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Physiological equivalent temperature as an indicator of the UHI effect with the city of Prague as an example

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Abstract

Description of an Urban Heat Island (UHI) using the difference in air temperature is one of the world's most studied characteristics. If, however, one wants to express how the temperature is perceived by humans, one must consider the overall effect of air temperature, wind speed, air humidity and radiation flows, which is expressed using temperature bioclimatological indexes. One of them is the so-called physiological equivalent temperature (PET), which is used for quantification of the overall effect of meteorological parameters combined with human energetic balance and which is perceived by humans. The RayMan (Matzarakis et al 2007, 2010) microscale models in the city of Prague were used to simulate biometeorological conditions describing the effect on humans using PET.

Key words: Physiological equivalent temperature, UHI, RayMan, Prague,

Introduction

Studying climates of cities is a very current topic especially because the population density of cities and metropolises is on the rise. In developing countries the ratio of urban population is about 50 % and in developed countries more than 75 % (Lambin and Geist, 2006). The effects of the climate on such a large population are therefore quite important and meanwhile the activities of such a large group of people influence the climate of that particular region itself.

In the context of the current climate change and possible increase of extreme situations such as heat waves, the quality of life in large cities can significantly decrease, including impacts on human health, or even worse, increase the population mortality rate.

Built-up areas in cities create a urban climate, for which there exists a particular specific regime of most meteorological parameters (Dobrovolný et al, 2012). This regime is not only different between cities and countryside, but also between city centers and their suburbs. The reason for the creation of this specific city climate lies in several factors (e.g. Oke, 1981). First are the heat and radiation properties of active surfaces, which are crucial for the intensity of absorption and reflection of short-wave electromagnetic radiation and emission of long-wave radiation. Another factor is the change of the active surface, because the current usage of synthetic materials (asphalt and concrete) leads to changes in energetic balance, including decreased intensity of evaporation. Also geometric layout of active surfaces has negative effects, as it increases the total area and creates the so-called street valleys and increases surface roughness. Human activities also lead to the production of waste heat and increase atmospheric pollution (for example heating, industries, transportation). The increasing intensity of urban heat islands is not an issue just for climatologists, but especially for city architects and designers, who should aim to decrease this undesirable effect by using new technologies and findings and thus increase the quality of life of people living in the cities. To help to achieve this goal there is the project “UHI – Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon”, financed from the Central Europe Programme, which ends this year. Its goal was to begin cooperation between experts from various fields and integration of their results. The Czech Republic was also invited to join this project and was represented by the Czech Hydrometeorological Institute (CHMI), Faculty of mathematics and physics of the Charles University and the Institute for planning and development of the capital city of Prague.

Materials and methods

The urban heat islands are often analyzed based on the individual meteorological elements, most commonly the air temperature. This, however, is not an ideal indicator of human perception. For this reason, various bioclimatological indexes were developed. These take into account not just the air temperature, but consider the combined effect of other factors as well, such as humidity, wind speed, radiation characteristics and other non-meteorological factors like clothing, gender, age etc.

As an index for the assessment of the changes in thermal bioclimate, the physiological equivalent temperature (PET) was used. It is defined “as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed” (Höppe 1999). It is one of the most commonly used indices for thermal bioclimate, so results can be easily compared to those from other studies (Matzarakis and Endler 2010; Lin et al. 2010a, b; Lopes et al. 2011). Another big advantage of PET is the use of °C as unit, making results more easier for interpretation by people without knowledge in the field of human biometeorology.

As is the case with many other thermal bioclimatic indices, PET is also based on a human energy balance model. For the case of PET, the Munich Energy Balance Model for Individuals (MEMI, Höppe 1984), is used. One of the most important determining factors for PET is the mean radiant temperature, Tmrt. Tmrt is defined as the temperature of a perfectly black and equal surrounding environment that leads to the same energy balance as the current environment (VDI 1998; Fanger 1972).

The PET index was calculated using the numerical model RayMan developed by Meteorological Institute of the Albert-Ludwigs University Freiburg (Matzarakis et al. 2007, 2010; Matzarakis and Rutz 2010; Röckle et al. 2010). The input data used were hourly measurements from meteorological stations operating in the area of the city of Prague (Karlov, Ruzyně, Kbely, Klementinum and Libuše;

fig. 1). The parameters used for calculation were air temperature, air humidity, wind speed and radiation or cloudiness.

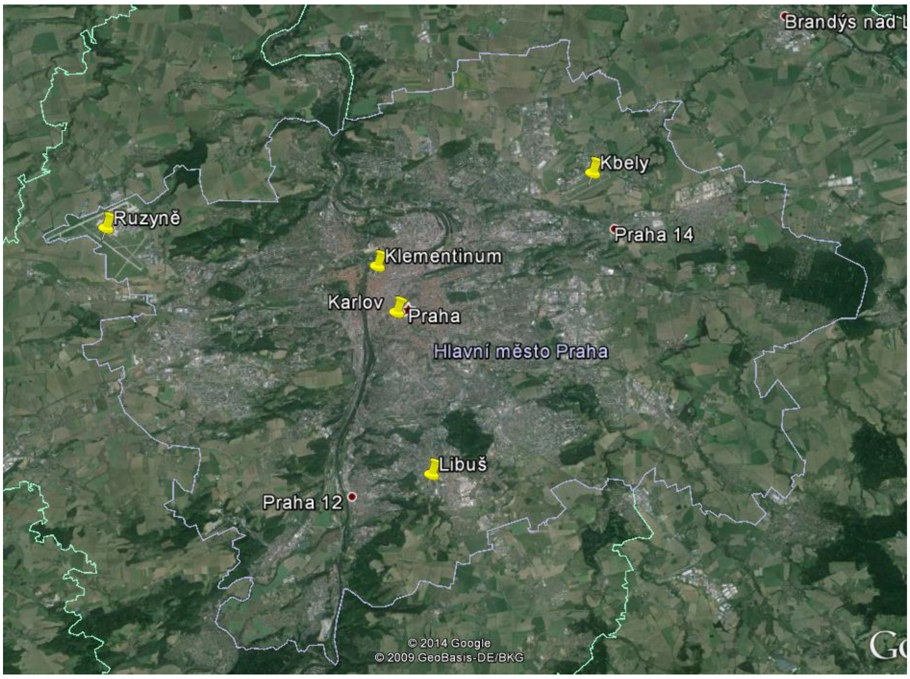


Fig. 1. Map of Prague showing the meteorological stations for which the physiological equivalent temperature has been calculated

Results

Physiological equivalent temperature has the same annual pattern as the average air temperature, its actual values being on average lower. Particularly during winter months, this temperature index decreases significantly lower compared to the standard air temperature. The maximum values of both characteristics show different behavior. PET, just like the average values, is lower during winter, but during the summer, the maximal values are substantially higher than the air temperature. The standard deviation is higher for PET compared to air temperature in both cases (fig. 2).

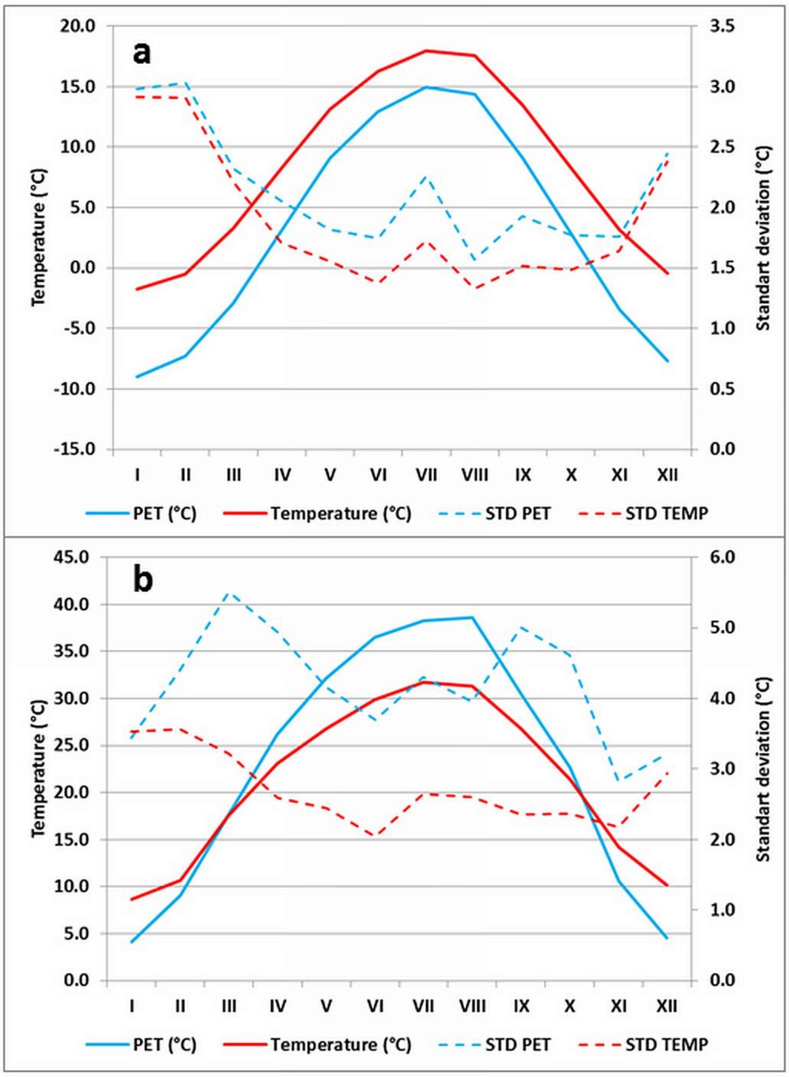


Fig. 2. Annual cycle of average (a) and maximal (b) values of PET (°C) and air temperature (°C) including standard deviations for the station in Prague-Ruzyně during 1961-2013.

In order to compare the behavior of physiological equivalent temperature, two stations were chosen – Prague Karlov representing a typical urban station, and Prague Ruzyne, which is located in the city suburb. The period for which there are equivalent hourly measurements of the individual meteorological parameters is from 2005 to 2013. As figure 3a shows, the highest values of PET are reached in Prague Karlov at the turn of July and August between 10 AM and 4 PM and the average value for the period between 2005 and 2013 exceeds 30 °C. Conversely, the lowest PET values are observed at the end of

January from 0 AM to 9 AM, where the average values for the period between 2005 and 2013 decrease below -10 °C.

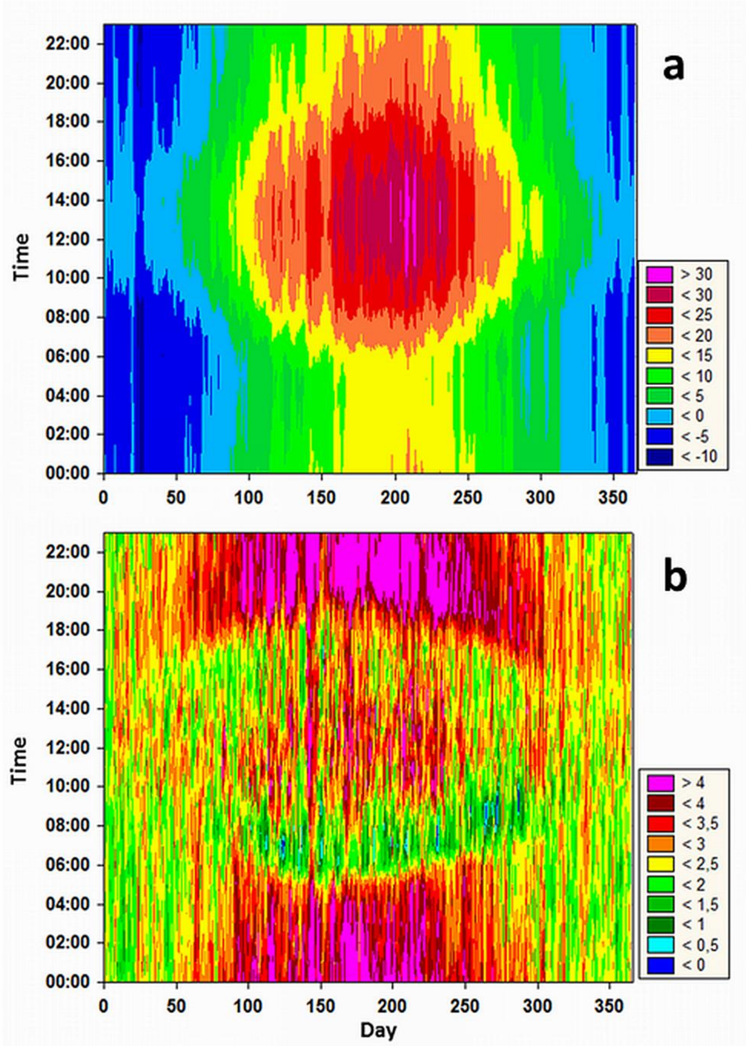


Fig. 3. The course of physiological equivalent temperature, PET (°C) at the Prague Karlov station (a) compared to the Prague Ruzyně station in the period 2005-2013

The largest difference between the PET determined in Prague Karlov and Ruzyně was just after sunset during the summer half-year. At this time, the feel-like temperature in Karlov was more than 4 °C higher than in Ruzyně (fig 3b). Another case where there is a larger difference between PET of the city center and the PET of the suburbs occurs around noon and in the afternoon, again in the summer half-year. Here, however, the difference is not so significant. The smallest difference was determined around the time of sunrise in the summer half-year, the actual value of this difference being less than 1.5 °C. For the rest of the year and hours the difference between feel-like temperature of the city center and the city suburb is usually about 2 to 3 °C.

The physiological equivalent temperature was used to calculate the same temperature characteristics that exist for air temperature, such as the number of summer and tropical days, including the number of hours with PET above 30 °C. The number of summer days is defined as days with maximum temperature of at least 25 °C and a tropical day is a day with maximum temperature of at least 30 °C. These characteristics were calculated for Prague Ruzyne and Prague Karlov. Only values since 2005 can be compared.
For the station in Prague Ruzyně, there is on average 50 PET summer days. As can be seen from figure 4a, the number of PET summer days in Karlov is 40 % higher than in Ruzyně during the period between 2005 and 2013. The largest difference was in 2005, the smallest the year after. The number of tropical days in Prague determined using the standard air temperature is around 10, for the PET however, this number increases to approximately 25 per year. During 2005 and 2013 the difference in the number of these days in the city center and city suburbs (Karlov vs Ruzyně) was very variable. In 2006 and 2007, the difference was just a few days. In contrast, during 2005 and 2011, the number of these days was 2.5 times higher in the city center than in the suburbs (fig 4b). When comparing the number of hours where PET is above 30 °C, the difference between city center and suburbs is even more apparent. In 2011 there was 3 times more of these tropical hours in Karlov compared to Ruzyně (fig 4c).

Discussion

To understand the city climate, it is more convenient to study how citizens really perceive the environment rather than studying the individual meteorological parameters, which when analyzed separately usually only provide understandable information to climatologists. In order to better utilize climatological results in practice, it is more convenient to use bioclimatological characteristics. As can be seen from the results of this work, the difference between physiological equivalent temperature in the center and suburbs of the city of Prague can be at some situations substantial. The goal should be to use the cooperation of climatologists, architects and urban designers in order to mitigate the negative effects of living in cities using new types of materials or by increasing the green areas. Large difference between the feel-like temperature is observed at night during the summer half-year, where one can see that the city center retains more heat accumulated during the day and cools down slower. This of course reduces the quality of sleep and it is difficult to ventilate homes enough (sometimes due to noise or pollution), which increases health problems of the citizens or can decrease work efficiency the next day. Therefore, also the economical results of that particular region can worsen.

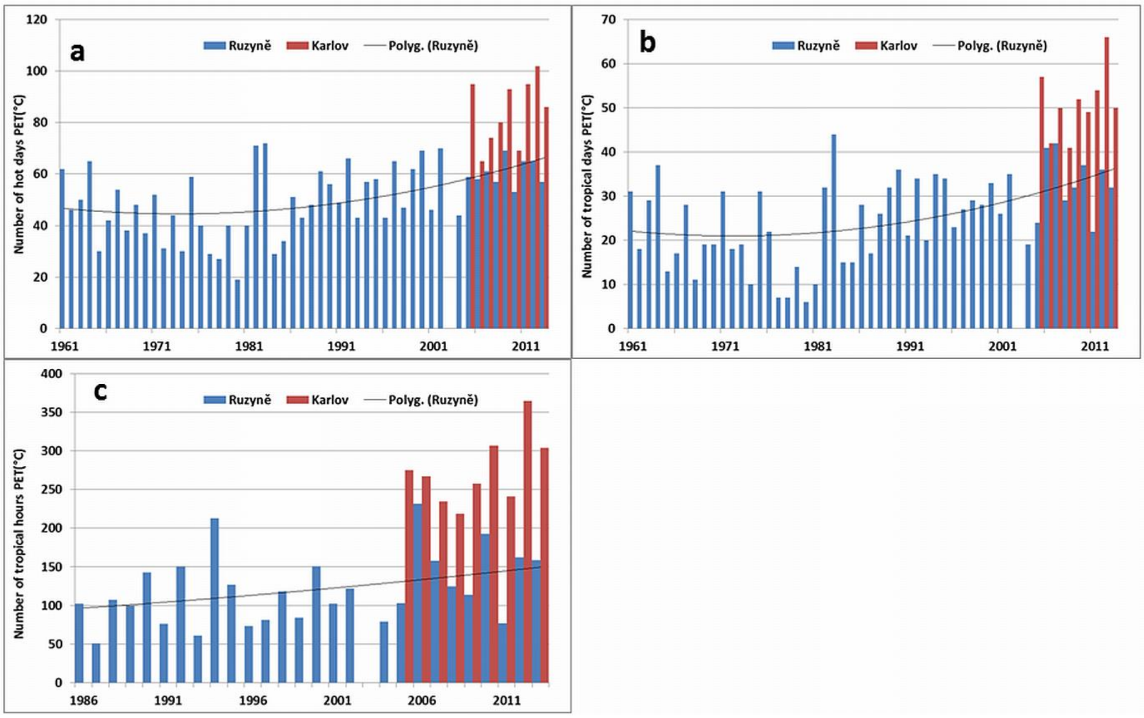
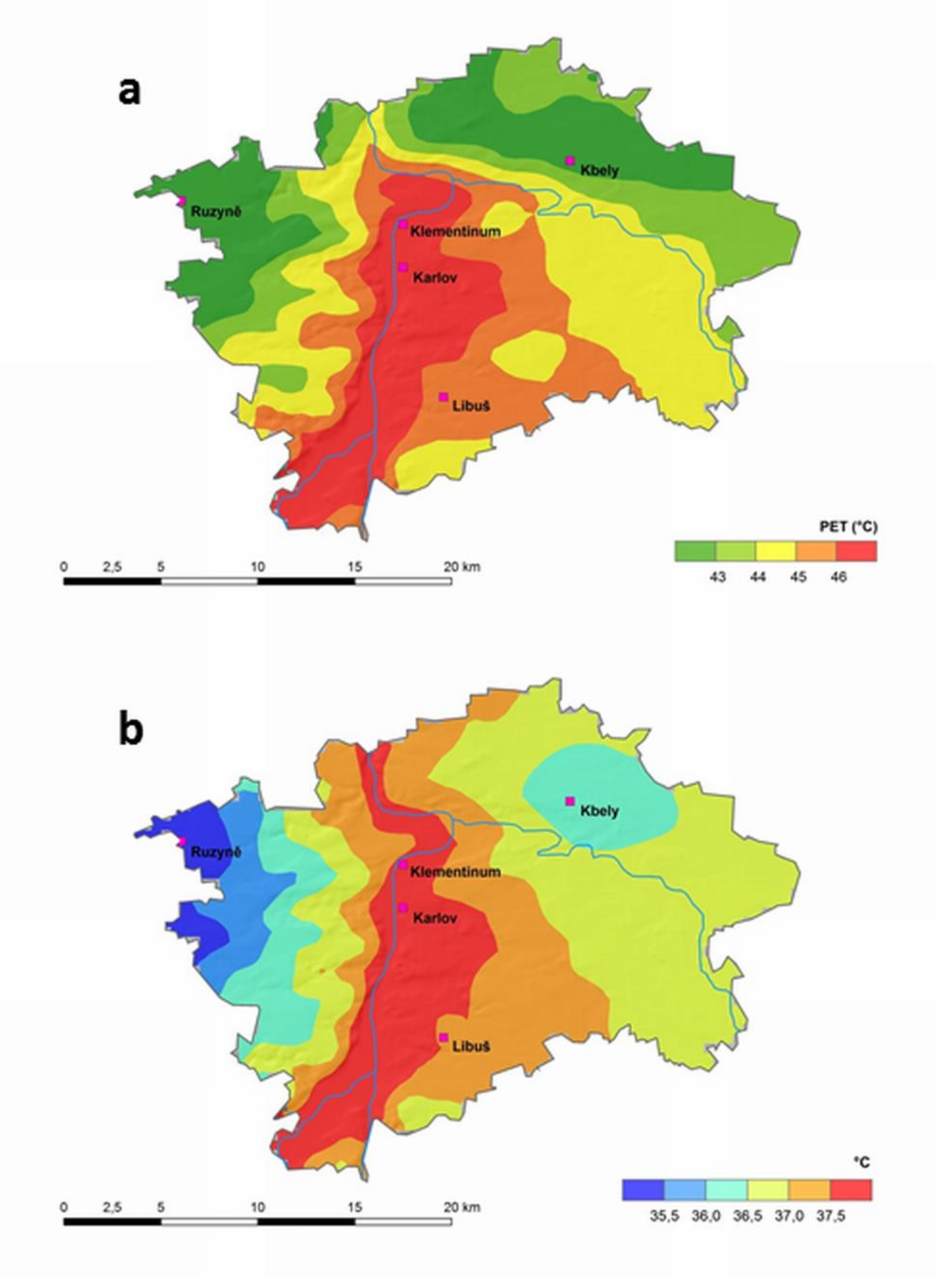


Fig. 4. Number of PET summer days (a); tropical days (b) and number of hours with temperature above 30 °C (c) at the stations in Prague Ruzyně and Prague Karlov

The city overheats substantially during warm summer days. Because Prague is a popular tourist destination, especially during summer months, worsening of temperature conditions can lead to decrease of tourism and tourists aiming for destinations where the feel-like temperature is lower. For example on 28th July 2013, the maximum air temperature at many places in Prague exceeded 35 °C

(Karlov 37 °C; fig 5a). Physiological equivalent air temperature even reached 48.1 °C (Karlov; fig 5b). For the maximum air temperature, the difference between Karlov and Ruzyně was 3 °C, but using the PET, the temperature in the suburbs was 7 °C lower than in the city center.



Obr. 5. PET - Physiological equivalent temperature (a) and maximum air temperature (b) on 28th July 2013 in Prague

Conclusion

This work presents the less known bioclimatological characteristic called the physiological equivalent temperature (PET), which is used especially to study the urban heat islands. The calculation of this temperature indicator does not include just one meteorological parameter, but rather takes into account the combined effect of temperature, humidity, radiation and other non-meteorological parameters such as surface, human radiation and clothing etc. Physiological equivalent temperature was calculated for the region of Prague. A substantial difference between the city center and suburbs was determined. The largest differences were during night hours during the summer half-year when the Prague city center retains heat accumulated during the day much more. If the temperature comfort of the city center worsens, it could also negatively influence health of the citizens, economy and tourism. An interdisciplinary cooperation of climatologists, architects and other institutions responsible for city planning is therefore necessary.

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Summary

Popis tepelného ostrova města (UHI) pomocí rozdílu mezi teplotou vzduchu sice patří mezi celosvětově nejvíce studované charakteristiky, pokud ale chceme vyjádřit tepelné vnímání člověka, musíme uvažovat celkový účinek teploty vzduchu, rychlosti větru, vlhkosti vzduchu a toků radiace, které je vyjádřeno pomocí tepelných bioklimatologických indexů. Jedním z nich tzv.

fyziologicky ekvivalentní teplota (PET), která se používá pro kvantifikaci celkového účinku meteorologických parametrů kombinovaných s energetickou bilancí člověka a vnímanou lidmi. K simulaci biometeorologických podmínek popisujících vliv na člověka pomocí PET byly použity mikroměřítkové modely RayMan (Matzarakis et al 2007,2010) pro oblast města Prahy.

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