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Applied climatology: 'heat waves'

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I Introduction

Weather and climate impact many human activities. Thus, climate data and information are used extensively in a broad range of social, economic and environmental applications. Evidence of this is provided by the wide range of studies presented in previous progress reports on applied climatology in this journal. These have focused on urban and agricultural meteorology, biometeorology, energy use and the energy industry, weather and climate forecasting and climate services, climate impact assessment, air quality, drought and flooding, road climatology, and wind and winter weather.

In this brief progress report attention is directed to recent studies (since 2000) on heat waves: their definition and description; their effects on human health; underlying causes; and future scenarios for increased frequency and impact. As noted by Sheridan (2004), in contrast to hurricanes, tornados or other severe storms, the awareness of 'heat' as an atmospheric hazard has been largely under-recognized. However, heat waves are a major cause of weather-related deaths that have broad geographic impacts. In the summer of 2003, for example, it is estimated that the heat wave that affected Western Europe, particularly France and Spain, claimed more than 35 000 lives (Schar *et al.*, 2004). The heat wave of 1998 in India resulted in an estimated loss of life of 15 000 (De *et al.*, 2004). Moreover, future climate scenarios suggest that in a 'warmer world' heat vulnerability may increase significantly (Meehl *et al.*, 2000; McGeehin and Mirabelli, 2001). Tol (2002), for example, suggests that worldwide an additional 350 000 people could die from heat-related cardiovascular and respiratory problems for every 1°C increase in the global mean temperature.

II Definitions of heat waves

Robinson (2001) draws attention to the fact that analyses of the frequency, severity, duration and areal extent of heat waves are complicated by the absence of consistency in their definition in the published literature. Different threshold temperatures

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and durations of these temperatures are used in different studies. This is in part, of course, appropriate. Human thresholds to heat do vary from place to place and from time to time. Prior conditioning, both through living in a particular climate and through recent exposure to extreme events also has an influence, as do social and cultural practices. Furthermore, understanding heat vulnerability is much more complex than a maximum temperature. Humidity, for example, has been shown to have a compounding impact – heat stress increased with very high dew points in Chicago in 1995 (Sparks *et al.*, 2002; Changnon *et al.*, 2003), but also increased with low humidity in Seville, Spain (Diaz *et al.*, 2002a). Recent work, by Gaffen and Ross (1999) and Robinson (2001), has focused on developing long-term quality-controlled humidity datasets to facilitate longer-term climatological analyses of heat stress.

The commonly adopted definition of a heat wave implies that it is an extended period of unusually high atmosphere-related heat stress, which causes temporary modification of lifestyles and which may have adverse health consequences for the affected population (Robinson, 2001). Thus, although a meteorological event, most studies recognize that heat waves cannot be assessed without reference to human impacts. McGregor *et al.* (2002) describe simple empirical indices, such as the effective temperature and discomfort index, which attempt to integrate thermal and humidity effects in the environment into one single value. Watts and Kalkstein (2004) present a comprehensive summer index, based on apparent temperature and other derived meteorological variables (including cloud cover, cooling degree days and consecutive days of extreme heat), that evaluates daily relative stress for locations throughout the USA based on deviations from the norm. Using this index they document that overall highest heat-related mortality rates are associated with the highest heat stress values, but high individual heat stress values are not always associated with the highest mortality rates. Frich *et al.* (2002) describe the Heat Wave Duration Index (HWDI) (maximum period >5 consecutive days with maximum temperature >5°C above the 1961–90 daily normal maximum), an indicator developed to monitor changes in climate extremes worldwide. However, the authors acknowledge such an index has little value in warm climates with low day-to-day variability. For example, this index does not define heat waves for Kuwait, a location that frequently experiences temperatures in excess of 40°C.

More complex biophysical models that model the human–environment exchange of heat based on human energy balance equations (for descriptions of some of the foundational work see Driscoll, 1985; Kalkstein *et al.*, 1996) also continue to be used. McGregor *et al.* (2002) present the details and application of one such comfort index, the predicted mean vote (PMV), in an assessment of the thermal climate for Athens, Greece for the period 1966–95 (context for the summer Olympics of 2004). Matzarakis *et al.* (1999) describe the physiological thermal index (PET), which they state is preferable to the PMV in part because of its units (°C) which make it more comprehensible for urban or regional planners. They present results graphically and as bioclimatic maps. Spagnolo and De Dear (2003) propose a physiologically relevant comfort index (OUT_SET*), an outdoor version of the widely used indoor comfort index, the standard effective temperature (SET*), which incorporates air and mean radiant temperatures, relative humidity, air velocity, clothing insulation and activity level. The index is of interest to many end-users focused on outdoor activities – event planners and the tourism industry in particular.

Sheridan (2004) stresses the importance of synoptic climatological methods in studies of heat waves, arguing that they provide a more holistic approach to linking the atmosphere to human health. Sheridan (2002a) describes the Spatial Synoptic Classification (SSC), which characterizes each day at a given location into eight weather types. Based on this approach health-related problems, not surprisingly, are shown to be greatest with the hottest and most humid weather types. Other factors, notably conditions most outside the usually accustomed range, and the length of time for which conditions persist, also strongly affect mortality rates. Domonkos *et al.* (2003), in central and southern Europe (1901–98), also adopted a synoptic-based approach, and linked changes in heat wave frequency, mainly in the northern sites, to the frequency of anticyclonic conditions over the study sites. For Madrid, Garcia *et al.* (2002) identified two different synoptic situations under which extremely hot days exist. In another study, Nasrallah *et al.* (2004) examined circulation patterns associated with heat waves in Kuwait. Changes in regional circulation, specifically related to the northward displacement of the Subtropical Jet Stream, and a build up of a ridge of high pressure at the 500 hPa level, were determined to be key factors. Kysely (2003), in a study of the Prague-Klementinum temperature series of the Czech Republic, determined that heat waves that peaked in the 1940s to early 1950s and early 1990s, were strongly linked to particular synoptic regimes, specifically situations with an anticyclone or ridge over Europe in the summer season. The potential of this approach is further underscored by the fact that the heat/health warning system that underlies the European Union Framework V project on the assessment and prevention of acute health effects of weather conditions in Europe (PHEWE) is based on a synoptic approach and forecast meteorological variables to predict and alert city residents to potentially oppressive weather conditions (G. McGregor, personal communication, March 2004).

III Effects on human health

Heat kills by taxing the body beyond its abilities. When subject to extreme heat, the body attempts to maintain its ideal temperature by varying blood circulation and perspiring. The threshold ambient temperature at which more people are at risk for heat-related health problems varies by location. High humidity compounds the effects by reducing evaporation and thus rendering perspiration a less effective cooling mechanism. Heat waves tend to take the greatest toll in cities, given that urban centre tend to have enhanced temperatures compared with their rural surroundings. However, as documented by Sheridan (2002b), heat-related mortality is a rural issue too. A number of recent studies have shown that air pollution (notably ozone and total suspended particulates) can exacerbate the health-damaging effects of high temperatures by further stressing the body's respiratory and circulatory systems (see, for example, the work of Smoyer *et al.*, 2000a, in Birmingham AL, USA, and Rainham and Smoyer-Tomic *et al.*, 2003 in Toronto, Canada).

The effects of heat waves on the population have been described in a broad array of geographic settings. Diaz *et al.* (2002a,b) in a study of Seville, Spain, for example, demonstrated that mortality for all causes increased by up to 51% above the average in the group over 75 years of age for each degree Celsius beyond 41°C (their threshold for the definition of extremely hot days). The effects were more noticeable for cardiovascular than for respiratory diseases, with greater effects for men than women. For their study, the authors conclude that low relative humidity enhances the effects of high temperatures, particularly through the effects of ozone. Laschewski and Jendritzky (2002) investigate the climate sensitivity of health in southwest Germany using daily mortality data for a 30-year period and a complete heat budget model. Their results show mortality related to heat waves to be more pronounced than that associated with cold spells, but mortality rates are lower than average in weeks following a heat wave. Similarly, Huynen *et al.* (2001) found that mortality increased during all the heat waves studied (1973–97) in the Netherlands, with the elderly most affected by extreme heat. Smoyer *et al.* (2000b) analysed heat-related mortality of the elderly in metropolitan areas of Southern Ontario, Canada. Demographic, socioeconomic and housing factors were also evaluated. Those cities with the highest heat-related mortality have relatively high levels of urbanization.

Weisskopf *et al.* (2002), in a study of two heat waves in Milwaukee WI, USA, in 1995 and 1999 documented that heat is not the only factor influencing heat-related mortality. In Milwaukee, changes in public health preparedness and response following the 1995 event contributed to reductions in mortality in 1999. This conclusion is supported by Palecki *et al.* (2001) who document similar declines in mortality in the city of Chicago, USA, for these two events. However, these authors do acknowledge that the 1999 event was slightly less severe in terms of the two-day maximum apparent temperature and the event was preceded by warmer temperatures, which allowed short-term acclimatization prior to the final intense days.

Two longer-term studies (Davis *et al.*, 2002a,b), raise questions about the validity of projections of future US mortality increases, given that most studies assume that weather–mortality relationships have not changed over time. Their results, which are based on decadal-scale changes in the relationships between human mortality and hot, humid weather for 28 US cities (Davis *et al.*, 2002a) and six major metropolitan areas (Davis *et al.*, 2002b), indicate an overall decline in heat-related mortality in most cities, associated with increased use of air conditioning, improved health care and heightened public awareness of the biophysical impacts of heat exposure. These studies and those of Palecki *et al.* (2001) and Weisskopf *et al.* (2002) highlight the importance of, and potential for, societal response in mitigating effects of excessive heat.

It is important to note that heat waves have other impacts too. For example, Smoyer-Tomic *et al.* (2003), in an overview of heat waves in Canada, document effects on human behaviour, forest fires, livestock productivity, construction and transportation difficulties, and power demand.

IV Historic trends and future scenarios

One possible outcome of predicted global climate change is an increase in the frequency and intensity of heat waves. Beniston (2004) suggests that the 2003 heat wave that affected much of Europe bears a close resemblance to many regional climate model projections for summers in the latter part of the twenty-first century. Thus, he argues, the event can serve as an analogue of summers in coming decades. However, a rise in the mean temperature does not necessarily lead to a rise in extreme temperature events (Frich *et al.*, 2002). Recent studies that have involved the application of GCM and regional climate models and analyses of the historic record have generated varying results.

Bell *et al.* (2004), in a study using a regional climate model focused on California, demonstrate that statistically significant increases in daily minimum and maximum temperatures occur with a doubling of atmospheric carbon dioxide concentration. In their study, increases in daily temperature lead to increases in prolonged heat waves. Similar conclusions are presented by Jauregui and Tejeda (2001). Their study, which applies the concept of effective temperature, presents scenarios of human climate conditions for Mexico City based on results from both GCM regional predictions for CO_2 doubling and temperature trend projections. The greatest impact is projected in the warm season with a shift to warmer conditions and greater potential for heat stress for most of the city. However, Huth *et al.* (2000), demonstrate difficulties in simulating heat waves in their control run with GCM scale outputs when evaluated against historical data for the Czech Republic, underscoring the problems of downscaling information from GCMs to local scales, and the need for proper validation of GCM output before climate impact studies are conducted. Dessai (2003a,b) in a study of climate–mortality relationships for Lisbon, Portugal, using two regional climate models with different assumptions about seasonality and acclimatization, also highlight the uncertainty of results depending on which regional climate model is chosen.

Increasingly, climate change detection and attribution studies of instrumental records have focused on changes in extreme events. Wang and Gaffen (2001), for example, show that in the past half century, the mean summertime temperature in China has increased, with nights warming more than days, and that number of extremely hot and humid days as well as heat waves lasting several days have also increased over the period. Mietus and Filipiak (2004) in their study of temperature records for Gdansk, Poland, suggest the duration of heat waves is increasing. In contrast, Easterling *et al.* (2000) and Robeson (2004), both of whom analyse historical climatological data for the USA, indicate that while there is evidence that across the USA there have been decreases in the number of days below freezing and an earlier onset of the frost-free season, trends in maximum temperatures are much less consistent and, in fact, there may have been a slight downward trend in the number of extremes. Both studies point to problems with the length of record considered in previous studies, issues of site exposure and inadequate consideration of regional differences. Frich *et al.* (2002) suggest that longer heat wave duration (HWDI) during the second half of the twentieth century has been observed in Alaska, Canada, central and eastern Europe, Siberia and central Australia. However, shorter heat waves have occurred in southeastern USA, eastern Canada, Iceland and southern China. Despite mixed results, they suggest globally an upward trend in heat wave duration, though it is not statistically significant.

V Final comments

Much progress has been made in the definition and understanding of heat waves and their effects. However, much still remains to be done, particularly in the realm of forecasting and the development of better planning and mitigation strategies to deal with effects. New initiatives are underway in this realm, building on earlier watch/warning systems (e.g., Kalkstein *et al*., 1996). As one example, the EU Framework V project on the assessment and prevention of acute health effects of weather conditions in Europe (PHEWE) (G. McGregor, personal communication, March 2004), focuses on the effects of weather on mortality and health, with an emphasis on the development of improved public warning systems (to be piloted in five cities: London, Paris, Barcelona, Rome and Budapest).

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