Analysis of cooling and heating degree days in the United States from 2015 to 2024

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Abstract. A sizable portion of the electricity consumed in buildings is due to the thermal load associated with the location of these buildings. Specific environmental characteristics can be translated into factors that allow researchers to understand the correlation between temperature changes and the energy necessary to heat and cool buildings. Heating Degree Days (HDD) and Cooling Degree Days (CDD) are parameters used to evaluate temperature changes depending on location. This study uses publicly available data to analyze the percentage change in HDD and CDD at 1,389 locations across the United States and finds sizable trends in both have occurred over the last 10 years. Importantly, there is no attempt here to attribute causes to these trends but rather report them. At each location, both HDD and CDD are plotted vs. year, and fit to a linear curve. The percentage change for each location is tabulated, and averages taken. Remarkably, the results show an increase in both CDD and HDD indices of 35.45% and 8.42% respectively, meaning on-average it got substantially hotter in summer, and colder in winter. The ultimate goal is to understand how the changes can be translated into the electricity usage pattern for cooling and heating across the country and affect electrical grid requirements going forward.

1 Introduction

Scientists and researchers have developed local models to project the effects of global warming, enabling policymakers to plan actions to address its risks effectively [1]. In their studies on the public perception of climate change, Lorenzoni and Pidgeon present data on how populations in different parts of the world perceive the consequences of climate change. Particularly in the US, it is notable that individuals are concerned about the changes in their daily lives as a result of global warming. However, many acknowledge that it is a complex issue and is directly related to government and public policies [2]. These studies demonstrate that the effectiveness of actions aimed at lessening the impact of global warming is a combination of public awareness and public policies at both small and medium scales.

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Previous studies focused on specific regions in the US, bringing a variety of downscaling methods to project the impacts of temperature rise in those areas. The work of Hayhoe et al. focuses on historical atmosphere-ocean general circulation models (AOGCMs) in comparison to temperature and precipitation records in the Northeast region of the US, which comprises the states such as New York, Pennsylvania, and Massachusetts [3]. Conversely, Yazar et al. explored the socio-economic aspects of climate change perception in the region of Phoenix, Arizona. It introduced a thorough investigation of the influence of social factors on susceptibility and adaptability in the face of extreme change in weather patterns [4]. Although these studies present impactful results, to offer a more complete evaluation of the effects of temperature changes in the US territory, it is important to analyze data at a small spatial scale across a larger territory, offering a broader outlook.

To address this gap, this study presents a data-driven analysis that shows the pattern of CDD and HDD indices throughout the US over the last decade. The results of the data collection are then analyzed statistically, presenting the R^2 value of their linear fit. Even though it is important to consider the relevance of both mean climate and extreme events occurrence in modelling climate data [5], the purpose of this body of work is to report the change of HDD and CDD indices, solely focusing on their variations and identifying extreme data points and not accounting for most severe events. Although, of course, climate change is the only known driver that could have caused these changes over the last 10 years, no direct correlation is drawn between the effect of greenhouse gas emissions and the results found, as the goal is to merely present the data collected and identify an average index variation for each location. The data presented in this study is suitable for evaluating and predicting electrical grid consumption based on historical temperature changes.

This paper is divided into sections, where Section 2 presents the data collection methods, outlining the changes in the CDD and HDD indices, along with a brief case study on one of the locations with extreme results. Lastly, Section 3 is a summary of the conclusions and suggestions for further investigation.

2 Methods, Discussion and Results

The existence of Urban Heat Islands (UHI) is widely documented and studied, and factors such as Cooling Degree Days (CDD) and Heating Degree Days (HDD) are taken into consideration when performing such analysis. What distinguishes UHI from the adjacent rural areas and thus reflects on CDD and HDD variations is the presence of more buildings and concrete in the urban areas [6].

A degree day is the difference between the average daily temperature and the reference temperature, also known as a building's balance point. Equation 1 shows how the calculation is made:

$$DD = \Sigma(\theta_o - \theta_b) \quad (1)$$

where DD are the degree days, θ_o represents the outside temperature, and θ_b represents the balance point [7]. If the difference is positive, the result is CDD. If the difference is negative, the result is HDD. Due to the evolution of building conditions and building envelope elements, 60 degrees is considered a better balance point than the standard 65 degrees established in the 1930s and therefore used in this body of work to characterize the data points collected [8]. CDD and HDD analysis serve to gauge the energy load required to a building to provide comfortable conditions to its inhabitants, along with helping monitor ideal conditions for outdoor labor and activities [9]. At a bigger level, trends in HDD and CDD can indicate patterns of energy use and overall impacts of climate and environmental changes. From an economic standpoint, there is a direct correlation between the higher temperatures and the higher demand for cooling in buildings and residences. As the temperature outdoors rises, so does the thermal load to maintain comfort indoors [10].

2.1 Dataset Description

The data used in this analysis consists of 1,389 points, each representing a Zip Code in the US territory, including Alaska and Hawaii. ArcGIS Pro was the software used for the mapping and the coordinate collection. For each location, the CDD and HDD values of the years 2015 through 2024 were collected and analyzed on Origin, resulting in 10 data points for each location. With that information, a Linear Fit was performed to determine the last decade's trend in the increase or decrease of the indices. All the weather data presented in this study is open-source and available online [8]. Besides the average, the R^2 values of each linear fit are also shown.

The coefficient of determination (COD) is represented by the quotient of the sum of the squares of the regression (REGSS) and the total sum of the squares (TSS) as shown in Equation 2. The purpose of this coefficient is to measure the fit of the proposed model to the data set, allowing the evaluation of its quality. The COD varies from 0 to 1 and the higher the value, the better the fit and lower the unexplained variations.

$$R^2 = \frac{REGSS}{TSS} = \frac{\sum_{i=1}^{n} \left(\widehat{Y}_i - \bar{Y}\right)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2} \tag{2}$$

Where $\widehat{Y}_i$ is the estimated value, $\bar{Y}$ is the mean and Y_i is the data point analyzed [11]. In this work COD and R^2 will be used interchangeably.

2.2 CDD Trends

To demonstrate the CDD trend in the US territory, all the data points are translated into percentage change. Figure 1 illustrates the results of this evaluation nationwide. For locations where the percentage change is positive, there is an increase in temperature, creating a need for additional cooling in commercial and residential buildings to maintain comfort.

 https://doi.org/10.1051/e3sconf/202671207003

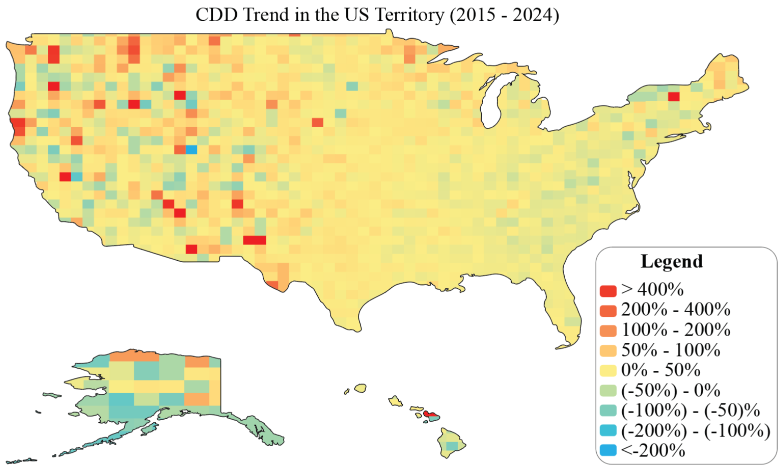


Fig. 1. CDD trend across the US Territory in the past decade.

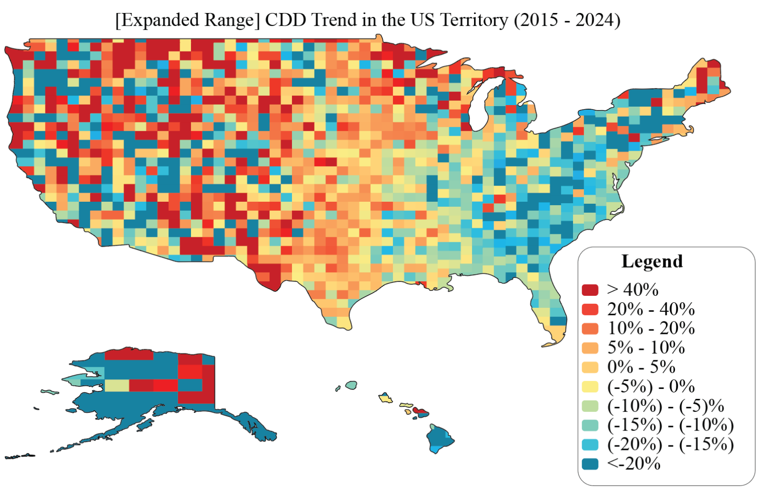
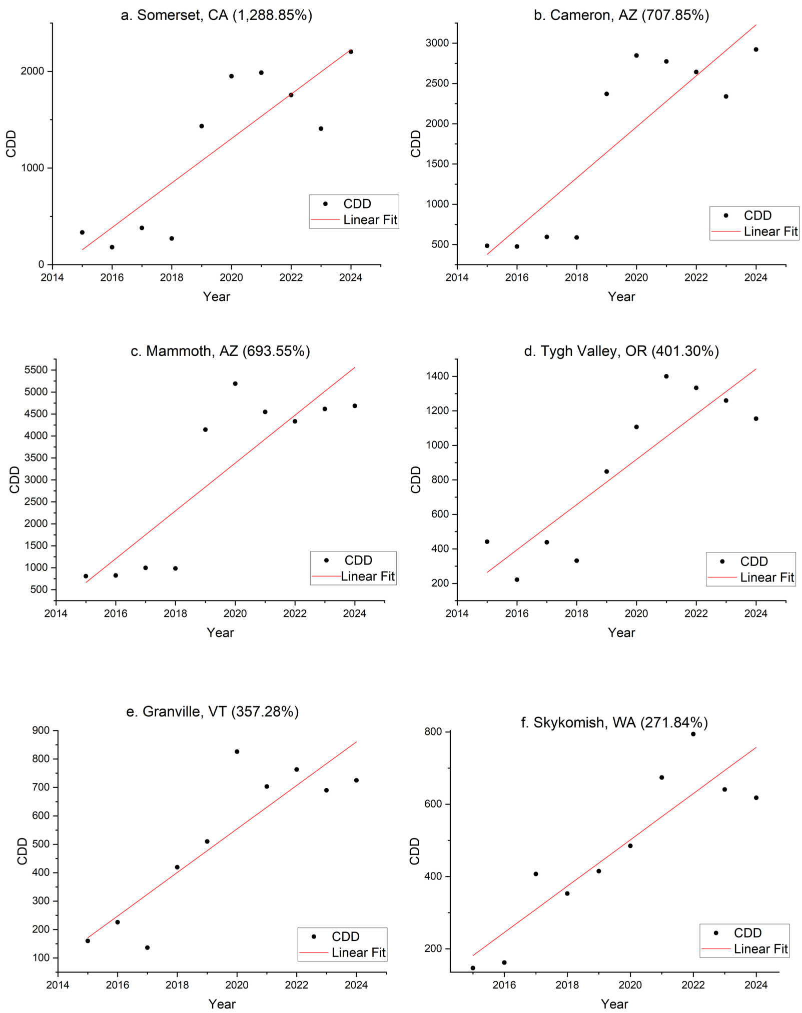


Fig. 2. Expanded Range - CDD trend across the US Territory.

The conclusion upon observing Figure 1 is that states such as Arizona, California, New Mexico, and Alaska are areas in which various zip codes have experienced high positive changes in the CDD index, indicating that these locations have had a considerable temperature increase over the past decade. Figure 2 presents the expanded range of changes between -20% and 40%. There are 1,003 locations within that range, which represent 72.21% of the samples analyzed.

Graph 1 contains the linear fit of the CDD index for the locations with the most extreme changes. Further investigation would be required to evaluate the source of such changes, as this work focuses primarily on reporting the indices. However, it is important to note that there are various locations with over 200% increase.



Graph 1. Graph set showing the CDD Trend for a. Somerset, California; b. Cameron, Arizona; c. Mammoth, Arizona; d. Tygh Valley, Oregon; e. Granville, Vermont and f. Skykomish, Washington.

After analyzing all the data collected for the CDD index change, the average calculated was 35.45%, which can be translated as a 35.45% increase in cooling requirements. The COD of all the locations analyzed is shown in Figure 3 below.

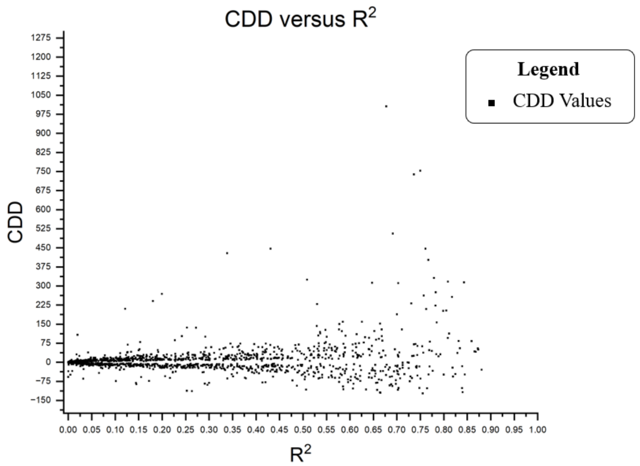


Fig. 3. CDD trend data points versus their respective R^2 values. This plot shows that locations with high linearity also have large trend lines, which are mostly positive, meaning it got hotter in summer.

Figure 3 shows that locations with considerable changes in their CDD index are also the ones with high linearity, which enhances the confidence in the data collected.

2.3 HDD Analysis

Analogous to the previous section, the HDD analysis follows the same structure. Figure 4 presents the percentage changes in HDD values across the United States. The locations with higher HDD values are shown in blue, indicating an increased need for heating during the cooler months. Figure 6 presents the expanded range of values, focusing on the locations with variations between 40% and -20% in their HDD.

The intent of this plot is to emphasize the mild variances without the interference of the highest values, which are the focus of Figure 5. From the data points collected, 1,224 are in this middle range, representing 88.12% of all samples.

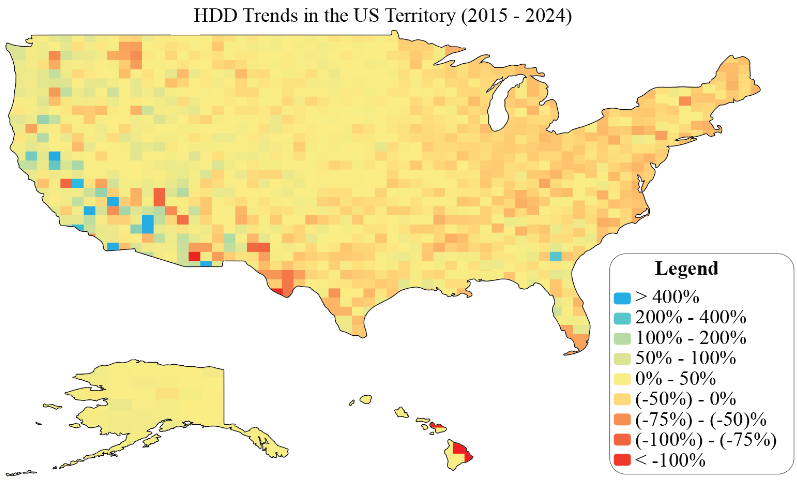


Fig. 4. HDD trend across the US Territory in the past decade.

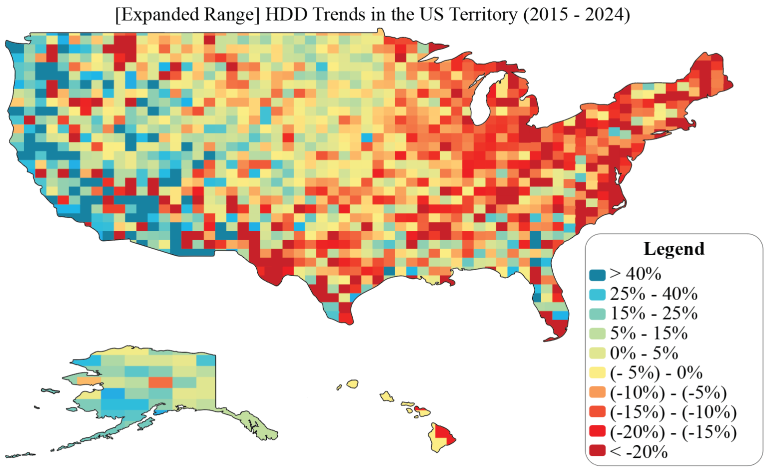
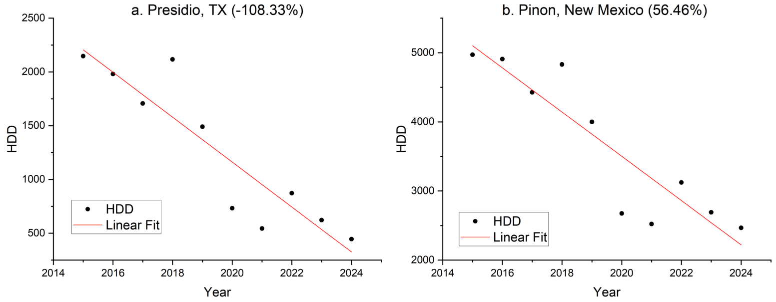


Fig. 5. Expanded Range - HDD trend across the US Territory.

Observing Figure 5, it becomes clear that the East Coast of the United States has experienced an increase in the temperature, signalled by the decrease in the heating requirements over the period analyzed. Whereas the West Coast experienced the reverse pattern change, with temperatures lowering and an increase in cooling requirements.

Using the collected samples to calculate the HDD average, the result was an increase in heating requirements by 8.42%. What can be concluded is that the increase in heating predominant on the West Coast has driven the national average up, while the middle part of the country remains in a milder range. Graph 2 shows 6 locations in which the trends are negative for HDD, representing areas in which the heating requirements have lowered in the past decade.



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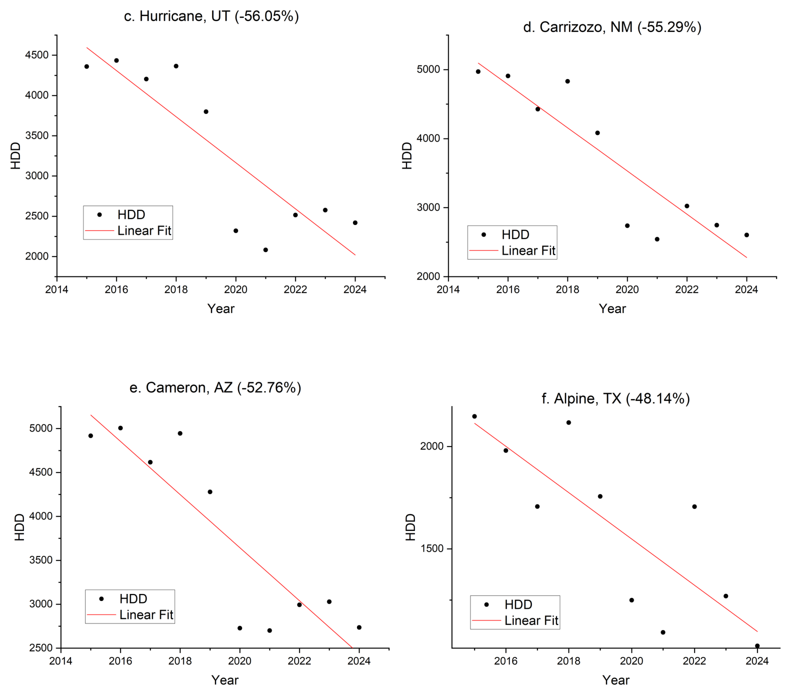


Graph 2. Graph set showing the HDD Trend for a. Presidio, Texas; b. Pinin, New Mexico; c. Hurricane, UT; d. Carrizozo, New Mexico; e. Cameron, Arizona and f. Alpine TX.

Observing the examples presented in both Graph 1 and 2, one location is repeated, Cameron, AZ, but other locations, such as Fredonia (AZ), Plains (MT), Granville (VT), and Leakey (TX), have shown the same behavior. In total, 455 data points presented a positive CDD change while having a negative HDD change, which can be interpreted as a steady temperature increase throughout the last decade. These locations account for 32.97% of the samples analyzed.

Figure 6 shows the plot of the HDD values versus their R^2. Comparing with the CDD versus R^2 plot, locations with significant changes in CDD showed higher linearity, whereas for HDD a few of the higher changes presented a COD between 0.25 and 0.5. Remarkably, the average change in HDD is positive, meaning that while on average it got hotter in summer, it also got colder in winter.

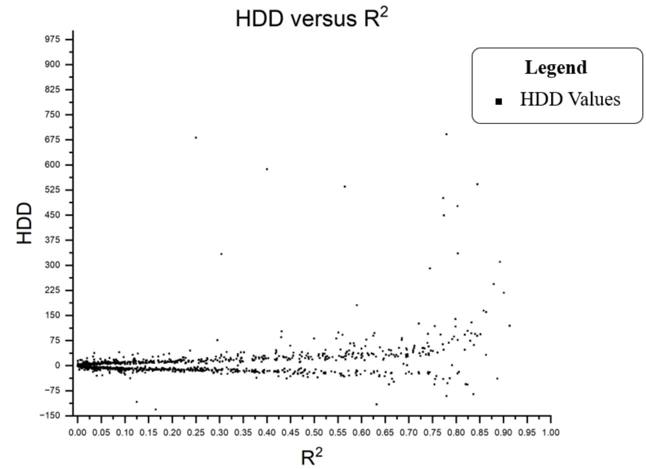
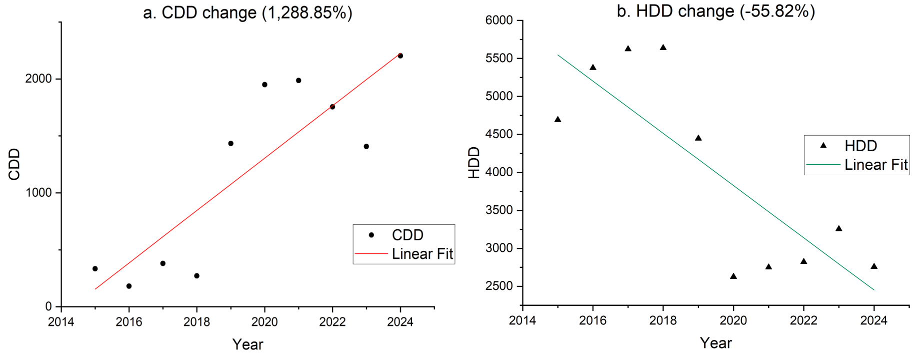


Fig. 6. HDD trend data points versus their respective R^2 values.

It is important to note that there are four deserts in the US territory: the Sonoran, the Mojave, the Chihuahuan, and the Great Basin. These deserts, along with vast arid and semi-arid regions, cover states such as Arizona, California, Texas, New Mexico, Utah, Oregon, and Idaho. These explain why certain areas have very high cooling but also high heating requirements. The desert climate tends to be very cool in winter months due to its type of vegetation and lack of clouds [12].

2.4 Case Study - Somerset, CA

Located in El Dorado County in Northeast California, Somerset sits at 630 meters (2,130 feet) above sea level in the Sierra Nevada Hills. According to the data collected, Somerset is one of the locations with the most prominent patterns in both CDD and HDD, with over a 1,000% increase in CDD and a 55.82% decrease in HDD, as shown in Graph 3. In this subsection, some extreme events will be analyzed in hopes of understanding the pattern in this location.



Graph 3. Graph set showing the a. CDD and b. HDD Trend for Somerset, California.

A noticeable change has happened from 2018 to 2020, with CDD increasing over 600% and HDD decreasing by 53%. This can be caused by many factors, but a big event that occurred in this time frame was the transition from El Niño to La Niña. El Niño can occur every 2 to 7 years and does not have to be followed by La Niña, but in this specific time frame analyzed, El Niño was followed by a multiyear La Niña. Although primarily the southern part of California is the one consistently affected, Northern California also suffers from climate pattern changes [13].

The 2018-2019 El Niño was considered mild and lasted from October 2019 until June 2019, followed directly by a multiyear La Niña, with the latter lasting from 2020 until 2023, with sea surface temperature remaining low until the end of 2023. Even if La Niña is considered a cold-weather phenomenon, it can also bring drier summers and enhance the risk of wildfires, which are common in California. Although rare, the 2020-2023 La Niña transitioned to a strong El Niño, which ceased mid-2024 [14, 15].

The occurrence of El Niño and La Niña is one of many factors that can shape climate patterns, but it is realistic to consider that consequent occurrences, such as the ones observed from 2018 to 2024, have an impact on the CDD and HDD data collected in Somerset, CA.

3 Conclusion

This study presents the results of an analysis of CDD and HDD data for various zip codes in the United States. In total, 1,389 locations were mapped on ArcGIS with data collected from 2015 to 2024. The index data for CDD and HDD were then analyzed in Origin to create a linear fit, establishing the trends for heating and cooling at each location.

Upon analysis, the data shows a gradual increase in both indices. CDD has seen a 35.45% increase, while HDD has seen an 8.42% increase. The most extreme occurrences are in states such as New Mexico, Texas, Arizona, and California. This work presents the visual results of data collected over the past decade, outlining the rise in temperature throughout the US territory, including the continental US, Alaska, and Hawaii. Most of the data points show a low to moderate, steady increase in temperature in the last ten years. A brief case study in one of the locations with the most prominent changes was presented by the end of section 2, pointing to the consequent occurrences of El Niño and La Niña as one of the possible causes of such noticeable variation.

Further investigation is advised regarding the volume of data points analyzed and cross-referenced with extreme climatic conditions throughout the country, elevation profile, and population density, as this work focuses on merely reporting the index changes in various locations across the US territory over the past decade.

This research was supported by the United States Department of Energy (DOE) (DE EE0010195).

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