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Key Points:

- The 2018 heatwave successively affected northern and central Europe, and temperature in Finland and northwest Russia broke historical record
- The moisture-temperature coupling was strong in central Europe, which was relatively weak in northern Europe during 2018 heatwave
- Land cover plays a critical role in determining the occurrence and strength of soil moisture-temperature coupling

Supporting Information:

Supporting Information S1

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Similarities and Differences in the Mechanisms Causing the European Summer Heatwaves in 2003, 2010, and 2018

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Abstract The mechanisms causing European heatwaves in recent years, particularly their differences among several heatwaves, are poorly understood. Here atmospheric circulation anomalies and soil moisture-temperature coupling during the summer 2018 heatwave are comprehensively examined and compared with the 2003 and 2010 heatwaves using ERA5 reanalysis, model simulations, and eddy covariance flux measurements. We show that the 2018 heatwave successively affected northern and central Europe, and the peak temperature in Finland and northwest Russia broke historical records of the past 40 years. Although three heatwaves were all initially triggered by atmospheric circulation anomalies, the strong moisture-temperature coupling were found to further strengthen the 2003 and 2010 heatwaves. This coupling was also strong in central Europe during 2018 heatwave, but was weak in the northern European center of the heatwaves. The high temperature in 2018 was mainly due to increases in the amount of net surface radiation caused by the clear skies associated with reduced precipitation. Furthermore, we also find that land cover plays a critical role in determining the occurrence and strength of soil moisture-temperature coupling. Cropland/grassland depletes soil moisture more readily than forests, thereby triggering a more rapid release of sensible fluxes as observed during 2018 heatwave.

Plain Language Summary In summer 2018, Europe was attacked by strong heatwave. This heatwave successively affected northern and central Europe, and temperature in Finland and northwest Russia broke historical records. Similar with heatwaves happened in 2003 and 2010, the 2018 heatwave was triggered by atmospheric circulation anomalies. However, different from the strong soil moisture-temperature coupling during 2003 and 2010 heatwaves, this coupling was relative weak in northern Europe during 2018 heatwave because of the relatively small soil moisture deficits.

1. Introduction

In recent years, droughts and associated heatwaves in Europe have caused widespread concern. The devastating heatwaves that struck Europe in 2003 and 2010 both had significant impacts on local natural and socioeconomic systems, including increasing numbers of wildfires and heat-related deaths, and water scarcity that reduced crop yields (Fischer & Schar, 2010; Schar et al., 2004; Seneviratne et al., 2006). In summer 2003, continuous record-breaking high temperatures caused ~70,000 heat-related deaths in western and central Europe. Gross primary productivity was estimated to have been reduced by 30%, coinciding with a large drop in grain yields (Ciais et al., 2005). The more severe 2010 heatwave exceeded the amplitude and spatial extent of the 2003 heatwave, particularly in eastern Europe and western Russia (Barriopedro et al., 2011). It caused ~55,000 deaths, reduced crop yields by ~25%, and led to ~US\$15 billion total economic loss (Peters et al., 2010). Increasing greenhouse gas concentrations are projected to not only shift temperature distribution to higher temperatures but also enhance the interannual variability of summer temperatures in Europe, and are expected to trigger more frequent, persistent, and severe droughts and heatwaves (Meehl & Tebaldi, 2004; Räisänen, 2002; Samaniego et al., 2018).

A number of studies have investigated the mechanisms that trigger European extreme heatwaves (García-Herrera et al., 2010; Horton et al., 2016; Lhotka et al., 2018; Miralles, Teuling, et al., 2014). Results generally indicate that atmospheric circulation anomalies and feedback between soil moisture and



air temperature through biophysical mechanisms are responsible for these heatwaves. Atmospheric circulation anomalies over northern Europe under heatwaves are often associated with omega blocking, which is usually caused by instability of the westerlies and low-pressure compression on one or both sides (Cassou et al., 2005; Rebetez et al., 2009). In addition, large-scale, high-pressure synoptic systems (anticyclones) with clear skies increase solar radiation and reduce heat advection, which are preconditions for heatwaves (Fischer et al., 2007; Miralles, Teuling, et al., 2014). Strong soil moisture-temperature coupling will further warm the air and prolong the duration of a heatwave (Miralles et al., 2012; Seneviratne et al., 2010). Warm atmospheric conditions increase evaporation, and thereby accelerate the depletion of soil moisture. The cooling effect of evaporation decreases when the soil moisture is low, leading to increases in sensible heat from the surface to the atmosphere. Fischer et al. (2007) reported that soil moisture-temperature coupling can amplify the summer extremes in Europe, which typically account for 50%–80% of the number of hot summer days, and thus prolong heatwave duration. Stéfanon et al. (2014) estimated that a reduction of soil moisture caused as much as 20% of the temperature anomaly in western Europe during heatwaves. Diurnal heat advection and nighttime heat generation promote the growth of the atmospheric boundary layer, which leads to a gradual accumulation of heat and enhances soil desiccation (Miralles et al., 2014).

In summer 2018, central Europe experienced the worst heatwave since 2003. This heatwave was caused by a combination of prolonged precipitation deficits and abnormally high temperatures beginning in May 2018 (Somini, 2018). Satellite images reveal a rapid shift of vegetation color from green to brown across central and northern Europe during the summer of 2018 (Liberto, 2018). The biomass accumulation from satellite observations has been found to reduce 15–25% even exceeding 25% locally (Toreti et al., 2019), implying strong impacts of the heatwave on the local ecosystem. Most of Europe was affected by this heatwave, but the effects were strongest in central and northern Europe, including Germany, Benelux, Italy, Spain, Sweden, and Finland (Vogel et al., 2019). This led to concern for the effects of the heatwave on agriculture, forests, pastures, and wildfires. Some studies have explored the potential attributions of this strong heatwave. The positive North Atlantic Oscillation and stationary Rossby wave-7 pattern were suggested to be responsible for the 2018 European heatwave (Drouard et al., 2019; Kornhuber et al., 2019). In addition, Vogel et al. (2019) argued that this extreme event could not have occurred without anthropogenic climate change. However, these studies do not take into account the effect of the land-atmosphere interactions during this extreme heatwave. In addition, how the spatiotemporal characteristics and cause of this heatwave differs from those of 2003 and 2010 is an important, yet unanswered question.

Using reanalysis data, model simulations, and in situ eddy covariance flux measurements, this study investigates the characteristics and mechanisms of the 2018 European heatwave in relation to those in 2003 and 2010. Two questions are addressed: (1) what are the spatial and temporal differences between the 2003, 2010, and 2018 heatwaves? and (2) whether these three heatwave events are driven by the same mechanisms or different magnitudes of the same mechanisms. If not, what are the differences?

2. Data and Methods

2.1. Data

The daily 2-m air temperature, surface energy (latent and sensible fluxes), soil moisture (0–7 cm), net surface radiation, and 500-hPa geopotential and sea level pressure data with a $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution for the period 1979–2018 were obtained from the ERA5 data set provided by the European Centre for Medium Range Weather Forecasts (https://cds.climate.copernicus.eu/cdsapp#!/data-set/reanalysis-era5-single-levels?tab= form). The climatic conditions from May to September when heatwaves usually occurred were analyzed in this study. We use air temperature at 12:00 UTC as a proxy of the maximum temperature of the day according to previous studies (Miralles, Gash, et al., 2014; Sinclair et al., 2019). Noted that the original kelvin (K) unit of temperature from ERA5 was converted to centigrade (°C) for the ease of reading. Other meteorological variables are daily means, which are calculated as an average of data at 00:00, 06:00, 12:00, and 18:00 UTC. The ERA5 data sets are the latest European Centre for Medium Range Weather Forecasts reanalysis and replace the ERA-Interim reanalysis, which has proved highly reliable for investigating climate change (Dole et al., 2011). The ERA5 data sets retain advances made in ERA-Interim's hydrological cycle, which improve the accuracy of heat flux and moisture estimates for the atmospheric boundary layer (Hersbach, 2016; Hersbach & Dee, 2016), which is, in turn, crucial for investigations of the physical mechanisms of heatwaves.

Gridded daily actual evaporation and potential evaporation data products with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ for 1979–2018 were retrieved from the Global Land-surface Evaporation: the Amsterdam Methodology version 3.3 data set (https://www.gleam.eu/#downloads). The Global Land-surface Evaporation: the Amsterdam Methodology v3.3 data set contains surface and root-zone soil moisture and various components of land evaporation, such as bare-soil evaporation, open-water evaporation, actual evaporation, and potential evaporation. Potential evaporation is calculated based on surface net radiation and near-surface air temperature from the latest reanalysis of ERA5 using the Priestley–Taylor equation (Martens et al., 2017; Miralles et al., 2011). Actual evaporation is calculated by combining estimates of potential evaporation and evaporative stress, which is simulated based on microwave vegetation optical depth and root-zone soil moisture.

We use the gridded daily gauge-based precipitation data set from the Climate Prediction Center (CPC; https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.global-precip.html) with $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution (1979–2018). The CPC data set integrates 30,000 daily gauge-based in situ measurements and satellite estimates into a comprehensive suite of precipitation products with high accuracy over the global land surface. The CPC data set better represents the spatial distribution patterns and temporal changes of rainfall than other similar gauge-based products (Xie et al., 2007; Xie et al., 2010).

The in situ eddy covariance flux measurements (latent and sensible fluxes) were obtained from the European Fluxes Database Cluster (http://www.europe-fluxdata.eu/home/data/request-data) and the Ministry of Education and Culture in Finland (https://avaa.tdata.fi/web/smart/smear/download). Data from nine flux towers were collected from the above two websites. For our analysis, we ultimately selected four flux tower sites (Figure S1 and Table S1 in the supporting information) with observations available for 2018 that were affected by the heatwave (Aubinet et al., 2001; Gilmanov et al., 2007; Kolari et al., 2007; Moureaux et al., 2006). These half-hourly data are quality-checked by the site PIs. Daily data are calculated as an average of the half-hourly data.

2.2. Methods

2.2.1. Heatwave Days

Several approaches have been proposed to define heatwave days (HWDs), but temperature is always an essential factor because of its near-ubiquitous measurements and its direct effects (Perkins, 2015). One popular definition is based on positive deviations from the 90% quantile of the climatological maximum temperature distribution (Lhotka & Kyselý, 2015). Another widely used definition comes from the World Meteorological Organization. HWDs were defined as a period when at least five consecutive days during which the daily maximum temperature exceeded the climatological mean over the reference period 1961–1990 by at least 5 K. These methods are both based on the local climatology and have been used to facilitate comparisons across locations and over time, even with large differences in the base temperature. In this study, we use the World Meteorological Organization's definition and redefine the reference period as 1978–2002, before the 2003 heatwave, using ERA5 2-m temperature data. Note that, because of a distinct warming trend in Europe, this modification to the reference period is expected to lead to fewer HWDs (Barriopedro et al., 2011; Teuling et al., 2010).

2.2.2. Climatological Means of Climate and Surface Energy Variables

To calculate anomalies in temperature, precipitation, soil moisture, surface energy fluxes, and 500-hPa geopotential and sea level pressure for a specific day, the climatological mean for the reference period is determined as follows: we first calculated the average for each day in the period 1978–2002, and then calculated a 31-day moving average, which is frequently used to calculate seasonal cycles of climatic variables (Barriopedro et al., 2011; Miralles, Teuling, et al., 2014; Miralles, Gash, et al., 2014), and is applied here to eliminate the effects of short-term weather variations.

2.2.3. Record-Breaking Temperatures

To identify where record-breaking temperatures occurred during an extreme summer, we use the same method as Barriopedro et al. (2011), which is as follows: (1) daily temperature anomalies were calculated by subtracting the climatological mean for a particular day of the year; (2) a running mean of daily temperature anomalies for a 31-day period was calculated, centered on each summer day from 1978 to the year before the extreme summer; (3) the historical maximum temperature for each grid point was obtained for all summer days from 1978 to the year before the extreme summer; and (4) a record-breaking point is



finally identified if the running temperature anomalies for a specific day in the extreme year surpass the corresponding historical maximum temperature. Above calculation steps are illustrated clearly in Figure S2. **2.2.4. Moisture-Temperature Coupling Metrics**

The strength of soil moisture-temperature coupling is assessed using the diagnostic π proposed by Miralles et al. (2012), which is calculated as follows:

$$\pi = e' \times T' \tag{1}$$

$$e' = (Rn - \lambda E)' - (Rn - \lambda Ep)'.$$
⁽²⁾

The primes represent daily anomalies of each variable expressed as the number of standard deviations relative to the climatological mean. *Rn*, *E*, *Ep*, and λ are the surface net radiation, actual evaporation, potential evaporation, and latent heat of vaporization, respectively. *T* is the daily temperature anomaly, λE indicated the latent fluxes, and *e* indicates the effect of soil moisture deficits on the energy balance. When soil moisture is sufficient to meet atmospheric demand, the actual evaporation equals the potential evaporation, and *e* is zero. As a soil moisture deficit gradually appears, the atmospheric demand increases and the actual evaporation decreases significantly, but the potential evaporation remains constant or changes slightly. Finally, *e* becomes positive and increasing. Hence, increases in *e* indicate a change in surface energy due to a lack of soil moisture. The temperature will rise abnormally when some latent fluxes convert into sensible fluxes, and then π will be enlarged.

3. Results and Discussion

3.1. Characteristics of Three Heatwaves

The spatial locations of the three heatwaves are evident in mean 10-day temperature anomaly maps covering the largest anomalous days (Figure 1, left column). To investigate the evolution of these heatwaves, the temporal variation of temperature anomalies at the center of each heatwave is shown in Figure 1 (right column). The heatwave centers were defined as areas where have experienced large positive temperature anomalies.

The largest temperature anomalies and most record-breaking points were observed in western Europe in summer 2003. France was the worst affected, with temperatures in most areas that broke historical records and a maximum summer temperature that reached 41.9 °C (Figures 1a and b and Table 1). France experienced four heatwave events during the summer of 2003, with a total of 31 HWDs. The longest event persisted for 12 days from 2 to 13 August when average temperature anomalies were 9.6 °C above the historical means. Compared with the 2003 heatwave, the 2010 heatwave had higher peak temperatures and a larger spatial extent (Figures 1c and d). Temperatures in eastern Europe and western Russia broke records. In the center of the heatwave, western Russia experienced four heatwave events with a summer total HWDs of 51, and a maximum summer temperature that reached 41.5 °C (Table 1). The longest heatwave occurred from 14 July to 18 August, lasting 36 days. This region experienced a temperature 13.4 °C higher than average for half the summer.

The 2018 heatwave successively affected northern and central Europe, with maximum temperature anomalies in both areas that exceeded the historical mean by ~8 °C (Figures 1e and f and Table 1). The heatwave first affected northern Europe, with northern Finland, Norway, and northwest Russia experiencing record-breaking temperatures. In Finland, the heatwave lasted from 9 July to 2 August (20 days), and the peak temperature reached 33.1 °C, which is extremely unusual for a region located near the Arctic Circle with an average summer temperature of 15 °C. This exceptional peak temperature broke historical records of the past 40 years. Given the warming trend in Europe since the twentieth century, even older records may be broken. This exceptional warming increased the mortality rate, especially in elderly people without air conditioning, and also led to wildfires, ice melt, and a surface energy cycle imbalance (Borton, 2018; Hickok, 2018). The heatwave subsequently affected central Europe. Germany experienced the heatwave from 23 July to 9 August (18 days), and a total HWDs of 21. Although temperature records in this region were not broken because of the more serious 2003 megaheatwave, the HWD was relatively concentrated and the heatwave lasted longer. This exceptional heatwave caused many nuclear power plants to shut down because the warm water in the river could not adequately cool the reactors (Vogel et al., 2019). The reduced oxygen levels in the warm river water also caused the death of many freshwater fish (Leistung, 2018). According to





Figure 1. Spatiotemporal evolution of summer temperature during three heatwave periods. (a) Mean 2-m temperature anomalies (relative to 1979–2002) during 2003 heatwave period (4–13 August). Black points indicate grids with record-breaking temperature, and the point size indicates exceedances of the historical maximum temperature. The blue polygon indicates the center of heatwave. (b) Evolution of temperature anomalies in France during summer 2003; HWDs are indicated by color shading. Vertical lines indicate the start and end of the heatwaves. (c) Same as in (a) but for 1–10 August. (d) Same as in (b) but for anomalies in Western Russia during summer 2010. (e) Same as in (a) but for 24 July to 2 August. (f) Same as in (b) but for anomalies in Finland and Germany during 2018 summer.

the German Farmer's Association, the harvest of rapeseed was down by 30% and grain down by 20% in 2018 (Grieshaber, 2018).

Although the average temperature anomaly during the 2018 heatwave was lower than that of the other two heatwave events, the persistent temperature anomaly, exceeding 5 °C, was enough to cause serious damage, particularly in northern Europe.

3.2. Possible Mechanisms

3.2.1. Anomalies in Atmospheric Circulation

Typically, positive sea level pressure anomalies indicate an anticyclone, which favors air subsidence, clear skies, and solar heating. When neighboring positive and negative Z500 anomalies occur together, omega

Table 1

Maximum Summer Temperature Over the Central Region of Three Megaheatwaves, and Mean 10-Day Temperature, Precipitation, Sensible, Latent, Net Radiation, and Soil Moisture Over the Central Region

Heatwave	Central region	Maximum TMP (°C)	TMP (°C)	July PRE (%)	August PRE (%)	Sensible (%)	Latent (%)	Net-Rad (%)	SM (%)
2003	France	41.9	9.6	-25.5	-53.8	43.5	-5.9	27.5	-33.6
2010	Russia	41.5	13.4	-61.2	-25.8	26.1	20.2	36.5	-41.2
2018	Germany	36.4	8.0	-41.5	-48.1	121.9	-11.8	31.0	-40.1
	Finland	33.1	7.6	-60.1	-44.9	75.1	8.0	28.8	-23.2
Mean		38.2	9.7	-47.1	-43.2	66.6	2.6	30.9	-34.5

Note. TMP, PRE, Net-Rad, and SM indicate the anomalies of temperature, precipitation, net radiation, and soil moisture, respectively.





Figure 2. Distribution of 10-day average 500-hPa geopotential and sea level pressure anomalies during three heatwave periods. Anomalies are relative to the climatological average for the period 1979–2002. (a and b) Data for the 2003 heatwave period (4–13 August). (c and d) Data for the 2010 heatwave period (1–10 August). (e and f) Data for the 2018 heatwave period (24 July to 2 August).

blocking will form, which reduces zonal flow and the advection of warm air (Lhotka et al., 2018; Sumner, 1954). During the three heatwaves, the locations of abnormal high pressure indicated by positive *Z*500 anomalies are spatially consistent with extreme temperature observations and positive sea level pressure anomalies (Figure 2). When high-pressure systems are slow moving or stationary, they restrict the progression of synoptic systems and change the jet stream direction (Barnes et al., 2012; Pfahl et al., 2015). The jet stream is a core of strong winds ~5–7 miles above the Northern Hemisphere that blows from the west to the east, regulates atmospheric circulation, and transports moisture (Woollings et al., 2010). When the jet stream is hindered, moisture transported in the atmosphere can decrease, resulting in less precipitation and water availability.

Thus, atmospheric circulation anomalies are confirmed to be the primary trigger of heatwave occurrence (Brunner et al., 2018). To investigate the mechanism underlying this relationship, Z500 and sea level pressure anomalies were assessed for 30-day periods prior to the three heatwave onsets. Before the 2003 heatwave, an abnormal high-pressure system (anticyclone) formed over northern Europe in mid-July, then gradually moved south, and finally, a blocking formed over France and Germany (Figure S3). By the first half of August, the western Europe was dominated by a persistent blocking pattern and an anticyclonic curvature (Black et al., 2004; Cassou et al., 2005). Before the 2010 heatwave, high-pressure built up roughly in mid-June and persisted for more than six weeks over eastern Europe (Schneidereit et al., 2012). It gradually became concentrated and elevated, finally forming an extreme high-pressure system (blocking) in August over western Russia (Figure S4). This long-lasting blocking has found to be related to the quasi-stationary Rossby waves, transients, and large-scale modes on different time scale (Dole et al., 2011). Before the 2018 heatwave, a stripped high-pressure system formed over northern Europe in late June, which was produced by the combination of the positive phase of the North Atlantic Oscillation and the Rossby wave-7 pattern (Drouard et al., 2019; Kornhuber et al., 2019). As a low-pressure system over the North Atlantic gradually moved south, squeezing the high-pressure system, and finally forming a blocking over northwest Europe (Figure S5). The abnormal high-pressure system initially formed over northern Europe, and then gradually expanded southward and affected central Europe. This is the reason Finland experienced the heatwave earlier than Germany.





Figure 3. Mean 10-day net radiation, soil moisture, and heat flux anomalies in Europe during three heatwave periods. Anomalies are relative to the climatological average for the period 1979–2002. (a–c) Surface net radiation anomalies. (d–f) Soil moisture (0–7 cm) percentage anomalies. (g–i) Latent flux anomalies. (j–l) Sensible flux anomalies. To highlight the effect of surface flux on temperature, (g)–(i) and (j)–(l) use opposite legend; red legends indicate positive contribution, and blue legends indicate negative contribution.

3.2.2. Regional Soil Moisture-Temperature Feedback

In addition to atmospheric circulation, soil moisture-temperature coupling also plays an important role in the occurrence of heatwaves, as soil moisture controls the partitioning of available surface energy between sensible and latent heat fluxes (Berg et al., 2014). Because the air subsidence caused by a high-pressure system is not conducive to the formation of precipitation, which was below the historical mean during and prior to the three heatwave periods (Figure S6). Over the central regions of the heatwaves, precipitation decreased by 26% (54%) and 61% (26%) relative to the historical mean in July (August) in 2003 and 2010 (Table 1), respectively. In the summer of 2018, total precipitation in central Europe was the lowest percentiles relative to the 1976–2005 distribution (Toreti et al., 2019); Germany and Finland experienced a reduction of precipitation of 42% (48%) and 60% (45%) in July (August), respectively. The clear skies associated with this reduced precipitation led to increases in the amount of net surface radiation, which means more energy poured into these regions. The largest increase of net radiation (37%) was observed in Russia in 2010, followed by Germany (31%) and Finland (29%) in 2018, and France (28%) in 2003 (Figures 3a–3c).

Precipitation reductions also directly decreased soil moisture (Figures 3d–3f). The spatial distributions of soil moisture deficits, precipitation deficits, and heatwaves are similar. Surface soil moisture (0–7 cm) deficits reached 34% and 41% at the center of 2003 and 2010 heatwaves, respectively. In the 2018 heatwave, we find that compared to Germany, which experienced large soil moisture deficits (40%), Finland had relatively small soil moisture deficits (23%) despite having more severe precipitation deficits. A potential reason for



Figure 4. Mean 10-day π anomalies in Europe during three heatwave periods. Anomalies indicated by the values of standard deviations (σ) are relative to the climatological average for the period 1979–2002. (a) Data for the 2003 heatwave period (4–13 August). (b) Data for the 2010 heatwave period (1–10 August). (c) Data for the 2018 heatwave period (24 July to 2 August).

this is that Finland is close to the Arctic, where annual average temperatures and evaporation are relatively low, and soil moisture is less prone to evaporation than at lower latitudes. Another possible explanation involves moisture supply from the snowmelt or the melting of permafrost (Harris et al., 2009; Payette et al., 2004; Virtanen et al., 2002) at high latitudes. In contrast, soil moisture in central Europe and western Russia is mainly supplemented by precipitation, and is more likely to be depleted during the periods of high temperature and increased solar radiation.

The changes in soil moisture and net radiation were accompanied by a shift in latent and sensible fluxes. During the 2003 heatwave, latent flux decreased by 6% in France (Figure 3g). To balance the increased net radiation and decreased latent flux, sensible flux significantly increased by 44%. In the 2010 heatwave, latent flux increased by 20% in western Russia, whereas sensible flux increased 26%. The increased latent flux seems to conflict with the observed large deficits of soil moisture (Figure 3c). We speculate that the potential reason is that the increased precipitation in August (Figure S6) enhanced the latent flux but could not compensate the continued decrease of soil moisture, because this heatwave is the longest lasting among three heatwaves. In the 2018 heatwave, because of different soil moisture conditions, latent flux in Germany decreased by 12% and sensible flux significantly increased by 122%, whereas latent and sensible fluxes in Finland increased by 8% and 75%, respectively. To highlight the change in the partitioning of surface energy, Bowen ratio defined as the ratio of sensible fluxes to latent fluxes was calculated (Figure S7). Large Bowen ratios were mainly observed in areas with strong soil moisture deficits during 2003 and 2018 heatwaves, implying a great influence of soil moisture on surface energy partitioning. However, low Bowen ratios were observed in the central region of 2010 heatwave which should be attributed to the enhanced precipitation in August.



Figure 5. Exchange of latent and sensible fluxes by land cover based on flux tower data in the central region of the 2018 heatwave. The site name and ecosystem type (bracket; IGBP class) are indicated below the histogram. The BE-Lon and BE-Vie sites are located in Belgium, and the DE-Gri and FL-Var sites are located in Germany and Finland, respectively.

To quantify effects of soil moisture-temperature coupling on heatwaves, we used the diagnostic π , described by Miralles et al. (2012). For the 2003 and 2010 heatwaves, there were widespread high values of π in regions with significant soil moisture deficits, particularly in France and southwest Russia (Figures 4a and 4b), indicating that soil moisture-temperature coupling was triggered and the deficit of soil moisture in these regions led to more sensible flux and increased temperatures. Noting that there are lower values of π in the northwest Russia than southwest Russia, the reason is that southwest Russia experienced a persistent soil moisture deficit, whereas northwest Russia experienced enhanced precipitation in August, which provided water to evaporation (Figure S6). Thus, extreme deficiency of soil moisture resulted in higher values of π in southwest Russia. During the 2018 heatwave, central and northern Europe had distinct π couplings. In the central region of the heatwave, northern Germany, which experienced severe soil dryness, had high π values, indicating a strong soil moisture-temperature coupling. In contrast, Finland had small π values because of the relatively small soil moisture deficits. This indicates that soil moisture-temperature coupling likely contributed only slightly to the extreme high temperatures in Finland in 2018. Increased warm-air advection and solar heating caused by the high-pressure system may be responsible for the high temperatures.

3.2.3. Differences in Energy Exchange Over Forests and Cropland/Grassland

Previous investigations have shown that land cover affects soil water content through evaporation and plays an important role in regulating surface energy and atmospheric water conditions (Joslin et al., 2000; Kauwe et al., 2019; Seneviratne et al., 2006). The vegetation in northern Europe and northern Russia is mainly forest, but in western and central Europe and northwest Russia it is mainly cropland (Figure S8). To investigate the differences in energy exchange over forests and cropland/grassland, we used flux tower data for the central region of the 2018 megaheatwave and analyzed changes in latent and sensible fluxes.

During the 2018 heatwave, the latent fluxes anomalies at grassland sites (DE-Gri in Germany; -1 W m^{-2}) and cropland sites (BE-Lon in Belgium; $+2 \text{ W m}^{-2}$) were relatively low (Figure 5). Vegetation over the two sites with shallow root profiles is vulnerable to soil moisture stress. This means that small reductions in soil moisture can restrict transpiration, and lead to an increase in sensible fluxes (Kauwe et al., 2019; van Heerwaarden & Teuling, 2014). When soil moisture is deficient, increased net surface radiation is primarily used to increase the sensible flux (+19 and +18 W m^{-2} , respectively). Thus, a heatwave would be amplified by significant increases in sensible fluxes and decreases in latent fluxes in these regions. At forest sites (FL-Var in Finland and BE-Vie in Belgium), deeper root profiles make the forest less susceptible to surface drying (Joslin et al., 2000; Vogt et al., 1995; Zeng, 2001), so latent flux still increases slightly (+7 and +13 W m⁻², respectively), but sensible heat flux greatly increases (+25 and +59 W m⁻², respectively) which should be attributed to the large increases in net radiation. The net radiation is defined as the difference between short-wave radiation (SW) and long-wave radiation (LW). Teuling et al. (2010) comprehensively investigated the surface heat fluxes during 2003 heatwave, and suggested that the net radiation is higher over forests than over grassland/cropland during heatwave due to similar downward SW, smaller upward SW, larger downward LW, and smaller upward LW over forest than grassland/cropland during the heatwave (Teuling et al., 2010). Above observations are also verified by ERA5 reanalysis data (Figures 3f, 3i, and 3l), which indicate the same lack of precipitation, severely deficient soil moisture at the DE-Gri and BE-Lon sites, and negative latent flux anomalies. Although the soil moisture at the FL-Var and BE-Vie sites was slightly deficient, latent flux was positive. Both in situ observations and reanalysis of heat fluxes during the 2018 suggest that cropland/grassland depletes soil moisture more readily than do forests, triggering a more rapid release of sensible fluxes of the former than the later. This allows forests to withstand heatwaves better than cropland/grassland, as was found in an investigation of the 2003 heatwave by Teuling et al. (2010). Therefore, differences in land cover may be another reason that heatwaves are more likely to occur in central Europe, eastern Europe, and western Russia (regions dominated by cropland/grassland) than in northern Europe and northern Russia. Under clear skies and high temperatures, cropland/grassland consumes soil water more readily than do forests.

4. Conclusions

This study compared the characteristics and possible mechanisms of three heatwaves in Europe with a highlight on 2018. The 2018 heatwave centered in the northern and central Europe in contrast with 2003 heatwave in the east and 2010 heatwave in the west. For the heatwaves in 2003, 2010, and 2018, atmospheric circulation anomalies caused by omega blocking and anticyclones are the primary reason for heatwave occurrence. We observed strong soil moisture-temperature coupling during the 2003 and 2010 heatwaves. This coupling was also strong in central Europe during 2018 heatwave, while was weak in northern Europe mainly due to the relatively small soil moisture deficits. We propose that land cover is another important reason for the difference in strengths of soil moisture-temperature coupling among three heatwaves. Regions dominated by croplands/grasslands lose soil moisture more readily than do forested regions, and thereby rapidly increase sensible fluxes.

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