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Long-term forecasting of flow and water temperature for cooling systems: case study of the Rhone River, France

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Abstract Electricity production from nuclear power plants needs water intake for cooling systems. Due to climate change, an electricity producer such as EDF (Electricity de France), could be impacted by an increase of the air temperature, which may cause a problem to fulfilling legal environmental limits and/or safety limits. This will have direct consequences on electricity production capacity. Thus EDF is interested in the future evolution of water temperature and discharge for the rivers where its industrial sites are located. This paper presents a case study of the cross-boarder Rhone basin at Viviers (73 000 km^2, France). Long-term forecasting of the thermal and hydrological regimes of this river was established, starting from the modelled system and forced by observed climatic variables. The hydrological model coupled with a thermal model was calibrated and controlled with the historical data. The data set includes meteorological variables, discharge, and water temperature data from the last 35 years. The watershed is influenced by Lake Leman in the upstream part of the basin, and by the presence of several tributaries characterized by various hydrological regimes (from glacier-fed to rain-fed). Rhone River runoff is also influenced by glaciers in the headwaters and by reservoir management for hydroelectricity. All these characteristics have to be taken into account when extrapolating this model to other climate conditions. The selected future scenarios were run using results of six coupled regional models (RCM-GCM) by the European project ENSEMBLE.

Key words water temperature; rivers; air temperature; runoff; climate change; cooling sources; Rhone River, France

INTRODUCTION

For electricity production from nuclear power plants (NPP), Électricité de France (EDF) has to take water from rivers as a cooling source and to release warm water downstream. Heat waves may have a strong impact on this cooling process because thermal regulatory standards (maximum temperature of the river) can be exceeded with extreme water temperature. Supervising the future evolution of water temperature is crucial, especially in the context of climate change.

River water temperature is dependent of air temperature (Erdinger *et al.*, 1968; Gosse *et al.*, 2008) but also on discharge conditions (Gu *et al.*, 1998; Caissie *et al.*; 2006, Gooseef *et al.*; 2006, Gosse *et al.*, 2008). Air temperature controls a great part of the water temperature through heat exchange, and discharge acts as a factor in heat dilution and transport.

The global average air temperature is expected to increase by about 1–3ºC by the end of this century in response to an increase of greenhouse gases according to (IPCC, 2001). There is no consensus regarding the evolution of precipitation (GIEC, 2007). However some studies (Somot *et al.* (2008) and Giorgi (2008) indicate a high probability of precipitation reduction, especially in the winter season for temperate latitudes like the middle part of Europe. This could lead to a decrease in runoff. These climate changes will influence the thermal regime of rivers.

The objective of this study is to investigate the evolution of the thermal regime of the Rhone River under climate change. The analysis of future river water temperature requires both a hydrological model (rainfall–runoff model) and a thermal model. This paper presents the development of a complete model of the Rhone River watershed (Viviers gauging station, 70 900 km^2), which consist of three types of thermal models and nine embedded rainfall–runoff models. Then, these models are extrapolated to future climate using GCM (Global Circulation Model) outputs to estimate the impact on runoff and thermal modes.

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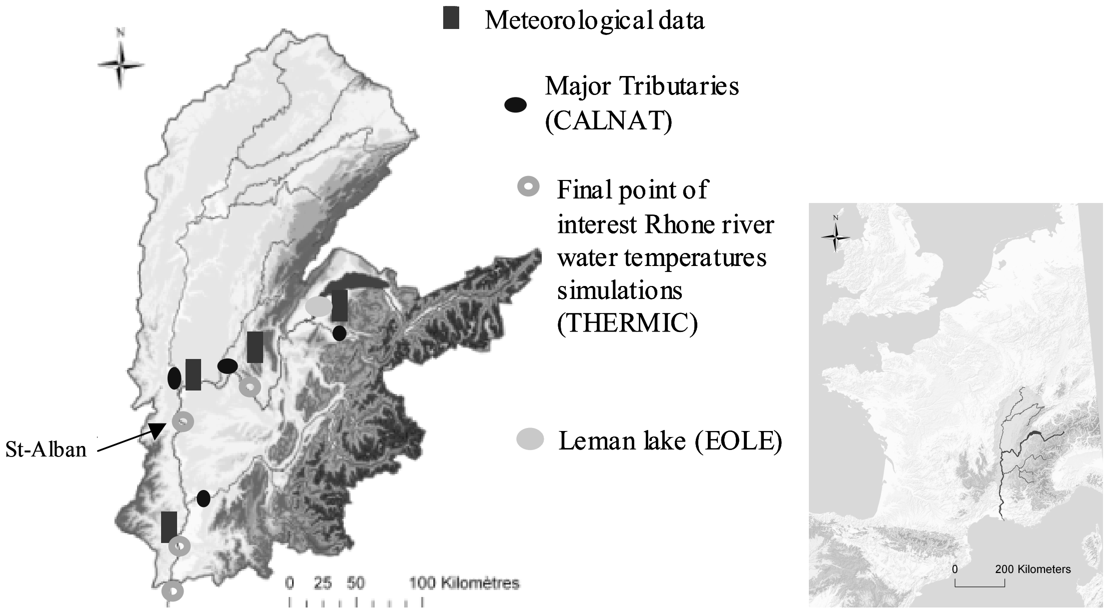

Fig. 1 Location of the case study (Rhône at Viviers) and location of points final of interest for water temperature simulations (equivalent of upstream NPP position) and location of meteorological data.

STUDY AREA

The Rhone River watershed at Viviers station covers an area of 70 900 km^2 (Fig. 1) and contains four NPP, which produce 23% of French electricity. The locations of these four NPP are the major points of interest for water temperature evolution.

The watershed contains a major part of the French and Swiss Alps, a lower mountain area and large plains. A large range in hydrological regimes occurs along the Rhone River and on its four major tributaries (from glacier-dominated to rain-dominated regimes). The presence of lakes, reservoirs and their management, especially Lake Leman (volume of 89 km^3), influence the thermal and hydrological regime of the Rhone River. A thermal regime specific for this river, downstream of Lake Leman, is due to the propagation and transfer of upstream water temperature anomalies (with attenuation) because of large depths and velocities in the streambed (Khalanski *et al.*, 2008).

MODELLING METHODOLOGY

The first step of this study consists of building the model in the present climate (with observed meteorological data) and fitting the model with observed flow and water temperature data. For better robustness, our tool has to take into account the major characteristics of this river that can influence the thermal and hydrological regime. We use a combination of different types of thermal models and an embedded rainfall–runoff model. All model parameters are calibrated with a split-sample test schema (for climatic transferability) (Xu, 1999) for the period from 1980 to 2004, using the Nash efficiency criterion.

Rainfall–runoff model

The rainfall-runoff model used here is a version that derives from the daily time-step CEQUEAU model (Charbonneau *et al.*, 1977). According to the type of hydrological regime, the Rhone basin model was divided into 12 distributed sub-models (for intermediate basins) CEQUEAU with 10 × 10 km grids. Therefore 12 vectors of 26 parameters were optimized (one for each basin). A specific glacier routine was integrated into the CEQUEAU scheme. The snow and glacier routine is a degree day approach. For basins with a large influence due to hydroelectricity, a reservoir management model based on dynamic programming was implemented to simulate reservoir operation (Yeh, 1985).

Thermal models

Three types of deterministic thermal models were used for water temperature simulation. The Lake Leman outlet is the upstream condition and the four major tributaries of the Rhone downstream of the Lake Leman set the boundary conditions. The simulated outflow is mixed with Rhone River runoff at the confluence and propagated. The CALNAT (Gosse, 2008) model is used for the tributaries and EOLE (Salençon, 1994) for the simulated Lake Leman outlet. Another tool, called TRACER-THERMIC, was added for water temperature propagation along the streambed of the Rhone. This last model uses the upstream simulated water temperature and runoff as inputs.

The water temperature of a river like the Rhone depends mainly on the local meteorology, and on its hydrological regime (runoff), which influence its hydraulic characteristic (width, velocity). The TRACER-THERMIC model is based on the simple approach of a 1-D transport/diffusion equation:

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}=D_L\frac{\partial^2 T}{\partial x^2}+\frac{\Phi_a}{\rho c_p H} \tag{1}$$

where T is water temperature (°C); t is time step on the x axis; c_p is specific heat of water (J kg^{-1} K^{-1}; Φ_a is flux heat exchange with the atmosphere (W m^{-2}); D_L is longitudinal dispersion coefficient; U is flow velocity (m s^{-1}); h is water depth (m); and P is water density (kg m^{-3}).

The atmospheric parameters were obtained from the meteorological data set and spatio-temporal coordinates for terms that depend on solar radiation. The cross-section parameters U and H were calculated from the stage–discharge relations.

For the water temperature simulation at the boundary conditions (tributaries), the concept of equilibrium temperature was used. A wide and shallow river can be conceptually assimilated as a homogeneous lake. This conceptualised lake exchanges energy with the atmosphere without additional inputs, nor significant exchanges with the bottom (Edinger *et al.*, 1968). Thus, considering a steady state, the water temperature variation along the river can be neglected from temporal evolution. Thus, the water temperature evolves only according to the atmospheric weather conditions and water depth. With this concept, the CALNAT model was used as a 0-D approach (as a simplification of the 1-D equation):

$$\frac{\partial T}{\partial t}=\frac{\Phi_a}{\rho c_p H} \tag{2}$$

For the water temperature simulation of the Lake Leman outlet, a vertical 1-D thermal model (EOLE) was used. EOLE simulates the thermal stratification of the lake. A conceptual model was used to simulate upwelling (cool water coming up from the bottom of the lake) depending on the direction and intensity of the wind. Also, the thermal model had to operate at a less than daily time step because water temperature varies diurnally, synchronously with air temperature. Consequently, the meteorological data needed to be at the same time step.

Simulations of the NPPs thermal effluent are included in the model because of thermal propagation along the Rhone River. This tool mimics the thermal effluent of each NPP as a function of the power output of reactors and legal limits, with the upstream streamflow and water temperature used as input data.

DATA SET

Observed data used

For correct calibration of the models, long-term data sets reflecting varying climate conditions were needed. The hydrological model inputs precipitation and air temperature (min/max; for snow and glacier routines and ETP) at a daily time step. For the calibration, runoff at a daily time step is necessary at the outlet of each embedded model. These daily data were available since 1969 from the EDF and Meteo France networks.

For the thermal model, a 3-hour time step was used. Data inputs are the following: runoff (the outlet of the rainfall–runoff model) and meteorological data (from four stations, Fig. 1): air temperature, humidity, air-pressure and cloud cover. Water temperature upstream of NPPs and the major tributaries have been measured by EDF at a 3-hour time step since 1977. Historical data from the outlet of Leman Lake were available from the OFEV website since 1981 http://www.hydrodaten.admin.ch/e/index.htm.

Future climate data set and downscaling method

The future climate is estimated from meteorological output from Global Circulation Model (GCM) with downscaling methods to adapt the GCM output to our models. For this, the information derived from coupled Regional Circulation Model (RCM)-GCM model was used. The spatial resolution of the RCM was appropriate to our model (25 km^2). But using the RCM, the difficulty of simulating the present state accurately and precisely is problematic, especially for precipitation (Frei, 2006). In addition, the results are not very reliable at a time scale of less than a month (Prudhomme, 2002). Consequently, the RCM-GCM results could not be used directly. Thus, an indirect method was used to calculate the changes between past climate and future climate. Moreover, it is recommended that several models be used to account for some of the uncertainty (Déqué, 2005).

The current objectives are to evaluate the sensitivity of the system on longer time scales, i.e. monthly and inter-annual, than at the model time step for the next century. A very simple method was established from five coupled RCM-GCM of the European ENSEMBLE project (Van der Linden & Mitchell, 2009) (Table 1). Data were extracted for three distinct periods, including the 2030s (2015–2045), the 2050s (2035–2065) and the 2085s (2070–2100) for the evaluation of trends. From these climate simulations, stationary tri-decadal monthly mean temperature and precipitation changes (and other climatic variables necessary for the thermal model) were calculated between the simulation period and the data reference period (1981–2004). These changes were used to create inferred conditions for the three future periods.

Table 1 Description and origin of the five couples of GCM_RCM used.

Institute	DMI	KMNI	MPI	SMHI	SMHI
Scenario	A1B	A1B	A1B	A1B	A1B
GCM	ARPEGE	ECHAM5-r3	ECHAM5-r3	BCM	ECHAM5-r3
RCM	HIRHAM	RACMO	REMO	RCA	RCA
Spatial scale	25 km	25 km	25 km	25 km	25 km
On charts	DMI-ARPEGE	KMNI-RACMO	MPI-ECHAM5	SMHI-BCM	SMHI-ECHAM5

MODELLING AND ANALYSIS

The rainfall–runoff model was run for each of the 12 sub-basins, after CALNAT and EOLE had been run for the boundary and upstream conditions. Finally, TRACER-THERMIC propagated water temperature and runoff, which were mixed at the outlets of major tributaries.

Due to the scope of this paper, only the thermal model results are discussed. Outputs of the rainfall–runoff models were acceptable compared to the observed data, but are not discussed here.

Results from observed climate

After calibration, the thermal model was validated against observed climate. This validation is fundamental for the confidence that we could expect in the future simulations. An acceptable relationship between observed and simulated water temperature simulation was noticed for all simulations of this case study (Nash Criterion from 0.80 to 0.95 for a validation period 1995–2004). To illustrate the results, one point of application of the thermal models is represented, i.e. upstream of St Alban NPP (Fig. 1) because the site is far enough downstream to evaluate each of the thermal models (and indirectly the rainfall–runoff models). The results are illustrated in Fig. 2 (left) for the warmest year of the validation period (2003).

In the thermal regime (the aggregation of 3-hour time step data to the monthly data), good model results were observed and especially for warmer periods during summer (the period of interest). The large difference in summer temperature between the two stations is also shown for the associated models in Fig. 2 (right).

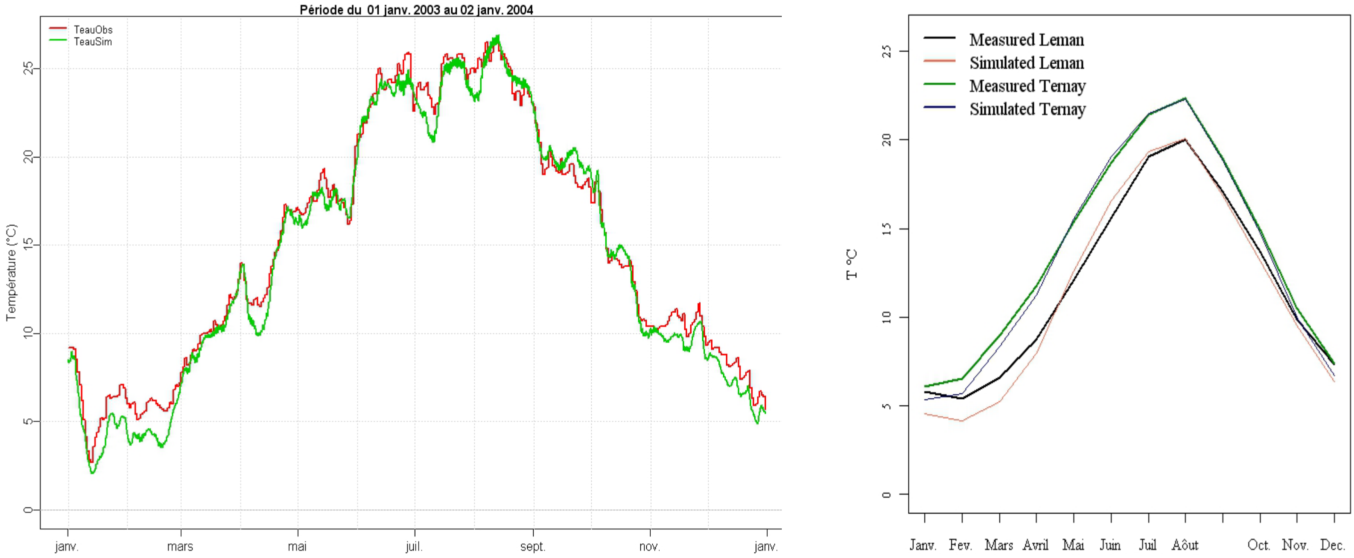

Fig. 2 (left) Three-hour observed (black) and simulated (grey) outlet water temperatures upstream of the St Alban station. (right) Monthly mean of simulated and observed outlet water temperatures of Leman Lake and the St Alban stations.

Future thermal modes of the Rhone River

Because of limitations in our downscaling methods, the results for long-term changes of water temperature were estimated only using monthly mean water temperature. For all of the periods analysed and all climate models used, water temperature was predicted to increase during summer. For the 2030s, all climate models indicate a slight temperature increase (<1°C) during summer. But starting in 2050 (except SHMI-BCM), the predicted increase is larger (+1.5°C) than in 2030, and water temperature increases could also appear during winter. The predicted water temperature increase is highest in the third period (+2.5°C to +3°C during summer, especially in August). It is interesting to notice that all climate models show maximum changes during summer, except SMHI-BCM where the changes were consistently smaller than for the other models. The DMI-ARPEGE climate model predicted the most significant warming. The results are illustrated for the St Alban station in Fig. 3. All other points of interest of the thermal model show the same tendencies and the same intensity for the thermal regime change. However, the results for runoff changes are highly heterogeneous among the climate models, except for low flows during August. The water temperature scenarios are highly correlated with the air temperature scenarios from the climate models (see example in Fig. 4 for St Alban station and the closest meteorological station) than the long-term flow scenarios.

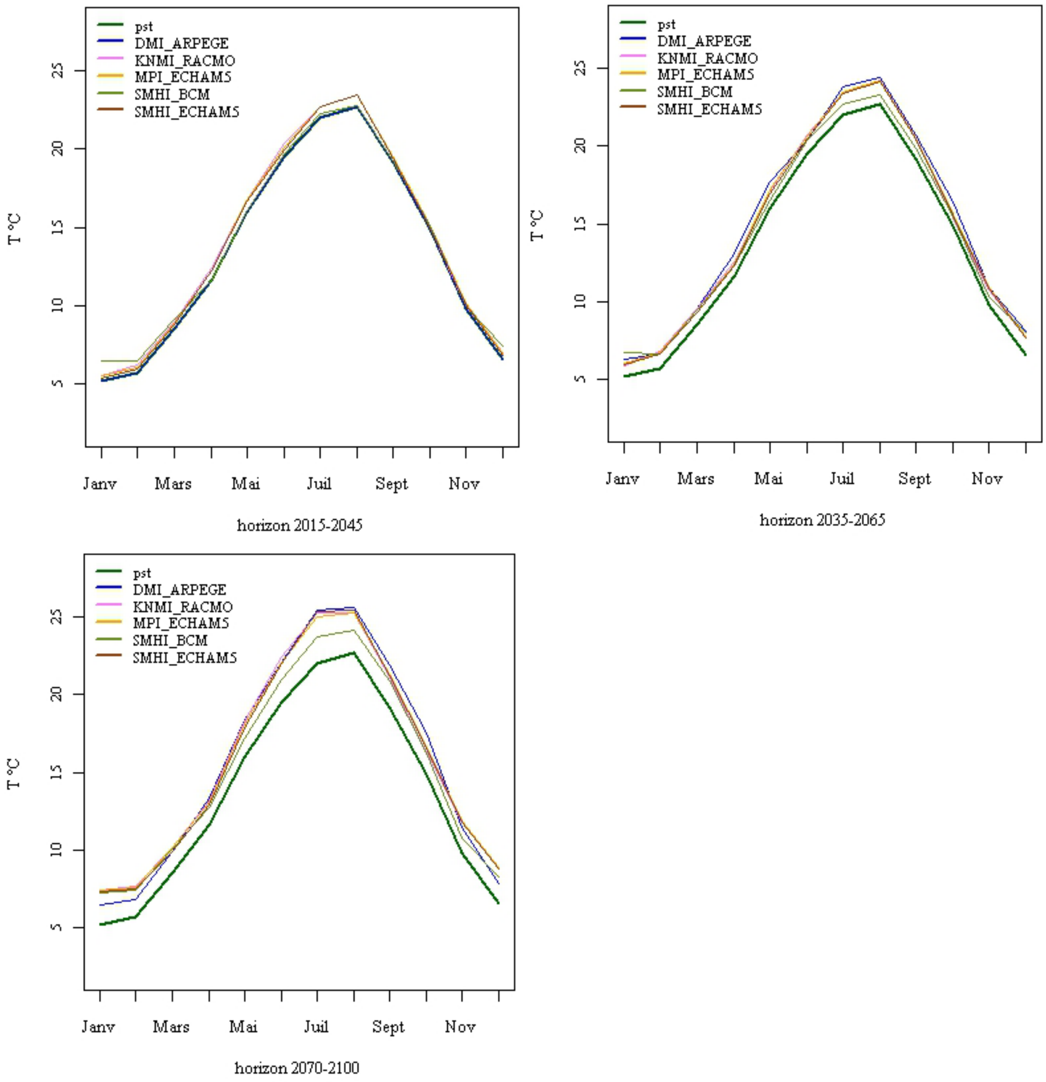

Fig. 3 Long-term changes (°C) of the annual thermal pattern (monthly means) at St Alban station, as compared to the present time (pst), predicted by five RCM-GCM models.

CONCLUSION

For long-term changes of thermal regime, a simple and robust model forced only by climate data was necessary. Due to the runoff influences on water temperature, the scenarios for runoff also had to be estimated. A specific modelling tool for runoff and water temperature was built for the case study of the Rhone River, where EDF needs to anticipate change in thermal regime. To evaluate the long-term changes of water temperature, the first step was the calibration of thermal and rainfall–runoff models with observed climate data. The second step consisted of forcing these models with future meteorological data from climate models. For this, anomalies for three future periods derived from five coupled RCM-GCM models from the European ENSEMBLE project were used. The results suggest more intense increases in water temperature during summer (up to +3°C towards the end of the century) than during winter with each climate model producing similar results. Moreover, water temperature regimes were most highly correlated with air temperature regimes.

But these initial results need to be further analysed. To keep these results in perspective, it is necessary to improve the use of the RCMs and other downscaling methods. In this context, taking into account the changes of daily extremes can be envisaged.

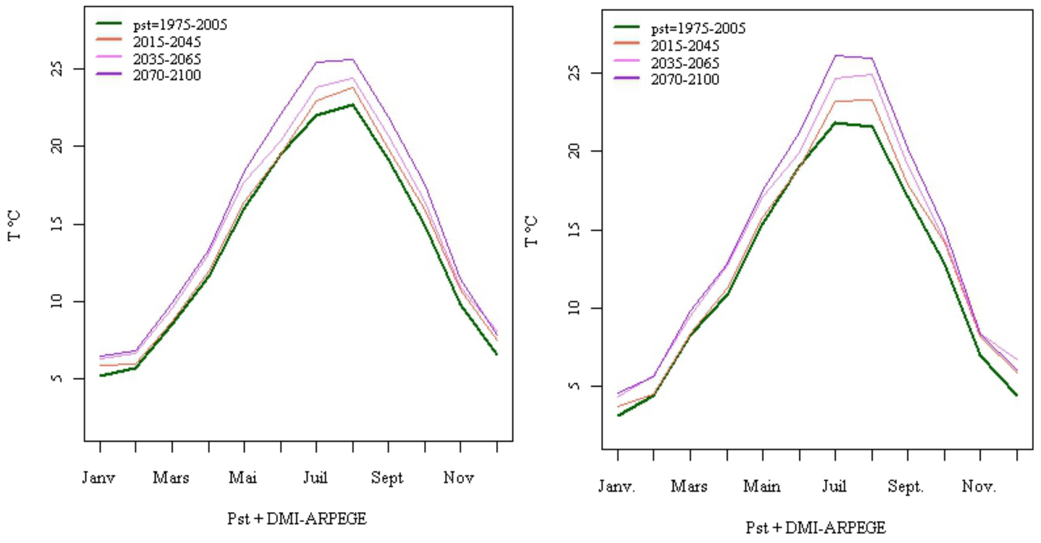

Fig. 4 Long-term predicted water temperature changes (monthly mean values) between present time (pst) and three future periods, using the GCM-RCM DMI-ARPEGE model for the St Alban station (left), and predicted air temperatures for the same periods (Lyon meteorological station) (right).

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