


## RESEARCH ARTICLE

# Impacts of El Niño–Southern Oscillation on heat waves in the Indochina peninsula

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National Natural Science Foundation of China, Grant/Award Number: 41871029, 41401052

This study examines the impacts of El Niño–Southern Oscillation on the frequency, duration, magnitude, and timing of heat waves (HWs) in the Indochina Peninsula during 1979–2017. It is found that preceding winter El Niño (La Niña) events prominently amplify (weaken) the HWs in most areas of Indochina by increasing (decreasing) the occurrence of HW events and the number of participating HW days, prolonging (shortening) the duration, and elevating (reducing) the amplitude of such events. These influences are even stronger for severe HWs (i.e., longest and hottest events) than for regular ones with average duration and intensity. Further examinations show that the atmospheric circulation during El Niño events is featured by a weakened Walker circulation that is characterized by an anomalously sinking motion over the western North Pacific (WNP) and Asia and a rising motion over the eastern tropical Pacific. The anomalous subsidence over WNP/Asia is accompanied by suppressed precipitation, and the WNP anticyclone is also enhanced and moves more westward. These patterns are in accordance with the atmospheric controls of HWs in Indochina, thereby favoring the occurrence and sustenance of HW events in the peninsula. La Niña event causes the mostly opposite changes of El Niño, thus inhibiting the HW activities in Indochina.

**KEYWORDS**

El Niño–Southern, Oscillation, extreme climate event, heat wave, Indochina

**1 | INTRODUCTION**

Heat waves (HWs) exert notable influences on human health and the natural and ecological environment (Easterling *et al.*, 2000; Kovats and Kristie, 2006; McMichael *et al.*, 2006; Forzieri *et al.*, 2017). Under global warming, such events have been increasing remarkably in the past decades, and are projected to intensify in the coming decades (Cowan *et al.*, 2014; Kunkel *et al.*, 2010). In addition to these long-term trends, the synoptic and atmospheric characteristics accompanying HWs in various sectors have also been examined in many previous studies using both observations and model simulations (Grotjahn *et al.*, 2016; Lu and Chen, 2016; Ward *et al.*, 2016; Luo and Lau, 2017).

At synoptic scale, HWs in many regions are accompanied by increased surface pressure, suppressed precipitation, and anomalously sinking air motion (Loikith and Broccoli, 2012). Atmospheric blocking is also an important factor for HWs in Europe (Sillmann and Croci-Maspoli, 2009; Dole *et al.*, 2011). HWs in Asian sector are accompanied by high surface pressure, low-level anticyclone, decreased precipitation, and increased solar radiation (see a review by Lu and Chen, 2016). The westward extension or intensification of the western North Pacific (WNP) subtropical high acts as a dominant contributor to HWs in Asia (Ding *et al.*, 2010; Luo and Lau, 2017; Zeng *et al.*, 2017).

At the interannual scale, HWs in East Asian sector are related to the East Asian jet stream, Asian monsoons, and

the El Niño–Southern Oscillation (ENSO) as well (Hu *et al.*, 2013; Wang *et al.*, 2013; 2014; Luo and Lau, 2017; Chen *et al.*, 2018). As a major source of climate variability at both global and regional scales (Ropelewski and Halpert, 1987; Trenberth, 1997; Chang *et al.*, 2000; Wang *et al.*, 2000; Wu and Wang, 2002; Lau and Nath, 2006; Li *et al.*, 2010), ENSO poses significant impacts on hot extremes in many regions such as the Australian, European, Indian, and American sectors (Della-Marta *et al.*, 2007; Kenyon and Hegerl, 2008; Arblaster and Alexander, 2012; White *et al.*, 2014; Murari *et al.*, 2016; Sun *et al.*, 2016). For instance, extreme maximum temperatures are significantly cooler over Australia, Canada, and South Africa during strong La Niña events than El Niño events and warmer over the American sector (Arblaster and Alexander, 2012). The association between hot extremes in southeastern China and ENSO–monsoon coupled systems has also been revealed by Wang *et al.* (2014). More recently, Luo and Lau (2018a) suggested that, compared to those in non-El Niño, HWs in most parts of China are significantly prolonged during El Niño summers.

These studies greatly contribute to enhancing our understanding of HWs. Nevertheless, much fewer investigation has been conducted to extreme climate events in developing Asian countries such as the Indochina Peninsula (Supari *et al.*, 2017; Ge *et al.*, 2018; Luo and Lau, 2018b). The peninsula is located between the Indian Ocean (IO) and Pacific Ocean (PO) (Figure 1a), and its climate is characterized by South and East Asian monsoons, both of which have a close association with ENSO at the interannual scale. The long-term trend, synoptic behaviors, and atmospheric controls of HWs in Indochina have been examined in our previous study (Luo and Lau, 2018b). However, the interannual variations of HW activities in this region have not been understood. To gain a more comprehensive understanding of HWs

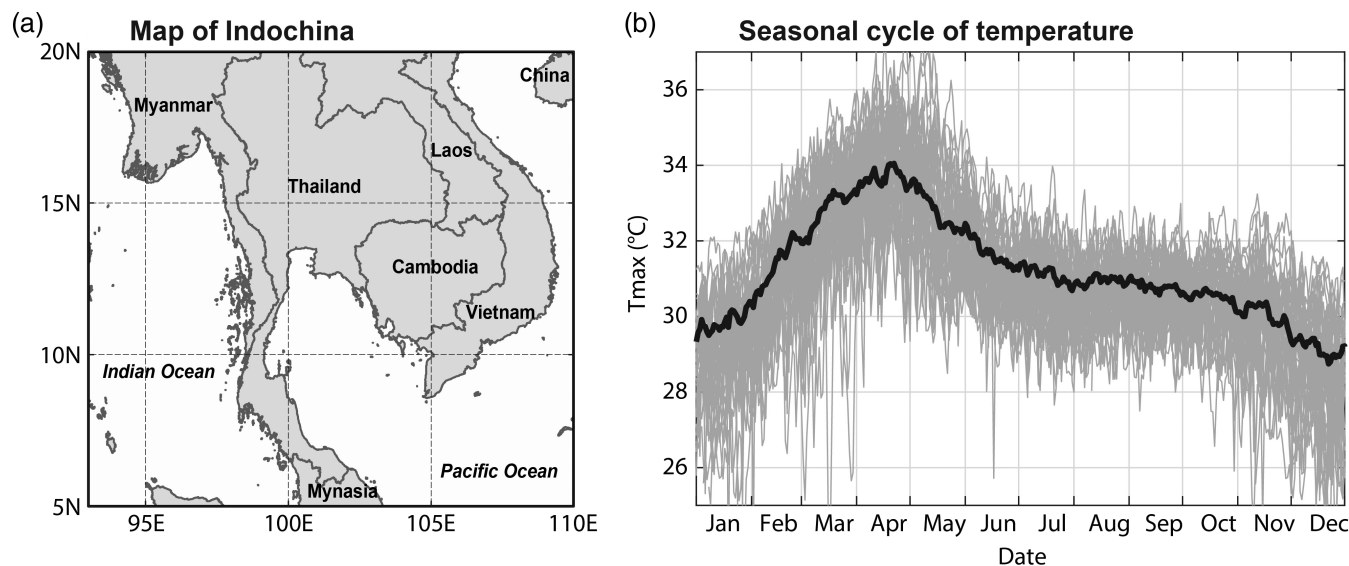
across the Indochina Indochina, in the present study, we wish to examine the impacts of ENSO on the frequency, duration, and amplitude of HWs in Indochina at the inter-annual scale.

The rest of this paper is organized as follows. Section 2 introduces the datasets and method used in this study. The impacts of ENSO on various aspects of HWs in Indochina are examined in Section 3, and the possible mechanisms underlying these effects are also discussed. Section 4 summarizes the primary findings of this study.

## 2 | DATASET AND METHODOLOGY

The climate over Indochina is characterized by tropical monsoon circulations, with a prominently hot season from March to May (Figure 1b). The mean daily maximum temperature ( $T_{\max}$ ) in this season is higher than  $32^{\circ}\text{C}$ , and high temperatures and HWs regularly occur in this season. In the current research, daily  $T_{\max}$  data in the Indochina Peninsular in March–May over the period of 1979–2017 is collected from the CPC Global Temperature dataset provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, at <https://www.esrl.noaa.gov/psd/>. The dataset has a spatial resolution of  $1 \times 1^{\circ}$ . Besides, we also use the NCEP/NCAR Reanalysis I dataset (Kalnay *et al.*, 1996) to reveal possible mechanisms underlying the ENSO–HW relationship.

HW events are identified separately for each grid based on its corresponding daily  $T_{\max}$  time series. To identify HW event, we adopt the definition of Lau and Nath (2014) and Luo and Lau (2017). First, the 90th ( $T_1$ ) and 75th ( $T_2$ ) percentiles of the population of daily  $T_{\max}$  values over the reference period 1961–1990 are computed. Then an HW event at a grid is defined when its  $T_{\max}$  is higher than  $T_1$  for three consecutive days or more, when the event-averaged value of



**FIGURE 1** Map of Indochina (a) and the climatological annual cycle of daily  $T_{\max}$  in Indochina during 1979–2017 (b). Light curves in (b) indicate the annual cycles for individual years

**TABLE 1** Definitions of HW measures used in this study and their anomalies during El Niño and La Niña years in 1979–2017

Category	Measure	Definition	El Niño	La Niña
Frequency	HWN	Yearly number of HW events (events)	+0.58	−0.58
	HWF	Yearly sum of participating HW days (days)	+9.72	−7.40
Duration	HWD	Length of the longest yearly event (days)	+4.64	−3.30
	HWL	Average length of all yearly events (days)	+2.44	−1.87
Amplitude	HWA	Hottest day of the hottest yearly event (°C)	+0.53	−0.62
	HWM	Average magnitude of all yearly events (°C)	+0.15	−0.21

$T_{\max}$  is higher than  $T_1$ , and when  $T_{\max}$  is higher than  $T_2$  throughout the event. To gain a comprehensive understanding of HW activities, we focus on eight different metrics of HW including frequency, duration, and magnitude, as defined in Table 1. To emphasize the interannual variation, the long-term trends in HW measures are removed using linear regression.

ENSO events are identified by the Niño3.4 index, which is obtained from the NOAA Climate Prediction Center at [http://www.cpc.noaa.gov/products/analysis\\_monitoring/enso\\_stuff/ensoyears.shtml](http://www.cpc.noaa.gov/products/analysis_monitoring/enso_stuff/ensoyears.shtml). A mature El Niño (La Niña) event is defined when the boreal winter Niño3.4 index is larger (smaller) than  $0.9$  ( $-0.9$ )°C, as suggested by Chou *et al.* (2003) and Li *et al.* (2014). An ENSO spring is then defined as the months of March, April, and May following the mature phase of ENSO. Thus, the seven El Niño springs of 1983, 1987, 1992, 1995, 1998, 2010, and 2016, and the six La Niña springs of 1985, 1989, 1999, 2000, 2008, and 2011 are analyzed in this study to assess the impacts of ENSO on HWs in Indochina.

### 3 | RESULTS

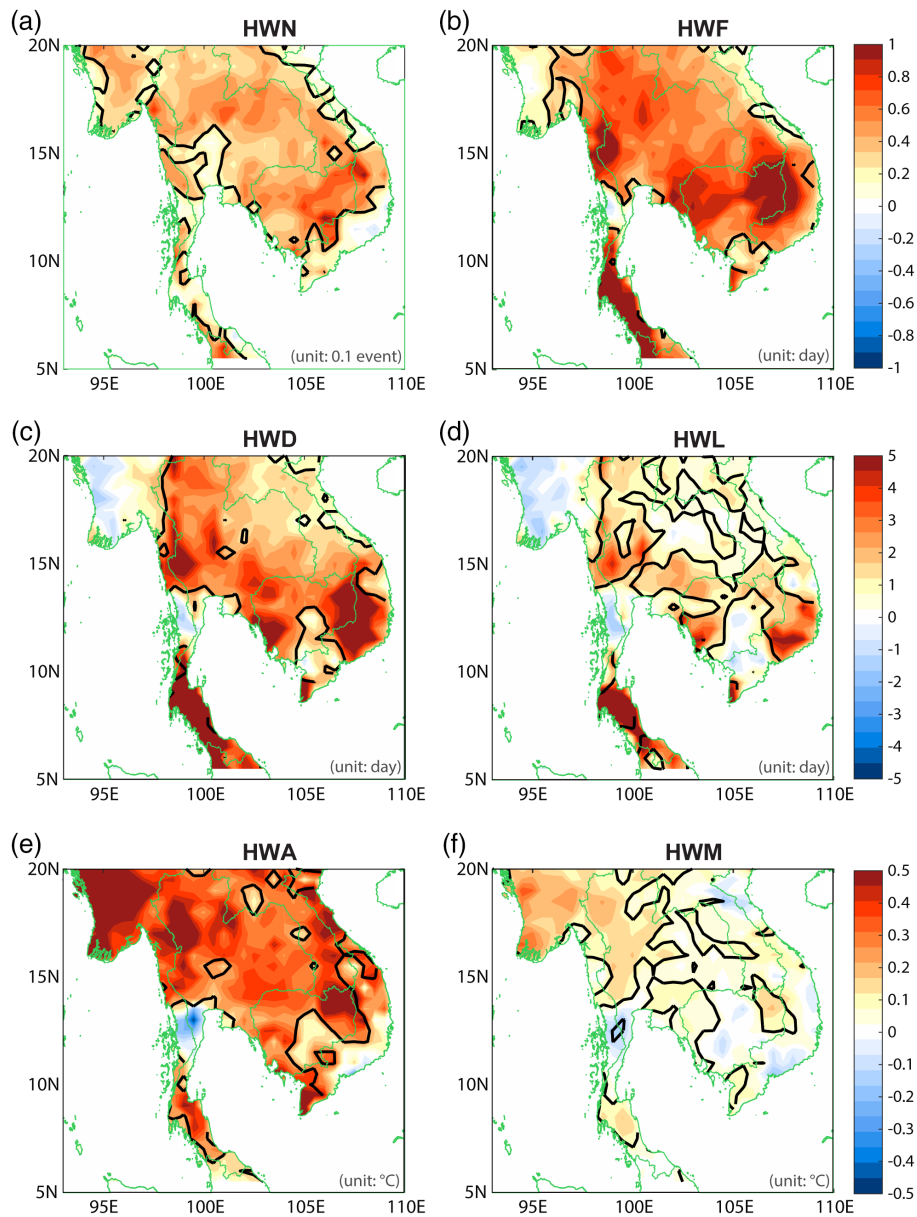
To examine the possible impacts of ENSO on HWs, we first calculate the regression coefficients of the detrended HW measures onto the preceding winter Niño3.4 index. These results are shown in Figure 2. It indicates that all aspects of HWs, including frequency, duration, and amplitude, in most parts of Indochina are stronger during El Niño events than La Niña events. To highlight the contrast between El Niño and La Niña events, boxplots of HW measures are also created for HWs at all land grid points in Indochina (Figure 3). The figure further demonstrates that El Niño prominently intensifies HWs in Indochina, while La Niña weakens these events.

Specifically, as indicated in Figure 2a,b and Table 1, HWN and HWF in nearly all parts of the Indochina Peninsula during El Niño years are larger than the corresponding measures during La Niña years. On average, there are 0.58 more HW events and 9.72 more HW days per year during El Niño, while La Niña years have 0.58 fewer events and 7.40 fewer HW days per year (Table 1 and Figure 3a,b). The durations of HW in most parts of Indochina are also longer during El Niño than in La Niña episodes (Figures 2c,d and

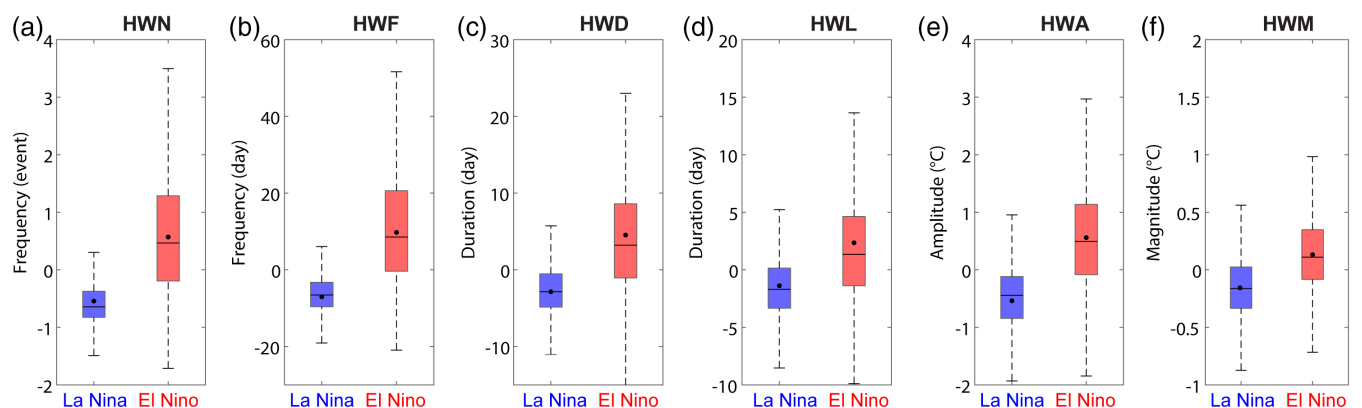
3c–d). The prolonging/shortening effects of El Niño/La Niña on the duration of the longest yearly HW event (note the increase of HWD by +4.64 days during El Niño and decrease by −3.3 days during La Niña) are stronger than the effects on the average duration of all yearly events (note the increase of HWL by +2.44 days during El Niño and decrease by −1.87 days by during La Niña). This result signifies that the impacts of ENSO on extreme long-lived HW events are stronger than the impacts on the more general events with average lifespans.

Besides frequency and duration, Figure 2e and f shows that most areas of Indochina bear more intense HW events during El Niño than during La Niña years. The patterns of HWA and HWM are similar to those for HW frequency and duration (see Figure 2a–d). During El Niño, the intensities of the HW at most grids are increased. By comparing Figure 2e and f (see also Figure 3e,f), it is noted that the effect of El Niño on the amplitude of the hottest HW event of the year (i.e., HWA) is larger than the effect on the averaged amplitude of all events in the calendar year (i.e., HWM). This finding again suggests that intense HW events are substantially more amplified by El Niño than those events with average intensity. The results for HWA and HWM in Table 1 and Figure 3e,f confirm that El Niño (La Niña) has an amplifying (weakening) effect of  $0.53^{\circ}\text{C}$  ( $0.60^{\circ}\text{C}$ ) for the yearly hottest event. These perturbations are approximately three times larger than the corresponding effects on the average HW amplitude, that is,  $0.15^{\circ}\text{C}$  ( $0.21^{\circ}\text{C}$ ) for El Niño (La Niña).

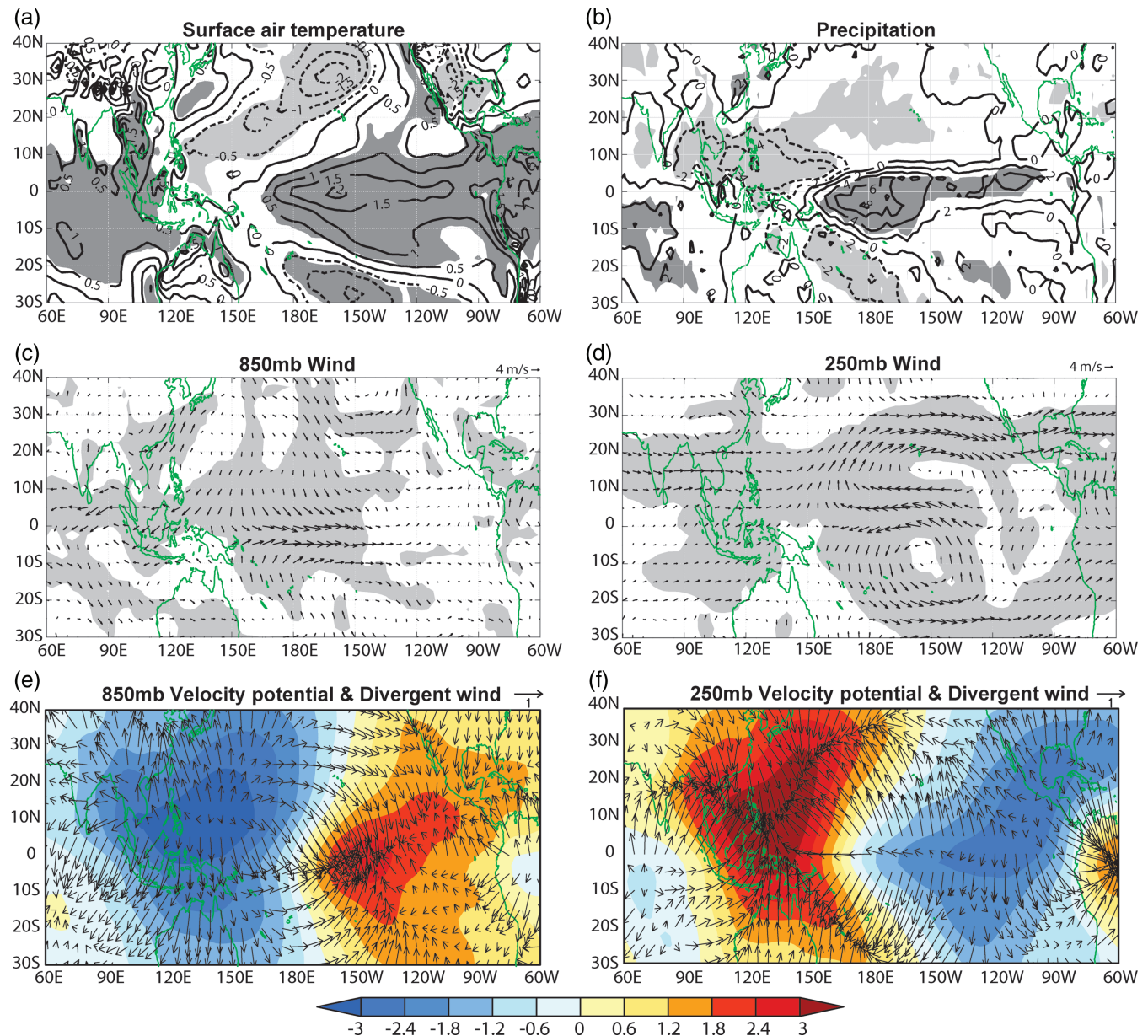
In our previous study (Luo and Lau, 2018b), we found that HWs in Indochina in spring season are accompanied by suppressed precipitation, and anomalously drier and sinking air motion over the Indochina. During HWs, Indochina is also covered by anomalous westerly and southwesterly prevails over the East Asian region, showing a weakening of the East Asian winter monsoon circulation (see Figure 10a of Luo and Lau, 2018b). Here, we perform a composite analysis of the prevalent atmospheric conditions in El Niño and La Niña years to elucidate how ENSO events act on these HW-related synoptic and atmospheric circulations. These composite charts are produced from the differences between the El Niño and La Niña events. It is noted that we examine the composite charts for El Niño and La Niña episodes independently and found that their results are mostly opposite to each other. Therefore, we present the composite charts of the



**FIGURE 2** Regression of detrended (a) HWN, (b) HWF (scaled by  $10^{-1}$ ), (c) HWD, (d) HWL, (e) HWA, (f) HWM, (g) HWO, and (h) HWE with the winter Niño3.4 index during 1979–2017. Thick contour indicates significance at the 0.05 level



**FIGURE 3** Boxplots of the detrended (a) HWN, (b) HWF, (c) HWD, (d) HWL, (e) HWA, (f) HWM, (g) HWO, and (h) HWE in Indochina during El Niño (red) and La Niña (blue) events of 1979–2017. Dots denote their corresponding means



**FIGURE 4** Difference of (a) surface air temperature, (b) precipitation, (c) and (d) 850- and 250-mb wind, and (e) and (f) 850- and 250-mb velocity potential (shading) and divergent wind (vector) between El Niño and La Niña springs of 1979–2017 (i.e., El Niño minus La Niña). Solid (dashed) contour in (a) and (b) denotes positive (negative) difference, with dark (light) shading denoting positive (negative) difference significant at the 5% level. Shading in (c) and (d) denotes significance at the 5% level for either zonal or meridional components

differences between the El Niño and La Niña events (i.e., El Niño minus La Niña), as shown below.

Figure 4a,b gives the composite differences in surface air temperature and precipitation between El Niño and La Niña years. During El Niño episodes, anomalously warming surface air temperature appears over the eastern tropical PO, the entire northern IO, and the Indochina Peninsula (Figure 4a). The increased temperature over Indochina is consistent with the intensified HW activity in the peninsula. In addition, as shown in Figure 4b, there is less precipitation in El Niño than in La Niña years over the WNP region and northern IO. These suppressed precipitation anomalies also cover all parts of Indochina. Such drying conditions associated with

El Niño can also contribute to the amplified HW activity in the peninsula.

The composite differences in wind field at 850-mb and 250-mb levels are depicted in Figure 4c,d. Prominent westerly wind anomalies appear in central tropical PO, and an anomalous low-level anticyclone is observed over the WNP region (Figure 4c). The strengthened WNP anticyclonic pattern is associated with anomalous westerly wind over Indochina and southwesterly winds over East Asia. This feature is consistent with the wind patterns that accompany the HW events in Indochina (see Figure 10a of Luo and Lau 2018b). At the 250-mb level (Figure 4d), an anomalous anticyclonic circulation appears over southeastern China, and strongly

anomalous westerlies prevail over subtropical Asia (i.e., 20–25°N) and western tropical PO. Again, these results agree well with upper-level circulation pattern accompanying the HWs in Indochina (see Figure 10c of Luo and Lau, 2018b). These findings indicate that El Niño induces similar circulation conditions to the atmospheric controls of HWs in Indochina. That is, El Niño provides a favorable atmospheric background for the occurrence and persistence of HWs in Indochina.

The composite charts for velocity potential and divergent wind are also examined in Figure 4e,f. During El Niño (Figure 4e), one large-scale convergence center (which corresponds to positive velocity potential anomaly) in the lower atmosphere over the eastern tropical PO and one divergence center (which corresponds to negative velocity potential anomaly) over the WNP region. In the upper atmosphere, divergence and convergence centers are, respectively, seen over the eastern tropical PO and the WNP region (Figure 4f). These circulation features show an anomalously weakened Walker circulation. This weakened Walker circulation consists of one rising branch over the eastern tropical PO and one sinking branch over the WNP region. The sinking branch also covers the northern IO and most parts of Asia and Australia. This anomalously sinking branch weakens the convective activities over the Asia-western Pacific areas, in accordance with less-than-normal precipitation over these areas (see Figure 4b). Meanwhile, this sinking anomaly and its reduced precipitation can increase the latent heat release over the WNP region, thus intensifying the WNP anticyclone as well (see Figure 4c).

Based on the above analysis, we can depict the mechanisms underlying the influences of ENSO on HWs in Indochina. During El Niño, warming anomalies in eastern tropical PO lead to warming in the atmosphere and such changes propagate to the WNP/Asia region via the modification of the Walker circulation. This anomalous Walker circulation is characterized by a sinking branch over the WNP/Asia and rising branch over eastern tropical PO. The former decreases the precipitation over the same area and strengthens the WNP anticyclone and moves it more westward to Asia. The suppressed precipitation and drying atmosphere over these areas is favorable for the HWs in Indochina. Meanwhile, the strengthened WNP prevails westerly and southwesterly wind over the Indochina and East Asia, consistent with atmospheric controls of HWs in Indochina (see Figure 10 of Luo and Lau, 2018b). These changes together create an advantageous environment for the occurrence and sustenance of HWs in the Indochina Peninsula. In the case of La Niña, it mostly causes the opposite changes of El Niño, thus inhibiting the HW activities in Indochina.

#### 4 | SUMMARY

The impacts of ENSO on the HW activities in the Indochina Peninsula are examined in this study. It is found that the

frequency, duration, and amplitude of HWs in most parts of Indochina are amplified during El Niño years and weakened during La Niña years. These effects exerted by ENSO are even more substantial for the extreme HW events with the longest duration or highest amplitude than regular ones. ENSO affects HWs in Indochina mainly via the modification of the Walker circulation. El Niño induces an anomalous circulation pattern that is characterized by low-level convergence (high-level divergence) centers over the eastern tropical PO and a low-level divergence (high-level convergence) center over the WNP/Asia region. The enhanced subsidence over the WNP/Asia region is accompanied by suppressed precipitation and the intensification and westward extension of the WNP anticyclone, thus providing a more favorable environment for enhancing HW activities in Indochina. In the case of La Niña events, these changes are reversed, and the HWs in Indochina are weakened.

Previous studies in the literature raise our concern with intensifying trends of HW events. It is documented that long-term trends in HW characteristics are associated with global warming, and human activities also contribute to these trends (Christidis *et al.*, 2011; Coumou and Rahmstorf, 2012). The results of our study indicate that, under global warming background, ENSO is also an essential factor for modulating HW activity. Some recent studies suggested more frequent occurrences of strong El Niño events under global warming (Cai *et al.*, 2014; Chen *et al.*, 2017; Xia *et al.*, 2017). If such an association between El Niño and global warming indeed exist, then global warming may further intensify HW events indirectly through its impacts on ENSO activity. In the relationship of ENSO and HWs revealed in our study, it is likely that HWs in Indochina will become even more frequent and stronger in the future.

#### ACKNOWLEDGEMENT

This study was funded by the National Natural Science Foundation of China (No. 41871029, 41401052).

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**How to cite this article:** Lin L, Chen C, Luo M. Impacts of El Niño–Southern Oscillation on heat waves in the Indochina peninsula. *Atmos Sci Lett*. 2018;19:e856. <https://doi.org/10.1002/asl.856>