The California Heat Wave 2006 with Impacts on Statewide Medical Emergency: A space-time analysis

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The unprecedented July 2006 California heat wave was associated with an accelerating trend in regional humid heat wave activity that is related to global warming. In this work, we identify and summarize effects of that meteorological extreme event on California morbidity as quantified by daily emergency department (ED) visits data aggregated at the county level. Besides local county-level daily correlation analysis, we use canonical correlation analysis (CCA) to summarize space-time relationships between ED visits and temperature as well as humidity. We find intriguing spatial patterns of public health impacts of heat and humidity that potentially suggest modulation by various factors including demographics, adaptation and acclimatization that may be related to local climatology and social factors determining access to air conditioning. Health outcomes as measured by ED visits are found to be generally more sensitive to extreme heat and humidity in coastal counties and the north-central part of the Central Valley, which are known to be more affected by coastal influences, than in inland counties.

Keywords: *Heat waves, public health, canonical correlation analysis, temperature, humidity, morbidity, climate change*

Climate change and human health are intimately tied to each other on many levels. On the largest essential scale, climate change is a global symptom of the malaise of a global society where many individuals in an overpopulated world are consuming much more energy than is natural or healthy for them to consume. This energy is consumed mainly in the forms of heating and cooling, transportation, and manufacturing of food and consumer goods. Per capita, most of the excess energy is consumed in developed countries, but a rising "standard of living" in the most popu-

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lated developing countries necessitates a great acceleration in energy consumption. Continued reliance on fossil fuels will continue to fuel climate change for decades and likely centuries to come.

There are many ways in which the changing climate can feed back on the health of individuals, even and particularly those who are least responsible for climate change, while individuals with energy intensive lifestyles are buffered from many ill effects of climate change by air conditioning and other adaptation measures. Specific regions of the world have distinct environmental vulnerabilities and are already experiencing specific climatic changes which can be said to be "tips of icebergs" of changes to come. The changes with the most directly palpable impacts have to do with changing frequencies and intensities of extreme weather events (e.g. Tebaldi et al., 2006).

Among such regional changes already underway and likely due to global climate change is the observed accelerating increase in heat wave activity in California and Nevada (Gershunov et al., 2009). What is particularly disturbing about this trend is that heat waves are becoming more humid and are therefore expressed more strongly in nighttime minimum temperatures. Humidity increases the health burden of heat waves because people, animals and plants thriving in this arid and semi-arid Mediterranean-type climate are, on average, acclimatized and have adapted to traditionally dry daytime heat and efficient nighttime surface radiative cooling. Water vapor is the main and strongest greenhouse gas, i.e. it absorbs longwave terrestrial radiation and impedes radiative cooling. Therefore, there is less nighttime respite from heat when humidity is high. This presents a double challenge for health: exposure to humid heat is potentially more difficult to physiologically accommodate, and high nighttime humidity does not provide sufficient environmental cooling and opportunity for reduction in physiological stress. Moreover, humid heat waves tend to last longer due to the observed stronger coupling of maximum and minimum temperatures during humid extreme heat events (Gershunov et al., 2009).

The health threat of humid heat is especially critical given potential lack of acclimatization and adaptation to humidity and nighttime heat. Insufficient adaptation may be reflected in low penetration of air conditioning in California where statewide air conditioning saturation is quite low by United States national standards. According to data from the 1998-2002 Consumer Expenditure Survey, California ranks 38th (of 50 States) in the nation in terms of installed central or window air conditioning, with only 54% of homes with cooling capacity. The numbers range dramatically within the state, with coastal areas containing far fewer air conditioning units. For example, coastal San Francisco has 21% saturation and Los Angeles (which includes coastal and inland areas) has 51% saturation, while inland Sacramento has 85% (Sailor and Pavlova, 2003). These large disparities are largely driven by very different climates between sub-regions (coastal vs. inland, north vs. south, valleys vs. mountains and deserts), as well as variation in social determinants within sub-regions with respect to population access to or use of air conditioning in the climatically and socially complex state of California. The lack of cooling capacity in coastal areas is especially important when assessing the potential impacts of climate change on health outcomes due to extreme (relative to usual local conditions) heat events.

An unprecedented heat wave of the humid variety with unprecedented health impacts occurred in the second half of July 2006 (Kozlowski and Edwards, 2007; Margolis et al., 2008; Gershunov et al., 2009; Knowlton et al., 2009). The event has been studied extensively from meteorological and climate perspectives and in the context of regional heat waves observed over six decades. The unique nature of this humid heat wave whose daytime and especially nighttime signatures surpassed all previous regional heat waves on record beginning in 1948 was partially related to the long-term trend in regional heat wave activity that is consistent with expectations from global warming (Gershunov et al., 2009). The hottest in a recent rash of unusually humid heat waves, the 2006 event was preceded by a prelude of humid heat about a week before the onset of hottest temperatures accompanied by high humidity on July 23, 2006. For example, maximum and minimum temperatures exceeded 44°C and 28°C (far exceeding the previous minimum temperature record), respectively, in Sacramento, the State Capital. Minimum temperatures remained over 23°C for 7 days in Sacramento, which is located in California's central valley, an area that during this event experienced severe morbidity and mortality impacts among people, as well as farm animals. Maximum and especially minimum temperatures broke records at many other locations as well. This heat wave lasted the entire second half of July impacting a great majority of California. It is important to note that while no single heat wave can be entirely caused by climate change, climate change is making unprecedented heat waves more and more likely. In California, it is changing the basic character of hot extremes making them more humid and hotter at night.

Heat and health outcomes have been recently extensively studied in Europe in the aftermath of the 2003 heat wave. Clearly and consistently with numerous previous studies, health risks are elevated by air pollution (Fischer et al., 2004; Stedman, 2004; Gosling et al. 2008). Although Russian health data are not publicly available, it is safe to say that the aerosols emitted from peat fires did not help to weather the heat of summer 2010 in and around Moscow. Nighttime heat, or minimum temperature, also exacerbates health effects of daytime or maximum temperature (Hemon and Jougla, 2003; Grize et al., 2005; Gosling, 2008). For example, Grize et al. (2005) attributed excess mortality in the summer of 2003 in Switzerland to the compounding effect of elevated minimum or nighttime temperature. In California, coroner's reports indicated some of the victims of the July 2006 heat were found to have functioning air conditioning, but did not turn it on (Margolis et al., 2008), perhaps to save money on their electric bills (most of the victims lived in areas where a majority of inhabitants' incomes were below poverty guidelines) and/or because they expected the typically strong nighttime cooling, which did not occur. Data from the coroner's reports suggested that psychiatric and other co-morbidities, along with inadequate social connections, may have also contributed significantly to inadequate use of adaptive measures, such as turning on functional air conditioners, or seeking medical assistance (Margolis et al., 2008).

Previous studies considered mortality and the 2006 heat wave as they evolved daily in time and separately in seven specific individual counties (Ostro et al., 2009). Based on coroners' reports, deaths designated as due to hyperthermia numbered 147, while actual mortality estimated from time-series analyses of vital statistics records was 2-to-3 times greater. Ostro et al. (2009) estimate that there was almost a 2% increase in daily mortality per 1°C apparent temperature increase during this period of excessive heat and humidity – almost a 3-fold increase compared to normal summertime conditions. Knowlton et al. (2009) studied hospitalizations and emergency department visits as they were expressed in space over the entire heat wave period (17 days, according to their reckoning) when statewide surveillance individual case data for all-cause and specific diagnoses were aggregated first to county, then to six distinct geographic regions. Interesting regional differences in ED visits were reported, with ED visits showing a notably stronger signal in some cooler coastal areas as compared to inland regions with much higher temperatures, suggesting that "population acclimatization and adaptive capacity influenced risk" (Knowlton et al., 2009). This previous morbidity study focused on spatial signals in health data aggregated and analyzed over separate sub- regions and over the 17-day-long heat wave, i.e. in a way that did not account for the daily temporal evolution in weather and morbidity over space and time. Here, we analyze daily morbidity data aggregated at the county-level together with daily temperature and humidity using local correlations as well as canonical correlation analysis (CCA), a multivariate statistical method that is not new to many disciplines, but is not commonly used in epidemiology. This method can resolve space and time signals in two fields of variables simultaneously in a single model, allowing us to consider common signals at different counties as they co-evolve in time. The hypothesis we examine is whether there exists a coherent spatial structure in county-level day-to-day associations between ED visits and weather variables (temperature and humidity). Our aim is to identify and describe such coupled signals, an aim for which CCA is ideally suited. Among other points of interest in such analyses is whether there was a leading edge of the event such that the health impacts in one area of the State might have preceded those observed in other areas, and potentially could have informed an earlier public health response in areas affected later in the heat wave thereby reducing morbidity and mortality.

In this paper we examine the daily space-time signal that the July 2006 heat wave left in emergency department (ED) visits records. We focus on illness due to all internal causes plus heat-related illness (classified as an external cause), as well as on ED records sub-sampled by psychological causes and by age-groups. Section 2 introduces the weather and ED data as well as methodology for their analysis in a common coupled framework. Section 3 presents the results followed by conclusions in section 4.

DATA AND METHODOLOGY

Methodology: Canonical Correlation Analysis (CCA)

CCA is a technique to examine and summarize the information contained in the cross-correlation matrix between two sets of variables. The right and left eigenvectors form the linear combinations of each of two sets of variables that are optimally correlated with each other. They can be arranged in order of maximum correlation and each coupled pair of linear combinations is orthogonal to the others. CCA can be viewed as an extension of multivariate linear regression to the case of multiple predictors and predictants, although no causal direction is implied from one set of variables to the other. When applied to geographically distributed time series of predictor and predictant fields of variables that are characterized by some level of spatial dependence or autocorrelation, CCA identifies spatial patterns in both fields that are temporally coupled or co-evolve in time, i.e. their temporal evolutions are optimally correlated.

CCA was originally developed by Hotelling (1935, 1936) to identify and quantify associations between two sets of variables and was initially used in the social sciences. CCA is not limited to discrete or continuous data. In climate prediction, CCA has been used, to match patterns in two fields of variables, typically with the intension to forecast one with the other, i.e. the predicted with the predictor (Barnett and Preisendorfer, 1987; Gershunov and Cayan, 2003; Alfaro et al., 2006). Of course, CCA can also be used as a purely diagnostic tool to examine associations between two fields of variables (e.g. Gershunov and Roca 2004). This is the way CCA is applied here, as originally intended by Hotelling (1935, 1936), to diagnose associations between two fields of variables – one describing weather, the other describing health outcomes. The method itself does not imply a causal direction of the association, theory and/or common sense. For example, here we assume that health outcomes do not impact weather, but rather that weather can impact health outcomes.

In our context, daily temperature or humidity constitutes a weather field – daily data (see below) at grid cells matched to California counties – while ED visits constitute the health field with daily observations aggregated at the county level. The weather and health fields are observed on the same days. The time series are not required to be co-located or evaluated at the same number of spatial locations (variables), although here they are. Nevertheless, CCA does not prefer co-located associations, but rather looks for relationships (correlations) between time series of spatial patterns given by left and right eigenvectors of the cross-correlation matrix of the variables making up the two fields. In this case, since the number of observations (days in July) is less than the number of variables (spatial points – counties), we pre-filter/describe the fields by their principal components (PCs), which are themselves time series of spatial patterns independently computed for the weather and health variables. This is done to reduce the dimensionality of the data. We use 10 PCs (together explaining more than 90% of the total field variability in each field) to characterize each field and as inputs to the CCA. The resulting pairs of canonical correlates (CCs) are ranked in terms of their temporal correlation coefficients, the quantity maximized by the CCA. In other words, the leading pair of CCs is characterized by the highest correlation attainable between two pairs of linear combinations of the original variables, i.e. spatial patterns in each field. Subsequent CCs are characterized by lower correlations and are orthogonal to the preceding ones. Here, we will only discuss the leading CCs. There is no guarantee that the co-evolving patterns explain significant amounts of variance in either field. If they do, it is because they represent real and significant relationships.

Weather data

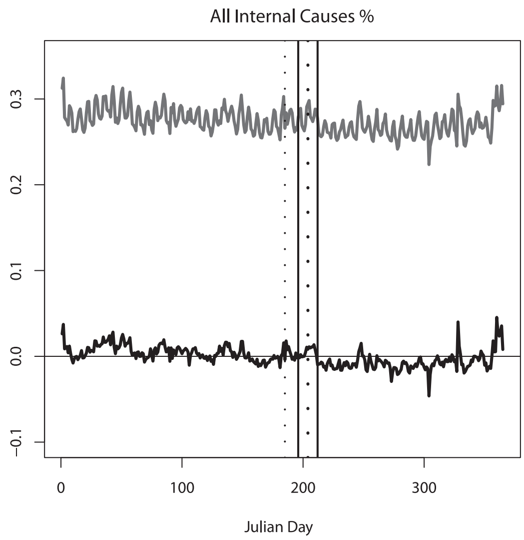
Temperature and absolute humidity data come from the North American Regional Reanalysis (Messinger et al., 2006) that combines the available meteorological observations and a dynamical weather model to produce a complete and physically consistent data set of all atmospheric and surface variables of importance at a 32km spatial resolution grid and 3-hourly temporal resolution. We averaged these high frequency data to daily timescales and each California county (or groups of small counties) was matched geographically to its nearest neighbor temperature/humidity grid to obtain an accurate estimate of temperature and humidity for each particular county during July 2006. Relative humidity was calculated from absolute humidity and temperature and used in all calculations. Note that *in situ* or direct measurements of humidity are not available over California with anything near the required spatial resolution. The temperature analysis, however, was repeated using *in situ* station measurements and yielded similar results to those presented below.

Health data – Emergency Department Visits

Daily emergency department data (ED) for 2006 was obtained courtesy of the California Department of Public Health and the California Office of Statewide Health Planning and Development (OSHPD; Sacramento, CA) for each of 58 California counties. Prior to accessing the data, Investigational Review Board (IRB) approval was obtained from the California Health and Human Services Agency (CHHSA) Committee for the Protection of Human Subjects in Research. Records were extracted based on codes described in the *International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM;* Centers for Disease Control and Prevention, 1979*)*. As in Knowlton (Knowlton et al., 2009) and previous studies examining human health and heat waves, ED visit data for all-causes (i.e., all causes including internal and external causes) were broken down into sub-categories using the ICD-9-CM codes (All Internal Causes: ICD9=001-799.9; plus Heat-Related Illness ICD9=992, classified as an external cause). Due to very low counts in 11 small counties, in accordance with OSHPD guidelines to ensure confidentiality of health data, the data for these counties were combined into three multi-county geographically defined groups.

County and statewide, all internal causes ED data for California from the summer heat wave of 2006 were broken down further into the following categories: all internal causes for patients younger than 65 years of age, all internal causes for patients 65 years of age or older, all internal causes for males, all internal causes for females, all mental health causes, all mental health causes for patients by age-group (less than 65-years of age, or 65 years and older), as well as the subset with a diagnosis of "depression". To indirectly adjust for location-specific underlying population size and potential vulnerability (unmeasured), for a given county daily ED counts for each of the categories were converted to a daily proportion of the total annual number of ED counts. For brevity, we will show all-internal-cause results. However, analysis of 'all causes' and the different age range subgroups showed sensitivity to the late July heat wave.

Figure 1: State-wide emergency department (ED) visits for all internal causes aggregated (averaged) over all counties (gray curve) in daily visits expressed as a percentage of total annual visits for each county.



Note: The black curve is obtained from the gray one by removing the least-squares fitted double harmonic weekly cycle from each county's data (see text). The vertical lines are as follows: thick dots mark July 23, the peak of the 2006 heat wave; solid lines mark the beginning and end of the heat wave – July 15th to the 31st; the thin dotted line marks July 4th – a patriotic holiday in the United States that traditionally includes excessive drinking, barbequing and fireworks and around which there is a traditional annual spike in ED visits (for all causes, including internal causes).

ED data span all of 2006 and are characterized by a well-known and pronounced weekly cycle (Figure 1). We have modeled this weekly cycle by fitting double harmonics (sine/cosine waves of weekly and sub-weekly periodicities) to the 365 days worth of 2006 ED data at each county using least squares regression and subtracted it out of the ED data thus obtaining the black curve on Figure 1. The unique flat protracted peak or "bump" in ED visits is visible at and following the heat wave peak of July 23 (Figure 1, thick dotted vertical line). This smooth bump followed by a decrease in state-wide ED visits is coincident and consistent with the temporal evolution of the unprecedented humid heat wave of July 2006, i.e. health problems are exacerbated by accumulating effects of extreme temperature and humidity which linger, followed by relative respite when environmental conditions return to normal.

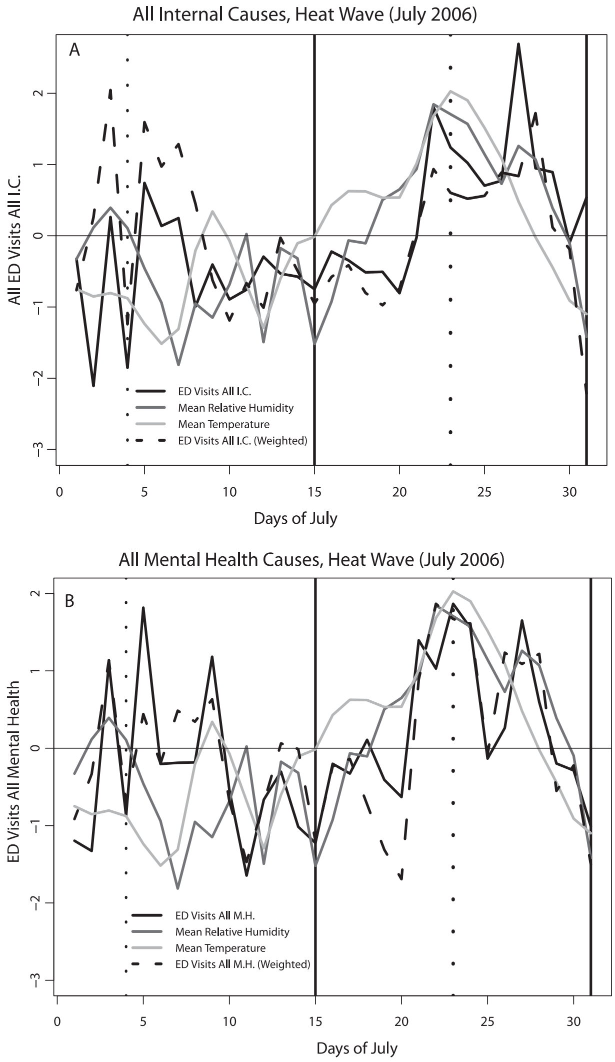
RESULTS

General statewide and local county-level relationships

A closer look at July 2006 (Figure 2) shows that state-wide temperature and humidity ramped up more or less in unison from mid-month to July 23 (22^{nd} for relative humidity) and then ramped down for the rest of the month with humidity experiencing a secondary peak around July 27^{th}. State-wide ED visits also increased starting with July 21^{st} when both temperature and humidity were high and increasing rapidly. There appears to be a lagged relationship between extreme temperature and all-internal-cause ED visits, perhaps a cumulative heat stress effect with local (in time) ED peaks in phase with spikes in humidity. An even more pronounced spike in ED visits caused by mental health issues is also evident (Figure 2b), but the relationship with temperature appears to be more contemporaneous, i.e. no lag is observed.

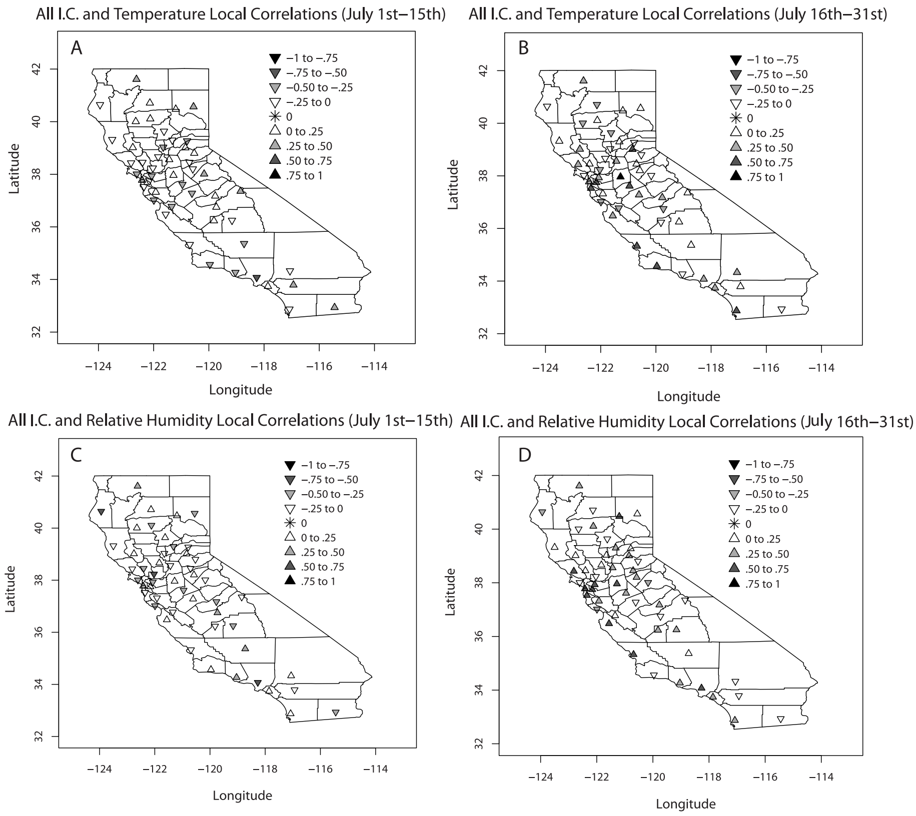
In order to explore these relationships in the finer spatial context allowed by our data, we first examine the local correlations between daily weather and ED visits. These results are split into early and late July to accentuate the differences seen when strong weather signals are absent and present, respectively. Figure 3 shows that at the county-level, same as at the state level (Figure 2), strong positive correlations of ED visits with both temperature and humidity are observed only for the second half of July, but only specific counties, mostly in the Bay Area, as well as the Northern Central Valley and Central-South Coast display strong contemporaneous relationships. ED visits correlated with both temperature and humidity show a rather similar pattern of local county-level relationships. We have also examined the local lead-lag structure. We do not show these results here, but note that for those counties showing strong positive relationships (dark gray upright triangles), the strongest relationships are either contemporaneous or ED visits lag meteorology by a day or two. Moreover, these all-internal-cause ED results are generally indicative of results obtained for sub-sets of the ED data (e.g. all internal causes by age group, not shown).

Figure 2: July 2006 daily temperature and humidity averaged over California, as well as ED visits both as a percentage average and as an average weighted by total annual ED visits per county (i.e., an approximation of population weighting).



Note: Panels (a) and (b) describe the state-wide evolution of all-internal-cause ED visits and for mental health causes, respectively. All indices are plotted in common standard deviation units. Dotted vertical lines mark July 4th as well as July 23rd, a Sunday, the peak of the event. Solid vertical lines mark July 15th and 31st – the start and end of the heat wave.

Figure 3: County-level daily temporal correlations between all internal cause ED visits and temperature (a,b) and humidity (c,d) for the pre-heat first half of July (a,c) and the second half of July when the heat wave actually occurred (b,d).

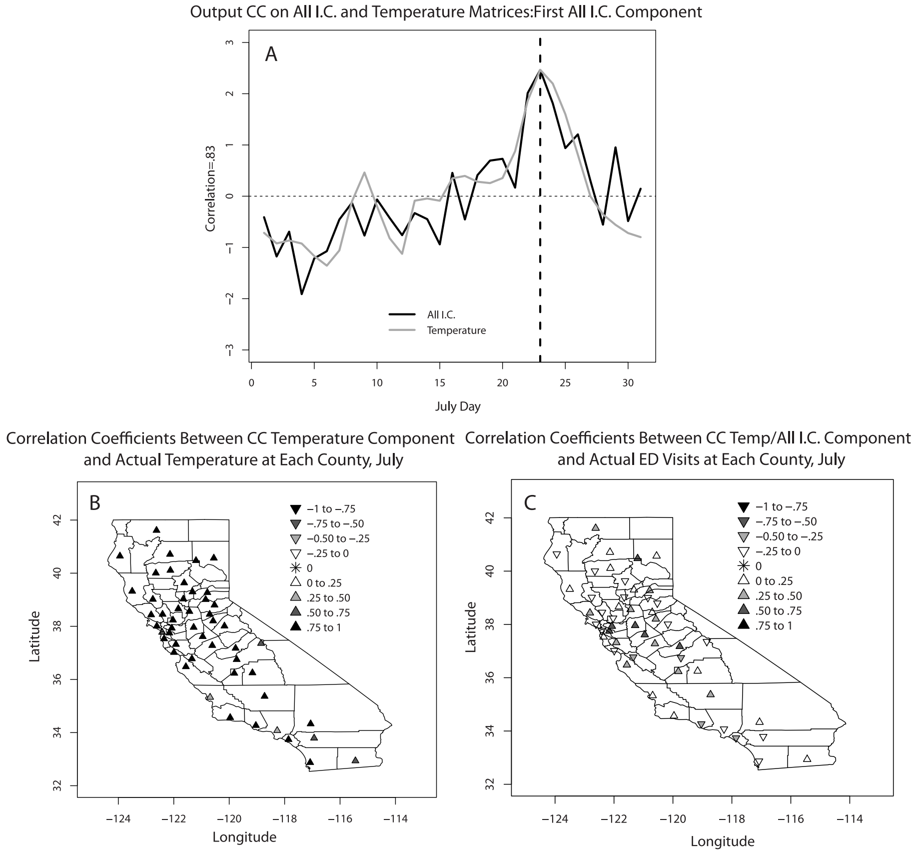


Canonical Correlation Analysis (CCA)

CCA is performed as described above for the *entire* month of July including the early half of the month when there were no strong local positive relationships between ED visits and meteorology, which was not unusual, while the dominant signal in ED visits was related to festivities surrounding the 4th of July (Figure 3).

The leading canonical correlation pattern pair for the analysis of the temperature field with the all-cause ED visits field (Figure 4a,b,c) shows the pattern of the heat wave as it co-evolved with ED visits in northern California (Figure 4b). The temporal evolution of these two patterns is correlated at 0.83 and resembles the main statewide averaged pattern shown in Figure 2. The spatial pattern of temperature is state-wide but most strongly expressed in Northern California. The associated ED visits pattern captures counties in the Bay Area, the northern-central Central Valley and the North-Central Coast where ED visits were sensitive to the heat wave. In these regions, the optimally-coupled spatial patterns and their temporal evolutions are clearly delineated by the leading CCA mode.

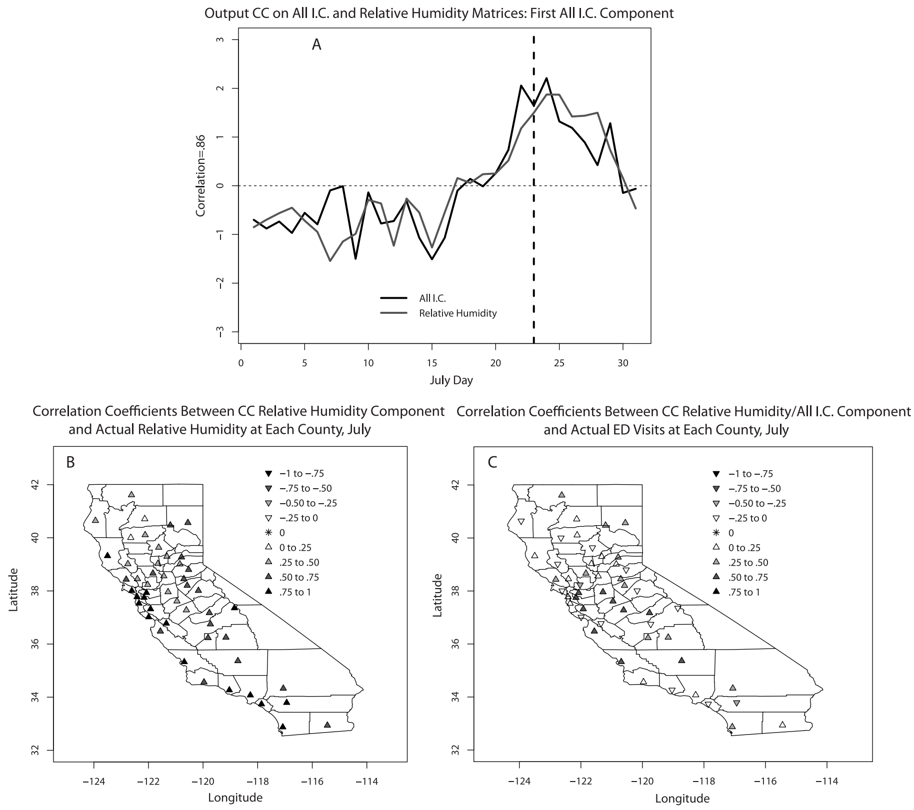
Figure 4: Canonical Correlation Analysis (CCA) of all-cause daily ED visits and temperature for the entire month of July.



Note: The time series (a) represent the temporal evolution of the temperature (b) and ED visits (c) patterns. These spatial patterns are displayed in correlation units between the original county-level data and the time series of their respective pattern evolutions (a). The correlation between these pattern evolutions (gray for temperature, black for ED) is the quantity being maximized by the CCA.

The 2006 heat wave developed somewhat differently along the South Coast counties, where we also know from Figure 3 that the contemporaneous relationship between meteorology and ED visits was significant. The same pattern of heat wave and related health impacts does not hold along the south coast, otherwise it would have been summarized by the same leading canonical variate. As it happens, the local patterns are different at different south-coastal counties, i.e. no single pattern describes all these counties. For example, in San Diego county the heat wave and associated ED visits peaked on July 22, a day before the main statewide peak and other differences made for contemporaneous correlations that are not summarized by the leading mode of the CCA. If south coast counties differed in a mutually consistent way from the counties represented by CC1, their relationships with local weather would have been summarized in a lower-order (e.g. 2nd or 3rd) canonical correlation mode. However, there are important unique features to these south coastal links and, where they are detectable, these local relationships are scattered over several higher order modes alongside with those representing other sub-regions of the state. These localized county-level links should be considered individually in a much longer report, whereas here, we focus only on signals that are spatially coherent across counties.

Figure 5: Canonical Correlation Analysis (CCA) of all-cause daily ED visits and humidity for the entire month of July.



Note: The time series (a) represent the temporal evolution of humidity (b) and ED visits (c) patterns. These spatial patterns are displayed in correlation units between the original county-level data and the time series of their respective pattern evolutions (a). The correlation between these pattern evolutions (gray for humidity, black for ED) is the quantity being maximized by the CCA.

The leading patterns from the humidity – all-cause ED visits CCA (Figure 5) show a similar general behavior to that described in Figure 4. However, humidity is most coherently expressed along the coast and it tends to be related with somewhat more variance in ED visits than does temperature alone. Again, ED visits tend to be coherent for counties clustered around, east and south of the Bay Area, while south coastal counties tended to vary more idiosyncratically in July 2006. Certainly, by including all of July, rather than only the second half as was done for the local correlations (Figure 3), more local differences can be present and comparing local correlation magnitudes to those derived from CCA, we are asking more from the CCA. In any case, these local differences are to some extent apparent in higher order CCs not shown here.

Although not shown here, the all-internal-cause age-specific (less than or greater than or equal to 65 years of age) variants of this analysis show very similar patterns to those summarized in Figures 4 and 5. Mental health results are generally less-strongly related to heat and humidity, however they also display similar CCA patterns, although somewhat stronger in southern California. Aside from there being fewer cases, i.e., a smaller sample size, ED visit patterns evident from data for reported mental-health-related diagnoses likely reflect complex relations with an array of clinical co-morbidities, as well as heat and humidity. Relative humidity is somewhat more closely associated with mental-health-related visits than is temperature.

DISCUSSION AND CONCLUSIONS

Both extreme temperature and humidity affected morbidity as identified in emergency department visits in California. Temporal relationships clearly show influences of heat and humidity on ED visits statewide as well as at the county level for certain counties. Given extreme temperatures, high humidity shows a somewhat broader (i.e. stronger at more counties) association with health outcomes than does temperature variability in this traditionally semi-arid summertime climate regime. Populations in coastal counties including the densely populated San Francisco Bay Area may have less acclimatization and greater vulnerability to heat and humidity due to their typically cool summertime climate and less adaptive capacity due to less air conditioning. On the other hand, populations in habitually hot southeastern desert counties (which are more sparsely populated) are protected by acclimatization and broader air conditioning penetration. Such differences, as well as those due to demographics (e.g. age, income and educational levels, etc.) can increase or reduce resilience of the local population to humid heat stress. It is therefore not surprising that the impacts of humid heat on ED visits are not as coherent in space as the distributions of heat and humidity. Clearly, demographic and other spatially-distributed modifications of health risks due to heat should be carefully studied. Using a wide range of analytic methods we are currently conducting an in-depth investigation of determinants of vulnerability for heat wave-related morbidity and mortality across California in the recent past. Those analyses are being conducted at a local scale (i.e., sub-county) as well as individual case-level. The results will further inform the observations we note here at the county-level and will be used to project health risks due to future heat wave activity under various scenarios of climate change.

While local correlation analysis helped identify counties with strong health sensitivities to heat, Canonical Correlation Analysis helped identify and summarize the coherent patterns in which the heat wave of July 2006 and its health effects/outcomes developed over space and time. For example, in northern California the heat wave gained heat and humidity beginning in mid-July 2006 with a peak in magnitude around July 23 and stressed health in counties located in the San Francisco Bay Area, North-Central Coast and the northern half of the Central Valley. This part of the Central Valley is affected by cooling Pacific Ocean influences via the "Delta Breeze" which may affect acclimatization to heat as well as adaptation (e.g., air conditioning penetration).

The heat wave evolved somewhat earlier along the South Coast and relations with health impacts showed local county-level idiosyncrasies that deserve future study. Many factors could have been at play determining county-level responses including demographics, predominance of new (air conditioned as in Orange County) versus older (non-air-conditioned) homes such as in Ventura and Santa Barbara counties, as well as the possibly different behavior of other factors such as the Marine Layer low coastal stratus clouds that have a cooling influence and are common for coastal counties. An interesting question of scale emerges. Statewide signals are cleaner and stronger than those recorded at any individual county level. However, CCA is able to pick out this signal and clearly summarize which of the counties are mostly responsible for producing it. Once again, the counties with a coherent signal reflected in statewide averages tend to be in and to the east and south of the Bay Area. We were unable to identify a coherent leading edge of the event across several counties such that the health impacts in one part of the State might have preceded those observed in other areas.

Given strong trends towards more intense and frequent humid heat wave activity in semi-arid California, these results portend challenges for the health sector, as well as for the energy and agriculture sectors that were not addressed here. Canonical Correlation Analysis was found to be a useful tool for identifying and summarizing coherent weather – health relationships in space and time. The statistical formalism adapted here will be expanded in our future work to include additional variables and autoregressive components to better detect relevant signals and answer more specific questions about their causes. This work raises questions about what determines human health vulnerability and sensitivity to heat and humidity, as well as about what controls signal detection. These questions require finer resolution health, demographic and energy usage data along with more detailed meteorological analyses that include pollution data and focus specifically on coastal versus inland areas. Attempting to answer these questions can lead to future reductions of the health burden associated with regional heat waves even as heat waves become more frequent, intense, humid and longer-lasting.

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