Spatiotemporal Modeling of Heat and Cold Waves in Northeast Syria: A 23-Year Analysis

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Abstract: *Extreme weather conditions, particularly heat waves and cold waves pose a threat to society by impacting habitability, health, and social interactions. In recent decades, the effects of heat stress on public health have been of great concern worldwide. As a result, human biometeorological indices are widely used to assess the links between the outdoor environment and human well-being. This study examines the spatiotemporal modelling of heat and cold indices over 23 years in Northeast Syria. Two indices are considered to evaluate the degree of heat and cold stress in the outdoor environment: the Heat Index (HI) and thermo-hygrometric index (THI). Daily meteorological data, encompassing air temperature and dew point temperature, were acquired from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land reanalysis between 2000 and 2022, and with a global resolution of 0.1°. This data set is accessible and processed through Google Earth Engine (GEE). The spatial distribution of these indices reveals significant spatiotemporal variability. The northern areas of southeast and western Syria show increased vulnerability to heat according to the HI index, while the southernmost part of northeast Syria shows pronounced vulnerability to cold according to the THI index. This suggests that a significant proportion of the population living in these areas is likely to be more vulnerable to specific health problems. This situation could potentially trigger socio-economic ramifications related to cold waves in northeast Syria and to heat waves in the west and south. Therefore, the indices used play a crucial role in assessing heat levels in the environment and protecting individuals against heat-related illnesses.*

Keywords: Heat Waves, Cold Waves, Syria, ERA5-Land, Google Earth Engine

Introduction

Climate extremes, such as heat waves and cold waves, are becoming more frequent and severe due to global climate change. These extreme temperature events can profoundly impact public health, agriculture, and infrastructure (Serrano-Notivoli et al., 2022). Heatwaves pose significant risks, particularly during prolonged periods of elevated temperatures, while cold waves can lead to serious consequences in terms of frost damage and cold stress, affecting both people and livelihoods (Hu et al., 2019). Understanding these events' spatial and temporal distribution is crucial for implementing effective adaptation and mitigation strategies.

In the absence of local meteorological data, the use of global reanalysis datasets, such as ERA5-Land, offers a reliable alternative for monitoring climate extremes (Espinosa et al., 2023). These datasets provide high-resolution information on temperature, humidity, and other atmospheric variables, enabling a detailed analysis of heat and cold stress across regions. In this study, we utilize the Heat Index (HI) and Temperature-Humidity Index (THI) to map and analyze the distribution of heatwaves and cold waves in Northeast Syria from 2000 to 2022. The objective is to identify the region’s most vulnerable to extreme temperature events and examine their trends over time, providing insights into climate variability's potential risks.

By combining spatial distribution maps and trend analysis, this research aims to inform policymakers and local authorities on the necessary steps for public health preparedness and climate adaptation. The findings of this study are critical for developing early warning systems and for implementing long-term strategies to reduce the adverse impacts of heat waves and cold waves on the region's population and economy.

Study Area:

The northeastern region of Syria, situated between the Euphrates River, Türkiye, and Iraq, has been designated as the study area for this research. The latitude and longitude of the designated zone span from 34 to 37 °N and 38 to 42 °E, respectively, encompassing an area of approximately 50,000 km² (Figure 1). The region is situated inside the Fertile Crescent, which is characterized by its arable soil and traditionally serves as a principal agricultural center of the nation (Tull, 2017).

Figure 1. The geographical location of the study area.

Data and Method:

a. Data Collection:

Due to the absence of consistent and reliable local meteorological data in Northeast Syria, publicly accessible reanalysis data serves as an essential alternative. ERA5-Land offers significant advantages, combining observations with model outputs to provide a continuous and coherent climate dataset with a spatial resolution of 9 km, covering the period from 1950 to the present (Muñoz-Sabater et al., 2021). This enables accurate long-term climate analysis, particularly useful for regions with sparse observational networks. Through Google Earth Engine (GEE), we accessed ERA5-Land data and efficiently extracted daily maximum and minimum temperature values as well as dew point temperature, which were essential for calculating thermal comfort indices for heatwaves and cold waves. The powerful analytical capabilities of GEE enabled comprehensive spatial and temporal analysis, despite the lack of localized observational data, allowing us to map and monitor extreme temperature events throughout the study area.

b. Indices Used:

In this study, two key thermal indices were employed to assess heat stress and human discomfort during extreme temperature events: the Heat Index (HI) and the Temperature-Humidity Index (THI). HI, also known as the apparent temperature, is a widely used measure that combines air temperature and relative humidity to estimate the temperature perceived by the human body (Awasthi et al., 2021). The formula for the HI (Steadman, 1979) is developed by using multiple regressions, such as the Poisson Regression analysis technique on the meteorological data:

$$HI\,(^{o}F) = -42.379 + 2.04901523 \times T + 10.14333127 \times RH - 0.22475541 \times T \times RH - 6.83783 \times 10^{-3} \times T^{2} - 5.481717 \times 10^{-2} \times RH + 1.22874 \times 10^{-3} \times T^{2} \times R + 8.5282 \times 10^{-4} \times T \times RH^{2} - 1.99 \times 10^{-6} \times T^{2} \times RH^{2} \quad (Eq.\ 1)$$

Where T is the air temperature in degrees Fahrenheit (F), RH is the relative humidity in percentage. This index is particularly useful for quantifying heat stress during heatwaves, as high humidity levels impede the body's ability to cool down through perspiration (Awasthi et al., 2021).

The THI is another valuable measure for assessing thermal comfort and discomfort (Segnalini et al., 2012). It takes into account both temperature and humidity but is simpler in formulation compared to HI. The THI can be calculated using the following equation:

$$THI = T - (0.55 - 0.55 \times RH) \times (T - 14.5) \qquad (Eq.\ 2)$$

where T is the temperature in degrees Celsius, and RH is the relative humidity as a fraction.

c. Method:

The methodology of this study is inspired by the method of (El Morjani & Idbrahim, 2011), with the distinction that the latter integrates station data for NOAA dataset, while we incorporate ERA5-Land data to calculate thermal indices. ERA5-Land data provides essential variables such as temperature and dew point temperature, which are necessary for calculating relative humidity. Using these data, the HI and the THI are computed for each pixel within the study area. These indices are averaged over three-day intervals, the minimum duration typically used in research to capture heatwave and coldwave events. The maximum values of these indices for each year are then extracted, enabling a detailed analysis of extreme temperature events over time.

The resulting maps are classified into categories, identifying the area's most vulnerable to heat waves and cold waves. This approach allows for the generation of classified distribution maps, which provide a spatial representation of temperature extremes, enabling a more nuanced understanding of their geographic distribution and potential impact zones.

Results and Discussion

a. Heatwave and Coldwave Mapping:

Figure 2 represents the spatial distribution of heatwaves (top) and cold waves (bottom) in the study area. The spatial averages of these extreme events provide a visual representation of how persistent extreme temperature conditions are geographically distributed. The heatwave map reveals more intense heat episodes, particularly concentrated in the eastern and southeastern parts of the region, as indicated by the more intense red and orange shades. This suggests that these areas are more prone to prolonged periods of extreme heat, possibly due to their proximity to arid zones or geographical characteristics. The HI values in this map range between 97.89°F and 101.1°F, which correspond to Moderate to High-risk levels, as classified in Table 1.

Table 1. The classification of heat index, associated risk levels, and the health issues they may induce (Fotso-Nguemo et al., 2022).

Heat index	Risk level	Classification	Associated health problems
< 80	Extremely low	Safe	No significant stress
80 - 90	Low	Caution	Fatigue is possible with prolonged exposure and/or physical activity
90 - 105	Moderate	Extreme caution	Heat cramps, heat exhaustion, and heat stroke are possible with prolonged exposure and/or physical activity
105-130	High	Danger	Heat cramps and heat exhaustion are likely. Heat stroke probable with prolonged exposure and/or physical activity
≥ 130	Very high	Extreme danger	Heat stroke is highly likely and imminent

These values signify conditions necessitating heightened vigilance due to potential hazards, including heat-related health complications such as heat cramps, heat exhaustion, and heat stroke, which may arise from extended exposure or physical exertion. This underscores the need for interventions to protect vulnerable populations in areas with high heatwave intensity.

In contrast, the coldwave map highlights areas that are more frequently subjected to extreme cold conditions, with the strongest coldwave events indicated by the darker blue shades in the northern and central parts of the region. The THI values for the coldwave map range from 0.67 °C to 6.28 °C, placing these areas within the cold thermal comfort class (Table 2) as modified by Toy et al. (2007). These values suggest that these regions are experiencing significant cold stress during coldwave events, with potential health risks associated with prolonged exposure to low temperatures. The classification of these coldwave conditions emphasizes the importance of preparedness, including ensuring proper shelter and heating for the affected populations during periods of extreme cold.

Table 2. Correlation between human thermal comfort and the thermohygrometric index (THI) (Toy et al., 2007).

Human thermal comfort class	THI value (oC)
Cold	-1.7 to +12.9
Cool	+13.0 to +14.9
Comfortable	+15.0 to +19.9
Hot	+20.0 to +26.4
Very hot	+26.5 to +29.9

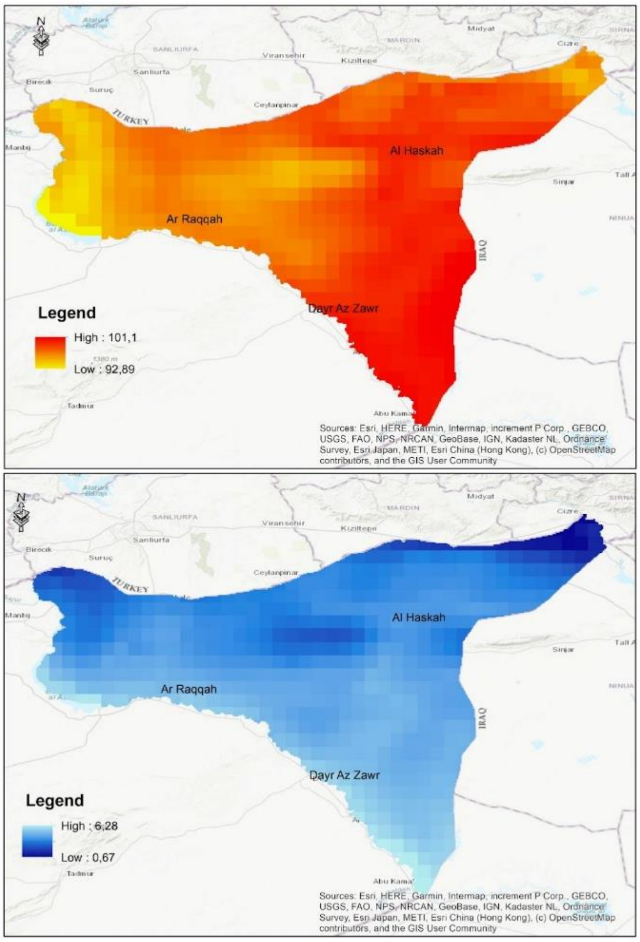

Figure 2: Spatial distribution of heatwaves and coldwaves hazard indices in Northeast Syria.

b. Heat and Coldwave Trend

Regarding the heatwave trend, there is a notable fluctuation in heat stress levels throughout the period. The early 2000s show high levels of heat stress, with values exceeding 101°F in 2000, followed by a slight decrease until 2005. After a period of variability, heat stress levels rise again, peaking around 2015 and 2020, reaching nearly 100°F (Figure 3b). This suggests periodic increases in the intensity of heatwaves, with certain years experiencing more severe heat conditions than others. Despite the fluctuations, the overall trend indicates that heat stress levels remain relatively high, signaling a persistent risk of heatwaves.

In contrast, the coldwave trend shows more pronounced fluctuations in average thermal stress. The early 2000s were marked by average levels of thermal stress. However, a notable decline was observed after 2005, followed by a period of less intense coldwave activity. Around 2015, a sharp peak was observed, indicating the reduction of extreme cold events (Figure 3a). In recent years, cold wave intensity seems to be decreasing once again, although it does not reach the same extremes as in previous years. This variability reflects the irregular nature of cold waves, with occasional intense cold events amidst periods of lower thermal stress.

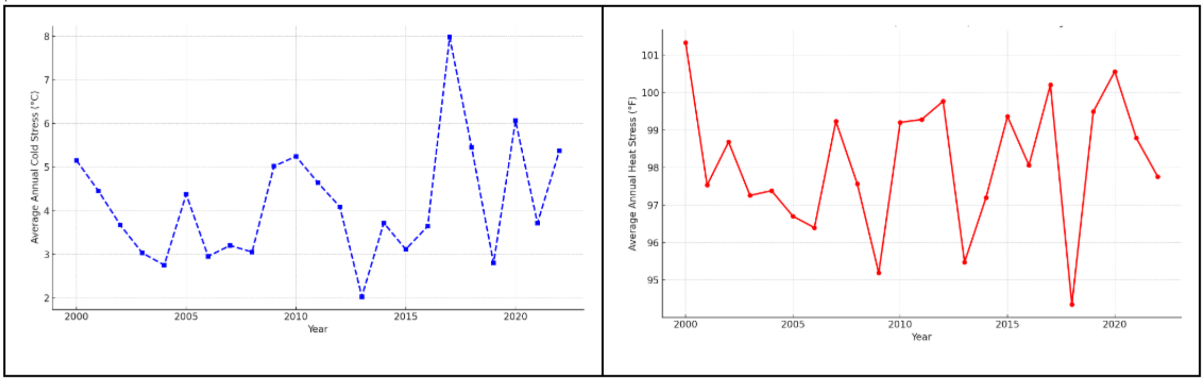

Figure 3. Trends of average annual heatwave and coldwave intensity in Northeast Syria (2000 - 2022).

Conclusion and Recommendation

This study highlights the spatio-temporal variability in the intensity of heatwaves and coldwaves in Northeast Syria from 2000 to 2022 using the Heat Index (HI) and the Temperature-Humidity Index (THI). The spatial and temporal analysis reveals that certain regions, particularly in the east and southeast, are more prone to prolonged heatwaves, posing significant health risks. The trend analysis shows periodic fluctuations in heat stress, with notable peaks around 2017 and 2020, indicating a persistent and growing threat of extreme heat in the region. In contrast, coldwaves exhibit more irregular patterns, with fewer extreme cold periods around 2015.

Both heatwaves and coldwaves present serious threats to public health, agriculture, and infrastructure, especially in regions with limited adaptive capacity. The combined spatial distribution maps and temporal trends suggest the need for strengthened monitoring systems, public health preparedness, and climate adaptation strategies. Future research should focus on other characteristics of heatwaves and coldwaves, including their number, duration, and frequency, as well as the integration of exposure and vulnerability data to improve forecast accuracy and response measures to mitigate the impact of extreme temperature events on vulnerable populations in Northeast Syria.

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