How Punjab experienced the heat stress conditions for the last 70 years and understand the climate change impacts

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1 Abstract

This study examines the historical heat stress conditions in the Punjab region of India over the past 70 years and evaluates the impacts of climate change. Utilizing daily Universal Thermal Climate Index (UTCI) data from 1950 to 2023, the research offers a comprehensive analysis of temperature and humidity patterns across the state. Data was obtained from the Copernicus Climate Data Store and processed using Python programming, with visualizations created in Python and Google Colab. Results show a significant increase in heat stress conditions in Punjab over the past seven decades, with more frequent and intense heatwaves observed in recent years. The findings highlight the urgent need for climate change mitigation strategies and adaptive measures to protect the region's population, agriculture, and economy from the adverse effects of rising temperatures and humidity. This study contributes to the existing body of knowledge on climate change impacts and serves as a valuable resource for policymakers, researchers, and stakeholders working towards a sustainable and resilient future for Punjab.

2 Introduction

Climate change has become a pressing issue worldwide, leading to significant changes in the frequency and intensity of extreme weather events. One aspect of this phenomenon is the increase in heat stress, which has severe implications for human health, agriculture, and ecosystems. This study aims to analyze the historical trends of heat stress conditions in the Punjab region of India over the last seven decades, utilizing the Universal Thermal Climate Index (UTCI) as a measure of thermal comfort. By examining data from 1950 to 2023, this research seeks to understand the impacts of climate change on the region and provide insights into potential adaptation strategies for the future.[1][2]

2.1 ERA5-HEAT DATA set and Universal Thermal Climate Index (UTCI)

The dataset, known as ERA5-HEAT (Human thErmAl comforT), offers a detailed historical record of human thermal stress and discomfort in outdoor environments. Representing the current state-of-the-art in bioclimatology data record production, ERA5-HEAT focuses on two primary variables: Mean Radiant Temperature (MRT) and the Universal Thermal Climate Index (UTCI).
Both MRT and UTCI are derived from the European Centre for Medium-Range Weather Forecasts' (ECMWF) ERA5 reanalysis, a globally recognized source for consistent and complete climate data. By combining model data with worldwide observations, ERA5 serves as an excellent proxy for observed atmospheric conditions.
The ERA5-HEAT dataset covers the period from January 1940 to near real-time and is regularly updated as new ERA5 data becomes available. With a global scope (excluding Antarctica), the dataset is organized on a 0.25Â° x 0.25Â° regular latitude-longitude grid and provides hourly surface-level data.
Produced by the European Centre for Medium-range Weather Forecasts, ERA5-HEAT is available in NetCDF format, adhering to the Climate and Forecast (CF) Metadata Convention v1.6. The dataset has multiple versions, with v1.1 being the latest and an upcoming version expected in early 2023..
The two main variables of ERA5-HEAT are:
Mean Radiant Temperature (MRT) : measured in Kelvin (K), represents the uniform temperature of a fictional black-body radiation enclosure (emission coefficient $\mu = 1$) that would result in the same net radiation

energy exchange with a person as the actual radiation environment, considering their posture and clothing.
Universal Thermal Climate Index (UTCI) : measured in Kelvin (K), defines the air temperature of a reference outdoor environment that would cause the same physiological response (sweat production, shivering, skin wettedness, skin blood flow, and various body temperatures) in a human body as the actual environment, considering the combination of air temperature, wind, radiation, and humidity.
In summary, ERA5-HEAT is an invaluable resource for understanding the historical impacts of outdoor conditions on human thermal comfort, enabling researchers and policymakers to develop strategies for mitigating adverse effects on human health.
In this research project we will focus only on Universal Thermal Climate Index (UTCI) as variable.

The Universal Thermal Climate Index (UTCI) is a comprehensive measure that evaluates the level of thermal stress experienced by the human body in various atmospheric conditions. This index is derived from a combination of four key environmental factors: air temperature, humidity, ventilation, and radiation. By incorporating these factors into human heat balance models, UTCI provides an equivalent temperature that represents how a person would feel under a reference environment with standardized values for these variables.
UTCI offers a broad scale that extends from extreme cold stress to extreme heat stress, effectively capturing the entire spectrum of thermal comfort. The index serves as a valuable tool in assessing the impact of different environmental conditions on human well-being, enabling researchers and policymakers to better understand the consequences of climate change and develop targeted adaptation strategies.
[*Thermal comfort indices derived from ERA5 reanalysis*]

2.2 Region of Interest

Punjab is a state located in the northern part of India. It shares its borders with the Indian states of Jammu and Kashmir, Himachal Pradesh, Haryana, and Rajasthan, as well as the neighboring country of Pakistan. Punjab's geography and environment can be characterized by several unique features:
Landforms: Punjab is primarily a flat plain, with an average elevation of around 300 meters above sea level. The state is divided into three distinct regions: the Shivalik Hills in the northeast, the Punjab Plain in the central and southwestern parts, and the Malwa Plateau in the southeast.
Rivers and water resources: Punjab is home to several major rivers, including the Sutlej, Beas, Ravi, Jhelum, and Chenab. These rivers originate from the Himalayas and are essential sources of water for irrigation and hydroelectric power generation.
Climate: Punjab experiences a semi-arid to subtropical climate, with three main seasons ; hot summer (April to June), monsoon (July to September), and cool winter (December to February). The state receives an average annual rainfall of around 600-700 millimeters, mostly during the monsoon season.
Vegetation: Punjab has a diverse range of vegetation, including subtropical dry evergreen forests, tropical thorn forests, and tropical dry deciduous forests. Some common tree species are kikar, shisham, babul, and mulberry.
Agriculture: Punjab is known for its fertile agricultural land and is often referred to as the "*Granary of India*." The figure given below (Figure1:Basemaps:Land Cover) shows the land cover area of Punjab State. The primary crops grown in the state include wheat, rice, cotton, sugarcane, and maize.
Overall, Punjab's geography and environment are characterized by diverse land forms, a semi-arid to subtropical climate, significant river systems, and a rich biodiversity, making it an agriculturally and culturally

vibrant state in India.

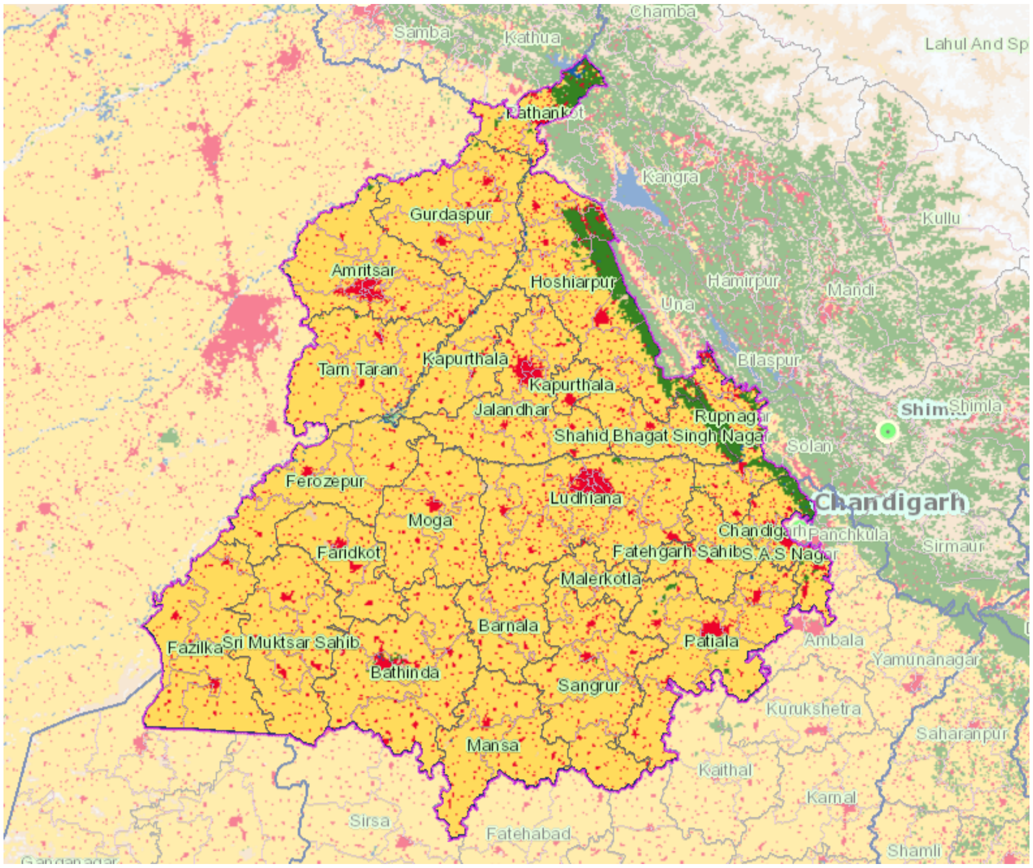

Figure 1: Basemaps:Land Cover:Punjab State

[*Bharatmaps*]

2.3 Why Thermal stress matters

Adverse effects on human health can occur when individuals are exposed to extreme temperatures, whether hot or cold. Heat stress, for example, is associated with numerous health risks, including dehydration, heat cramps, and potentially fatal conditions during heatwaves.[3] Conversely, exposure to extreme cold can also result in health issues, such as frostbite, hypothermia, and increased mortality rates. Exposure to thermal stress can severely disrupt normal bodily functions if rapid increases in core body temperature are not effectively regulated through behavioral adjustments and the body's involuntary cooling mechanisms. In the United States alone, around 200 heatstroke deaths occur annually, and this number is anticipated to rise due to factors such as an aging population, increasing obesity rates, and global warming.
Although heat illness can affect all individuals, the specific risk factors and causes of heat stroke vary between younger adults and the elderly. A better comprehension of the body's thermoregulatory processes in response to heat stress, coupled with the advancement of innovative prevention and treatment methods, can help reduce the incidence and severity of heat-related illnesses across all segments of society.

3 Methodology

Data Source: Thermal comfort indices derived from ERA5 reanalysis were obtained from the Copernicus Climate Data Store (CDS) API. The dataset contain Universal Thermal Climate Index (UTCI), which are essential for evaluating thermal comfort and heat stress.

CDS API Data Request and Collection: Using the CDS API, data specific to the Punjab region was requested and collected. The data was extracted in the form of netCDF files for the period between 1950 and 2023.

Data Storage and Handling: The downloaded netCDF files were organized and compressed into ZIP files for efficient storage on Google Drive. Google Colaboratory was chosen as the working platform for data processing and analysis. Python programming language , was utilized to handle data extraction, manipulation, and visualization tasks.

Data Extraction and Organization: The zipped data files were extracted, and the data was organized into separate groups, each containing data for a decade. Each group was further processed to focus on the Punjab region's specific geographical coordinates.

Data Processing: For each decade, the daily average UTCI and Monthly average UTCI were calculated to observe trends and variations at a finer temporal resolution.

Data Combination: All daily average data was combined into a single Pandas DataFrame to facilitate further analysis and visualization.
Temperature Conversion: The UTCI values in Kelvin were converted to Celsius to make the results more intuitive and relatable.
Stress Category Definition: 10 stress categories were defined based on UTCI ranges, encompassing thermal conditions from extreme heat stress to extreme cold stress: Extreme Heat Stress, Very Strong Heat Stress, Strong Heat Stress, Moderate Heat Stress, No thermal stress, Slight Cold Stress, Moderate Cold Stress, Strong Cold Stress, Very Strong Cold Stress, Extreme Cold Stress[1]

Monthly Average Data Calculation: To identify seasonal trends, the monthly average UTCI was calculated for each year.
Visualization: Various visualizations were created to analyze and present the data:

Heat maps: UTCI trends was visualized using heat maps to represent temporal variations in thermal comfort conditions. Yearly Average UTCI with Trendline: Line plots were used to depict the average annual UTCI values and the overall trend throughout the period of 1950-2023.

Spatial maps: The spatial distribution of UTCI values across the Punjab region was visualized using shapefiles, providing geographical context to the analysis.

Distribution of Stress Categories: Bar charts were employed to represent the proportion of days falling

Table 1: Stress Category

S.No	UTCI Celsius(°C)	Stress Category
1	More than 46	Extreme Heat Stress
2	38 to 46	Very Strong Heat Stress
3	32 to 38	Strong Heat Stress
4	26 to 32	Moderate Heat Stress
5	9 to 26	No Thermal Stress
6	0 to 9	Slight Cold Stress
7	-13 to 0	Moderate Cold Stress
8	-27 to -13	Strong Cold Stress
9	-40 to -27	Very Strong Cold Stress
10	Less than -40	Extreme Cold Stress

under each stress category, helping understand the frequency and intensity of different thermal stress conditions.

By following this systematic methodology, a comprehensive analysis of heat stress conditions in Punjab over the last 70 years was conducted, revealing valuable insights into climate change impacts and guiding future adaptation strategies.

4 Visualization

With the collected data (Daily average, Monthly average, Yearly average data) graphs were plotted.

4.1 Yearly average UTCI values (1950-2023)

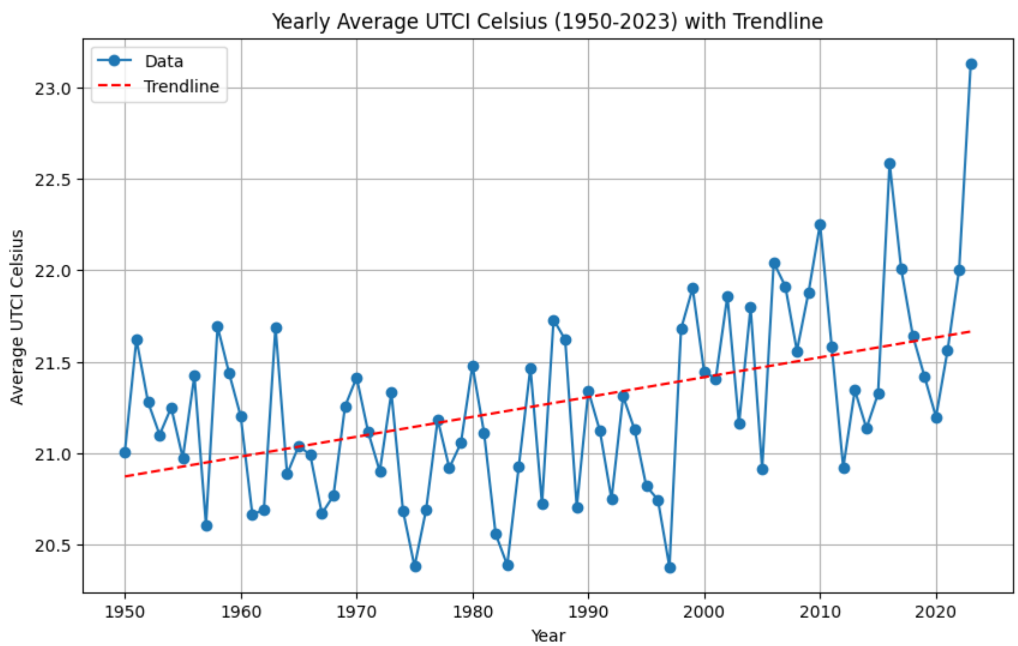

Figure 2: Yearly Average

The slope of the line is **0.011**

- Here the slope of line is positive and increasing, denoting an increase in yearly average UTCI values throughout the years
- The lowest value of yearly average UTCI Celsius is observed between 2000 and 1970
- After the year 2000, there is a gradual increase in Yearly average UTCI values

4.2 Monthly Average UTCI values (1950-2023)

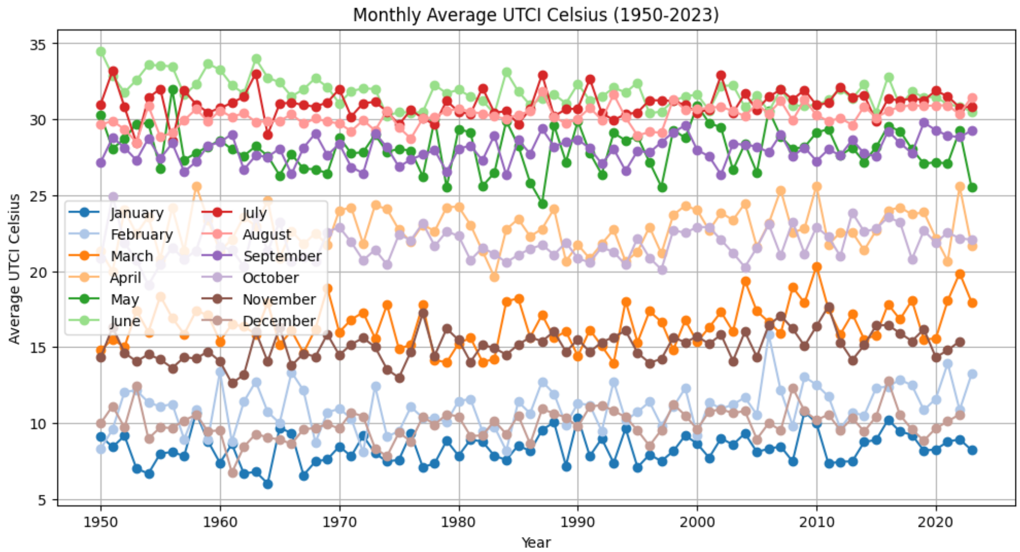

Figure 3: Monthly Average

- The month of May, June, July, August, September shows a average UTCI values (between 35 and 25)
- June and July month marks greater Average UTCI values.
- Highest Average UTCI value was observed in 1950 during the month June
- Minimum or lowest average UTCI values are observed during the month of December and January
- Lowest average UTCI values was observed in between 1960 and 1970 during the month of January

4.3 Stress category and Occurrence

Data: Daily Average data

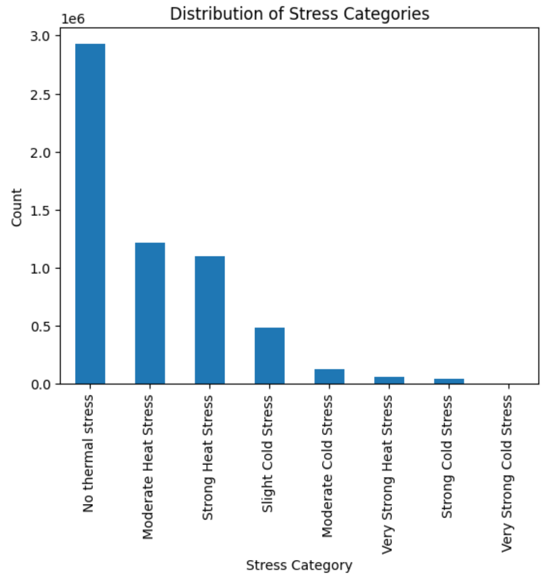

Figure 4: Stress category

4.4 UTCI Celsius Heat Map and Monthly UTCI Distribution

Time scale: 1950-2023

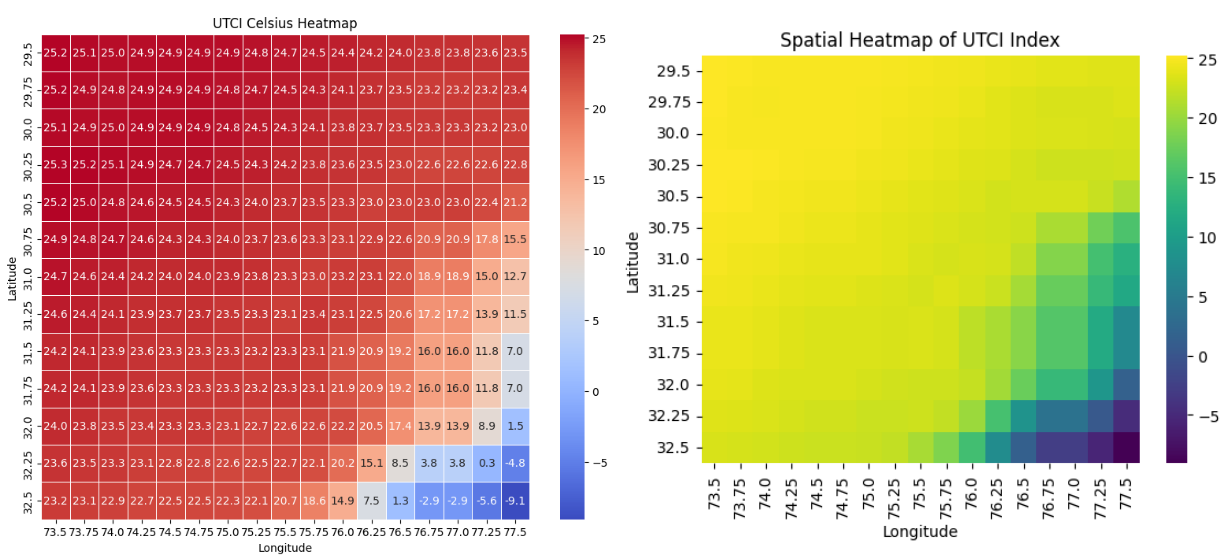

Figure 5: HeatMaps

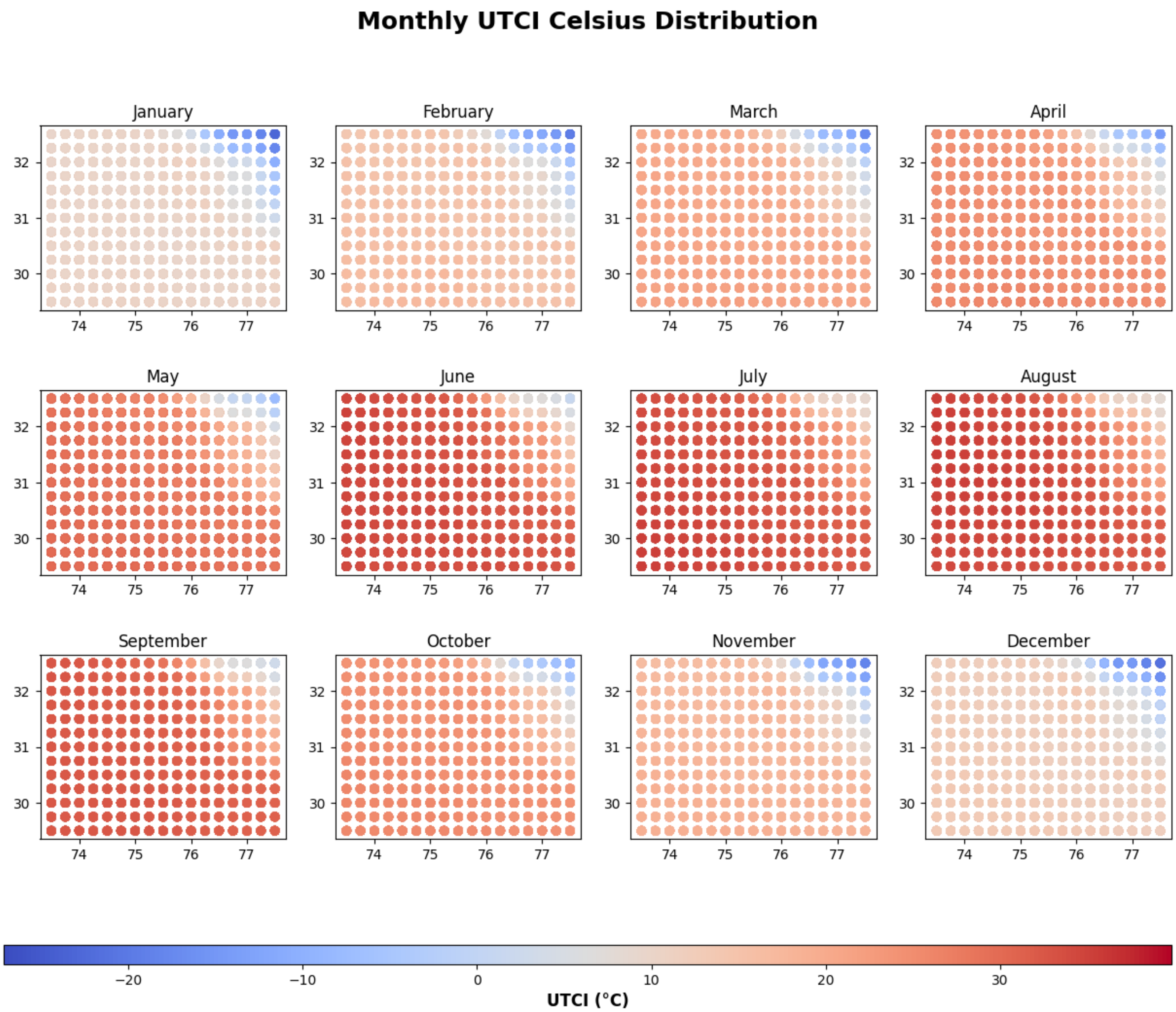

Figure 6: UTCI Distribution

4.5 Punjab:Monthly UTCI distribution and stress category distribution

Time scale: 1950-2023 Data: Monthly average UTCI values

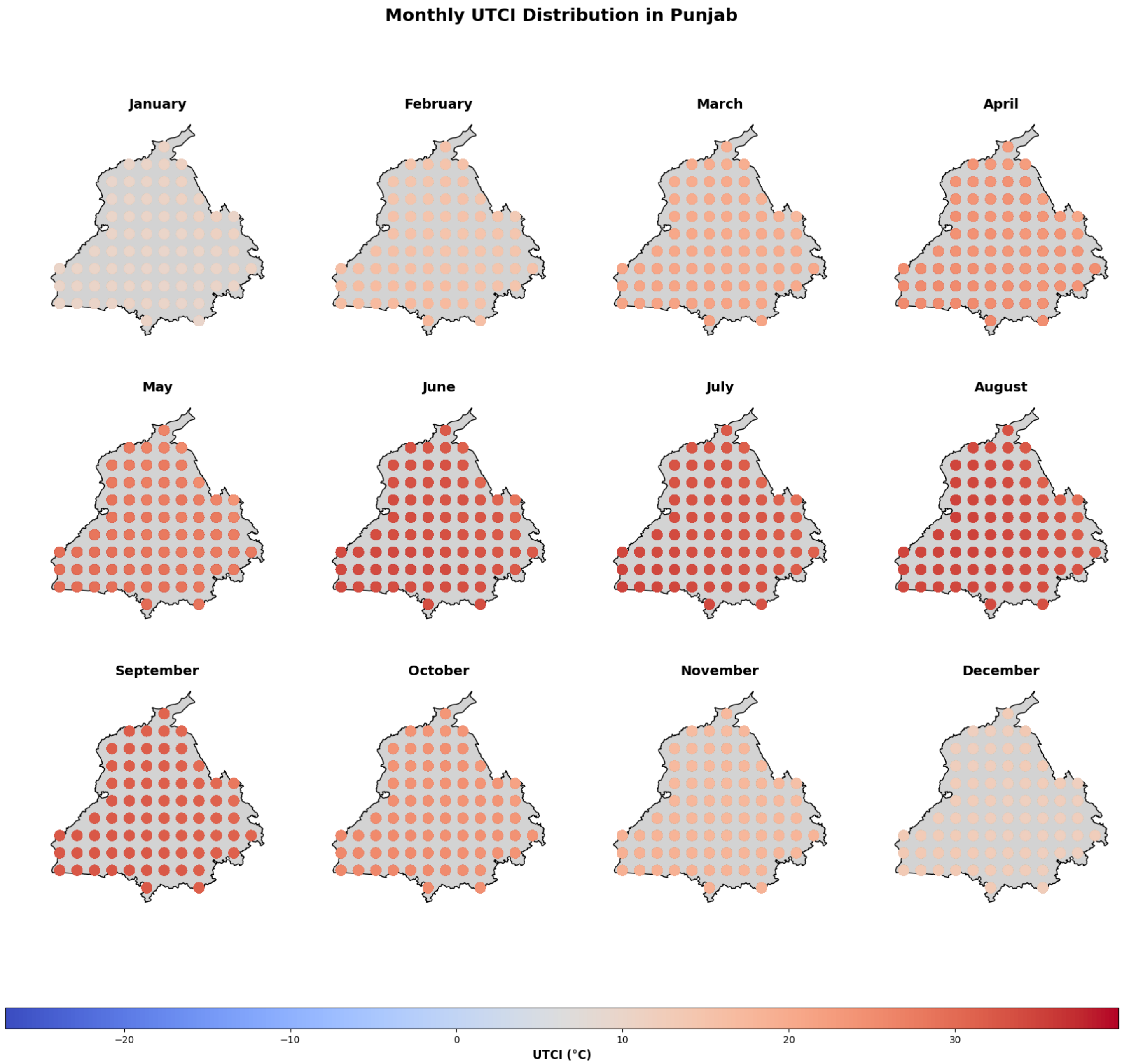

Figure 7: UTCI Distribution (Punjab)

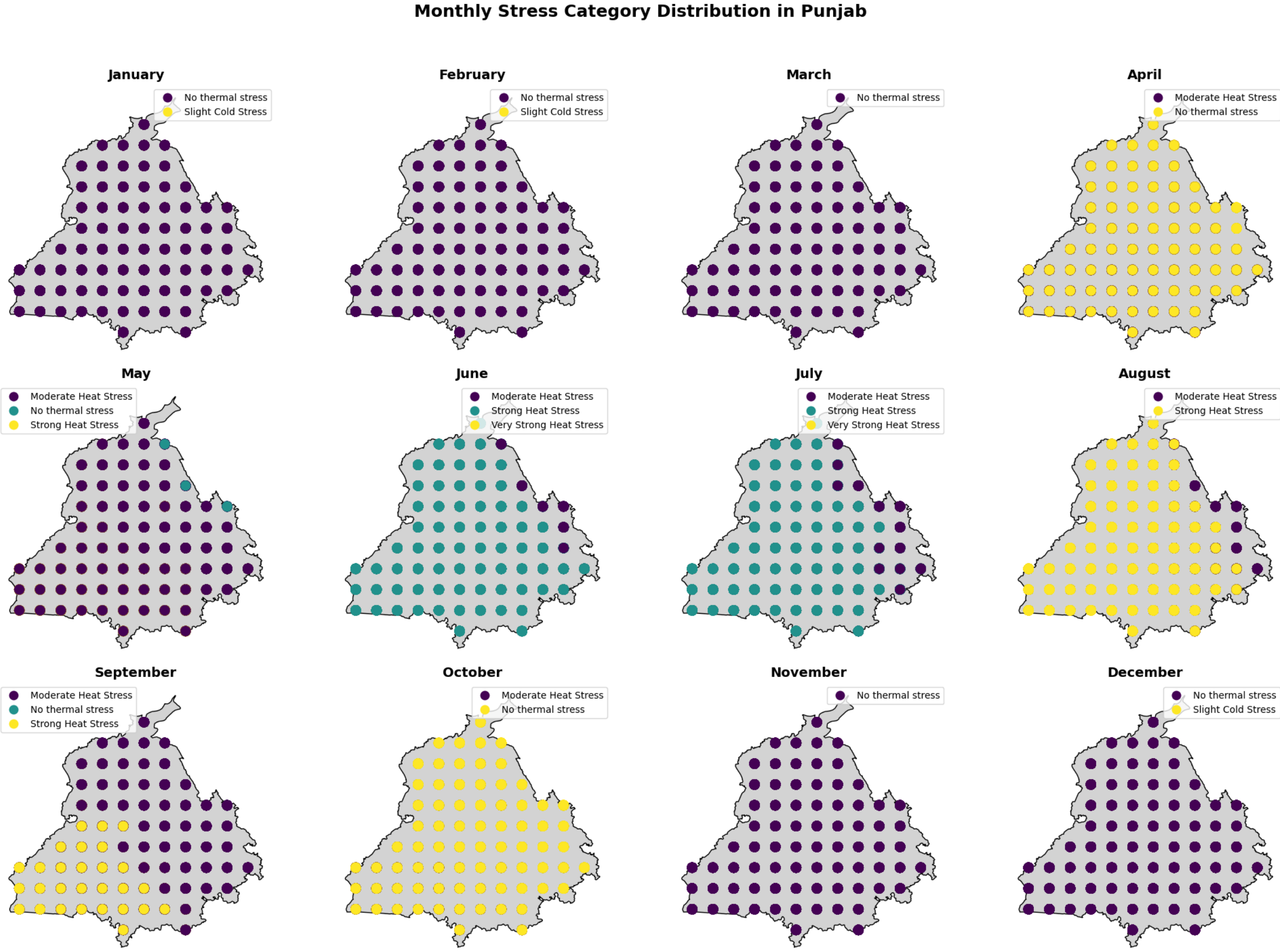

Figure 8: Punjab stress distribution

5 Result

My analysis of the Universal Thermal Climate Index (UTCI) data for the period 1950-2023 reveals several significant trends and patterns in the study area. The following are my findings organized by visualization graphs:

- **Yearly Average UTCI Celsius (1950-2023) with Trendline**

The yearly average UTCI Celsius data, represented by a red dashed trendline, shows a gradual increase over the years. This upward trend indicates a warming climate during this period. Despite the general increase, there are year-to-year fluctuations in UTCI, with some years experiencing higher temperatures and others showing slight decreases. Around 2020, there is a notable spike in UTCI, reaching its highest point on the graph, which could be related to climate events or other factors. This increasing trend in yearly average UTCI Celsius is significant for climate research as it highlights the long-term impact of rising temperatures.

- **Monthly Average UTCI Celsius (1950-2023)**

The monthly average UTCI Celsius data shows that June experiences the highest average UTCI values, while January exhibits the lowest trend. This suggests that the summer months are associated with higher thermal stress levels, whereas winter months experience milder thermal conditions.

- **Distribution of Stress Category: Bar Graph**

This bar graph represents daily average data, unlike others that depict monthly averages. My analysis shows that "No Thermal Stress" has the highest count, indicating its prevalence, followed by "Moderate Heat Stress." "Strong Heat Stress" occurs less frequently but remains significant. These results highlight the importance of understanding the varying levels of thermal stress experienced in the region.

- **UTCI Celsius Heat Map**

The UTCI Celsius Heat Map demonstrates that both latitude and longitude play essential roles in determining thermal stress levels. This finding emphasizes the significance of geographic factors in understanding thermal comfort and potential health impacts on residents in the area.

- **Monthly UTCI Celsius Distribution**

Analysis of monthly UTCI distribution shows higher UTCI values from May to September, with peaks during June, July, August, and September. Conversely, December, January, and February recorded the lowest UTCI values. This pattern corresponds with seasonal temperature variations, with higher thermal stress levels occurring during summer and lower thermal stress in winter.

- **Monthly UTCI Celsius Distribution in Punjab**

My investigation of UTCI distribution in Punjab helped visualize and interpret the range of UTCI values specific to this region. I noted the lowest UTCI values in January and the highest in June, July, August, and September. This finding corroborates the general seasonal pattern observed in the monthly UTCI distribution analysis.

- **Monthly Stress Category Distribution in Punjab**

Analysis of stress category distribution in Punjab revealed specific trends throughout the year. January, February, March, and December were characterized by "No Thermal Stress," while April and October primarily experienced "No Thermal Stress" with some "Moderate Heat Stress." In May, "Moderate Heat Stress" was the dominant category, followed by "Strong Heat Stress" in June, July, and August. September saw a near-equal distribution of "Moderate Heat Stress" and "Strong Heat Stress" across the region. Notably, there were no instances of "Extreme Cold," "Very Strong Cold," "Strong Cold," "Moderate Cold," "Slight Cold," "Very Strong Heat Stress," or "Extreme Heat Stress" observed in my analysis. These results provide valuable insights into the seasonal and geographic variations in thermal stress levels within the study area, emphasizing the importance of appropriate adaptive measures to ensure the well-being of the local population.

6 Summary and Discussion

This study analyzed Universal Thermal Climate Index (UTCI) data from 1950 to 2023 to identify trends and patterns in thermal stress levels within the study area. Key findings include:

1. An overall increasing trend in yearly average UTCI Celsius, indicating a warming climate.
2. Highest average UTCI values occurred in June, while January showed the lowest trends.
3. "No Thermal Stress" and "Moderate Heat Stress" were the most common categories observed.
4. Geographic factors, such as latitude and longitude, play a significant role in thermal stress levels.
5. Seasonal variations in thermal stress levels, with higher values during the summer months and lower values during the winter.
6. Specific trends in stress category distribution in Punjab throughout the year, with "No Thermal Stress" dominating during winter months and "Moderate Heat Stress" and "Strong Heat Stress" prevalent during summer months.

Discussion; Our findings highlight the importance of understanding and addressing the increasing trend in thermal stress levels within the study area. This observed increase can have potential implications for human health, especially during summer months when outdoor activities are more common. In light of this, developing targeted measures to mitigate thermal stress in urban environments is essential.Furthermore, the influence of geographic factors on thermal stress levels underscores the need for tailored approaches to heat mitigation that consider local conditions. This may include green infrastructure, urban planning strategies, and climate-sensitive building designs. Seasonal variations in thermal stress levels suggest that heat mitigation efforts should be seasonally-adaptive, with a focus on addressing the heightened thermal stress experienced during the summer months. This could involve promoting awareness campaigns and providing heat-relief resources during these critical periods. Lastly, the observed trends in stress category distribution within Punjab provide valuable insights into regional thermal conditions and can inform localized heat mitigation strategies to ensure the well-being of the population.

Limitations: Managing large files in Python can be challenging, especially when working with netCDF formats and limited RAM. In such cases, utilizing the Climate Data Operators (CDO) command-line utility in Linux is more efficient for chunking and processing large files. Additionally, *ncview* and *ncdump* are useful command-line tools for quickly visualizing netCDF data, offering a practical alternative to Python libraries . It will be better to use Linux for this particular task. This study can be made more advanced and efficient using many software like QGIS (Geographic Information System) and various techniques.

Future Research; Future research should focus on exploring the effects of thermal stress on various demographic groups and identifying effective interventions that can help communities adapt to rising temperatures. Additionally, the potential impacts of climate change on thermal stress levels and the implications for public health warrant further investigation.

7 Acknowledgements

I would like to express my sincere gratitude to the individuals who have contributed to the success of this project. First and foremost, I would like to thank my supervisor, Dr. Raju Attada , for his invaluable guidance, continuous support, and encouragement throughout the duration of this project. His expertise and insights have been instrumental in shaping the direction and quality of this work. I am also immensely grateful to Dr. Krishna K Shukla for providing essential instructions and sharing his knowledge, which greatly enriched the research and analysis process. His inputs have significantly enhanced the overall quality of the project. Special thanks to Mr. Deepak, who provided vital assistance in the coding aspect of this project. His technical expertise and dedication were essential to the smooth execution of the data analysis. Without the collective contributions and support of Dr. Raju Attada , Dr. Krishna K Shukla , and Mr. Deepak, this project would not have been possible. Their efforts and commitment are genuinely appreciated.

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[3] "Ecmwf releases 40-year dataset on weather-induced thermal stress," 2020.