The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2210-18

MedCLIVAR Workshop on: "Scenarios of Mediterranean Climate Change under Increased Radiative Active Gas Concentration and the Role of Aerosols

23 - 25 September 2010

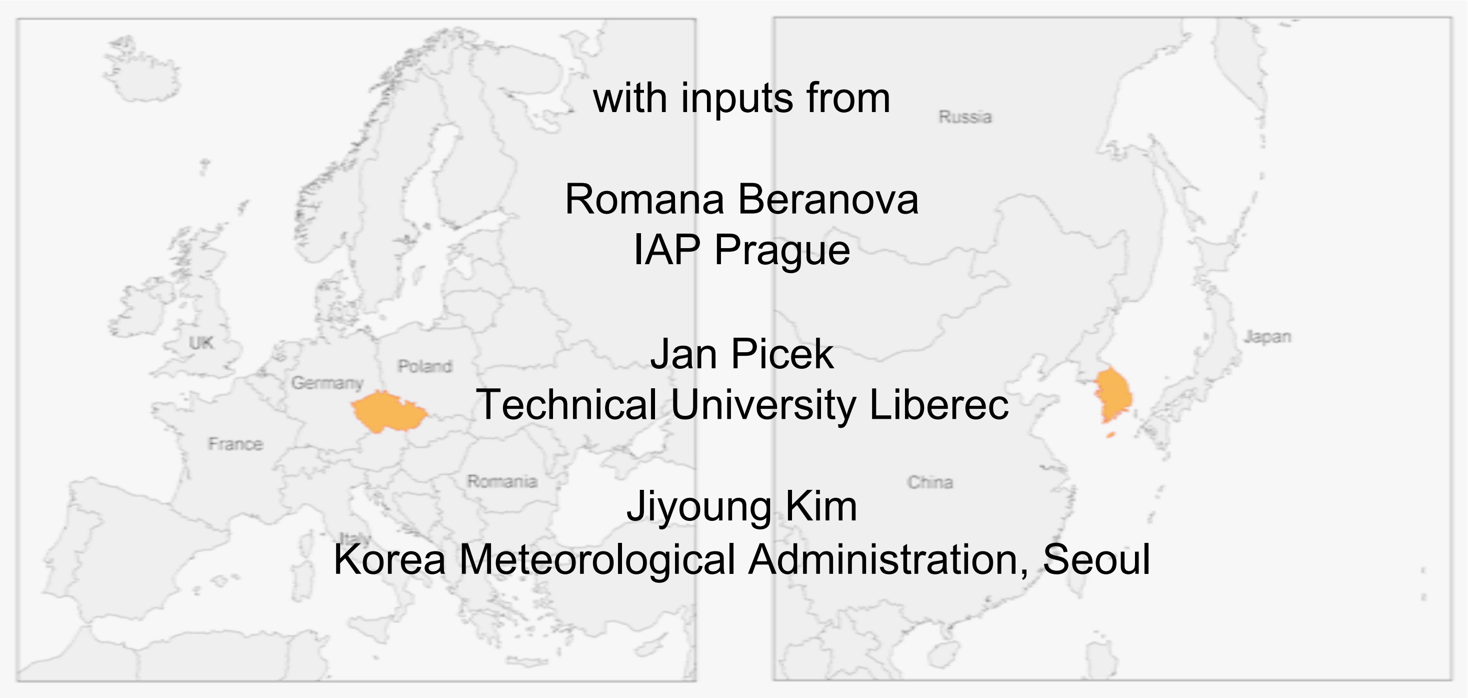
Estimating recurrence probabilities of severe heat waves in a changing climate

KYSELY Jan

Institute of Atmospheric Physics
Prague
Czech Republic

Estimating recurrence probabilities of severe heat waves in a changing climate

Jan Kysely
Institute of Atmospheric Physics, Prague, Czech Republic



with inputs from

Romana Beranova
IAP Prague

Jan Picek
Technical University Liberec

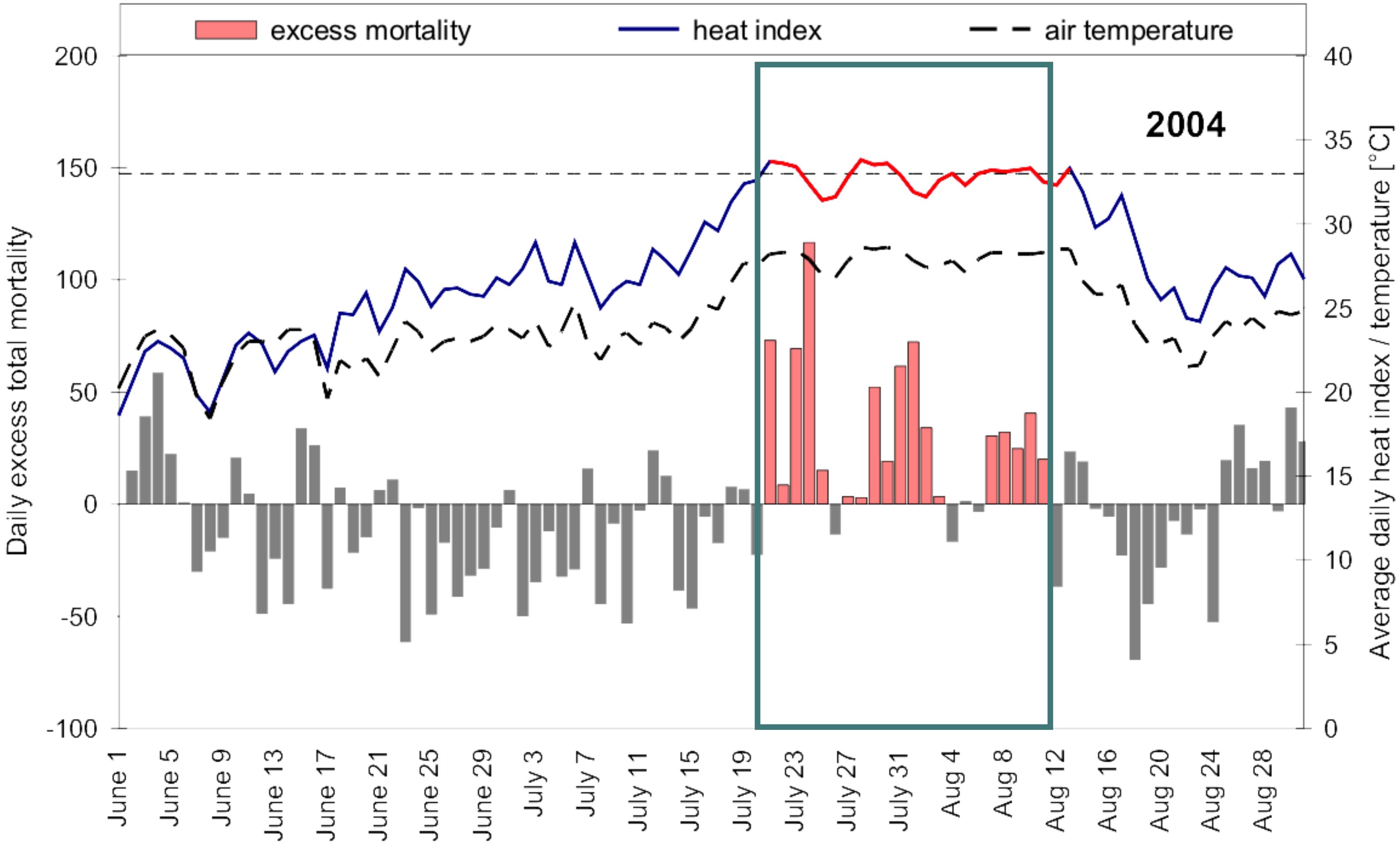
Jiyoung Kim
Korea Meteorological Administration, Seoul

Outline

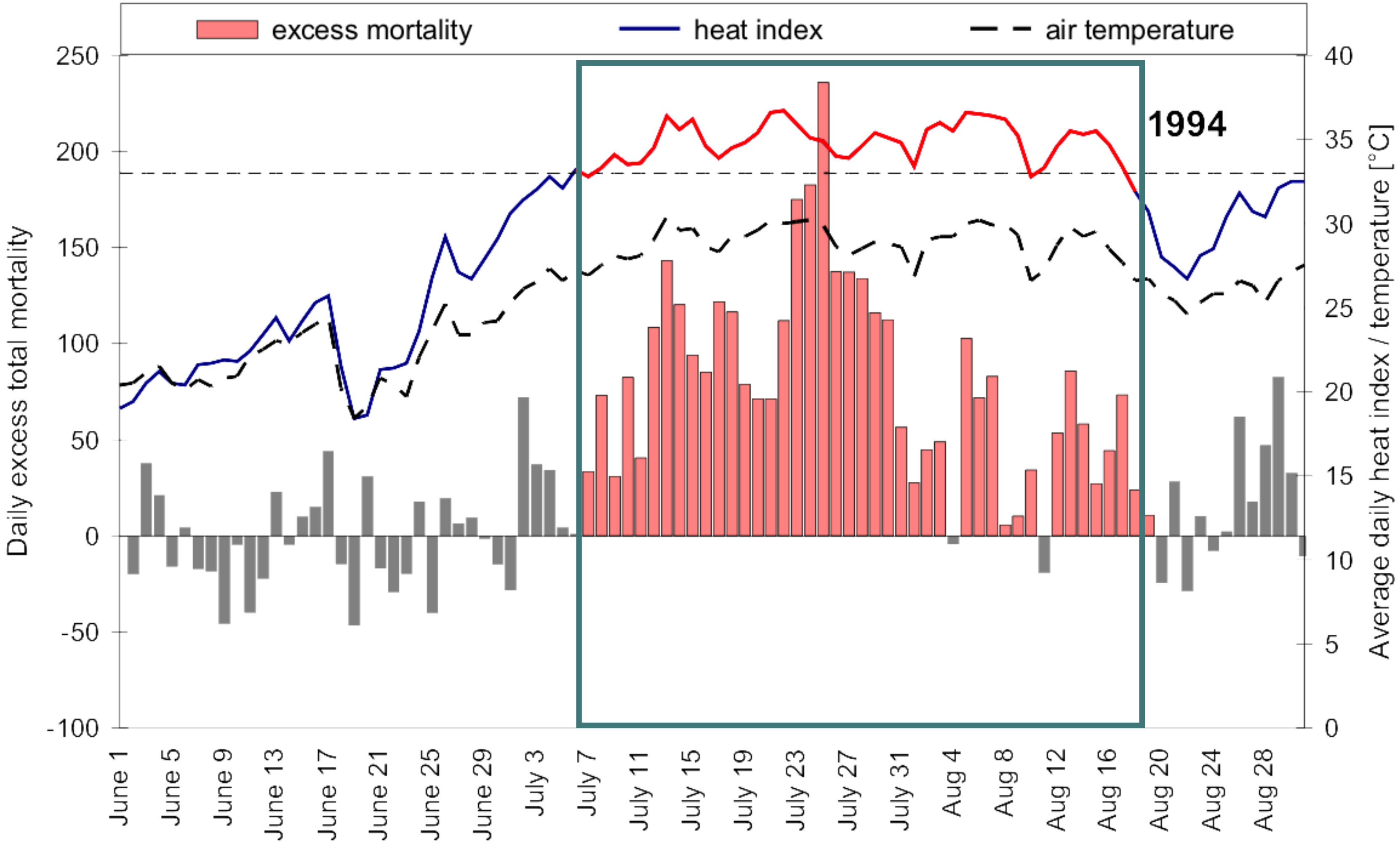
1. Motivation
2. Stochastic time series modelling
3. Model validation
4. Recurrence probabilities of heat waves in a non-stationary climate (climate change scenarios)
5. Conclusions

Regions under study:

central Europe (the 2006 heat wave) & east Asia (the 1994 heat wave)



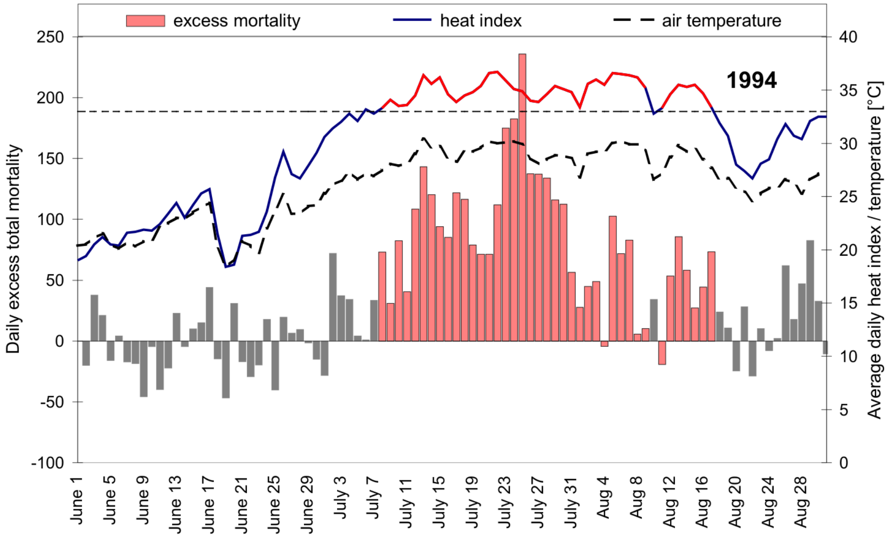
Air temperature, heat index and excess mortality in
summer 2004, South Korea



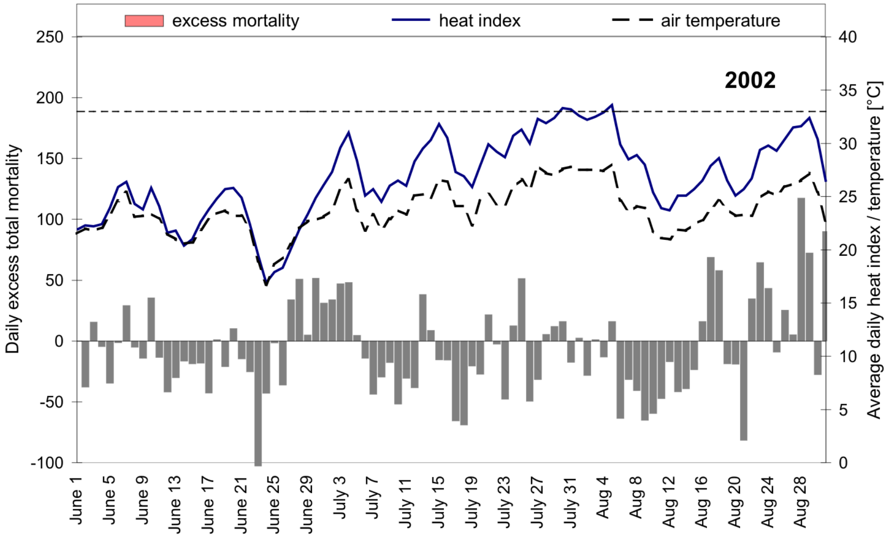
Air temperature, heat index and excess mortality in **summer 1994, South Korea**

>3000 excess deaths; excess mortality in all age groups

absence of efficient heat-watch-warning system (HWWS)



summer 1994



‘usual summer’ (2002)

Documented large natural disasters affecting Korean Peninsula since 1901

(Kysely and Kim 2009, Climate Research 38:105-116)

Year	Death toll	Event	Affected region over which death toll is given
1994	3384	Heat waves	South Korea
1936	1104	Typhoon	South and North Korea
2006	844	Flooding	North Korea
1959	768	Typhoon Sarah	South Korea and Japan
1972	672	Seoul, Kyonggi flood	South Korea
2007	610	Flooding	North Korea
1969	408	Gyeongsangbukdo, Gyeongsangnamdo, Gangwon flood and landslides	South Korea
1987	345	Chungchongnamdo, Chollanamdo, Kangwon flood and landslides	South Korea
1998	324	Massive rain, floods and landslides	South Korea
2002	246	Typhoon Rusa	South Korea

~3400 excess deaths represent net excess mortality as no mortality displacement effect appeared after the heat waves

Temperature extremes in GCMs

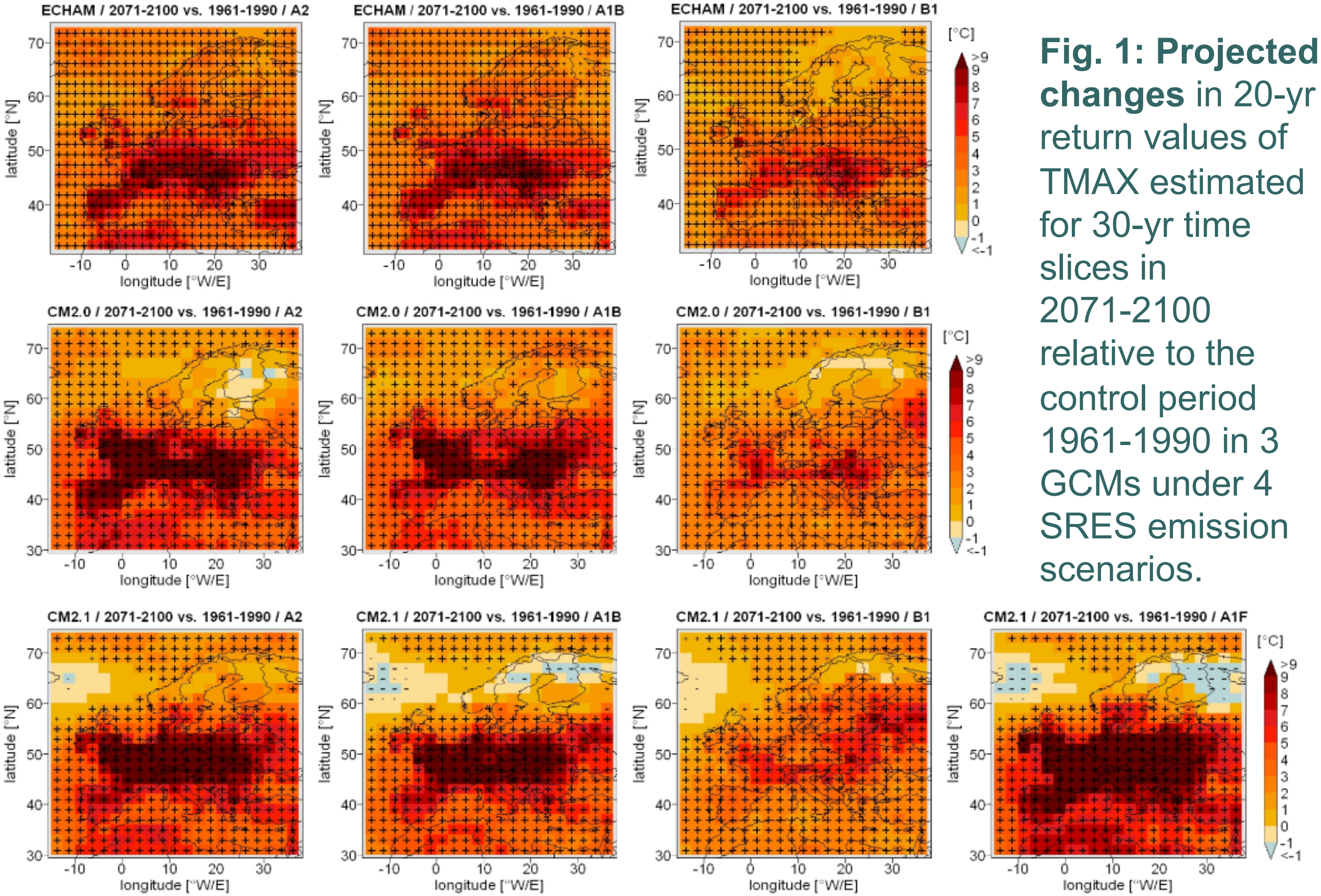
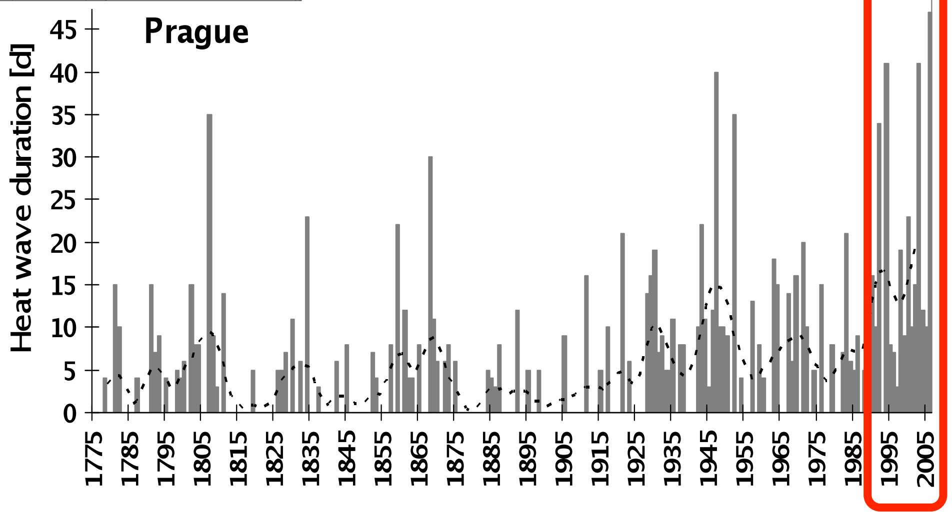


Fig. 1: Projected changes in 20-yr return values of TMAX estimated for 30-yr time slices in 2071-2100 relative to the control period 1961-1990 in 3 GCMs under 4 SRES emission scenarios.

Kysely et al., Global and Planetary Change 2010

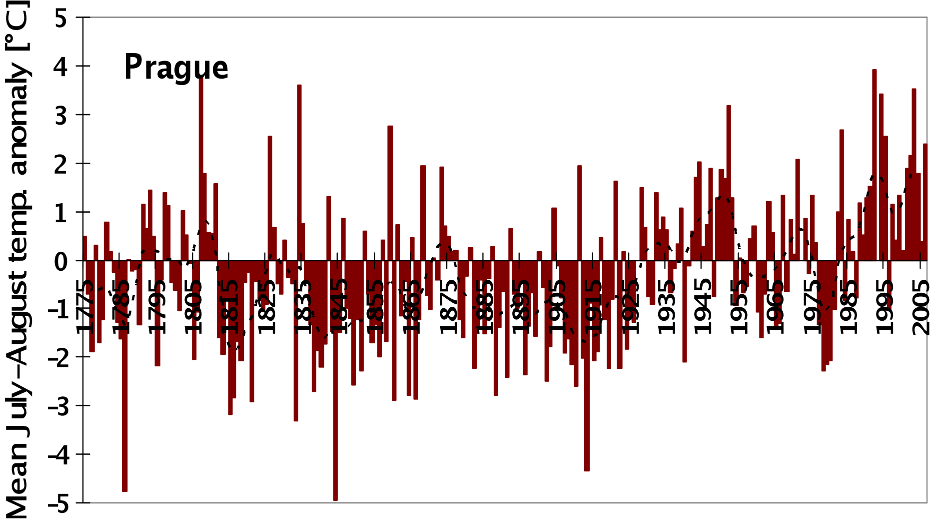
Heat waves in long-term temperature series



summers with the most severe heat waves cluster in the 1990s and 2000s

2006 – the longest heat wave in Prague since 1775 (33 consecutive days) – how likely is a recurrence?

July 2006 – the warmest month on record in several European countries, including Germany, Belgium, the Netherlands and the UK



Central Europe

East Asia

the 2006 heat wave

the 1994 heat wave

How to view the recent severe heat waves in the “climate change perspective”?

Stochastic time series modelling

- Stochastic model – replicates basic features of the temporal structure of daily temperature series
- Large number of “realizations” of recent/future climate → allows for estimating probabilities of heat waves
- Advantageous in studying spells of extremes (heat waves)
- First-order autoregressive model AR(1); the order of the model determined by a test on autoregression rank scores (Hallin et al. 1997)
- Seasonal cycle & long-term trend considered as deterministic parts → deviations from the deterministic part simulated by the AR(1) model as the stochastic component

Stochastic time series modelling

- The AR(1) model is based on 3 parameters of TMAX series, the mean ($\mu(t)$), the variance ($\sigma^2(t)$) and the first-order autocorrelation coefficient ($\Phi(t)$)

- Recursion formula

  $\mathrm{TMAX}(t) = \mu(t) + \Phi(t)\,(\mathrm{TMAX}(t\text{-}1) - \mu(t\text{-}1)) + \varepsilon(t)$

  seasonal cycles in all 3 parameters and a long-term trend in the mean considered explicitly (the deterministic part)

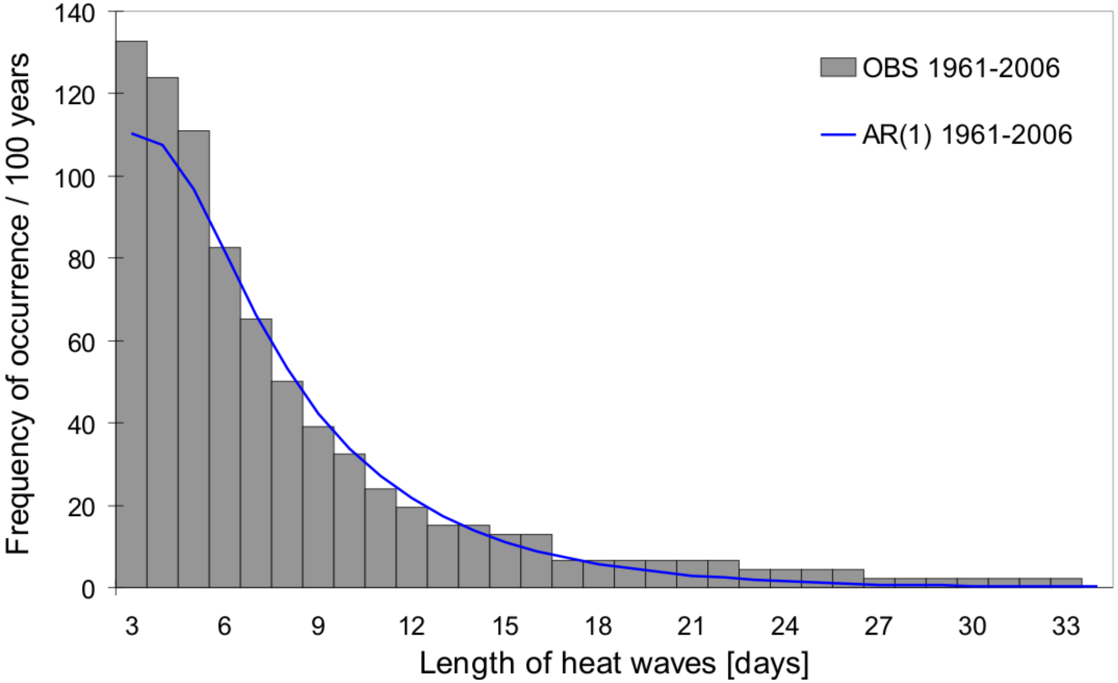
  $\varepsilon(t)$ generated for each day from $N(\mu(t), \sigma_\varepsilon^2(t))$ distribution where the variance of $\varepsilon(t)$ is $\sigma_\varepsilon^2(t) = (1-\Phi^2(t))\sigma^2(t)$

- The model parameters estimated from detrended observed data over 1961-2006

  More detail on the AR(1) model in Kysely 2010, Int. J. of Climatology 30:89-109

Validation of the stochastic model

- The AR(1) model validated with respect to the simulation of heat waves in recent climate
- 100 000 artificial series of TMAX corresponding to 1961-2006 in Prague



→ The model provides characteristics of heat waves and temperature threshold exceedances that are in a good agreement with observations

Fig. 3: Cumulative frequency of heat waves lasting x days in observed and AR(1)-simulated data in 1961-2006.

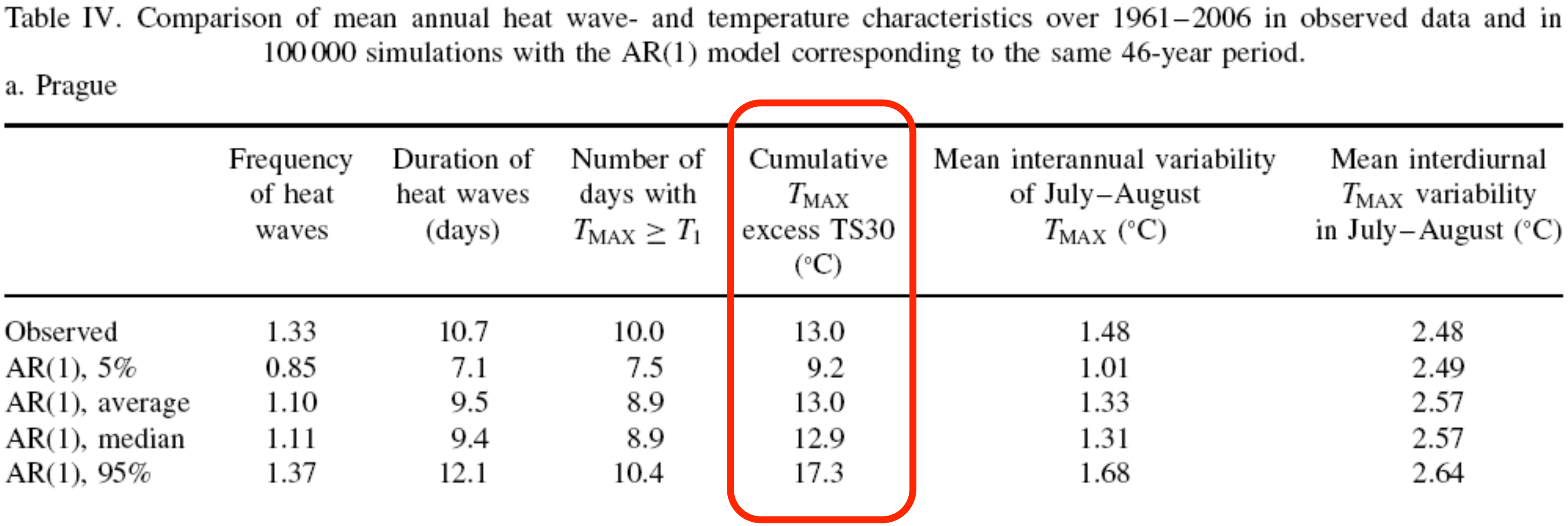


Table IV. Comparison of mean annual heat wave- and temperature characteristics over 1961–2006 in observed data and in 100 000 simulations with the AR(1) model corresponding to the same 46-year period.

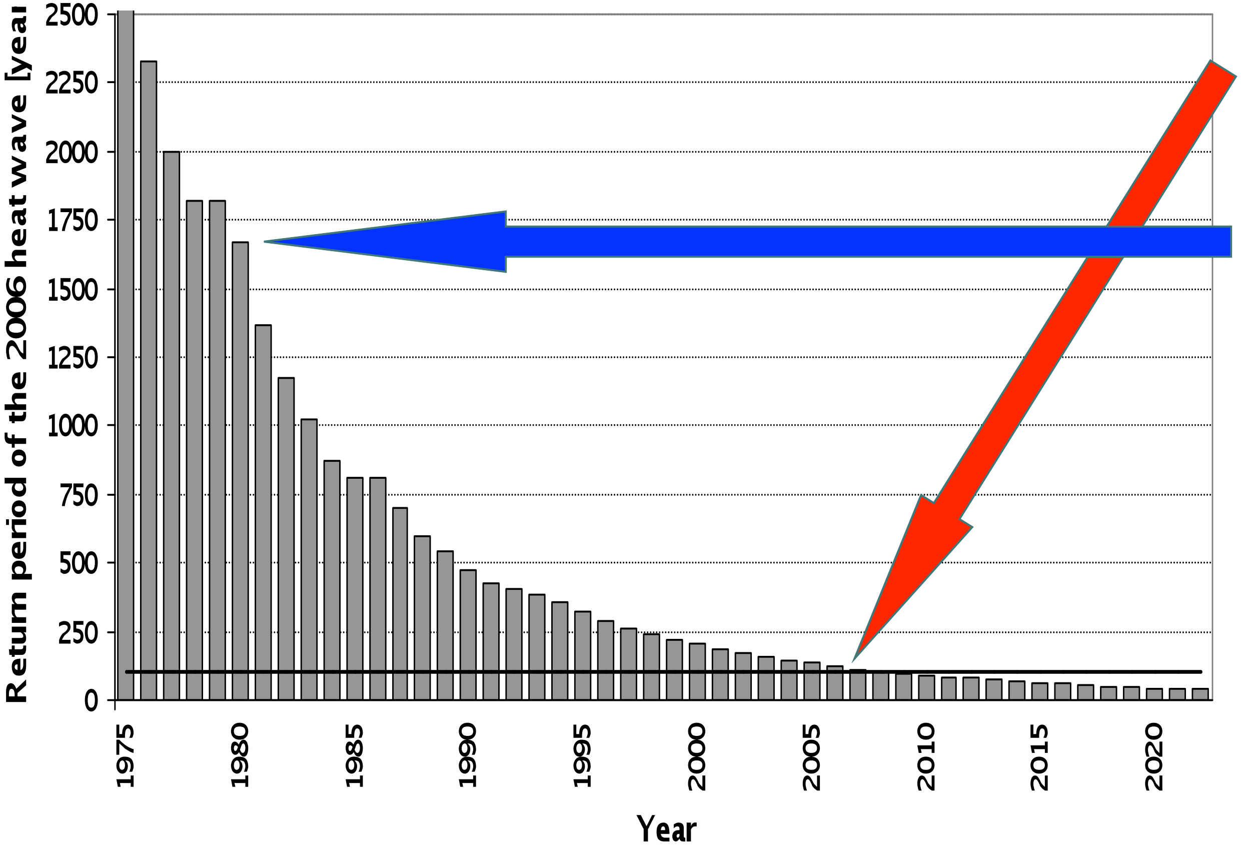
a. Prague

	Frequency of heat waves	Duration of heat waves (days)	Number of days with $T_{MAX} \geq T_1$	Cumulative T_{MAX} excess TS30 (°C)	Mean interannual variability of July–August T_{MAX} (°C)	Mean interdiurnal T_{MAX} variability in July–August (°C)
Observed	1.33	10.7	10.0	13.0	1.48	2.48
AR(1), 5%	0.85	7.1	7.5	9.2	1.01	2.49
AR(1), average	1.10	9.5	8.9	13.0	1.33	2.57
AR(1), median	1.11	9.4	8.9	12.9	1.31	2.57
AR(1), 95%	1.37	12.1	10.4	17.3	1.68	2.64

→ Good agreement for other heat wave characteristics as well, the observed values close to the AR(1) average and within the 90% CI

Probability of the 2006 heat wave

- Estimated return period from stochastic model simulations



in **2006**: ~120 years

sharply increases towards more distant past: ~1700 years in **1980**

(estimates of return period severely biased if based on the assumption of a stationary climate!)

Climate change simulations

- Recurrence probabilities estimated under several climate change scenarios
- Various rates of summer warming over 2007-2100 & change in variance
- Ensemble of 24 RCM simulations under SRES-A2 and SRES-B2 employed to estimate the possible late 21st century increase in mean July-August TMAX with respect to the reference 1961-1990 period; RCMs data taken from the PRUDENCE project database

SRES-A2: +5.7ºC (averaged over the RCM runs)
SRES-B2: +4.2ºC

[the projected warming large BUT the average scenario for the late 21st century (warming close to 5ºC relative to 1961-1990) consistent with the trend estimated over 1961-2006 (0.5ºC/decade) if extrapolated toward future]

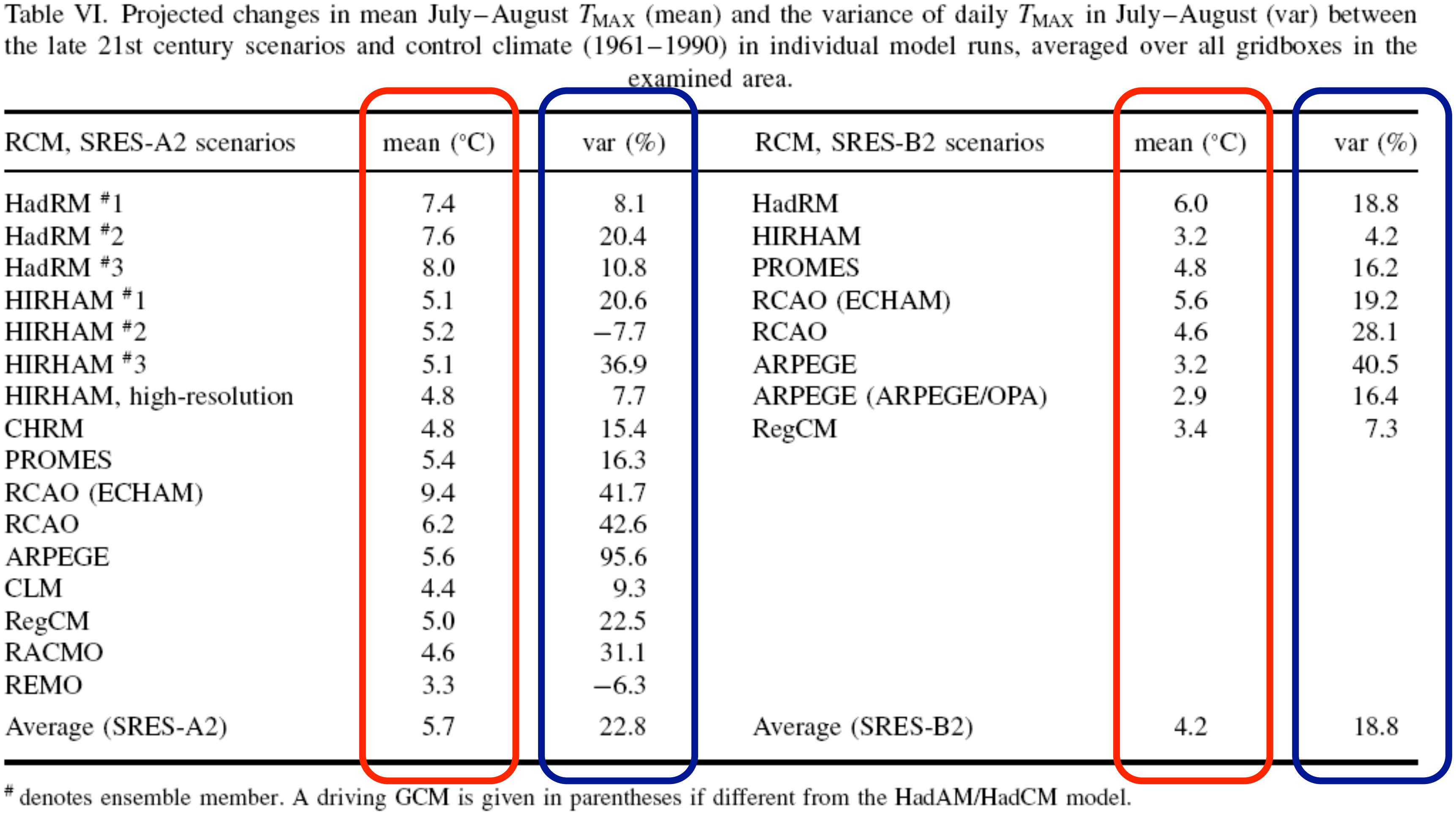


Table VI. Projected changes in mean July–August T_{MAX} (mean) and the variance of daily T_{MAX} in July–August (var) between the late 21st century scenarios and control climate (1961–1990) in individual model runs, averaged over all gridboxes in the examined area.

RCM, SRES-A2 scenarios	mean (°C)	var (%)	RCM, SRES-B2 scenarios	mean (°C)	var (%)
HadRM #1	7.4	8.1	HadRM	6.0	18.8
HadRM #2	7.6	20.4	HIRHAM	3.2	4.2
HadRM #3	8.0	10.8	PROMES	4.8	16.2
HIRHAM #1	5.1	20.6	RCAO (ECHAM)	5.6	19.2
HIRHAM #2	5.2	−7.7	RCAO	4.6	28.1
HIRHAM #3	5.1	36.9	ARPEGE	3.2	40.5
HIRHAM, high-resolution	4.8	7.7	ARPEGE (ARPEGE/OPA)	2.9	16.4
CHRM	4.8	15.4	RegCM	3.4	7.3
PROMES	5.4	16.3			
RCAO (ECHAM)	9.4	41.7			
RCAO	6.2	42.6			
ARPEGE	5.6	95.6			
CLM	4.4	9.3			
RegCM	5.0	22.5			
RACMO	4.6	31.1			
REMO	3.3	−6.3			
Average (SRES-A2)	5.7	22.8	Average (SRES-B2)	4.2	18.8

[#] denotes ensemble member. A driving GCM is given in parentheses if different from the HadAM/HadCM model.

Climate change simulations

- Estimates of return periods associated with extreme heat waves in a future climate based on the AR(1) simulations over 2007-2100, under 3 assumptions that differ in the rate of warming:

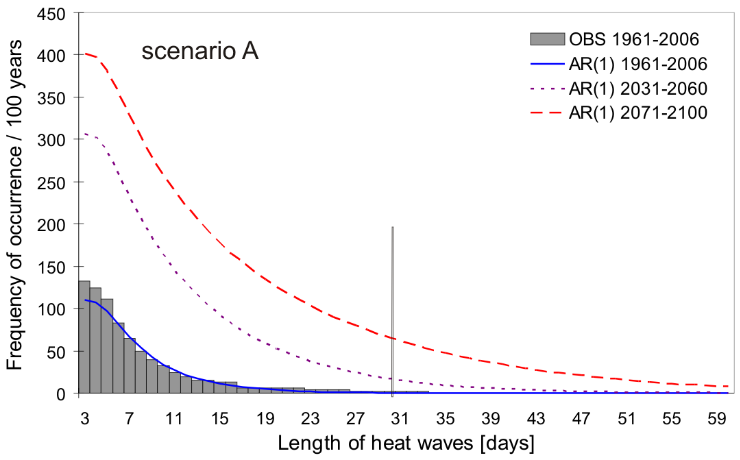
  A) warming of 0.5ºC/decade (mid-estimate, taking into account both emission scenarios and all RCMs);

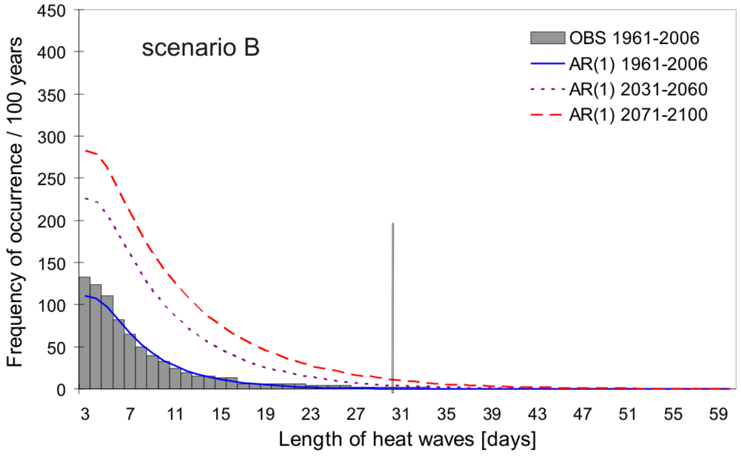
  B) warming of 0.2ºC/decade (represents lower bound of the uncertainty range);

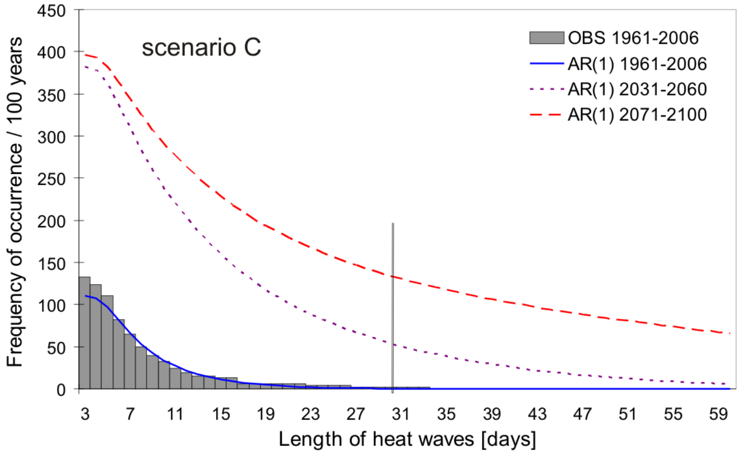
  C) warming of 0.9ºC/decade (upper bound).

Climate change simulations

- Since global warming is expected to be supplemented by a rise in interannual variability of summer temperatures, driven by a decline in spring and summer precipitation and a strong land-atmosphere coupling (Seneviratne *et al.*, 2006; Fischer *et al.*, 2007) → **additional scenario A-var** with a variance increase of 2.5%/decade over 2007-2100, combined with the mid-scenario of warming (0.5°C/decade)







scenario A – heat waves lasting >=33 days:

- mean annual frequency 0.54 in 2071-2100, 0.12 in 2031-2060

⇕

once in ~8 yrs

scenario B – heat waves lasting >=33 days:

- mean annual frequency only 0.07 in 2071-2100, 0.03 in 2031-2060

⇕

once in ~30 yrs

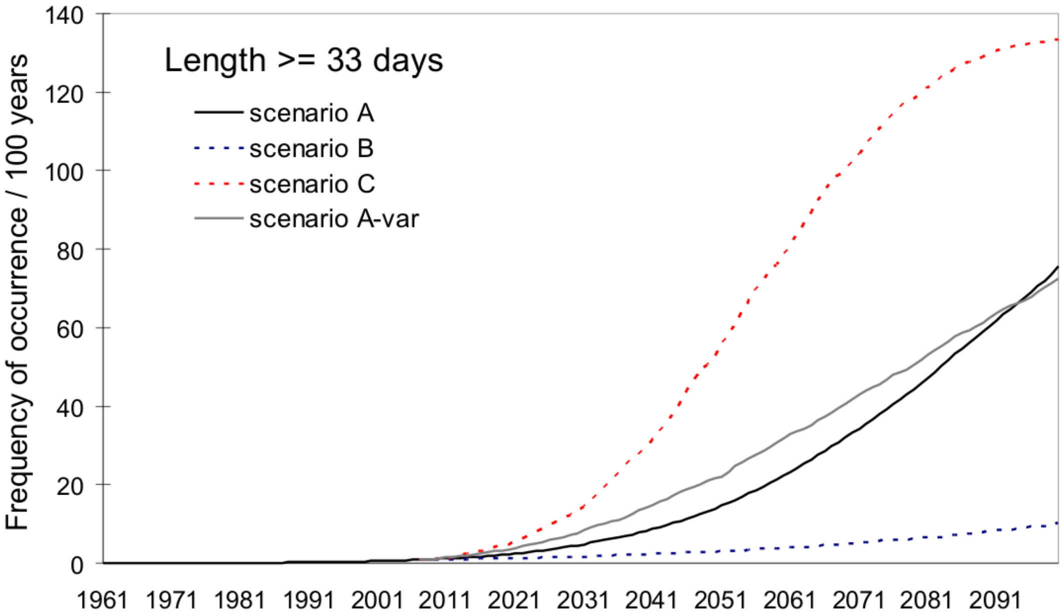
scenario C – heat waves lasting >=33 days:

- mean annual frequency 1.24 in 2071-2100, 0.44 in 2031-2060

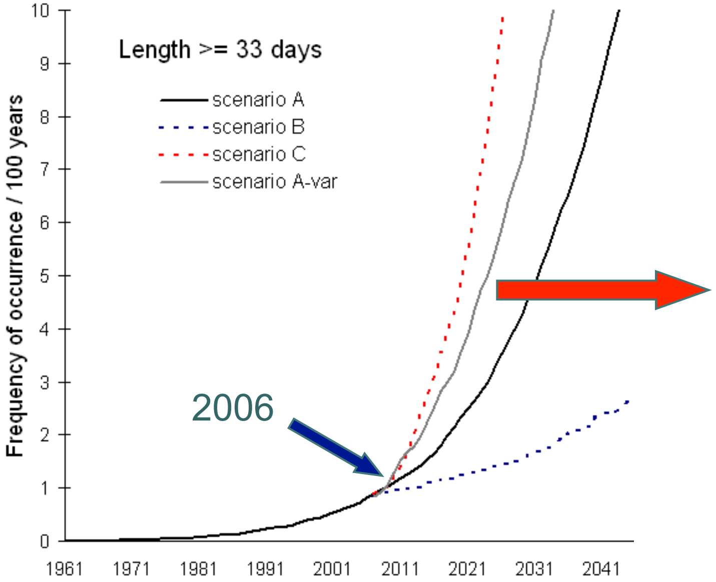
⇕

once in ~2-3 yrs

→ large dependence on the scenario & associated uncertainty

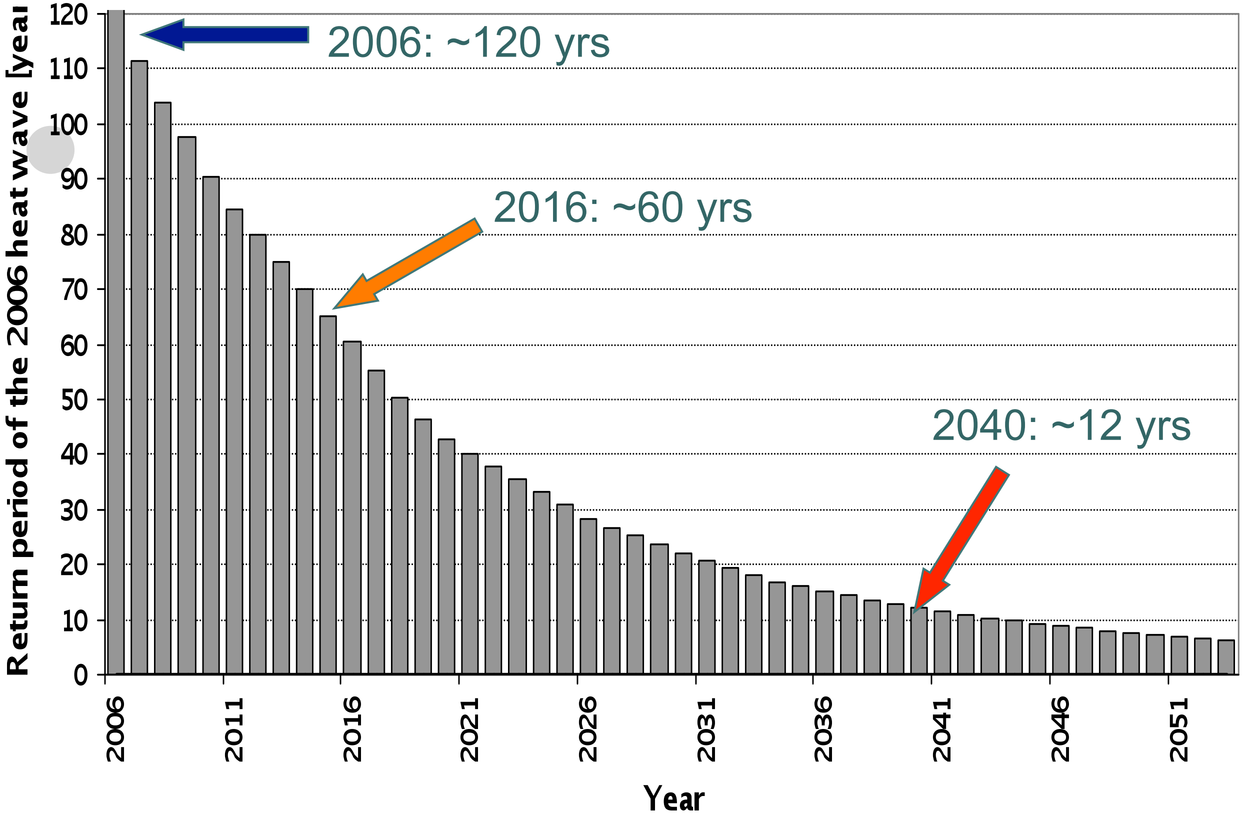


<u>Possible future changes</u> in probability of the 2006 heat wave:



→ large dependence on the scenario already for near future

variance increase (A-var) → substantial increase of probability of long heat waves in near future relative to scenario with the same warming but no change in variance (A)



2006: ~120 yrs

2016: ~60 yrs

2040: ~12 yrs

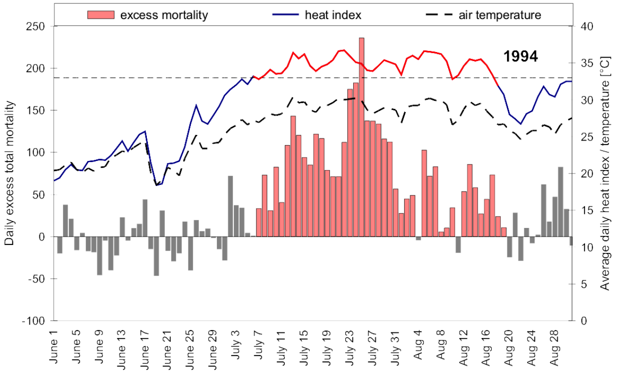
Mid-scenario A:

the return period declines by factor of 2 in **2016** compared to 2006, and by factor of 10 around **2040**

around **2070**: ~3 yrs

at the **end of the 21st century:** ~1.5 yrs

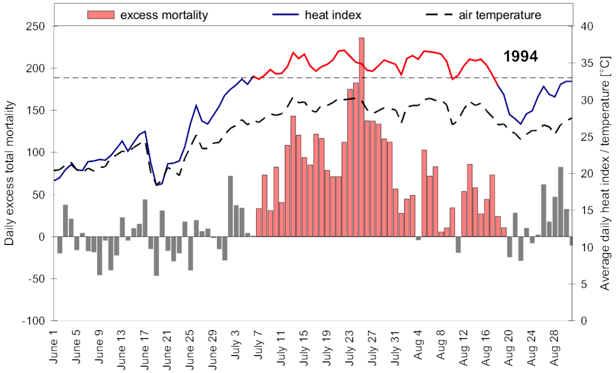
The 1994 heat wave in Korea



- <u>‘Present climate’ experiment:</u> parameters of the AR(1) model estimated from the mean temperature series for South Korea over 1971–2000; the AR(1) model used to generate artificial time series of TAVG corresponding to the reference period 1971–2000

- <u>‘Climate change scenario’ experiment:</u> warming of 0.4°C/decade over 2001–2060 assumed (a mid-scenario based on climate model projections); the other parameters of the AR(1) model kept unchanged in time

The 1994 heat wave in Korea



- Present climate simulations: the return period in the order of hundreds of years if stationarity of temperature time series is assumed

- Climate change simulations (warming of 0.4°C/decade over 2001–2060)

  → the return period estimated to decrease to around 40 (10) years in the 2021–2030 (2041–2050) decade

  → even a moderate warming would severely impact on the occurrence of extreme temperature events

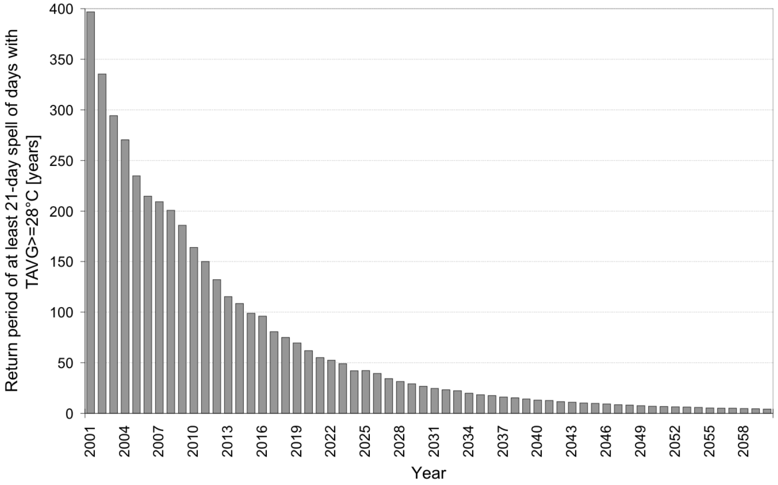


Fig. 5: Changes in the return period of at least 21-day spell with average daily temperature (TAVG) ≥ 28°C based on simulations with the AR(1) model assuming a warming trend of 0.04°C/year over 2001–2060.

Conclusions 1/2

- The AR(1) model captures the observed heat wave characteristics for the present climate
- Large uncertainty associated with recurrence probabilities of heat waves under a climate change arises from uncertainty of future climate development
- Return periods decline sharply even under a moderate warming trend
- Changes in variance of daily temperature may further increase probabilities of severe heat waves
- Mid-scenario warming of ~0.5°C/decade: the recurrence probability of the central-European heat wave of 2006 doubles in around 10 years and increases by an order of magnitude in around 30 years!

Conclusions 2/2

- Warming rate of ~0.5°C/decade typical of European summers over last few decades → return periods of severe heat waves have already decreased substantially

- Even the lower-bound scenario yields a considerable decline of return periods associated with intense heat waves

- BUT the most severe recent heat waves appear to be typical rather of a late 21st century than a mid-21st century climate

- The recently observed changes in summer temperatures & heat waves likely to be at least partly linked to human activities BUT natural climatic variability also important (links to Atlantic Multidecadal Oscillation [AMO]?)

- The methodology may be transferred to other regions in which temporal structure of daily temperature series is approximated by an autoregressive model, including the Mediterranean region

More detail in

Kyselý J., 2010: Recent severe heat waves in central Europe: how to view them in a long-term prospect? *International Journal of Climatology,* **30**, 89-109.