Could Climatological Knowledge Help to Prevent a Mass Panic?

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1 Open Questions

The initial research objective was to capture the metabolic heat flux, the heat given off by people's bodies, in order to determine if it exerts a lasting influence on the air temperature of a space crowded with people comparable to a sold-out stand of a football stadium. Assuming successful detection of this phenomenon, the next question to be answered was, if this anthropogenic influence modified the thermal conditions enough to lead to microclimatic changes in temperature events. Moreover, would it be possible to change the wind direction behavior, because of changed thermodynamics in the spectator areas? Furthermore could this be a problem especially if tear gas was to be emitted in certain sections of the stands? And would this lead to a panic reaction by the spectators, who are involved within a substantially larger area, because of the thermally induced, faster spread of the particular gas used? Based on this, now, the ongoing question is, if computer simulations and gas dispersion modeling can assist with an analysis of the current situation as well as of potential risks and possibly in designing an emergency plan suited for coping with such eventualities.

2 Research Fundamentals

The metabolic heat produced by the human body and transmitted through the skin to the surroundings forms the basis of the research conducted in the stands of a football stadium. This flux is the product of the body's metabolism, which, in its broadest sense, can be understood as the sum total of chemical reactions going on inside the human organism.[1] Influencing the metabolism in the most varied ways are internal and external factors that include body size and shape, the particular person's activity state, body and ambient temperature and the time of day and year. Metabolic processes divide into anabolism and catabolism.

A part of the energy available to the body is used inter alia to maintain body temperature. The heat produced has to leave the body, since otherwise the organism would be in danger of overheating. This heat release, also termed metabolic heat flux, ultimately takes place through conduction, radiation, convection and evaporation.[1,2] In most cases, these heat transfer paths transpire simultaneously and can be measured or also calculated. Depending on the content of the heat output, a further distinction can be drawn between moist and dry heat release. In what follows, we will only consider dry heat release, which makes up the largest share of the body's heat output (70 to 80%).

Conduction, thermal radiation, and convection play a decisive role in researching metabolic heat flux, because they form the basis for analyzing the microclimatic modifications in the examined area. Accordingly, these three factors involved in dry heat transfer can be measured and recorded through the change in air temperature or radiated temperature. In general, it is recognized that the body of a person at rest or engaging in light activity has a metabolic rate of about 40 or 80 W m^{-2}. If we assume that e.g. a soccer fan is engaging in the equivalent of heavy physical labor or athletic exertion, his concomitantly higher energy requirements will lead to an increase in metabolic rate to 200 to 240 W m^{-2}.[3] This theoretical determination alone suffices as a starting point to understand that the increased energy requirements produce more heat, which then has to be released through the skin as needed.

3 Measurement Methods

The research primarily concentrated on the entire area of the so-called West Curve in the Fritz Walter Stadium, located in the city of Kaiserslautern, Germany. The choice fell on this area, because this is where spectators gather in constant numbers for every home match, independent of the drawing power of the visiting team. Hence, results for individual match days are better comparable. The total research area is 6124 m^2 and can accommodate 14750 spectators.

Five temperature and humidity sensors were installed in the West Curve. Depending on location, they were positioned at heights ranging from 2 to 2.5 meters above ground level, ensuring that temperature changes above head height were recorded rather than the temperature surrounding an individual person or group. On game days, the instruments were turned on at least four hours before the spectators arrived. This made it possible to record the untainted air ahead of time. With the help of a "peripheral ground station" installed 2 meters above ground level on a grassy surface outside the stadium, temperature trends with and without spectators could be compared. Each sensor took two data readings per minute.

In addition to air temperature and humidity, thermography was used to record surface or radiated temperatures in the West Curve or of the spectators. Thermography allowed nearly simultaneous recording of changes in the West Curve's thermal system. Thermography thus could readily provide clues if, and in which form, modifications of the local climatic conditions were to be expected.

Three wind instruments were installed in addition at the edge of the pitch, in the middle of the block, and in the upper stands to register any eventual, clear influence on the microclimatic situation in the West Curve. Wind conditions were measured with sonic anemometers, which permitted an extremely accurate reading, especially of the expected thermally caused wind field changes.

The area of investigation was analyzed due to its microclimatic situation by the simulation model ENVI-met 3.2. Thereupon it was possible to determine different spectator situations during the course of a football match in a three-dimensional way and also in mutual dependence of the local climate.[4] Therefore, a catalog of measures has been simulated with different constellations of spectators. These simulations were performed using the example of the West Curve, which has obviously the most heat stress, because the effect of temperature modifications by the metabolic heat flux shows up here most clearly.

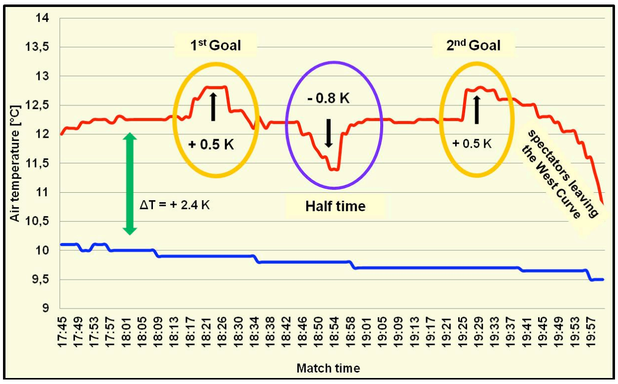

Figure 1: Temperature history in the course of a Bundesliga match (red curve = West Curve standing room block; blue curve = peripheral ground station); two obvious temperature spikes due to the spectators' basal metabolisms receiving additional stimulation during the match (goal; yellow circles); temperature collapses during half time (purple circle), if the West Curve "thins out" and large spaces open up between the spectators, and at the end of the match, respectively.

4 Results

4.1 Local Climate Modifications

Evaluating the temperature trends in the course of a Bundesliga match revealed different indications of anthropogenic influences on the microclimate that had not been expected to this degree when the research started.[5] With an average difference of $\Delta T = 2.43$ K, the temperature difference between the stadium station and the peripheral station is apparent at first glance (see Fig. 1). Comparing the temperature trends eventually reveals that the temperatures inside and outside the stadium developed differently as spectators entered the stands in increasing numbers. The previous, almost congruent trend disappears with increasing number of visitors. The blue and red temperature graphs steadily diverge and shortly before the start of the match reach their interim maximum ($T_{max} = 1.8$ K). This can be interpreted as a clear indication that the difference between the two measurement locations is in large part due to the metabolic flux given off by the almost 15,000 spectators. The presence of this mass of people and the increased release of heat due to their activities are responsible for an abnormal change in the West Curve's air temperature.

The significant temperature difference during the entire match is not the only phenomenon, which can be observed. Unmistakable temperature spikes point to the spectators‘ basal metabolism receiving additional stimulation during the match. The actual temperature difference increases once again due to the higher energy required for singing and cheering on the team. A comparison with the play-by-play shows that the temperature outliers correspond with when the home team scores goals. Accordingly, the body is stressed even more by the goal delirium and it reacts once again with an increased heat production that is comparable to a short-term, intense athletic activity. The actually prevailing temperature difference increases by a further 0.5 K (see Fig. 1; yellow circles). These recordings can be validated with the help of thermal images, reflecting the situation in the West Curve shortly before and after scoring. The radiated temperature rises to > 40°C. Additional energy warms the surrounding air through conduction, heat radiation, and convection. What the thermal images show almost instantly can also be registered on the temperature sensors with an approximate two-minute lag. This serves to indicate that it can take 1.5 to 2 minutes for the spectators‘ heat throw-off to modify the ambient air masses and hence induce an increase in temperature.

A third phenomenon noted in every match that further supports the results generated by the metabolic heat flux is the temperature collapse during half time (-0.8 K). The West Curve "thins out" and large spaces open up between the spectators (see Fig. 1; purple circle). The temperatures drop, as both the temperature history as well as the relevant thermal images show.

The phenomenon of the emptying spectator's ranks can also be observed towards the end of every match, when people begin to exit the stadium, sometimes quite quickly. The temperatures in the stadium and in the periphery converge within 15 to 25 minutes. This effect is more pronounced when the home team is having a bad match. Departure by the first disappointed people can then be tracked well before the match ends. If sizable groups exit the West Curve about 15 minutes before the game ends the temperature drop ensues (see Fig. 1).

4.2 Microclimate Modeling

Microclimate modeling of the West Curve validates the results of the in situ measurements. The entire simulation almost completely confirms the temporal progress of the temperature changes recorded by the in situ readings. The simulation reveals to the greatest possible extent that the layering above the stands is broken up by convection and that the warmer air masses rise. However, the wind vectors indicate that it does not necessarily have to become a convective rise, but that the wind field is first to change. The wind picks up speed and flows above the heads before starting to go up.

This simulated motion of the air once again is confirmed by the results of the stationary measurement of wind speed and wind direction. Hardly any air movements can be detected before the match and during its first few minutes. Gusts of wind swooping from outside to the inside of the stadium roof are the exception. Finally, as the match proceeds, due to the convection flow, air movement sets in. Originating from the edge of the pitch, the stream of air sweeps above the heads up to just below the upper stands in the stadium. From there, the wind field turns upwards. Hence, a convective movement is evident, caused by the changed updrafts, which, apparently, do not move directly upwards, because of the stands structure, but instead mostly follow the stands before rising.

4.3 Gas Dispersion Modeling

Reflecting the changes in thermal relationships and the modified movements of air we pursue the question of what would happen if someone succeeded in emitting tear gas in the research area. And furthermore, could a potential risk occur for spectators in the stadium? The basis for asking this question is provided by the fact that some gases spread more rapidly with rising ambient temperatures. [6-9] Diverse emitted gases thus could involve a wider expanse. As a consequence this would mean that a greater number of people in a larger area would be impacted. So is it possible to answer this question by doing a simple gas dispersion calculation and a subsequent simulation of the situation?

We assume that the emission's origin is identical for all calculations, i.e. the center of the stands area of the West Curve. We change the ambient temperature by 1 K and 2 K, respectively. The first calculation of gas dispersion assumes an empty West Curve. On the basis of calculation models by [7] and [8] the spread of the emitted gas is negligible. For the dispersion with an increased air temperature of 1 K the gas would undergo a 3.6 times larger expansion. However, the extreme scenario characterized by increasing the ambient temperature by 2 K proved to be even more expansive, with a 13-fold increase in area. Assuming that each square meter of surface area can accommodate three persons, this means that for 1 K about 30 and for 2 K > 95 persons would be affected. But this is only a theoretical calculation by parameters given in literature.

Also these initial calculations merely depict an ideal state that would exist if we could posit a situation with no exchanges in the atmosphere of the stands. But the results of the wind measurements and microclimatic situations have previously shown that the alterations in the wind field cannot be ignored. So the next important question is what happens when the emerging thermal conditions are taken into account. Finally, one more open question is if the air sweeping over the stands can increase the gas dispersion. Perhaps such a gas funnel that tracks the stands could swirl over an area occupied by > 250 persons.

We suggest that the real problem, however, is not just the gas emission. Probably the situation will be worse, because we will not only have directly impacted persons, but also their neighbors which will be confused about what happened. So within a very short time large masses will be set in motion. Now, will there be enough security personnel to solve the problem of a huge crowd of people in motion?

Concerning the real situation in the West Curve, the next question is what will happen, if the predicted escape routes were no longer feasible, because the thermal updraft is moving the gas into this area? The next step must be a dispersion calculation taking into account that there is an influence of microclimatic conditions. In a real-life emergency, security personnel would perhaps guide the spectators precisely to where the gas, following the thermals, would wind up. Perhaps, the only avenue for escape in such a case would be the opening of the gates to the pitch.

Taking the dispersal direction and behavior of tear gas into account reveals an until-now ignored safety aspect stemming from modifications of the air temperature and the wind field during a Bundesliga match. Hence, it could finally be asked, if the clubs are aware of this problem?

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