Co-occurrence of Extreme Heat and Pollution in the Southwest United States

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ABSTRACT

In this research paper we examine the co-occurrence of extreme heat and humidity in the Southwest United States between 2003 and 2023. Using simple statistical regression analysis, time series analysis, and spatial compositing, we demonstrate that humidity, when coinciding with extreme heat, tends to exacerbate air pollution. Specifically, we find that humidity and heat have the largest impact of PM d <2.5μm and carbon monoxide (CO) with a lesser impact on other pollutants. We hypothesize the hygroscopic nature of PM2.5 particles and the reactive CO molecules with NOx and VOC compounds lead to amplified reaction rates during extreme heat and humidity. Next, we examine the meteorological conditions associated with the co-occurrence of extreme heat and humidity in Los Angeles and Sacramento. We demonstrate that heat waves in Los Angeles are associated with strong northwesterly winds, originating in the Mojave Desert, that are associated with anomalous warm atmospheric heat transport. This is also associated with decreased on-shore winds from the Pacific Ocean, which typically have a cooling effect. Decreased onshore winds resultantly lead to an exacerbation of heat conditions. These findings can contribute to further prevention of possible wildfire events caused by extreme heat conditions, and also lead to further protections against cases of extreme pollution in the southwestern United States.

KEYWORDS

co-occurrence of extreme heat and pollution, climate change, Southwest United States, compound events, air pollution

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1 INTRODUCTION AND RELATED WORK

The southwestern United States is known for an abundance of wildfires ranging from man-made camping accidents to large scale forest fires. Despite decades of research, there is still much to improve in our understanding and preparation for wildfires. One particular area of research that requires further exploration is the co-occurrence of extremes events. For example, many fires, such as the Dixie and August Complex fires, co-occur during significant heat waves. Recent scientific study has shown that the frequency of co-occurring extreme heat, wildfires, and air pollution will increase due to anthropogenic global warming [1] [10] [11]. Here, we focus on examining the impact of co-occuring extreme temperature and humidity on air pollution.

There are several decades worth of literature examining the physical drivers and impacts of heat waves. Extreme heat can have profound negative impacts on human society, including affecting economic productivity, human mortality, and agricultural yield. These have shown that the frequency and intensity of extreme heat will increase due to global warming from the anthropogenic emission of greenhouse gases. Such studies have been conducted documenting all continents and parts of the globe, confirming that these effects have global consequences [4] [12]. These studies provide valuable insight into the long term effects that heat waves have on the environments of places rather than just the effects they have on humans.

Similar to extreme heat, air pollution has been shown to be exacerbated by anthropogenic emissions of greenhouse gases and other pollutants. A study by Schnell et al. 2017 [12] analyzed co-occurrences of extreme temperature, surface ozone, and particulate matter over the eastern United States. The study concluded that temperature was a key factor to the increased levels of ozone and PM2.5 in the atmosphere. Pollution levels have also increased in countries such as the United States, Portugal, and the United Kingdom [11] [8]. Pollution is a human health risk and can impact respiratory and cardiac-associated mortality. As a result, examining the co-occurrence of extreme heat and pollution can have implications in health research as well [2].

As such, our research looks to further this goal by analyzing the impact of humidity on the co-occurrence of extreme heat and air pollution in the southwest United States. By analyzing the effect of heat and humidity on the anomalous occurrence of pollutants, we use a composite map analysis to understand the difference in pollutant occurrence over the western United States during humid and dry heat waves. We also use a time series analysis to perform a case-study of several historical extreme heat events. The aim of this study is to improve our understanding of how pollution differs between dry heat waves and humid heat waves in the Southern western United States.

2 METHODOLOGY

2.1 Dataset

This study uses the CAMS (Copernicus Atmosphere Monitoring Service) global reanalysis dataset, which provides comprehensive

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information about atmospheric composition, including temperature, humidity, and pollutants. CAMS is widely recognized in the field of atmospheric science for its high-resolution global data and assimilation of satellite observations. It was selected for its reliability, accessibility, and relevance to studying heatwave and pollution interactions.

We downloaded data from the CAMS global reanalysis dataset, covering January 1, 2003, through December 31, 2023. The spatial domain spans latitudes 32°N to 42°N and longitudes 114°W to 124°W, with each grid point spaced 0.7 degrees apart in both latitude and longitude. For each grid point and time step, the following variables were collected:

- Vector wind speeds (`u10` and `v10`).
- 2-meter temperature (`t2m`).
- Mean sea level pressure (`msl`).
- Concentrations of particulate matter with diameter <2.5 μm (`pm2p5`).
- Total column concentrations of carbon monoxide (`tcco`), methane (`tc_ch4`), nitrogen dioxide (`tcno2`), and ozone (`gtco3`).
- Total column water vapor (`tcwv`).

This produced a 3-dimensional dataset, structured with x and y coordinates for spatial positions, variable values for each of the chosen parameters, and a z-axis representing dates from 2003 to 2023. All variables were numerical, allowing for comprehensive statistical and graphical analyses. The NetCDF (nc) dataset was converted into a pandas DataFrame for efficient manipulation and visualization.

Table 1: List of CAMS variables and their abbreviations used in the study.

Name	Abbreviation
10-meter U wind component	u10
10-meter V wind component	v10
2 meter temperature	t2m
Mean sea level pressure	msl
Particulate matter d $\leq$ 2.5 μm	pm2p5
Total column carbon monoxide	tcco
Total column methane	tc_ch4
Total column Nitrogen Dioxide	tcno2
GEMS Total Column Ozone	gtco3
Total column vertically-integrated water vapor	tcwv

2.2 Preprocessing

Firstly, the preprocessing stage involved narrowing down the dataset to focus on relevant parameters, specifically anomalies in temperature and humidity during the months of May through September. The goal was to identify patterns in heatwaves and humidity, particularly during summer months leading into wildfire season. We use the 95th percentile of 2-meter temperature values during the months of May, June, July, August, and September to extract heat waves from our data set. The purpose of this specifically is to extract the warmest days possible across the time period, and to specifically extract summer days leading into wildfire season as these days have the most relevance to overall pollution values. Similarly, we use the 90th percentile of water vapor during these same months to find the set of most humid days during this timespan. This process creates two datasets consisting of the 95th percentile of 2-meter temperature values for a location, and the 90th percentile of total column water vapor values for that same location. Intersecting the two sets gives us one combined dataset of the most hot and humid days for a specific x and y grid point.

2.3 Methods

Most formal research done in this topic uses a combination of mathematical models or neural network models to effectively predict such cooccurrences. These studies are out of the scope for this paper. Due to this, our paper will use a combination of two methods: time series analysis and composite map analysis.

Time series analysis is used to investigate the temporal relationship between heat waves, humid events, and pollutant levels. For this, anomalies in temperature and humidity were extracted for specific heat wave and humid wave events within a 10-day frame. Temperature or humidity served as causation variables, which were plotted on individual axes. Concurrently, pollutant levels, such as particulate matter (PM2.5) or total column ozone, were plotted on a dual y-axis within the same graph. This dual y-axis approach creates overlapping line charts, where one line represents temperature or humidity, and the other line represents the pollutant of interest. This visualization effectively highlights the temporal correlation and potential lead-lag relationships between these variables. Such analysis provides a detailed understanding of how individual heatwave or humid wave events impact pollutant levels in the atmosphere across the selected geographic region.

Composite map analysis was performed using the Cartopy library in Python to explore the spatial dynamics of atmospheric variables during heatwave and humid wave events. By mapping wind vectors, pressure gradients, and gradients of other atmospheric variables, we generated averaged maps that provide a comprehensive snapshot of the meteorological and atmospheric conditions during these events. Additionally, difference maps were created to isolate the effects of humidity during heatwaves. By calculating the differences in atmospheric conditions between hot days and humid-hot days, we were able to further investigate the influence of humidity on pollutant levels, such as ozone and particulate matter, during extreme weather events. These spatial analyses allow us to examine not only the localized effects of heatwaves and humidity but also broader patterns that may emerge across the study region.

3 RESULTS

3.1 Composite Map Analysis

The composite map analyses are presented in Figures 1–12. Figures 1–6 focus on Los Angeles, while Figures 7–12 highlight Sacramento. Each figure consists of three panels:

(1) The left panel represents the variable's average anomaly during hot days (95th percentile of `t2m`).
(2) The middle panel shows the anomaly during hot and humid days (95th percentile of `t2m` and 90th percentile of `tcwv`).
(3) The right panel illustrates the difference between the hot and humid day anomalies and the hot day anomalies.

Figures 1–6 display the behavior of six atmospheric variables in Los Angeles during anomalous events: 2-meter temperature (`t2m`), particulate matter (`PM2.5`), carbon monoxide (`tcco`), methane (`tc_ch4`), nitrogen dioxide (`tcno2`), and ozone (`gtco3`).

Los Angeles, California (34.05 N, 118.25 W)

Figure 1: 2-meter temperature

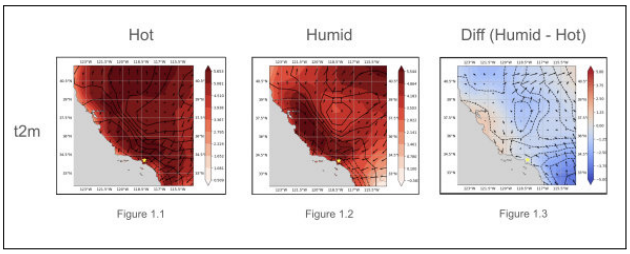


Figure 2: Particulate Matter d < 2.5µm

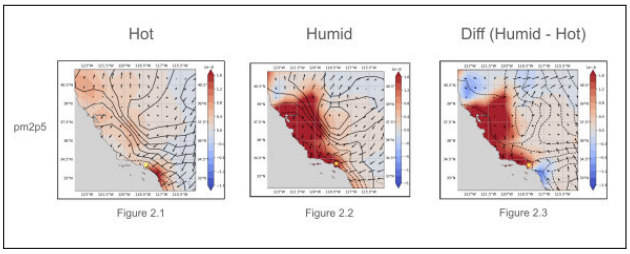


Figure 3: Total Column Carbon Monoxide

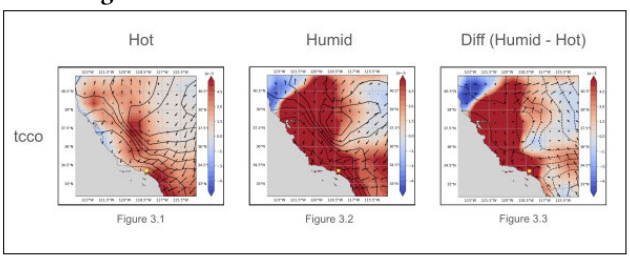


Figure 4: Total Column Methane

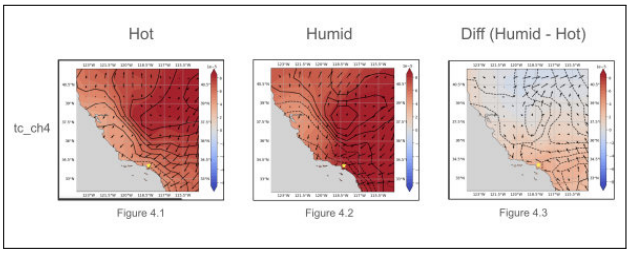


Figure 5: Total Column Nitrogen Dioxide

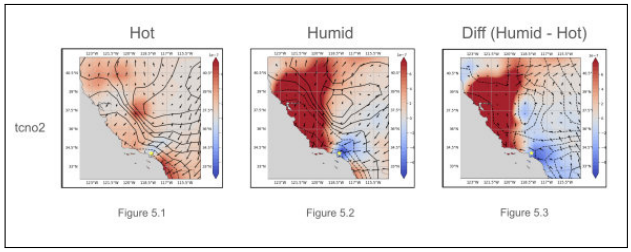
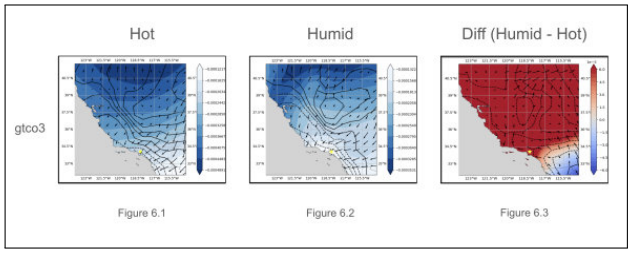


Figure 6: Total Column Ozone



In Los Angeles, composite map analyses reveal notable patterns for the six atmospheric variables during anomalous events. The 2-meter temperature (t2m, Figure 1) shows minimal differences between hot and hot-humid days, as the anomalies are inherently tied to the hot-day criteria, with slightly lower values on humid days due to stricter filtering. Particulate matter (PM2.5, Figure 2) exhibits significant positive anomalies on humid days, with widespread increases across the western portion of the state and the Central Valley, compared to the more localized anomalies near Orange County and San Diego on hot days. Carbon monoxide (Figure 3) displays substantially higher anomalies on humid days, with positive differences observed across the region except for inland desert areas, which remain largely unaffected. Methane (Figure 4) anomalies are generally small but consistently positive, with hot days contributing to markedly elevated levels compared to average conditions. Nitrogen dioxide (Figure 5) presents a more complex trend: hot days show negative anomalies near Los Angeles, whereas humid days result in significant positive anomalies extending north through the San Francisco Bay Area and Central Valley, as captured in the difference map. Lastly, ozone (Figure 6) is the only variable negatively correlated with heat, with hot days resulting in reduced ozone levels. However, humid days mitigate this reduction, leading to less pronounced negative anomalies and slightly higher ozone levels than on hot days alone.

Sacramento, California (38.58 N, 121.50 W)

Figure 7: 2-meter temperature

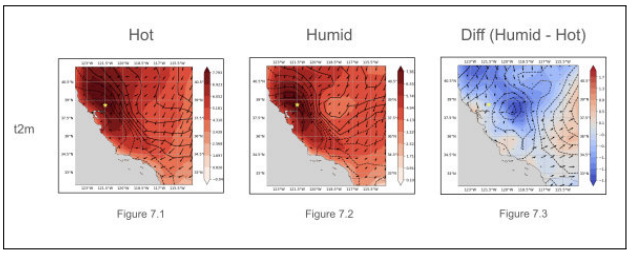


Figure 8: Particulate Matter d < 2.5µm

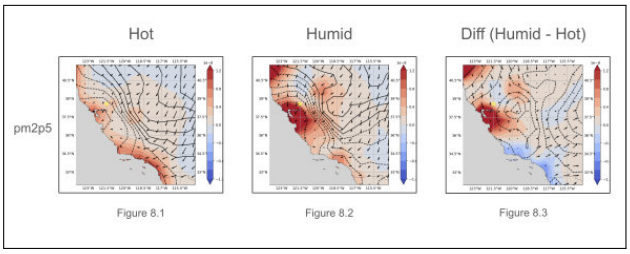


Figure 9: Total Column Carbon Monoxide

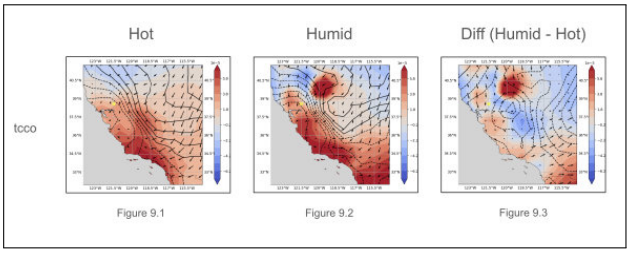


Figure 10: Total Column Methane

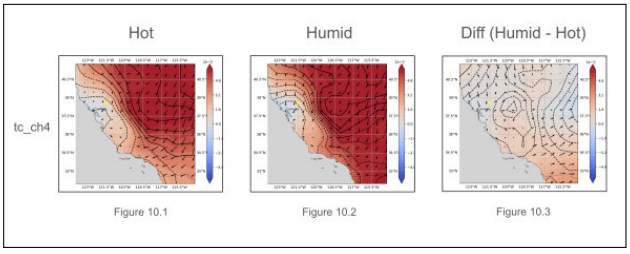


Figure 11: Total Column Nitrogen Dioxide

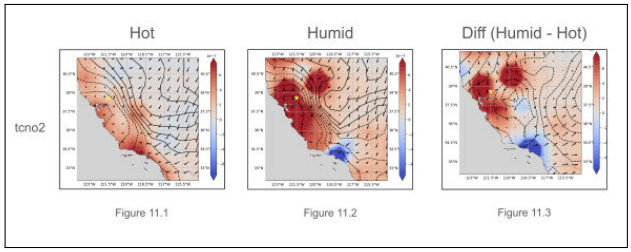
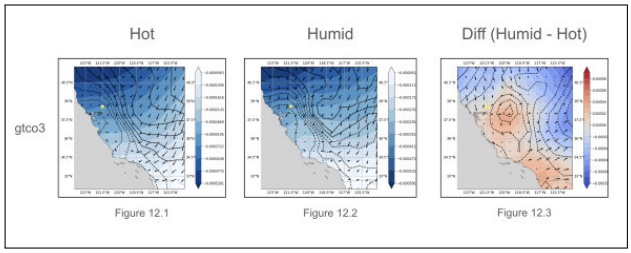


Figure 12: Total Column Ozone



In Sacramento, the trends in composite map analyses largely align with those observed in Los Angeles, with some regional distinctions due to its inland location. Temperature anomalies (t2m, Figure 7) show negligible differences between hot and hot-humid days. Particulate matter (PM2.5, Figure 8) demonstrates a similar trend to Los Angeles, with significantly higher anomalies on humid days, particularly across the Central Valley and surrounding regions. Carbon monoxide (Figure 9) anomalies in Sacramento are smaller on humid days compared to Los Angeles at the center of axis, reflecting its inland position, but still show positive differences, indicating the influence of humidity. Methane (Figure 10) follows the same pattern as in Los Angeles, with modest positive differences and elevated anomalies on hot days. Nitrogen dioxide (Figure 11) anomalies differ slightly, as coastal areas show negative differences, while inland areas, including Sacramento and regions to the north and east, exhibit positive differences on humid days, compared to Los Angeles which still exhibits negative anomalies. Ozone (Figure 12) trends are consistent with Los Angeles, with lower anomalies on hot days and less pronounced negative anomalies on humid days, suggesting a similar mitigating effect of humidity on ozone reductions caused by heat.

3.2 Time Series Analysis

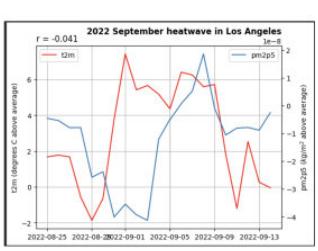


Figure 13.1

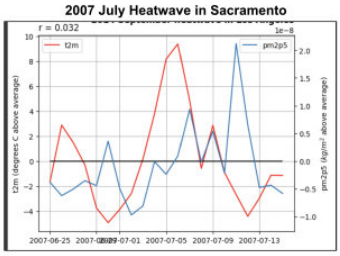


Figure 13.2

To further investigate the lead-lag relationship between temperature and pollutants, specific examples provide valuable insights. Figures 13.1 and 13.2 illustrate two notable heatwaves: the September 2022 heatwave in Los Angeles and the July 2007 heatwave in Sacramento. Both events exhibit significant temperature anomalies, with peak temperature variations ranging from 7 to 9°C (approximately 14 to 16°F) above typical values. A clear correlation is observed with particulate matter (PM2.5), as PM2.5 concentrations surge approximately 2 to 3 days following the peak of the heatwaves. These instances are representative of common heatwave patterns, and by aggregating multiple cases, we identify a general trend linking temperature anomalies to pollutant fluctuations. Although natural variation in PM2.5 and other pollutants exists, these examples demonstrate that substantial heat anomalies play a significant role in shaping pollutant levels, thus providing a clearer understanding of their dynamic relationship.

4 DISCUSSION

Humidity's variability has significant impacts on multiple pollutants as discussed in the Los Angeles and Sacramento examples. The factors influencing specific variables' variations result from unique, but linked chemical processes that occur in the atmosphere. As such, each variable must be studied individually to examine the nature of our results.

4.1 PM2.5

In the instance of PM2.5, the size is the key factor why it is significantly higher on humid days. Hygroscopy is a process where a particle readily bonds with other particles around it without assistance of added pressure, heat, or circulation. PM2.5 particles are naturally very hygroscopic, and bond with the increased water vapor in the atmosphere, thus leading to larger PM2.5 molecules. These are detected as higher values by montoring equipment [2]. Similarly, aerosols, small bundles of solids and liquids suspended in the air, tend to increase during humid events. Thus, previously non PM2.5 matter can be converted into matter that is detected and classified as PM2.5, thus increasing its detections.

4.2 Carbon Monoxide

Carbon monoxide also showed a significant increase on humid days. The main attributing factor is the way this variable was measured. The full name of the variable is total column carbon monoxide, which refers to the total amount of carbon monoxide present in a specific vertical shaft of the atmosphere from the ground to the top of the atmosphere. As a result, mixing within a column is not a viable explanation, although humidity does often lead to thermal inversions that would allow for restrained column mixing. Instead, a viable explanation could be the low rates of oxidation. CO typically reacts with hydroxyl radicals (OH) in the atmosphere which allows its concentration to disperse over time. Water vapor, however, is a reacting agent that can exacerbate this process, resulting in larger CO values. Similarly, CO is a common byproduct of many other pollutants' reactions, like Volatile Organic Compounds (VOCs) and Nitric Oxide compounds (NOx) [14] [6].

4.3 Methane

Methane has much smaller, but still positive anomalies on humid days than hot days. Similar to CO, the measurement of methane is throughout the total atmospheric column, eliminating mixing and the elevation of a measurement from a factor. Consequently, the lack of dispersion of methane is attributed to a variety of factors. Heat waves are generally associated with high pressure systems, and moist air can trap methane in stagnant air masses, causing its measurements to increase on humid days. As well as this, similar NOx and VOC reactions can cause methane not to react with hydroxyl groups as much as they would on a hot, dry day due to the introduction of water vapor [5]. In a similar case to carbon monoxide, methane would increase, but not at the same rate due to its reactions tending to be slightly less frequent. A more biological explanation is also plausible. Humidity can sometimes lead to increased moss, fungi, and plants grown in soil, contributing to the flow of groundwater and reservoirs. This water can lead to methane-producing bacteria that also contribute, although on a smaller scale, to methane in the atmosphere.

4.4 Nitrogen Dioxie

Nitrogen dioxide (NO2) shows a negative correlation with humidity in the center of axis for Los Angeles, but not for Sacramento. The negative correlation is due to the transformation of NO2 into a different compound, nitric acid (HNO3). In the atmosphere, NO2 reacts with hydroxyl (OH) molecules to form nitric acid, and elevated humidity levels act as a key catalyst in this reaction. As a result, this essentially drains most NO2 from the atmosphere. Nitrogen dioxide is also part of the NOx family of gases, and this reduction in gases can also lead to the exacerbating effects of carbon monoxide and methane in the atmosphere. In contrast, the positive anomalies observed in Sacramento can be attributed to the influence of local atmospheric conditions, such as lower humidity levels and the proximity of the regio to agricultural areas, which can contribute to increased NO2 emissions.

4.5 Ozone

Although ozone has a large difference between humid heat and dry heat, all composited anomalies are negative. Ozone negatively correlates with heat. Ozone is typically associated with nitrogen dioxide, which means that NO2 and O3 reactions are used to regenerate NO and oxygen gas, leading to the reduction of both gases. This is known as the NO2-O3 equilibrium shift [6]. Despite this, the increase in ozone is evident. A plausible explanation for this

circumstance is that increased water vapor plays a role in this reaction. Water vapor can cause the formation of peroxy radicals (RO2) along with typical oxygen gas. As a result, atomic oxygen can combine with the oxides in these radicals to reform O3, thereby regenerating it at the expense of nitrogen dioxide, which is not regenerated at the same rate.

5 CONCLUSION AND LIMITATIONS

5.1 Summary

In this paper we examined the co-occurrence of extreme heat and humidity in the Southwest United States between 2003-01-01 and 2023-12-31. We use a combination of simple statistical regression analysis, time series analysis, and spatial compositing to demonstrate that humidity, when coinciding with extreme heat, tends to exacerbate air pollution. Specifically, we find that humidity and heat have the largest impact of PM d <2.5µm and carbon monoxide (CO), with a lesser, but still significant impact on ozone (O3), nitrogen dioxide (NO2), and methane (CH4). We hypothesize that humidity has a larger impact of CO and PM2.5 because the hygroscopic nature of PM2.5 particles and the reactive CO molecules with NOx and VOC compounds lead to exacerbated results especially in extreme heat and humidity. Additionally, we examine the meteorological conditions associated with the co-occurrence of extreme heat and humidity in Los Angeles and Sacramento. We demonstrate that heat waves in Los Angeles are associated with strong northwesterly winds, originating in the Mojave Desert, and anomalous warm atmospheric heat transport due to large pressure gradients between said areas. This is also associated with decreased on-shore winds from the Pacific Ocean, which typically have a cooling effect, but are non-present in these situations due to the reversal of the winds. Similar studies have been conducted for other regions of the globe [3], however, to the best of our knowledge, this is the first study systematically examining the co-occurrence of extreme heat, humidity, and pollution in the Southwestern United States.

5.2 Limitations

There are several limitations to this study and avenues for additional analysis. First, we do not examine the robustness of our heatwave definition. We define heatwaves using a 1-day exceedance of the historical 95th percentile of 2-meter temperature. While this quantile-based measurement of heatwaves is standard in past studies, most studies require that this occurs for 3 or more consecutive days. The definition used here simplifies the complexity of heatwaves and overlooks multi-day thresholds that are more robust. If given additional time, we would explore the robustness of our results using various heatwave definitions from other studies. Second, we would like to more thoroughly examine the meteorological conditions associated with the co-occurrence of extreme heat, humidity, and pollution. For example, we may investigate the impact of regions with climatological inversions (e.g., the Central Valley of California and Los Angeles) and compare rural versus urban centers. Finally, we do not control for the impact of wildfires, which may influence the results of this study. Wildfires can both trigger heatwaves and be exacerbated by them, and while humidity can play a role, it is unlikely to be the only contributing factor. The significance of humidity relative to other factors cannot be fully determined in this study. Further research should isolate the independent effects of various factors, including wildfires, to increase the robustness and accuracy of studies on this topic.

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