Northern Europe is typically characterized by wet conditions, where the total evaporation and transpiration (together, “evapotranspiration”) largely depend on atmospheric energy supply. Dirmeyer et al. (2021) report that in the hot and dry summer of 2018 evapotranspiration became water-limited such that decreased evaporative cooling amplified the heatwave temperatures. This way, drought magnitude increased beyond a critical point with consequent disruptions in ecosystem services.

The land surface provides essential ecosystem services for society. Soils and vegetation take up atmospheric CO$_2$ (Heimann & Reichstein, 2008), their moisture can attenuate wildfires (Forkel et al., 2019, O.S., Hou, et al., 2020), and their evaporative cooling can mitigate hot temperatures (Seneviratne et al., 2012). These services depend on the meteorological conditions; high radiation and low rainfall can induce water stress in ecosystems and consequently limit their services (Figure 1). In semiarid regions experiencing dry seasons such as Central North America and Southern Europe, the lack of water supply limits evapotranspiration, a condition known as water limitation (Mueller & Seneviratne, 2012). This is usually not the case for northern Europe, where normally wet and cloudy weather creates conditions where evaporation rates are limited by energy supply.

However, the 2018 summer drought introduced water-limited conditions to Great Britain and large parts of Northern Europe (Dirmeyer et al., 2021). Thereby, this region became a hot spot of land-atmosphere interactions; in addition to the prevailing impact of the meteorological conditions on soils and vegetation (atmosphere → land), soil moisture availability affected vegetation functioning and therefore evapotranspiration and the (near-surface) atmospheric moisture and energy budgets (land → atmosphere).

This process is reinforced through a positive feedback (Seneviratne et al., 2010; Teuling, 2018); decreasing evapotranspiration contributes to warmer temperatures which in turn increases the evaporative demand which further depletes the soil moisture. Also, the increased atmospheric dryness can hinder cloud formation (Teuling et al., 2017), leading to more incoming radiation, which also contributes to warmer temperatures. Moreover, this feedback loop can spread impacts in space by advection of drier air masses to neighboring regions (Schumacher et al., 2019), and in time through lagged recovery of the vegetation after severe water stress (Bastos et al., 2020).

Soil moisture is a key variable controlling the land-atmosphere coupling regime and its strength (Seneviratne et al., 2010). Dirmeyer et al. (2021) determine soil moisture thresholds across Europe, below which evaporative cooling becomes water-limited, enhancing peak temperatures. These thresholds vary in space, highlighting the role of vegetation and soil types in modulating land-atmosphere interactions (Denissen et al., 2020). While potential threshold variations in time, for example in response to land cover change, are yet to be investigated, their estimates can inform (near-)future forecasts and anticipation of record-breaking temperatures.

Estimating these thresholds from observation-based data sets (Denissen et al., 2020) is only possible in regions that have already entered a water-limited regime to reveal the underlying soil moisture. In other regions, we have to rely on (future) modeling experiments to provide such estimates. This requires an accurate representation of the land-atmosphere coupling, including the different processes shaping near-surface weather between energy- and water-limited conditions (Flach et al., 2018). Land surface models are imperfect in this respect (Best et al., 2015; Dirmeyer et al., 2018; O. S., Dutra, et al., 2020). Nevertheless, they are indispensable tools; particularly in view of ongoing climate change, which increases the occurrence probability of unprecedented conditions as in 2018. Modeling and forecasting should rely on physical laws rather than empirical relationships that might not be applicable under transient conditions (O. S., Dutra, et al., 2020). Continued model development that improves and expands the representation of relevant processes will further enhance their applicability (Balsamo et al., 2009; Lawrence et al., 2019; Thum et al., 2019).
The development of land surface models, and the understanding of relevant processes and interactions, is promoted by a growing suite of observational data (Balsamo et al., 2018). The benefits of jointly analyzing measurements and model simulations in this context are demonstrated by Dirmeyer et al. (2021); in situ measurements are limited in temporal and spatial coverage but represent ground truth and can be used to test how well models can represent the analyzed relationship and that their simulations can accordingly be employed to extend the analyses in time and space. Satellite and ground-based Earth observations of multiple variables are assimilated by models to yield high-quality reanalyses, as for example the ERA5 (Hersbach et al., 2020) used by Dirmeyer et al. (2021). Furthermore, machine learning is an emerging tool in Earth system science (Reichstein et al., 2019) to derive large-scale data sets of, for example, soil moisture (O. S. & Orth, 2021) or evapotranspiration (Jung et al., 2019) by establishing relationships between respective in situ observations and meteorological data which are then used for spatiotemporal extrapolation. Such
independent data-driven estimates can be used to validate and assess process-based models. In addition, within hybrid modeling setups, machine learning may be applied to assist models more directly through, for example, the estimation of parameter values in time and space.

The results of Dirmeyer et al. (2021) illustrate that hot spot regions of land-atmosphere coupling can occur in comparatively wet and cold climate in the case of extreme events. The strong coupling, which is well known to occur in semiarid regions (Koster et al., 2004), thereby shifts and extends to humid regions (Se neviratne et al., 2006). Such land-surface regime shifts may become more frequent and pronounced in the future (Dirmeyer et al., 2016); warming temperatures increase the evaporative demand which can lead to drier soils, independent of trends in precipitation. Overall, this highlights the key role of soils and vegetation for near-surface climate: while they might amplify the atmospheric climate change signal by intensifying hot extremes and the depletion of water resources (Orth & Destouni, 2018), smart management of them can alleviate changes at regional scales (Davin et al., 2014; Destouni et al., 2013; Teuling et al., 2010; Thiery et al., 2020).

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