Hydrological forecasting on glacier systems: Temperature forecasting corrections

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Introduction

The OPT-HE project (Operational Prevision Tool for HydroElectricity, 2014-2017) aims at enhancing existing hydrological forecasts for hydropower production. It regroups industrial partners from hydropower sector (Alpiq, Group-e, Romande Energie, SEFA, SIG), research partners (EPFL, ETHZ) and MeteoSwiss around e-dric.ch, an engineering company specialized in hydrological forecasting for hydropower production and floods.

The hydrological forecasts for hydropower production allow to predict inflows in order to optimize the management of reservoirs (quantity and timing of production), to determine the future electricity production plan and to protect infrastructures from floods. They represent a great potential for an increase of renewable power production revenue without any new infrastructure cost.

The main paths of inquiry of the research project are related to every model process enhancement that could be beneficial to hydrological forecasting for hydropower production (short term to seasonal). For example, enhancing the assimilation of observed and forecast meteorological data, optimizing the initialization of the forecasts and defining a dynamic but reasonable uncertainty range for forecasts are core topics of this project.

In this paper, the authors focus on operational glacier flow forecasting. These particular operational forecasts are provided for the Alpiq hydropower company. First, the operation of this forecasting chain and of the modeling approach is described. Then, after a short description of the case study, the Massa river at the outlet of Aletsch glacier (Swiss Alps), the performance of the model calibration and of perfect forecasts is presented. As the temperature is the main forcing variable of glacier and snow melt, the performance of the temperature forecasts is then assessed. This analysis allows to provide corrections of temperatures and new forecasts, whose performances are compared to previous ones.

1. Forecasting chain

The main processes of the forecasting chain are divided into two parts. The first part consists in calculating the real-time conditions of the basin (soil saturation, snow pack, etc.) in order to provide the latest state of the basin using the RS Hydropower model. The second part consists in feeding the same hydrological model with meteorological forecasts in order to get a discharge prediction.

1.1 Generating initial conditions

The RS Hydropower model is a semi-distributed rainfall-runoff model able to take into account a great variety of hydrological processes such as glacier dynamics, snow melt, subsurface flow and surface runoff. Basins are divided into elevation bands in order to consider the snow and glacier melt as a function of elevation. Focusing on glacier flow modelling, the model operation is described in Fig. 1.

As presented on Fig. 1, each elevation band contains a cascade of reservoirs. The meteorological information is taken from gauging stations that can be located inside or outside the basin. This information is then used to feed the snow model that can accumulate snow (if temperature is negative), melt snow (if both snow pack and temperature are positive), convert snow to ice in a glacier area and do nothing in any other case. As a function of this information, soil or glacier are fed by relevant input variables. The soil model is able to take into account the subsurface flow and, if saturated, the runoff model drives water faster to the outlet. The glacier model is able to accumulate ice, transfer mass to the band downstream and melt to the outlet of the basin, as a function of temperature, radiation and rainfall.

The hydrological models (Snow, Glacier and Soil GSM-SOCONT) have been initially developed within the framework of different research projects, namely CRUEX (Bérod, 1994), MINERVE (Hamdi & al., 2003 and 2005) and SWURVE (Schäfli et al., 2005). More recent extensions (GR3 plus for soil and Glacier balance) have been developed by e-dric.ch to achieve different projects related, for example, to operational inflow forecast and climate change.

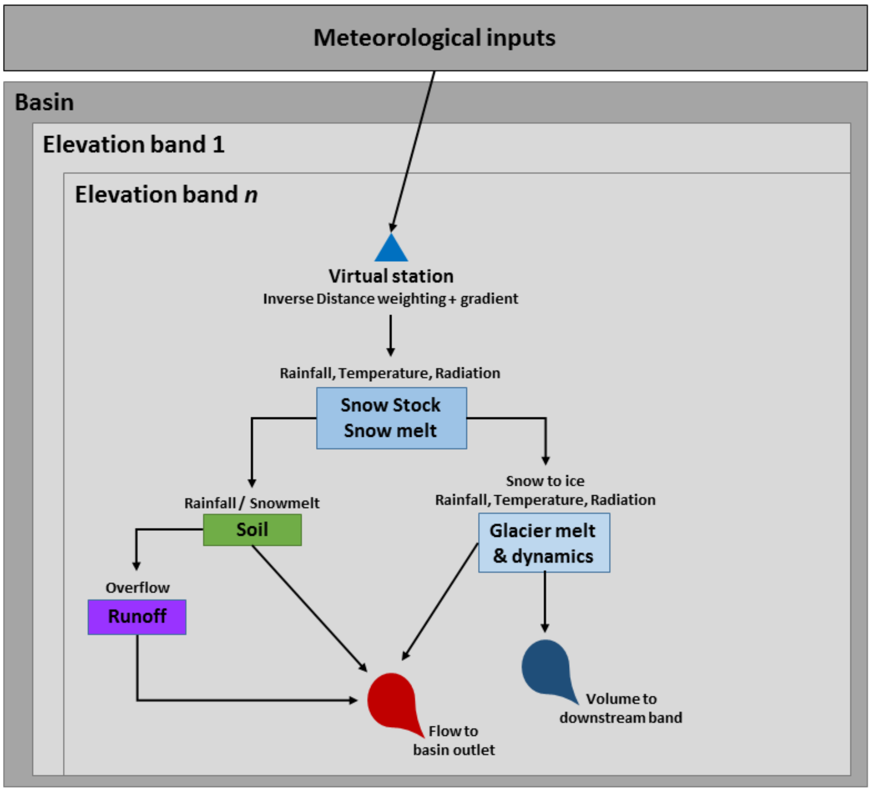

Fig. 1 : schematic description of the RS Hydropower operation.

This model is calibrated over the longest duration for which data is available in order to ensure its robustness. This calibrated model is then used in operational conditions to provide the initial conditions on the basin and an initial discharge in real time. Meteorological data is collected every hour and allows to run a calculation of the past 24 hours at the same frequency using initial conditions from the past simulations (Fig. 2).

Using discharge measurements, this simulation is updated as a function of the volume difference between observation and simulation over the past 24 hours. The process calculates the observed and simulated volumes and tries to minimize the difference between these two values by adjusting the initial filling of the different reservoirs. Even with a high quality calibration, the sum of the processes involved in a rainfall-runoff hydrological simulation, and *a fortiori* adding snow and glacier melt, is so complex that some periods will be poorly simulated. It would be illusory to perfectly model all these processes in all the possible conditions (Beven, 1989). Updating initial conditions is thus a relevant solution for operational real time simulation.

1.2 Generating forecasts

Once initial conditions are generated, forecasts can be provided by replacing the meteorological stations data (past) by outputs of meteorological forecasting models (future). The meteorological model outputs are provided as regular grids. In this study, the MeteoSwiss COSMO7 model is used. It gives temperature and precipitation data at points located every seven kilometres whose elevation represents very roughly the important variations of Swiss Alps. The lead time is 72 hours.

Thus, the virtual stations are no longer fed by observations from stations but by values at these points. The four closest points are considered and inverse distance weighting ponderation plus elevation gradients are applied. In the beginning of the forecast, the updated initial conditions are applied and from this point, discharge forecasts are produced every hour with the forecast data of COSMO7 (Fig. 2).

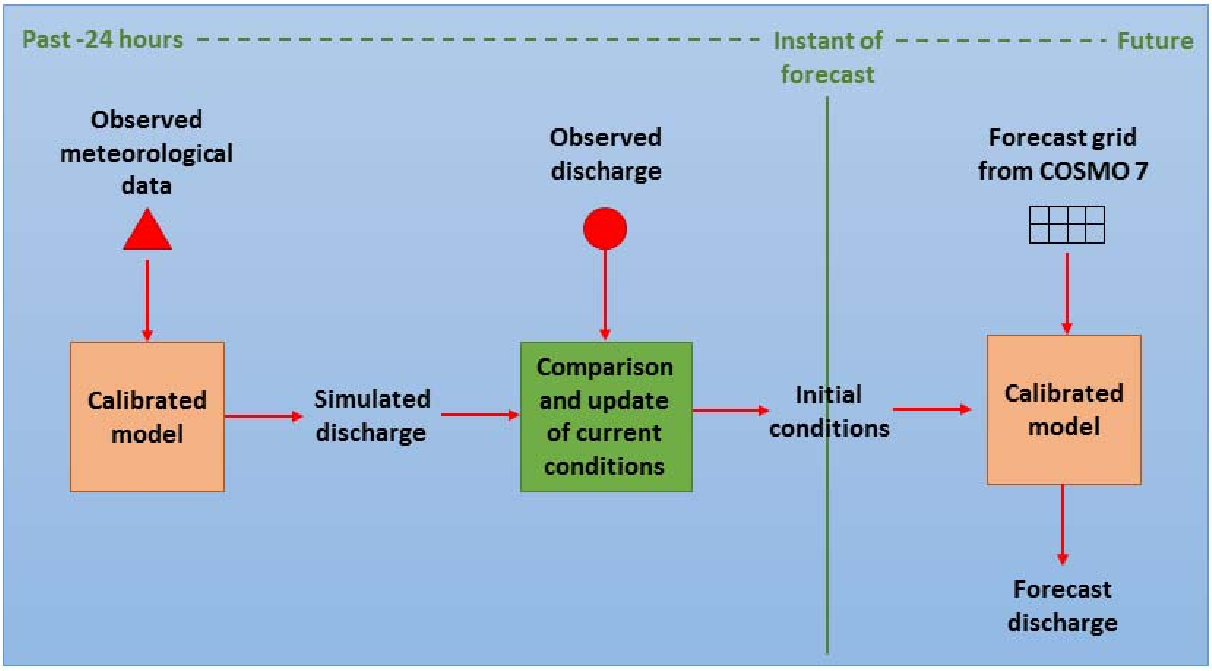

Fig. 2 : schematic description of the forecasting chain.

2. Case study: The Massa river (Aletsch glacier)

The Massa river, in the Valais Swiss Alps, is mainly fed by the Aletsch and surrounding glaciers melt. The basin surface is 195 sq. km. in which 65.9% is covered by glaciers. The station elevation is 1'446 m a.s.l. while the average elevation of the basin is 2'945 m a.s.l. and the maximum elevation corresponds to the Jungfrau summit at 4'158 m a.s.l. Fig. 3 shows a map of the different elements of the basin. The Gebidem reservoir is quite small regarding the discharge feeding (a few millions of cubic meters, while the average discharge in the season is close to 30 $m^3.s^{-1}$ and is able to reach 150 $m^3.s^{-1}$). Thus, the forecasts are particularly important to manage production and to avoid spilling.

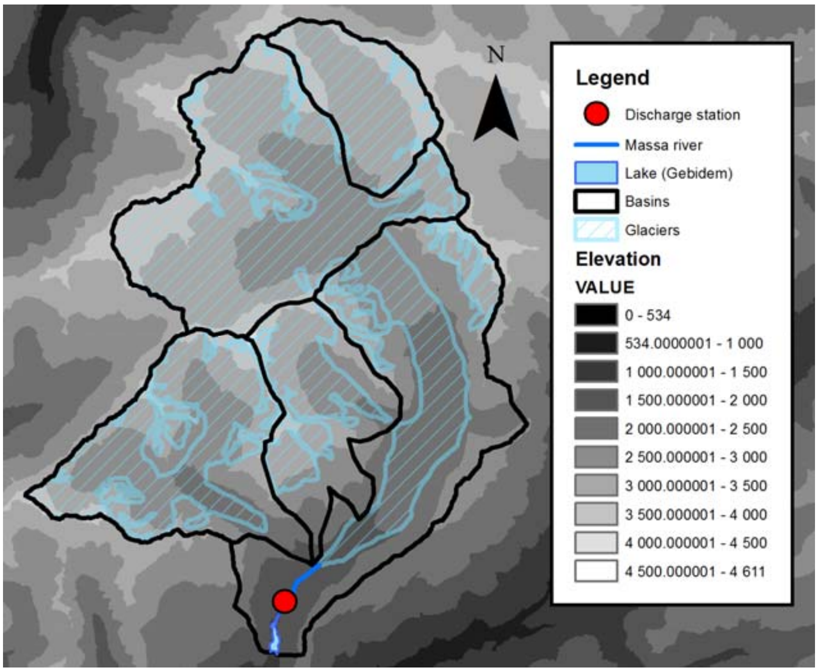

Fig. 3: map of the Massa in Blatten-bei-Naters basin.

3. Model performance

3.1 Calibration

The calibration of the model over the 2009-2014 period is presented. This calibration represents the real time performance of the model as it is generated in the same conditions as the real time ones. The simulation begins the first of October which allows to assume a negligible snow pack. The next winter provides a snow pack to be melted and converted to ice next year. The volume balance of the simulation gives a small overestimation of 1%. The Nash criterion (Nash and Sutcliffe, 1970) for all the values is 0.92, which is very high. As winter lasts about six months with discharges under one $m^3.s^{-1}$, we calculated the Nash criterion to discharges above one $m^3.s^{-1}$. This results in a value of 0.89, which remains very high. The mean absolute percentage error (MAPE) of the April-September period is 26%, mainly due to spring and autumn periods. The Fig. 4A presents this performance using the multiannual averages of simulation and observation over the 2009-2014 period. The Fig. 4B presents the yearly volumes observed and simulated. The purpose is to assess the ability of the model to reproduce the interannual variations. It can be seen that the model succeeds to reproduce the yearly volume trends.

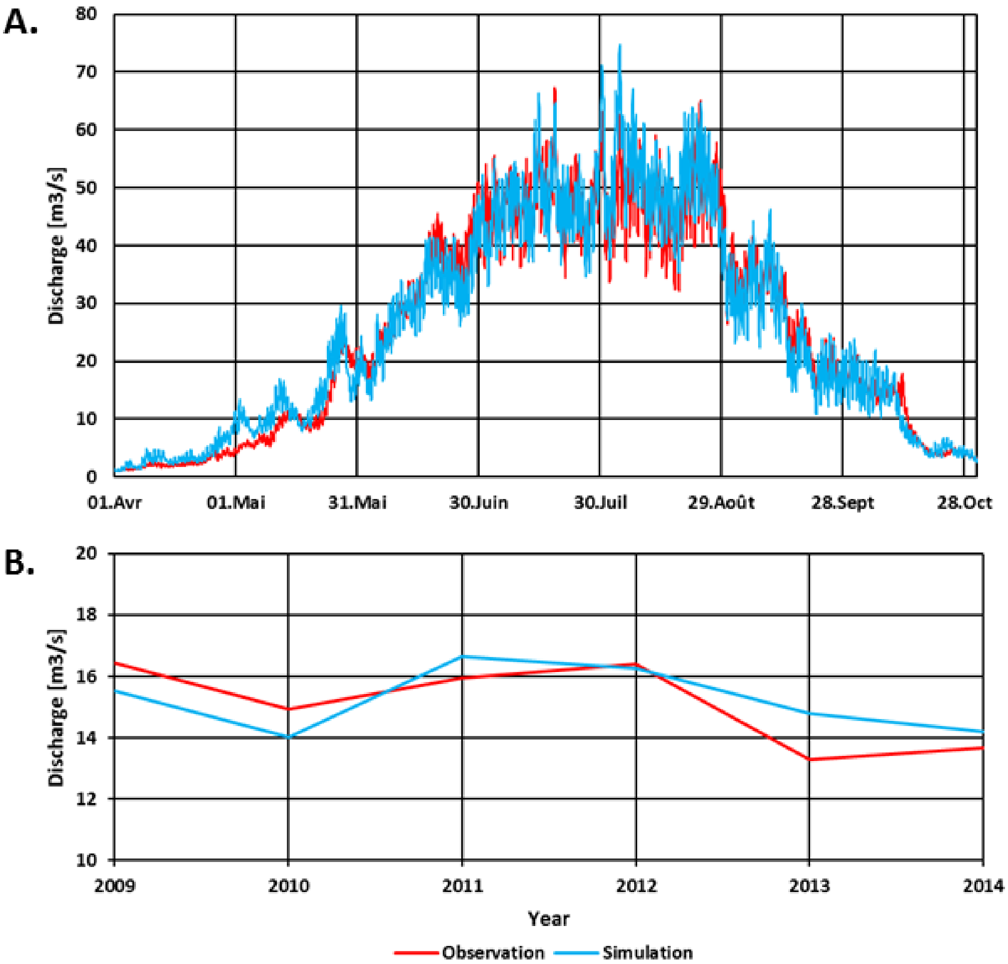

Fig. 4 : A.: 2009-2014 multiannual average of simulated and observed; B.: 2009-2014 interannual average simulated and observed discharge.

3.2 Perfect forecasts

Perfect forecasts are used to assess the performance of the forecasting chain regardless of the quality of the meteorological forecasts. In practical terms, they use the same initialization than real forecasts (real time simulation updated) but instead of meteorological forecasts, meteorological stations are used. Thus, they can only be made a *posteriori*, for analysis purposes, as the future meteorological observations are unknown. Here, the 6:00 AM forecasts for tomorrow 0h-0h are assessed. This lead time is the most important for producers. It will be called D1 for day one. In accordance with hydropower partners, the MAPE is mainly used to assess the forecasts. The perfect forecast performance over the 2009-2014 period is 16% in terms of MAPE. The initialization update is thus enhancing the results by 10% at D1, which proves its efficiency. The Nash criterion is 0.92.

4. Performance of temperature forecasts

In the case of the Massa river, the discharge is mainly fed by snow and glacier melt. Thus, temperature is the main forcing variable. Temperature forecasts are analysed at the grid points but the density of meteorological stations is lower than the density of grid points. In order to get a reference for performance assessment, observed data need to be interpolated at all the grid points. Standard gradient values for Switzerland are used. These values generally give excellent results when simulating discharges with meteorological stations, which validates them. Nevertheless, a risk of bias in these references still exists.

Fig. 5 shows the performance of temperature forecasts of COMSO7 for the whole Switzerland. The absolute biases and their standard deviation are represented. One can notice that in the mountainous parts, biases are very strong.

More precisely, in the south-western part, the Valais region, biases are generally high but the values are lower for some points in the middle of the valley. The most efficient point is close to the city of Sion and is called PT 4588.

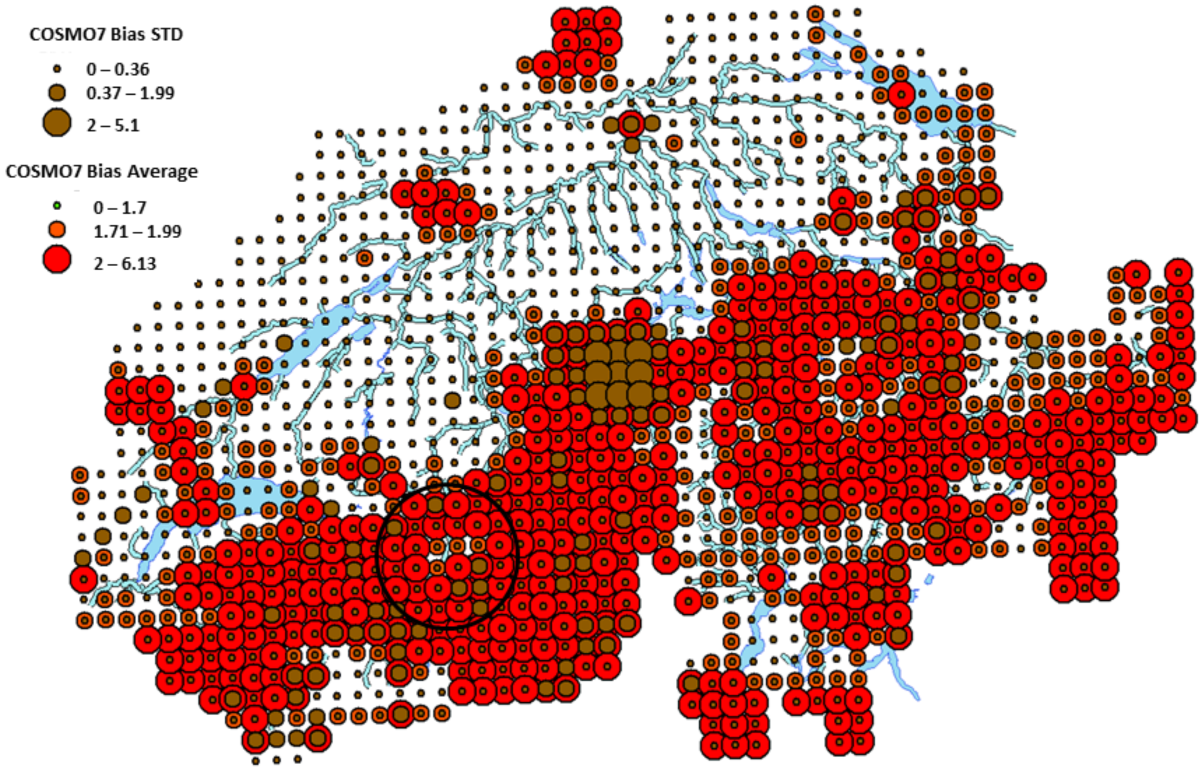

Fig. 5: average absolute biases of the COSMO7 D1 temperature forecasts and standard deviation related to these averages. The points in the circled area present a lower bias.

As an example of raw forecasts performance, the station of Zermatt is used. This station could be used for simulation (and thus perfect forecasts) without any modification. As can be seen in Fig. 6, the average D1 forecast presents a very negative bias.

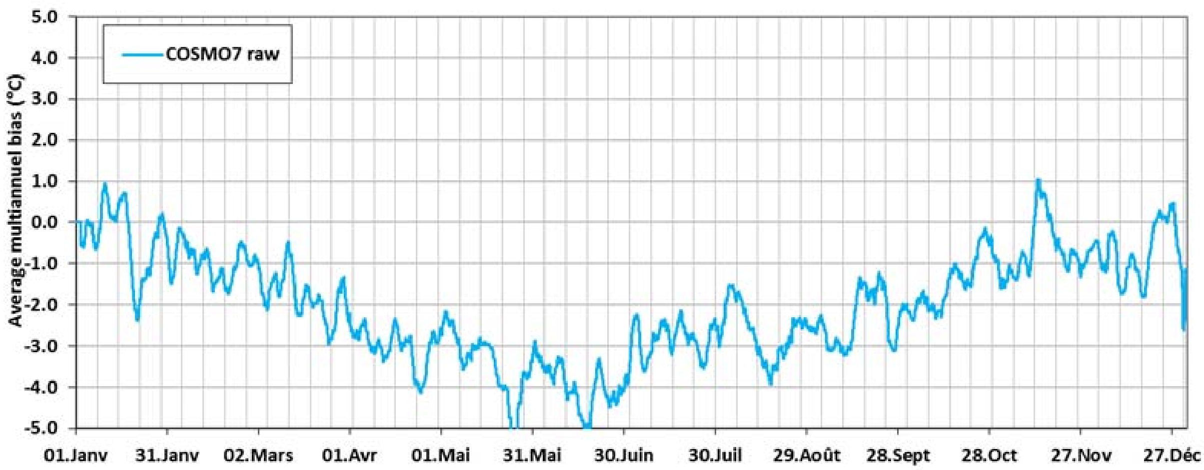

Fig. 6: 2009-2014 multiannual COSMO7 temperature forecast for D1 in Zermatt.

In such conditions, it is easy to conclude that discharge forecasts are going to be strongly underestimated. Corrections are thus necessary.

5. Corrections

Two types of corrections are considered and are complementary to each other. They are described in this section.

5.1 Based on COSMO7 best point

The best point mentioned in section 4, PT 4588, has a small bias. It is possible to use only this point for forecasts and to trust interpolations to provide values in the surrounding models. An example of the results obtained with this correction is shown in Fig. 7.

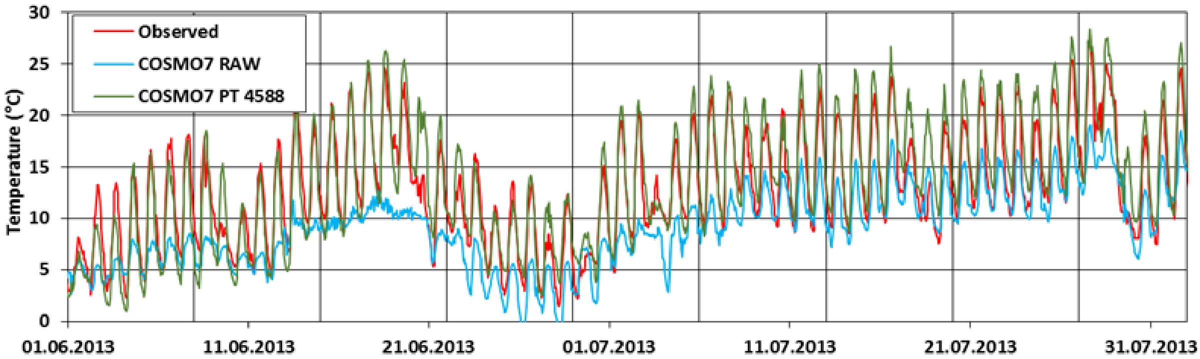

Fig. 7: Example of raw and PT 4588 corrected COSMO7 forecasts versus observations in Zermatt (June and July 2013)

Besides providing a new proof of the relevance of the practiced interpolations, this example shows that the performance of this method is satisfying.

5.2 Based on residual biases

The PT 4588 method is clearly more efficient than the use of raw forecasts. Nevertheless, residual biases still exist. The purpose of the residual biases method (RB) is to check if theses biases are seasonal, or at least, more or less regularly observed, in order to apply a complementary correction. The multiannual average of these biases is applied to each year as a correction of the PT 4588 forecasts. If the bias remaining after this last correction is close to 0, the method is considered reliable. An example of such a robust result is shown in Fig. 8 for Zermatt.

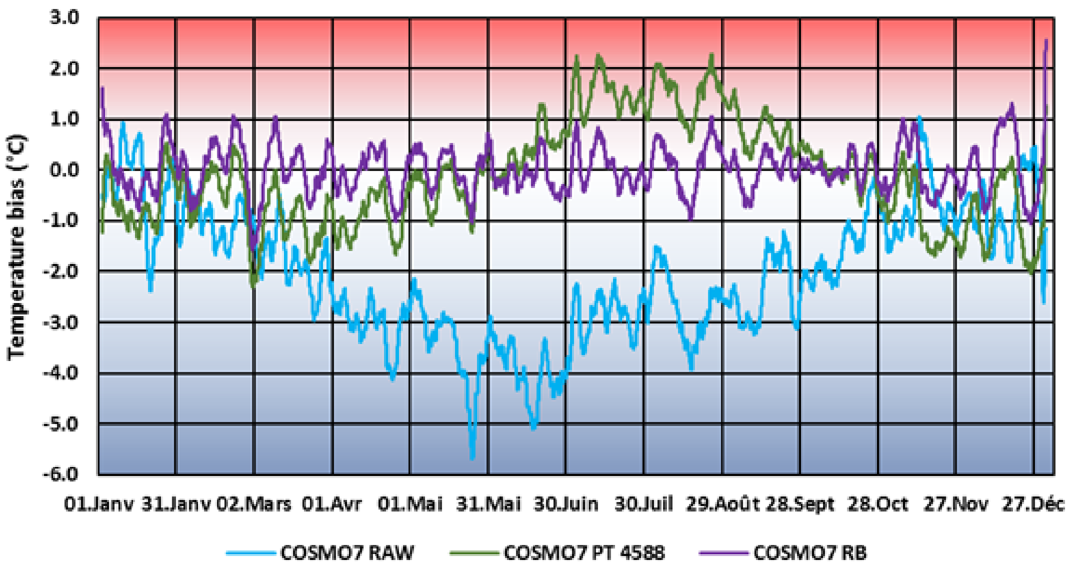

Fig. 8: Zermatt: biases of the raw forecasts compared to the PT 4588 biases used to produce the RB correction whose biases are also shown.

As for Zermatt, the final bias of most of the stations tested is close to 0 and in any case, lower than the COSMO7 PT 4588 one. One can suppose that this method leads to a best estimate of temperatures at every point considered in the Valais region as all the surrounding stations allow to assess best results.

5.3 Impact on discharge forecasts

The impact on discharge forecasts is assessed in terms of Nash criterion, MAPE and quartiles of absolute percentage error on an hourly basis on the Massa discharge at D1. The Fig. 9 presents these results.

	Nash	MAPE	APE 25%	APE 50%	APE 75%
Perfect forecasts	0.92	16%	5%	10%	18%
COSMO7 RAW	0.78	24%	10%	22%	33%
COSMO7 PT 4588	0.78	24%	8%	16%	29%
COSMO7 RB	0.89	18%	6%	12%	20%

Fig. 9: results over the 2009-2014 period for all the types of forecasts tested

The results of the perfect forecasts are a reference performance that cannot be surpassed. Only an enhancement of the model calibration or processes could enhance this result.

COSMO7 RAW leads to poor performance for all the considered criteria. The PT 4588 method only enhances quartiles of absolute percentage error. Nash and MAPE remain unchanged. The decrease of performance would really be visible at two days and more of lead time, due to the inertia of the system. The RB method gives the best results, close to the perfect forecast ones for all the criteria. It provides an absolute gain of 0.11 in terms of Nash, 6% in terms of MAPE, 4% for APE 25%, 10% for APE 50% and 13% for APE 75%, regarding the raw forecasts. This shows that the forecast makes less large mistakes in addition to decrease the global error.

6. Conclusions

The forecasts of glacier discharge require a complex modelling of all the processes involved in the hydro-meteorological relation. It also needs to be updated in real time conditions to enhance initialization. Most of all, the raw forecasts in mountainous areas are often of poor quality, leading to strong underestimations of the discharge. Using only the best points of the model allows to achieve a better performance but the best performance is obtained by correcting the temperatures from the best point as a function of an average residual bias. This brings results close to the perfect forecast ones, which is independent of meteorological forecasts errors.

The contribution of this method to reservoir and production management and to energy trading is important. The success of these experiences led to apply the RB method to most of the basins in the Valais region, but also in the Grisons area (south-eastern Switzerland).

Nevertheless, this method presents a few limitations. The first is the risk of a change in the grid of the meteorological model, or in the calculation processes of this numerical weather model. This would make all the corrections wrong and thus, strongly degrade the forecasts. There is a need for stability over a few years in order to calculate and apply the corrections. The second risk is adjacent to the first: if the meteorological model is stopped in favour of a new one, the only hope to keep on providing high quality forecasts is that the new model performs a lot better or that it is launched with available archives. These archives are available for the new COSMO-E model of MeteoSwiss, which will allow to define new corrections, lower than the COSMO7 ones, as the raw performance seems to be better.

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