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Evaluating soil water storage distribution in a tempo-spatial domain with a new statistical model

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Time stability of soil water storage (SWS) was usually used to infer overall SWS distribution, assuming the spatial pattern of SWS was the same at different time. However, temporal change of SWS usually varies spatially, resulting in the changes of spatial pattern of SWS. In addition, controlling factors of SWS has been extensively explored. However, most of controlling factors are identified by their correlations to the spatial distribution of SWS, and few focused on the spatial distribution of temporal changes in SWS.
The objective of this study was to develop a statistical model which considers both time-invariant spatial pattern of SWS and spatial variability of temporal change in SWS. Specific attentions were given to (1) the controlling factors of the spatial structure of temporal change in SWS and (2) estimation and prediction of SWS distribution with the new model.
The model divides spatial SWS series into time-invariant spatial pattern, space-invariant temporal change, and space- and time-dependent redistribution term. The redistribution term is responsible for the temporal change in spatial pattern of SWS. Empirical orthogonal function was used to separate the total variations of redistribution term into the sum of product of spatial structures (EOFs) and temporally-varying coefficients (ECs). Model performance was evaluated using SWS data of 0-1.0 m layer from St. Denis National Wildlife Area at the Canadian Prairie (SDNWA) and LaoYeManQu watershed on the Chinese Loess Plateau (LYMQ).
Two significant EOFs (EOF1 and EOF2) were found in both areas, which explained 70.8% and 78.4%, respectively, of the total variations of redistribution terms. EOF1 resulted in more changes (recharge or discharge) of SWS at wetter locations, while the role of EOF2 varied with time irrespective of soil water conditions in both areas. The EOF1 of redistribution term was mainly controlled by depth to $CaCO_3$ layer, organic carbon content, and curvature in SDNWA and by silt content, total biomass yield, and organic carbon content in LYMQ. The weight of EOF1 was greater at more extreme soil water conditions, and EC1 was significantly linearly correlated with the spatial mean SWS. The roles of EOF1 resulted in more change (recharge or discharge) of SWS at wetter locations in both areas. The measured soil water storage distribution can be simulated very well by the model. If only EOF1 was considered, reasonable SWS distribution estimation with high NSCE values (from 0.77 to 0.98 in SDNWA, and from 0.95 to 0.99 in LYMQ) was obtained. With SWS measurement at the most time-stable location, mean SWS at unobserved date can be well predicted, with NSCE values from 0.69 to 0.79 in SDNWA and from 0.60 to 0.82 in LYMQ.
This model combined with time stability analysis showed a great potential in downscaling of soil moisture distribution in the landscape. The two study areas have drastically different soil, vegetation, climate, topography, and cultivation history. The good performance of this model in both areas may indicate its general applicability to most climatic regions, which need to be verified.