Synoptic features responsible for Heat waves in Central-Africa, a region with strong multi-decadal trend

Lisuo Hu\textsuperscript{1,2,3}, Jing-Jia Luo\textsuperscript{4}, Gang Huang\textsuperscript{2,3,5}, Matthew C. Wheeler\textsuperscript{6}

\textsuperscript{1}State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China

\textsuperscript{2}State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

\textsuperscript{3}University of Chinese Academy of Sciences, Beijing, China

\textsuperscript{4}Institute of Climate and Application Research (ICAR)/CICFEM/KLME/ILCEC, Nanjing University of Information Science and Technology, Nanjing, China

\textsuperscript{5}Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

\textsuperscript{6}Bureau of Meteorology, Melbourne, Victoria, Australia

\textsuperscript{*Corresponding author: Jing-Jia Luo, NUIST, jingjia_luo@hotmail.com; and Gang Huang, hg@mail.iap.ac.cn

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Abstract

Central-Africa (CA) is identified as a location of a large positive trend of the occurrence of heat wave (HW) during 1979-2016, appearing to result mostly from a regime shift around the year 2000. Therefore, we study the evolution of synoptic features associated with the occurrence of HW events in CA. It is found that the HW-related circulation is typically characterized by an anomalous convergence in the upper troposphere but there are important differences for HW events occurring in the south region of CA (CA_S) versus the north region (CA_N). For the occurrence of the HW events in CA_S, the anomalous subsidence associated with upper troposphere anomalous convergence is the dominant factor for their occurrence and magnitude: the strong subsidence leads to warming through greater solar insolation. The HW events in CA_S are also accompanied by an anomalous surface anticyclone in the north with anomalous northerly flow transporting heat into the CA_S region. In contrast, although the HW events in CA_N are also associated with upper troposphere anomalous convergence, the intensity of the convergence is weak with small solar insolation. Instead, the anomalous warm advection is the main factor for determining the magnitude of the HW events in CA_N, induced by the prevailing northerly winds acting on the anomalous temperature gradient. Thus, the synoptic features associated with HW events in the CA_N and CA_S are quite different despite their nearby locations. The discovered dominant factors for the HW events in CA can be used to improve the forecast skill.
1. Introduction

As a result of anthropogenic global warming, extreme heat (EH) is projected to become more intense, more frequent, and longer lasting in the coming decades and has attracted great attention by society and in the scientific literature (e.g., Meehl and Tebaldi 2004; Kunkel et al. 2010; IPCC 2013; Lau and Nath 2012; Weaver et al. 2014). EH exerts notable influences on both socioeconomic and public health, increasing the consumption of electricity and water, causing forest fires, crop losses, and heat-related illness, such as heat stroke, heat exhaustion, and various respiratory and cardiovascular diseases (Zhang and Wang 2002; Meehl and Tebaldi 2004; Luber and McGeehin 2008; Coumou and Rahmstorf 2012; IPCC 2012; Lu and Chen 2016).

For example, western Russia suffered a record-breaking heatwave in 2010, causing 55000 heat-related deaths, 500 wildfires, and a 30% reduction in its grain harvest (Dole et al. 2011; Grumm 2011; Coumou and Rahmstorf 2012). In fact, EH is reported to be the most dominant cause of weather-related human mortality among heat, cold, drought, storm, and flood events (IPCC 2013). Therefore, the increasing threat of EH calls for a detailed understanding of the physical causes of its occurrence.

EH is often accompanied by notable changes in the ambient atmospheric circulation and precipitation fields, as well as in the condition of the nearby land and ocean surface (Hu et al. 2011, 2012; Lau and Nath 2012, 2014; Luo and Lau 2017). Since large-scale circulation is generally considered as a major factor affecting temperature, previous studies have suggested that anticyclonic anomalies induce the
occurrence of EH in various regions (Meehl and Tebaldi 2004; Maheras et al. 2006; Gershunov et al. 2009; Chen and Lu 2015; Lu and Chen 2016; Luo and Lau 2017).

Air temperature is increased through both adiabatic heating and increasing solar radiation at the surface induced by subsidence, which is associated with anomalous anticyclone (Black et al. 2004; Zaitchik et al. 2006; Loikith and Broccoli 2012; Chen and Lu 2015).

Not only the vertical flow but also the horizontal flow affects air temperature through temperature advection. During the July-August over the eastern Mediterranean region, Ziv et al. (2004) found that the temperature anomaly is attributed to the combined effect of horizontal advection by prevailing northwesterly winds and the warming associated with subsidence. Moreover, Harpaz et al. (2014) concluded that the occurrences of EH in the eastern Mediterranean region are controlled by the intensity of the temperature advection, but not by the prevailing subsidence: the weakening of the northeasterly winds prior to hot events is the dominant factor.

However, the features of the atmospheric general circulation associated with the occurrence of EH in difference regions exhibit significant spatial differences. The circulation affecting neighboring cities (such as Madrid, Spain and Lisbon, Portugal) can be quite different (García-Herrera et al. 2005). For instance, southerly anomalies transporting heat from the south is the dominant factor for the occurrence of EH in Madrid, while anomalous easterly airflows that have been previously heated is important to the EH in Lisbon. In the North America, Loikith and Broccoli (2012)
investigated the characteristics of observed atmospheric circulation patterns associated with temperature extremes and found that patterns vary based on latitude, season, and distance to important geographic features (i.e., mountains, coastlines), and pointed out that anomalous circulation responsible for EH over the southern domain is distinct from the typical anticyclonic anomaly for other regions. EH in China also has a similar discrepancy. Chen and Lu (2015) compared the composite synoptic circulation anomalies associated with extreme heat in eastern China and classified them into three categories: typical extratropical pattern, monsoonal pattern, and foehn pattern (strong winds blowing from the mountains to the plains result in foehn effect, which involves drier and warmer air) (Lu and Chen 2016). This indicates that the impacts of monsoon and topography should be taken into consideration. Hence, it is necessary to consider the diversity and regional features when studying the circulation associated with the occurrence of EH in each location.

Engelbrecht et al. (2015) found that temperatures over parts of the subtropics and central tropical Africa have been rising at more than twice the global rate. Both the relatively strong signals of projected climate change in Africa and the relatively low economic developments of Africa increase its vulnerability to the adverse impacts of climate change (Engelbrecht et al. 2015; Nangombe et al. 2018). Africa is one of the most vulnerable continents due to its high exposure and low adaptive capacity (IPCC 2014). In particular, there are tens of millions of subsistence farmers in Africa who depend on agriculture. In the past three decades, Africa suffered 27% of the world’s reported fatalities from natural catastrophes (614250 people) and experienced 1560
Previous studies mainly focus on the synoptic circulation associated with EH in extratropical regions (Loikith and Broccoli 2012; Chen and Lu 2015; Luo and Lau 2017). However, there are few studies that focus on the HW-related circulation in tropical regions. For example, Fontaine et al. (2013) analyzed the recent changes in heat waves occurrences and atmospheric circulation in Northern Africa during spring and summer, but did not investigate the synoptic features that are responsible for heat waves events. In the present study, we analyze synoptic features and circulation patterns accompanying the occurrence of heat wave events in Central-Africa (CA): a location of strong multi-decadal trends of EH. This study is expected to improve the understanding of EH in CA that may help improve the forecast of the occurrence of EH in this region.

The remainder of this paper is organized as follows. Section 2 introduces the datasets used in this research and definitions of EH. In section 3, CA is chosen because of its strong multi-decadal trends and further it is divided into two subregions for detailed analysis. Section 4 provides a discussion of the evolution of synoptic and circulation patterns associated with HW events. Section 5 examines the dominant factor affecting the magnitude of HW events. The main conclusion and discussions is offered in Section 6.
2. Data and Definitions

2a. Data

For the analysis focusing on the satellite era (1979-2016), daily maximum temperature (Tmax) datasets are provided by one observationally based gridded product and retrieved from two atmospheric reanalysis. These datasets are listed as below:

(1) The Berkeley Earth Surface Temperature (BEST; Rohde et al. 2013a, b), which provides data on a $1^\circ \times 1^\circ$ grid from 1880 until recent years.

(2) The European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011), which provides data on a horizontal resolution of 0.75° latitude by 0.75° longitude, and 23 pressure levels from 1000 to 200 hPa.

(3) The national Centers for Environmental Prediction (NCEP) – U.S. Department of Energy (DOE) AMIP-II reanalysis (NCEP2; Kanamitsu et al. 2002) during 1979-2016 on a $1.904^\circ \times 1.875^\circ$ grid.

We primarily make use of the daily Tmax anomalies in this study, which are computed by subtracting the climatological seasonal cycle (1979-2016). The latter is obtained by computing the 38-year averages for individual calendar days and then performing a 31-day running mean. Anomalies rather than actual temperatures are used to avoid temporal biases associated with seasonal variations in climatological mean temperature; such biases could be acute during the transition seasons (e.g., Loikith and Broccoli 2012).
To analyze the pertinent synoptic features responsible for HW events, we have to use reanalysis data. Barbier et al. (2018) indicated that ERA-Interim is better than NCEP2 in characterizing heat waves in Sahel, with fewer departures from BEST for ERA-Interim. Hence, ERA-Interim reanalysis data is used to define extreme heat firstly, and then compared with BEST gridded data and NCEP2 reanalysis data due to the fact that data are sparse in the Africa. The observed results presented in this study are obtained from daily grids retrieved from reanalysis data of mean 2m temperature (Tmean), surface temperature (Ts), precipitation (Pr), surface pressure (Ps), surface wind at 10m, wind from 1000 to 200 hPa, 500hPa vertical velocity (omega), 850hPa specific humidity (q), surface solar radiation (ssrd), and downwards surface sensible heat flux (hfss). To calculate the daily anomalies of these variables, we utilized the same method for the temperature anomalies.

2b. Definitions

Prolonged exposure to extremely high temperatures can lead to heat-related illnesses and result in an increase in mortality, especially in the elderly (Kilbourne 1997; Sandor and Howe 1997; Luber and McGeehin 2008; Lippmann et al. 2013). Mortality risk begins to rise as the temperatures increases from population-specific threshold values, producing a J- or V-shaped relation. There are important differences in vulnerability between populations, depending on climate, culture, infrastructure (housing), and other factors (Curriero et al. 2002; Baccini et al. 2008; Kovats and Hajat 2008). Kovats and Hajat (2008) indicated that most homes have an indoor temperature of 63°F to 87°F (17.2°C to 30.6°C), and people do not comfortably live
in temperature outside this range. Even the tolerance range of an individual is usually much less than this and the range becomes narrower with age or illness (Kovats and Hajat 2008).

Kim et al. (2017) investigated the trend of outbreak of thermal illness patients based on temperature during 2002-2013 in Korea. They found that the number of patients with heat-related illnesses increased as the daily maximum temperature increased on degree above 29.5°C. In addition, other studies showed that temperature above 80°F (26.7°C; Deschenes and Moretti 2009) and 90°F (32.2°C; Barreca 2012; Barreca et al. 2016) leads to the increasing of mortality. The specific temperature thresholds associated with human health are around 30°C although differences exist among the previous studies.

The 90th percentile of the Tmax anomaly distribution (TX90) on a given day $d$ is defined by all 31-day intervals from 1979 to 2016 centered on the calendar day. Therefore, the impact of the jump between the monthly climatology has been avoided. To analyze EH associated with human health, hot days (HDs) are defined as those days when daily Tmax anomaly is above the TX90 and daily Tmax exceeds 30°C. When HDs lasting for three consecutive days or more, heat wave (HW) events are identified. We examine the HW events with two measures, including the yearly number of HW events (HWN) and yearly sum of HW days (HWD).

3. Region selection and subregion classification

The climatology and trends of HDs, HWN, and HWD during 1979-2016 derived from the ERA-Interim reanalysis data are depicted in Fig. 1. Spatial distributions of
the climatology of these variables display a zonally elongated structure with the maximum located around 10°-30°N. EH frequently occur over the regions which mainly reside in the Central and North Africa, Arabian, India, and the Indian Peninsula. Both the HDs and HW indices (HWN and HWD) show an increasing trend in the most parts of the northern hemisphere except India Peninsula where an insignificant decreasing trend is identified. The results clearly show that the Central-Africa (CA: 0°N-15°N, 15°E-30°E) is a location with strong multi-decadal trends of EH. During 1979-2016, the HDs have increased significantly by approximate 20 days/10yr, HWN by 2.5 events/10yr, and HWD by 15 days/10yr, respectively. Because of the increasing threat of EH in the CA, it is important to improve our understanding of the physical mechanisms for EH that underpin the forecast of EH.

Regime shift is defined as a rapid shift of climate status from one relatively stable to another. It is detected by a method developed by Rodionov (Rodionov 2004; 2006) based on a sequential t-test (details of regime shift detection are provided by NOAA, available at https://www.beringclimate.noaa.gov/regimes/#userconsent#). As shown in Fig. 2, both the HDs and HW indices exhibit prominent upward trends during 1979-2016 but with apparent regime shifts around 2000. There are 14.79 hot days, 1.54 heat wave events and 6.85 heat wave days per year on average during 1979-2000, and 45.96 hot days, 5.25 heat wave events and 25.56 heat wave days on average during 2001-2016. Due to the low spatial and temporal coverage of observational data prior to 1979 and the availability of satellite data for assimilation in reanalysis since
1979, our analysis is focused on the period of 1979-2016 only. We note that the regime shift around the year 2000 might be induced by multi-decadal variability or global warming or the combination of the both. This warrants future studies possibly with longer historical records. We found that the multi-decadal linear trends during the two periods before and after 2000 are actually small (Fig. 2). This indicates that the multi-decadal trends of EH in CA during 1979-2016 largely result from the regime shift, not from a linearly steady increase. To eliminate the effects of the regime shift on identifying EH and compositing synoptic features during HW events, daily anomaly is calculated by removing the 31-day running mean of climatological seasonal cycle based on two periods: 1979-2000 (period 1) and 2001-2016 (period 2) from actual values, respectively.

In addition, ERA-Interim, NCEP2 and BEST were compared to evaluate the uncertainties of ERA-Interim reanalysis data. Spatial distributions of climatology of extreme heat are similar between ERA-Interim (Fig. 1a, 1c and 1e) and BEST (Fig. A1a, A1c and A1e) with pattern correlation coefficients valued 0.902, 0.905, and 0.902 respectively, but the results derived from ERA-Interim underestimates the mean state of extreme temperature to some extent. Although some differences of linear trends are found, CA is a location with strong multi-decadal trends of EH both in ERA-Interim and BEST. As shown in Fig. A2, both the HDs and HW indices based on the BEST exhibit positive trends with an inter-decadal shift around 2000, which is consistent with the results based on the ERA-Interim generally. And the correlation coefficients of the time series of regionally-averaged HDs, HWN and HWD in CA
between the BEST and the ERA-Interim data are 0.79, 0.74 and 0.74 respectively. In contrast the correlations between the BEST and the NCEP2 data are 0.26, 0.24 and 0.30. Therefore, Compared to the NCEP2, the ERA-Interim is better in capturing the EH in CA with fewer discrepancies from the BEST. And hence we use the Tmax and pertinent variables derived from the ERA-Interim.

To examine the spatial structure of the daily Tmax field in the CA, an empirical orthogonal functions (EOF) analysis is conducted of the daily Tmax anomalies over this region during 1979-2016. The first and second EOF mode explains 51.3% and 22.3% of the total variance, respectively. It is seen from Fig. 3(a) and Fig. 3(b) that the EOF modes exhibit a dipole pattern between the south and north region of CA (the boundary is around 7°N). This indicates that CA could be divided into two subregions considering its spatial discrepancy of variations: south region of CA (CA_S; 0°N-7°N, 15°E-30°E) and north region of CA (CA_N; 7°N-15°N, 15°E-30°E).

In addition, correlation coefficients are computed between the individual daily Tmax anomalies in each grid and the spatial mean of CA_S (Fig. 3c) and CA_N (Fig. 3d) for verifying the rationality of the classification. As Shown in Fig. 3c, high correlation coefficients mainly occur between 0°N and 7°N, suggesting that Tmax anomaly in each grid in CA_S covaries with the spatial mean of CA_S. Meanwhile, high correlation coefficients mainly reside between 7°N and 15°N in Fig. 3d, and this indicates that Tmax anomaly in each grid in CA_N covaries with the spatial mean of CA_N. In addition, both the seasonal cycle of temperature and precipitation are different in CA_S and CA_N. The southward and northward movement of zonal
precipitation band contributes to difference climate feature in CA_S and CA_N. Hence, it is necessary and rational to divide CA into two subregions for better exploring the synoptic features responsible for the HW events in the two regions.

After the subregion classification, regional HW events are identified by the spatial average of daily Tmax anomalies and Tmax in the CA_S and CA_N, respectively. The 90th percentile values of the spatial mean Tmax anomaly distribution are calculated using the same method for individual grid TX90. A regional HW event is identified in the region when the spatial mean of Tmax anomaly is higher than TX90 and spatial Tmax exceeds 30°C for three consecutive days or more. For example, the daily spatial mean of Tmax, Tmax anomaly and TX90 time series in 2016 depicts that 6 HW events and 13 HW events occurred in CA_S and CA_N, respectively (Fig. 4). As shown in Fig. 4, CA_S experience HW events mostly during winter, whereas HWs in CA_N occur during autumn and spring. This indicates that HW events in the two subregions do not take place simultaneously.

Heat waves in CA_S mostly occur in winter and spring, with 40 events in winter and 26 events in spring (out of the total 69 events). In CA_S, since the daily maximum temperature are below 30°C during the rainy seasons, heat waves are mostly occur during dry seasons (winter and early spring). The heat waves in CA_N occur throughout the year, with 54 events in spring, 49 events in summer, 51 events in autumn and 50 events in winter. There are 21 HW events (94 HW days) took place simultaneously in CA_S and CA_N, indicating that 30.4% (10.3%) HW events and 27.4% (9.7%) HW days in CA_S (CA_N) are concomitant with CA_N (CA_S).
Therefore, the level of concomitance between the heat wave occurrences over CA_S and CA_N is low, which is consistent with the results from the EOF analysis of desasonalized time series of Tmax.

4. Evolution of synoptic features during HWs

Based on the spatial average of Tmax and Tmax anomaly, 69 and 204 HW events are found in CA_S and CA_N, respectively. In CA_S, there are 40 and 29 HW events during 1979-2000 and 2001-2016 with average length of HWs being 4.8 days and 5.2 days, respectively. In CA_N, there are 115 and 89 HW events during 1979-2000 and 2001-2016 with average length of HWs being 5.0 days and 4.4 days, respectively.

In this section, to depict the typical synoptic patterns associated with the occurrence of HW events, we use the identified HW events to construct composite patterns. The synoptic features are examined with the composite anomalies of the pertinent variables responsible for the HW events. The evolution of the average composite patterns are shown from 5 days before the occurrence to 5 days after the end of HW events. To find out if there is contamination between the events that occur close to each other, we composite the cases only when the days before the beginning and after the end of HW events are not superimposed with the period of another HW events. With this criterion, the number of cases used in composite analysis for the evolution of HW events are shown in Table. 1.

4a. CA_S

Since the composite evolution features of the Tmax, Tmax anomaly, and pertinent variables during two decadal epochs before and after 2000 are similar (Fig. 5) after
removing the regime shift, the cases of HW events in the two periods are composited together. The discussion of two periods separately in Fig. 5 is to verify the existence of the regime shift which impact needs to be removed. Due to the significant increase of Tmax from P1 to P2, a majority of HW events occur during P2 if the anomalous Tmax and pertinent variables are calculated without removing the impact of the regime shift.

As shown in Fig. 5c, a positive anomaly of Tmax occurs during the whole period from ds-5 to de+5. The anomaly is 1.12°C at ds-5 and basically persists until ds-2, and then the anomaly rapidly increases to 2.69°C at ds-0. After the end of HW events, the anomaly decreases dramatically to 1.45°C at de+1 and then slowly decreases to 0.86°C at de+5. The Tmax anomaly decays more rapidly after the HW events than the increases before the HW events. The dramatic increase and decrease of temperatures during the HW events suggest that the occurrences of HW events are mostly induced by synoptic disturbances (Chen and Lu 2015). Due to the large spread among the HW events, especially before ds-2 and after de+1, strong case-to-case differences exist. And hence, composite analysis based on a large number of cases are necessary to obtain statistically robust results; this is another reason why we composite the cases of HW events during the two periods together.

Associated with the positive anomaly of Tmax, a dry condition with precipitation anomaly of about -6 mm/day during the HW events is detected (Fig. 5d). In accordance with an upper tropospheric convergence (i.e. positive anomalies of velocity potential at 200hPa) (Fig. 5e) and a lower tropospheric divergence indicated...
by negative anomalies at 850hPa (Fig. 5f) before and during the HW events, the anomalous subsidence of about $3 \times 10^{-4}$ hPa/s occurs during the HW events (Fig. 5g). The subsidence not only can induce the negative specific humidity anomaly at 850hPa (Fig. 5h), but also can increase the solar radiation at surface (Fig. 5i) and increase the surface temperature (Fig. 5b). Because the surface temperature is larger than 2m air temperature (Fig. 5a; Fig. 5b), it provides positive sensible heat flux from surface to air (Fig. 5j) and hence increases the surface air temperature. In addition, HW events are also partly attributed to a northerly wind anomaly of -0.4 m/s (Fig. 5k) that brings about a weak warm advection anomaly of 0.1°C/day at the beginning of HW events despite large spread among the events (Fig. 5l). The anomalous northerly wind and the warm temperature advection decrease gradually afterwards.

Most of the features associated with the heat wave events in CA_S show a signal before the event, but not after, with a quick transition to neutral conditions, especially the velocity potential at 200hPa (Fig. 5e) and 850hPa (Fig. 5f), vertical velocity at 500hPa (Fig. 5g) and specific humidity at 850hPa (Fig. 5h). Most fields return to around zero soon after the heat wave events, suggesting that the evolution of HW event is asymmetric and these events have little downstream effect or ability to precondition other events.

Fig. 6 shows the evolution of velocity potential and divergent wind at 850hPa and 200hPa, vertical velocity at 500hPa, and latitude-altitude cross section of wind between 15°E and 30°E, associated with the HW events in the CA_S. Composite maps in Fig. 6 are shown from top to bottom for the days from ds-3 to de+1. As
shown in Fig. 6, a prominent convergence center in the upper troposphere and a divergence center in the lower troposphere appear in the north of CA_S (around 25°N) during three and two days before the HW events onset (ds-3; ds-2). This is associated with downward air motion over the north of CA_S, with the greatest subsidence occurring between 500hPa and 400hPa. On one day before the HW events (ds-1), the upper troposphere convergence center split into two centers (Fig. 6, 2nd column). Its southern center becomes dominant with a regional subsidence center occurring over the CA_S. The southern center then intensifies and reaches a peak on the day of HW events beginning (ds-0), accompanying by a strong subsidence from 700hPa to the upper troposphere (4th column in Fig. 6). Afterward, the anomalous upper troposphere convergence and whole column subsidence over the CA_S weaken (ds-avg) and diminish in the following days, as the system moves gradually eastward (de+0; de+1).

Fig. 7 shows the evolution of near-surface anomalies, including (1st column) Tmax anomaly, (2nd column) surface pressure anomaly, (3rd column) daily mean surface air temperature and 10m wind anomaly, and (4th column) precipitation anomaly. The results depict strong localized features with the warm Tmax anomaly in the CA_S accompanied by a cold Tmax anomaly at north of CA_S, especially before the occurrence of HW events (ds-3 to ds-1). The evolution features of the Tmax anomaly and precipitation anomaly are similar in the CA_S, as a warm Tmax anomaly and a dry anomaly rapidly strengthen from ds-2 to ds-0, and persist during the HW events. Finally, these anomalies decrease dramatically after the end of HW events (de+1). The evolution of anomalous Tmax and precipitation are associated
with the warm and dry air column above CA_S, resulting from the anomalous upper
troposphere convergence and whole column subsidence. The persisting negative
precipitation anomaly leads to the negative soil moisture anomaly, which in conducive
to the occurrence of heat wave through increasing sensible heat flux and reducing
latent heat flux (Lorenz et al., 2010; Alexander 2011; Perkins and Sarah 2015). In
addition, there is a positive surface pressure anomaly in the north of CA_S from ds-3
to ds-0. Because the maximum mean temperature locates around 10°N, the anomalous
northerly wind induced by the surface anomalous anticyclone brings a weak warm
advection to CA_S.

For HW evens in CA_S, the occurrences of an anomalous convergence center in
the upper troposphere and divergence center in the lower troposphere induce strong
subsidence anomalies, which leads to warming through greater solar insolation.
Meanwhile, small amount of significant warm advections associated with HW events
across the entire period are found from ds-1 to ds+1 (Fig. 5l). Therefore, the enhanced
solar radiation induced by strong subsidence anomalies is the major contribution to
the occurrences of HW events over CA_S, while anomalous temperature advection is
the minor contributions.

4b. CA_N

In CA_N, HW events in the two decadal epochs before and after 2000 are
composited together, in terms of the similar composite evolution features of the Tmax,
Ts, Tmax anomaly, and anomalous pertinent variables between the two epochs (Fig.
8). As shown in Fig. 8c, the Tmax anomaly is 0.60°C at ds-5 and slowly increases to
1.11 °C at ds-2. Then the anomalous Tmax rapidly increases to 2.51 °C at the beginning of HW events. After the end of HW events, the anomaly decreases dramatically to 1.51 °C at de+1 and then slowly decreases to 0.50 °C at de+5.

A negative anomaly of precipitation of about -3 mm/day is detected during the HW events (Fig. 8d). An anomalous subsidence of about $1.5 \times 10^{-4}$ hPa/s (Fig. 8g) occurs before and during the HW events, especially at ds-1, ds-0, and ds+1, which is associated with the anomalous convergence at the upper troposphere (Fig. 8e) and divergence at the lower troposphere (Fig. 8f). Associated with the downward air motion, temperature is increased through positive anomalous solar radiation at surface (Fig. 8i). Since the surface temperature is increased due to the positive solar radiation anomaly and is larger than 2m air temperature (Fig. 8a; Fig. 8b), more sensible heat flux is released from surface to air (Fig. 8j). The HW events are accompanied by an anomalous southerly wind, which increases gradually during the HW events and reaches a peak of 0.4 m/s at de-0. Whereas an anomalous warm advection occurs with a peak value of 0.42 °C/day at ds-0, and then decreases gradually during the HW events. Hence, the evolutions between the anomalous southerly wind and the warm advection during the HW events are opposite, suggesting that the anomalous southerly wind is not the dominate factor responsible for the anomalous warm advection in the CA_N.

Compared to the evolution of the pertinent variables associated with HW events in the CA_S (Fig. 5), the magnitudes of anomalous precipitation, velocity potential at 200 hPa and 850 hPa, subsidence at 500 hPa, specific humidity at 850 hPa, surface solar
radiation, and downwards sensible heat flux are smaller in the CA_N. But the value of anomalous horizontal temperature advection is larger in the CA_N than in the CA_S. Else, anomalous features associated with HW event tend to last longer in the CA_N than in the CA_S.

Fig. 9 shows the evolution of velocity potential and divergent wind at 850hPa and 200hPa, vertical velocity at 500hPa, and latitude-altitude cross section of wind between 15°E and 30°E, associated with the HW events in the CA_N. Composite maps in Fig. 9 are displayed from top to bottom for the days from ds-3 to de+1. A dipole pattern of a large negative velocity potential anomaly in the northwest and a large positive anomaly in the southeast at 200hPa occurs at ds-3 and strengthens gradually from ds-3 to ds-0, especially the positive anomalous velocity potential (i.e. convergence) becomes stronger (Fig. 9, 2nd column). After the occurrence of HW events, the dipole pattern migrates toward east with the negative anomalous velocity potential getting stronger. The evolution of the anomalous velocity potential and divergent wind at 850hPa and 200hPa induce the evolution of vertical air motion. A dipole pattern of an anomalous ascent motion mainly around the Mediterranean and subsidence along from Arabian Peninsula to CA_N exists at ds-3. The dipole pattern of the anomalous subsidence intensifies gradually and reaches a peak at ds-0, and then becomes weak and moves eastward during ds-avg to de+1. At ds-0 (Fig.9, 3rd column), an anomalous subsidence center at 500hPa appear in the CA_N with largest downward air motion between 500hPa and 400hPa (Fig.9, 4th column). This subsidence center weakens and diminishes in the following days.
Fig. 10 shows the evolution of near-surface anomalies associated with the HW events in CA_N, including (1<sup>st</sup> column) wind at 10m and anomalous Tmax, (2<sup>nd</sup> column) surface pressure anomaly (3<sup>rd</sup> column) daily mean temperature and anomalous wind at 10m, and (4<sup>th</sup> column) precipitation anomaly. Over the Mediterranean, an anomalous cyclone associated with the anomalous divergence in the upper troposphere and convergence in the lower troposphere occurs at ds-3 and strengthens gradually from ds-3 to ds-1. Because the maximum mean temperature is located near 10°N (figure not shown), the anomalous southerly wind induced by the anomalous cyclone brings an anomalous warm advection to the north of CA_N. Hence, positive Tmax anomalies in the north of CA_N are larger than those in the CA_N during the days from ds-3 to ds-0 (Fig.10, 1<sup>st</sup> column). Based on this anomalous temperature gradient before and in the beginning of HW events, an anomalous warm advection is transported from north to CA_N by the mean northerly wind. As the anomalous cyclone weakens and migrates eastward from ds-avg to de+1, an anomalous northerly wind occurs, and hence there is no warm advection anomaly in the north of CA_N. Meanwhile, associated with the increasing Tmax anomaly in the CA_N, anomalous temperature gradient between the north and CA_N decreases after the onset of HW events, and thus the anomalous warm advection decreases gradually during the HW events. This is consistent with the evolution of horizontal anomalous temperature advection (Fig. 8l). In addition, the evolution of the negative precipitation anomaly in the CA_N is associated with the warm and dry air column, resulting from the anomalous subsidence and upper troposphere convergence.
The occurrence of HW events in the CA_N are partly attributed to the positive solar radiation anomaly at surface due to the subsidence induced by the anomalous convergence in the upper troposphere and divergence in the lower troposphere. Associated with the anomalous temperature gradient between the CA_N and its north resulted from the anomalous cyclone in the north, the anomalous warm advection associated with mean northerly wind plays an important role in the evolution of the positive Tmax anomaly in the CA_N, especially before and at the beginning of the HW events.

In addition, both the intensity and pattern of the anomalous convergence in the upper troposphere are different during the HW events over CA_S (Fig. 6; 2nd column) and over CA_N (Fig. 9; 2nd column). There is an anomalous convergence center over CA_S when HW events occur, whereas no anomalous convergence occurs during the CA_N HW events. In addition, the anomalous velocity potential shows a uniform pattern when HW occur over CA_S, in contrast to the dipole pattern in the CA_N HW events.

For the HW events in CA_S, Fig. 7 (1st column) indicates that positive Tmax anomalies dominate the CA_S with negative or neutral Tmax anomalies over CA_N. For HW events in CA_N, Fig. 10 (1st column) shows that positive Tmax anomalies occur over CA_N and north of CA_N with neutral anomalies over CA_S. Therefore, the level of concomitance between the heat wave occurrences over CA_S and CA_N is low, which is consistent with the results from the EOF analysis of deseasonalized time series of Tmax.
5. Factors contributed to the magnitude of HWs

We have illustrated the evolution of synoptic features associated with the HW events occurring in the CA_S and CA_N in the previous section. Because the magnitude of the HW events is one of the most important aspect of the HW activity and exerts notable influences on both socioeconomic and public health, it is important to explore dominate factors that influence the magnitude of the HW events.

As listed in Table 2, for the HW events during both the period1 (p1; 1979-2000) and period2 (p2; 2001-2016) in the CA_S, correlation coefficients between the Tmax anomaly and the anomaly of 500hPa omega (omega_500hPa), surface solar radiation (ssrd), surface temperature (Ts), and downwards sensible heat flux (hfss) are statistically significant at the 95% confidence level according to the Student’s t test. In contrast, anomaly correlation coefficients between the Tmax and the 10m meridional wind (v_10m), horizontal temperature advection (T_adv) are small and insignificant. Note that concerning the HW events in the CA_N, as shown in the previous section, anomalous wind is not the cause for the anomalous temperature advection, it does not make sensing discussing about the correlation coefficients between anomalous v_10m and Tmax. The results show that the anomaly correlation coefficient between the Tmax and T_adv is significant; the correlations with other variables are insignificant. This indicates that the main factors responsible for the magnitude of HW events in the CA_S and CA_N are different.

For HW events in the CA_S during the period 1979-2016, a statistically significant positive correlation (with a correlation coefficient of 0.42) between the
Tmax anomaly and the 500hPa vertical velocity anomaly is found for all years, indicating that the intensity of HW events increases with stronger subsidence. Since surface solar radiation is enhanced by subsidence, there is also a positive correlation coefficient of 0.46 between the Tmax and surface solar radiation anomaly. Solar radiation increases surface temperature directly and then raises air temperature indirectly through positive sensible heat fluxes from surface to air; this relation is reflected by the negative correlation coefficient of -0.71 between the Tmax and downward sensible heat flux. Hence, in the CA_S, the magnitude of the HW events are associated with the intensity of the sensible heat flux released from surface to air due to increased surface temperature, which is affected directly by increasing surface solar radiation resulted from the stronger subsidence.

For HW events in the CA_N, a positive correlation coefficient of 0.41 is seen between the anomalous Tmax and temperature advection during the period 1979-2016, indicating that a large portion of the variance in the magnitude of HW events in CA_N is explained by anomalous warm advection. In the previous section, we have identified that the anomalous warm advection in the CA_N is induced by the mean northerly wind of the anomalous temperature gradient between the CA_N and its north.

6. **Summary and discussion**

In this study, we have identified the CA as the location with a strong multi-decadal trend of EH during 1979-2016 in the Northern Hemisphere. We examined the evolution of synoptic features associated with the HW events in the CA. The regional

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averaged EH in CA depicts a strong multi-decadal trend owing to a regime shift around the year 2000; no linear steady increase is observed. The results show that the HW-related circulation is characterized by an anomalous convergence in the upper troposphere and a divergence anomaly in the lower troposphere. In general, surface temperature is increased by enhanced solar radiation at surface due to the stronger subsidence, which is induced by an anomalous convergence at 200hPa. Consequently, air temperature is heated by the positive sensible heat flux released from surface to air due to the increased surface temperature. However, distinctive features exist for the HW events in the CA_S and CA_N.

During the evolution before the occurrence of HW events in the CA_S, the upper troposphere convergence anomaly occupies a broad area with a center appearing firstly in the north of CA_S, then the center splits into two centers with the southern one overlaying the CA-S region. Hence, the CA-S region is dominated by a strong subsidence anomaly, which enhances the insolation at the surface, thus increasing the surface temperature. In the CA_N, a dipole pattern with an anomalous convergence in the southeast and a divergence anomaly in the northwest occurs and gradually strengthens before the occurrence of HW events. The CA_N region is covered by a weak convergence anomaly without a convergent center. Therefore, the positive solar radiation anomaly at surface associated with the anomalous subsidence is larger in the CA_S than that in the CA_N. These findings suggest that the subsidence associated with the anomalous convergence in upper troposphere contributes to the occurrence of HW events, especially in the CA_S.
The horizontal flow also plays an important role in increasing the air temperature via warm temperature advection. Because the maximum mean temperature is located around 10°N, the northerly wind anomaly induced by the surface anomalous anticyclone brings a weak anomalous warm advection to CA_S. Based on the anomalous temperature gradient between the CA_N and its north, the anomalous warm advection by the mean northerly wind contributes to the positive Tmax anomaly in the CA_N, especially at the beginning of HW events.

In the CA_S, the subsidence associated with the anomalous convergence in the upper troposphere is the dominant factor in both the occurrence and magnitude of HW events. Surface temperature increases due to the increased solar radiation at surface; this leads to a higher air temperature due to the positive sensible heat flux anomaly released from surface to air. Whereas in CA_N, the occurrence of the HW events is subject to the combined effect of the warming associated with a weak subsidence and horizontal warm advection. The latter is induced by prevailing northerly wind acting on the anomalous temperature gradient, and the anomalous warm advection is a main factor responsible for the magnitude of the HW events in the CA_N.

Our work finds the synoptic features and circulation patterns responsible for heat wave events in CA, as well as the factors responsible for their magnitudes. Based on these results, we can utilize the circulation patterns that lead to heat wave events as predictors to improve the forecast skill to some extent.

Because the synoptic features associated with HW events are quite different in the two regions (i.e., CA_S and CA_N), the diversity and locality features should be paid
attention when analyzing the EH-related synoptic factors. Previous studies suggested that extreme heat and its variation can be affected by various processes (Stefanon et al. 2012; Chen and Lu 2015; Lu and Chen 2016; Wang et al. 2013; 2016). Both the circulation anomalies and other factors such as urbanization and land-cover changes have been emphasized (Avila et al. 2012; Wang et al. 2013; Oleson et al. 2018; Luo and Lau 2017). For example, Luo and Lau (2017) investigated the urbanization effects on HW events in Southern China, and found that the urbanization contributes to nearly 50% of the increase in HW frequency in the Pearl River delta region.

Previous studies indicated that high temperature weather can be classified into two types: extreme heat, which features a very high Tmax; and tropical night, which features an extremely high minimum temperature (Tmin) (Wei and Sun, 2007; Park et al. 2012; Lu and Chen 2016). Tropical nights have a significant impact on sleep comfort and inhibit a person’s recovery from heat during daytime, thus increasing the threat of temperature extremes on human health (Yang et al. 2010). The processes controlling Tmax and Tmin are likely to be distinct (Lu and Chen 2016): maximum temperature is often influenced by the incoming surface shortwave radiation whereas the minimum temperature is very sensitive to the amount of water vapor sometimes (Barbier et al. 2018). Hence, it is valuable to perform similar analyses based on tropical night.

While public human health depends largely on temperature, other variables such as specific humidity, wind speed, and solar radiation are also important; human health is more severely influenced by the simultaneous occurrence of high temperature, high
humidity, and weak wind (Robinson 2001; Epstein and Moran 2006; Blazejczyk et al. 2012; Pal and Eltahir 2015). Under hot conditions, high humidity reduces sweat evaporation from the human body needed for cooling, and hence consequently increases heat stress. Similarly, weak wind fails to remove heat due to small evaporation (Wu et al. 2017). Hot days and HW events are defined based on the temperature criterion in the present study. It is of great necessity to extend the definition of EH by combining temperature and the other pertinent variables in future studies.

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Appendix

Figure A1 and A2 here
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Table 1: The number of cases used in composite analysis for the evolution of HW events in CA_S/CA_N. ds-0 denotes the day when HW events begin, ds-1 (+1) denotes one day before (after) ds-0; d-avg denotes the average between the beginning and end of HW events; de+0 denotes the day when HW events end, de+1 denotes one day after the end of HWs, etc.

<table>
<thead>
<tr>
<th>ds-5</th>
<th>ds-4</th>
<th>ds-3</th>
<th>ds-2</th>
<th>ds-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>57(CA_S)/174(CA_N)</td>
<td>61/181</td>
<td>63/188</td>
<td>65/198</td>
<td>69/204</td>
</tr>
<tr>
<td>ds-0</td>
<td>ds+1</td>
<td>ds-avg</td>
<td>de-1</td>
<td>de+0</td>
</tr>
<tr>
<td>69/204</td>
<td>69/204</td>
<td>69/204</td>
<td>69/204</td>
<td>69/204</td>
</tr>
<tr>
<td>de+1</td>
<td>de+2</td>
<td>de+3</td>
<td>de+4</td>
<td>de+5</td>
</tr>
<tr>
<td>69/204</td>
<td>65/198</td>
<td>63/188</td>
<td>61/181</td>
<td>57/174</td>
</tr>
</tbody>
</table>
Table 2: Correlation coefficients between the anomalies of Tmax and v_10m, T_adv, omega_500hPa, ssrd, Ts, and hfss during HWs for the two decadal epochs (p1 vs. p2).

<table>
<thead>
<tr>
<th>CCR</th>
<th>v_10m</th>
<th>T_adv</th>
<th>omega_500hPa</th>
<th>ssrd</th>
<th>Ts</th>
<th>hfss</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA_S p1</td>
<td>-0.25</td>
<td>0.18</td>
<td>0.42*</td>
<td>0.47*</td>
<td>0.48*</td>
<td>-0.77*</td>
</tr>
<tr>
<td>CA_S p2</td>
<td>-0.23</td>
<td>0.09</td>
<td>0.42*</td>
<td>0.46*</td>
<td>0.50*</td>
<td>-0.65*</td>
</tr>
<tr>
<td>CA_N p1</td>
<td>0.30*</td>
<td>0.29*</td>
<td>-0.10</td>
<td>-0.02</td>
<td>0.61*</td>
<td>-0.10</td>
</tr>
<tr>
<td>CA_N p2</td>
<td>0.42*</td>
<td>0.51*</td>
<td>-0.13</td>
<td>-0.06</td>
<td>0.77*</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

* is statistically significant at the 95% confidence level according to the Student’s t test.
Figure 1. Climatology and linear trend of HDs (a, b), HWN (c, d) and HWD (e, f) during 1979-2016 derived from the ERA-Interim reanalysis data in North Hemisphere. Dot denotes significance at the 95% confidence level according to student’s $t$ test. Black boxes donate the CA region.
Figure 2. Time series of the annual number of regionally-averaged HDs (a), HWN (b) and HWD (c) in CA derived from the ERA-Interim reanalysis data during 1979-2016. Also shown are the detected regimes with each regime shift significant at the 5% level.
Figure 3. The first EOF mode (a), second EOF mode (b) of daily Tmax anomalies, and correlation coefficients of daily Tmax anomaly between the individual grids and spatial mean of CA_S (c) and CA_N (d). Dot denotes significance at the 95% confidence level according to student’s t test, and green lines indicate the 7 degrees of north latitude.
**Figure 4.** The daily spatial average of Tmax (blue line), Tmax anomaly (red line) and TX90 (green line) time series in 2016 over the CA_S (a) and CA_N (b). The black dashed line indicates the occurrence of regional HW events, as each peak represents an HW event.
Figure 5. Evolution of the composite of the (a) maximum air temperature, (b) maximum surface temperature, and anomalous (c, d) maximum air temperature and precipitation, (e, f) velocity potential at 200hPa and 850hPa, (g) vertical velocity at 500hPa, (h) specific humidity at 850hPa, (i) surface solar radiation, (j) downwards sensible heat flux, (k) meridional wind at 10m, (l) horizontal temperature advection during the period from 5 days before to 5 days after the HW events in the CA_S. ds-0 denotes the day when HW events begin, ds-1 (+1) denotes one day before (after) ds-0; de+0 denotes the day when HW events end, de+1 denotes one day after the end of HW events, etc. Red, blue, and black line indicates the composite based on 1979-2000, 2001-2016, and 1979-2016, respectively, and the markers denote significance at the
95% confidence level according to student’s $t$ test. Lightgray shading indicates the spread (i.e. $\pm 1$ standard deviation) of the cases during 1979-2016.
Figure 6. Composite maps of the evolution of (1st column) anomalous velocity potential (shading) and divergent wind at 850hPa and (2nd column) 200hPa, (3rd column) anomalous vertical velocity at 500hPa, and (4th column) vertical-meridional cross sections of anomalous winds from 1000hPa to 200hPa of the 15°E-30°E and

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vertical velocity (filled contours) before, during and after the occurrence of HW events in the CA_S. ds-0 denotes the day when HW events begin, ds-1 (+1) denotes one day before (after) ds-0; de+0 denotes the day when HW events end, de+1 denotes one day after the end of HW events, etc. Thick black rectangle denotes the location of CA_S. Dot denotes significance at the 95% confidence level according to student’s t test. For the winds, black vectors indicate that either the zonal (vertical) or meridional wind anomaly is significant.
Figure 7. As in Fig. 6, but for composite maps of the evolution of (1st column) anomalous Tmax, (2nd column) anomalous surface pressure, (3rd column) Tmean (shading) and anomalous 10m wind, and (4th column) anomalous precipitation before, during and after the occurrence of HWs in the CA_S. For the winds, black vectors indicate that either the zonal or meridional wind anomaly is significant.
Figure 8. As in Figure 5, but for the composite results of the HW events in CA_N and the difference in y-axes.
Figure 9. As in Figure 6, but for the results of HW events in CA_N.
Figure 10. As in Fig. 6, but for composite maps of the evolution of (1st column) wind at 10m and anomalous Tmax, (2nd column) anomalous surface pressure, (3rd column) Tmean (shading) and anomalous 10m wind, and (4th column) anomalous precipitation before, during and after the occurrence of HWs in the CA_N.
Figure A1. Climatology and linear trend of HDs (a, b), HWN (c, d) and HWD (e, f) during 1979-2016 derived from the BEST gridded data in North Hemisphere. Dot denotes significance at the 95% confidence level according to student’s t test. Black boxes donate the CA region.
Figure A2. Time series of the annual number of regionally-averaged (a) HDs, (b) HWN and (c) HWD (blue lines) in CA and their 9-year moving mean (red lines) derived from the BEST gridded data. R represents the correlation coefficients between the BEST and the ERA-Interim/ NCEP2, respectively.