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Water temperature forecasting for Spanish rivers by means of nonlinear mixed models

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ABSTRACT

Study region: 43 rivers in Spain with measurement stations for air and water temperatures.
Study focus: River water temperatures influence aquatic ecosystem dynamics. This work aims to develop transferable river temperature forecasting models, which are not confined to sites with historical measurements of air and water temperatures. For that purpose, we estimate nonlinear mixed models (NLMM), which are based on site-specific time-series models and account for seasonality and S-shaped air-to-water temperature associations. A detailed evaluation of the short-term forecasting performance of both NLMM and site-specific models is undertaken. Measurements from 31 measurement sites were used to estimate model parameters whereas data from 12 additional sites were used solely for the evaluation of NLMM.
New hydrological insights for the region: Mixed models achieve levels of accuracy analogous to linear site-specific time-series regressions. Nonlinear site-specific models attain 1-day ahead forecasting accuracy close to 1 °C in terms of mean absolute error (MAE) and root mean square error (RMSE). Our results may facilitate adaptive management of freshwater resources in Spain in accordance with European water policy directives.

1. Introduction

In rivers, variations in water temperature influence processes across all levels of organization, from individual organisms to the ecosystem scale (Caissie, 2006). Temperature is associated with most physical and chemical properties of flowing waters and regulates interactions among the compartments that constitute a lotic ecosystem. For example, river water temperature impacts on dissolved oxygen concentration (Allan, 1995) and metabolic rates of various organisms (Brey, 2010). Furthermore it affects growth, emergence and survivorship of invertebrates, predator-prey encounter rates, interaction strengths (Rall et al., 2010), and the spatio-temporal patterns of invertebrate and fish assemblages (Gustafson, 2008).

Recent research has shown that some cold-water fishes are endangered by unsuitably warm temperatures in a way that further warming would result in net habitat loss (Isaak et al., 2010; Wenger et al., 2011). In addition, changes in thermal regimes present negative economic impacts in fisheries (Hague and Patterson, 2014). Understanding the dynamics

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of water temperatures in rivers and their association with climatic conditions, topography and human activities, will enhance prediction of thermal shifts and will facilitate management of freshwater biodiversity (IPCC, 2013) in accordance with water policy directives such as the European Water Framework Directive (Directive 2000/60/EC of the European Parliament).

During the last 20 years, researchers have developed a wide variety of short-term forecasting models for stream water temperatures. Models fall in two categories: (i) deterministic (Caissie et al., 2007; Benyahya et al., 2010), and (ii) statistical (Caissie et al., 1998; Caissie et al., 2001; Benyahya et al., 2007). Deterministic models quantify energy fluxes between the river and its surroundings (atmospheric and streambed) and calculate water temperature variability over specific time scales using a heat budget approach (Caissie, 2006). Once calibrated for a given region, such models can be applied to different areas only if the 'new' physical characteristics are known. However, the large amount of data necessary, and the time and expense required to their development, hinders their wide use (Benyahya et al., 2007).

Statistical models are simple, require fewer input data and can be widely applied, given that air temperature sampling stations are commonly available (Caissie et al., 1998; Caissie, 2006). Time-series models achieve short-term forecasting accuracy comparable to deterministic models (i.e., errors within 1–2 °C for daily time steps; Caissie, 2006). Moreover, such models have been used to forecast water temperatures in rivers based on meteorological scenarios derived from Global Climate Models (Stefan and Sinokrot, 1993; Mohseni et al., 2003; Mantua et al., 2010; Jeong et al., 2013). A drawback of the statistical approaches, emphasized by Caissie (2006), is lack of transferability: multiple site forecasts from statistical models are carried out independently and are confined to locations with available historical data on air and water temperatures.

This work aims to address the aforementioned drawback by examining the generalization capability of a new model class in river temperature forecasting, namely nonlinear mixed models (NLMM), in regions with insufficient data for site-specific models. The adopted methodology focuses on short-term forecasting and is not site-specific. The dynamics of water temperatures in a set of measurement sites are described by a general model with parameters that may depend on environmental and geographical factors such as maximum or minimum annual temperature and elevation. Guillemette et al. (2009) and Daigle et al. (2010) also presented models that collectively analyze river temperatures from multiple measurement sites. The abovementioned works were based on different statistical tools (kriging and multivariate regressions, respectively) relative to the ones presented herein, and provided forecasts at the monthly level.

Mixed models have been applied in a wide variety of disciplines; they are useful in settings where repeated measurements are made on the same statistical units. In this article, NLMM were based on nonlinear site-specific models, similar to the ones proposed by Mohseni et al. (1998), Caissie et al. (2001), Larnier et al. (2010) and Hague and Patterson, (2014). Prior to NLMM development, the short-term forecasting performance of alternative site-specific models was evaluated and the dependence of their parameters on environmental and geographical factors was examined. This research focuses on the Iberian Peninsula, a region with a high biodiversity threatened by climate change (Thuiller et al., 2011). Our analyses used daily measurements from 43 temperature stations, each station located at a different river.

2. Methods

2.1. Study area

The Iberian Peninsula is located between the Atlantic Ocean and the Mediterranean Sea, and bridges the African and European continents (Fig. 1). This unique position, combined with a complex orography, explains its important climatic diversity (MIMAM, 2004). In general, the northern Iberian Peninsula shows mild winters and summers with annual rainfall between 800 and 1500 mm, average temperatures of 9 °C in winter and 18 °C in summer. The southern part has mild winters and hot summers (annual rainfall between 250 and 600 mm and average temperatures of 11 °C in winter and 23 °C in summer), and the central areas experience cold winters and hot summers (annual rainfall typically above 400 mm and average temperatures of 4 °C in winter and 24 °C in summer). The region can be roughly divided into humid (>750 mm/year), dry (∼350–750 mm/year), and arid areas (<350 mm/year). The humid area is found in the north part of the peninsula and in high-elevation ranges. The dry area is the largest, including the Guadalquivir and Ebro depressions, both Central Plateaus and most part of the Mediterranean coast. The arid zone is relatively small and constrained to the southeast.

Iberian rivers can be grouped in those flowing into the Atlantic Ocean and those flowing into the Mediterranean Sea. Five out of the main eight rivers of Spain flow directly into the Atlantic Ocean (Miño, Duero, Tajo, Guadiana and Guadalquivir) whereas three flow into the Mediterranean Sea (Ebro, Júcar and Segura). The orography of the territory determines the length and characteristics of the rivers, with Atlantic rivers being longer than Mediterranean rivers (MIMAM, 2004). The latter are typically torrential and highly irregular in terms of flow. Rivers flowing to the Cantabric Sea (north of the Iberian Peninsula) are short but carry large amounts of water because of strong and frequent rainfalls. Water from the Pyrenees feeds the Ebro River in the northeast, whereas water from the Baetic Range feeds the Guadalquivir River in the south part of Spain. In summary, climatic, geological, geomorphological, lithological and historical diversity provide with heterogeneity and recognizable particularities the hydrography of Spain, which can be considered one of the most varied in Europe (MIMAM, 2004).