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Dynamics and characteristics of compound heatwaves over Asia

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सार – पूर्वी एशिया (EA) में लू की बढ़ती आवृत्ति कृषि, जल प्रबंधन और लोगों की आजीविका को प्रभावित करती है। हाल के वर्षों में, लू की रिकॉर्ड-तोड़ घटनाएँ हुई हैं जिससे अत्यधिक सूखे की आवृत्ति में वृद्धि हुई है। पूर्वी एशिया (EA) में लू की दो प्रमुख प्रणाली शुष्क परिस्थितियों से निकटता से संबंधित हैं, लेकिन उनके अस्थायी विकास कुछ अलग हैं। लू की पहलीप्रमुख प्रणाली पूर्वी एशिया (EA) के उत्तरी भाग में दिखाई देती है, जो ग्रीष्म के आरंभ में शुरू होती है और पूरे ग्रीष्म काल तक चलती है। लू की दूसरी प्रणाली मध्य चीन और कोरिया में होती है और ग्रीष्म के बाद की अवधि में नकारात्मक वर्षा विसंगतियों से निकटता से संबंधित होती है और यह जुलाई या अगस्त में शुरू होती है। इस अध्ययन में युग्मित वायु-सतह जलवायु प्रतिक्रिया-प्रतिक्रिया विश्लेषण (CFRAM) का उपयोग करके लू से संबंधित सतह के तापमान विसंगतियों की मात्रात्मक प्रतिक्रिया की जांच की गई है। लू की पहली प्रणाली से संबंधित उष्णता विसंगतियों को आमतौर पर बादल, गुप्त उष्मा और सतह की गत्यात्मक प्रक्रियाओं द्वारा नियंत्रित किया जाता है। अत्यधिक शुष्क परिस्थितियों में मृदा की नमी की कमी के कारण सतह से वायुमंडल में उष्णता को कम करके इसकी व्याख्या की जा सकती है। जबकि लू की दूसरी प्रणाली से संबंधित सतह के उष्ण होने में बादलों की प्रतिक्रिया और वायुमंडलीय गतिशील प्रक्रिया का योगदानहोता है। प्रतिचक्रवातीय परिसंचरण विसंगतियों से जुड़े बादल क्षेत्र में कमी से सूर्यताप में वृद्धि होती है और यह सतह की उष्णता को प्रभावित करता है। हालाँकि, उच्च तापमान की घटनाओं पर आर्द्रता के प्रभाव का अभी तक पूरी तरह से पता नहीं चला है। इस प्रकार, इस अध्ययन में संयुक्त रूप से लू की पहचान की गई है जो सापेक्ष आर्द्रता की स्थिति के साथ वर्णित हैं और युग्मित मॉडल इंटरकंपेरिसन प्रोजेक्ट (CMIP6) मॉडल सिमुलेशन के चरण छह का उपयोग करके पूर्वी एशियामें दो प्रकार के लू के भावी अनुमानों का सुझाव दिया गया है। CMIP6 मॉडल ने ग्रीनहाउस गैस सांद्रता में अनुमानित वृद्धि के जवाब में शुष्क लू की तीव्रता और नम लू के दिनों में वृद्धि का अनुमान लगाया है।

ABSTRACT. The increasing frequency of heatwaves in East Asia (EA) affects agriculture, water management and people's livelihoods. In recent years, record-breaking heatwaves have occurred corresponding to extreme drought and are increasing in frequency. The two leading modes of heatwaves over EA are closely related to dry conditions, but their temporal developments are somewhat different. The first major mode of heatwaves appears over northern EA, starting in early summer and lasting throughout the summer. The second mode of heatwaves occurs over central China and Korea and is closely related to negative precipitation anomalies during late summer and starts in July or August. This study investigated the quantitative feedback attribution of heatwave-related surface temperature anomalies using the coupled air-surface climate feedback-response analysis (CFRAM). The warming anomalies related to the first mode of heatwaves are usually controlled by cloud, latent heat and surface dynamics processes. It can be explained by reducing heat release from the surface to the atmosphere due to the lack of soil moisture under severe dry conditions. While surface warming related to the second mode of heatwaves is contributed by cloud feedback and atmospheric dynamic process. Reduction in cloud area associated with anticyclonic circulation anomalies induces increased insolation and it affects surface warming. However, the effect of humidity on high-temperature events has not yet been fully explored. Thus, this study identified compound heatwaves that are described simultaneously with relative humidity conditions and suggested the future projections of two types of heatwaves over EA using phase six of the Coupled Model Intercomparison Project (CMIP6) model simulation. CMIP6 models projected intensification of dry heatwaves and increased moist heatwave days in response to projected increases in greenhouse gas concentrations.

Key words – Heatwave, Feedback attribution, CFRAM, East Asia, Compound heatwave.

1. Introduction

The combined effects of high temperature and low precipitation can have significant impacts on ecosystems and human societies, even if individual events do not result in extreme conditions. This is because multiple stressors can more quickly exceed a system's ability to cope. In general, compound extreme events are defined as more than two events that impact societal and environmental damage occur simultaneously. Despite the importance of compound extreme events, East Asia has received little attention in the study of compound extreme events. In particular, compound heatwaves defined as combined extreme hot events with drought events are the most typical compound events that have attracted increased attention. Recently, record-breaking extreme heat events following severe droughts are frequently reported. Europe is extensively and frequently threatened by compound thermal events (Agha Kouchak *et al*., 2014; Hao *et al*., 2018; Russo *et al*., 2019). In Africa, increasing trends for summer drought and heatwaves have been observed and projected (Lyon, 2009; Engdaw *et al*., 2022). A significant increase in compound heat events has been highlighted in the United States (Albright *et al*., 2010; Mazdiyasni and Kouchak, 2015). Moreover, exacerbated compound heat events have been investigated in some regions in China (Kong *et al*., 2020; Li *et al*., 2019; Luo and Lau, 2017). Due to this lack of understanding of compound extreme events, there are considerable uncertainties in predicting extreme events.

In most previous studies, they have investigated compound extreme heat events with precipitation values such as anomalies (Hao *et al.*, 2018), Standardized Precipitation Index (Kong *et al*., 2020; Mazdiyasni and Kouchak, 2015) and precipitation deficit (Lu *et al*., 2018). It is reasonable to expect that a negative correlation between temperature and precipitation could lead to a positive association between the occurrences of heatwaves and droughts (Zscheischler *et al*., 2018). In addition, the co-occurrence of drought and heatwave may intensify the magnitude of individual risks through soil moisture-atmosphere coupling (Shukla *et al*., 2014). High temperatures can exacerbate drought severity by significantly increasing evaporation (Dai, 2013). A dry surface favors more sensible heating of the atmosphere and consequently higher temperatures (Greve *et al*., 2014; Mueller and Seneviratne, 2012; Seneviratne *et al*., 2006). Understanding the drought-heatwave relationship is necessary to estimate the risk of co-occurrence-related impacts. In addition, identifying hotspots and detecting temporal changes in a compound heatwave and drought is important for responding to adverse effects and developing adaption strategies.

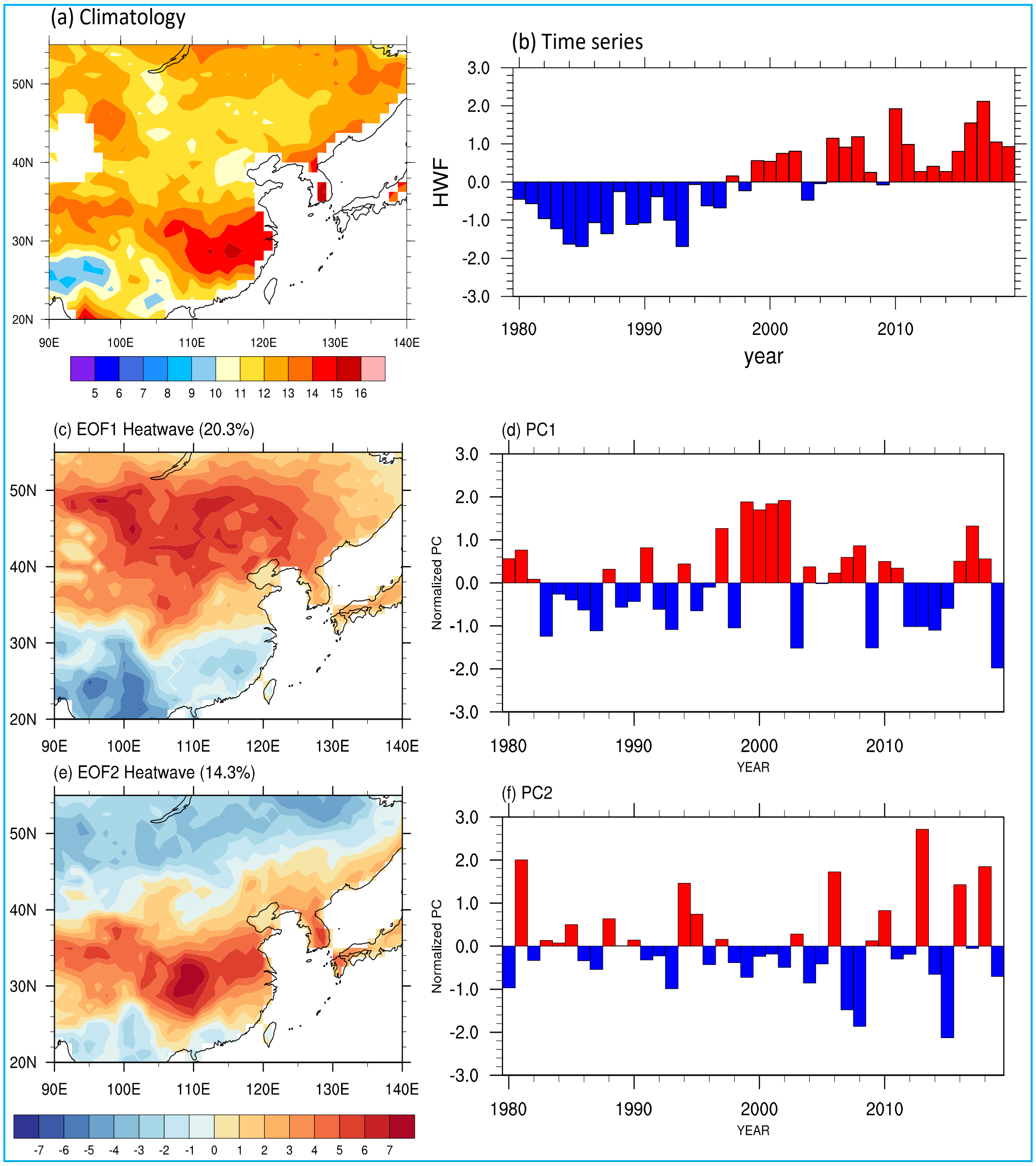
Here, we examined the major leading modes of heatwaves over East Asia and their temporal evolutions. Then we reviewed and identified the compound heatwaves related to drought and quantified the feedback attributions of compound heatwaves related to surface temperature anomalies. Moreover, compound heatwaves are described simultaneously with relative humidity conditions over East Asia and their future projection from phase six of the Coupled Model Intercomparison Project (CMIP6).

2. Heatwaves over East Asia

A heatwave is a prolonged period of sustained hot weather compared to the expected temperature in the area for that day. Many previous studies have defined heat waves using percentile thresholds, such as the 90th or the 95th percentiles of the climatological temperature values. Similarly in this study, the heatwave is defined as the temperatures exceeding the 90th percentile of the daily mean temperature during the warm season (May to October) for at least three consecutive days. The 90th percentile is calculated as a single threshold for the entire period from 1980 to 2019. To characterize the heatwaves, we identified the total number of heatwaves per year. Meso-scale heatwave analysis through downscaling is also one method to investigate the localization of heatwaves, but in this study, we used the reanalysis datasets and CMIP6 model simulations to eliminate the simulation-based biases.

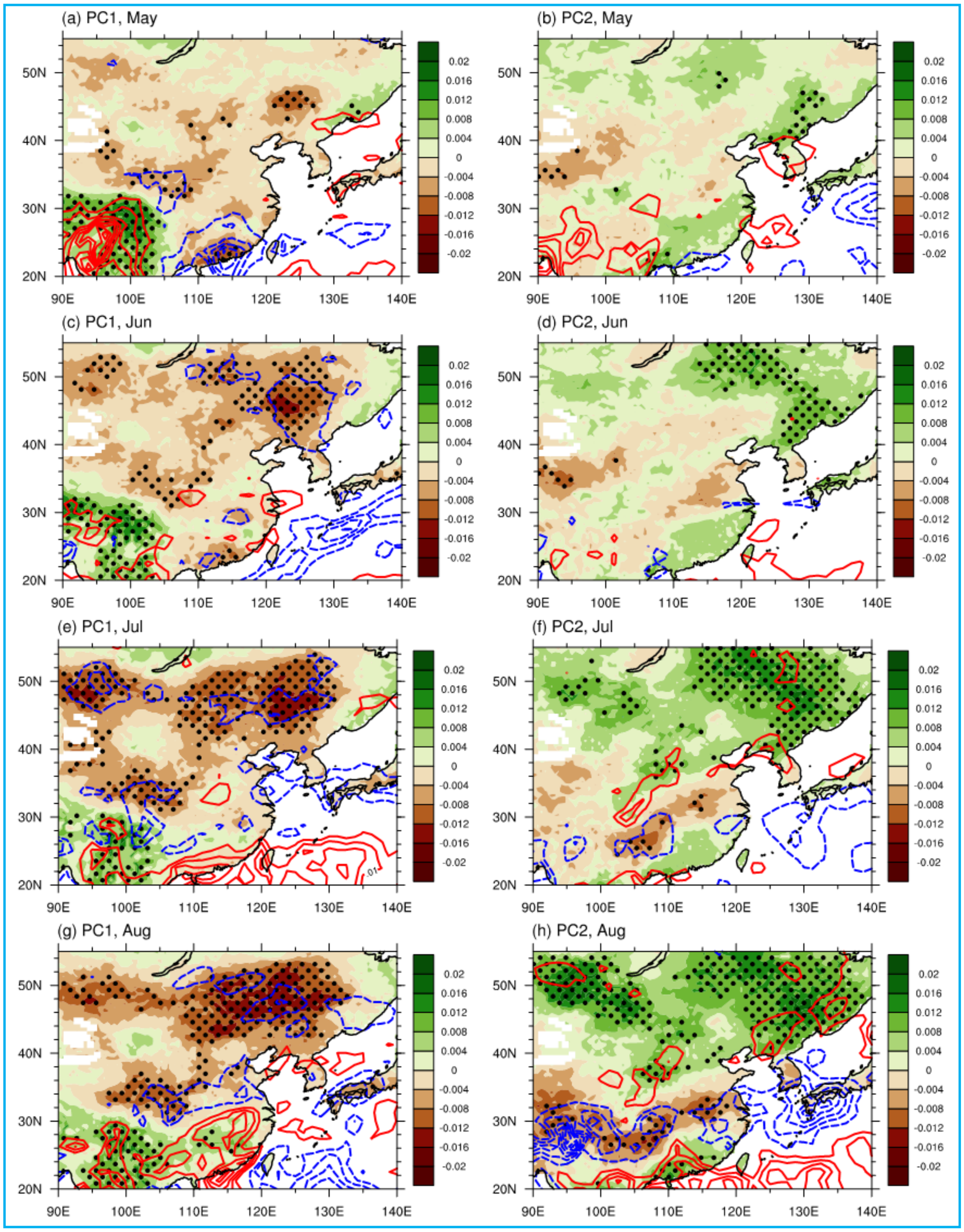
Fig. 1(a) shows the climatology of heatwave days during the period from 1980 to 2019. The heatwaves typically occur more than 10 days per year over East Asia. It happened most frequently in southeastern China. The heatwaves gradually increase with global warming [Fig. 1(b)]. Similar results were obtained when the daily maximum temperature was used instead of the daily mean temperature to define the heatwaves (not shown). Therefore, the characteristics of dry and moist heatwaves are not highly sensitive to whether the daily maximum or daily mean temperature is used to determine heatwaves. This increasing trend has been reported in many previous studies. The frequency and intensity of recent heatwaves have increased globally (Perkins-Kirkpatrick and Lewis, 2020; Russo *et al*., 2014), particularly in Europe (Rousi *et al*., 2022), Asia (Rohini *et al*., 2016; Ha *et al*., 2020, 2022) and the United States (Habeeb *et al*., 2015). Seo *et al*. (2021) and Ha *et al*. (2022) showed the spatial distribution and linear trend of heatwaves over East Asia. Moreover, Zhang *et al*. (2020) suggest that increased heatwaves over East Asia were a predominant feature in the 2000s.

We employed EOF analysis using the heatwave days in summer based on the criteria of 90th percentile and



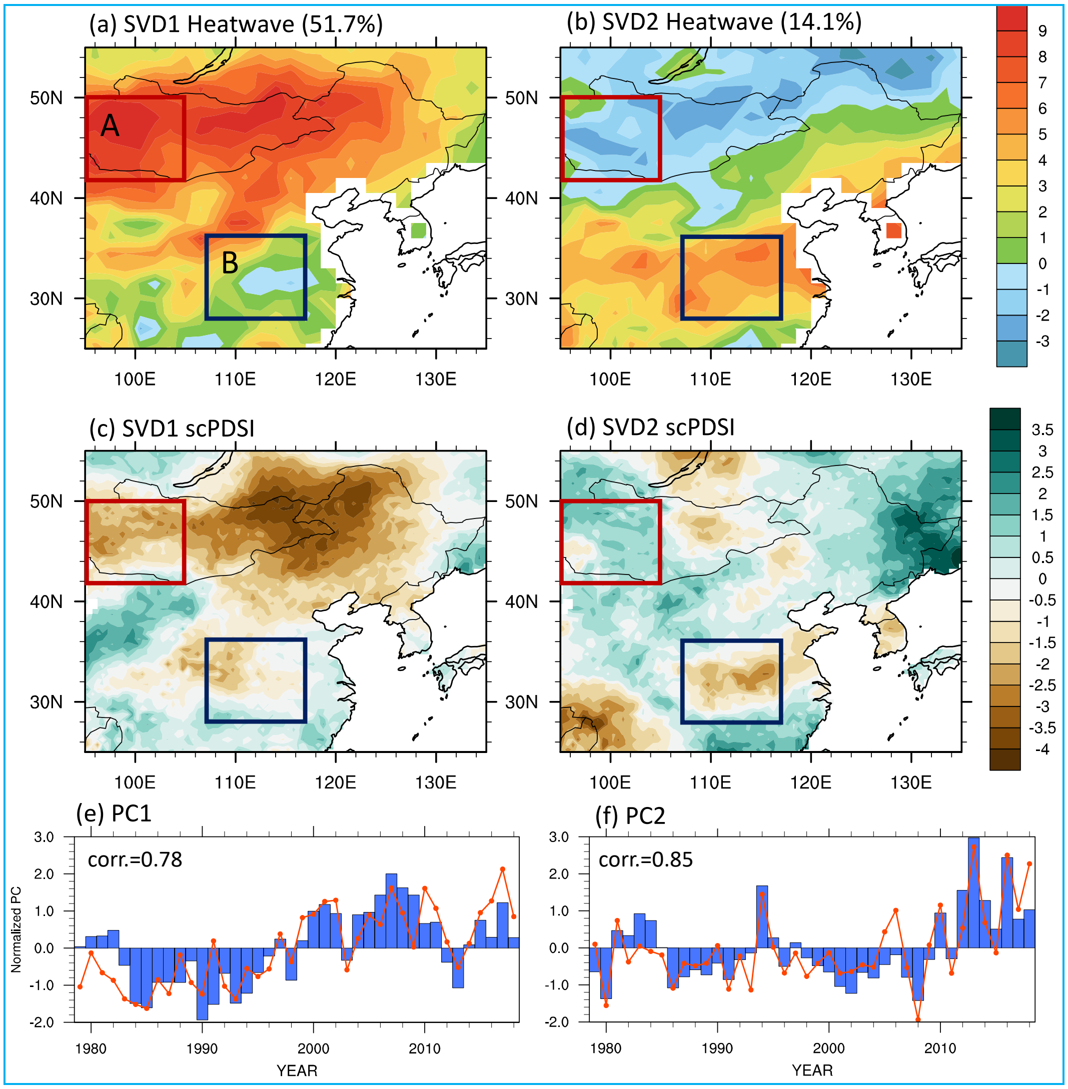
Figs. 1(a-f). (a) Climatology of heatwave days (days/year) over East Asia, (b) its normalized time series during the period from 1980 to 2019, (c) The first EOF mode for heatwave days in MJJASO from 1980 to 2019 and (d) its PC time series and (e, f) Same as (c, d) but for the second mode. Heatwave days are defined as periods in which the daily mean temperature is above the 90th percentile for at least 3-days

more than three consecutive days for individual summers during the period from 1980-2019 to obtain the major modes of characterizing heatwaves [Figs. 1(c-f)]. The first leading mode of heatwaves accounts for about 20.3% of the total variance [Fig. 1(c)]. The first mode clearly shows the dipole pattern in a north-south direction, up to40°N and above in northern China. This mode shows the intensified heatwaves over northern East Asia. The principal components (PC) time series represent the interannual variability of heatwaves. The second leading mode of heatwaves explains about 14.3% of the total variance [Fig. 1(e)]. Unlike the first mode, the variability of the second mode shows a maximum in central China and South Korea. To investigate the dryness and precipitation anomalies associated with the leading modes of the heatwave, the regression fields of drought index and precipitation against PCs are shown in Figs. 2(a-h). The self-calibrating Palmer Drought Severity Index (scPDSI)



Figs. 2(a-h). Regression fields of scPDSI (shading) and precipitation (contour) against the PC time series of heatwaves over East Asia. The stippling denotes the 95% confidence level using the P-value

is used as the drought index to detect drought conditions. This data was taken from the Climate Research Unit (CRU) version 4.05. It is the basis of the concept of supply and demand in the water balance equation, thus integrating pre-precipitation, runoff, moisture supply and evaporation demand at the surface level. Corresponding negative anomalies in these PDSI patterns associated with PCs appear in summer over East Asia. Although these two heatwaves are closely related to dry conditions, there are somewhat differences in their temporal evolution. The negative anomalies associated with EOF1 mode were reinforced throughout the summer with negative



Figs. 3(a-f). First and second singular value decomposition (SVD) modes of total heatwave days and scPDSI during the warm season (MJJASO) for the period 1979-2018: (a), (b) spatial modes of total heatwave days; (d), (e) spatial modes of scPDSI and (c), (f) their normalized PC time series. The blue bar and red line in (e-f) denote normalized PC time series of heatwave and scPDSI, respectively. (adapted from Seo *et al*., 2021)

precipitation anomalies from June to August. However, the dry conditions associated with the EOF2 are affected by low precipitation in July and August. The strong negative anomalies of precipitation are zonally allocated along 25° N to 35° N. It means that the monsoon precipitation is closely related to the EOF2 mode of heatwaves over central East Asia and the Korean Peninsula.

3. Compound heatwaves and feedback attribution

Most heatwaves that occur over East Asia are accompanied by dry conditions. These extremely hot and dry compound extreme events have focused on the synergetic effects of widespread wildfires, which can damage to crops and cause human mortality (Fischer and Schär, 2010; Perkins *et al.*, 2012; Trenberth *et al.*, 2014). The spatial patterns of compound heatwaves are heterogeneous because of the different regionalities in temperature anomalies, precipitation and other hydrological changes. The evolution of these compound heatwaves is controlled by various land surface fluxes such as background aridity, anthropogenic factors and large-scale changes in climate patterns. Therefore, it is necessary to examine the compound dry heatwaves under drought conditions.

Seo *et al.* (2021) defined the compound heatwave with drought as the heatwaves that co-occurred in severely dry conditions. Severely dry condition is defined as the scPDSI of less than -3. They also provide the co-variability of heatwaves and drought index by demonstrating the two major modes of singular value decomposition (SVD) [Figs. 3]. Similar to EOF analysis, the SVD is commonly used as a statistical technique to investigate co-variability between two spatial-temporal variables. In this study, two variables were applied: the number of heatwave days and the scPDSI of the warm season (May to October) over East Asia. The first spatial mode indicates that the dry and very warm conditions in northern East Asia were enhanced by an increase in heatwaves and a decrease in scPDSI. In accordance with the spatial distribution of SVD1, the PC1 of heatwave has a significant correlation with the drought index in East Asia (r = 0.78) and tends to increase. The spatial pattern of the SVD2 of heatwave shows a distinct east-west extension pattern over central China, the Korean Peninsula and Japan. The variability of SVD2 accounted for 14.1% of the total covariance. The SVD2 of scPDSI is consistent with the distribution of heatwaves to the southern part of 45° N. In comparison, the opposite phase appears at 45° N north latitude. The second PC time series showed a sharp increase since the late 1990s and the correlation coefficient of the two fields is 0.85. It suggests that since the late 1990s, the compound heatwave and drought have tended to increase. Furthermore, the variability of scPDSI also indicates current dry conditions across northern East Asia, suggesting favorable conditions for simultaneous extreme heat and drought conditions. To compare different mechanisms of compound heatwaves in terms of feedback attributions, two regions with closely linked heatwave days and drought index are selected in Fig. 3(a) as compound heatwave regions. We named these two compound heatwave regions Area A and B. Area A is closely related to the heatwaves and drought index in the first primary mode of SVD analysis, while area B is related to each other in the second primary mode.

Using the Coupled atmosphere-surface climate Feedback-Response Analysis Method (CFRAM) (Cai and Lu, 2009; Lu and Cai, 2009), feedback attribution to heatwave was calculated in this study [Fig. 4]. The CFRAM is an efficient diagnostic method that decomposes local temperature anomalies into partial temperature changes due to individual radiation and atmospheric dynamics feedback. This method is based on differences in the total energy balance within an atmosphere-surface column at a given horizontal location between two climate states. The difference in the energy flux terms between the new and unperturbed equilibrium states satisfies can be written as :

$$\Delta\frac{\partial \vec{E}}{\partial t} = \Delta\vec{S} - \Delta\vec{R} + \Delta\vec{Q}^{\text{non-radiative}} \qquad (1)$$

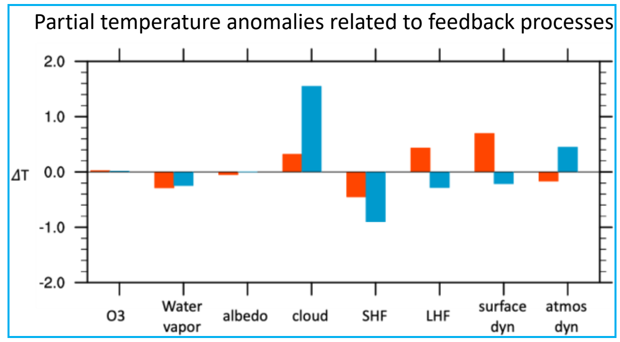


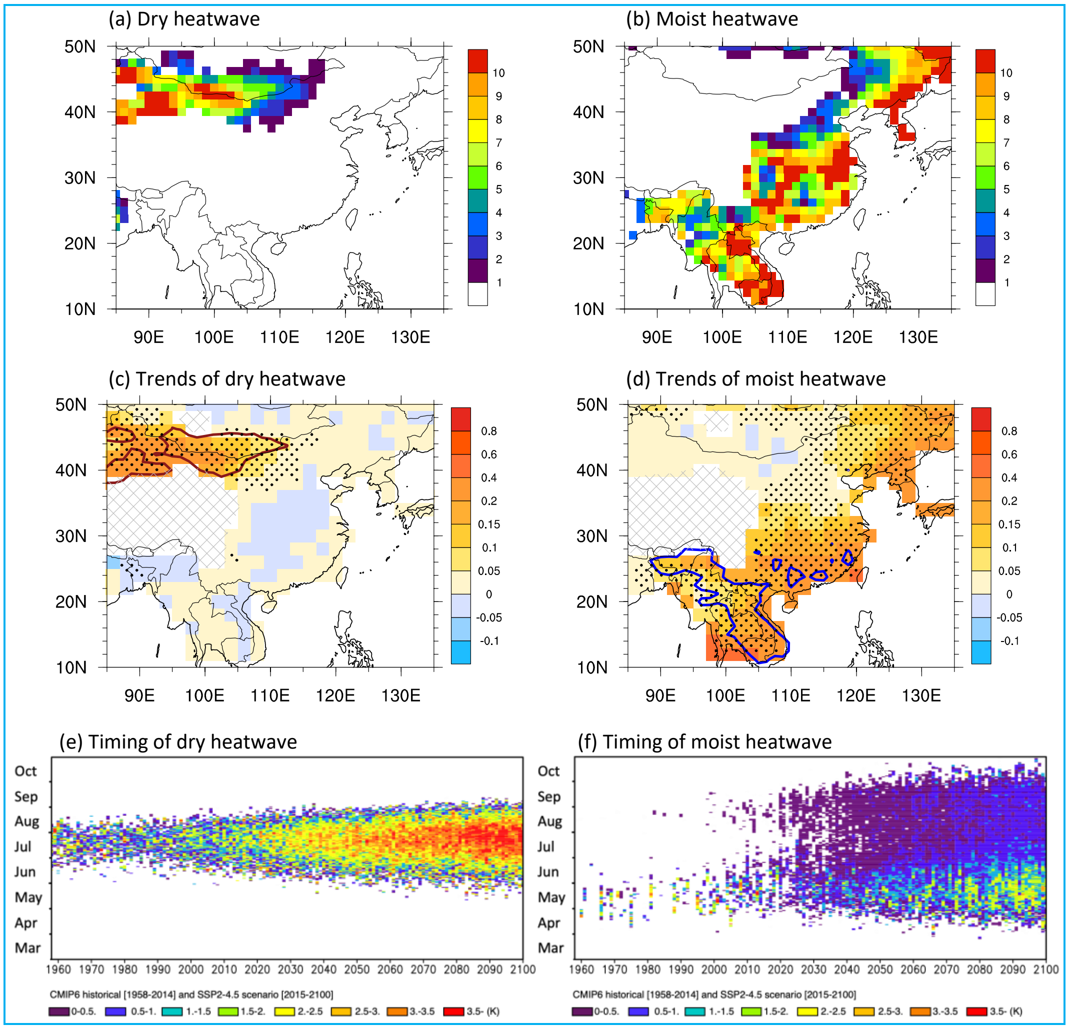
Fig. 4. Partial temperature anomalies related to feedback processes over area A (red) and area B (blue) in Fig. 3(a)

where, $\Delta\frac{\partial \vec{E}}{\partial t}$ is the change in energy storage, $\vec{R}$ is the divergence of the longwave radiation flux, $\vec{S}$ is the convergence of the shortwave radiation flux and $\vec{Q}^{\text{non-radiative}}$ is the vertical profile of the convergence of the total energy caused by convective, turbulent and large-scale atmospheric motions. According to the linear approximation, we finally obtained the local temperature differences between two equilibrium climate states as :

$$\Delta\vec{T} = \left(\frac{\partial \vec{R}}{\partial \vec{T}}\right)^{-1}\Big[\Delta\left(\vec{S}-\vec{R}\right)^{(w)} + \Delta\left(\vec{S}-\vec{R}\right)^{(c)} + \Delta\left(\vec{S}-\vec{R}\right)^{(O_3)} + \Delta\vec{S}^{(\alpha)} + \Delta\vec{Q}^{(SH)} + \Delta\vec{Q}^{(LH)} + \Delta\vec{Q}^{(\text{atmos\_dyn})} + \Delta\vec{Q}^{(\text{sfc\_dyn})}\Big] \qquad (2)$$

where, w, c, O_3, α, SH, LH, sfc_dyn and atmos_dyn represent water vapor, cloud, ozone, surface albedo, sensible heat flux, latent heat flux, surface dynamics and atmospheric dynamics, respectively. We used the CFRAM to quantify the individual radiative and dynamical processes associated with the dry heatwave-related surface temperature anomalies. We have divided the regional temperature change comes from net radiational heating or cooling and non-radiational heating or cooling, called dynamic heating or cooling. The radiational heating includes water vapor, cloud, ozone, albedo feedback and dynamic heating consistent with sensible heating, latent heating, atmospheric dynamics including advection and surface dynamics including soil dynamics.

In area A, heatwaves can coincide with drought conditions and have intensified in recent periods. In this region, surface dynamics and latent heat flux are the main drivers in increasing the heatwave-related surface temperature [Fig. 4]. The partial temperature change due to the latent heat flux is due to a decrease in the surface-atmospheric latent heat flux related to reducing the soil



Figs. 5(a-f). (a) Climatology of (a) dry heatwaves and (b) moist heatwaves during the period from 1958 to 2019 calculated by JRA-55 reanalysis. Linear trends of (c) dry heatwave days per year and (d) moist heatwae days per year during the period from 1958 to 2014 based on the historical runs in CMIP6 models. The stippling in (c, d) indicate the 90% confidence level using the *P*-value. The red and blue contours in (c) and (d) represent areas with trend above 0.15 days/year based on JRA-55 data during 1958-2019 for dry and moist heatwaves, respectively. The hatched areas indicate above 2000 m in geopotential height. (e, f) Timing of dry and moist heatwaves using CMIP6 historical simulation during 1958 to 2014 and SSP2-4.5 scenarios from 2015 to 2100. (adapted from Ha *et al*., 2022)

moisture. This is associated with reduced evaporative cooling or transpiration of water from the surface, reducing heat release from the surface to the atmosphere, contributing to surface warming (Seo *et al.*, 2021). Moreover, surface dynamics processes provided more than warming temperatures in dry heatwave regions, whereas, in area B, strong relationships between heatwaves and scPDSI are shown to increase after the 2010s. Area B has stronger properties in cloud feedback and atmospheric dynamics feedback. The cloud feedback leads to warm temperature anomalies through increasing solar insolation caused by decreasing cloud amount, which is associated with the anomalous high-pressure system. The importance of cloud feedback versus latent heat flux processes, their association with compound heatwaves, droughts, wildfires, atmospheric waves and more insights into surface feedback should be investigated in further studies.

4. The comparison of dry and moist heatwaves

As mentioned in the previous chapter, studies have been reported on extreme heat events in dry conditions. Then, what about extreme heats in wet conditions? Some studies have considered an association between high humidity and heat waves (Sherwood, 2018) because of the combined effects on human body temperature regulation (Schär, 2016) and labor productivity loss (Dunne *et al.*, 2013). Few studies compare and analyze dry and wet heat waves. Some previous studies have investigated spatial distributions and trends for both types of heat waves. For example, Ding and Qian (2011) investigated the geographic patterns and temporal changes of regional wet and dry heat waves in China. Xu *et al.* (2021) showed regional trends in dry and wet heat waves in different sub-regions of China and An and Zuo (2021) used self-organized maps to identify different circulation types associated with dry and wet heat waves in northern China. In particular, Ha *et al.* (2022) introduced dry and wet heatwaves across East Asia and identified heatwaves with relative humidity below or above 33% or 66%. Dry heatwaves are dominant over northwestern East Asia adjacent to major desert regions [Fig. 5(a)]. The regional trend in heatwave duration was an increase in dry heatwaves [Fig. 5(c)]. In contrast, the occurrence frequency of moist heatwaves increased, especially over southern East Asia and closer to the ocean moisture sources [Fig. 5(b)]. The increasing trend of a moist heatwave is evident in regions dominated by moist heatwaves [Fig. 5(d)]. There is an uneven distribution of water sources between the south and north of East Asia. Water is abundant in the south and less in the north. Therefore, regional differences exist in terms of relative humidity.

Dry heatwaves and moist heatwaves are expected to damage agriculture and cause more damage to the human body, respectively, so there is concern about the increasing trends of both heatwaves. In this study, we also showed how two heatwaves will develop by 2100 in response to projected increases in greenhouse gas concentrations from CMIP6 simulations. To quantify changes in compound heatwaves due to anthropogenic warming, we investigated the timing of heatwaves from March to October in individual years within the 1979-2100 period based on historical climate simulations [Figs. 5(e&f)]. It indicates the heatwave activity, including the occurrence, duration, starting date of the first episode and amplitudes. The intensity of dry heatwaves will be enhanced [Fig. 5(e)]. The amplitude o dry heatwaves will increase up to 4.9K at the end of the 21^{st} century in the SSP2-4.5 scenario compared to the 90^{th} percentile of daily mean temperature for the historical simulation. This result is consistent with Almazroui *et al.* (2021), which suggests that the intensity of the hottest days over extra tropical regions and the frequency of extremely hot days over the tropics are projected to increase. The occurrence of moist heatwaves will be more than double that of dry heatwave days [Fig. 5(f)]. Even though the intensity of moist heatwaves is weaker than that of dry heatwaves, the persistence will be longer. The moist heatwave will occur in March and persist until late September at the end of the 21^{st} century. Both heatwaves are expected to increase in frequency and intensity, especially dry heatwaves will become more frequent with enhanced amplitudes and moist heatwaves will occur for prolonged periods with an earlier start and a later end of heatwave seasons. These results show that characterizing heatwaves in different regions and determining their underlying physical processes are essential for providing more accurate information on the combined effects of humidity and temperature. The results of this study are expected to be widely used in the development of strategies for adaptation to agricultural and water resources.

5. Conclusions

This review provides evidence that the principal mode of heatwaves over East Asia corresponds to dry conditions and their temporal evolution is somewhat different. The dry heatwaves over northern East Asia are related to the first leading mode of heatwaves that start in early summer and they persist in summer. While dry heatwaves over central China and Korea accordance with the second mode of heatwaves start in July or August. They are closely related to late summer negative anomalies of precipitation.

These two leading modes of heatwaves over East Asia coincide with dry conditions, thus, the characteristics of the compound heatwave and drought in East Asia were examined. We described feedback attribution for surface temperature anomalies associated with compound heatwaves and drought in individual radiative and dynamic feedback processes. The results show that the roles of latent heat fluxes and surface dynamic processes acted as positive feedback to warming the surface temperature by reducing the heat release from the surface to the atmosphere due to the lack of soil moisture based on severe dry conditions. In addition, cloud feedback also resulted in warm temperature anomalies through increased solar insolation due to decreased cloud cover associated with anomalous anticyclonic circulation. These results contribute to improvement in understanding of compound extreme heat events throughout radiative and dynamic feedback processes.

Finally, it suggests substantial differences between future changes in the two types of heatwaves in greenhouse gas concentration. We have shown future climate projections for two types of heatwaves in East Asia. Both dry and moist heatwaves will be intensified and occur more frequently. In particular, more intensification of dry heatwaves and a substantial increase in moist heatwave days in response to projected increases in greenhouse gas concentrations.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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