfall corrections (cf., Figure 1d–1f). The DJF and ANN snow depth differences are statistically significant at the 5% level over most of Eurasia (except western Europe) and most of Canada (except the western part) (not shown). The negative numbers in Figure 2 are very small and statistically insignificant. Comparisons with snow depth climatology from *Foster and Davy* [1988] revealed that the positive biases in CLM3-simulated snow depth over many high-latitude regions are slightly enlarged in the COF run. This is because the enhanced winter precipitation leads to increases in ground snow depth (Figure 2). The differences in soil water content within the top 1-m depth is generally small (<4%) and statistically insignificant. This may be partly because the largest corrections occur in DJF when most of the northern latitudes are covered by snow and the changes in (solid) precipitation mainly increase snow accumulation on the ground.

3.3. Runoff and Evaporation

[12] As pointed out above, the increased snowfall from the bias corrections (cf., Figure 1) mainly enhances winter snowpack accumulation, which results in little change in DJF (total) runoff (Figure 3a). The accumulated snowmelts in late spring and early summer, leading to large increases (0.4–0.6 mm day^{-1}, statistically significant) in May-June-July (MJJ) runoff over the regions with large increases in snowfall (i.e., northern Russia, eastern coastal Canada, and along the coasts of the Bering Strait) (Figure 3b). The increase in annual mean runoff (0.02–0.40 mm day^{-1}, Figure 3c) is spatially more homogenous than that for MJJ, and most of the areas in Figure 3c with values >0.10 mm day^{-1} are statistically significantly at the 5% level. Comparisons with runoff climatology from *Fekete et al.* [2002] revealed that the corrected precipitation reduces the negative runoff biases over most midlatitudes but increases the positive biases over most high latitudes and Europe (not shown). Figure 3d–3f shows the DJF, JJA, and ANN differences in surface evaporation between the two runs. These changes are generally small (<0.10 mm day^{-1}) and statistically insignificant. This is expected since the bias corrections mostly increase winter snowfall and surface evaporation in high-latitude winter is very small.

3.4. Streamflow

[13] The CLM3 routes runoff into river channels and simulates streamflow directly on a 0.5° grid. This allows us to use the historical records of streamflow measurements to evaluate land surface hydrology at river-basin scales, although the relatively coarse resolution of 0.5° sometimes makes the matching with streamflow gauges difficult. Figure 4 compares, on logarithmic scales, the CLM3-simulated mean downstream river flow rates from the CON and COF runs with observations from nearby gauges (from *Dai and Trenberth*, 2002 and update) for the largest 63 rivers whose mouths are located north of 45°N. The CON simulation (open circles with crosses inside in Figure 4) overestimates the annual flow rate for the large rivers and underestimates the flow for the smaller rivers compared with the observations. The bias corrections increase streamflow for most of the rivers by 5–25%, therefore reducing the negative biases for the smaller rivers but enlarging the positive biases for the larger rivers (dots in Figure 4). This leads to larger mean biases in the COF run for the 63 rivers as a whole than in the CON run, although the correlation with observations is slightly higher in the COF run (Figure 4). The result further suggests that runoff in the CLM3 is too high over many large northern river basins.

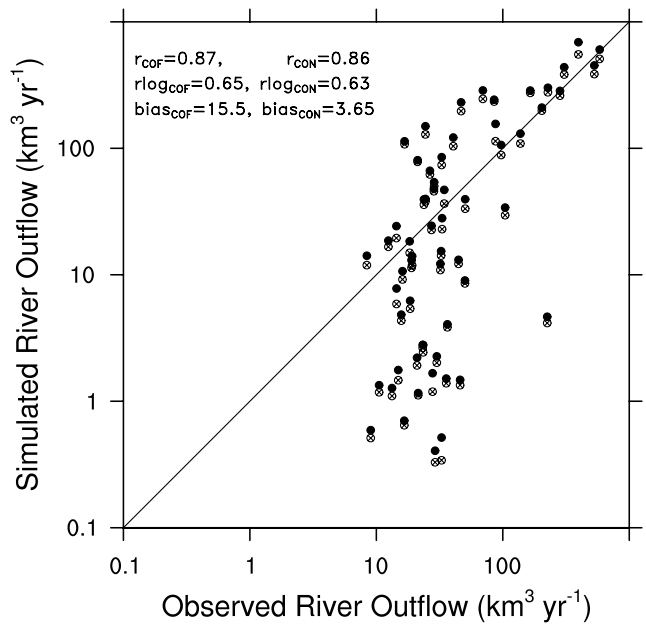

Figure 4. Scatterplot (on a logarithmic scale) of observed (from *Dai and Trenberth*, 2002 and update) and CLM3-simulated 1973–2004 mean streamflow (km^3 yr^{-1}) at the farthest downstream stations for the 63 largest rivers whose mouths are located north of 45°N. Solid dots are for the CON run and open circles with crosses inside are for the COF run. The linear (r) and logarithmic ($r_{\log}$) correlation coefficients and the mean biases (simulated − observed) are also shown.

[14] Seasonal variations of streamflow for six large northern rivers are shown in Figure 5. All these high-latitude rivers have a sharp peak flow in June resulting from snowmelt, and the CLM3, which includes a snow model, reproduces this peak except for the Lena and Yukon Rivers whose June peak is delayed to July in both runs. On the other hand, large mean biases exist for some of the rivers (for example, the Ob and Lena Rivers). The precipitation-bias corrections increase the streamflow for the six rivers, especially during May to July, as enhanced snowfall resulting in more snowmelt in MJJ, while its effect on the seasonal phase is relatively small (except for some improvements for Pechora) (Figure 5). The increase in streamflow

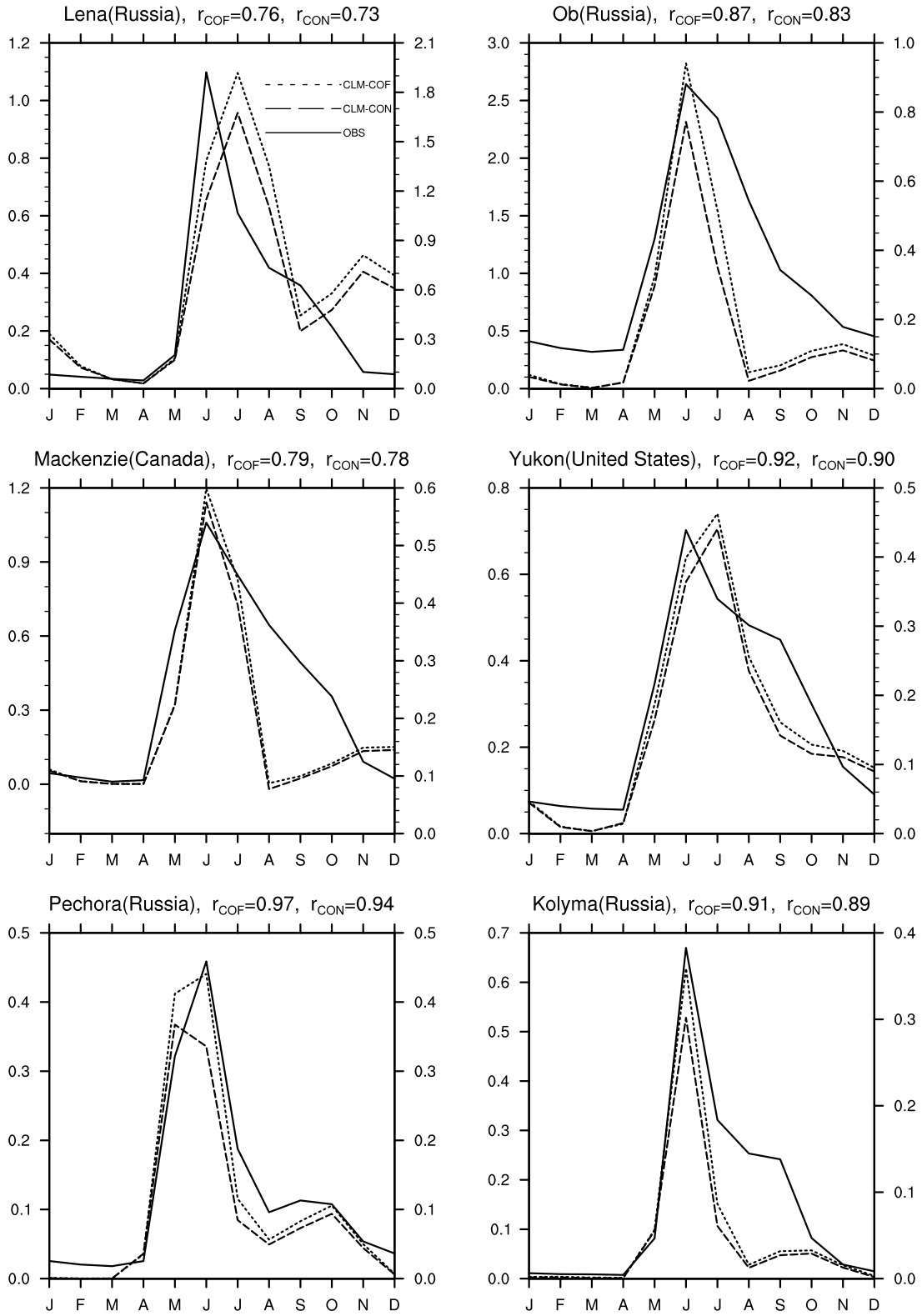

Figure 5. 1973–2004 mean annual cycle of downstream flow (10^2 km^3 month^{-1}) for six large northern rivers from observations (solid line) and the CLM3 COF (short-dashed line) and CON (long-dashed line) runs. Note the different scales for the simulated (left ordinate) and observed (right ordinate) flow rates.

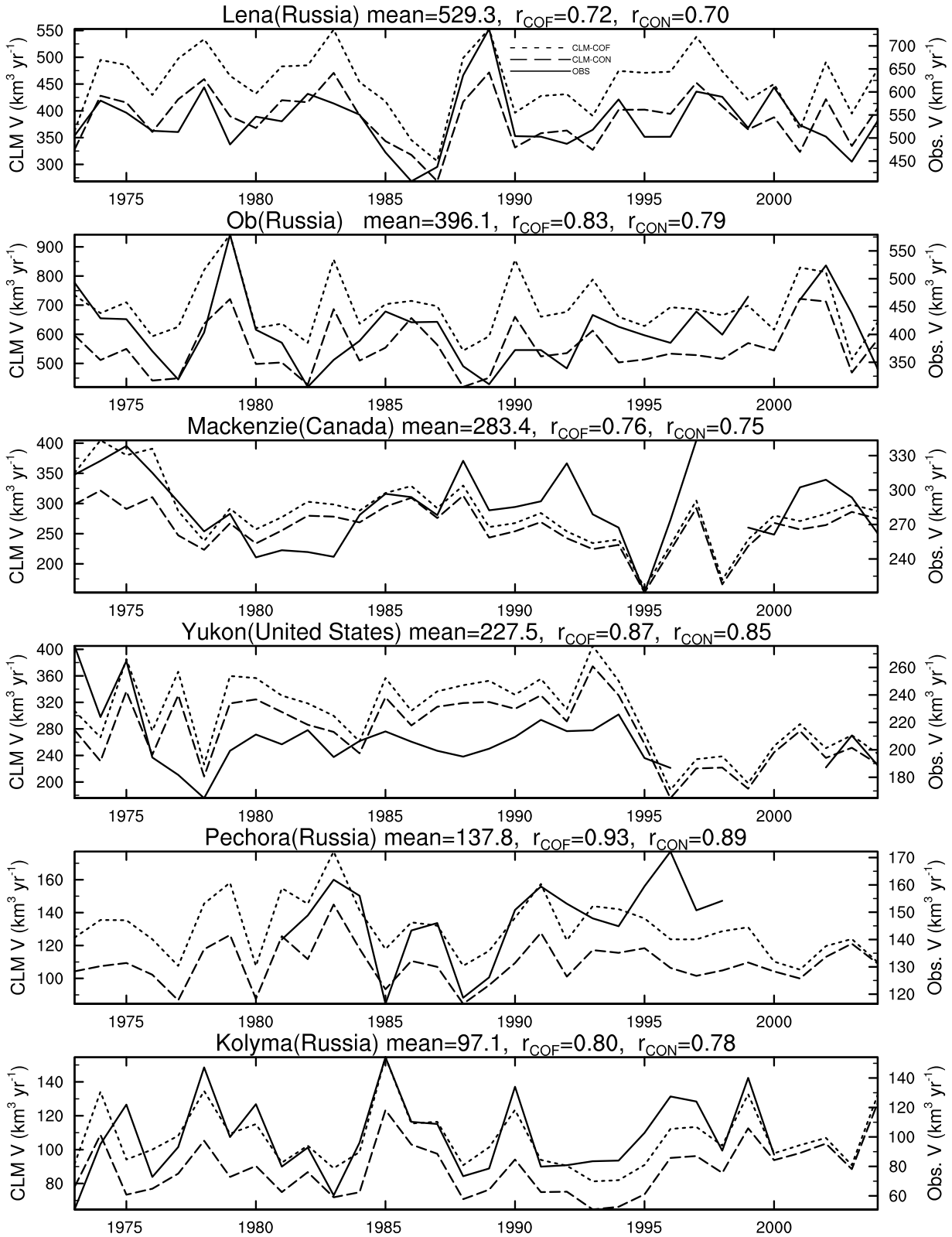

Figure 6. 1973–2004 time series of annual downstream flow (km^3 yr^{-1}) for six large northern rivers from observations (solid line, right ordinate) and the CLM3 COF (short-dashed line) and CON (long-dashed line) runs (left ordinate).

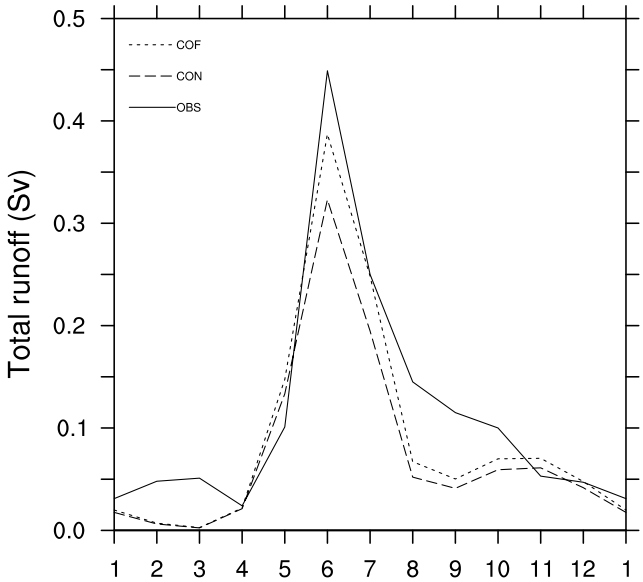

Figure 7. Long-term mean annual cycle of freshwater discharge (in *Sv*, 1 *Sv* = 10^6 m^3 s^{-1}) into the Arctic Ocean from observations (solid line, from *Dai and Trenberth*, 2002) and the CLM3 COF (short-dashed line) and CON (long-dashed line) runs.

does not always lead to improved simulation (for example, for the Ob and Yukon Rivers) because of the mean positive biases already in the CON run (e.g., associated with representation of frozen soil, *Niu and Yang*, 2006), although the seasonal correlation with observations is generally improved in the COF run.

[15] To evaluate the variability at time-scales longer than one year, Figure 6 compares the 1973–2004 time series of annual mean streamflow from the observations and the two CLM3 simulations for the six large rivers in the northern latitudes. In general, the CLM3 simulates the year-to-year variations reasonably well, with correlation coefficients ranging from 0.70 to 0.93. The precipitation-bias corrections increase the simulated streamflow substantially and improve the correlation with observations slightly. While the increased streamflow is expected, the higher correlation suggests that the time-varying corrections of rain gauge under-catch errors also improve the temporal variations of precipitation in the northern latitudes. Figure 7 shows the 1973–2004 mean annual cycle of freshwater discharge into the Arctic Ocean from the CLM3 simulations compared with observations. Both the CON and COF runs produce a sharp June peak as in observations, with the COF being closer to the observed peak runoff because of enhanced winter to spring snowfall.

4. Summary and Concluding Remarks

[16] A comprehensive land surface model, namely the CLM3, was used to quantify the impacts on land hydrology of the corrections for under-catch errors in daily precipitation data during 1974–2004 [*Yang et al.*, 2005] over the northern latitudes (north of 45°N). The bias corrections result in large increases (0.4–0.5 mm day^{-1}) in cold-season snowfall over northern Russia, eastern coastal Canada, and along the coasts of the Bering Strait; while the changes in warm-season rainfall are relatively small. The two CLM3 simulations forced with (COF) and without (CON) the precipitation-bias corrections show that the enhanced snowfall in the COF run increases snow accumulation on the ground (by 6–18 cm for DJF), which in turn increases May to July runoff (by 0.4–0.6 mm day^{-1}) and streamflow (by 5–25%) substantially for most major rivers in the northern latitudes. The increased runoff and streamflow do not, however, always lead to reduced model biases because the CLM3 overestimates runoff over many large river basins in the northern latitudes, although the simulation of the discharge into the Arctic Ocean has been improved. The precipitation-bias corrections also improve the mean annual cycle and temporal variations of streamflow for major northern rivers during the 1973–2004 period. This improvement likely results from more realistic spatial and temporal variations in the corrected precipitation data. Examinations of other hydrometeorological fields, such as soil moisture, surface evaporation, and sensible heat flux, revealed small and statistically insignificant changes associated with the precipitation-bias corrections. This latter result suggests that these surface fields are largely controlled by (the same) air temperature, humidity, and other atmospheric forcing used for the model.

[17] The above results suggest that the corrections for under-catch errors in rain gauge records, which have been used often without corrections to create various precipitation climatology and data sets, are important for surface water balance analyses over the northern latitudes. Water balance and land surface models forced with uncorrected precipitation, as usually have been the case, either underestimate surface runoff and streamflow or are tuned to incorrect parameterizations over the north latitudes. Thus, it is important to use bias-corrected precipitation in terrestrial water balance analyses and land surface modeling.

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