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Estimating extremes in climate change simulations using the peaks-over-threshold method with a non-stationary threshold

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ABSTRACT

The paper presents a methodology for estimating high quantiles of distributions of daily temperature in a non-stationary context, based on peaks-over-threshold analysis with a time-dependent threshold expressed in terms of regression quantiles. The extreme value models are applied to estimate 20-yr return values of maximum daily temperature over Europe in transient global climate model (GCM) simulations for the 21st century. A comparison of scenarios of changes in the 20-yr return temperatures based on the non-stationary peaks-over-threshold models with conventional stationary models is performed. It is demonstrated that the application of the stationary extreme value models in temperature data from GCM scenarios yields results that may be to a large extent biased, while the non-stationary models lead to spatial patterns that are robust and enable one to detect areas where the projected warming in the tail of the distribution of daily temperatures is largest. The method also allows splitting the projected warming of extremely high quantiles into two parts that reflect change in the location and scale of the distribution of extremes, respectively. Spatial patterns of the two components differ significantly in the examined climate change projections over Europe.

1. Introduction

Increasing frequencies and the severity of climatic extremes, including high summer temperatures (e.g. Frich et al., 2002; Klein Tank and Koennen, 2003; Moberg and Jones, 2005; Alexander et al., 2006; Della-Marta et al., 2007; Nicholls and Alexander, 2007; Alpert et al., 2008; Fang et al., 2008; Kyselý, 2008, 2010; Beniston, 2009), have revived questions on potential links between those anomalies and global anthropogenic climate change. The issue of changing probabilities of extremes is highly topical since extreme events are associated with major socio-economic consequences, and it has been well established that climate change may be perceived most through the impacts of extremes (IPCC, 2007). In developed countries, increased vulnerability of populations to the impacts of climatic extremes (in terms of increasing number of victims and material loss; also in relation to a larger density of people and assets located in areas with high risk of impacts) has been observed and studied in the recent past.

In Europe, the unusually hot and dry summer of 2003 (e.g. Beniston and Diaz, 2004; Trigo et al., 2005) was an example of such an event with pronounced negative effects on the environment, ecosystems and human society (Ciais et al., 2005; Kosatsky, 2005; Rebetez et al., 2006; Trigo et al., 2006). It was the warmest summer over large parts of Europe since at least 1500, and its exceptionality is illustrated by the fact that over a majority of the European continent mean temperature of June, July and August was more than 3 standard deviations higher than the long-term mean, exceeding 5 standard deviations in some areas (Schär et al., 2004). Record-breaking daily temperatures were reached at numerous locations throughout Europe.

Estimates of high quantiles of distributions of many meteorological variables (corresponding e.g. to 20-, 50- or 100-yr return values) are needed for practical purposes, including dimensioning of civil engineering works. In addition to the design value estimates themselves, it is also important to obtain measures of their accuracy and uncertainty as well as projections of how they may change in the future, for example due to climate change. The development of methods for estimating design values and recurrence probabilities of extreme events in a changing environment is therefore not only appealing from the theoretical point of view but also needed in practical applications.

The widely used statistical methods of extreme value analysis, based on either block maxima or peaks-over-threshold representation of extremes (e.g. Coles, 2001; Katz et al., 2002), assume stationarity of extreme values. Such assumption is often violated due to existing trends or long-term variability in the investigated series. This is also the case for climate model simulations with variable external forcings,

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originating, for example, from increasing greenhouse gas concentrations in the atmosphere.

One of the challenging ideas among recent advances in the field of statistical modeling has been the development of models for extreme events with time-dependent parameters (or more generally models incorporating covariates; Coles, 2001). Such models may be applied not only into the (non-stationary) observed data but also utilized in generating scenarios of their future changes using climate model outputs. The models enable estimating frequencies of extremes under conditions for which trends or long-term variability have been detected and/or where it is reasonable to assume that such trends or variability will continue into the future.

The non-stationary extreme value models have been used to investigate possible recent and/or future development of various climatic variables and events: Parisi and Lund (2000) studied the annual cycle of arrival times and return period properties of landfalling Atlantic Basin hurricanes over 1935–1998; Caires et al. (2006) analyzed significant wave heights and their projected return values estimated according to climate change scenarios up to the end of the 21st century; Bengtsson and Nilsson (2007) investigated a possible temporal trend of recorded storm damage in Swedish forests during 1965–2007; and Yiou et al. (2006) analyzed long-term trends of flood amplitudes and frequencies in two major rivers in central Europe.

Nevertheless, the majority of studies using non-stationary extreme value models have focused on temperature extremes. Kharin and Zwiers (2005) examined non-stationary distributions of annual maxima of daily temperatures (and precipitation amounts) in transient climate change simulations from the CGCM2 model; Nogaj et al. (2006) analyzed the temporal evolution of extreme events of high and low temperatures and their amplitude and frequency changes over the last 60 yr in the North Atlantic region; Parey et al. (2007) dealt with the development of non-stationary extreme value models of high temperatures for data observed at 47 stations in France over 1950–2003; Laurent and Parey (2007) estimated 100-yr return values of temperature in France in a non-stationary climate according to past observations and future climate change scenarios; and Abaurrea et al. (2007) analyzed the observed changes in summer maximum daily temperatures during 1951–2004 in the northeast of the Iberian Peninsula.

This paper deals with extreme value models with time-dependent parameters for the estimation of (time-dependent) high quantiles of maximum daily air temperatures in transient climate change simulations from global climate models (GCMs). We focus on methodological issues that have not been dealt with in sufficient detail, and we propose a framework for estimating distributions of extremes and return levels based on the peaks-over-threshold (POT) methodology adapted to a non-stationary case. The key features of the proposed models are (1) use of a time-dependent threshold in the POT analysis, modeled in terms of regression quantiles, and (2) selection of the optimum model for the dependence of parameters of the extreme value distribution on time according to likelihood ratio tests. The estimates based on the non-stationary extreme value models are compared with results of classical stationary POT models of temperature extremes in order to highlight errors that would result from application of the usual stationary extreme value models in data influenced by a long-term trend.

2. Data

Coupled atmosphere and ocean general circulation models (global climate models, GCMs) comprise the most frequently used tool in global climate modeling (IPCC, 2007). This study makes use of two GCMs, CM2.0 and CM2.1, outputs of which are available with daily resolution in the form of transient climate change simulations under increasing greenhouse gas concentrations according to SRES emission scenarios over 2001–2100.

CM2.0 and CM2.1 are coupled models of the NOAA Geophysical Fluid Dynamics Laboratory (GFDL). They have a horizontal resolution of 2.5 × 2.0° (longitude × latitude) and 24 vertical levels; the ocean model resolution is 1° in both latitude and longitude, with 50 vertical levels. The two models employ the same grid but differ in significant ways; for example, entirely different atmospheric dynamical cores are used. More details on the CM2.0 and CM2.1 models are given in Delworth et al. (2006). Knutson et al. (2006) dealt with a reproduction of basic climatological variables including surface air temperature in simulations over the 20th century in CM2.0 and CM2.1. Reichler and Kim (2008) estimated errors and uncertainties in the mean over 1979–1999 of many climate elements simulated by CM2.1. The CM2.1 model was also included in a group of five GCMs evaluated in detail by van Ulden and van Oldenborgh (2006) with respect to the reproduction of atmospheric circulation and relations between the circulation and surface air temperature in Europe.

The examined transient runs of the GCMs are summarized in Table 1. These involve the SRES A2, A1B and B1 emission scenarios for the 21st century, as well as the additional A1FI in the case of CM2.1.

The study deals with maximum daily air temperatures (TMAX) over Europe and the adjacent North Atlantic, i.e. a region extending approximately from 15°W to 40°E and 30° to 75°N. The number of gridpoints in the area is 462.

3. Methods

3.1. Methods of extreme value analysis

The most frequently used statistical approaches to estimating recurrence probabilities of extreme events are those based on modeling the tail of the distribution of the underlying variable (Coles, 2001). If the sample of extreme values is formed by maxima over each interval of a given length (e.g. one year), the method is known as “block maxima” and leads to the Generalized Extreme Value (GEV) distribution. However, if the whole time series of a variable that generates extremes is available, it is usually beneficial to involve all values exceeding a given high threshold (respecting a minimum distance between selected events so that their independence is preserved) into the analysis; the method is known as POT and leads to the Poisson process model for threshold exceedances and the Generalized Pareto distribution (GPD) for their magnitudes (see Appendix A for details). Both these classical methods assume

Table 1
Summary of the examined GCM simulations.

GCM	Run	Description	Period examined
CM2.0, 2.1	20C3M	The IPCC 20th Century experiment for years 1860–2000[a]	1961–1990
CM2.0, 2.1	A2	The IPCC SRES A2 experiment for years 2001–2100, initialized from the end of the 20C3M experiment	2001–2100
CM2.0, 2.1	A1B	The IPCC SRES A1B 720 ppm stabilization experiment for years 2001–2100, initialized from the end of the 20C3M experiment	2001–2100
CM2.0, 2.1	B1	The IPCC SRES B1 550 ppm stabilization experiment for years 2001–2100, initialized from the end of the 20C3M experiment	2001–2100
CM2.1	A1FI	Fossil fuel intensive SRES A1FI emission scenario experiment initialized from the end of the 20C3M experiment	2001–2100

[a] Several forcing agents varied during the experiment in a manner based upon observations and reconstructions for the late-19th and 20th centuries. The time-varying forcing agents were atmospheric CO_2, CH_4, N_2O, halons, tropospheric and stratospheric O_3, anthropogenic tropospheric sulfates, black and organic carbon, dust, sea salt, volcanic aerosols, solar irradiance, and the distribution of land cover types.