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The role of soil moisture–atmosphere coupling in summer light precipitation variability over East Asia

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Abstract

This study investigates the role of soil moisture feedbacks in influencing interannual variability of summer light precipitation frequency over East Asia by analyzing two long-term simulations with and without interactive soil moisture using the Weather Research and Forecasting model coupled with the Noah land model. It is shown that soil moisture–atmosphere coupling significantly amplifies interannual variability of summer light precipitation frequency over many areas, in particular the climatic and ecological transition zones, contributing to 30–60% of the variance. The results suggest that soil moisture-atmosphere coupling constitutes an important cause explaining the variations of summer light precipitation events over East Asia. Copyright © 2012 Royal Meteorological Society

Keywords: soil moisture feedbacks; regional climate modeling; summer light precipitation variability

1. Introduction

Precipitation is one of the most important variables describing our climate. Summer precipitation, which supplies necessary water for growing crops, is critical to human life and entire ecosystem. There are numerous studies exploring its changes, effects, mechanisms and prediction. Most of them focused on summer heavy or extreme precipitation, which can lead to a local flooding and runoff in a short period of time and thus bring tremendous losses of economy (e.g. Easterling *et al*., 2000; Gong and Wang, 2000; Zhai *et al*., 2005; Trenberth, 2011). However, light precipitation has received little concerns. Light precipitation allows water more time to soak into the soil and result in little surface runoff and streamflow, leaving soils much wetter at the end of day (Trenberth *et al*., 2003; Sun *et al*., 2006). Some studies have reported that the reduction of light precipitation frequency can cause occurrence of drought events (e.g. Yan and Yang, 2000; Qian *et al*., 2009, 2010; Lei and Duan, 2011; Lei *et al*., 2011). These facts thus highlight the need for improving our understanding of summer light precipitation variations.

Summer light precipitation frequency, which makes a major contribution to total precipitation frequency, has experienced evident interannual and decadal variations over East Asia during the last several decades. (e.g. Yan and Yang, 2000; Gong *et al*., 2004; Liu *et al*., 2005, 2011; Qian *et al*., 2007, 2009, 2010; Ren *et al*., 2010; Lei *et al*., 2011). Summer light precipitation variations over East Asia has been previously attributed to changes in the atmospheric circulation (e.g. Gong *et al*., 2004; Zhou and Yu, 2005; Qian *et al*., 2010), global or regional warming and changes in aerosols (e.g. Gong and Wang, 2000; Zhao *et al*., 2006; Qian *et al*., 2007, 2009, 2010; Liu *et al*., 2009; Lei *et al*., 2011; Liu *et al*., 2011). Recently, soil moisture–atmosphere coupling has been demonstrated to play a key role in influencing summer precipitation variability over particular areas (e.g. Koster *et al*., 2004; Zhang *et al*., 2008a, 2008b; Seneviratne *et al*., 2010). However, the role of soil moisture feedbacks in summer light precipitation is not clearly identified. In this study, we use two Weather Research and Forecasting (WRF) model simulations described by Zhang *et al*. (2011) to investigate the role of soil moisture–atmosphere coupling in influencing interannual variability of summer light precipitation frequency over East Asia.

2. Approach

In this study, two regional climate model simulations are examined, employing the WRF model coupled with the Noah land model (Zhang *et al*., 2011). The model domain spans 8160 km (west–east) by 5760 km (south–north) at 60 km grid spacing, centered at eastern China. The control run (CTL) integrates for the period of January 1979 to December 1999, driven with the National Centers for Environmental Prediction (NCEP)-Department of Energy (DOE) reanalysis. The other experiment (SoilM) repeats summer simulation with the same model setup, except that soil moisture value at each time step is prescribed as the climatology of CTL. The climatology of CTL is produced by averaging hourly soil moisture data for 1980–1999, which keeps diurnal and subseasonal evolutions but removes interannual variability. For more details of model configuration refer to Zhang *et al*. (2011).

The 0.5 °C gridded daily precipitation data set from the East Asia gauge-based analysis (Xie *et al*., 2007) is used to investigate simulated summer light precipitation of CTL. The data set has been constructed using the optimal interpolation-based technique to gauge observations at over 2200 stations collected from several individual sources. In this study, we analyze summer (June–July–August) light precipitation events with daily precipitation less than and equal to 2 mm ($p \leq 2$ mm day^{-1}), 5 mm ($p \leq 5$ mm day^{-1}) and 10 mm ($p \leq 10$ mm day^{-1}). The variance analyses are applied to objectively quantify the contribution of soil moisture feedbacks to the interannual variability of summer light precipitation frequency.

3. Results

Figure 1 compares geographic distributions of summer mean light precipitation frequency over East Asia during 1980–1999 between observations and WRF model simulations. The observed summer mean light precipitation frequency with $p \leq 2$ mm day^{-1}, $p \leq 5$ mm day^{-1} and $p \leq 10$ mm day^{-1} exhibits a similar pattern. The observed summer light precipitation frequency is relatively high over the Northwest and

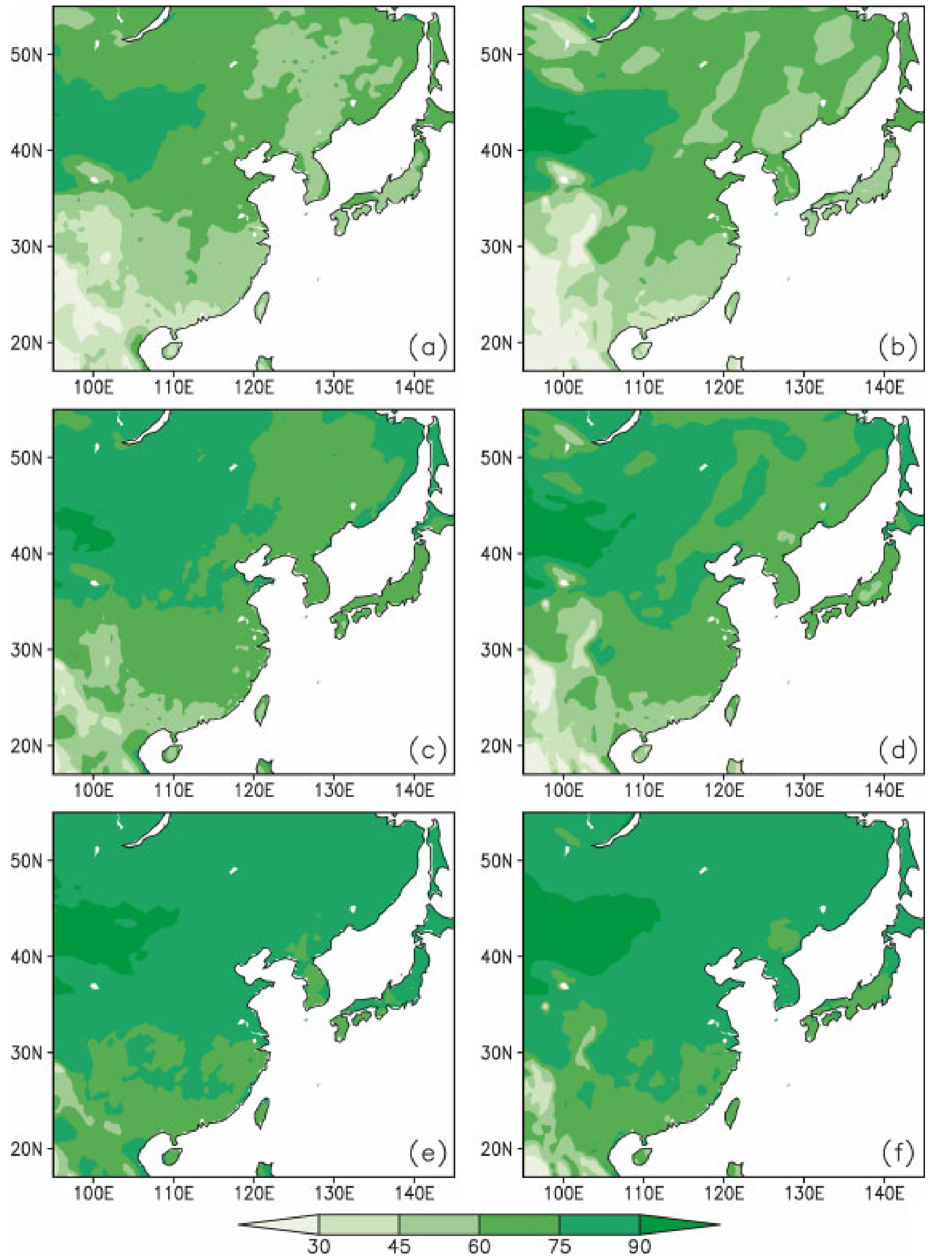

Figure 1. Observed (left) and modeled (right) summer mean light precipitation frequency (days per year) for the period 1980–1999: (a, b) $\leq$2 mm day^{-1}, (c, d) $\leq$5 mm day^{-1} and (e, f) $\leq$10 mm day^{-1}.

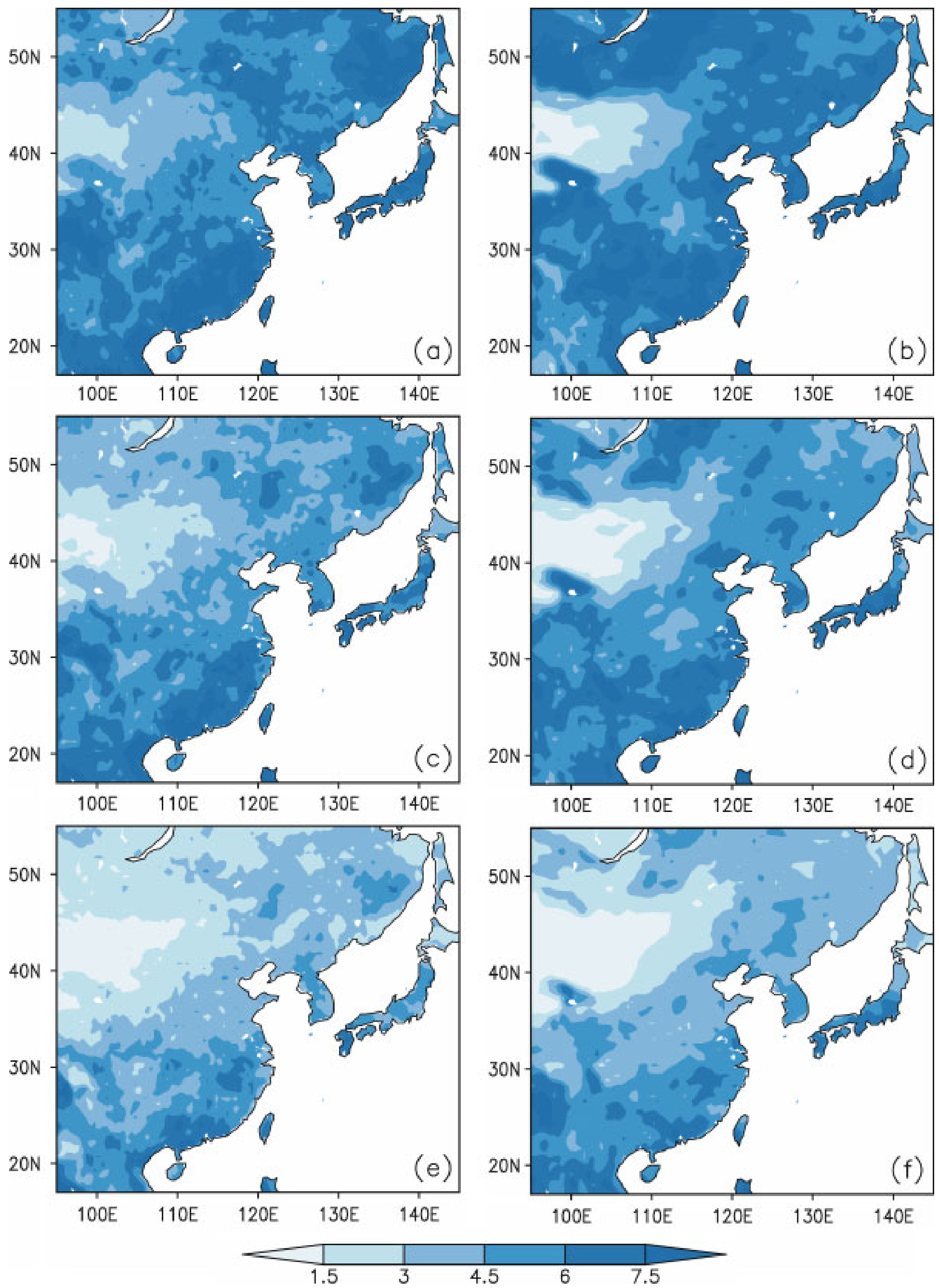

Figure 2. Observed (left) and modeled (right) standard deviation of summer light precipitation frequency (days per year) for the period 1980–1999: (a, b) $\leq$2 mm day^{-1}, (c, d) $\leq$5 mm day^{-1} and (e, f) $\leq$10 mm day^{-1}.

relatively low over the tropics and southern China. The WRF model captures the observed summer light precipitation frequency pattern rather well. For the magnitude, WRF model generally simulates the observed summer light precipitation frequency well over most areas of East Asia except for some areas of the Northwest, where summer light precipitation frequency is overestimated.

Figure 2 compares geographic distributions of interannual variability of summer light precipitation frequency expressed by its standard deviation over East Asia during 1980–1999 between the observations and WRF model simulations. The observed light precipitation variability with $p \leq 2$ mm day^{-1} shows a clear southeast to northwest gradient, with maximum value appearing over the tropics and southern China, and minimum value over the Northwest. A similar pattern is seen for interannual variability of summer light precipitation with $p \leq 5$ mm day^{-1} and $p \leq 10$ mm day^{-1}. The WRF model captures the features very well. The model biases mainly occur over some areas of the Northwest and the tropics, where interannual variability of summer light precipitation frequency is underestimated.

To examine the changes induced by soil moisture–atmosphere coupling, we compute the differences in standard deviation of summer light precipitation frequency between CTL and SoilM because soil moisture

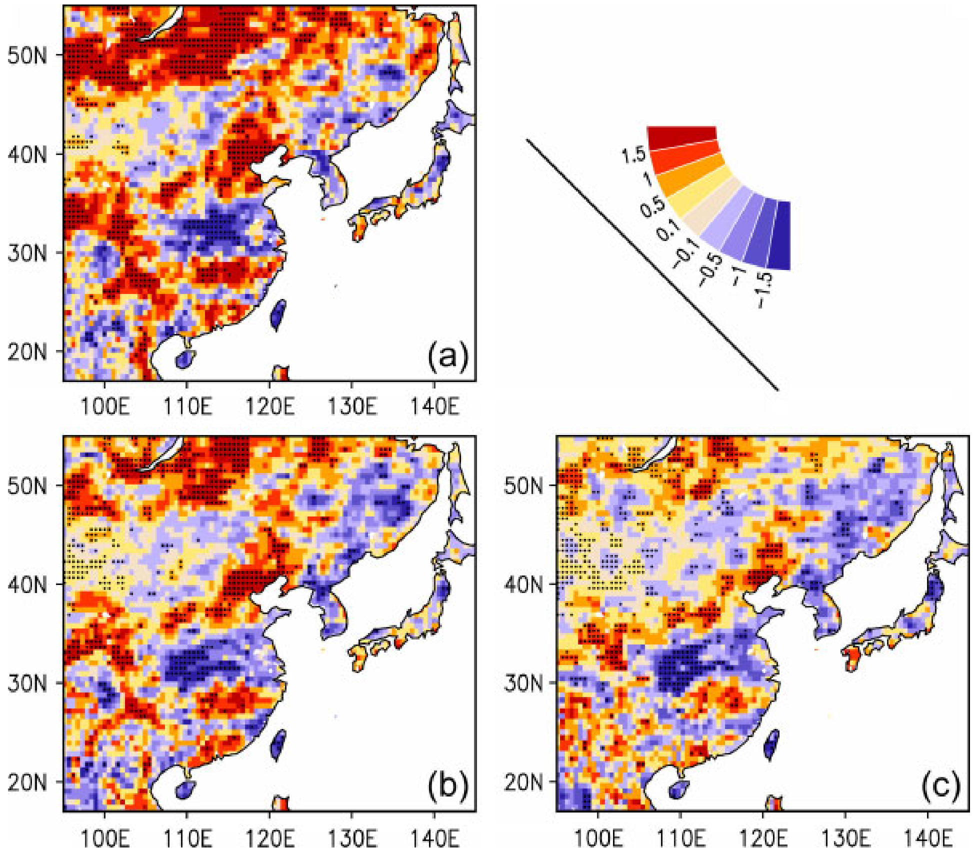

Figure 3. Differences in standard deviation of summer light precipitation frequency (days per year) between CTL and SoilM: (a) ≤2 mm day^{-1}, (b) ≤5 mm day^{-1} and (c) ≤10 mm day^{-1}. The solid circles represent that the values are significant at the 90% level by *F* test.

interactions are disabled in SoilM. Figure 3 presents that the differences in standard deviation for summer light precipitation frequency with $p \leq 2$ mm day^{-1}, $p \leq 5$ mm day^{-1} and $p \leq 10$ mm day^{-1} show a similar pattern. The soil moisture–atmosphere coupling generally exerts amplifying effects on interannual variability of summer light precipitation frequency over East Asia. Meanwhile, we note that the amplifying effects depend on climate regimes. The significantly amplifying effects mainly appear over the climatic and ecological transition zones of the southern Siberia–northern Mongolia region and northern China with the magnitude on the order of 0.5–1.5 days per year. The most significantly amplifying effects are found for the light precipitation events with $p \leq 2$ mm day^{-1}, which have more grid cells passing the 90% confidence level. The amplifying effects are also seen over many areas of western China, and a portion of southern China. In contrast, significantly damping effects are limited to small areas, mainly appearing over some areas of the Yangtze-Huai River Valley. The damping effects may be caused by negative soil moisture feedbacks or large-scale processes (e.g. Giorgi *et al.*, 1996; Findell and Eltahir, 2003; Cook *et al.*, 2006). Generally speaking, soil moisture has much less significant effects on summer light precipitation frequency over humid and arid regions than those over the climatic and ecological transition zones.

We further calculate the ratio of the difference in interannual variance between CTL and SoilM to the variance in CTL, which reflects percent contribution of soil moisture–atmosphere coupling to the variance of interannual summer light precipitation frequency (Figure 4). Again, the light precipitation events with $p \leq 2$ mm day^{-1}, $p \leq 5$ mm day^{-1} and $p \leq 10$ mm day^{-1} exhibit a similar pattern. Over the regions, where significant changes occur, soil moisture–atmosphere coupling makes a large contribution to interannual variability of summer light precipitation, accounting for 30–60% of the total variance.

In this study, we also analyze the role of soil moisture–atmosphere coupling in summer moderate (10–20 mm day^{-1}) and heavy precipitation (≥20 mm day^{-1}) (not shown). The results show that the role of soil moisture–atmosphere coupling in moderate and heavy precipitation is much lesser than that of light precipitation. This is consistent with the result that precipitation extremes are not significantly affected by soil moisture variability over the Europe found by Jaeger and Seneviratne (2011).

Recent studies demonstrated that summer light precipitation frequency experienced remarkable interannual variations over East Asia (e.g. Yan and Yang, 2000; Gong *et al.*, 2004; Qian *et al.*, 2007, 2009, 2010; Ren *et al.*, 2010; Liu *et al.*, 2011). Our results indicate that soil moisture feedbacks contribute much to

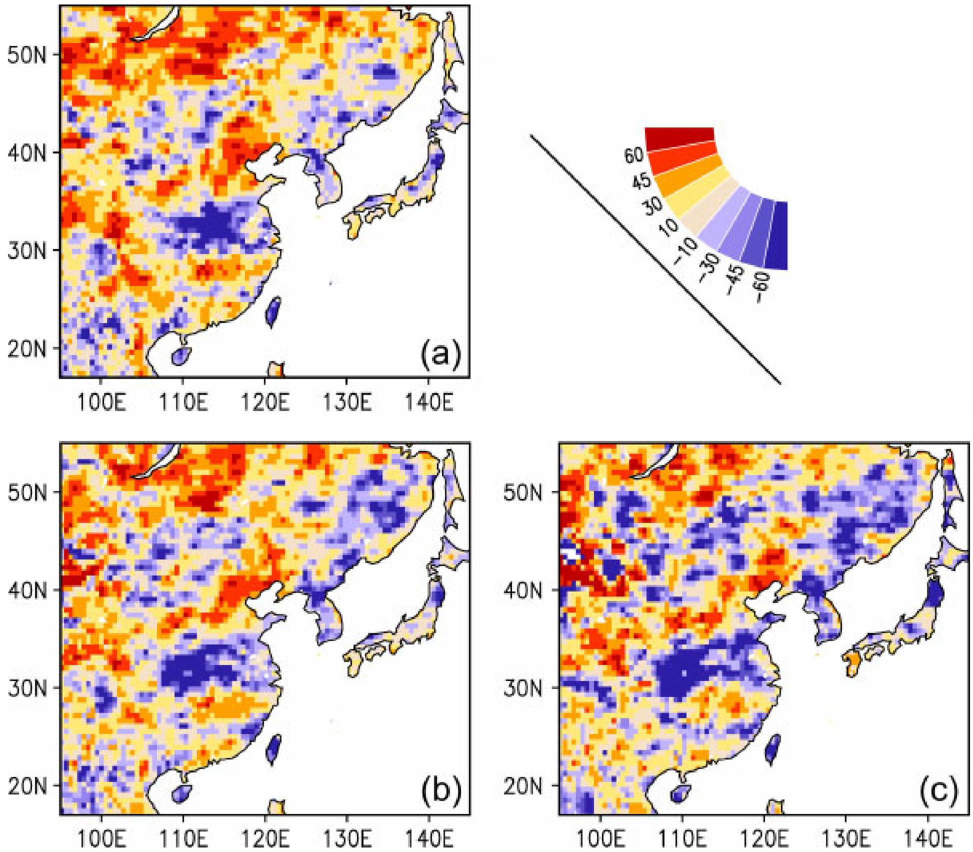

Figure 4. Percent contribution of soil moisture–atmosphere coupling to the variance of interannual summer light precipitation frequency: (a) ≤ 2 mm day^{-1}, (b) ≤ 5 mm day^{-1} and (c) ≤ 10 mm day^{-1}. The percentage is calculated as the ratio of the difference in interannual variance between CTL and SoilM (CTL minus SoilM) to the variance in CTL.

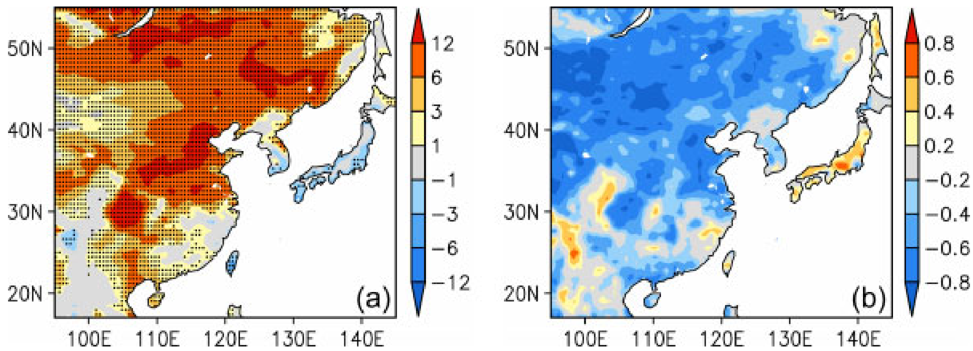

Figure 5. (a) Differences in standard deviation of summer latent heat flux w m^{2} between CTL and SoilM and (b) correlations between summer latent heat flux and light precipitation frequency ($p \leq 2$ mm day^{-1}).

the observed interannual variability over many areas of East Asia, in particular the climatic and ecological transition zones. In addition, summer light precipitation frequency has been found to have apparently decreasing trends over East Asia in the last several decades (Qian *et al.*, 2009, 2010). The role of soil moisture–atmosphere coupling in the decreasing trends of light precipitation frequency is subject to further investigation.

Soil moisture affects precipitation mainly through its effects on evapotranspiration or latent heat flux. Over the areas where soil moisture has significantly amplifying effects on summer light precipitation frequency variability, soil moisture generally shows strong effects on interannual variability of latent heat flux (Figure 5(a)), and latent heat flux has close linkages with summer light precipitation frequency for $p \leq 2$ mm day^{-1} (Figure 5(b)). Over most of other areas, either soil moisture has small effects on latent heat flux or connections between summer latent heat flux and light precipitation frequency are weak. Similar results are seen for $p \leq 5$ mm day^{-1} and $p \leq 10$ mm day^{-1} (not shown). Correlations of latent heat flux with moderate and heavy precipitation frequency are generally much less significant than those with light precipitation frequency. This may

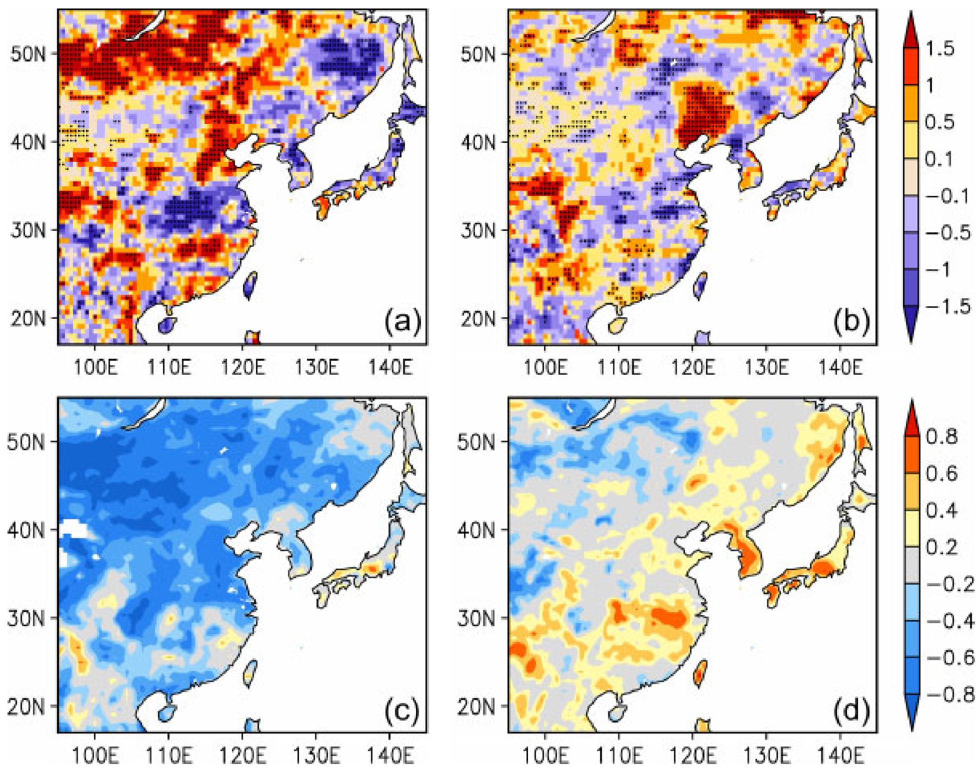

Figure 6. (a) Differences in standard deviation of summer convective light precipitation frequency (days per year) ($p \leq 2$ mm day^{-1}) between CTL and soilM, (b) same as (a) but for summer large-scale light precipitation frequency, (c) correlations between summer latent heat flux and convective light precipitation frequency ($p \leq 2$ mm day^{-1}), and (d) same as (c) but for summer large-scale light precipitation frequency.

explain why soil moisture has much smaller effects on the moderate and heavy precipitation than those on light precipitation. We also calculate correlations of summer evaporative fraction (calculated as the ratio of latent heat flux to the sum of latent and sensible heat fluxes) and summer light, moderate and heavy precipitation frequency, and find that the results are generally consistent with those of latent heat flux.

Changes in convective light precipitation frequency variability resemble those of total light precipitation frequency variability (Figure 6(a)). In contrast, changes in large-scale light precipitation frequency variability are much less significant (Figure 6(b)). Also, latent heat flux is much more closely linked to convective light precipitation frequency than large-scale light precipitation frequency (Figure 6(c) and (d)). The results indicate that soil moisture feedbacks on summer light precipitation frequency variability mainly depend not only on the ability of soil moisture to affect latent heat flux, but also on the ability of latent heat flux to affect convection.

4. Conclusions

In this study, we have analyzed two long-term WRF experiments with coupled and uncoupled soil moisture evolution to investigate the contribution of soil moisture–atmosphere coupling to the interannual variability of summer light precipitation frequency over East Asia. The WRF model is able to simulate climate mean and interannual variability of summer light precipitation frequency over East Asia well both in spatial pattern and magnitude; therefore, it can be used to explore the role of soil moisture feedbacks in the light precipitation frequency variability. The soil moisture–atmosphere coupling significantly amplifies interannual variability of summer light precipitation frequency over the climatic and ecological transition zones of the southern Siberia–northern Mongolia region and northern China, many areas of western China, and portion of southern China, accounting for 30–60% of the variance. The results help identify that soil moisture–atmosphere coupling is an important cause responsible for summer light precipitation variations and would contribute the skill to summer light precipitation prediction.

Previous regional climate model studies over the Europe demonstrated that soil moisture–atmosphere coupling can make a large contribution to summer total precipitation variability over particular areas (Seneviratne *et al.*, 2006; Jerez *et al.*, 2012), but generally play a relatively small role in influencing extreme precipitation (e.g. Jaeger and Seneviratne, 2011). Similar results are seen in WRF model simulations over East Asia according to Zhang *et al.* (2011) and this study. This study represents the first demonstration that soil moisture feedbacks can make an important contribution to summer light precipitation variations over East Asia. Meanwhile, we should mention that the results need to be confirmed further with other regional climate models in order to evaluate their model dependency, and also the role of soil moisture–atmosphere coupling in light precipitation frequency should be investigated by observational data in the future.

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