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Investigation of heat waves with fuzzy methods☆

T. Kiseliova*, M. Fandoeva, A. Sikharulidze

Iv. Javakhishvili Tbilisi State University, Faculty of Exact and Natural Sciences, University St. 2, 0145 Tbilisi, Georgia

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ABSTRACT

The paper concerns influences of global warming on health of the population. We consider an important parameter of global warming – a heat index – that is a characteristics of a human thermal comfort and represents a combination of air temperature and relative humidity. Based on the heat indexes, we propose a new approach – the fuzzy methods – to investigate heat waves which, if defined properly, can be used to assess the potential impacts of climate change on human health, e.g., in the heat-health warning systems. We find typical characteristics of heat indexes during different time periods, using most typical fuzzy expected values. We use these typical characteristics to process heat waves. Our results are applied on the data collected in the Ministry of Preservation of the Environment of Georgia during 1955–1970 and 1990–2007 years as well as free accessible meteorological data of air temperature and relative humidity during August 2003 in Paris (France) and Tbilisi (Georgia).

1. Introduction: heat index and heat waves

1.1. Heat index

The global warming is a well-known problem that has a great impact on human health. Among several parameters that allow to estimate this effect (among others, for example, variation on the intensity of solar radiation, wind speed, etc.) a heat index (HI) is often used. HI is usually defined as a combination of air temperature and air humidity. HI determines the human-perceived equivalent temperature. A good example of the difference between HI and a true temperature would be comparing the climates of Miami and Phoenix. Miami averages around 90 °F in summer due to the easterly trade winds coming from the Atlantic Ocean, but it has a high humidity (e.g. 75%). Phoenix averages around 104.5 °F in summer, but typically has a low humidity (e.g. 10%). According to HI, the relative temperature in Miami will be 109.5 °F, but the relative temperature in Phoenix will be lowered due to the lower humidity, around 98.6 °F. Given sunshine, Miami is likely to feel hotter than Phoenix.

There are several ways to estimate HI: by special formulae (for example, Steadman [30]) or by special tables where empirical data are collected. For example, Fig. 1 shows dependencies, i.e., HI, between relative humidity and air temperature in °C (modified from [3]). The data in this table are subjective estimations of the human thermal comfort in Celsius. In general, in applications, HI is measured in Fahrenheit.

1.2. Heat waves

A heat wave notion is closely related to HI. In a general sense a heat wave (HW) can be defined as a prolonged period of excessive heat. Similarly to the descriptions of HI there is no universal and rigorous descriptions of HW: subjectiveness and uncertainty is a part of existing definitions. We list some examples below.

1.3. Different approaches to investigate heat waves

Recently, continuing reports of human mortality because of the effects brought on by extreme heat events worldwide support the necessity for research of HWs. However, defining HW as a hazard is not universal over space because of the differences in climate norms and different types of uncertainty in the estimations.

American Meteorology Society [4] defines HW as a period of abnormally and uncomfortably hot and unusually humid weather. Typically HW lasts two or more days.

In [5] HW is defined as consecutive days with temperature above 30 °C.

The ICARO Project [2] defines HW by means of a temperature threshold of 32 °C combined with a minimum duration of 2 days. This definition is similar to a definition used in the United States: 90 °F (32.2 °C) and a minimum duration of 2 days.

There appears to be no official Australian definition of HW [2]. The difficulty in defining HW in Australia has been in establishing an appropriate HI with an acceptable event threshold and duration, and relating it to the climatology of the area under investigation.

☆ This document is a collaborative effort.

* Corresponding author. Tel.: +995 555450091.
E-mail addresses: t.kiseliova@web.de (T. Kiseliova), fandoeva@yahoo.com (M. Fandoeva), anikge@yahoo.com (A. Sikharulidze).

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RH (%)	Temperature (°C)															
	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
90	28.04	30.73	33.75	37.08	40.72	44.68	48.95	53.54	58.45	63.67	63.67	75.06	81.22	87.71	94.51	101.62
85	27.85	30.22	32.89	35.87	39.14	42.71	46.58	50.76	55.22	59.99	65.06	70.43	76.1	82.07	88.34	94.91
80	27.67	29.74	32.1	34.74	37.67	40.88	44.37	48.14	52.21	56.54	61.17	66.08	71.28	76.75	82.51	88.56
75	27.48	29.28	31.36	33.69	36.3	39.17	42.31	45.72	49.39	53.33	57.53	62.01	66.75	71.76	77.03	82.57
70	27.29	28.86	30.67	32.73	35.04	37.6	40.41	43.47	46.78	50.34	54.15	58.21	62.52	67.08	71.89	76.95
65	27.11	28.46	30.03	31.84	33.88	38.66	38.66	41.41	44.38	47.58	51.02	54.69	58.59	62.73	67.09	71.69
60	26.93	28.08	29.45	31.03	32.83	34.84	37.07	39.52	42.18	45.05	48.14	51.44	54.96	58.69	62.64	66.81
55	26.74	27.73	28.92	30.31	31.89	33.67	35.64	37.81	40.18	42.75	45.51	48.47	51.63	54.98	58.53	62.28
50	26.56	27.42	28.45	29.66	31.05	32.62	34.36	36.29	38.39	40.68	43.14	45.78	48.59	51.59	54.77	58.12
45	26.38	27.13	28.03	29.09	30.32	31.7	33.24	34.94	36.81	38.83	41.02	43.36	45.86	48.52	51.34	54.33
40	26.21	26.86	27.67	28.61	29.69	30.91	32.28	33.78	35.43	37.22	39.14	41.21	43.42	45.77	48.27	50.9
35	26.02	26.63	27.36	28.2	29.17	30.26	31.47	32.8	34.26	35.83	37.53	39.34	41.28	43.34	45.53	47.83
30	25.84	26.42	27.09	27.87	28.75	29.73	30.82	32	33.28	34.67	36.16	37.75	39.44	41.24	43.13	45.13

Note: Exposure to full sunshine can increase HI values by up to 10°C

Fig. 1. Heat index chart (temperature and relative humidity).

Various heat or thermal comfort indices have been developed to evaluate heat-related stress (e.g., Temperature Humidity Index [35]), combining air temperature, humidity, and, additionally, in some cases, wind, direct sunlight and nighttime recovery. Two of the most widely used indices in Australia are the apparent temperature (work of Steadman [30]) and the Relative Strain Index, derived by authors [7] and discussed in the Goldfields-Eucla climatic survey [1].

Temperatures that would indicate whether a specific location was under the effect of HW would be in the top 5% for a continuous three-day period. The United States National Weather Service uses the measure of apparent temperature, which is also based on the work of Steadman [30,31].

In [28] HW was defined as a period of at least 48 hours during which neither the overnight low nor the daytime high HI falls below the National Weather Service heat stress thresholds (40 °C and 105 °F, respectively), except at stations for which more than 1% of both the annual high and low HI observations exceed these thresholds, in which case the 1% values are used as HW thresholds.

In the work [8] the author defines the notion of HW based on a heat stress. In turn, a heat stress is based on the 24-hour period estimations of HI, and is represented by a value that identifies by summed heat values above 32.2 °C (90 °F) and 40.6 °C (105 °F) subtracted the number of hours of recorded thresholds (32.2 °C (90 °F), 40.6 °C (105 °F) and above) times these thresholds. Then accumulated values (Table 1) describe five Categories of a heat stress: each day is assigned a number from 0 to 5, 0 means no stress (Category 0 is not included into Table 1). In order for HW to be identified, consecutive days must be classified as Category 1 or higher. To classify each HW as individual hazards, the logical solution was to assign the highest value from recorded values of heat stress during the consecutive days. Named as an event, HW with daily categories listed as 1-2-2-3-2-2, for example, would be a 6-day event registering as Category 3 HW.

Table 1
The daily heat stress classification system in Fahrenheit [8].

	Category of a heat stress	HI-90 °F	HI-105 °F	Recovery
1	Minor	≥40	–	–
2	Moderate	≥80	≥1	≤10
3	Strong	≥120	≥10	≤6
4	Severe	≥160	≥20	≤2
5	Extreme	≥260	≥35	0

Let us again underline that there is no unique definition of HW, all existing definitions are imprecise.

In this paper, we propose a new approach to define and investigate HW.

1.4. Why it is important to define a heat wave properly?

Extreme heat is a hazard that is capable of causing economic problems and potentially high mortality rates across several regions simultaneously [8]. We should be able to define what does it mean that a period of time was undertaken by HWs or, in spoken words, that some days, weeks or even months were extremely hot or very hot. This definition can not be based on the value of one HI (for example, in a day), because the frequency, magnitude and duration of the HIs as well as day-to-day magnitude variability, overall frequency of HIs, seasonal timing of events are important characteristics to define HW. Thus, the problem is to define how hot was this or another period of time, which criteria to choose: maximum value of HIs, or the number of days with a high HI, or an intensiveness, or a relativity of HIs, or may be something else?

To combine different parameters as well as to capture above mentioned subjectiveness and imprecision in perception of a heat we propose a new methodology. We used methods based on fuzzy set theory. We chose two methods, the method of fuzzy expected value (FEV) and the method of clustering fuzzy expected value (CFEV) [16,29,37], compared them. The last one we have adapted due to our practical demands.

Roughly our new methodology can be described as follows: we ask experts to define "hot weather" and a corresponding fuzzy set. Then we calculate, using real values of HI, the most typical value of the fuzzy set for these values during a particular period, say August (notice, that shorter or longer period can be taken as well). Our results allow to say that this month was extremely hot, very hot, hot, very warm, warm or normal. If obtained characteristics are "very hot" or "extremely hot", we conclude that this month was impact by a severe HW or an extreme HW. Analogically, "hot" corresponds to strong, "very warm", corresponds to a moderate HW and "warm" to a mild HW (see Table 2). Notice, that linguistic terms *normal, warm, very warm, hot, very hot, extremely hot* we use to deal with HIs, they are defined as shown in Fig. 4, whereas words *mild,*