Climatology and Trends of Heat Index, Human Discomfort Index, and Energy Per Capita for CONUS and Meso-America

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Air temperature and humidity affect human comfort and health in warm and humid climates, and consequently energy demands from buildings to maintain indoor comfort levels. An effective way to measure the overall effect of temperature and humidity on human comfort (or discomfort) is using the heat index (HI), a measure of how people "feel" when exposed to warm and humid environments. This research aims to investigate the spatial and temporal changes and trends of HI and associated energy per capita (EPC) to maintain human comfort in the Continental US (CONUS) and the Meso-America (the Caribbean, and Northern Regions of South America). Hourly air temperature and relative humidity datasets were collected from three sources: the National Center for Environmental Prediction, the North American Regional Reanalysis (NARR), and surface weather stations for a period of 30 years: 1990–2019. The algorithm used for the HI is similar to the one used by the US National Weather Service whereas the EPC is based on the ventilation requirements per person. Results for HI and EPC climatology for the summer season indicate the largest increasing values in Southeast US, followed by the Greater Antilles, and then the Lesser Antilles. Results of the analysis depict positive EPC rate of 2 kW h per year for the summer season for the Southern Greater Antilles. These trends using NARR data were found to be statistically significant and correlate very well with selected weather stations. The actual trends of electricity consumption per person per year for the CONUS suggest, in general, a correlation with increasing maximum HI.
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1 Introduction

In terms of demand and supply of goods and vulnerability of infrastructure to climate change, energy infrastructure and operation may be one of the most vulnerable aspects of society to climate change. Human comfort thresholds for space heating and cooling are largely determined by climate, and these demands present themselves differently in different geographical locations. Warming climates can result in increased energy demands in tropical regions or decreased energy demands in high latitude regions during the winter. When exposed to repeated and prolonged extreme weather conditions such as heat waves or winter storms, climate patterns can pose a high risk to the energy infrastructure. The aim of this article is to study and analyze the relations between climate changes and energy throughout the Continental US (CONUS) and Meso-America.

Heat is the leading cause of weather-related mortality in the United States, so correctly anticipating and planning for excessive heat conditions is critical [1,2]. The heat index (HI) is an effective tool for calculating the effect of excessive heat and serving as an early warning measure. The HI scale is a measurement of human discomfort and stress affected by ambient temperature and relative humidity (RH) [3]. Different than air temperature alone, HI accounts for the effects of moisture content in the atmosphere, making it a better indicator of the impact on human health and mortality [3]. Furthermore, extreme weather events are occurring with more frequency and with longer duration across the world as a result of climate change [4]. Heatwaves are extreme climate events that are expected to rise by 40% over the baseline in the 2020s, and a 20% increase from 2020 to 2050 in dense cities such as New York City (NYC), and 10% in China over the next ten years relative to the previous decade [4,5]. As evidence, summer temperatures in the United States have been rising in recent years and are expected to continue to rise over this century [6,7]. To protect communities, in US, heat alerts and warnings are given when the HI is greater than or equal to 40.7 °C (105.8 °F) during the day and greater than or equal to 26.7 °C (80.8 °F) at night for at least two consecutive days [8,9].

Moreover, tropical coastal areas have strong energy needs for building air conditioning as a result of the warming climate and the sensitivity to warmer ocean waters, which frequently reach 50% of the overall energy budget [10]. In the case of the Island of Puerto Rico, net energy use in the residential sector was approximately 35% of total energy generated in 2005 [11]. In Barbados, the requirement for air conditioning accounted for 48.2% of overall electrical energy used in hotels [12]. Furthermore, in 2013, residential and commercial energy demand in the United States accounted for 72% of total electrical energy produced [13]. In addition, heating, ventilation, and air conditioning (HVAC) use more electricity than other components of residential and commercial facilities, accounting for 26% and 40% of overall electrical energy, respectively [14]. Many high-energy-consuming states, such as California and Texas, underestimated cooling demand by as much as 10–15% based only on air temperature in present and future climatic scenarios [15]. The results demonstrated that air temperature is a necessary but insufficient variable for determining the climatic sensitivity of cooling loads, and that near-surface humidity is just as important [15]. As a result, in most countries, HVAC energy per capita (EPC) usage is a good measure of building energy consumption and total energy demand. In a warming climate, energy demand is a crucial mitigating factor necessary to achieve human health and economic activities.

This study examines the relationship between energy and climate patterns in the CONUS and the Meso-America region, including HI trends, HI thresholds, human discomfort index (HDI), spatial and temporal energy trends on a per capita basis, and the strong correlation between these variables. The methods discussed here can be used in almost any other region in the world.

The key goal of this study is to calculate the trends on EPC needed to reduce the negative effects of regional warming on human health. To achieve this aim, the EPC is analyzed as a function of the spatio-temporal trends in the time frame of 1990–2019 for the CONUS and Meso-America.

2 Data and Methods

This section describes a framework for estimating HI climatology, HDI, and projecting EPC using historical reanalysis data and simulation methods.

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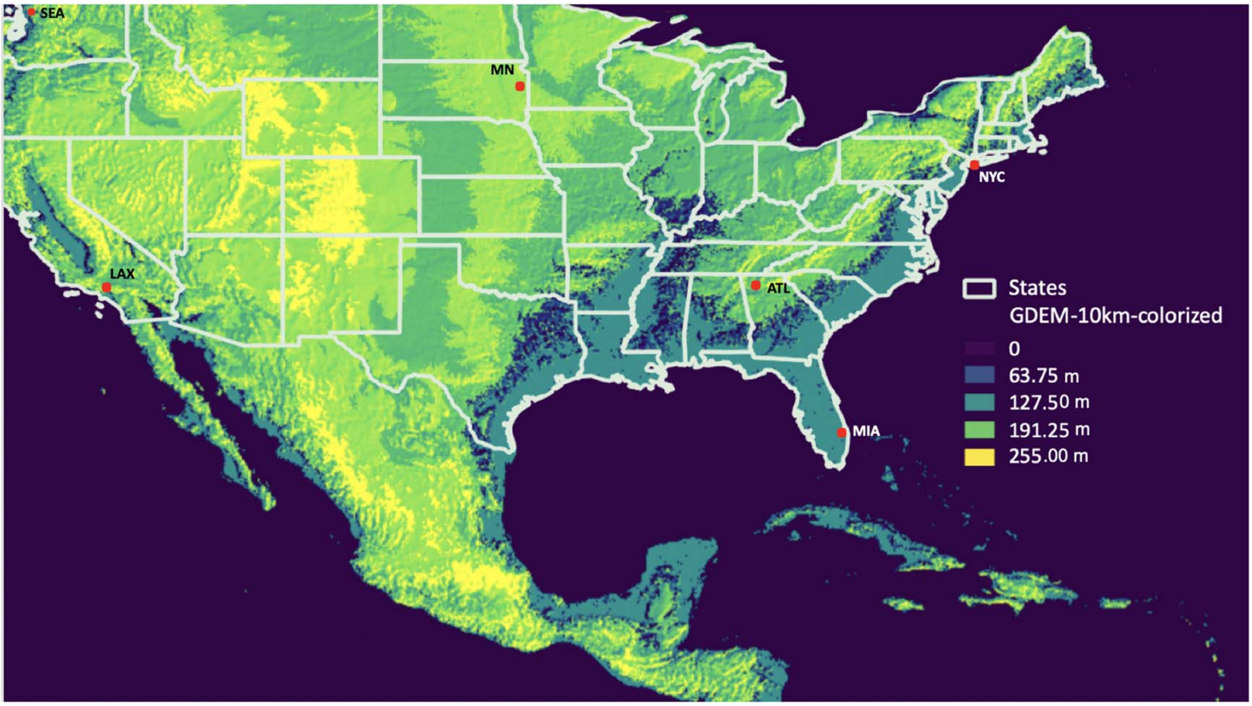

Fig. 1 Topographic map of CONUS and Meso-America

2.1 Reanalysis and Energy Data.

In order to investigate the spatial and temporal distribution and trends of HI and EPC in different regions of the CONUS and the Meso-America, hourly air temperature and RH datasets were collected from two sources: The National Center for Environmental Prediction (NCEP) and the North American Regional Reanalysis (NARR) and surface weather stations for a period of 30 years: 1990–2019. NARR is a high-resolution satellite and observational record with a spatial grid resolution of 349 × 277 that is approximately 0.3 deg (32 km) resolution at the lowest latitude. NARR has a temporal coverage of 8-times daily values which is considered as high for these regions. The algorithm used in our study to determine the HI is similar to the one used by the NWS measuring air temperature in degrees Fahrenheit (T) and RH in percent. The region of interest is shown in global digital elevation map (see Fig. 1) with selected sites of interest highlighted which are Seattle (SEA), Minneapolis (MN), NYC, Miami (MIA), Los Angeles (LAX), and Atlanta (ATL).

2.2 Heat Index, Human Discomfort Index, and Energy Per Capita.

Steadman's table is an HI chart based on temperature and RH provided by the NWS [16,17] and a representation of the dangers of heat stress [18]. Also, at low RH, the HI indicates a high risk of heat-related illness at extremely high temperatures (40 °C). Furthermore, the Steadman's table is represented by the Rothfusz regression, which is widely acknowledged by the scientific community with an error of ±0.72 °C [19,2]:

$$\begin{aligned}\mathrm{HI} = {} & -42.379 + 2.04901523 \times T + 10.14333127 \\ & \times \mathrm{RH} - 0.22475541 \times T \times \mathrm{RH} - 6.83783 \times 10^{-3} \\ & \times T^2 - 5.481717x10^{-2} \times \mathrm{RH}^2 + 1.22874 \times 10^{-3} \\ & \times T^2 \times \mathrm{RH} + 8.5282x10^{-4} \times T \\ & \times \mathrm{RH}^2 - 1.99x10^{-6} \times T^2 \times \mathrm{RH}^2 \end{aligned} \quad (1)$$

When the air temperature is extreme and the RH is very low or high, this equation is modified [2]. Some HDI definitions include dry and wet bulb temperatures, as well as black globe temperature [20–22]. However, due to the difficulties of measuring the black global temperature, these definitions have drawbacks [20,23]. Other models, such as Thom's discomfort index, are more suitable for mid-latitude regions and cold climates because they operate for temperatures varying from 24 to 27 °C. In this work, linear regression is conducted to investigate the trends on average, max, and min summer HI on a per grid basis. Because of the climate adaptation, people in tropical areas are more comfortable at higher air temperatures [22]. As a result, a new HDI is required, which is based on people's actual thermal feelings and is specific to various temperature zones. The following HDI was originally proposed by Angeles et al. [24]:

$$\mathrm{HDI} = \frac{\mathrm{HI} - \mathrm{HI}_{\mathrm{ref}}}{\mathrm{HI}_{\mathrm{ref}}} \quad (2)$$

where $\mathrm{HI}_{\mathrm{ref}}$ is the HI at the reference comfort level of 22.2 °C and 50% RH. A cooling state is represented by a positive HDI, while a warming state is represented by a negative HDI. These requirements cause regions with high demand for HVAC systems to be identified.

The EPC is based on the ventilation requirements per person when in indoor conditions. In order to dilute odors from human bio effluents and substitute absorbed oxygen, typical indoor building requirements are maintained at an ambient temperature of 22.2 °C, 50% RH, and a ventilation rate of 25.5 m^3/h (or 15 CFM) of outside air per person [25,26]. As a result, the energy consumption per capita (EPC) (in kW) for these typical ventilation conditions can be defined as [24]

$$\mathrm{Energy} = \frac{25.5\,\mathrm{m}^3/\mathrm{h} * \mathrm{pair} * (h_{\mathrm{env}} - h_{\mathrm{ref}})}{3600} \quad (3)$$

Here, h_{env} refers as the outside enthalpy estimated using the local air temperature and the mixing ratio, 3600 is the unit conversion from kJ/h to kW, and $h_{\mathrm{ref}} = 47.2$ kJ/kg is the reference indoor enthalpy ($T = 22.2$ °C and 50% RH). EPC differs from a building's total energy load, which is based on factors such as internal heat gains, solar radiation, and other factors, whereas EPC is solely weather-related and is a major predictor of how much energy a person would require to attain human comfort. It is presumed in this article that energy needed for human comfort is a key predictor of total energy demands in buildings, where energy for ventilation represents close to one-third of the total energy, offset by conventional HVAC systems performance (which have typical coefficient

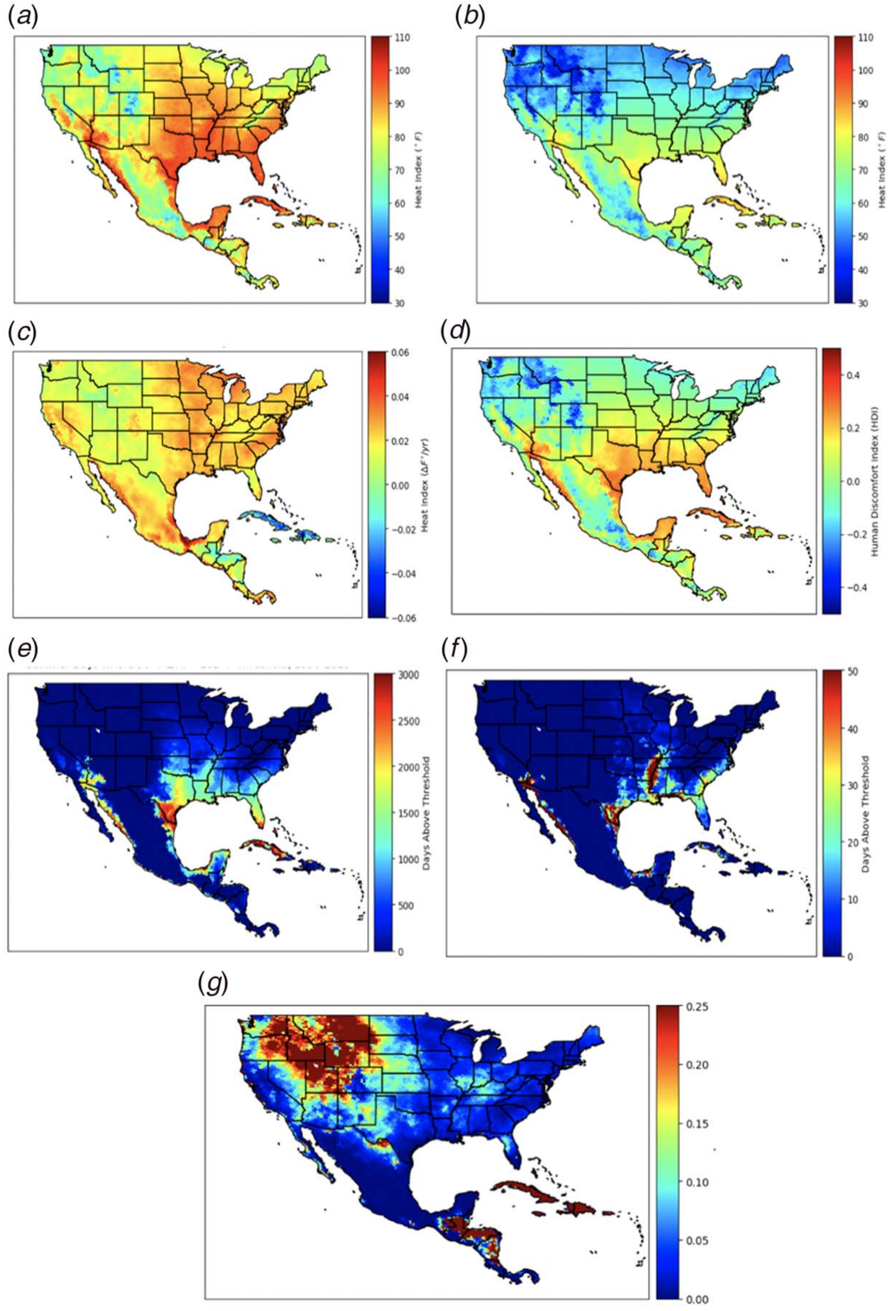

Fig. 2 Climatology of (*a*) maximum summer mean HI 1990–2019, (*b*) minimum summer mean HI, 1990–2019, (*c*) summer HI trend, 1990–2019 (°F/year), (*d*) mean summer HDI, 1990–2019, (*e*) summer days between 90 °F ≤ HI ≤ 102 °F, 1990–2019, (*f*) summer days HI ≥102 °F, 1990–2019, and (*g*) summer HI trend *p*-value, 1990–2019. Climatology, grid averages, and grid trends were computed using 3-h NCEP–NARR data during a 30-year period (1990–2019).

of performance of 3.0). This is more accurate for regions where building energy accounts for approximately half of the overall energy budget [10,27].

3 Results and Discussion

The aim of this study is to determine the effects of regional warming on energy demand per capita across the entire CONUS and Meso-America. We assume that as the HI continues to rise, energy demands per capita will rise in different regions with a changing HI pattern during the summer months. The specific issues of how climate impacts HI trends remain completely unanswered. The spatial distribution of HI and overall energy consumption per capita should indicate that there is a connection between energy for space cooling and climate change.

3.1 Heat Index and Human Discomfort Index. Results from our analysis for the HI and HDI can be seen in Fig. 2. Figures 2(*a*) and 2(*b*) display the patterns of HI, maximum, and minimum for the continental United States and Meso-America for the years 1999–2019. It demonstrates the mean maximum and minimum HI for the summer season (June, July and August) showing highest

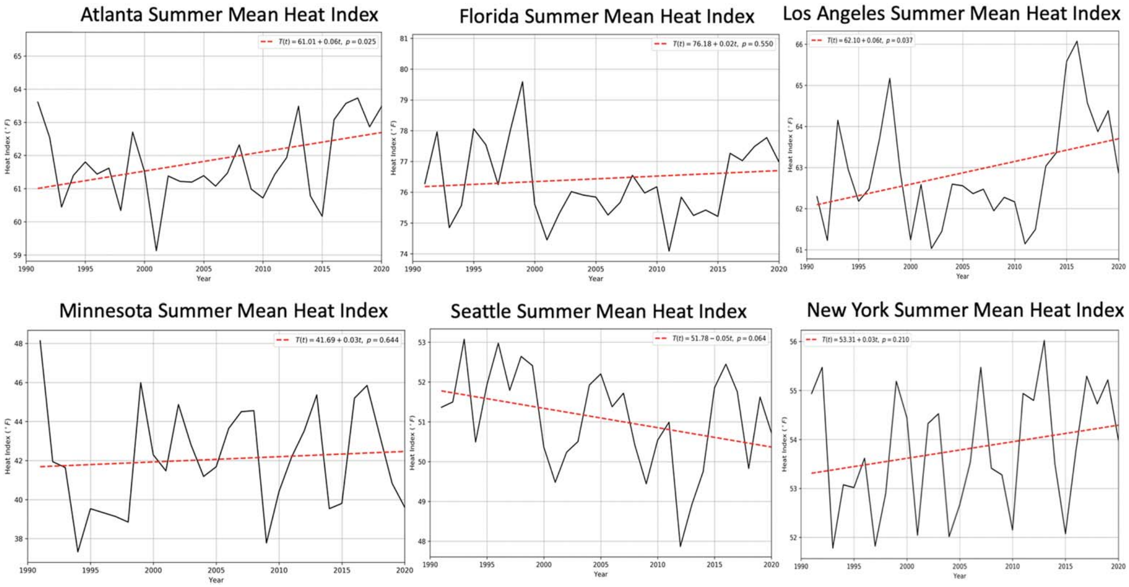

Fig. 3 Summer mean HI of different sites

Table 1 Comparison between weather station HI trends and NARR trends

City	NCEP HI trend (°F/year)	NARR HI trend (°F/year)
NYC	0.03	0.038
ATL	0.06	0.055
MIA	0.02	0.018
LAX	0.06	0.058
SEA	−0.05	−0.03
MN	0.03	0.045

values for Southeast US, followed by the Greater Antilles, Meso-America, and then the Lesser Antilles. The variation of maximum summer mean HI indicates highest values within the range of 100–110 °F for Southeast US and the Greater Antilles while the minimum summer mean HI values can be observed as 90 °F or above for this region. This makes it most vulnerable to encounter more frequent heat waves per year than other regions with more than 3000 days where the mean HI per day was greater than 90 °F and smaller than 102 °F for the past three decades as shown in Fig. 2(*e*). Meso-America and Lesser Antilles observed maximum summer mean HI to be within the range of 90–100 °F whereas

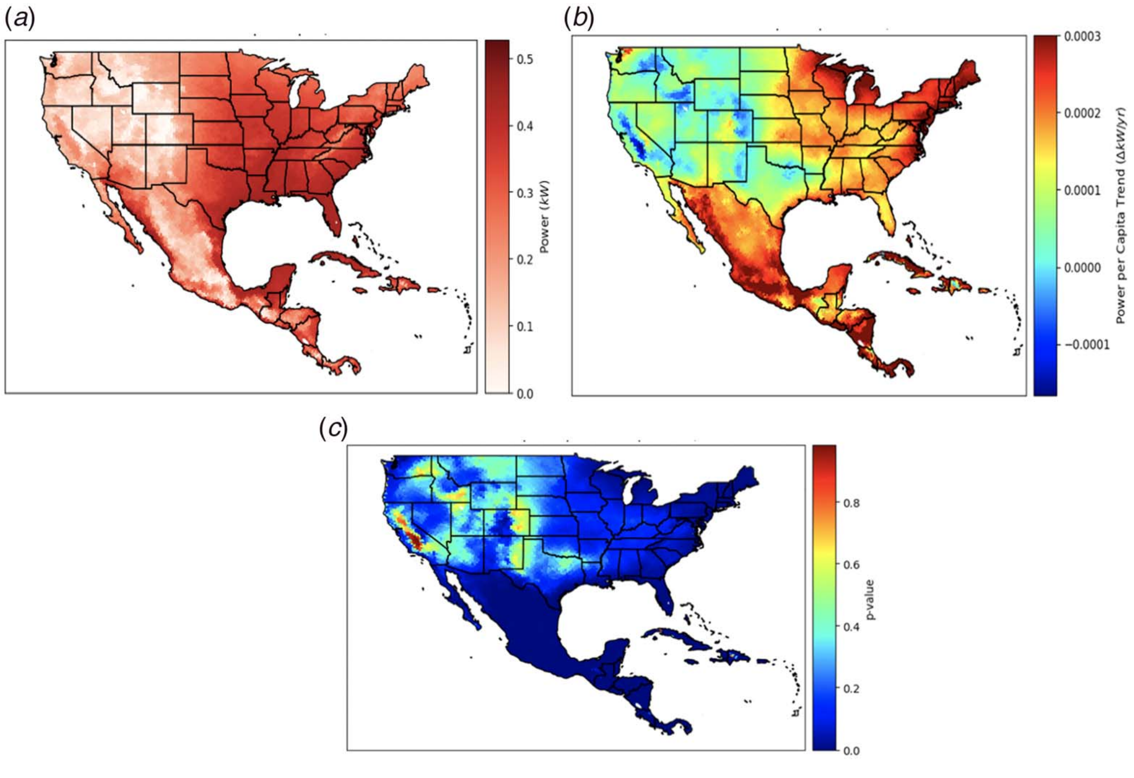

Fig. 4 Climatology of (*a*) peak summer PPC (kW), 1990–2019, (*b*) summer peak EPC trends, 1990–2019 (kW/year), and (*c*) summer mean PPC trend *p*-values, 1990–2019

the minimum summer mean HI values varied from 70 °F to 80 °F. The number of summer days per grid within the threshold of risk has been found to be more than 2000 days for Lesser Antilles. The trend in the HI (Fig. 2(*c*)) has a notably increasing pattern 0.058 °C year^{-1}(0.108 °F year^{-1}), and the trends are more prominent in the Meso-America than in Antilles 0.048 °C year^{-1}(0.088 °F year^{-1}) or the Southeast US 0.015 °C year^{-1} (0.03 °F year^{-1}), while in Greater Antilles it was found to be decreasing. Figure 2(*g*) shows the statistical significance of these trends, with most regions found to be significant at 95% or higher. These increasing trends are evidence of a warming climate.

The time series of mean summer HI (see Fig. 3) using weather station datasets illustrated that Eastern regions and Midwest observed more warming than Western regions. The spatial trends using NARR data were found to correlate very well with selected weather stations (Table 1) and were also determined to be statistically significant (Fig. 2(*g*)). The net result is a relatively high HDI (see Fig. 2(*d*)) in the Southeast and Southwest US, and the Caribbean. This will likely translate into increasing energy demands, which we present in the next sub-section.

3.2 Power Per Capita (kW) Consumption. Figure 4 illustrates the mean summer power per capita (PPC) (kW) and summer peak PPC trends (in kW/year) for the region; this is the mean of the actual peak energy consumed at a given hour. Red scale means energy is being consumed, while lighter red refers for no need for energy for cooling purposes. The Caribbean reaches a threshold of EPC of 0.35 kW/person. The spatial distribution correlates very well with the HI and HDI as expected with maximum values in the Southeast. Peak summer PPC climatology (Fig. 4(*a*)) illustrates that the southeast US, Yucatan, Greater Antilles (except Haiti and Dominican Republic), Northern Mexico along Gulf of California, and Gulf of Mexico reach a threshold of EPC of 0.35 kW/person. The largest HVAC EPC (0.3 kW/person) requirement is observed in Southern states along the Gulf of Mexico coast while the lowest or even zero is detected in Puerto Rico, the Dominican Republic, and Lesser Antilles. In addition, almost all the Western states of US were found to have lowest to no energy requirements for HVAC system per person (see Fig. 4(*a*)). The trend in the summer power demand per person (Fig. 4(*b*)) has a notably increasing trend of 0.0003 kW/year, and the trends are more noticeable in the Meso-America, Northeast US, and Greater Antilles than in Western states 0.0001 kW/year. These spatial trends using NARR data were found to be statistically significant with a *p*-value of less than 0.05 (Fig. 4(*c*)) for most of the regions.

3.3. Energy Per Capita (kW h) Consumption. The climatological EPC for the full summer season, averaged over the entire CONUS and Meso-America from 1990 to 2019, shows that the Southeast US and Greater Antilles except Haiti and Dominican Republic have the highest total energy demand for cooling, exceeding 750 kW h per capita (Fig. 5(*a*)) for the entire summer season and about 200 kW h per month (see Fig. 5(*c*)). These regions have the largest maximum summer EPC (175–200 kW h per month) (Fig. 5(*c*)), with maximum energy demands fluctuating between 700 and 800 kW h per capita over the summer (Fig. 5(*b*)).

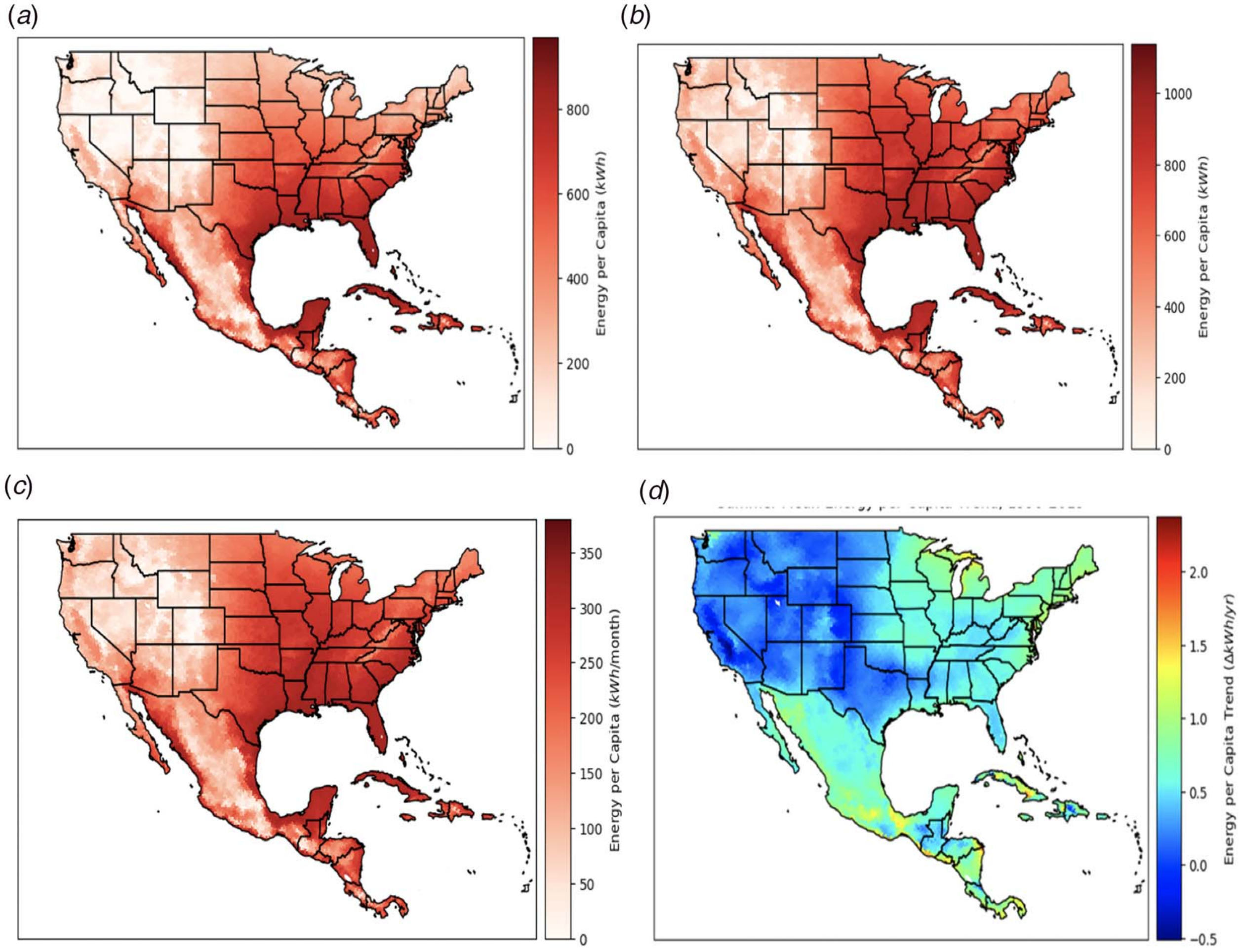

Fig. 5 **Climatology of (*a*) summer mean EPC, 1990–2019 (kW h), (*b*) maximum summer EPC, 1990–2019 (kW h), (c) maximum summer EPC per month, 1990–2019 (kW h/month), and (*d*) summer mean EPC trend, 1990–2019 (kW h/year)**

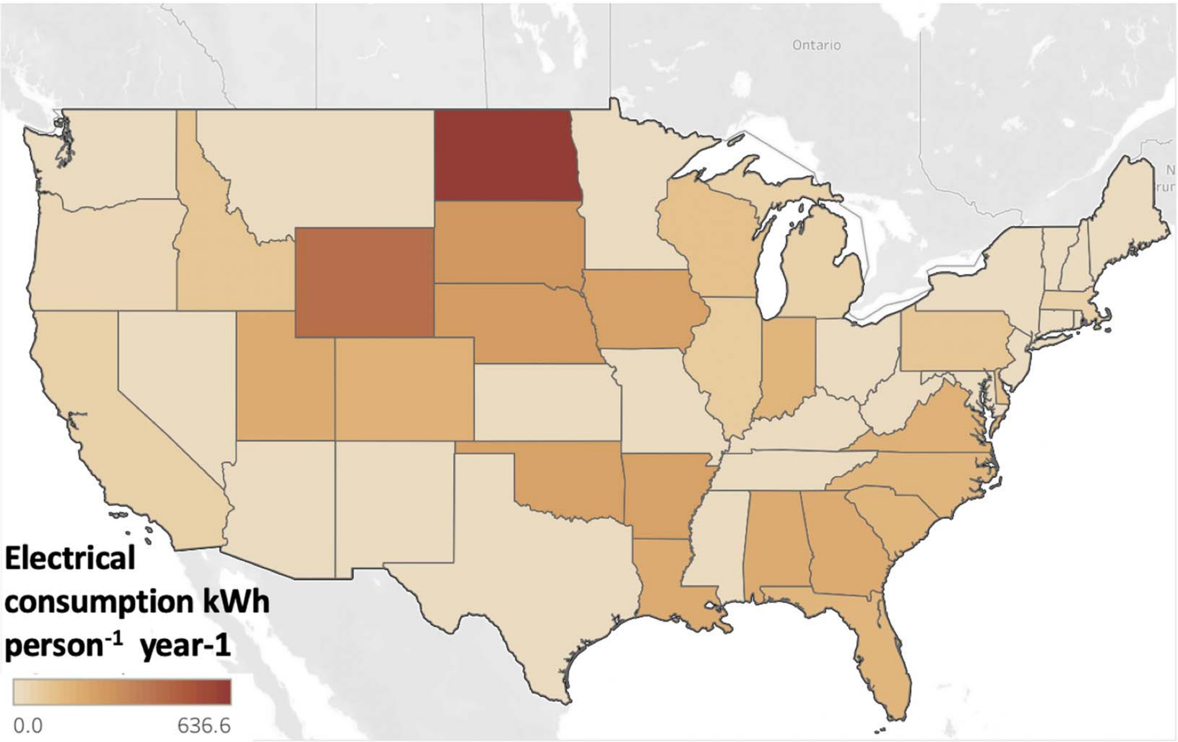

Fig. 6 Annual US electric power consumption per capita trends 1990–2019 by state

When analyzing the changes over time or temporal trends, it is observed that the Caribbean Sea and the Greater Antilles display an average positive rate of change of 1–2 kW h EPC per year (Fig. 5(*d*)). There is no discernible pattern in Southern Mexico. However, noticeable trends exist in Central Mexico, ranging from 1 to 1.5 kW h per year. As a result, the Southeast US and Caribbean countries are becoming regions with growing energy demand for HVAC systems per capita (Fig. 5(*d*)). On the other hand, Western states of US and the Southern Greater Antilles (Dominican Republic and Puerto Rico) tend to have overserved decreasing trend of −0.3 kWh/year.

3.4 Electrical Consumption. For the years 1990–2019, data on state-level electricity usage in the CONUS were acquired from the Energy Information Agency. Annual electric power consumption data were available, which was normalized using population data per state [28]. Finally, using linear regression values for electric power consumption from 1990 to 2019, a state-level map was generated. Figure 6 depicts overall energy growth in nearly all states, with reduced increase in the Western Pacific and Northeastern coastal regions. Electricity consumption in the Midwest and Southeast coastal regions showed substantial trends in the range of 300–600 kW h per person per year. The greatest values were found in Nevada and Wyoming with 630 and 433 kW h per person per year, respectively, whereas Ohio was the only state with no discernible trend. This finding is generally consistent with the energy consumption conducted using NARR data showing increased electric power consumption from 1990 to 2019 (Fig. 5). In general, the distribution of electricity consumption per person per year (Fig. 6) implies a correlation between rising maximum HI (Fig. 2(*c*)) and rising total energy consumption per capita (Fig. 5(*d*)).

4 Conclusions

As a response to recently observed climate change, this study conducted a trend analysis for the spatial and temporal distributions of HI, energy consumption per capita, and human comfort in the whole CONUS and Meso-America. The HI and a newly defined HDI were used in the environmental energy evaluation. The regions with relatively higher maximum HI and positive HDI were also the areas with highest energy demand consumption per capita.

Summer mean and maximum HI and HDI climatology show the highest values along the Gulf of Mexico coast, in the Greater Antilles, and in some regions along the Gulf of California coast in the Southwest of the United States. The highest HI and HDI contribute to a maximum energy requirement for air conditioning systems, indicating that these are the same regions with ventilation requirements to achieve human comfort in buildings. With the exception of Haiti, Dominican Republic, and Western US, which have no trends, the Southern states and the Greater Antilles point to an EPC in the range of 175–200 kW h per month for the summer season (1990–2019), with a growing trend varying with rates of change of 1.5 and 2.0 kW h per year and the mean power per person consumption was found to have a notable increasing trend of 0.0003 kW/year for these regions.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtained from the corresponding author upon reasonable request. The data and information that support the findings of this article are freely available.[2] The authors attest that all data for this study are included in the paper.

Nomenclature

h_{env} = the outside enthalpy estimated using the local air temperature and the mixing ratio
EPC = energy consumption per capita (kW h) to maintain indoor human comfort levels
HI = the heat index is an effective tool for calculating the effect of excessive heat and serving as an early warning measure. The HI scale is a measurement of human discomfort and stress affected by ambient temperature and RH
HDI = a human discomfort index indicates the quantifiable level of human discomfort from a reference benchmark
PPC = the mean peak power per capita (kW) for the region is the mean of the actual peak energy consumed at a given hour to maintain indoor comfort levels
$\mathrm{HI}_{\mathrm{ref}}$ = the heat index at the reference comfort level of 22.2 °C and 50% RH

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