Feedback attribution to dry heatwaves over East Asia

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Abstract

Summer heatwave events have exhibited increasing trends, with sudden increases occurring since the early 2000s over northeastern China and along the northern boundary of Mongolia. However, the mechanism behind heatwaves remains unexplored. To quantitatively examine the feedback attribution of concurrent events related to surface temperature anomalies, the coupled atmosphere–surface climate feedback-response analysis method based on the total energy balance within the atmosphere–surface column was applied. The results demonstrate that the contributions of the latent heat flux and surface dynamic processes served as positive feedback for surface warming by reducing the heat release from the surface to the atmosphere because of deficient soil moisture based on dry conditions. Cloud feedback also led to warm temperature anomalies through increasing solar insolation caused by decreasing cloud amounts associated with anomalous high-pressure systems. In contrast, the sensible heat flux played a role in reducing the warm temperature anomalies by the emission of heat from the surface. Atmospheric dynamic feedback led to cold anomalies. The influence of ozone, surface albedo, and water vapor processes is very weak. This study provides a better understanding of combined extreme climate events in the context of radiative and dynamic feedback processes.

1. Introduction

Extreme climatic events can occur simultaneously, exacerbating the associated environmental and societal impacts. Most analyses of climate and weather extremes tend to focus on a single climate event, such as heatwaves, droughts, floods, and storms. However, this univariate approach may underestimate the effects of concurrent and compound extremes.

The interaction and dependence between temperature and precipitation have been widely recognized (Hao et al. 2013, Shukla et al. 2014, Seo et al. 2018). Recent research suggests that combined precipitation and temperature effects may be more important than their respective individual effects (Trenberth et al. 2014). Several studies have focused on severe droughts that occurred corresponding to record-breaking temperature events in many regions, including Asia, Europe, India, and North America (Perkins et al. 2012, Mazdiyasni and AghaKouchak 2015, Zscheischler et al. 2018, Kong et al. 2020, Yu and Zhai 2020). For instance, Mazdiyasni and AghaKouchak (2015) reported no statistically significant trend in drought risk in the southern and western United States; however, the risk of simultaneous severe drought and heatwaves increased sharply. A study related to concurrent droughts and heatwaves over India also examined the substantial increase in the frequency of concurrent events and their spatial extent over India in recent years (Sharma and Mujumdar 2017). Over the past few decades, frequent heatwaves associated with severe drought and desertification trends during summer have been observed in northern China (Li et al. 2019b, Kong et al. 2020, Yu and Zhai 2020).

Previous studies have investigated the mechanisms of concurrent heatwave and drought events from the perspective of dynamical processes associated with large-scale atmospheric circulation. High-pressure anomalies are representative characteristics...
of most concurrent heatwave and drought events (Fischer et al 2007, Zampieri et al 2009); however, atmospheric circulation alone is not sufficient to explain the maintenance of compound events since concurrent heatwaves and droughts that are driven only by high-pressure systems occur on much shorter timescales, such as a span of few days. The monsoon climate of East Asia is a crucial factor in understanding extreme temperature and hydrological events over the region. Ding et al (2007) indicated that a significant weakening of the East Asian summer monsoon over the recent 20 year period was caused by a southward shift of the tropical upper-level easterly jet. This weakening caused northern and northeastern China to suffer from droughts, whereas the Yangtze River basin and southern China exhibited marked increases in precipitation. This implies that the large-scale atmospheric circulation and intrinsic regional climate characteristics provide favorable conditions for maintaining and strengthening hot and dry extreme events.

Even though anomalous anticyclonic circulation exists, land and atmosphere interactions are necessary for simultaneous heatwaves and droughts (Fischer et al 2007, Lorenz et al 2010, Whan et al 2015). The land–atmosphere feedback processes initiated by soil moisture anomalies can strongly modulate near-surface heat and aridity through high-pressure systems in the mid-troposphere (Miralles et al 2014, 2019, Wang et al 2019). Previous studies have indicated that dry soil conditions with persistent anticyclonic circulation would amplify soil moisture–atmosphere feedbacks in future climate change. Here we use the Coupled atmosphere–surface climate feedback-response analysis method (CFRAM) (Cai and Lu 2009, Lu and Cai 2009) to estimate quantitative contributions of individual radiative and dynamical processes including albedo, cloud, water vapor, ozone, sensible/latent heat flux, surface and atmospheric dynamics to the temperature changes related to dry heatwaves. The advantage of the CFRAM is that radiative and non-radiative processes can be decomposed. This methodology can help us gain a better understanding of the temperature anomaly sources. The CFRAM has been applied to quantify the relative contributions of radiative and dynamical feedbacks to the surface and atmospheric temperature anomalies associated with polar warming amplification (Taylor et al 2013), the Northern annular mode (Deng et al 2013), the Siberian high variability (Park et al 2015), the El Niño–Southern Oscillation (Park et al 2012, Hu et al 2016), and the East Asian winter monsoon variations (Li and Yang 2017). Their results show that the CFRAM is an efficient analysis to evaluate and understand which process is crucial for modulating surface and atmospheric temperature. Therefore, the goal of this study is to understand the key contributors among various feedback processes for the changes in concurrent heatwave-induced surface temperature anomalies using the CFRAM. We discuss the changes in surface temperature between strong and normal dry heatwave years attributed to individual feedback processes and examine the physical mechanisms for the features of dry heatwaves over East Asia.

2. Methods

We used daily 2 m air temperature data from the ERA-Interim reanalysis dataset (Dee et al 2011) for the heatwave definition. In this study, a heatwave event was defined as having temperatures exceeding the 90th percentile of the average daily temperature for the warm season for at least three consecutive days (Meehl and Tebaldi 2004, Perkins and Alexander 2013, Russo et al 2014). The 90th percentile is calculated as a single threshold for the total period, 7360 days for the 40 years from 1979 to 2018 (40 years × 184 days). We used the total heatwave days as the sum of heatwave days during the considered period, for each year. To detect drought events, monthly self-calibrating Palmer Drought Severity Index (scPDSI) data were obtained from the Climate Research Unit version 4.03 (Barichivich et al 2020). The scPDSI data for the global land surface (excluding Antarctica) spanned the 1901–2018 period at a monthly temporal resolution, with a spatial resolution of 0.5° × 0.5°. Concurrent extreme events were defined as heatwave events that occurred under simultaneously severely dry conditions. An instance of severely dry conditions is defined as scPDSI < −3.
To quantify the contributions of individual radiative and dynamical processes to the dry heatwave-related surface temperature changes, we used the CFRAM in this study. The CFRAM is a computationally efficient, off-line diagnostic tool that decomposes local temperature anomalies into partial temperature changes due to individual radiative and atmospheric dynamical feedback. To conduct the calculations in the CFRAM, the atmospheric/surface temperature, specific humidity, ozone mixing ratio, cloud amount, cloud liquid/ice water content, surface albedo, sensible/latent heat flux, surface pressure, surface net downward shortwave flux, and surface downwelling shortwave flux data were obtained from the ERA-Interim reanalysis datasets. These datasets are gridded with a standard 1.5° latitude × 1.5° longitude grid and 37 vertical levels ranging from 1000 to 1 hPa. This study focused on 40 years, spanning 1979–2018, during the warm season (May to October).

Solar insolation at the top of the atmosphere (TOA) \(I\), one of the input variables for the radiative transfer model (RTM), is calculated as:

\[
I = \left( \frac{R_0}{R_E} \right)^2 \frac{S_0}{\pi} \left( H \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin H \right),
\]

where \(S_0\) is the solar constant (1360.89 Wm\(^{-2}\)), \(\varphi\) is the latitude, \(\Delta\) is the solar declination angle \((-23.45^\circ \leq \delta \leq 23.45^\circ\), \(R_E\) is the distance of the Earth from the Sun, \(R_0\) is its annual mean, and \(H\) is the length of a half-day:

\[
H = \cos^{-1} (-\tan \varphi \tan \delta),
\]

\[
\delta = 23.45^\circ \times \sin \left( \frac{360^\circ - 365\times(n + 284)}{365} \right).
\]

Here, \(n\) is the day of the year, with \(n = 1\) for January 1 and \(n = 365\) for December 31. We also calculated the distance from the Earth to the Sun as:

\[
\left( \frac{R_0}{R_E} \right)^2 = \sum_{k=0}^{2} (a_k \cos kt + b_k \sin kt),
\]

where \(t = 2\pi d/365\), with \(d = 0\) for January 1 and \(d = 364\) for December 31. The coefficient for the calculation of the Sun–Earth distance is shown in table S1.

CFRAM was developed by Lu and Cai (2009) based on differences in the total energy balance within an atmosphere–surface column at a given horizontal location consisting of \(M\) atmospheric layers and a surface layer between two climate states. In this study, the two climate states denote the strong dry heatwave years and normal years. It can be written as:

\[
\Delta \frac{\partial E}{\partial t} = \Delta \bar{S} - \Delta \bar{R} + \Delta \bar{Q}_{\text{non-radiative}},
\]

where \(\Delta \frac{\partial E}{\partial t}\) is the change in energy storage, \(\bar{S}\) is the convergence of the shortwave radiation flux, \(\bar{R}\) is the divergence of the longwave radiation flux, and \(\bar{Q}_{\text{non-radiative}}\) is the vertical profile of the convergence of the total energy caused by turbulent, convective, and large-scale atmospheric motions. According to the linear approximation, the sum of the partial energy perturbations caused by individual radiative feedback processes can be expressed as:

\[
\Delta \bar{S} \approx \Delta \bar{S}^{(w)} + \Delta \bar{S}^{(c)} + \Delta \bar{S}^{(r)} + \Delta \bar{S}^{(O_3)},
\]

\[
\Delta \bar{R} \approx \Delta \bar{R}^{(w)} + \Delta \bar{R}^{(c)} + \Delta \bar{R}^{(O_3)} + \frac{\partial \bar{R}}{\partial T} \Delta \bar{T},
\]

\[
\Delta \bar{Q}_{\text{non-radiative}} = \Delta \bar{Q}^{(\text{SH})} + \Delta \bar{Q}^{(\text{LH})} + \Delta \bar{Q}^{(\text{atmos, dyn})} + \Delta \bar{Q}^{(\text{sf, dyn})},
\]

where \(w, c, r, O_3, \text{SH}, \text{LH}, \text{atmos, dyn},\) and \(\text{sf, dyn}\) represent water vapor, cloud, surface albedo, ozone, sensible heat flux, latent heat flux, atmospheric dynamics, and surface dynamics, respectively. The matrix \(\frac{\partial R}{\partial T}\) is equivalent to the Planck feedback parameter in the partial radiative perturbation method (Wetherald and Manabe 1988) but in a more general sense is obtained by including the vertical structure of radiative fluxes. In contrast, the Planck feedback parameter in Wetherald and Manabe (1988) is referred to as the radiative flux at the TOA. Substituting equations (6)–(8) into (5):

\[
\Delta \bar{T} = \left( \frac{\partial \bar{R}}{\partial T} \right)^{-1} \left\{ \Delta \left( \bar{S} - \bar{R} \right)^{(w)} + \Delta \left( \bar{S} - \bar{R} \right)^{(c)} + \Delta \left( \bar{S} - \bar{R} \right)^{(r)} + \Delta \bar{Q}^{(O_3)} + \Delta \bar{Q}^{(\text{SH})} + \Delta \bar{Q}^{(\text{LH})} + \Delta \bar{Q}^{(\text{atmos, dyn})} + \Delta \bar{Q}^{(\text{sf, dyn})} \right\}.
\]

We obtain equation (9), which denotes that the local temperature differences between two climate states can be decomposed into eight partial temperature differences. The local temperature differences between two climate states are expressed by the sum of the radiative energy input caused by different climate states and energy flux perturbations that are not caused by the radiation change associated with temperature changes. The radiative energy differences and the Planck feedback matrix are performed using the Fu-Liou RTM (Fu and Liou 1992). For more details, refer to Cai and Lu (2009), Lu and Cai (2009), and Park et al (2012).

3. Results

3.1. Relationship between heatwaves and drought conditions

Figure 1 shows the number of heatwave days, the drought index (scPDSI), and the number of concurrent events over East Asia during the warm
season. There are dominant areas in which heatwaves frequently occur in southeastern China, Korea, and Japan, and heatwave events have increased since the mid-1990s. The drought index exhibits a spatial pattern different from that of heatwaves, and the drought frequency is calculated using a drought index that represents severe and extremely dry conditions. Regions in which drought occurs most frequently include northeastern China and the northern boundary of Mongolia, whereas the East Asian summer monsoon regions have less frequent droughts. Longer-lasting droughts can have devastating effects. East Asia experienced prominent dry conditions for at least ten consecutive years during the 2000s (figure 1(e)). Heatwaves under dry conditions coincided with the spatial distribution of the drought index and these events were relatively rare before the late 1990s but have become more frequent since the early 2000s. Their time series were significantly correlated with the drought index \(r = -0.64\) and with heatwaves \(r = 0.71\). The linear trends of heatwaves represent the increase over most of East Asia, but they do not coincide with the spatial distribution of the total heatwave days. Despite the frequent occurrence of heatwaves over southern East Asia during the last 40 years, the linear trends represent a more slowly increasing pattern, whereas northern East Asia has exhibited rapidly increasing trends. The linear trends in the drought index and dry heatwaves show similar spatial patterns, with increasing trends over northern China. Therefore, the compound events are affected by the regional characteristics of dryness, but their frequency tends to be closely related to heatwave events. The results imply that compound events have occurred more frequently and significantly over East Asia, since the early 2000s.

To examine the co-variability of heatwaves and droughts, we performed a singular value decomposition (SVD) analysis of the total summer heatwave days and summer scPDSI (figure 2). The first SVD mode explained 57.5% of the total covariance, and the first spatial mode showed an increase in heatwaves and a decrease in scPDSI, indicating enhanced dry and extremely warm conditions over northern East Asia. Consistent with the spatial distribution of SVD1, the principal components (PCs) of the heatwaves are significantly correlated with scPDSI over East Asia \(r = 0.76\) and showed an increasing trend. The spatial patterns of the second mode of heatwaves showed a strong zonally elongated pattern along with central China, the Korean peninsula, and Japan, with 17.2% of the total covariance. The second SVD mode of scPDSI coincided with a heatwave; however, negative anomalies still occurred over northern East Asia. The second PC time series captured a sudden increase since the early 2000s and the time coefficients of both fields are closely correlated, with a 0.79 correlation coefficient. This denotes that
the heatwave events have since tended to increase, and the variability of scPDSI indicated well-organized dry conditions over northeastern East Asia, suggesting favorable conditions for simultaneous heatwaves and droughts.

To understand and evaluate the relative contributions of the various radiative and dynamical feedback processes during the strong concurrent heatwaves and droughts, we used scatterplots to select years involving the two climatic states (figure 3). We contrasted the composite strong concurrent state with normal years, as defined below, in the warm season and obtained a process-resolving decomposition of the heatwave-related temperature anomalies according to equation (9). We identified the strong (weak) years as those in which the normalized heatwave was higher (lower) than 0.5, and the scPDSI was lower (higher) than $-0.5$ simultaneously; the normal years were selected by excluding the strong and weak years. Following these criteria, a total of 7 (5), strong (weak), years, and 28 normal years were identified for the period 1979–2018 and were used to construct the composites (figures 3 and S1 (available online at stacks.iop.org/ERL/16/064003/mmedia)). All the strong years have existed since the 2000s, as shown in figure 1. We also adopted the 2 m air temperature and precipitation or soil moisture data instead of the heatwave index and scPDSI (figures 3(b) and (c)). Although the data in some years were out of range, they showed a distribution, approximately similar to that of the indices.

3.2. Partial temperature anomalies related to feedback processes
To validate the performance of the CFRAM, the surface and atmospheric temperature anomalies derived from the ERA-Interim dataset during the strong years and the sum of the CFRAM-derived partial temperature changes at the surface, 0.8-sigma, 0.7-sigma, 0.5-sigma, and 0.2-sigma levels are shown in figure S2. The spatial structure and magnitude of the two fields were highly similar. A strong warm-core was
Figure 3. Scatter diagram between (a) the normalized anomaly of heatwave days (HWD) and scPDSI, (b) the normalized anomaly of precipitation and temperature, and (c) the normalized anomaly of soil moisture and temperature in MJJASO over East Asia (95°E–135°E, 20°N–55°N). Red, blue, and black numbers indicate strong, weak, and normal years for dry heatwaves over East Asia.

found over East Asia at the surface and in the mid-troposphere. In the lower stratosphere, cold temperature anomalies existed, and a clear baroclinic structure was present over East Asia in both the reanalysis data and in the CFRAM-derived temperature anomalies. Therefore, the CFRAM performed reasonably well in reproducing the heatwave-related temperature anomaly fields directly derived from the ERA-Interim data.

In general, the term ‘forcing’ is defined as an energy input to the system; ‘response’ and ‘feedback’ are defined as the output of the system and an induced input from the output, respectively. In using CFRAM for climate model feedback analysis, ‘forcing’ is defined as an external perturbation profile in the atmosphere–surface column, ‘response’ is defined as a vertically varying atmosphere–surface temperature profile, and ‘feedback’ is defined as any energy flux perturbations that are not directly caused by the long-wave radiation change caused by temperature changes (Lu and Cai 2009).

From this perspective, the partial temperature changes caused by the eight radiative and non-radiative feedback processes obtained through CFRAM are presented in figure 4. Warm temperature changes related to clouds, latent heat flux, and surface dynamics affected the total temperature changes (figures 4(e), (g), and (h)). In particular, cloud feedback was the main driver of warm temperature anomalies; it is affected by radiative energy flux perturbations caused by changes in the cloud amounts and cloud liquid/ice water content (figure 4(e)). Reduced cloud amounts accompanied by anticyclonic circulation affected the insolation over East Asia and modulated the warm surface. The latent heat flux was caused by changes in the surface latent heat flux from the surface to the atmosphere associated with evaporation or transpiration of water at the land surface (figure 4(g)). As heatwaves occur under drought conditions, the land has less soil moisture than it had in normal states (figure 5(d)). Therefore, a reduced latent heat flux leads to less heat release through less evaporation or transpiration from the surface to the atmosphere and contributes to the increasing temperature at the surface.

Surface dynamic processes are induced by energy perturbations at the surface caused by changes in soil heat diffusion, heat storage anomalies, and surface turbulent sensible/lateral heat flux anomalies (figure 4(h)). The majority of the surface dynamic feedback can be explained by the sensible and latent heat flux, and soil moisture might contribute to the formation of temperature anomalies. While the sensible heat flux and atmospheric dynamic feedback produced a cooling effect over the concurrent heatwave regions (figures 4(f) and (i)), the effects of the sensible heat flux indicated signs opposite to those of the latent heat flux. As the emission of the sensible heat increases from the warm surface, the effects of the sensible heat feedback act toward cooling the surface temperature. These feedback processes partially counteract the effects of warm temperatures (figure 4(f)). The total contribution of sensible and latent heat flux to surface temperature change is surface cooling in most dry heatwave regions (figure S3). It notes that the sensible heat flux effect is larger than that of latent heat flux. It also implies that surface dynamics due to horizontal heat diffusion in the soil and heat storage anomalies, provide localized temperature anomalies of warming over the dry heatwave regions. Atmospheric dynamic processes are the terms of the energy perturbations caused by changes in large-scale atmospheric motions (figure 4(i)). These terms are linked to the distribution of atmospheric pressure, temperature advection, and wind. The partial temperature changes caused by ozone, water vapor, and albedo feedback were weak (figures 4(b)–(d)).

3.3. Possible causes of concurrent heatwave-related temperature anomalies

To examine the possible causes of the heatwave-related partial temperature changes, we investigated
Figure 4. (a) Total temperature anomalies (K) and CFRAM-derived partial temperature changes due to (b) ozone feedback, (c) water vapor feedback, (d) surface albedo feedback, (e) cloud feedback, (f) sensible heat flux change, (g) latent heat flux change, (h) surface dynamics, and (i) atmospheric dynamics in composite concurrent heatwave summer. Dotted regions indicate the area where the number of concurrent heatwave days is more than 2 d yr$^{-1}$ in figure 1(c).

Figure 5. Differences of (a) surface temperature (K) (shading) and total precipitation (mm) (contour), (b) geopotential height at 500 hPa (m) (shading) and cloud amount (contour), (c) latent (shading) and sensible heat flux (contour) (W m$^{-2}$), and (d) soil moisture (m$^3$/m$^3$) (shading) and evaporation (mm) (contour) between strong and normal years of concurrent heatwave summer (MJJASO).

The differences in the surface temperature, total precipitation, geopotential height at 500 hPa, cloud amounts, latent and sensible heat flux, soil moisture, and vapor pressure deficit between the strong and normal years of heatwaves and droughts during the warm seasons (figure 5). Over East Asia, the observed areas of warm temperature anomalies and dry conditions were consistent with the area of anticyclonic
flow with positive anomalous geopotential height (figures 5(a) and (b)). The enhanced anticyclonic anomalies induced sinking motion, contributing to a decrease in precipitation during the warm seasons (figure 5(a)). Dry surface conditions caused by less precipitation reinforced the warm anomalies, thereby acting as a positive feedback to maintain dry conditions and intensify the warm states at the surface. Moreover, the positive geopotential height anomalies reduced the cloud cover, resulting in more solar insol-ation (figure 5(b)). Negative cloud amounts provided additional warming in the East Asia domain via the associated increase in solar insololation (Ha et al 2020). Related to cloud feedback, the surface response could re-intensify the anomalous atmospheric conditions, thereby providing positive partial temperature changes.

The differences in the sensible and latent heat fluxes showed signs opposed to those of the partial temperature changes. Sensible heat flux works effectively to release heat from the surface to the atmosphere, whereas turbulent latent heat flux transports less heat from the surface (figure 5(c)). Warm temperature anomalies lead to enhanced transpiration from the available soil moisture, albeit with a lower total surface latent heat flux, and, hence, to a parched surface. It strongly reduces latent cooling and thereby has substantial impacts on the amplitude of extreme temperatures (Perkins et al 2012, Seneviratne et al 2014). Therefore, a positive sensible heat flux change leads to a more conductive heat release from the surface to the atmosphere, resulting in cooling at the surface. In contrast, a positive latent heat flux change indicates that the turbulent latent heat is trapped in the surface, and they contribute to a warmer surface.

The negative anomalies of the soil moisture matched well with the warm surface temperature (figure 5(d)). There was also a general agreement between the soil moisture exchange and evaporation. As mentioned previously, soil moisture contributes to latent/sensible heat flux processes and surface dynamic feedback and has thus been emphasized in many heatwave and drought studies (Miralles et al 2014, Whan et al 2015, Wang et al 2019, Zhang et al 2019, 2020, Choi et al 2020). Soil deficits restricted surface evaporation and generated conditions favorable for sensible heat fluxes to the atmosphere, whereas latent heat flux tended to have an opposite response. These processes offered drier conditions with negative evaporation at the surface, which indicated the critical roles of land–atmosphere interactions through soil moisture in the positive feedback of atmospheric circulation, surface warming, and soil dryness.

4. Conclusion and discussion

The combined effects of high temperatures and low precipitation could significantly affect ecosystems and human society, even if individual events may not result in extreme conditions. This study focused on the features of concurrent heatwaves and droughts over East Asia. Our results indicate that the frequency of concurrent heatwaves and droughts has increased in most parts of East Asia, especially in northeastern China and along the northern boundary of Mongolia. The spatial distribution was similar to that delineated by the drought index, but the frequency of occurrence was primarily correlated to the heatwave events alone. Concurrent events have tended to increase since the early 2000s. The first two principal modes of the heatwave and drought index also showed increasing trends over northeastern China after the early 2000s. In particular, the second mode of heatwaves and scPDSI supported an abrupt increase in the PC time series.

We also demonstrated the feedback attribution from individual radiative and dynamical feedback processes to surface temperature anomalies associated with concurrent heatwaves and droughts. We applied CFRAM to decompose these variables into eight partial temperature changes, including ozone, water vapor, albedo, cloud, sensible latent heat flux, latent heat flux, surface dynamics, and atmospheric dynamics. It was found that the latent heat flux, cloud cover, and surface dynamics provide a warming effect on the surface temperature anomalies related to intense heatwaves and drought events. The cloud feedback led to increasing solar insolation at the surface, which directly affected the formation of warm surface temperatures. High-pressure systems and dry air conditions are related to the decrease in cloud cover, adding cloud-induced warming to the total warm temperature change. The latent heat flux provided the most substantial warming effect on the surface temperature anomalies as a reduction of the heat released from the surface to the atmosphere; this implies that soil moisture attribu-tions are important. This feedback effect accounted for most of the surface dynamic processes. In contrast, the sensible heat flux and atmospheric dynamic processes play a role in reducing warm temperature anomalies.

This study provides a better understanding of combined extreme climate events in the context of radiative and dynamic feedback processes. It has been suggested that heatwaves and droughts intensify and propagate via land–atmosphere feedback; however, knowledge about the initiation and evolution of heatwaves and droughts remains limited. In addition, soil moisture deficit closely related to vegetation changes, and it could bring the decrease of absorption of solar radiation through the albedo effects. Further research associated with how net radiation consid-ering longwave radiation flux affects surface heating should be able to help this issue. Land–atmosphere interactions could be key to resolving the unrevealed problems about the generation of these concurrent
extreme climate events, and these interactions should be explored further in future research.

Data availability

The drought index used in this study, scPDSI, is available from the Climatic Research Unit server: https://crudata.uea.ac.uk/cru/data/drought/. The data that support the findings of this study are openly available at the following URL/DOI: http://apps.ecmwf.int/datasets/.

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