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Spatial and temporal analysis of outdoor human thermal comfort during heat and cold waves in Iran

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A R T I C L E I N F O

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A B S T R A C T

The past two decades of the 20th century and the first of the 21st century have been characterized by global temperature rise and increased frequency of weather-induced extreme events such as heat and cold waves. Using mean daily meteorological observations from 1995 to 2014, the Physiological Equivalent Temperature (PET) was used to detect heat and cold waves at 155 climate stations in Iran. Additionally, the acclimatization approach was introduced to evaluate human adaptation to interannual thermal perception. This paper, for the first time, uses PET and includes an analysis of consecutive days, as well as statistical filters to measure thermal adaptation of humans to extreme temperature events in Iran. This study presents a valuable first step for the quantification of cold waves and cold stress as well as heat waves and heat stress. Results showed that based on three thresholds resulting from different methods, no cold wave (CW) is observed in southwestern Iran and stations in the coastal strip of northern Persian Gulf and Oman Sea. Based on three thresholds, most frequent cold wave occurrence is observed for areas and highlands of North West, North East and the Zagros mountain range with different frequencies for different thresholds. Compared with cold wave, heat waves have been detected throughout the country. Although maximum threshold of the occurrence of this climate hazard occurs at Iran's southern coast, the most frequent occurrence was observed in boarder areas of eastern Iran. On the other hand, findings of the present study confirm the fact that the risk of heat waves in Iran is more serious than that of cold waves.

1. Introduction

Human activities and wellbeing are strongly influenced by extreme climate events such as heat waves (HW) and cold waves (CW). Heat and cold waves can put human health at risk and increase mortality rates, especially for elderly people, children and people who have serious health problems (Ballester et al., 2003; Ding and Ke, 2013; Roshan and Nastos, 2018).

Spinoni et al. (2015a,b) believed that in scientific literature, heat and cold waves (but in particular heat waves) are usually described by few parameters: the number of events, frequency, duration or length, severity and/or intensity, amplitude and/or magnitude (e.g. Frich et al., 2002a,b; Kostopoulou and Jones, 2005; Beniston et al., 2007; Fischer and Schär, 2010; Kuglitsch et al., 2010; Russo and Sterl, 2011; Perkins et al., 2012). Depending on the authors and the goal of the study, such quantities may be defined with slight differences from one paper to another. Defining the temperature threshold for heat and cold events is a key step in risk assessment, but there is no consistent standard in the existing literature (Dong et al., 2015). Studies typically define heat and cold waves as exceeding fixed absolute values or deviations from the normal (Robinson, 2001). Although there is no universally accepted definition, heat waves are understood to be periods of unusually hot and dry or hot and humid weather that have a subtle onset and cessation, a duration of at least 2–3 days, usually with a discernible impact on human and natural systems (McGregor et al., 2015). For example, the Netherlands uses a period during which T_{max}>25 °C for ≥5 days, provided that at least 3 days in this period have a T_{max}>30 °C (Garssen et al., 2005), while the US National Weather Service (NWS) suggests a T_{max} (daily maximum temperature) of ≥40.6 °C (105 °F) for excessive heat warning (NWS, 2015).

Also several methods exist for characterizing the definition of a cold spell (Huynen et al., 2001; Analitis et al., 2008; Kysely et al., 2009). Ma et al. (2013) defined a cold spell as a period of at least seven consecutive days with daily average temperature below the third percentile of temperature distribution during the study period Revich and Shaposhnikov

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(2008); Hassi (2005); Ma et al. (2011).

Changes in warm and cold extremes were reported for the global scale and many regions around the world (Frich et al., 2002a,b). Donat et al., 2013 updated analyses for temperature and precipitation extreme indices since the beginning of the twentieth century. In recent years, high-impact heat waves, claiming tens of thousands of lives, occurred in Europe in 2003 (Beniston, 2004; Christoph and Gerd, 2004; Levinson and Waple, 2004) and Russia in 2010 (Barriopedro et al., 2011; Dole et al., 2011; Trenberth and Fasullo, 2012; Twardosz and Kossowska-Cezak, 2013).

Marked changes of air temperature were also observed in Iran over past decades. It was reported that the diurnal air temperature range, the number of frost days, ice days, cool days and cool nights decreased at the majority of stations operated by the Iran Meteorological Organization (Rahimzadeh et al., 2009). In the arid to semi-arid regions of Iran, winter air temperatures markedly increased (Tabari and Hosseinzadeh Talaee, 2011). The urban heat island effect in Tehran intensified due to urban sprawl (Roshan et al., 2009, 2010). Ahmadnezhad et al. (2013) reported that, in Tehran, total excess mortality resulted from 17 heat waves occurring from 2001 to 2011, was 1,069 (8.9 deaths per heat wave day). In 2013 summer, a heat wave sequence extended over three weeks with air temperature exceeding 40 °C, and broke the air temperature record for the past 60 years in the capital of Iran.

The heat wave sequence induced unhealthy conditions and caused 1923 deaths (Sanaee et al., 2013). Simulations of future climate indicate that Iran will face a significant air temperature increase in the coming decades. Roshan and Orosa (2015) reported that the air temperature increase is projected to be 1.35 °C until the end of the 21st century.

Yazdanpanah and Alizadeh (2011), have used Markov chains to estimate the probability of occurrence of heat waves with periods of different duration. In this study, using long-term data from five stations of the Kerman province in Iran, heat waves were divided into short and long term groups. The results showed that the most consecutive heat wave was in April and the least one was in September. But what has not been considered in this study is the lack of a valid indicator to determine the heat waves, because only the air temperature deviation from a long-term average has been considered.

Abbasnia et al. (2016) studied heat wave characteristics in the warm period of the year as a climatic hazard in Iran. They used the daily maximum temperature to extract the intensity, frequency and duration of heat waves using percentile thresholds of 90, 95, and 98. The results showed that the average heat waves intensity increases between 3 and 4 °C more during summer than spring. Also heat wave frequency increased by about 4 times more during summer than spring. Generally, in the higher percentile thresholds heat wave frequency reduced, but intensity and duration increased.

Roshan and Nastos (2018) evaluated the probability of occurrence of the Universal Thermal Climate Index (UTCI) extreme heat and cold stress classes over Iran using Markov chain. Their findings, based on the UTCI thermal index, provide evidence that the highest frequency of cold stress appears in North West, west and north east regions of Iran, while the highest frequency of occurrence of heat stress is related to the southern half of Iran and the Persian Gulf and Oman Sea. The findings showed that a total of 83.7% of the stations have experienced UTCI classes of very strong (VSHS) or even extreme (EHS) heat stress indicating that Iran faces more VSHS and EHS events against cold stress events.

On the other hand, the Iranian population are exposed to severe cold waves. Reviewing cold extremes in the Iranian city Kerman, Khanjani and Bahrampour (2013) found that an increase in cardiovascular (0.6% per °C) and respiratory (average of 2.5% per °C) mortality was associated with decreasing air temperature and more cold wave occurrences.

In another study Asakereh (2010) applying a first order Markov chain model investigated the frequency and persistence of early and late frosts in the city of Zanjan. Results of that study showed that the probability of early and late frosts in autumn and spring is higher than its probability in other seasons of the year.

Due to the variability of bioclimatic indices, Abegg et al. (1998) divided all measures into three main groups: simple and preliminary, combined, and bioclimatic indices. The advantage of combined indices and bioclimatic indices is that they consider complex relations between the mechanisms of regulating body temperature and physiological systems of human thermo-circulation. One of the most widely known and applied index of this group is physiologically equivalent temperature (PET) (Roshan et al., 2016b).

The PET (°C) is based on a complete heat budget model of the human body (Höppe, 1999), and it provides the equivalent temperature of isothermal reference environment with a water vapor pressure of 12 hPa (50% at 20 °C) and less air (0.1 m/s), at which the heat balance of a reference person is maintained with core and skin temperature equal to those under the conditions being assessed (Basarin et al., 2015). Today, the use of composite indicators that are based on the balance of the human body, e.g. PET, is very common in thermal comfort assessments and heat and cold stresses (Nastos and Matzarakis, 2013, 2013, Roshan and Nastos, 2018).

There are some studies that calibrated the thermal classes of PET, a state-of-the-art human thermal indices, for their specific climate, such as Lin and Matzarakis (2008) for Taiwan, Yahia and Johansson (2013) for Damascus, and Syria or Kovács et al. (2016) for Hungary and Roshan et al. (2017a,b) for Iran. It should be noted that the aim of the present work is not to define and use new thermal zones for Iranian sites. We used the conventional PET classes in this paper for all climatic zones of Iran. Therefore, its application should be considered only as an indicator at this stage of the research. The present study can be the base of subsequent work where we will use calibrated PET classes.

Although the past and future changes in mean air temperature and air temperature extremes have been well analyzed for Iran from a meteorological perspective, there is no comprehensive assessment of the risk of human exposure to heat waves and cold waves. Therefore, in this study, the Physiological Equivalent Temperature (PET), which allows a physiologically significant assessment of thermal conditions for humans, was used for assessing the spatial and temporal pattern of heat and cold waves in Iran.

2. Materials and methods

2.1. Meteorological data

Mean daily meteorological data including air temperature (T_a), relative humidity (RH), wind speed (U) and cloudiness (C) from 155 stations, operated by the Iran Meteorological Organization in the period from 1995 to 2014, were used in this study. The stations are distributed across the country covering an elevation range of −26 m to 2,986 m (Fig. 1).

In this study, 155 studied meteorological stations were tested regarding the randomness and normality of the data distribution, using Run test and Kolmogorov–Smirnov test respectively. The results of these tests indicate that the data used follows a completely random and normal pattern. As for missing values, gaps with a maximum length of 3% of the total time series length were filled by applying linear regression using data from neighboring stations.

To generate bioclimatic maps, 155 weather stations were used. In order to assess the accuracy of the produced maps, we use training and testing method in the Geostatistical model to separate 80 percent of the stations as training stations and 20 percent as test stations. Thus, using the Kriging method and based on 80% of the stations, an 80% map was generated and then, based on the remaining 20% stations, validation was performed. Then, the calculated error was estimated from the difference between the observations and the predicted data and was turned into absolute error. Next, the ratio of absolute error to the observations was calculated. Based on this, the average relative error was 6.4%. Therefore, it can be claimed that the accuracy of the generated map with a resolution of 0.05 geographical degrees is equal to 93.6 percent, which is acceptable.