The health burden of fall, winter and spring extreme heat events in Southern California and contribution of Santa Ana Winds

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Abstract

Background: Extreme heat is associated with increased morbidity but most studies examine this relationship in warm seasons. In Southern California, Santa Ana winds (SAWs) are associated with high temperatures during the fall, winter and spring, especially in the coastal region. Objectives: Our aim was to examine the relationship between hospitalizations and extreme heat events in the fall, winter and spring, and explore the potential interaction with SAWs. Methods: Hospitalizations from 1999–2012 were obtained from the Office of Statewide Health Planning and Development Patient Discharge Data. A time-stratified case crossover design was employed to investigate the association between off-season heat and hospitalizations for various diagnoses. We examined the additive interaction of SAWs and extreme heat events on hospitalizations. Results: Over 1.5 million hospitalizations occurred in the Southern California coastal region during non-summer seasons. The 99th percentile-based thresholds that we used to define extreme heat events varied from a maximum temperature of 22.8 °C to 35.1 °C. In the fall and spring, risk of hospitalization increased for dehydration (OR: 1.23, 95% CI: 1.04, 1.45 and OR: 1.47 95% CI: 1.25, 1.71, respectively) and acute renal failure (OR: 1.35, 95% CI: 1.15, 1.58 and OR: 1.39, 95% CI: 1.19, 1.63, respectively) during 1-day extreme heat events. We also found an association between 1-day extreme heat events and hospitalization for ischemic stroke, with the highest risk observed in December. The results indicate that SAWs correspond to extreme heat events, particularly in the winter. Finally, we found no additive interaction with SAWs. Discussion: Results suggest that relatively high temperatures in non-summer months are associated with health burdens for several hospitalization outcomes. Heat action plans should consider decreasing the health burden of extreme heat events year-round.

1. Introduction

In the context of increasing global temperatures due to climate change, recent attention has been given to study the population health effects of ambient heat. Heat waves are the extreme events associated with the most fatalities in the United States in the last 30 years, surpassing those attributed to flooding, hurricanes and tornadoes (NOAA 2018). Due to frequent extreme weather events and droughts experienced in recent years, California is an ideal region to study climatic influences on health (Mann and Gleick 2015). Additionally, projections show that the frequency, intensity and duration of extreme heat events is expected to continue to increase in California under climate change (Gershunov and Guirguis 2012). Heat-related health impacts during the warm season have been well documented in California; positive associations have been found between same-day apparent temperature and emergency hospital admissions from ischemic heart disease, ischemic stroke, cardiac dysrhythmia,
intestinal infection, dehydration, acute renal failure and heat illness (Knowlton et al 2009, Basu et al 2012, Guirguis et al 2014).

California’s coastal zone is a region of rapidly changing extreme heat event expressions and increasingly vulnerable in terms of observed heat-health impacts (Gershunov and Guirguis 2012, Guirguis et al 2014, 2018), likely due to limited physiological and technological acclimation (Guirguis et al 2018). With its moderate temperature year-round, areas of California also experience relatively high temperatures during the fall (September, October, November), winter (December, January, February) and spring (March, April, May), with average maximum temperatures of 25 °C, 20 °C, and 22.0 °C, respectively, in the Southern California coastal region averaged over 1999–2012 using daily gridded temperature data (Livneh et al 2015) (see figure 1). Research has found a significant impact emerging at temperatures of 22.7°C in the coastal region of San Diego County (Guirguis et al 2018). Additionally, in a study conducted in Maricopa county, Arizona, minimum risk temperature was found to be 22 °C for heat-related hospitalizations (Petitti et al 2015). These studies indicate that even moderate heat drives health impacts. Moreover, it has been recently suggested that the health burden of relative heat extends beyond the summer season; one study found higher mortality in the presence of hot and dry conditions in Los Angeles County during the winter months, associated with 4.4 total excess deaths per day (Kalkstein et al 2018).

However, by focusing on all-cause mortality, this previous study did not capture heat-morbidity signals or consider specific diagnoses, which may underestimate the overall impact of heat. In addition, all-cause mortality rather than specific diagnoses were considered. A study conducted in Australia also showed that warm spring temperatures were associated with increased hospital admissions for acute myocardial infarction specifically (Loughnan et al 2014).

Santa Ana winds are dry down-sloping winds rooted in cold air masses over the elevated Great Basin, which heat by compression (adiabatically) as they descend to sea level (Guzman-Morales et al 2016). They are a unique weather phenomenon in Southern California that occur primarily between September and May (Guzman-Morales et al 2016), and often lead to increased ambient temperatures during the typically ‘colder’ fall, winter and spring seasons. Santa Ana winds are associated with some of the hottest temperatures recorded in the Southern California coastal region. Santa Ana wind-generated cool season coastal extreme heat events are a special class of extreme heat events impacting the coastal region, and they are likely to become less frequent but warmer in the future (Hughes et al 2011, Guzman-Morales and Gershunov 2019). The spatially-explicit coastal expression, seasonality, and extreme dryness make SAW-driven extreme heat events unique among other types of heat waves in California (Gershunov and Guirguis 2012). SAWs have recently been linked to improved air quality, except, when they fan wildfire upwind, for which they are notorious for increasing air pollutant concentrations (Aguilera et al 2019). A study published in 1996 investigated the association between SAWs and asthma exacerbations in a Southern California emergency department and found higher admission rates during SAW events, but it did not consider their association with heat (Corbett 1996).

In this study, we examined the association between extreme heat events, Santa Ana winds and hospitalizations in the densely populated Southern California coastal region. This is one of the first studies to explore the relationship between off-season extreme heat events and morbidity, and further assess the contribution of SAWs. First, we examined the proportion of extreme heat events that are driven by SAWs. Second, we explored the burden of extreme heat events occurring in the fall, winter and spring on hospitalizations for various causes in the coastal region of Southern California. Lastly, we explored the influence of SAWs in the association between extreme heat events and hospitalizations to understand the association between SAW events and heat-related health outcomes. These results are important to better understand the implications of SAWs and extreme heat events on morbidity and inform policy to reduce the associated health burden. Future warming may intensify extreme heat events and may increase the health burden in all months, and it is urgent to adapt to these newly identified risks.

2. Materials and methods

2.1. Study population

As SAWs have been shown to be associated with high ambient temperature in the coastal region, this study focused on the coastal Southern California region, delineated by climate zones 6, 7, 8 and 9 (California 2017). This was further restricted to the rectangular area defined by (118.115°W, 35.081°N) at the NW point to (116.035°W, 32.053°N) at the most SE point, as previously outlined to study SAWs (Guzman-Morales et al 2016). The Zip Code Tabulation Areas (ZCTAs) included in this geographical area were ascertained using ArcGIS mapping software (ESRI 2017). ZCTAs were aggregated by the four climate zones considered in the study for analysis. The study population included all hospitalizations for the health outcomes of interest of residents in the defined study area from 1999–2012.

2.2. Hospitalization data

Unscheduled hospitalizations in California from 1999–2012 were obtained from the Office of Statewide Health Planning and Development Patient Discharge Data. Variables of interest included ZCTA,
day of the week, and hospitalization outcome, which was aggregated into daily counts for each ZCTA within the coastal domain. Hospitalization diagnoses were selected based on previous studies investigating heat and hospitalizations in California (Green et al 2010, Basu et al 2012). The following ICD-9 codes were considered: acute renal failure (584), cardiovascular diseases (CVD) (390–459) [including acute myocardial infarction (MI) (410), cardiac dysrhythmias (427), essential hypertension (401), ischemic heart disease (410–414), ischemic stroke (433–436)], dehydration/volume depletion (276.5), heat illness (992), mental health (290–319), and respiratory disease (460–519) (Control CfD, Prevention 2014).

2.3. Exposure data
Temperature data were downloaded from a publicly available dataset that collects data from approximately 20,000 National Ocean and Atmosphere Administration Cooperative Observer (NOAA COOP) stations across the United States (Cal-Adapt 2015). The data is based on meteorological station observations interpolated to a regular grid (1/16° × 1/16°) using the synergraphic mapping system (SYMAP) algorithm (Livneh et al 2015). Daily maximum and minimum temperature (°C) were derived from these 1/16° (~6 km) grid-ded observed data for all of California (Livneh et al 2015). Population-weighted centroids for each ZCTA were linked to the nearest temperature measurement using the geonear function in Stata15 SE. The distance from each centroid to a temperature measurement data point did not exceed 6 km. We used the daily Santa Ana Winds Regional Index (SAWRI) to represent Santa Ana winds. The SAWRI is defined as the regional mean wind speed (m s⁻¹) over the SAW domain located on the Southern California
and Northern Baja California region; the index is set to zero during non-Santa Ana conditions. The detailed description of the SAW domain and index has been previously described (Guzman-Morales et al 2016). Particulate matter data (PM$_{2.5}$) from 2002–2012 was downloaded from the U.S. EPA Community Multiscale Air Quality Modeling System and considered at the ZCTA level (EPA 2018).

In this study, extreme heat events are defined as the maximum temperature exceeding the 99th percentile threshold of the temperature distribution for each ZCTA for each season from 1999–2012. As several published studies have demonstrated effects of high temperature on morbidity in California in the warmer months (Green et al 2010, Basu et al 2012, Guirguis et al 2014, 2018), we chose to focus on the fall, winter and spring heat events in this study. Extreme heat events defined by the temperature distribution within the following seasons were considered for analysis: fall (September–November), winter (December–February), and spring (March–May). Extreme heat events were defined based on the relative scale in order to account for the hottest days within each season; monthly extreme heat event definitions were also created, and were defined as temperature exceeding the 99th percentile threshold during each month in the September-May time period, considering the days of extreme heat within each individual month. All definitions were considered as one or two-day extreme heat events, which is when the temperature exceeds the 99th percentile threshold for two consecutive days. Minimum temperature was also examined using the same thresholds as a supplementary analysis. One and two day heat events were considered, therefore extreme heat events and heat waves were used interchangeably in his manuscript.

To study the relative influence of SAWs, the relationship between SAWs and extreme heat events was evaluated. The percentage of extreme heat events that occurred during SAW events were calculated by season, month and climate zone. The relative excess risk due to interaction (RERI) of SAW was calculated for each extreme heat event definition and hospitalization outcome to determine if there is any additive effect of SAW on hospitalizations associated with extreme heat events.

2.4. Statistical analysis
A time-stratified case crossover design was used to study the association between extreme heat events and each hospitalization outcome (Basu et al 2008, Basu and Ostro 2008, Tong et al 2012). The methodology resembles the design and analysis of a case-control study, but controls are identified for the same individual as the cases in the study population; therefore, only time-varying variables are considered as covariates. Control days were selected based on the same day of the week of the hospital admission within the same month and year that the case occurred. The 99th percentile was chosen for the definition of extreme heat events for this analysis. By using this threshold, the analysis was restricted to shorter extreme heat event events (<7 d); this was to ensure no event overlapped with our defined control days.

A conditional logistic regression model was employed to study the association between extreme heat events and hospitalizations in each season and for each hospitalization diagnosis. A variable was created with weekly count of hospitalizations from influenza by climate zone to account for influenza incidence. A sensitivity analysis included continuous daily particulate matter (PM$_{2.5}$) as an additional covariate. Analyses were conducted for extreme heat in each season and hospitalization diagnosis for the entire region and by climate zone. Additional analyses were conducted considering extreme heat at the monthly level, as well as an aggregate of the monthly heat events for each season. The number of hospitalizations attributable to extreme heat events were also estimated for each season/month and diagnosis combination, by calculating an attributable fraction while accounting for the baseline hospitalization rate and number of extreme heat days.

To study the influence of SAWs, a binary variable was used based on the SAWRI index (Guzman-Morales et al 2016). Any positive SAWRI was defined as a SAW day. SAW were considered as an independent exposure for the main hospitalization diagnoses of interest; risks were calculated for each season. The relative excess risk due to interaction (RERI) and 95% CI was estimated to determine if there was interaction on the additive scale for SAW events on effects of extreme heat events in the fall, winter and spring (Vanderweele and Knol 2014). This analysis estimates the magnitude of interaction between SAW and extreme heat events to understand if SAWs may exacerbate or attenuate the association between extreme heat events and hospitalizations. All analyses were conducted using Stata15 SE software.

3. Results
Our study population included over 1.5 million hospitalizations in the Southern California coastal region (figure 1). For example, this includes 55,805 cases of dehydration, and 48,043 cases of acute renal failure in the fall, winter and spring seasons from 1999–2012. Table 1 depicts the mean and standard deviation of daily hospitalizations recorded for each hospital diagnosis, ranging from a daily average of less than one case of heat illness in all three seasons to 230.2 average daily cardiovascular-related diagnoses during the winter. Approximately 2,800 ZCTA-days were considered extreme heat events using the seasonal 1-day measures using maximum temperature, while the number of ZCTA-days considered extreme heat events for the monthly
definitions ranged from 867 in February to 1088 in October as well as April (table S1 is available online at "stacks.iop.org/ERL/15/054017/mmedia"). Temperature thresholds for extreme heat events and the percentage that occurred during SAW events are also described in table 1. The lowest threshold for extreme heat events in all of the ZCTAs included in the study varied from 31.68 °C in September to 22.8 °C in December (table S1). The prevalence of SAW events ranged by season, with the highest percentage of SAW days in the winter (51.3%), and the fewest in the spring (8.9%) (table 1).

In exploring the association between extreme heat event days and SAW, there was some variability by climate zone, although no specific pattern was observed. However, extreme heat events in the winter appeared to relate most closely to SAWs (figure 2). When considering extreme heat events in each season, 22.5% occur on a day with a SAW event in the fall, while 89.3% and 35% occur in the winter and spring, respectively. Extreme heat events in November to March correspond more closely to SAW days when compared with other months in the study (table S1). In fact, 100% of extreme heat event days in January occurred on SAW days, and 92.8% of extreme heat event days in November (table S1). When considering the case-crossover analysis, differences in exposure to heat waves between case and control days are described in the supplementary material, showing similar distributions (table S2).

Results of the conditional logistic regression suggest associations between extreme heat events and morbidity, particularly in the fall and spring. Out of the diagnoses investigated, dehydration and acute renal failure appeared to be the most strongly associated with non-summer extreme heat events, and therefore, were selected to be highlighted in the remainder of the analysis (figure S1). Heat illness could not be used in this analysis due to its small sample size. The conclusions of the sensitivity analysis including particulate matter (PM$_{2.5}$) as a covariate stayed the same, so the remaining analyses were conducted without this variable, due to the sample size restriction related to including the variable (missing PM$_{2.5}$ data 1999–2001) (table S3). A sensitivity analysis was also conducted eliminating periods with major wildfire events in Southern California; conclusions did not change, although precision decreased in the effect of extreme heat on dehydration hospitalizations in the winter (table S4).

For the diagnoses related to volume depletion (acute renal failure and dehydration), the strongest association was observed during the fall and spring, while little or no effect was observed during the winter (figure 3). Out of the cardiovascular diseases, ischemic stroke had a particularly strong association with extreme heat events with the monthly definition in December (OR: 1.30, 95% CI: 1.10, 1.54) (table S5). Although some diagnoses and extreme heat event definitions suggested a negative association, the majority of hospitalizations had positive associations with extreme heat events (table S5). When exploring the spatial variability in the association between extreme heat events and hospitalizations, no outstanding pattern was detected by climate zone. For example, when stratified by climate zone, there was no specific pattern in the fall, winter and spring for the three diagnoses with the strongest relationship with extreme heat event events: ischemic stroke, dehydration and acute renal failure (figure S1). However, effects were observed for these three diagnoses when considering extreme heat in each season and for many of the months individually, particularly in April and May for dehydration and acute renal failure (figure S2). When estimating attributable hospitalizations, results also showed differing burden by extreme heat event definition; the highest burden was observed for respiratory diseases from extreme heat events in the Spring, with 779 excess hospitalizations (table S5).

A sensitivity analysis was also conducted to examine the potential role of morbidity displacement, following a similar approach to what has been proposed for mortality displacement related to heat events (Saha et al. 2013). As evaluated by previous research, displacement of extreme heat was considered up to 15 d after the extreme heat event (Saha et al. 2013). This sensitivity analysis was conducted for hospitalizations for dehydration driven by extreme heat in the fall and spring, where the strongest effects are observed. Results indicated no morbidity displacement within 15 d of extreme heat events in the fall or spring, as no protective effect was found in days following days of extreme heat (table S6). We also accounted for relative humidity in sensitivity analyses by redefining extreme heat events with apparent temperature and examining associations with acute renal failure and dehydration. Relative humidity was estimated to high-resolution gridded surface meteorological data (Abatzoglou 2013). Results were similar and conclusions remained the same (table S7).

When considering SAW as the exposure of interest, results indicated direct effects of SAW on hospitalizations (table S8). Although most diagnoses showed imprecise estimates, some effects could be observed, particularly in the spring for dehydration and respiratory disease. Lastly, findings from calculations of the relative excess risk due to interaction of SAW and extreme heat events indicated no strong association. RERI values ranged from negative to positive values, and the majority of confidence intervals included 0, demonstrating no statistically significant results (figure S3). The RERI for extreme heat events in January could not be calculated due to these events and SAW being coincidental during this month. In conclusion, we did not find evidence that SAWs exacerbate or attenuate impacts of extreme heat events on hospitalizations. Although SAWs may
Table 1. Summary of daily temperature, air pollution, extreme heat thresholds, percentage during Santa Ana winds, and total hospitalization counts by diagnosis (ICD-9 codes) for the fall, winter and spring in southern California coastal region, 1999–2012.

| Environmental variables          | Fall (Sep-Nov) mean ± sd | Winter (Dec-Feb) mean ± sd | Spring (Mar-May) mean ± sd |
|----------------------------------|--------------------------|---------------------------|---------------------------|
| Max temperature (°C)             | 25.5 ± 5.1               | 19.85 ± 4.1               | 22.2 ± 4.5                |
| Min temperature (°C)             | 13.8 ± 3.6               | 8.05 ± 2.8                | 11.4 ± 2.9                |
| Santa Ana Winds (% days)         | 25.1 ± 43.4              | 51.35 ± 50.0              | 8.9 ± 28.5                |
| Lowest threshold for extreme heat (°C) | 31.68                   | 25.35                     | 29.95                     |
| Extreme heat events during Santa Ana winds (%) | 22.5                  | 89.3                      | 34                         |

Hospitalization count

- Acute renal failure (584): 12.6 ± 6.9, 12.75 ± 6.9, 12.3 ± 6.8
- Cardiovascular (all) (390–459): 212.5 ± 35.8, 230.25 ± 38.0, 224.2 ± 37.9
- Dehydration (276.5): 12.8 ± 5.0, 17.25 ± 8.2, 13.8 ± 5.6
- Heat illness (992): 0.1 ± 0.4, 0 ± 0.1, 0.1 ± 0.3
- Mental Health (290–319): 13.1 ± 4.3, 12.25 ± 4.0, 13.1 ± 4.2
- Respiratory disease (all) (460–519): 115.2 ± 21.5, 184.65 ± 44.8, 139.1 ± 30.1

Time varying covariates

- PM2.5 (µg m⁻³): 15.5 ± 9.6, 15.15 ± 9.5, 11.9 ± 6.7
- Influenza (487.1) (average weekly counts for climate zones): 1.9 ± 6.4, 5.35 ± 8.7, 1.5 ± 2.5

Figure 2. The proportion of extreme heat events that occurred during Santa Ana Wind events in the fall, winter and spring season in Southern California coastal region, 1999–2012.

not intensify extreme heat event related hospitalizations, they drive morbidity impacts by increasing the prevalence of extreme heat events, especially from November to February.

4. Discussion

Results of our study suggested that relative ambient heat outside of the summer season is associated with a health burden for various hospitalization diagnoses (table S5). This shows that although the absolute temperature is lower for extreme heat events in the fall, winter and spring than extreme heat events typically recorded during the summer season, health effects are observed. Out of the hospitalization diagnoses investigated, dehydration and acute renal failure are most strongly associated with non-summer heat (table 2). Extreme heat events defined at temperature percentiles are a policy-relevant measures as they are distinct thresholds of ambient temperature that can be used to activate heat warning systems. Moreover, understanding the specific meteorological cause can provide important nuance to warnings and intervention strategies.

We find that the intersection of extreme heat events and SAWs by season and month indicate that they can be, but are not systematically, concurrent. While extreme heat events during certain months...
(ex: January) correspond systematically to days with SAW events, other months (ex: September, May) have a low proportion of extreme heat event days during SAWs. This is likely because the prevalence of SAW days is lower during these months (table 1), and shows that extreme heat events are more strongly associated with SAWs in the winter months.

The absence of an additive interaction of SAW in the association between extreme heat events and hospitalizations indicate that the health burden of extreme heat events does not increase or decrease during a SAW event. However, extreme heat events systematically correspond to SAW events, especially during winter months, when SAWs are most common (Guzman-Morales et al 2016). This information can be useful in understanding and predicting extreme heat event events and related health burden, as most public policies aimed at preventing heat related illness focus only on the warm season when California extreme heat events have different causes, humidity profiles, as well as expressions/evolutions in space and time (Gershunov et al 2009, Gershunov and Guirguis 2012, Clemesha et al 2018). This demonstrates the importance of continuing to study various types of extreme heat events to determine which is the best predictor of health impacts with respect to specific
meteorological causes as well as other environmental and societal contexts.

It is plausible that the health impacts of extreme heat events that are observed in fall, winter and spring which correspond to moderate temperatures on the absolute scale are related to the population's ability to acclimate to high ambient temperatures. A manuscript investigating the effect of heat on health in San Diego County by climate zone indicated a lower temperature threshold for which significant health effects emerge in the coastal region at 22.7 °C compared to 32.2 °C in the desert region and suggest this is due to differences in acclimation (Guirguis et al 2018). Heat acclimation has been found to improve the neural activation of regulatory processes that control body temperature in humans (Barry et al 2020). This can explain our findings for non-summer extreme heat events, as the exposed population is not acclimated to high temperatures in these seasons. This could also change health-protective behaviors, such as turning on the air conditioning or seeking a cooler space. Interestingly, we generally found stronger effects of extreme heat in the spring and hospitalizations (table S5), although the temperature thresholds are lower than for extreme heat events in the fall (table S1). This could indicate that the population is more susceptible in the spring season as they are not acclimated to heat following the winter season.

December is the month with the highest association with extreme heat event events for hospitalizations for ischemic stroke (figure S3). This specific effect observed could also be related to the lack of acclimation of the population to heat during the winter period; these extreme deviations from the temperature distribution of that month could make it difficult for non-acclimated biological systems to respond. Additionally, research has shown that day-to-day variations in temperature may increase risk of ischemic stroke (Kyobutungi et al 2005). Therefore, the high risk for ischemic stroke reported in December may be due to the extreme heat event days corresponding to sudden large deviations from the average maximum temperature for that month, increasing variation day-to-day and associated risk. It is thought that temperature variations can alter blood viscosity and coagulability, which can increase risk of stroke (Kyobutungi et al 2005). Interestingly, a systematic review considering effect of temperature did not find a positive association between heat and stroke morbidity (Lian et al 2015). Further work should be conducted to confirm our findings and explore the potential effect of climatic variability on hospitalizations for ischemic stroke.

This is one of the first research study investigating the morbidity burden associated with extreme heat events in the ‘cooler’ seasons in southern California. The only previous study to our knowledge that has investigated winter heat and health demonstrated that high winter temperature is associated with increased relative risk for mortality in Los Angeles County (Kalkstein et al 2018). Our study adds to these findings by demonstrating an explicit connection to a specific weather pattern (i.e. SAWs) and that, in addition to winter, an association was also observed between extreme heat events in the fall and spring and specific hospital diagnoses, particularly for dehydration and acute renal failure. Additionally, our results demonstrate that the health impacts of extreme heat events outside of summer months reach beyond all-cause mortality, increasing the risk of hospitalizations due to various causes.

There are limitations of this study that are important to acknowledge. Humidity, a time-varierring environment exposure included in some studies on extreme heat and health, was not included as a covariate in the analysis. However, as SAWs are associated with extremely dry air, this may not be an issue for this study; additionally, the sensitivity analysis indicated that our results were consistent when considering apparent temperature, a measure that accounts for relative humidity. Also, all extreme heat events in this study were defined at the 99th percentile to limit the number of extreme heat events given the study design and maximize covariate balance with control days. The caveat of this approach is that we were unable to detect thresholds at which health effects start to be observed. However, the purpose of this study was to identify extreme events based on well-defined thresholds for a season/month, which are more easily actionable. In the future, it would be useful to investigate specific thresholds in different coastal locations, diagnoses and population characteristics.

The low number of heat illness cases diagnosed in the fall, winter and spring limited our ability to analyze this outcome. Heat illness has been shown to be the diagnosis most strongly associated with extreme heat events in a recent study on the elderly population in the United States (Hopp et al 2018) but it has also been thought to be underdiagnosed due to the effect of heat on multiple organs in the body which can lead to misdiagnosis (Camilo et al 2017). Furthermore, heat illness is not typically recorded unless a documented extreme heat event occurs (surveillance bias), and non-summer extreme heat events are less likely to be reported.

As we are testing various definitions of extreme heat and hospitalization diagnoses, there may be a multiple testing problem since we may observe positive findings solely based on chance; however, we do not rely on statistical significance as the only factor to deem relevance of our results. In future research, we would also like to explore the possibility of long-term morbidity displacement as stronger fall heat may change the impact of heat in subsequent seasons.
Importantly, SAWs are associated with the largest wildfires in Southern California, particularly in the fall when vegetation is highly flammable after the dry summers, emblematic of California’s Mediterranean climate (Westerling et al 2004). The results of our study do not appear to be confounded by fine particulate matter or wildfire events (tables S3 and S4), but in future work, it would be important to understand how SAWs drive associations with air pollutants (Aguilera et al 2019) and separate them from that of extreme heat events. Lastly, the populations impacted by extreme heat event events may differ based on season. Outdoor workers, such as farmers and construction workers, as well as homeless people, have been shown to be particularly susceptible to summer extreme heat events (Harlan et al 2012, Xiang et al 2013, 2015). Now that we have identified that heat events can affect morbidity beyond the summer season, it will be interesting to explore how subgroups that are demonstrated to be more vulnerable to heat during the summer, such as the elderly or minority populations, may have differential risks in the fall, winter and spring.

Many cities and regions have incorporated heat action plans to provide a framework for implementing heat response activities during extreme heat events aiming to decrease the impacts of high heat events on health (Lowe et al 2011, WMO 2015). In California, the forecasting system has been recently updated to include extreme heat wave events; the National Weather Service experimental Health Risk Index is used as an early warning system to identify potential heat risks, which provides guidance to decision makers to take action (NWS 2019). In some cities, local heat action plans have been shown to be successful at reducing health impacts of heat (Benmarhnia et al 2016). The results of our study should be used to inform a specific heat action plan that activates interventions during an extreme heat event to decrease their impacts, even in the fall, winter and spring. We could also explore the use of SAWs for forecasting and monitoring extreme heat event events. Forecasts of SAW have been shown to be skillful with up to a 6–7 d lead time (Jones et al 2010); our results suggest that SAW may have a role in improved predictions of extreme heat events and could be used to activate heat action plans to reduce health impacts.

Our study shows that the burden of high ambient temperature in Southern California is occurring at unexpected times, outside of the summer months, and that SAW is an important contributor to these extreme heat events in the cool season. Other areas of the world with temperate fall, winter and spring seasons may be experiencing a similar burden of which they may be unaware. Thus, more research investigating the health effects of ambient temperature beyond the standard warm season in areas with temperate climates is needed. In Southern California, the health impact of all extreme heat events, including those that occur outside of summer, and notably those driven by SAW, should not be ignored.

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Data availability statement
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Declaration of competing interests
The authors declare they have no actual or potential competing financial interests.

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