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The Relationship between Spring Soil Moisture and Summer Hot Extremes over North China

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ABSTRACT

The increase in the occurrence of hot extremes is known to have resulted in serious consequences for human society and ecosystems. However, our ability to seasonally predict hot extremes remains poor, largely due to our limited understanding of slowly evolving earth system components such as soil moisture, and their interactions with climate. In this study, we focus on North China, and investigate the relationship of the spring soil moisture condition to summer hot extremes using soil moisture data from the Global Land Data Assimilation System and observational temperature for the period 1981–2008. It is found that local soil moisture condition in spring is closely linked to summer hot days and heat waves over North China, accounting for 19%–34% of the total variances. Spring soil moisture anomalies can persist to the summer season, and subsequently alter latent and sensible heat fluxes, thus having significant effects on summer hot extremes. Our findings indicate that the spring soil moisture condition can be a useful predictor for summer hot days and heat waves over North China.

Key words: soil moisture, hot days, heat waves, climate prediction, North China

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1. Introduction

Hot extremes, which can cause severe societal, economic and ecological losses, have been shown to have had an increasing trend in the past several decades (Easterling et al., 2000; Meehl and Tebaldi, 2004; Alexander et al., 2006). A World Meteorological Organization (WMO) report showed that heat waves led to a 2300% increase in the loss of life in 2001–10 compared to 1991–2000 (WMO, 2013). In particular, the mega heatwaves that hit Europe in 2003 and the Russian Federation in 2010 caused over 66 000 and 55 000 deaths, respectively. Hot extremes over China have also become more frequent and severe in recent decades (Ren and Zhai, 1998; Zhai et al., 1999; Yan et al., 2002; Gong et al., 2004; Qian and Lin, 2004; Ren et al., 2010; Wang et al., 2012). For example, extraordinary heat waves struck many areas of China in 2013, leading to dramatic impacts on human life, property, agriculture, and water resources. The frequency and intensity of hot extremes have been projected to increase in the future over China and other regions of the globe (IPCC, 2012).

It is still a scientific challenge to accurately predict climate extremes such as heat waves one season or more in advance, limiting our ability to avoid or reduce their adverse impacts (e.g., Shukla, 1998; Zhang and Wu, 2014). Seasonal climate prediction must take advantage of the memories of slowing evolving earth system components. In this regard, the ocean has been considered as a critical predictor of seasonal climate anomalies (e.g., Cane et al., 1986). However, the ocean forcing is relatively weak in the midlatitude land areas in summer (e.g., Koster and Suarez, 1995; Dirmeyer et al., 2003; Douville, 2004). Similar to sea surface temperature, soil moisture also has a long memory, and thus can offer the potential for improving seasonal climate prediction, particularly regarding the summer season (e.g., Koster et al., 2004a; Seneviratne et al., 2006a; Zhang et al., 2008; Dirmeyer et al., 2009; Seneviratne et al., 2010; Wu and Zhang, 2013a). The importance of soil moisture to hot extremes has been highlighted in both observational and modeling studies (Durre et al., 2000; Diffenbaugh et al., 2005; Fischer et al., 2007; Teuling et al., 2010; Hirschi et al., 2011; Quesada et al., 2012; Chen and Zhou, 2013; Liu et al., 2013). For example, Zhang and Wu (2011) demonstrated that soil moisture feedbacks significantly enhance the occurrence of hot extremes over the areas outside of the arid and semi-arid regions in China. However, it is still unclear if antecedent soil moisture condition provide useful predictors for summer hot extremes.

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In this study, we focus on North China (37°–42°N, 108°–118°E), and investigate the relationship between spring (March–April–May) soil moisture and summer (June–July–August) hot extremes for the period 1981–2008. This region is a "hot spot" of soil moisture–temperature coupling, as established by the Global Land–Atmosphere Coupling Experiment (Koster et al., 2006) and previous statistical and regional climate modeling studies (Zhang and Dong, 2010; Zhang et al., 2011). Since soil moisture measurements in China have many missing data, we use soil moisture from the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004).

The paper is organized as follows. In section 2, we briefly describe the data and method used in this study. Section 3 examines the relationship of spring soil moisture to summer hot days and heat waves over North China. In section 4, the physical mechanism involved is discussed. A summary of the main findings is given in section 5.

2. Data and method

In this study, we use monthly soil moisture data from GLDAS version 1, at a resolution of 1°, for the period 1981–2008 (Rodell et al., 2004). The GLDAS soil moisture data have been evaluated extensively against observations (Berg et al., 2005; Kato et al., 2007; Syed et al., 2008; Zaitchik et al., 2010), and have been widely used to study the hydrological cycle, weather and subseasonal forecasting, and land–atmosphere interactions (e.g., Koster et al., 2004b; de Goncalves et al., 2006; Zhang et al., 2008; Wu and Zhang, 2013b). Berg et al. (2005) demonstrated that GLDAS soil moisture data agree well with observations over eastern China. Since surface soil moisture is immediately affected by precipitation, we use subsurface soil moisture from three land surface models including the Common Land Model (CLM; Dai et al., 2003), Mosaic (Chen et al., 1996) and Noah (Ek et al., 2003) with subsurface layer thicknesses of 9–138, 2–150 and 10–100 cm, respectively. We also use latent heat and sensible heat flux data from GLDAS to explore the physical processes that explain our findings. To test the robustness of our results, we use limited observed soil moisture data from the China Meteorological Administration (http://cdc.nmic.cn). We use observed soil moisture at a depth of 50 cm from two stations—Nangong (37.37°N, 115.38°E) and Fenyang (37.25°N, 111.76°E)—that have relatively complete data available for the period 1996–2008.

For this analysis, we use the number of hot days (NHD) and number of heat waves (NHW) to measure hot extremes. The two indices are defined based on daily maximum temperature at a resolution of 0.5° (CN05), developed by Xu et al. (2009). The CN05 dataset has been constructed by interpolating the data from 751 observation stations over mainland China. NHD is defined as the number of days with daily maximum temperature meeting or exceeding the mean 90th percentile for all summer days over the period 1981–2008. NHW is defined as the frequency of the occurrence of at least two consecutive hot days. In other words, one NHW event denotes two consecutive hot days or more than two consecutive hot days.

In this study, all data are linearly detrended before statistical analyses are performed. As a sample, Fig. 1 shows the original time series of spring soil moisture for CLM and summer hot days regionally averaged over North China, and the linearly detrended time series.

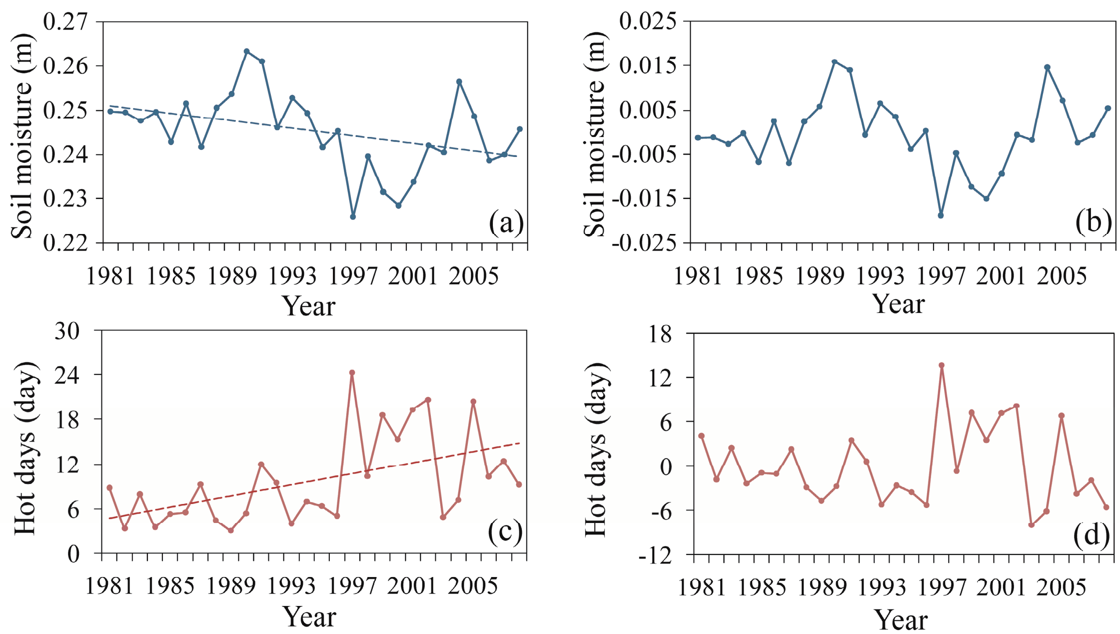

Fig. 1. Time series of regionally averaged original (a) spring soil moisture and (c) summer hot days over North China, and linearly detrended time series of (b) spring soil moisture and (d) summer hot days.

3. Spring soil moisture condition and summer hot extremes over North China

Figure 2 shows the correlation patterns of spring soil moisture with summer hot days averaged over North China (37°–42°N, 108°–118°E) for the period 1981–2008. The correlations from CLM, Mosaic and Noah exhibit a similar pattern, albeit with some differences. Over most areas of North China, the correlations between spring soil moisture and summer hot days are negative and significant at the 95% confidence level.

The correlation patterns of spring soil moisture with summer heat waves averaged over North China are presented in Fig. 3. The correlation patterns with heat waves are similar to those with summer hot days. For all three models, spring soil moisture anomalies mainly have negative correlations with the following-summer heat waves, with high correlations mainly appearing over North China.

Table 1 lists the correlation coefficients of regionally averaged spring soil moisture with regionally averaged hot days and heat waves over North China for the period 1981–2008. All correlation coefficients are negative and significant at the 95% confidence level. Among the three models, the spring soil moisture condition in CLM have the strongest correlations with summer hot days and heat waves.

We further use the observed soil moisture to test the robustness of the results from the GLDAS soil moisture. Since the observed soil moisture measurements over North China generally have many missing data, we use averaged soil moisture at a depth of 50 cm from two stations that have relatively complete data available. The correlations of observed spring soil moisture to summer heat waves and hot days regionally averaged over North China are −0.49 and −0.40 during the period 1996–2008, significant at the 90% and 80% confidence levels, respectively.

The above results show that the local spring soil moisture condition is closely linked to, and can provide a useful predictor for, summer hot extremes over North China. In the following section, we further examine if a clear physical linkage between spring soil moisture and hot extremes over North China exists in our statistical analysis.

Table 1. Correlation coefficients of regionally averaged spring soil moisture with regionally averaged summer hot days and heat waves over North China for the period 1981–2008. All data are linearly detrended before the correlation coefficient is calculated.

	CLM	Mosaic	Noah
Hot days	−0.52**	−0.44*	−0.45*
Heat waves	−0.58**	−0.48**	−0.51**

*Significant at the 95% confidence level,
**Significant at the 99% confidence level.

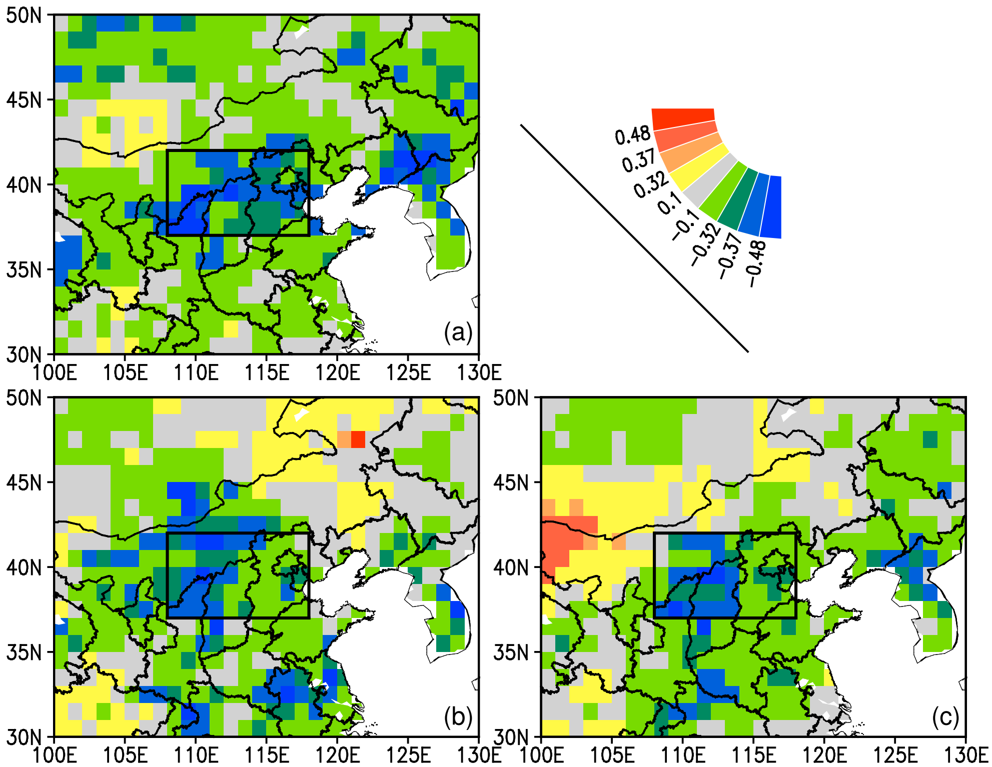

Fig. 2. Correlations of summer hot days averaged over North China (enclosed by the box) to spring soil moisture in (a) CLM, (b) Mosaic and (c) Noah. All data are linearly detrended before the correlation coefficient is calculated. Correlations of ±0.32, ±0.37 and ±0.48 are significant at the 90%, 95% and 99% confidence levels, respectively.

4. Physical mechanism

Figure 4 shows the autocorrelations of spring soil moisture to summer soil moisture over North China for the period 1981–2008. The autocorrelation coefficients of spring soil moisture to summer soil moisture are generally significant at the 90% confidence level over North China for the three models. In particular, they are significant at the 99% confidence level in most grids in CLM and Noah. We further estimate soil moisture memory using the decorrelation time,

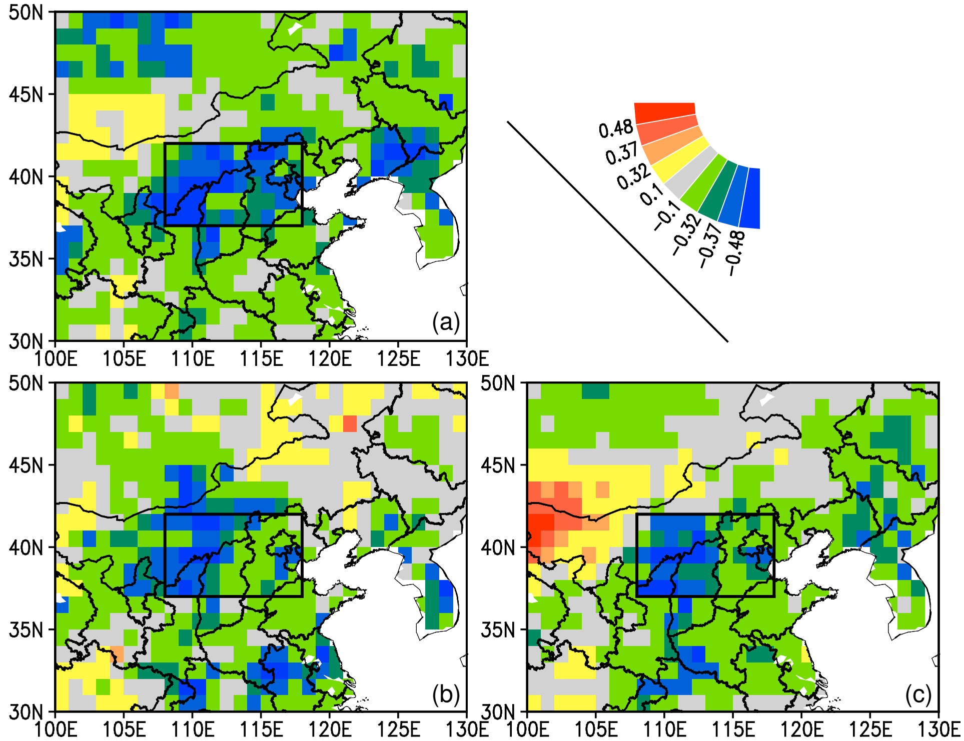

Fig. 3. Correlations of summer heat waves averaged over North China (enclosed by the box) to spring soil moisture in (a) CLM, (b) Mosaic and (c) Noah. All data are linearly detrended before the correlation coefficient is calculated. Correlations of ±0.32, ±0.37 and ±0.48 are significant at the 90%, 95% and 99% confidence levels, respectively.

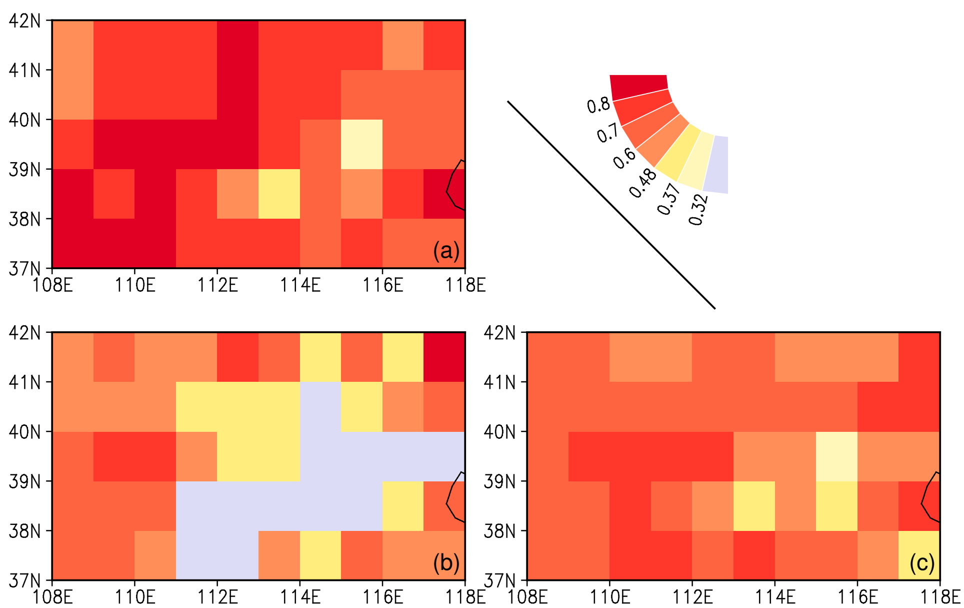

Fig. 4. Autocorrelations of spring soil moisture to summer soil moisture in (a) CLM, (b) Mosaic and (c) Noah. All data are linearly detrended before the correlation coefficient is calculated. Correlations of ±0.32, ±0.37 and ±0.48 are significant at the 90%, 95% and 99% confidence levels, respectively.

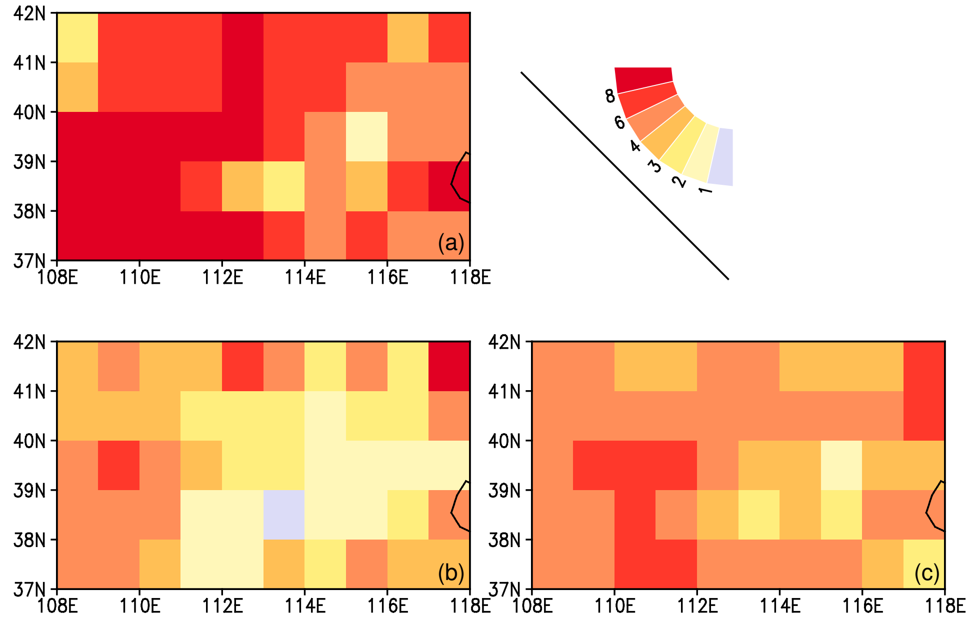

Fig. 5. Decorrelation time (in seasons) of soil moisture in (a) CLM, (b) Mosaic and (c) Noah. All data are linearly detrended before the decorrelation time is calculated.

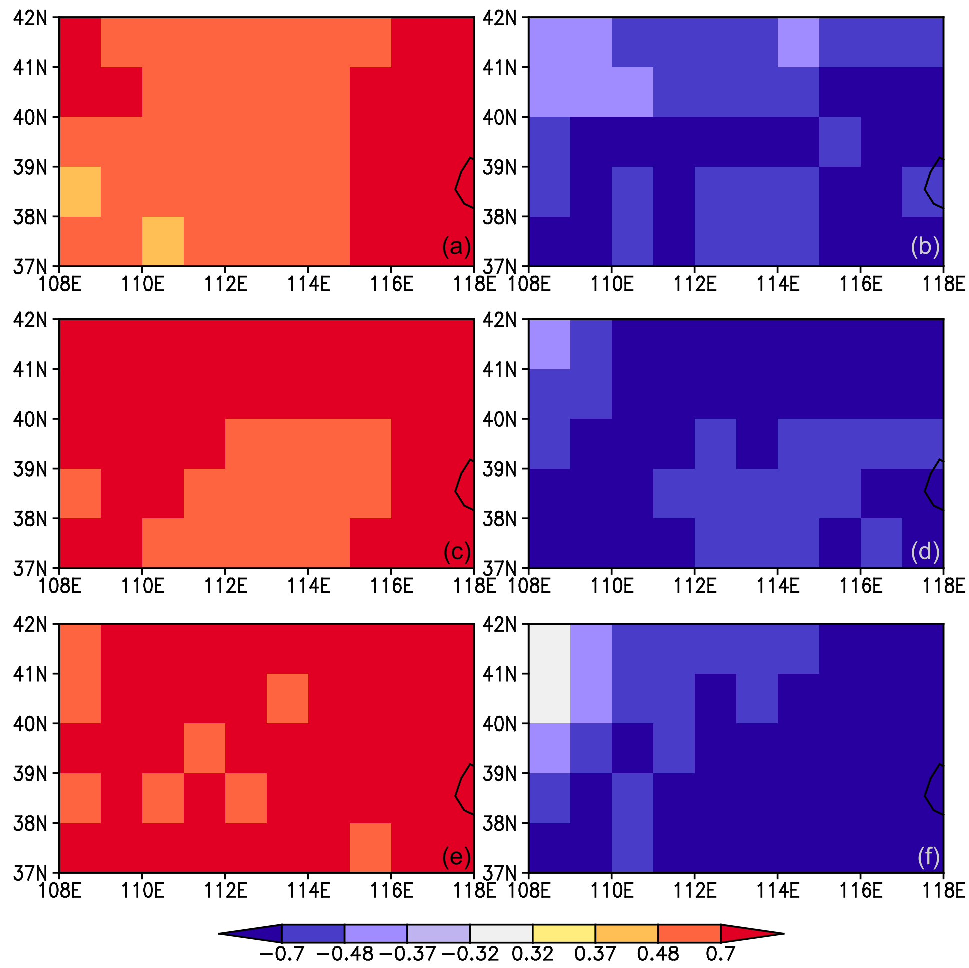

Fig. 6. Correlations of summer soil moisture to summer latent (left) and sensible heat (right) fluxes in (a, b) CLM, (c, d) Mosaic and (e, f) Noah. All data are linearly detrended before the correlation coefficient is calculated. Correlations of ±0.32, ±0.37 and ±0.48 are significant at the 90%, 95% and 99% confidence levels, respectively.

$$t_d = \frac{1+\alpha}{1-\alpha},$$

where α is the autocorrelation between spring and summer soil moisture (von Storch and Zwiers, 1999). Soil moisture generally has memory of one season or more in most grids over North China for the three models (Fig. 5). These results indicate that spring soil moisture anomalies can persist to the summer season over North China. Compared to previous studies, which have generally demonstrated that soil moisture has a memory of several months (e.g., Wu and Dickinson, 2004; Seneviratne et al., 2006b), the decorrelation time method used in this study may overestimate soil moisture memory length over some areas. Soil moisture affects, and is affected by, precipitation. We further calculate the correlations of regionally averaged spring precipitation to regionally averaged spring and summer subsurface GLDAS soil moisture averaged over North China for the period 1981–2008. The precipitation data are obtained from Climatic Research Unit (CRU) at a resolution of 0.5° [http://www.cru.uea.ac.uk/cru/data/hrg/, CRU TS v. 3.22 (Harris et al., 2014)]. The correlation coefficients are all positive with values ranging from 0.33 to 0.57. Plus, they are all significant at the 90% confidence level.

Previous global and regional climate modeling studies have demonstrated that summer soil moisture can strongly affect summer mean temperature and warm temperature extremes mainly through its effects on the partitioning of available energy into latent and sensible heat fluxes (Koster et al., 2006; Zhang and Wu, 2011). Our previous regional climate model simulation demonstrated that summer soil moisture affects hot extremes over North China and also many other areas of China, mainly through its modifications to latent heat and sensible heat fluxes (Zhang et al., 2011; Zhang and Wu, 2011). Here, we statistically examine the physical linkage between summer soil moisture and hot extremes over North China.

The first part of the linkage is from soil moisture anomalies to latent heat and sensible heat anomalies. Figure 6 shows that the correlations of summer soil moisture to summer latent and sensible heat fluxes are generally significant at the

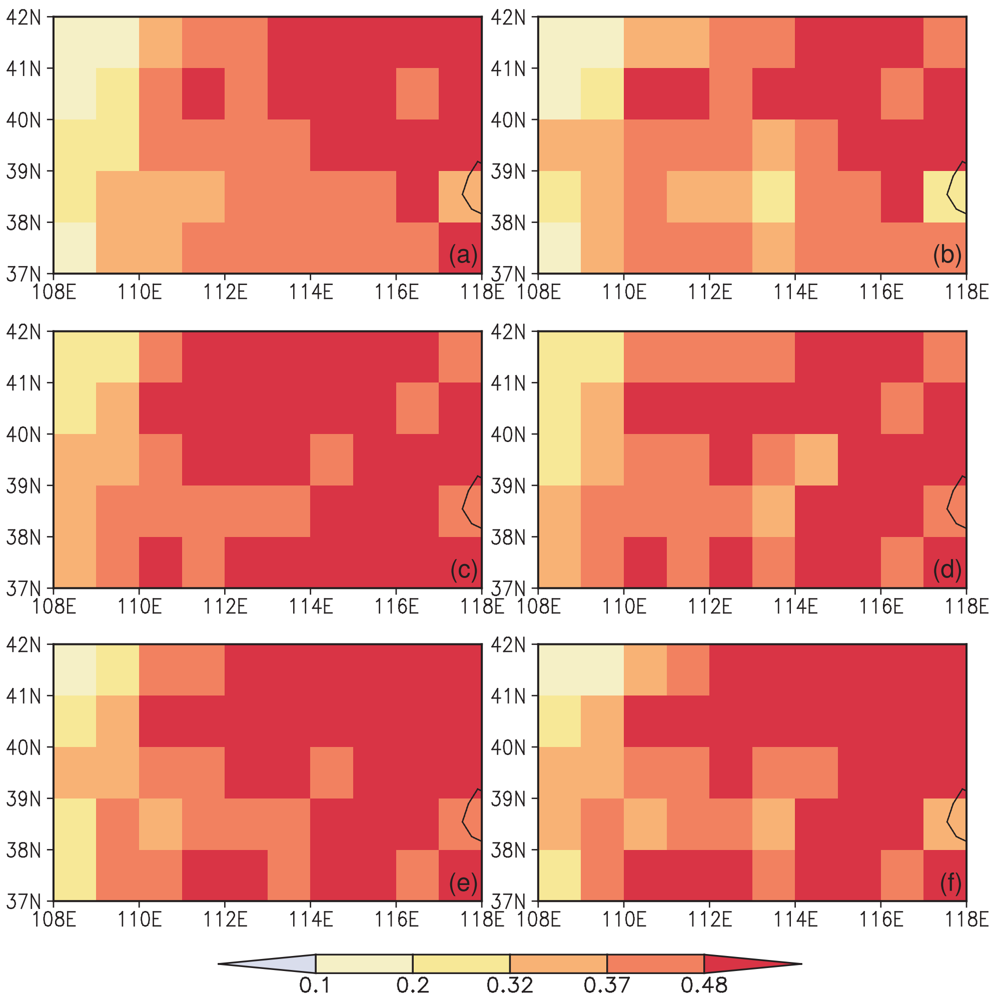

Fig. 7. Correlations of summer sensible heat flux to summer hot days (left) and heat waves (right) in (a, b) CLM, (c, d) Mosaic and (e, f) Noah. All data are linearly detrended before the correlation coefficient is calculated. Correlations of ±0.32, ±0.37 and ±0.48 are significant at the 90%, 95% and 99% confidence levels, respectively.

95% confidence level in all three models, indicating that summer soil moisture anomalies are closely related with summer latent and sensible heat fluxes.

We further look for the second part of the linkage from summer sensible heat flux to hot extremes. Figure 7 shows the correlations of summer sensible heat flux to summer hot days and heat waves over North China for the period 1981–2008. In all three models, summer sensible heat flux have strong and positive correlations with both hot days and heat waves, indicating that sensible heat anomalies induced by soil moisture anomalies can subsequently affect hot extremes over North China. It should be noted that soil moisture anomalies may also affect summer hot extremes over North China through its effects on atmospheric circulations (e.g., Taylor et al., 2011; Koster et al., 2014; Zhang et al., 2015).

5. Conclusions

Temperature extremes have much more important effects on natural and human systems than mean temperature. Over China and other regions of the globe, hot extremes have become more frequent and severe in recent decades, and have been projected to continually increase throughout the remainder of the present century. However, our current ability to predict hot extremes is largely limited by poor understanding of slowly evolving earth system components such as soil moisture, and their interactions with climate. In this study, we investigate the relationship of the spring soil moisture condition to summer hot extremes over North China, which is a "hot spot" of soil moisture–temperature coupling (e.g., Koster et al., 2006; Zhang et al., 2011).

The results show that the local spring soil moisture condition is closely related with hot extremes over North China. The correlation coefficients of regionally averaged spring soil moisture condition with regionally averaged hot days and heat waves range from -0.44 to -0.58, accounting for 19%–34% of the total variances. Spring soil moisture anomalies can persist to the summer season. Furthermore, it is found that summer soil moisture anomalies have a strong ability to affect summer latent and sensible heat flux, thus exerting substantial effects on summer hot extremes. Our findings indicate that the spring soil moisture condition is closely associated with summer hot extremes over North China, with a clear physical linkage. Since the spring soil moisture condition can be monitored easily, we recommend that spring soil moisture anomalies should be implemented into practical predictions of hot extremes over North China.

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REFERENCES

Alexander, L. V., and Coauthors, 2006: Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.*, **111**, D05109, doi: 10.1029/2005JD006290.

Berg, A. A., J. S. Famiglietti, M. Rodell, R. H. Reichle, U. Jambor, S. L. Holl, and P. R. Houser, 2005: Development of a hydrometeorological forcing data set for global soil moisture estimation. *Inter. J. Climatol.*, **25**(13), 1697–1714.

Cane, M. A., S. E. Zebiak, and S. C. Dolan, 1986: Experimental forecasts of El Niño. *Nature*, **321**(6073), 827–832.

Chen, F., and Coauthors, 1996: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.*, **101**, 7251–7268.

Chen, H. S., and J. Zhou, 2013: Impact of interannual soil moisture anomaly on simulation of extreme climate events in China. Part II: Sensitivity experiment analysis. *Chinese J. Atmos. Sci.*, **37**(1), 1–13, doi: 10.3878/j.issn.1006-9895.2012.11048. (in Chinese)

Dai, Y. J., and Coauthors, 2003: The Common Land Model. *Bull. Amer. Meteor. Soc.*, **84**, 1013–1023, doi: 10.1175/BAMS-84-8-1013.

de Goncalves, L. G. G.,W. J. Shuttleworth, S. C. Chou, Y. L. Xue, P. R. Houser, D. L. Toll, J. Marengo, and M. Rodell, 2006: Impact of different initial soil moisture fields on eta model weather forecasts for South America. *J. Geophys. Res.*, **111**, D17102, doi: 10.1029/2005JD006309.

Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, and F. Giorgi, 2005: Fine-scale processes regulate the response of extreme events to global climate change. *Proc. Natl. Acad. Sci. U. S. A.*, **102**, 15 774–15 778, doi: 10.1073/pnas.0506042102.

Dirmeyer, P. A., M. J. Fennessy, and L. Marx, 2003: Low skill in dynamical prediction of boreal summer climate: Grounds for looking beyond sea surface temperature. *J. Climate*, **16**, 995–1002.

Dirmeyer, P. A., C. A. Schlosser, and K. L. Brubaker, 2009: Precipitation, recycling and land memory: An integrated analysis. *Journal of Hydrometeorology*, **10**, 278–288, doi: 10.1175/2008JHM1016.1.

Douville, H., 2004: Relevance of soil moisture for seasonal atmospheric predictions: Is it an initial value problem? *Climate Dyn.*, **22**, 429–446.

Durre, I., J. M. Wallace, and D. P. Lettenmaier, 2000: Dependence of extreme daily maximum temperatures on antecedent soil moisture in the contiguous United States during summer. *J. Climate*, **13**, 2641–2651.

Easterling, D. R., G. A. Meehl, C. Parmesan, S. A. Changnon, T. R. Karl, and L. O. Mearns, 2000: Climate extremes: Observations, modeling, and impacts. *Science*, **289**, 2068–2074.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah land surface model advances in the National Centers for environmental Prediction operational mesoscale Eta model. *J. Geophys. Res.*, **108**(D22), 8851, doi: 10.1029/2002JD003296.

Fischer, E. M., S. I. Seneviratne, D. Lüthi, and C. Schär, 2007: Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophys. Res. Lett.*, **34**, L06707, doi:

10.1029/2006GL029068.

Gong, D.-Y., Y.-Z. Pan, and J.-A. Wang, 2004: Changes in extreme daily mean temperatures in summer in eastern China during 1955–2000. *Theor. Appl. Climatol.*, **77**, 25–37, doi: 10.1007/s00704-003-0019-2.

Harris I., P. D. Jones, T. J. Osborn, and D. H. Lister, 2014: Updated high-resolution grids of monthly climatic observations-the CRU TS3.10 Dataset. *Inter. J. Climatol.*, **34**, 623–642.

Hirschi, M., and Coauthors, 2011: Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, **4**(1), 17–21.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, C. B. Field and Coauthors, Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Kato, H., M. Rodell, F. Beyrich, H. Cleugh, E. van Gorsel, H. Z. Liu, and T. P. Meyers, 2007: Sensitivity of land surface simulations to model physics, land characteristics, and forcings, at four CEOP sites. *J. Meteor. Soc. Japan*, **85**A, 187–204, doi: 10.2151/jmsj.85A.187.

Koster, R. D., and M. J. Suarez, 1995: Relative contributions of land and ocean processes to precipitation variability. *J. Geophys. Res.*, **100**, 13 775–13 790, doi: 10.1029/95JD00176.

Koster, R. D., and Coauthors, 2004a: Regions of strong coupling between soil moisture and precipitation. *Science*, **305**, 1138–1140, doi: 10.1126/science.1100217.

Koster, R. D., and Coauthors, 2004b: Realistic initialization of land surface states: Impacts on subseasonal forecast skill. *Journal of Hydrometeorology*, **5**(6), 1049–1063, doi: 10.1175/JHM-387.1.

Koster, R. D., and Coauthors, 2006: GLACE: The global land-atmosphere coupling experiment. Part I: Overview. *Journal of Hydrometeorology*, **7**, 590–610.

Koster, R. D., Y. H. Chang, and S. D. Schubert, 2014: A mechanism for land-atmosphere feedback involving planetary wave structures. *J. Climate*, **27**, 9290–9301.

Liu, D., G. L. Wang, R. Mei, Z. B. Yu, and M. Yu, 2013: Impact of initial soil moisture anomalies on climate mean and extremes over Asia. *J. Geophys. Res.*, **119**, 529–545, doi: 10.1002/2013JD020890.

Meehl, G. A., and C. Tebaldi, 2004: More intense, more frequent and longer lasting heat waves in the 21st century. *Science*, **305**, 994–997.

Qian, W. H., and X. Lin, 2004: Regional trends in recent temperature indices in China. *Climate Research*, **27**, 119–134.

Quesada, B., R. Vautard, P. Yiou, M. Hirschi, and S. I. Seneviratne, 2012: Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nature Climate Change*, **2**(10), 736–741.

Ren, F. M., and P. M. Zhai, 1998: Study on changes of China's extreme temperatures during 1951∼1990. *Scientia Atmospherica Sinica*, **22** (2), 217–227, doi: 10.3878/j.issn.1006-9895.1998.02.10. (in Chinese)

Ren, G. L., G. L. Feng, and Z. W. Yan, 2010: Progresses in observation studies of climate extremes and changes in mainland China. *Climatic and Environmental Research*, **15**(4), 337–353, doi: 10.3878/j.issn.1006-9585.2010.04.01. (in Chinese)

Rodell, M., and Coauthors, 2004: The global land data assimilation system. *Bull. Amer. Meteor. Soc.*, **85**(3), 381–394, doi: 10.1175/BAMS-85-3-381.

Seneviratne, S. I., D. Lüthi, M. Litschi, and C. Schär, 2006a: Land-atmosphere coupling and climate change in Europe. *Nature*, **443**, 205–209, doi: 10.1038/nature05095.

Seneviratne, S. I., and Coauthors, 2006b: Soil moisture memory in AGCM simulations: Analysis of Global Land-Atmosphere Coupling Experiment (GLACE) data. *Journal of Hydrometeorology*, **7**, 1090–1112, doi: 10.1175/JHM533.1.

Seneviratne, S. I., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling, 2010: Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99**, 125–161, doi: 10.1016/j.earscirev.2010.02.004.

Shukla, J., 1998: Predictability in the midst of chaos: A scientific basis for climate forecasting. *Science*, **282**, 728–731.

Syed, T. H., J. S. Famiglietti, M. Rodell, J. L. Chen, and C. R. Wilson, 2008: Analysis of terrestrial water storage changes from GRACE and GLDAS. *Water Resour. Res.*, **44**, W02433, doi: 10.1029/2006WR005779.

Taylor, C. M., A. Gounou, F. Guichard, P. P. Harris, R. J. Ellis, F. Couvreux, and M. DeKauwe, 2011: Frequency of Sahelian storm initiation enhanced over meososcale soil-moisture patterns. *Nature Geoscience*, **4**, 430–433.

Teuling, A. J., and Coauthors, 2010: Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geoscience*, **3**(10), 722–727.

von Storch, H., and F. W. Zwiers, 1999: *Statistical Analysis in Climate Research*. Cambridge University Press, 484 pp.

Wang, H. J., and Coauthors, 2012: Extreme climate in China: Facts, simulation and projection. *Meteor. Z.*, **21**, 279–304, doi: 10.1127/0941-2948/2012/0330.

WMO, 2013: The global climate 2001–2010, a decade of climate extremes. WMO-No. 1103, 119 pp.

Wu, L. Y., and J. Y. Zhang, 2013a: Role of land-atmosphere coupling in summer droughts and floods over eastern China for the 1998 and 1999 cases. *Chinese Science Bulletin*, **58**(32), 3978–3985, doi: 10.1007/s11434-013-5855-6.

Wu, L. Y., and J. Y. Zhang, 2013b: Asymmetric effects of soil moisture on mean daily maximum and minimum temperatures over eastern China. *Meteor. Atmos. Phys.*, **122**, 199–213.

Wu, W. R., and R. E. Dickinson, 2004: Time scales of layered soil moisture memory in the context of land-atmosphere interaction. *J. Climate*, **17**, 2752–2764.

Xu, Y., X. J. Gao, Y. Shen, C. H. Xu, Y. Shi, and F. Giorgi, 2009: A daily temperature dataset over China and its application in validating a RCM simulation. *Adv. Atmos. Sci.*, **26**(4), 763–772, doi: 10.1007/s00376-009-9029-z.

Yan, Z., and Coauthors, 2002: Trends of extreme temperatures in Europe and China based on daily observations. *Climatic Change*, **53**, 355–392.

Zaitchik, B. F., M. Rodell, and F. Olivera, 2010: Evaluation of the Global Land Data Assimilation System using global river discharge data and a source-to-sink routing scheme. *Water Resour. Res.*, **46**, W06507, doi: 10.1029/2009WR007811.

Zhai, P. M., A. J. Sun, F. M. Ren, X. N. Liu, B. Gao, and Q. Zhang, 1999: Changes of climate extremes in China. *Climatic Change*, **42**, 203–218.

Zhang, J., Z. Y. Liu, and L. Chen, 2015: Reduced soil moisture contributes to more intense and more frequent heat waves in northern China. *Adv. Atmos. Sci.*, **32**(9), doi: 10.1007/s00376-014-4175-3.

Zhang, J. Y., and W. J. Dong, 2010: Soil moisture influence on summertime surface air temperature over East Asia. *Theor.*

Appl. Climatol., **100**, 221–226.

Zhang, J. Y., and L.Y. Wu, 2011: Land-atmosphere coupling amplifies hot extremes over China. *Chinese Sci. Bull*, **56**(31), 3328–3332.

Zhang, J. Y., and L. Y. Wu, 2014: *Impact of Land-Atmosphere Interactions on Climate over East Asia*. China Meteorological Press, 1–138. (in Chinese).

Zhang, J. Y., W.-C. Wang, and J. F. Wei, 2008: Assessing land-atmosphere coupling using soil moisture from the Global Land Data Assimilation System and observational precipitation. *J. Geophys. Res.*, **113**, D17119, doi: 10.1029/2008JD009807.

Zhang, J. Y., L. Y. Wu, and W. J. Dong, 2011: Land-atmosphere coupling and summer climate variability over East Asia. *J. Geophys. Res.*, **116**, D05117, doi: 10.1029/2010JD014714.