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# An underestimated role of precipitation frequency in regulating summer soil moisture

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## Abstract

Soil moisture induced droughts are expected to become more frequent under future global climate change. Precipitation has been previously assumed to be mainly responsible for variability in summer soil moisture. However, little is known about the impacts of precipitation frequency on summer soil moisture, either interannually or spatially. To better understand the temporal and spatial drivers of summer drought, 415 site yr measurements observed at 75 flux sites world wide were used to analyze the temporal and spatial relationships between summer soil water content (SWC) and the precipitation frequencies at various temporal scales, i.e., from half-hourly, 3, 6, 12 and 24 h measurements. Summer precipitation was found to be an indicator of interannual SWC variability with  $r$  of 0.49 ( $p < 0.001$ ) for the overall dataset. However, interannual variability in summer SWC was also significantly correlated with the five precipitation frequencies and the sub-daily precipitation frequencies seemed to explain the interannual SWC variability better than the total of precipitation. Spatially, all these precipitation frequencies were better indicators of summer SWC than precipitation totals, but these better performances were only observed in non-forest ecosystems. Our results demonstrate that precipitation frequency may play an important role in regulating both interannual and spatial variations of summer SWC, which has probably been overlooked or underestimated. However, the spatial interpretation should carefully consider other factors, such as the plant functional types and soil characteristics of diverse ecoregions.

**Keywords:** summer drought, precipitation frequency, climate change, plant functional types

 Online supplementary data available from [stacks.iop.org/ERL/7/024011/mmedia](http://stacks.iop.org/ERL/7/024011/mmedia)

## 1. Introduction

The frequency and intensity of extreme weather and climate events have shown profound impacts on both human society and the natural environment (Easterling *et al* 2000). Summer drought is one of the extreme climate issues that have tremendous impacts on ecosystem processes from both local to regional and global scales (Phillips *et al* 2009, Fensharm *et al* 2009, Ledger *et al* 2011). For example, a drought was reported to reduce 30% of gross primary production (GPP) and led to a net carbon source over the whole of Europe in 2003 (Ciais *et al* 2005). Global reduction of terrestrial net primary production (NPP) due to severe drought has also been reported, although the reasons and magnitudes are still unresolved (Zhao and Running 2010, Samanta *et al* 2011).

While the importance of summer drought has been recognized, it is still listed as one of the least understood issues in global environmental change (Breshears *et al* 2005, Piao *et al* 2009, Sowerby *et al* 2008, Mishra and Singh 2010, Ledger *et al* 2011). Soil water content (SWC, %) is an important indicator of drought (Peñuelas *et al* 2007, Piao *et al* 2009), and, therefore, efforts have been made to understand the relationships between SWC and climate change factors, including temperature (Li *et al* 2007), radiation (Ramanathan *et al* 2001) and precipitation (Knapp *et al* 2008). Among these factors, SWC is assumed to be mainly regulated by precipitation because of the role of SWC as the direct link between precipitation and ecological processes (Weltzin *et al* 2003, Pan *et al* 2003) as well as evidence of precipitation being affected by SWC (Eltahir 1998, Koster *et al* 2004).

Rather than precipitation quantity, recent results have shown that the pattern of precipitation may have more important impacts on ecosystem processes (Knapp *et al* 2002, Fang *et al* 2005). In particular, precipitation regimes are predicted to become more variable with more extreme rainfall events punctuated by longer intervening dry periods (Heisler-White *et al* 2008). These temporal changes in precipitation pattern would greatly affect the soil moisture but our ability to interpret such changes on ecosystem processes and the associated responses of soil moisture is still limited. This indicates an urgent need to evaluate the relationship between SWC and the frequency of precipitation, which in turn would be helpful to assess future droughts and their impacts.

Due to the lack of long-term observation data, the relationship between SWC and precipitation frequency is not well understood, with limited sites and plant functional types previously reported (Katul *et al* 2007, Piao *et al* 2009). These uncertainties associated with both interannual and spatial patterns between SWC and precipitation frequency prevent a full evaluation of feedbacks between ecosystem processes and climate change. With long-term (415 site yr) flux measurements world wide (75 sites), here we provide an investigation on the temporal–spatial relationships between

summer SWC and various precipitation frequencies derived from datasets of different temporal scales. The temporal pattern provides an opportunity to identify the response of interannual summer drought to precipitation frequency regimes while its spatial pattern will give insights into this response across regions and plant functional types. Such analysis will be useful for comprehending feedbacks between ecosystem processes and future climate change.

## 2. Materials and methods

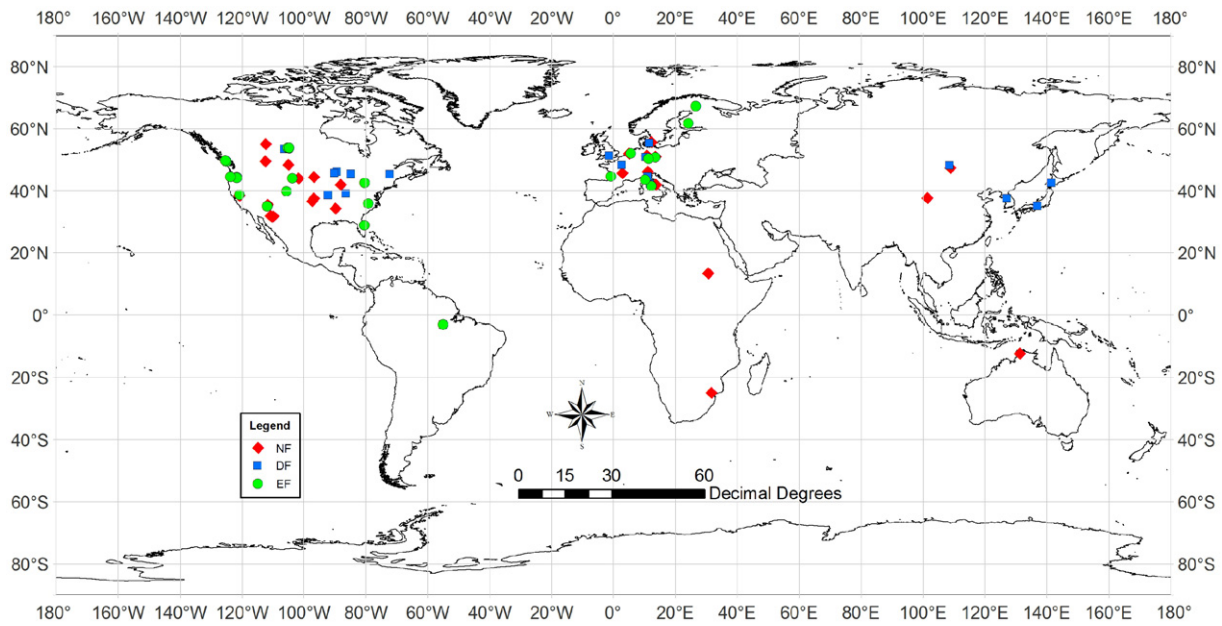
### 2.1. Study sites

A global search for flux data indicated that the availability of SWC data mainly restricts our analysis. As a result, we identified 75 flux sites which provided 415 site yr of data to support the temporal and spatial analyses between summer SWC and precipitation frequencies (figure 1). The data for each site employed in this study were downloaded from the following flux networks: AmeriFlux (<http://public.ornl.gov/ameriflux/dataproducts.shtml>), Fluxnet-Canada Data Information System ([www.fluxnet-canada.ca](http://www.fluxnet-canada.ca)), European Eddy Fluxes databases cluster ([www.europe-fluxdata.eu/newtcdc2/p\\_home.aspx](http://www.europe-fluxdata.eu/newtcdc2/p_home.aspx)), CarboAfrica Database ([www.europe-fluxdata.eu/newtcdc2/CarboAfrica\\_home.aspx](http://www.europe-fluxdata.eu/newtcdc2/CarboAfrica_home.aspx)), AsiaFlux (<http://asiaflux.net/>) as well as the Public FLUXNET Dataset Information ([www.fluxdata.org/DataInfo/default.aspx](http://www.fluxdata.org/DataInfo/default.aspx)). The rules for site selection were mainly regulated by data availability, data quality and data time duration. These sites covered diverse plant functional types which can be classified into three groups, including 30 non-forest sites (NF), 18 deciduous forest sites (DF) and 27 evergreen forest sites (EF). Detailed descriptions of each site and their regional climates are shown in supplementary table 1 (available at [stacks.iop.org/ERL/7/024011/mmedia](http://stacks.iop.org/ERL/7/024011/mmedia)).

### 2.2. Precipitation and SWC data

The available data for the months from June to August in each year were applied to calculate the summer precipitation frequency and soil water content (SWC, %). However, the months from December to February were used for sites in the Southern Hemisphere. With our analysis limited to the summer months, we had more opportunity to acquire good quality precipitation data without large gaps. For both precipitation frequency and SWC, summers with amounts of missing data (either precipitation frequency or SWC) larger than 10% (~440 half-hourly readings for the whole period of the summer months) were excluded to guarantee the quality of the data.

Precipitation data for all sites were obtained from the half-hourly meteorological measurements collected by on-site tipping bucket sensors, which transmit the registered data to



**Figure 1.** The spatial distribution of the 75 sites in this study. The NF (♦), DF (■) and EF (●) represent non-forests, deciduous forests and evergreen forests, respectively.

an indoor console (or digital transmitter unit). The half-hourly measurements were used to generate datasets of various temporal resolutions, including 0.5, 3, 6, 12 and 24 h (daily) products. Then, five precipitation frequencies were calculated (hereafter referred as 0.5, 3, 6, 12 and 24 h-PF), and each was determined as the number of time periods with precipitation recorded on the sensor from the respective observations ( $n$  = number of times with recorded precipitation). For the half-hourly precipitation data, a minimum threshold for precipitation was included (0.1 mm/half-hour), considering the accuracy of the sensor as well as avoiding very light rainfalls being counted as precipitation events.

Site-level SWC was consistently measured by time-domain reflectometry (TDR) type probes (30 min intervals) at a general depth of around 0–30 cm, which slightly differed for individual sites. We also averaged the multiple SWC measurements at different depths within 0–30 cm if these multi-depth data were available at a site. The mean values for the summer months were calculated to represent the summer SWC. Statistical results for summer precipitation and SWC for each site are shown in supplementary table 2 (available at [stacks.iop.org/ERL/7/024011/mmedia](http://stacks.iop.org/ERL/7/024011/mmedia)).

### 2.3. Radiation, temperature and latent heat data

To support the analysis between precipitation frequency and SWC, we also collected several auxiliary parameters, including the photosynthetic active radiation (PAR) and air temperature ( $T_a$ ). We further selected seven representative sites (CA-GRA, CA-OAS, CA-OBS, CA-OJP, CA-DF49, CA-DF88 and CA-DF00) in the Fluxnet-Canada network to explore the relationship between precipitation frequency and latent heat (LH), which is a main variable controlling evapotranspiration (ET). The selection of these seven

representative sites was based on the considerations that (1) they covered all three plant functional types (i.e., NF, DF and EF) in our analysis, (2) they had relatively long time of observation records (mean time of 9 yr), (3) they had good quality of data, (4) they covered the same forest with different ages (CA-DF49, CA-DF88 and CA-DF00 were harvested in 1949, 1988 and 2000, respectively), and (5) they covered forests of contrasting species (deciduous versus evergreen) at different sites from the same latitude. The radiation, temperature and latent heat were measured half-hourly using sensors mounted on the towers and the mean values for the summer months were calculated to compare with the precipitation frequencies.

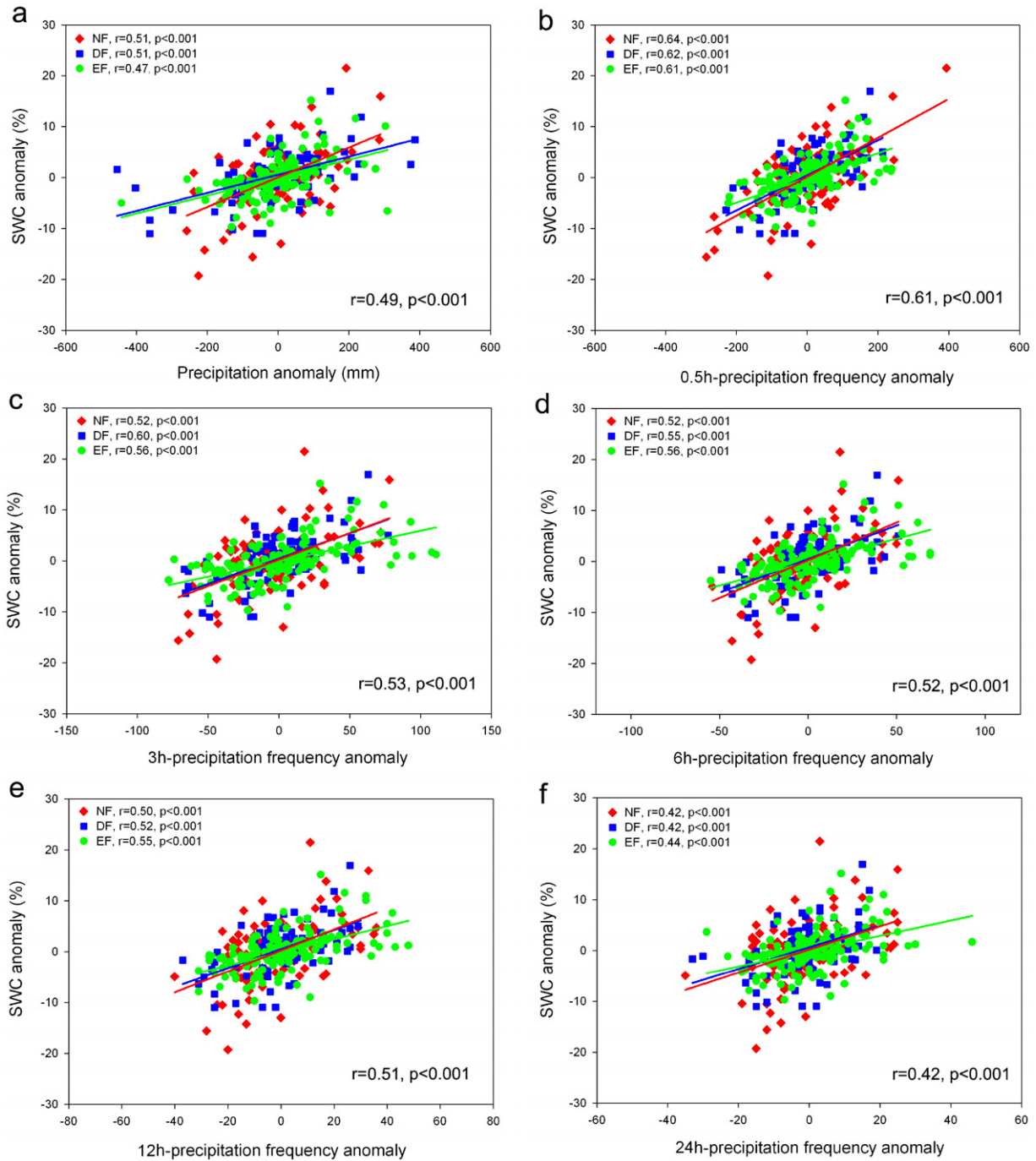
### 2.4. Statistical analyses

Both the temporal (within sites) and the spatial (across sites) relationships between summer SWC and precipitation frequency were analyzed in this study. The pairwise Pearson coefficient ( $r$ ) and  $p$ -value were used to evaluate these correlations. The temporal patterns between summer SWC and precipitation frequency were analyzed based on the year-to-year anomalies of both variables considering their diverse dynamic ranges across sites and regions:

$$A_i = x_i - x_{i-1}, \tag{1}$$

where  $A_i$  is the anomaly of a variable,  $x_i$  and  $x_{i-1}$  are the observations in years  $i$  and  $i - 1$ , respectively.

These correlations were also separated by plant functional types, i.e., for all NF sites (113 site yr), DF sites (78 site yr) and EF sites (149 site yr). To analyze the spatial pattern, the mean values as well as the standard deviations of the summer SWC and precipitation frequency were calculated for each site (i.e., 30 NF, 18 DF and 27 EF sites), both of



**Figure 2.** Temporal relationships between the interannual summer soil water content (SWC) anomaly and the anomalies of (a) precipitation quantity, (b) 0.5 h-precipitation frequency, (c) 3 h-precipitation frequency, (d) 6 h-precipitation frequency, (e) 12 h-precipitation frequency, and (f) 24 h-precipitation frequency. The NF (♦), DF (■) and EF (●) represent non-forests, deciduous forests and evergreen forests, respectively.

which were then used to test the relationships between the summer SWC and precipitation frequencies spatially.

### 3. Results and discussion

Relationships between the interannual variability of summer SWC and the precipitation and its frequencies are shown in figure 2. Precipitation showed a positive impact on summer SWC with a Pearson coefficient ( $r$ ) of 0.49 ( $p < 0.001$ ) for the overall dataset, and the coefficients were 0.51 ( $p <$

0.001), 0.51 ( $p < 0.001$ ) and 0.47 ( $p < 0.001$ ) for the datasets classified as NF, DF and EF, respectively. These results suggest that increase of summer precipitation favors soil moisture and mitigates summer drought. When the precipitation frequencies were explored to explain interannual variability in summer SWC, we observed improved results for all the sub-daily precipitation frequencies with the  $r$  ranging from 0.61 ( $p < 0.001$ ) for 0.5 h-PF to 0.51 ( $p < 0.001$ ) for 12 h-PF. Generally, these improvements

**Table 1.** Relationships between precipitation frequency (PF) anomalies and summer precipitation (PP), air temperature ( $T_a$ ) and photosynthetic active radiation (PAR) for non-forest (NF), deciduous forest (DF) and evergreen forest (EF) sites.

Precipitation frequency	Pearson coefficients	PP			$T_a$			PAR		
		NF	DF	EF	NF	DF	EF	NF	DF	EF
0.5 h-PF	$r$	0.73	0.61	0.70	-0.39	-0.46	-0.61	-0.52	-0.55	-0.49
	$p$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
3 h-PF	$r$	0.65	0.62	0.59	-0.41	-0.51	-0.59	-0.46	-0.60	-0.46
	$p$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 h-PF	$r$	0.60	0.60	0.59	-0.41	-0.51	-0.57	-0.41	-0.58	-0.46
	$p$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
12 h-PF	$r$	0.56	0.53	0.57	-0.42	-0.51	-0.58	-0.39	-0.54	-0.47
	$p$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
24 h-PF	$r$	0.51	0.53	0.51	-0.40	-0.36	-0.43	-0.32	-0.43	-0.35
	$p$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

were consistent, irrespective of differences in plant functional types and ecoregions. In contrast, an  $r$  equal to 0.42 ( $p < 0.001$ ) was acquired between the summer SWC and the 24 h-PF, implying the limited potential of daily precipitation frequency in explaining interannual SWC variability. Our results expand the previously reported dependence between storm frequency and summer soil moisture at stand level, suggesting that this relationship is robust for most vegetated areas globally. These observations reveal for the first time that the precipitation frequency may play an overlooked role in explaining interannual summer SWC compared to the commonly adopted precipitation quantity. However, this potential is also regulated by the temporal resolution on which the precipitation frequency is calculated.

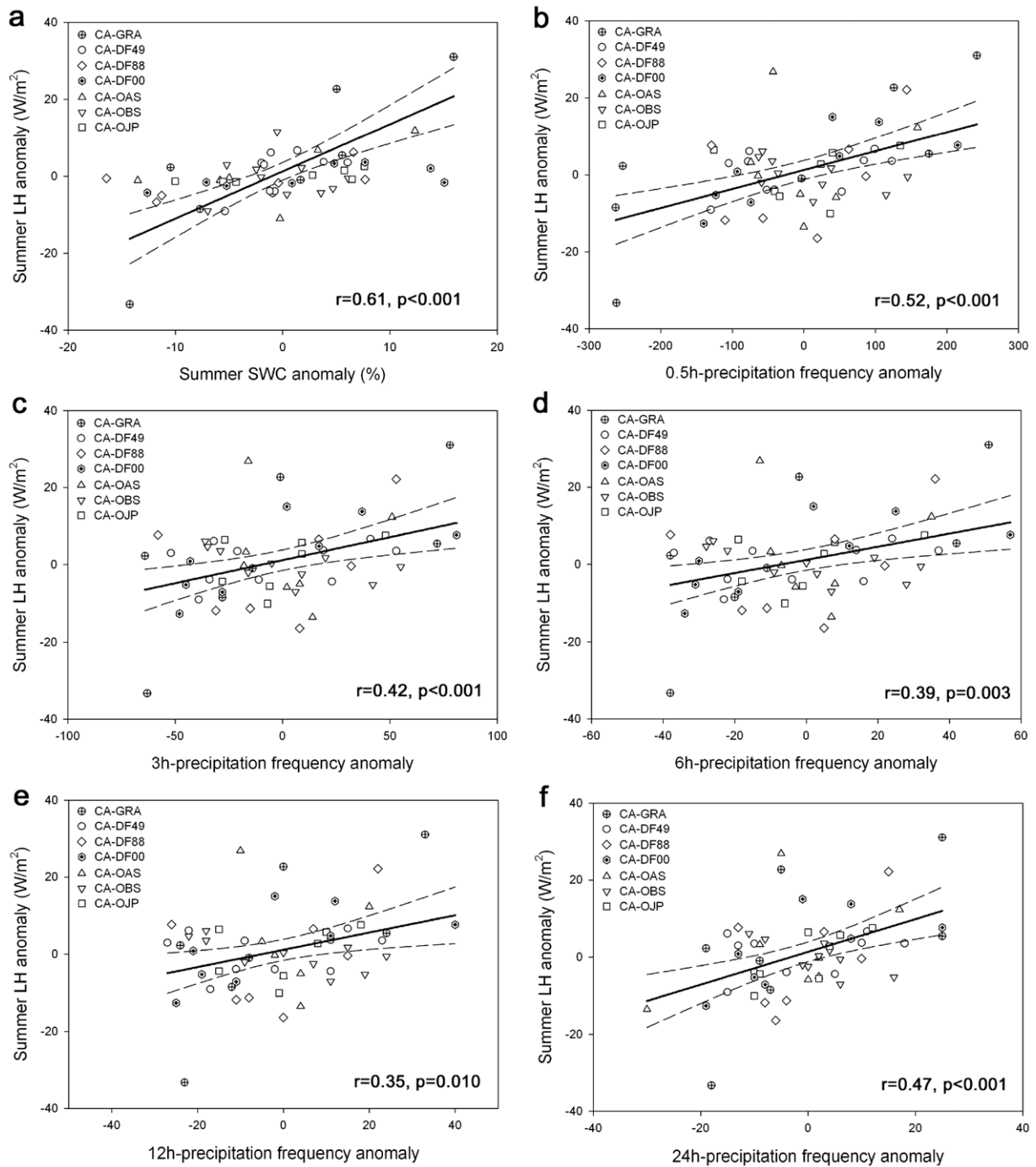
To better understand the interannual relationships between SWC and precipitation frequencies, we explored the impacts of precipitation frequencies on the total summer precipitation, mean air temperature ( $T_a$ ) and mean photosynthetic active radiation (PAR) for all sites, given that SWC is affected by both the total precipitation and evaporation (table 1). Significant correlations ( $p < 0.001$ ) were found between total summer precipitation and the five precipitation frequencies for all plant functional types, suggesting that increasing frequency of rainfall generally provides more water into the soil layer. By comparison, both  $T_a$  and PAR were negatively correlated with precipitation frequency, implying that higher frequency of rainfall mitigates drought impacts thereby enhancing SWC.

For the seven representative sites, we further found that the SWC was positively correlated with the latent heat with  $r$  of 0.61 ( $p < 0.001$ ) (figure 3). This relationship is consistent with the understanding that humid soil has a high evapotranspiration rate, which uses the latent heat as the main energy. Meantime, we also found that the latent heat was significantly ( $p < 0.05$ ) correlated with the five precipitation frequencies with  $r$  of 0.52, 0.42, 0.39, 0.35 and 0.47, respectively. Therefore, it is reasonable that the precipitation frequencies would correlate with the SWC.

Substantial variations were observed between summer SWC and both precipitation quantity and frequencies spatially (figure 4). Our results demonstrated that the spatial pattern of summer SWC cannot be explained by either precipitation or its frequencies. However, the correlation seemed to

differ substantially among plant functional types. While no correlation was observed between these indicators and SWC for forest ecosystems, significant relationships were identified between summer SWC and precipitation quantity ( $r = 0.54$ ,  $p = 0.004$ ) for the non-forest ecosystems. Similar results were also found when we explored the relationships of (a) minimum SWC and minimum summer precipitation, and (b) maximum SWC and maximum summer precipitation (data shown in supplementary table 2 available at [stacks.iop.org/ERL/7/024011/mmedia](http://stacks.iop.org/ERL/7/024011/mmedia)). In particular, all those precipitation frequencies can better explain summer SWC with  $r$  values of 0.72 ( $p < 0.001$ ), 0.73 ( $p < 0.001$ ), 0.72 ( $p < 0.001$ ), 0.72 ( $p < 0.001$ ) and 0.68 ( $p < 0.001$ ) for 0.5 h-PF, 3 h-PF, 6 h-PF, 12 h-PF and 24 h-PF, respectively, suggesting an unrecognized role of precipitation frequency in controlling the spatial patterns of SWC in non-forest ecosystems.

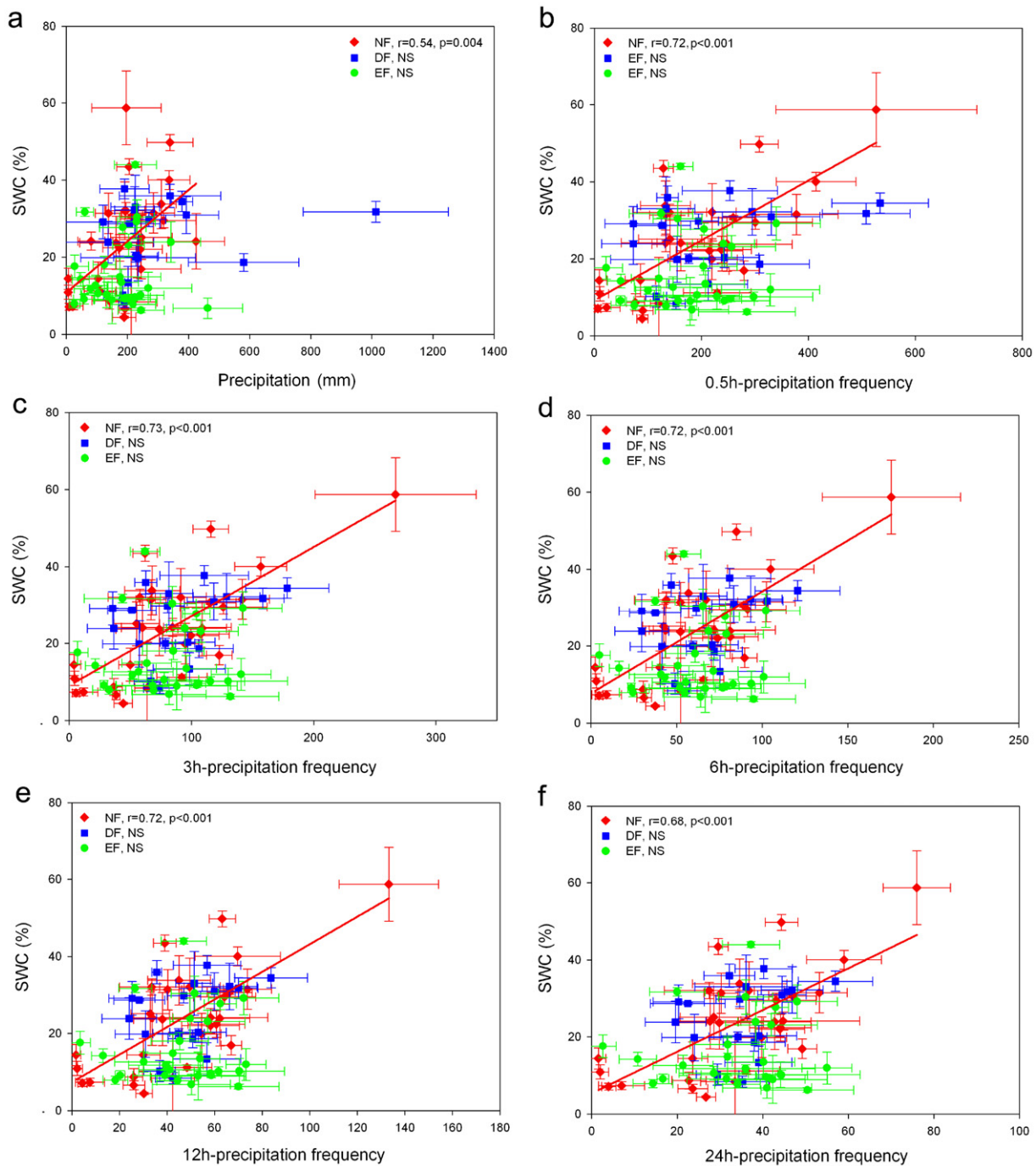
The interannual relationship between precipitation frequency and summer SWC differs from its spatial counterpart. Interannually, precipitation frequency was significantly correlated with SWC for all plant functional types. However, it was only for the non-forest sites that the precipitation frequency was found to be correlated with the SWC spatially. We used a year-to-year anomaly method to analyze the impact of precipitation frequency on interannual SWC variability. Therefore, the temporal relationship between precipitation frequency and SWC will not be affected by site specific soil properties (e.g., soil structures, chemical compositions, topography), which are vital for water holding capacity (Sowerby *et al* 2008, Ledger *et al* 2011). Hence, the impacts of precipitation frequency on interannual SWC variability will be more evident. When trying to interpret summer SWC spatially, on the contrary, these environmental forcing and soil characteristics are smoothed by averaging multi-year observations, which lead to equilibrium responses of SWC to the combined effects of covarying factors (e.g., climate, structure, species compositions). Therefore, no significant relationship was observed between summer SWC and precipitation frequency for forest ecosystems (both DF and EF sites). These differences potentially imply the important role of soil characteristics in regulating these correlations and challenges of trying to equate spatial and temporal SWC variability.



**Figure 3.** Relationships between interannual summer latent heat (LH) and the anomalies of (a) soil water content (SWC), (b) 0.5 h-precipitation frequency, (c) 3 h-precipitation frequency, (d) 6 h-precipitation frequency, (e) 12 h-precipitation frequency, and (f) 24 h-precipitation frequency for the seven Fluxnet-Canada representative sites (CA-GRA, CA-OAS, CA-OBS, CA-OJP, CA-Df49, CA-DF88 and CA-DF00).

A more complicated issue is the impact of plant functional type on the temporal–spatial relationships between precipitation frequency and summer SWC. Precipitation frequency can only explain the spatial patterns of summer SWC for non-forest ecosystems. We suggest that the different sensitivities of resisting drought influence non-forest and forest species is the main reason for these observations. Schwendenmann *et al* (2010) demonstrated that tree-based

systems may provide several mechanisms that can mitigate the impacts from extreme weather events such as drought. Light to moderate decrease in rainfall will not necessarily cause significant reduction in SWC as forests can extract water from deeper soil layers (Schume *et al* 2004). In contrast, non-forest ecosystems, e.g. grasslands and crops, are highly sensitive to drought and SWC may be more directly related to the availability of water. Such differences in sensitivity among



**Figure 4.** Spatial relationships between summer soil water content (SWC) and (a) precipitation quantity, (b) 0.5 h-precipitation frequency, (c) 3 h-precipitation frequency, (d) 6 h-precipitation frequency, (e) 12 h-precipitation frequency, and (f) 24 h-precipitation frequency. The NF (♦), DF (■) and EF (●) represent non-forests, deciduous forests and evergreen forests, respectively. The points represent data ( $\pm$ standard deviation) for each site. NS represents no significant correlation.

plant functional types to drought were also observed in the previous analysis of Schwalm *et al* (2010) where agricultural areas exhibited the highest sensitivity whereas the tropical region had minimal sensitivity to drought. Overall, these differences between non-forest and forest ecosystems can be attributed to the relative importance between water and other factors in regulating SWC temporally and spatially (Huxman *et al* 2004, Köchy 2008, Zha *et al* 2010). These results suggest that while interannual variability in summer SWC can

be better evaluated from precipitation frequencies, it seems problematic to model its spatial pattern based entirely on these indicators without factors accounting for soil characteristics, further implying the difficulties and challenges in interpreting summer drought globally.

There are several broad implications of this observed relationship between precipitation frequency and summer SWC. Precipitation frequency highlights the importance of precipitation patterns rather than the quantity alone in driving



ecological processes through soil water content (Weltzin *et al* 2003). It provides insights to improve the accuracy of ecosystem models that do not incorporate such mechanisms or considerations but intend to connect precipitation and soil moisture. The correlation between precipitation frequency and SWC holds the potential to bridge experimental results under manipulated precipitation patterns (e.g., equal precipitation quantity but differing in size and frequency) to natural settings, improving the role of precipitation variability (Knapp *et al* 2002). This method may provide a solution to analyze the temporal heterogeneity of precipitation that can lead to substantial differences in precipitation patterns even if the interannual summer precipitation totals are relatively stable. With the expected rates of longer and more severe periods of drought projected by climate change models, there is an urgent need for models and methods to mechanically link precipitation regimes and ecological processes. It is advisable that future models for the analysis of precipitation effects take precipitation frequency into consideration to improve the ability of climate models to predict quantitative ecosystem responses in future climate scenarios.

#### 4. Conclusions

Using long-term observations from multiple sites, we showed that the interannual variability in summer SWC at the regional scale was correlated with the precipitation quantity for each plant functional type. Spatially, the dynamic SWC pattern was also related to precipitation distribution, but this relationship was only observed in non-forest ecosystems. We also showed that interannual summer SWC is significantly correlated with several precipitation frequencies, which may have better potential than the precipitation quantity previously adopted. These results suggest that the role of precipitation frequency is probably underestimated, which may result from the difficulty in obtaining such information. With increased capability in data collection and processing, the pattern of precipitation should be considered in future ecosystem models to better link precipitation and ecosystem functioning. To the best of our knowledge, these analyses are first results for the impacts of precipitation frequency on summer SWC globally. Furthermore, we also showed the importance of the temporal resolution on which the precipitation frequency was based. While sub-daily precipitation frequencies better explain interannual summer SWC, our global analysis indicates that the precipitation frequency calculated at the daily temporal scale is not a good indicator of interannual summer SWC, and is even inferior to the summer precipitation quantity. These observations provide a feasible solution to better analyze interannual summer drought, especially considering the availability of precipitation forecasting data at the sub-daily temporal scale globally (e.g., NCEP, National Centers for Environmental Prediction).

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#### References

- Breshears D D *et al* 2005 Regional vegetation die-off in response to global-change-type drought *Proc. Natl Acad. Sci.* **105** 15144–8
- Ciais P *et al* 2005 Europe-wide reduction in primary productivity caused by the heat drought in 2003 *Nature* **437** 529–33
- Easterling D R, Meehl G A, Parmesan C, Changnon S A, Karl T R and Mearns L O 2000 Climate extremes: observations, modeling, and impacts *Science* **289** 2068–74
- Eltahir E A B 1998 A soil moisture–rainfall feedback mechanism. I. Theory and observations *Water Resour. Res.* **34** 765–76
- Fang J Y, Piao S, Zhou L M, He J S, Wei F Y, Myneni R B, Tucker C J and Tan K 2005 Precipitation patterns alter growth of temperate vegetation *Geophys. Res. Lett.* **32** L21411
- Fensharm R J, Fairfax R J and Ward D P 2009 Drought-induced tree death in savanna *Glob. Change Biol.* **15** 380–7
- Heisler-White J L, Knapp AK and Kelly E F 2008 Increasing precipitation event size increases above ground net primary productivity in a semi-arid grassland *Oecologia* **158** 129–40
- Hoffmann W A, Marchin R M, Abit P P and Lau O L 2011 Hydraulic failure and tree dieback are associated with high wood density in a temperate forest under extreme drought *Glob. Change Biol.* **17** 2731–42
- Huxman T E *et al* 2004 Convergence across biomes to a common rain-use efficiency *Nature* **429** 651–4
- Katul G G, Porporato A, Daly E, Oishi A C, Kim H S, Stoy P C, Juang J Y and Siqueira M B 2007 On the spectrum of soil moisture from hourly to interannual scales *Water Resour. Res.* **43** W05428
- Knapp A K, Fay P A, Blair J M, Collins S L, Smith M D, Carlisle J D, Harper C W, Danner B T, Lett M S and McCarron J K 2002 Rainfall variability, carbon cycling and plant species diversity in a mesic grassland *Science* **298** 2202–5
- Knapp A K *et al* 2008 Consequences of more extreme precipitation regimes for terrestrial ecosystems *Bioscience* **58** 811–21
- Köchy M 2008 Effects of simulated daily precipitation patterns on annual plant populations depend on life stage and climatic region *BMC Ecology* **8** 4
- Koster R D *et al* 2004 Regions of strong coupling between soil moisture and precipitation *Science* **305** 1138–40
- Ledger M E, Edwards F K, Brown L E, Milner A M and Woodward G 2011 Impact of simulated drought on ecosystem biomass production: an experimental test in stream mesocosms *Glob. Change Biol.* **17** 2288–97

- Li H, Robock A and Wild M 2007 Evaluation of intergovernmental panel on climate change fourth assessment soil moisture simulations for the second half of the twentieth century *J. Geophys. Res.* **112** D06106
- Mishra A K and Singh V P 2010 A review of drought concepts *J. Hydrol.* **391** 202–16
- Pan F, Peters-Lidard C D and Sale M J 2003 An analytical method for predicting surface soil moisture from rainfall observations *Water Resour. Res.* **39** 1314
- Peñuelas J *et al* 2007 Response of plant species richness and primary productivity in shrublands along a north–south gradient in Europe to seven years of experimental warming drought: reductions in primary productivity in the heat drought year of 2003 *Glob. Change Biol.* **13** 2563–81
- Phillips O L *et al* 2009 Drought sensitivity of the Amazon rainforest *Science* **323** 1344–7
- Piao S, Yin L, Wang X, Ciais P, Peng S, Shen Z and Seneviratne S I 2009 Summer soil moisture regulated by precipitation frequency in China *Environ. Res. Lett.* **4** 044012
- Ramanathan V, Crutzen P J, Kiehl J T and Rosenfeld D 2001 Aerosols, climate and the hydrological cycle *Science* **294** 2119–24
- Samanta A, Costa M H, Nunes E L, Vieira S A, Xu L and Myneni R B 2011 Comment on ‘Drought-induced reduction in global terrestrial net primary production from 2000 through 2009’ *Science* **333** 1093
- Schume H, Georg J and Herbert H 2004 Soil water depletion and recharge patterns in mixed and pure forest stands of European beech and Norway spruce *J. Hydrol.* **289** 258–74
- Schwalm C R *et al* 2010 Assimilation exceeds respiration sensitivity to drought: a FLUXNET synthesis *Glob. Change Biol.* **16** 657–70
- Schwendenmann L *et al* 2010 Effects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia *Glob. Change Biol.* **16** 1515–30
- Sowerby A, Emmett B A, Tietema A and Beier C 2008 Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils *Glob. Change Biol.* **14** 2388–404
- Weltzin J F *et al* 2003 Assessing the response of terrestrial ecosystems to potential changes in precipitation *Bioscience* **53** 941–52
- Yamaguchi M and Sharp R E 2010 Complexity and coordination of root growth at low water potentials: recent advances from transcriptomic and proteomic analyses *Plant, Cell Environ.* **33** 590–603
- Zha T, Barr A G, Kamp G, Black T A, McCaughey J H and Flanagan L B 2010 Interannual variation of evapotranspiration from forest and grassland ecosystems in western Canada in relation to drought *Agric. For. Meteorol.* **150** 1476–84
- Zhao M and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009 *Science* **329** 940–3