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Stochastic diffusion models to describe the evolution of annual heatwave statistics: A three-factor model with risk calculations

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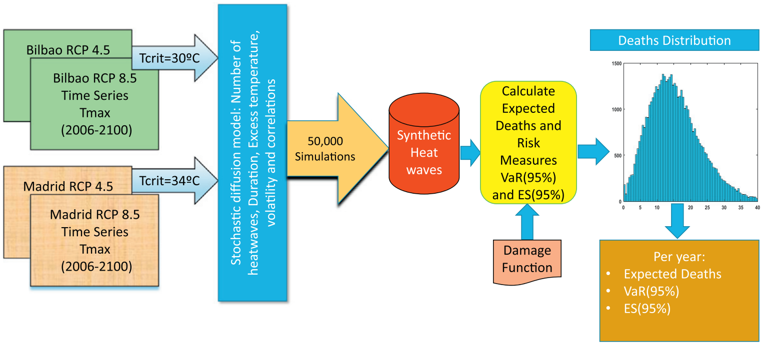
HIGHLIGHTS

- Probabilistic assessment of evolution of annual characteristics of heatwaves
- Stochastic diffusion models to represent annual statistics of heatwaves
- Long-term high-resolution time series contain information on stochasticity.
- Assessment of human health impacts from heatwaves in the context of climate change
- Risk metrics such as Value at Risk and Expected Shortfall are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

In view of risk assessments this paper proposes a stochastic diffusion model to characterise statistics of extreme events when climate- or environmental variables surpass critical thresholds. The proposed three-factor model captures trend and volatility of such statistics and could prove valuable for climate and environmental impact analysis in many systems such as human health, agriculture or ecology. The model supports decisions in view of lowering risks to acceptable levels.

We illustrate the development of the model for heatwave impacts on human health in the context of climate change. We propose a generic model composed of three random processes characterising annual statistics of heatwaves: a Poisson process characterising the number of heatwaves, a Gamma process characterising mean duration and a truncated Gaussian process capturing mean excess temperature of heatwave days. Additionally, potential correlations between the three processes are taken into account.

The model is calibrated with data obtained from a regional climate model for two cities in Spain. The suitability of the model for probabilistic analysis is tested with Monte Carlo simulations. We assess the time-dependent probability distributions of heatwave-related mortality and demonstrate how to obtain relevant risk metrics such as the 95th percentile and the average of the 5% of worst cases (ES (95%)).

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1. Introduction

1.1. Heatwaves

According to the World Health Organisation and the World Meteorological Organisation (WMO, 2015), heatwaves are among the most hazardous meteorological events, although in the past they have received far less attention than other apparently more spectacular and violent events such as floods, cyclones and hurricanes. Heatwaves can pose significant threats to human health, ecosystems and to energy-, water- and transport systems. They represent an important socio-economic problem. The Intergovernmental Panel on Climate Change, IPCC, warns of an increase in frequency, duration and magnitude of heatwaves in future decades (IPCC, 2012, 2013). The 2003 heatwave, which affected all of Europe, was presumably responsible for up to 70,000 deaths in 16 countries (Robine et al., 2008), and according to Stott et al. (2004), such severe heatwaves could become unexceptional events by 2040. Christidis et al. (2015) project a clear trend of increase in the frequency of heatwaves and a sharp reduction in the return period for the more extreme cases.

Mueller et al. (2016) found that the probability of hot summers is currently ten times higher compared to a scenario without climate change. Within the next two decades regions such as the Mediterranean, Western US, Canada, the Sahara and Southern Asia will start to be particularly affected by hot summers. The PESETA project estimated an increase in mortality between 1% and 4% for each degree Celsius increase in temperature in Europe, which would result in 30,000 additional deaths by 2030, and between 50,000 and 110,000 by 2080 (Paci, 2014).

Heatwaves are generally more serious in urban areas, due to the heat island effect, though rural areas are also susceptible to suffer severe impacts. Cities are especially vulnerable due to the urbanisation process leading to a gradual increase of the proportion of population living in urban areas.

Heatwaves typically occur when temperatures exceed thresholds according to climatologic or epidemiological criteria. Epidemiological thresholds depend on local climatic conditions and may be modified by other variables such as pollution or humidity and wind. The definition of a heatwave event depends on local climate and geographical conditions.

Perkins and Alexander (2013) argue that definitions for heatwaves are ambiguous and inconsistent and that in some cases it is high daytime temperatures that co-occur with high nocturnal temperatures or with high humidity that are critical. Windy conditions can also modify heat stress (WMO, 2015).

Areas that have not been at risk or at lower risk of extreme heat so far might become vulnerable in the future. In this context it becomes crucial to assess future hazards and the occurrence of high-impact events, in terms of intensity, duration and frequency. In view of proof of concept we consider here a single time series of maximum daytime temperature and look for a stochastic diffusion model that can characterise annual statistics of daily exceedances above a critical threshold temperature. Such a model could then be widely applied for assessing health impacts dependent on climatic- or epidemiological thresholds.

1.2. Stochastic diffusion models

For climate change impact- and adaptation assessments a good representation of the future evolution of relevant extreme events such as heatwaves is crucial. Such a representation should capture both evolution of trends and variability of its defining characteristics, as well as potential correlations.

Climatic variables, such as temperature, are typically available in the form of time series. These time series can stem either from observed historical observations or as outputs from climate models. In this context, stochastic models provide a means to capture generic information such as trends or variability of the number of annual heatwaves as well as related indicators such as duration and intensity. They allow summarising an entire time series through a model with calibrated parameters for deterministic and stochastic components. Such models can then be used to more easily compare time series from different origins (e.g. from different climate models). The calibrated model can be used for risk assessments, e.g. to compute risk metrics from probability distributions.

Stochastic diffusion models could be especially suited to estimate probability distributions of potential variables characterising heatwaves in terms of number of events, duration and intensity. A diffusion process is defined as a solution to a stochastic differential equation which generates a probabilistic distribution for each time t. A general introduction to such models can be found in Kloeden and Platen (1999) and in Dixit and Pindyck (1994). We can distinguish between discrete stochastic processes, where the variable takes on discrete values such as number of heatwaves per year and continuous processes in which the variable takes on values in a continuous range such as heatwave intensity.

Some authors have previously modelled heat wave characteristics using a Poisson process approach. Furrer et al. (2010) develop a model that considers the frequency modelled by a Poisson distribution, the duration as a geometric distribution and the intensity of heatwaves as a conditional generalized Pareto distribution. They calibrated the model with historical series of daily maximum temperature at three different stations. Wang et al. (2015) used the model of Furrer et al. (2010) to study heatwaves in China with information from the 30 Coupled Model Intercomparison Project Phase 5 (CIMP5) General Circulation Models (GCMs). Keellings and Waylen (2014) studied the maximum and minimum daily temperatures in Florida, considering the frequency, intensity, duration of heat waves. They used historical data from 1949 to 2000 to study the variability of heatwaves characteristics. They examined the changes in heat wave characteristics between two equal time periods. Abaurrea et al. (2007) analyse the summer maximum daily temperature in the Ebro river basing during the period 1951–2004; they calibrated a statistical model using a nonhomogeneous Poisson process and used it to obtain medium-term predictions of extreme heat events.

Our approach considers frequency of heatwaves, as well as their annual mean duration and the temperature exceedance on heatwave days. It allows for time-dependent changes in these characteristics caused by projected climate change of the 21st century. The model we propose with the three variables is a “mixed” model containing information on the evolution of annual statistics of heatwaves. It consists of two discrete processes (number of heatwaves per year and mean duration of heatwaves) and one continuous process (mean excess temperature of heatwave days). Previous applications with up to three variables have been conducted for continuous stochastic diffusion processes (Abadie et al., 2014). The approach allows for possible correlations among the three stochastic variables. Once calibrated, we demonstrate how to use the model for computing risk metrics of extreme events.

1.3. Risk metrics

After the model calibration, Monte Carlo simulations can be run in order to obtain annual distributions of the measures of interest: e.g. number of heatwaves as well as statistical properties such as the expected values and risk measures. We use risk measures with roots in financial engineering: Value at Risk (VaR) and Expected Shortfall (ES). They both characterise the risk properties of the probability density functions at a given percentile, e.g. the 95% level: