CHANGES IN THE OCCURRENCE OF EXTREME TEMPERATURE EVENTS

Autoreport on Doctoral Thesis

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ZMĚNY VE VÝSKYTU EXTRÉMNÍCH TEPLOTNÍCH JEVŮ

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1. INTRODUCTION

Ecosystems and various sectors of human activity are sensitive to extreme weather and climate phenomena, including heavy rains and floods, droughts, and high and low temperature, especially when they occur over extended periods. The domains in which extreme events affect human society were summarized by *Wigley (1985)*; they include among others agriculture, water resources, energy demand and mortality. Numerous climatological studies have recently focused on statistical characteristics and impacts of extreme high temperature events and temperature threshold exceedances.

Extreme climatic phenomena are the subject of investigation both because of their current impacts on society and the threat of their possible increases in frequency, duration and severity in the climate perturbed by enhanced concentrations of greenhouse gases in the atmosphere. Impacts of climate change would result rather from changes in climate variability and extreme event occurrence than from an increase in mean temperature (*Houghton et al., 1996; Watson et al., 1996*) and even relatively small changes in the means and variations of climate variables can induce considerable changes in the severity of extreme events (*Katz and Brown, 1992; Hennessy and Pittock, 1995; Colombo et al., 1999*). Such changes are likely to influence ecosystems and society severely.

Growing attention to extreme phenomena has therefore been paid recently in general circulation model (GCM) studies, both in validating the simulated present-day climate and analyzing the possible future climate. These studies have mostly concentrated on precipitation characteristics such as frequencies of extreme rainfall events and/or dry spells (e.g. *Joubert et al., 1996; Gregory et al., 1997; Huth et al., 2000a*) whereas extreme temperatures and/or heat waves were studied only occasionally (*Zwiers and Kharin, 1998; McGuffie et al., 1999; Trigo and Palutikoff, 1999*). The skill of GCMs in reproducing extreme temperature events is limited.

Extreme temperature anomalies often occur in groups. High persistence of time series may be a sufficient explanation of the experienced accumulation of extreme anomalies (*Domonkos, 1998*). Long-lasting extreme events such as prolonged periods with no precipitation or with high temperature impose enormous stress on animals and humans. Episodes of extremely high temperatures, especially in conjunction with water shortage, can damage plants (*Bassow et al., 1994; Watson et al., 1996*), e.g. by adversely affecting their key phenological stages. There are no generally given threshold values for delimitation of group of anomalies (which threshold must be exceeded, how long and how contiguous in time the exceedance should be). The thresholds and time periods of sensitive phenological stages alter among plant species and the economic impact of a threshold value exceedance depends on other factors, such as the type of soil, applied agrotechnical methods, crop protection facilities, etc. For example, *Mearns et al. (1984)* mention that the exceedance of 35 °C on five consecutive days is a very harmful event for corn yield in the U.S. Corn Belt.

High summer temperatures are harmful to human health as well. Many analyses that deal with heat stress related mortality do not consider the dry bulb temperature but the apparent temperature which attempts to quantify the effects of temperature and moisture on the human body (*Steadman, 1984*). For instance, the very intense heat wave in July 1995 that affected the midwestern United States caused well over 800 deaths, most of them in Chicago (*Whitman et al., 1997*). The analysis of *Karl and Knight (1997)* indicates that for Chicago such an extended period of continuously high daytime and nighttime apparent temperatures is unprecedented in modern times. *Changnon et al. (1996)* have presented the comparison of fatalities attributed to weather in the United States (e.g. tornadoes, floods, hurricanes, wind storms, etc.). The mean annual number of deaths caused by heat waves is much higher than that for any other extreme weather event.

The increase in daily mortality rates in heat waves was studied in Europe as well, namely in Great Britain (*Rooney et al., 1998*), the Netherlands (*Kunst et al., 1993; Mackenbach et al., 1997*), Belgium (*Sartor et al., 1995*), Spain (*Alberdi et al., 1995*), Portugal (*Falcao and Valente, 1997*), Italy (*Mammarella and Paoletti, 1989*) and Greece (*Matzarakis and Mayer, 1991*). Unusually hot summer seasons occurred in several continental territories of the Northern Hemisphere in the 1980s and 1990s, and central Europe was one of the affected regions. Hot summers in this area, often accompanied by droughts, cause considerable harm to agriculture.

This study deals with heat waves and issues concerning changes in their occurrence. Heat waves have not yet been analyzed in a complex way in the Czech Republic, as regards for instance their temporal and spatial variability and relationship to atmospheric circulation. A part of the thesis concentrates on a comparison of various approaches to climate modelling from the point of view of the ability of the models to simulate characteristics of extreme temperature events, which are closely related to statistical properties of time series.

2. HEAT WAVES IN THE CZECH REPUBLIC

Defining the heat wave is itself a challenge. Generally, there are two approaches to defining heat waves: the most extreme event lasting a required period in each summer is selected, or all heat waves with conditions exceeding a certain threshold are analyzed. In this study the latter approach was adopted, as it allows several heat waves in one year to be considered. The definition consists of three requirements imposed on a period to be treated as a heat wave: (i) T_{MAX} (daily maximum air temperature) $\geq$ T1 in at least 3 days; (ii) mean T_{MAX} over the whole period ≥ T1; and (iii) T_{MAX} ≥ T2 in each day. The threshold values were set to T1=30.0 °C, T2=25.0 °C, in accordance with a climatological practice commonly applied in the Czech Republic which refers to the days with T_{MAX} reaching or exceeding 30.0 °C and 25.0 °C as tropical and summer days, respectively. The introduced definition of the heat wave allows two periods of tropical days separated by a slight drop of temperature to make up one heat wave but, on the other hand, two periods of tropical days separated by a pronounced temperature drop below 25 °C treats as separate heat waves.

Among the heat wave characteristics employed, a special interest is placed on the cumulative T_{MAX} excess above 30.0 °C in heat waves (TS30) and the heat wave index (HWI) that is introduced as a measure of the heat wave severity. The definition of HWI is based on the combination of daily maximum and minimum temperature and precipitation characteristics of heat waves.

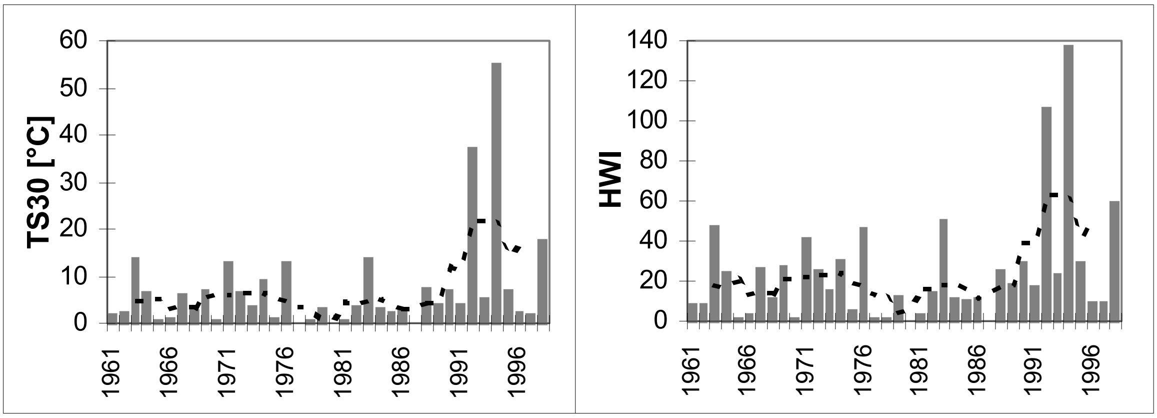

Fig. 1. Heat waves in the Czech Republic in 1961-1998. Annual cumulative T_{MAX} excess above 30.0 °C in heat waves (TS30) and annual heat wave index (HWI) are shown. Dashed curves depict 5-year running means. The values shown are averages over 51 stations in the Czech Republic.

The analysis of heat waves at more than fifty stations in the Czech Republic in the period 1961-1998 shows the temperature exceptionality of the 1990s when the three most extreme summer seasons (as regards heat waves; 1992, 1994 and 1998) occurred (Fig. 1). In 1992 and 1994, long periods with high air temperature and decreased interdiurnal temperature variability were related to persistent circulation patterns over Europe with high pressure systems influencing central Europe. The highest temperatures ever recorded in the Czech Republic, reaching 40 °C in south and central Bohemia, were observed in 1983 but extreme high temperatures were confined to relatively short periods and heat waves did not reach a severity comparable with 1992 and 1994. The extremity of the 1990s is even more expressed in the temporal distribution of long heat waves (lasting 12 days or more); their absolute frequency is higher in 1991-1998 then in 1961-1990 for most of the Czech Republic. The occurrence of long and severe heat waves in the 1990s may reflect an enhanced persistence of the atmospheric circulation over central Europe in summer season, because all groups of Hess-Brezowsky Grosswetterlagen have considerably increased residence times in 1988-1997 compared to long-term means.

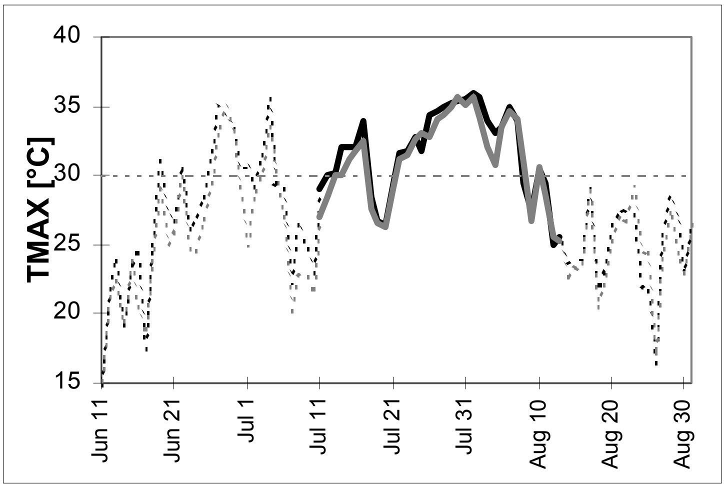

Fig. 2. Course of T_{MAX} in extreme 1994 heat wave (bold) at two south Moravian stations, Strážnice (light curve) and Pohoøelice (dark curve), where its duration exceeded 30 days. The course of T_{MAX} outside the heat wave is depicted by the dashed curve. The horizontal line shows the limit for a tropical day (30 °C).

The July and August 1994 heat wave must be treated as exceptional at least in the context of the whole 20th century. At Prague-Klementinum, this heat wave is the most severe during the period 1901-1997, and very likely even from the beginning of uninterrupted temperature measurements (1775). It was exceptional mainly in high cumulative T_{MAX} excess above 30 °C (TS30) and long unbroken period of tropical days and even days with $T_{MAX} \geq 32.0$ °C, although record-breaking daytime and nighttime temperatures were not reached (Fig. 2). The heat wave lasted 18-34 days at all stations up to 670 m a.s.l. and its duration reached 18 days even at the Svratouch station (737 m a.s.l.) where less then one tropical day per year is observed on average and where the number of tropical days during the 1994 heat wave was almost the same as within the 30-year period 1961-1990. No comparable heat wave appeared in 1961-1998 at most stations. Considering e.g. the cumulative T_{MAX} excess above 30 °C (TS30), it was 1.5- to 3-times higher in the 1994 heat wave than in the second most extreme heat wave, with exceptions of a few stations lying mainly in southwest Bohemia.

The first-order autoregressive model (AR(1)) is frequently used to simulate time series of T_{MAX} (*Mearns et al., 1984; Macchiato et al., 1993; Hennessy and Pittock, 1995; Colombo et al., 1999*) and provides characteristics of heat waves and temperature threshold exceedances that are in a good agreement with observations. Using AR(1) model of T_{MAX}, the return period of a heat wave lasting at least 34 days was estimated to be 700 years at Strážnice. This value must be treated as an upper limit because some deficiencies in simulating heat wave characteristics and interannual temperature variability are inherent to AR(1) model and, furthermore, the AR(1) model cannot describe all of the variability in T_{MAX}. The return period of the observed 18-day period of tropical days was estimated to be in the order of thousands of years. Theoretical extreme value distributions (GEV or Gumbel distribution) do not yield good results when applied to the maximum annual durations of heat waves / periods of tropical days since various methods of estimation of their parameters (see e.g. *Faragó and Katz, 1990*) lead to considerably different values. Besides, the omission of the most extreme year from the sample may change the result of hypothesis testing (H: k=0, where k is the shape parameter in the GEV distribution), and the return periods differ considerably even in their order. The probability of recurrence of such a long uninterrupted period of tropical days is small under present temperature conditions but an increase in mean summer T_{MAX} of 3 °C (which is a change that lies in the range of values indicated for central Europe by most current GCMs under doubled effective CO_2 concentrations) would result in a 100-fold increase in this probability.

The extreme July-August 1994 heat wave was associated with only a slight increase in mortality due to cardiovascular diseases in the city of Prague. The reason is that above-average temperatures had prevailed from mid-June, with several peaks accompanied with a significantly increased mortality. For instance, the increase in mortality due to cardiovascular diseases in Prague was of 33% during the 5-day period of consecutive tropical days lasting from June 25 to 29. The adaptability of a human body to long-lasting high temperatures, and the „harvesting“ effect which consists in a decrease in mortality after a hot period (*Kalkstein, 1993*), can explain why the increase in mortality during the extreme 1994 heat wave was only slight.

The spatial distribution of heat waves in a territory with a complex orography (like the Czech Republic) is primarily governed by the altitude. The frequency and intensity of heat waves decreases with increasing elevation. Heat waves are rare events in regions above 600 m a.s.l. and also at some lower-elevated stations that are influenced by microscale, toposcale and/or mezoscale climatic factors which are unfavourable for high summer T_{MAX}. An example is station Mìsto Albrechtice - Žáry (483 m a.s.l.) with five heat waves during 1992-1998 but none within 1961-1991. Due to the complex terrain the spatial distribution of heat waves was analyzed after the dependence of heat wave characteristics on altitude had been removed. A quadratic regression model was derived between the altitude and the annual duration of heat waves, and the multiplicative anomaly of the annual duration of heat waves (D') was used to measure whether the station is „cold" (D'<1) or „warm" (D'>1) in terms of the heat wave occurrence relative to its elevation.

Two warm regions (with D'>1) can be found in the Czech Republic when this approach is employed, namely, south Moravia (with most stations up to 340 m a.s.l.) and south Bohemia (most stations between 430 and 570 m a.s.l.). Within south Bohemia the sub-region surrounding Klatovy is the warmest. A large cool region (with D'<1) is located in north Moravia. Very similar features emerge when the pattern of mean summer (May-September) maximum daily temperature is analyzed (the dependence on altitude having been removed using a linear regression model). The largest discrepancy between the mean summer T_{MAX} and the duration of heat waves was found in the Klatovy sub-region, which is not warmer than other parts of south Bohemia region in terms of mean summer T_{MAX}. A possible explanation of an enhanced heat wave occurrence was proposed which counts on the influence of the foehn effect downwind of the mountains of the Czech and Bavarian Forests. In addition to the lee effects, topoclimatic and microclimatic factors related to the locations of stations Klatovy, Domažlice and Nepomuk play an important role as they prefer high day-time temperatures in summer (*Hostýnek, 2000*).

The Prague-Klementinum station is among the stations with the longest uninterrupted temperature series in central Europe (since 1775). Because possible sources of inhomogeneities (changes in the time of measurement, location of the thermometer, instrumentation, different observing practices etc.) may be reflected in the series, period 1901-1997 with the most reliable data was analyzed. The influence of the urban heat island intensification on the temperature series since 1922 was evaluated in an earlier study and found insignificant for the summer season (*Brázdil and Budíková, 1999*). As other possible sources of inhomogeneities were either not present in the period analyzed or assessed as negligible (*Hlaváč, 1937*), the temperature series can be considered homogeneous since 1901.

Concerning the twelve warmest summers (in terms of the mean July-August daily maximum temperature), a half of them appeared within 1943-1952, three in 1992-1995, and only three of them occurred as „isolated" in 1911, 1971 and 1983. The temporal distribution of heat waves corresponds to this pattern and shows two peaks during the 20th century, in the 1940s-early 1950s and in the 1990s. A very low occurrence of heat waves is typical in the beginning of the 20th century and (to a lesser degree) in the period around 1980. Upward trends in both the heat wave characteristics (annual duration, cumulative T_{MAX} excess above 30 °C) and mean summer temperature during 1910s-1940s and late 1970s-early 1990s are prominent features of the temporal distribution (Fig. 3). The decrease in interannual temperature variability (from ~ 3.0 °C to as low as ~ 0.5 °C in 5-year means) from 1910s to 1930s was concomitant with the temperature increase. While in the hot 1940-50s the interannual variability was on a relatively low level and fluctuated only slightly, in the early 1990s it reached maximum values since the 1910s.

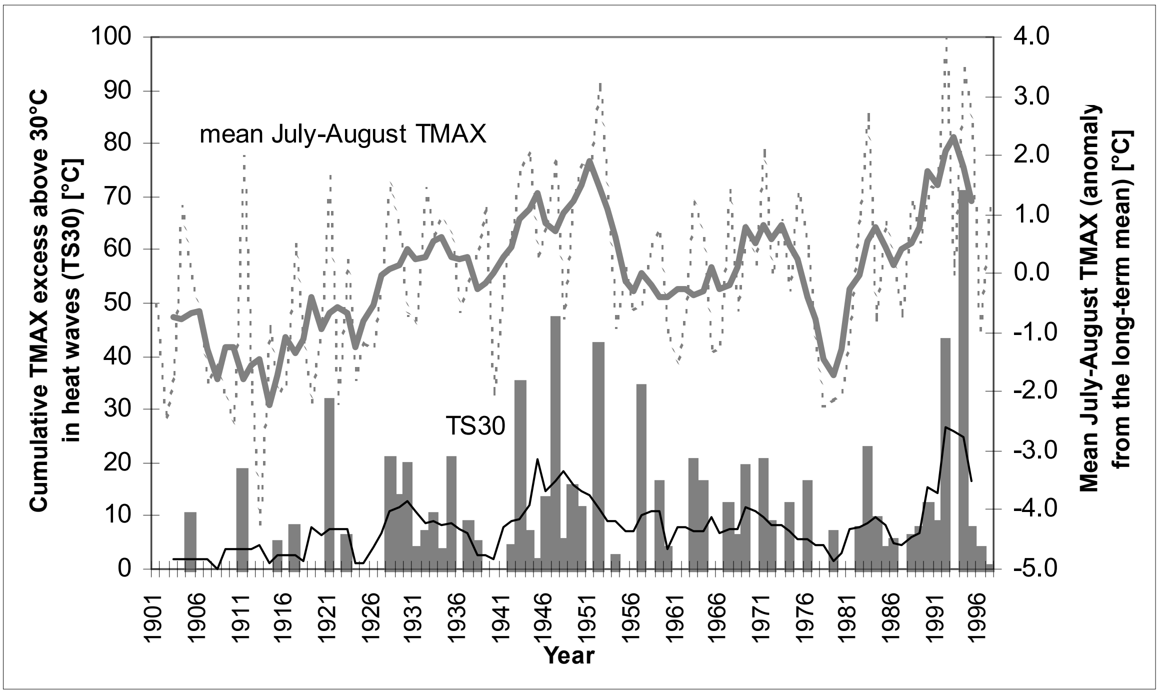

Fig. 3. Heat waves at Prague-Klementinum in 1901-1997 as measured by annual cumulative T_{MAX} excess above 30 °C in heat waves (TS30; bottom), and mean July-August T_{MAX} (expressed as an anomaly from the long-term mean; top). Both the variables are smoothed by 5-year running means.

The heat waves were more severe in 1992 and 1994 than in 1940s-1950s (as measured by cumulative T_{MAX} excess, TS30); TS30 reached 47.6 °C and 33.3 °C in the 1994 and 1992 heat waves, respectively, while only 21.9 °C in the most extreme heat wave within the 1940s-1950s period. Extreme heat waves occurred outside the generally hot periods, too, namely in 1957 (TS30=34 °C) and 1921 (TS30=31 °C); particularly worth noting is the fact that the second most severe heat wave (1957), which was associated with record-breaking daytime and nighttime temperatures, appeared in the year with mean summer temperature well below normal. The difference between the 1994 heat wave and any other during the 20th century cannot be attributed to the increased urban heat island.

The maximum heat wave occurrence in the 1940s - early 1950s as well as the almost total absence of heat waves in the first two decades of the 20th century and around 1980 may be a common feature for a larger area (at least of central Europe) as indicated by the comparison between two distant stations within central Europe, Prague-Klementinum and Basle (Switzerland), and by other studies dealing with central-European long-term temperature series (e.g. *Wagner, 1996*). On the other hand, the enhanced heat wave intensity in the 1990s is not observed in Basle. The presented nature of the temporal heat wave distribution in central Europe, which is dominated by a small number of large peaks, is probably similar to the U.S. where the maximum heat wave intensity falls on the 1930s. Thus, the estimated trends of extreme temperature event frequency or intensity are strongly influenced (even in their signs) by the fact whether the period with enhanced heat wave characteristics is included in the analysis or not (*Kunkel et al., 1999*).

3. THE ABILITY OF CLIMATE MODELS TO CAPTURE HEAT WAVE AND COLD WAVE CHARACTERISTICS

Coupled atmosphere and ocean general circulation models are the most frequently used tool in climate modelling. The models are able to qualitatively reproduce many of the features of the observed climate system not only in terms of means but also naturally occurring variability. Only a few studies dealt with the ability of GCMs to capture extreme temperature events (*Zwiers and Kharin, 1998; McGuffie et al., 1999; Trigo and Palutikof, 1999*) and found their skill in reproducing extreme temperature characteristics to be limited. It is obvious since GCMs have not been designed for simulating local climate features and their reliability decreases with increasing spatial resolution.

Studies of climate change impacts frequently require daily time series of climate variables for a future climate state at a specific site. There are several ways of obtaining site-specific daily time series, which are to a different extent based on GCM outputs. They include the method of statistical downscaling and stochastic weather generators. Statistical downscaling takes advantage of the fact that GCMs simulate large-scale upper-air fields more accurately than the surface local variables (*Kim et al., 1984; Huth, 1999*). It consists in identifying in the observed data the statistical relationships between the upper-air variables and the local surface ones, and applying them to control and/or perturbed GCM runs. The downscaled time series are fitted to a specific site and, if applied to present climate, can be adjusted to reproduce the original mean and variance. Weather generators produce synthetic time series, replicating the stochastic structure of observed variables, including means, variances, autocorrelations and crosscorrelations (*Richardson, 1981; Dubrovský, 1997*).

The three above-mentioned approaches to constructing daily temperature series were examined for their ability to reproduce the characteristics of extreme temperature events. (Both heat waves and cold waves were analyzed, the definition of cold waves in the time series of daily minimum temperature being analogous to the definition of heat waves, only with reversed inequalities and changed threshold values.) As for GCMs, the ECHAM3 and CCCM2 GCMs were used. Their basic descriptions can be found in *DKRZ (1993)* and *McFarlane et al. (1992)*, respectively. Due to the fact that CCCM2 simulates winter temperatures in central Europe unrealistically (*Kalvová et al., 2000*), cold waves were not analyzed in this model. The downscaled temperatures were calculated by multiple linear regression with stepwise screening from gridded 500 hPa heights and 1000/500 hPa thickness (for detailed description see *Huth et al., 2000b*). The relationships between large-scale fields and local temperature were identified in observations and then applied both to observations and control GCM outputs. The two possible ways of retaining the variance of the downscaled series, namely the variance inflation and addition of a white noise process were compared. Synthetic daily temperature series were produced by the stochastic weather generator Met&Roll (*Dubrovský, 1997*) and its modification (*Huth et al., 2000b*). It deals with four daily weather characteristics, maximum temperature (T_{MAX}), minimum temperature (T_{MIN}), sum of global solar radiation and precipitation amount. Standardized anomalies of T_{MAX} and T_{MIN} are modelled by the first order autoregressive model and their means and standard deviations are conditioned by a precipitation occurrence and day of the year. Two runs of the weather generator were analyzed, namely, one considering and one neglecting the annual variation of lag-0 and lag-1 correlations among T_{MAX}, T_{MIN} and solar radiation.

The term „model" will hereafter be used for GCMs, statistical downscaling and stochastic generator. For the list of models see Tab. 1.

To allow a fair comparison of direct GCM outputs with observations and other models, the GCM-produced temperatures must be de-biased. Here their distributions were adjusted to have the observed mean and standard deviation. The models have been compared against observations at six sites in central Europe (Fig. 4): Prague-Ruzynì, Strážnice, Kostelní Myslová (the Czech Republic), Hamburg, Würzburg (Germany) and Neuchâtel (Switzerland).

Tab. 1. The models used in the extreme temperature event analysis and the reference to their detailed descriptions.

Model	Described in
Direct output from ECHAM3 GCM	*DKRZ (1993)*
Direct output from CCCM2 GCM	*McFarlane et al. (1992)*
Downscaling from observations; variance retained by inflation	*Huth (1999)*
Downscaling from observations; variance retained by adding white noise	*Huth et al. (2000b)*
Downscaling from ECHAM3 GCM	*Huth et al. (2000b)*
Downscaling from CCCM2 GCM	*Huth et al. (2000b)*
Weather generator without annual cycle of correlations between T_{MAX} and T_{MIN}	*Dubrovský (1997)*
Weather generator with annual cycle of correlations between T_{MAX} and T_{MIN} included	*Huth et al. (2000b)*

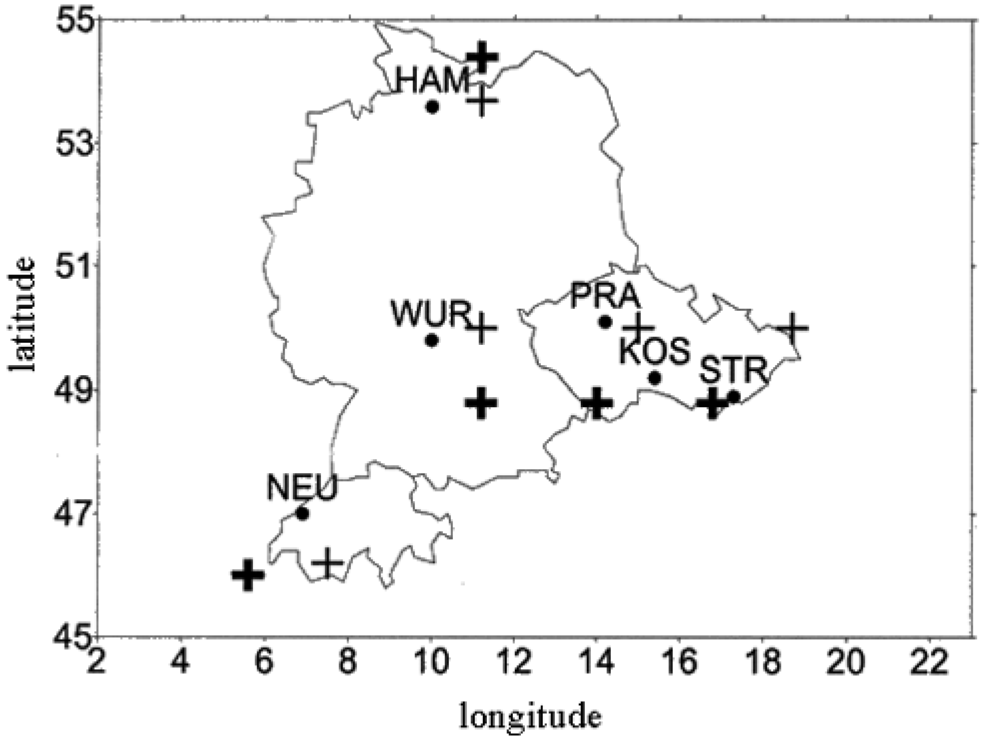

Fig. 4. Location of stations (NEU = Neuchâtel; WUR = Würzburg; HAM = Hamburg; KOS = Kostelní Myslová; STR = Strážnice; PRA = Prague) and the closest GCM gridpoints (bold crosses for ECHAM, thin ones for CCCM).

A comparison of direct GCM outputs, the statistical downscaling from large-scale atmospheric fields, and stochastic weather generator with observations shows that none of the models yields generally better results than the others as regards the simulation of extreme temperature events in central Europe.

The ECHAM3 GCM is the best among the models in simulation of cold waves (although the unadjusted temperatures are too high) and both the ECHAM3 and CCCM2 GCMs are fairly successful in reproducing frequencies and some other properties of heat waves, e.g. the temporal evolution with the highest temperature typically reached in the second half of their duration. Of the models analyzed, the ECHAM3 GCM is the only one that does not underestimate the extremity of cold waves. Due to the overestimated persistence of T_{MAX} (*Kalvová and Nemešová, 1998*), heat waves are too long in ECHAM, peak at too high temperatures and the inclusion of tropical days into prolonged periods is overestimated. The CCCM2 GCM yields better results for heat wave characteristics than ECHAM3. A deformation of the temperature annual cycle with a maximum shifted towards August leads to an unrealistic position of a typical heat wave in a year in both the ECHAM3 and CCCM2 GCMs. Since the errors in temperature persistence and annual cycles over continents appear to be common to many GCMs (cf. *Buishand and Beersma, 1993; Mao and Robock, 1998; Colombo et al., 1999*), at least some of the heat wave characteristics are likely to be misreproduced by other GCMs as well.

Since physical processes are explicitly included in GCMs only, some statistical properties of time series that are related to them (mainly to the radiation balance and atmospheric fronts) cannot be reproduced by other models. Too low frequency of both heat and cold waves in the downscaled times series is influenced by the unrealistic symmetry of the day-to-day temperature change distribution and (if variance is retained by adding white noise) by a too high interdiurnal variability. The underestimation is more pronounced in winter when it is strongly influenced by a lower number of T1 days due to an unrealistic symmetry of the T_{MIN} distribution. The white noise addition, which is the alternative approach to the variance inflation in fitting the observed variance to the downscaled series, leads to temperature series that are too variable, and is therefore unsuitable if one is concerned with the time structure and extreme temperature events. Although the inflation is a physically questionable concept, it yields temperature time series much closer to reality. The statistical downscaling from GCMs does not improve heat and cold wave characteristics derived from direct GCM outputs.

The stochastic weather generator is an alternative approach to GCMs in simulating heat waves; most of the heat wave properties are reproduced in a good agreement with observations. On the other hand, the simulation of cold waves is unrealistic since the generator strongly underestimates frequencies of extreme cold days and cold waves. The discrepancy results mainly from the difference of the observed T_{MIN} distribution in winter from the normal distribution (assumed by the model of the generator). Other imperfections of the generator are connected with the underestimated temperature persistence, overestimated interdiurnal variability and unrealistic symmetry of day-to-day temperature change distribution. The inclusion of the annual cycle of lag-0 and lag-1 correlations into the generator may worsen the results when the change due to the inclusion of the annual cycle has the same sign as the generator's bias which was present before the inclusion. Therefore, heat waves are better captured when the annual cycle of lag-0 and lag-1 correlations is omitted because the addition of annual cycle further reduces the lag-1 correlation of T_{MAX} in summer.

The ECHAM3 GCM was used to construct a scenario of the heat wave occurrence in perturbed (2×CO_2) climate in the region of south Moravia. The model deficiencies found out during the validation must be kept in mind when the results for 2×CO_2 climate are interpreted. The model bias in the right tail of T_{MAX} distribution in summer was eliminated by assigning percentiles in the observed and control climates that correspond to the threshold values T1 and T2 (used in the definition of a heat wave) in the distribution of T_{MAX}. Simulated heat wave characteristics were compared with characteristics observed at eight stations (and with their means over eight stations) and those derived from a spatially averaged temperature series. The conclusions concerning the simulated heat waves do not appear to be sensitive to what they are compared with: both the characteristics derived from the spatially averaged temperature and those obtained by averaging over eight stations yield similar results, which widely differ from the control simulation. In other words, the validation of heat waves appears to be insensitive to whether the GCM output is treated as a gridpoint or gridbox value.

The character of heat waves changes dramatically in the scenario climate. The frequency of heat waves is more than doubled, the average heat wave lasts more than a month and its peak temperature reaches almost 38 °C. The most extreme heat wave peaks at 46 °C, with T_{MAX} reaching at least 40 °C on seven consecutive days. The intensification of heat waves in $2\times CO_2$ climate follows primarily from a considerable temperature increase between $2\times CO_2$ and $1\times CO_2$ climates of the ECHAM3 GCM in the nearest gridpoint (ca 5 °C in summer season). Extremely long heat waves in $2\times CO_2$ climate result, apart from a direct temperature increase, from too high a persistence and too low an interdiurnal temperature variability that are inherent to the model climates. The increase in mean temperatures under doubled effective CO_2 concentrations may imply a much more pronounced change in extreme temperature events; the difference between peak temperatures reached during the most extreme heat waves in $2\times CO_2$ and $1\times CO_2$ climates is 8 °C. Due to the shortcomings that are common to the control and perturbed ECHAM3 outputs, and to current GCMs in general, the scenario of the heat wave occurrence under $2\times CO_2$ conditions is loaded with a considerable uncertainty.

More realistic estimates of the changes in the heat wave occurrence are likely obtained using an incremental scenario based on modifications of the mean and variance of T_{MAX} according to the difference between $2\times CO_2$ and $1\times CO_2$ model climates (*Nemešová et al., 1999*). E.g., the probability of occurrence of an unbroken period of tropical days lasting at least 18 days was estimated (using AR(1) model simulations with parameters changed according to the difference between $2\times CO_2$ and $1\times CO_2$ ECHAM3 climates) to be one in three years under $2\times CO_2$ conditions at station Strážnice.

4. RELATIONSHIP BETWEEN HEAT WAVES AND ATMOSPHERIC CIRCULATION

Surface meteorological variables are to a certain extent (which differs among variables) influenced by atmospheric circulation. The relationship between heat waves and circulation conditions was analyzed in two ways, using (i) objectively defined modes of variability and circulation types, and (ii) subjective Hess-Brezowsky catalogue of weather types (Grosswetterlagen).

The method (i) was employed to study the relationship between heat waves and atmospheric circulation in the ECHAM3 GCM and to compare it with observations. Heat waves were linked to the objectively defined circulation types and the modes of variability, the latter being identified in two important frequency bands, namely synoptic frequencies (periods 2.5 to 6 days) and low frequencies (periods > 10 days) (*Huth et al., 2000a*). In contrast to temperature and precipitation, large-scale circulation at the 500 hPa level over Europe is simulated relatively successfully by the ECHAM3 GCM, the most notable deficiency of the control climate being the lack of broad ridges over Europe. No general bias in the persistence of circulation types was found, which is in contrast with surface temperature (*Huth et al., 2000a*).

The occurrence of heat waves is associated with distinctive patterns of large-scale circulation. In particular, the observed heat waves tend to occur under non-zero amplitudes of all of the three low-frequency circulation modes. This means that conditions favourable for a heat wave occurrence are positive 500 hPa height anomalies over southern Scandinavia (mode 1), southwest Europe (mode 2), and to a smaller extent over Greece and negative anomaly over Ireland (mode 3). This could be expected since all these conditions support an inflow of warm air into central Europe and/or the presence of a ridge or anticyclone over there. The linkage between low-frequency modes and heat waves in the control ECHAM3 climate is considerably weaker; only the relationship of mode 3 with heat waves is simulated with a correct intensity. Unlike the low-frequency modes, the synoptic-frequency modes manifest no connection with heat waves both in observations and control ECHAM3 outputs.

The probability of a heat wave occurrence in south Moravia differs among objectively defined circulation types. Heat waves are favoured under warm anticyclonic types while situations with cyclonic conditions and cool west-northwest flows occur during heat waves only exceptionally or not at all. The relative contribution of circulation types to the formation of heat waves is changed in the control ECHAM3 climate. Cyclonic types remain unfavourable for heat waves but the contribution of the other types is levelled out, the difference between warm anticyclonic and cool northwest and zonal types being neglected. It means that the occurrence of heat waves under cooler situations (zonal and northwest flow) is enhanced relative to the observed climate.

The link between atmospheric circulation and heat waves is simulated incorrectly in the ECHAM3 GCM. Atmospheric circulation characterized by circulation types and modes of variability has less association with heat waves in the model climate than in the observed. This conclusion is in accord with findings concerning the simulation of circulation and its persistence (which are captured reasonably well) and the persistence of surface temperature and the heat wave characteristics (which are poorly reproduced). A likely explanation of the model's failure in simulating the linkage between circulation and surface temperature is that either the air-mass transformation plays too important a role and the advected air loses its original properties too quickly in the model or the model advection is too weak. Due to a realistic simulation of the sea level pressure variability and storm tracks in ECHAM (*Kaurola, 1997*) as well as the linkage between atmospheric circulation and heat waves under pronounced advection of a warm air, the more likely explanation is a too strong air-mass transformation in the model.

The heat wave occurrence is preferred under certain circulation conditions also when the subjective Hess-Brezowsky catalogue of weather types (Grosswetterlagen, GWL) is used (*Gerstengarbe and Werner, 1993; Gerstengarbe et al., 1999*). Almost 75% of heat wave days at station Prague-Klementinum during 1901-1997 occur under three prevailing groups of GWL which are characterized by (i) an anticyclone or a ridge of high pressure over central Europe, (ii) an anticyclone over Scandinavia and (iii) a situation with an inflow of warm air from southwest to southeast into central Europe.

Hess-Brezowsky classification of GWL was used to analyze the relationships between atmospheric circulation and heat waves in three cold (1901-1910; 1911-1920; 1973-1982) and three warm decades (1928-1937; 1943-1952; 1988-1997); „cold“ and „warm“ decades were determined according to the heat wave occurrence at Prague-Klementinum. From the set of GWL, (i) circulation types that are anticyclonic / cyclonic over Europe (*Gerstengarbe and Werner, 1993*) and (ii) circulation types with an increased / decreased heat wave occurrence were grouped together. Frequencies of these groups of GWL in cold and warm decades were compared to the climatological mean for the whole period of 1901-1997; only months of May to September were considered. Another characteristic of atmospheric circulation analyzed was the mean residence time of GWL in May-September.

Changes in frequencies of some groups of GWL in cold and warm decades are evident. E.g., situations with an anticyclone or a ridge over central Europe were more (less) frequent during all the warm (cold) decades compared to the long-term mean. A pronounced lack of the circulation types with south flow and the types with an anticyclone over Scandinavia is typical of cold decades 1901-1910 and 1911-1920, when the frequencies of GWL with north flow were considerably increased. A connection between high summer temperatures and atmospheric circulation is strong particularly for 1988-1997 when all the groups of GWL that are favourable (unfavourable) for heat waves have higher (lower) frequencies relatively to their long-term means. Furthermore, for the decade 1988-1997 the frequencies of anticyclonic (A) situations over central Europe are higher at the expense of cyclonic (C) situations. Whereas in the long-term mean the frequencies of both these groups are approximately the same (A 46%, C 44%), the prevalence of A (56%) over C (36%) is clear for the period 1988-1997. If circulation types favourable for heat waves are pooled together, the relationship between heat waves and circulation conditions is manifested also for the period 1943-1952.

For cold decades, the link to atmospheric circulation does not consist in the enhanced occurrence of the cyclonic GWL at the expense of the anticyclonic ones but mostly in a redistribution of frequencies among the groups of GWL that are favourable and unfavourable for heat waves. However, it is also clear that changes in the occurrence of extreme events do not necessarily reflect changes in the circulation conditions characterized by GWL. The pressure pattern and the location of atmospheric fronts differ in any single occasion from the „mean“ pattern of a relevant GWL which can further influence the advection, vertical motions, cloudiness etc. This is the reason why temperatures can be very different in the same GWL and in the same part of a year.

A conspicuous change in the atmospheric circulation in May to September is an enhanced mean residence time of circulation types in all the above-mentioned groups of GWL in 1988-1997 relative to the long-term mean. According to *Gerstengarbe et al. (1999)*, the catalogue of GWL is homogeneous which means that a change in the mean residence time of GWL does not reflect artificial disturbances in the time series. The character of the atmospheric circulation over Europe in summer has likely changed in the 1990s and the circulation appears to be more persistent.

The enhanced persistence of atmospheric circulation (not regarding whether the circulation types are favourable or unfavourable for heat waves) may be one of the causes of the occurrence of extremely long and severe heat waves in the 1990s. Unchanged or only little variable circulation conditions that persist for relatively long periods of time support anomalies of air temperature in one direction and the occurrence of uninterrupted periods with temperatures above / below normal. The increases of frequencies of the anticyclonic circulation types at the expense of the cyclonic ones, and of situations favourable for heat waves at the expense of those unfavourable lead to the observed fact that the higher persistence of circulation in the 1990s was reflected mainly in the occurrence of positive temperature extremes.

A statistically significant relationship was found between the index of the North Atlantic Oscillation (NAO) in spring (March-May, April-May) and the severity of heat waves at Prague-Klementinum in the following summer. This linkage does not hold for the mean summer temperature at Klementinum, which may indicate that the state of NAO is reflected more in the occurrence of extremes than in the mean temperatures. However, the percentage of variation explained by the relationship is very low, which prevents this linkage from using in climate predictions. Moreover, seasonal means of the NAO index are sensitive to the reference period that is used to standardize monthly sea level pressure data in Azores and Iceland (from which the NAO index was computed). The relationship loses its statistical significance when another reference period instead of 1901-1997 is employed.

5. CONCLUSIONS

The submitted thesis deals with extreme temperature events and changes in their occurrence. Its extent cannot be considered exhaustive; the objectives were to analyze the occurrence of heat waves, their temporal and spatial variability in the Czech Republic and relations to the atmospheric circulation, and to study the ability of climate models to capture main characteristics of heat and cold waves in central Europe. Changes in their frequency and/or intensity would play an important role in impacts of a climate change on ecosystems and society.

Up to now, a few studies have dealt with individual extremely hot summer seasons in the Czech Republic. However, these cases have not been compared among each other and in the context of the 20th century from the point of view of other characteristics in addition to, for instance, the mean temperature and the number of tropical days. A little attention has been paid to the spatial distribution of these extremes as well. The submitted thesis fills these blank spaces and presents the comprehensive analysis of heat waves in the Czech Republic as regards their spatial and temporal variability. An analysis of the temporal variability of extreme temperature events in long-term series within central Europe (which is hinted in the thesis as well) is a task for a possible future work.

As regards climate modelling, the aims of this thesis were to validate general circulation models, statistical downscaling and stochastic generator from the point of view of extreme temperature events in central Europe and to intercompare these various approaches to climate modelling. The presented results should be treated as new because only a marginal attention has so far been paid to the simulation of the time structure of daily temperature series and/or extreme temperature events in GCMs worldwide, and almost none in downscaling studies. Very few analyses compared the models based on various methods of climate modelling in terms of the time structure of daily series.

For a correct reproduction of characteristics of extreme temperature events, a correct representation of tails of the temperature distributions, lag-1 autocorrelations and higher statistical moments of the day-to-day temperature change distributions, is of essential importance. A good reproduction of the time structure and extreme events is necessary in studies that deal with impacts of climate change on society and ecosystems and an enhanced attention can be expected to concentrate on these issues in the near future.

A future work concerning extreme temperature events will probably focus on both analyses of observed time series (to detect changes in the occurrence, intensity and/or impacts of extreme events in the historical records) and validations of climate models. The ability of climate models to capture characteristics of extreme temperature events is currently limited but with advances in climate modelling and in methods of the adjustment or interpretation of model outputs (namely the methods of dynamical and statistical downscaling), an improvement in this domain is expected.

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