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Simulation of Discharge using Different Methods of Meteorological Data Distribution, Basin Discretization and Snow Modelling

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This contribution investigates the performance of discharge modelling when proceeding from rather simple methods of snowmelt modelling to more sophisticated, distributed approaches. In all cases, the conceptual HBV runoff model is used for the calculation of discharge from the Romanche River basin (French Alps, area = 224 km^2, 12.5 % glacierized), feeding the Lac de Chambon reservoir used for hydroelectric power production. The results show that when using temperature-index approaches, no gain in performance is achieved by the more detailed basin discretization. However, a clear gain is observed when the precipitation and air temperature distribution of the elaborate meteorological data analysis system "SAFRAN" is used as input to the conceptual snow model. When using the original version of the physically-based "CROCUS" snow model, a strong overestimation of discharge resulted during the main snow melt season. A revised SAFRAN model version employing a new radiation routine, and the use of a realistic distribution of snow cover in each sub-unit considered by CROCUS resulted in a discharge simulation performance which is as good as the one from the calibrated conceptual models. Sensitivity analyses of the various snow models investigating the hydrological consequences of climatic change show surprisingly similar results.

Introduction

It is the primary aim of this investigation to validate a physically-based snow model as applied on the basin scale. Previous applications included operational snow monitoring, avalanche risk assessment (Brun *et al.* 1992), and snow cover sensitivity studies in respect to climatic changes (Martin 1992; Martin *et al.* 1993). While these previous validations were achieved for individual points, this one is aimed at the calculation of daily discharge from a mountainous catchment as an integrated response over complex terrain. The performance of the physically-based snow model is compared with a conceptual approach employing a seasonally varied temperature index to calculate melt rates (Braun 1988). The influence of different basin discretizations (use of the lumped elevational distribution and taking into account different aspects) is also investigated. Furthermore, the influence of various methods of meteorological data interpolation in the performance of discharge modelling is assessed. In all cases, a conceptual, lumped runoff model as developed for Scandinavian catchments (Bergström 1976; 1992) and as adopted for glacierized catchments (Braun and Aellen 1990) is used to transfer to the basin outlet the melt rates as calculated over the various basin units considered.

The question must be posed as to whether discharge as an integrated response is a reasonable means to assess the performance of various snow models, in particular of a distributed, physically-based one. Blöschl (1990), Blöschl *et al.* (1991), and Kirnbauer *et al.* (1991) showed among others that the use of spatially distributed snow cover data was to be preferred, as the system complexity is reduced when the runoff process is excluded. In a possible future step, snow cover patterns as assessed by remote sensing methods should be used to fully appreciate the highly distributed results of a physically-based snow model as investigated here, and, it is hoped, in conjunction with a sophisticated, distributed hydrological model. It was felt, however, that in a first step it was worthwhile to validate the rather complex meteorological distribution method and the snow model on the basis of daily discharge, as these data are readily available and constitute "the bottom line" of performance.

Some Details on the Models Investigated

The SAFRAN-CROCUS Physically-Based Approach

In an ongoing project at the Centre d'Etudes de la Neige (CEN), detailed parameterizations of processes involved in the mass and energy exchanges in the snow cover and at the snow-atmosphere interface, including the description of snow metamorphism, have been investigated. These studies were aimed primarily at the operational monitoring of the state of the snow cover for the purpose of avalanche risk assessment in the French Alps (Navarre 1975; Brun *et al.* 1989). The necessary input variables at an hourly resolution are deduced by an objective (= automatic) analysis of various meteorological data with the aid of the SAFRAN program package as shown in Fig. 1 and described in more detail by Durand *et al.* (1993). Among the principal data sources are the standard meteorological observations (Synop), upper-air messages from radiosondes, the ancillary network of visual and

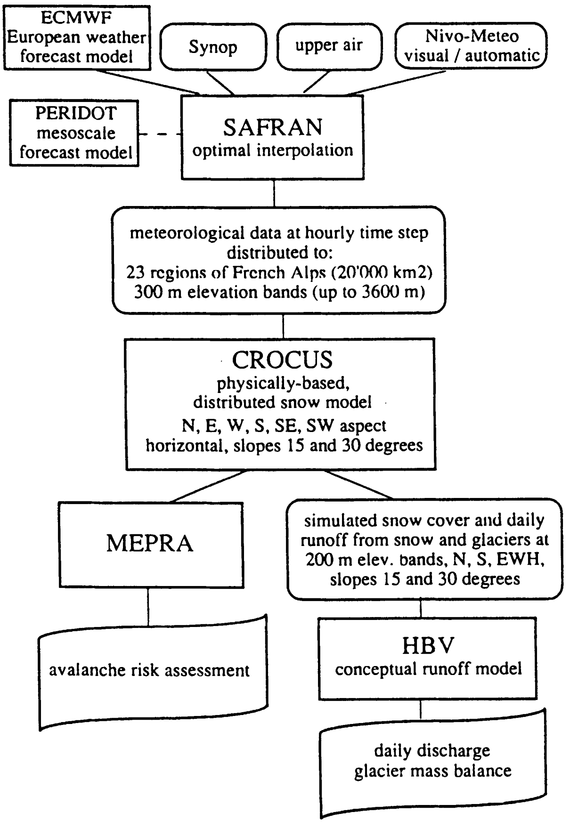

Fig. 1. Schematic overview of the SAFRAN-CROCUS physically-based snow cover modelling approach and consecutive discharge calculation by use of the HBV3 conceptual model.

automatic surface observations during the winter ski period (Nivo-Meteo, about 100 stations) and the altitudinal distribution of air temperature, wind and humidity as given by the French mesoscale forecast model PERIODOT (grid size of 35 km). For off-line applications such as the study presented here, the guess-field of the European Centre for Medium Range Weather Forecast (ECMWF) analyses are used. It is beyond the scope of this paper to describe the optimal analysis method applied. It may be of interest, however, to point out that orographic effects were taken into account for a first guess of precipitation based on a 5 km grid analysis by Bénichou and Le Breton (1987).

The meteorological data as derived by SAFRAN form the input to the physically-based CROCUS snow model (see Fig. 2), where the following snow cover variables are simulated: depth, density, temperature distribution, liquid water content, the various snow types in the individual stratigraphic layers, and melt runoff.

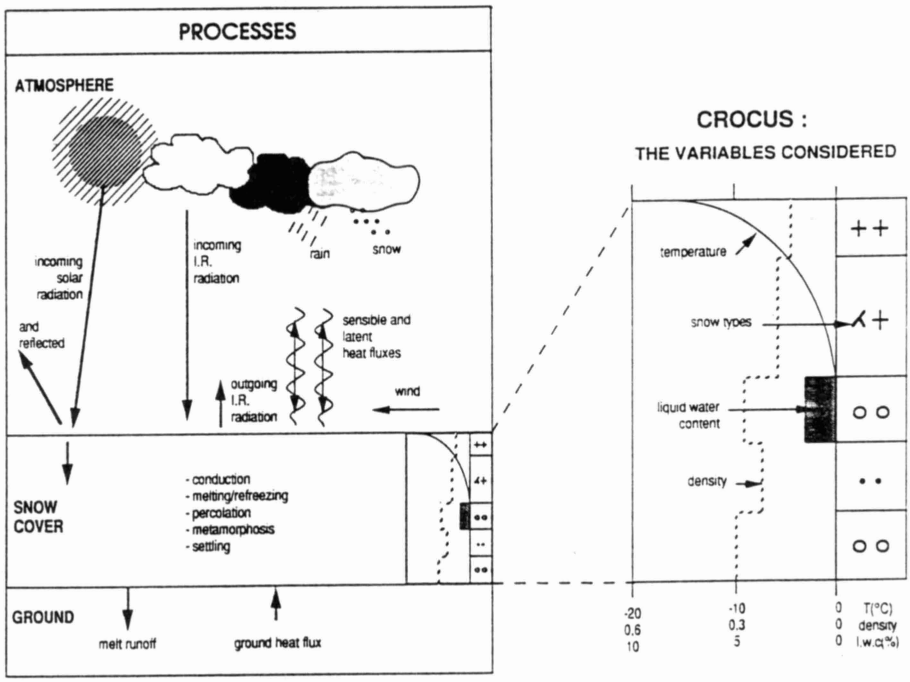

Fig. 2. Processes and variables considered in the CROCUS physically-based snow model.

In the application described here, daily water equivalent and runoff values are generated at 200 m intervals, three aspect classes (N, S and horizontal), and two slopes (15 and 30 degrees) for the two massifs of Grandes Rousses and Oisans (see Fig. 4). This version of CROCUS also simulates melt rates over the glacier ice as soon as the snow cover disappears, assuming an albedo of 0.3. Further details on the parameterization of the individual terms of the energy balance can be taken from Brun *et al.* (1989).

The Conceptual Modelling Approach

The performance of the physically-based modelling approach as presented above is compared with a conceptual snow and glacier melt model (ETH) which uses a rather modest data input. Based on the standard meteorological observations of daily air temperature and precipitation at stations preferably of strongly differing elevation, basin precipitation is calculated by employing a precipitation gradient and/or correction factors for snow and rainfall. Air temperature is distributed to the various elevations considered by a calculated temperature gradient if appropriate stations are available, or with a fixed value as is the case in this application. The model employs a seasonally variable temperature index to calculate snow and ice melt. Differing melt rates in southern and northern asepct classes in comparison with horizontal and East/West oriented units are controlled by one further model

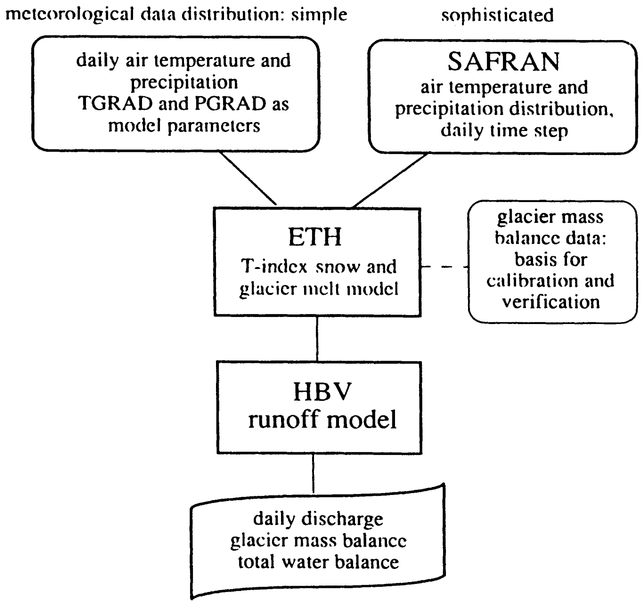

Fig. 3. Schematic overview of the conceptual snow cover modelling approach ETH and consecutive discharge calculated by use of the conceptual runoff model HBV3.

parameter. Meltwater is retained in the snow cover until the liquid water holding capacity is reached. More details concerning this model are given in Braun, Reynaud and Valla (1993).

In this analysis the sophisticated meteorological data interpolation method SAFRAN as described above was also used in conjunction with the conceptual snow model (see Fig. 3). Daily mean air temperature and precipitation values were derived for the two main mountain ranges (Grandes Rousses, Oisans) at 200 m vertical resolution.

In all snow model versions investigated the same conceptual runoff model HBV3 as described by Bergström (1976) was used to calculate the integrated response of the various melt rates as calculated in the various sub-units. Model parameters were calibrated employing a trial-and-error technique described by Braun and Renner (1992), using the years 1981/82 to 1985/86, and the subsequent 5 years for verification. The calibration of model parameters in a glacierized basin application is a rather tricky task. Braun and Aellen (1990) demonstrated that good discharge simulations can be achieved for the wrong reasons if calibration is based solely on measured discharge. Measured glacier mass balances greatly assisted the modellers in finding plausible parameter values which yielded both acceptable discharge and glacier mass balance simulations. In the application here, mass balance data were available for the Sarennes and St. Sorlin glaciers lying several kilometers NW of the basin (see Figs. 4 and 7, data from Valla 1989, and Vallon and Leiva 1989).

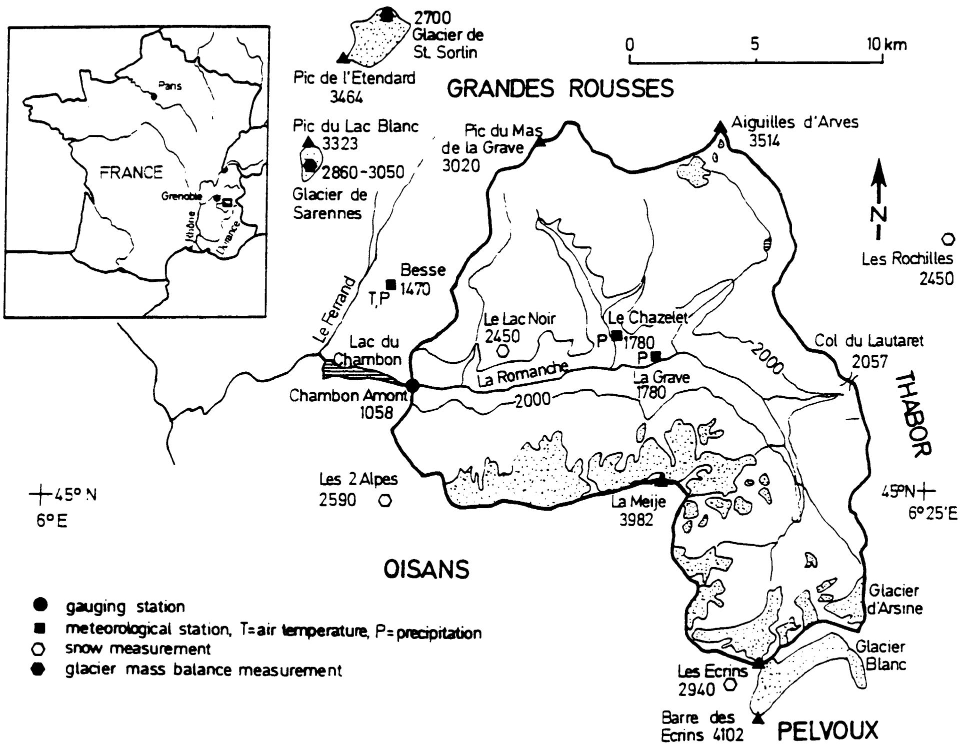

Fig. 4. Map of the Romanche basin: some locations of snow and glacier mass measurements and meteorological stations used for conceptual modelling approach.

The Romanche Basin and Meteorological Conditions 1981/82 to 1990/91

Figs. 4 and 5 give the location and the altitudinal distribution of the Romanche basin at Chambon Amont, having an area of 224 km^2 and a glacierization of 12.5 %. Discharge measurements are performed by Electricité de France (EDF), and continuous, automatic measurements of the snow-water equivalent are taken at the Lac Noir location at 2,450 m a.s.l., also by EDF. At the following Nivo-Meteo stations additional observations are made: Les 2 Alpes (2,590 m, manual snow and weather observations), Les Ecrins and Les Rochilles (2,940 and 2,450, respectively, Nivose stations, automatic measurements of snow depth), and previous snow cover modelling results were assessed for these locations among others and further discussed below.

Over the 10 years considered in the analysis, mean basin precipitation as determined by SAFRAN amounted to 1,200 mm/y, which is about 30 % more in comparison to the mean as determined at the meteorological stations of Le Chazelet

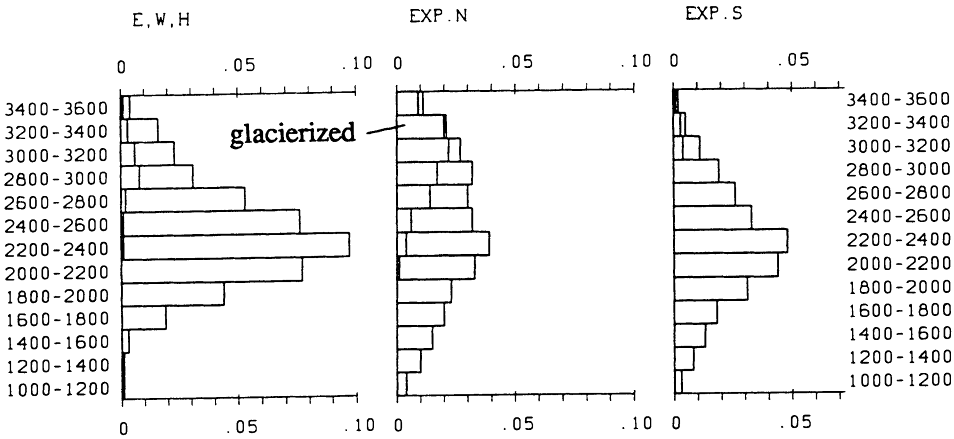

Fig. 5. Elevational distribution of aspect classes (sub-units) North, South and East/West/ Horizontal derived from a digital terrain model with a grid size of 75 m. Glacierized parts determined from maps, scale 1:25,000.

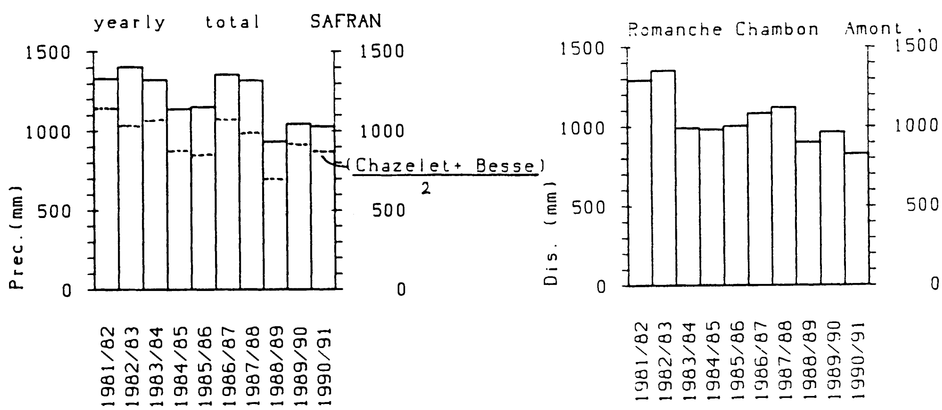

Fig. 6. Precipitation and discharge of individual hydrological years.

and La Grave. Mean discharge amounted to 1,050 mm/y, and the mean glacier mass balance considered for the total basin is about – 55 mm/y, based on the measurements on Sarennes and St. Sorlin glaciers. Figs. 6 and 7 show the inter-annual variation of these variables: precipitation ranges between 930 mm in 1988/89 and 1,400 mm/y in 1982/83, while discharge lies between 830 mm in 1990/91 and 1,350 in 1982/83. Centered glacier mass balances as defined by Reynaud (1988) are given since 1958/59, showing more or less balanced conditions until 1975/76, followed by a consistent mass gain until the mid-1980s, and then by a very strong mass loss until 1991/92.

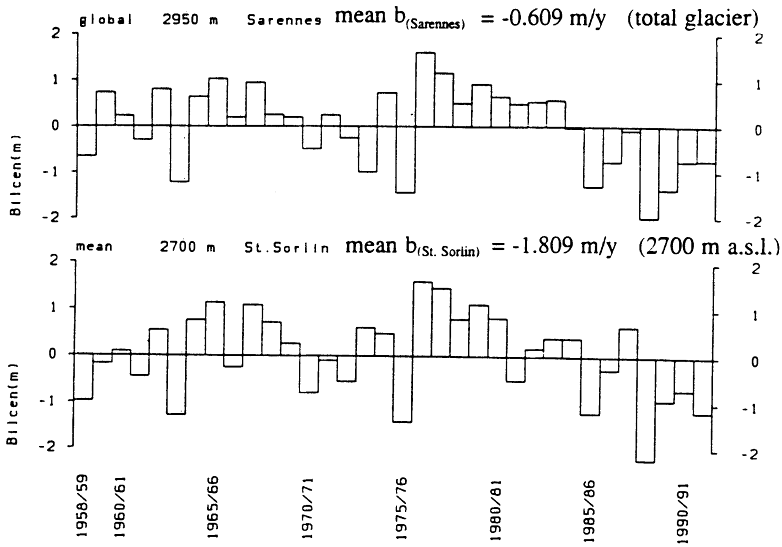

Fig. 7. Centered glacier mass balances of Sarennes and St. Sorlin glaciers over the last 34 years. Values for Sarennes are mean values over the whole glacier. Values for St. Sorlin are mean values at an elevation of abt. 2,700 m a.s.l. (data from Braun, Reynaud and Valla 1993).

Results

Numerical Criteria and Discussion of a Selected Case

Tables 1 and 2 give the overall performance of the various model versions expressed by the Nash-and-Sutcliffe (1970) efficiency criterion R^2 (perfect fit: R^2 = 1.0) and the difference between measured and simulated discharge ΔQ over the two 5-year periods investigated. From the values shown it is obvious that there is no gain in performance when considering different aspects in the conceptual ETH model calculations. However, modelling performance is noticeably increased when the sophisticated meteorological data interpolation method SAFRAN is employed in conjunction with the conceptual snow and glacier model.

When looking at the overall results of the original application of the SAFRAN-CROCUS physically-based models, a remarkable drop in modelling performance is observed (Table 2). It must be noted, however, that there was no calibration of the snow model, and the same values of the runoff model parameters were used as optimized with the conceptual melt model. In general, an overestimation of discharge is observed, particularly during the principal snowmelt seasons (see also Fig. 8). At first, this failure to model melt runoff correctly was attributed to an overestimation of the incoming short- and long-wave radiation, particularly at times when maintenance of the ancillary observation network of the Nivo-Meteo

Table 1 – Performance of different conceptual snow model versions over the calibration and verification periods: Nash-and-Sutcliffe efficiency criterion and difference between measured and simulated discharge (mm and % of total).

	ETH without aspect		ETH different aspects N,S,EWH		SAFRAN-ETH without aspect		SAFRAN-ETH different aspects N,S,EWH	
	R^2	ΔQ	R^2	ΔQ	R^2	ΔQ	R^2	ΔQ
Calibration 1981/82 -1985/86 Qtot = 5618 mm	0.79	36	0.78	-7	0.83	23	0.82	-20
Verification 1986/87 -1990/91 Qtot = 5098 mm	0.76	169 3.3%	0.76	108 2.1%	0.79	168 3.5%	0.78	150 3.1%

Table 2 – Performance of various verisions of SAFRAN-CROCUS physically-based snow model: Nash-and-Sutcliffe efficiency criterion and difference between measured and simulated discharge.

	SAFRAN-CROCUS original version		SAFRAN-CROCUS version 4 use of radiosonde data Lyon radiation model based on Giordani (1988)		SAFRAN-CROCUS version 6 radiation model as in version 4; distributed snow cover in each unit	
	R^2	ΔQ	R^2	ΔQ	R^2	ΔQ
Verification 1981/82 -1985/86 Qtot = 5618 mm	0.77	310 5.5%	0.80	-120 -2.1%	0.83	-273 -4.9 %
Verification 1986/87 -1990/91* Qtot = 5098 mm	0.73	319 6.5%	0.80	-5 0%	0.81	-110 -2.3 %

* until 31 July

stations is discontinued at the end of ski season. In seach to improve simulation results, the following steps were taken:

- Additional upper-air input data (Lyon radiosonde ascents) were used to improve radiation calculations;
- Alternative radiation parameterizations as given in the literature were testet; the one based on Giordani (1988) brough a significant improvement (SAFRAN-CROCUS version 4).

If we look at the simulations of the water equivalent of the snow cover for the year 1985/86 (Fig. 9), it is obvious that melt rates as given by the CROCUS model are much higher in comparison with the conceptual ETH model. If we compare the diminuation of measured snow depths at the two nivo-meteorological stations Les Ecrins and Les Rochilles with the simulated values above, we can conclude that

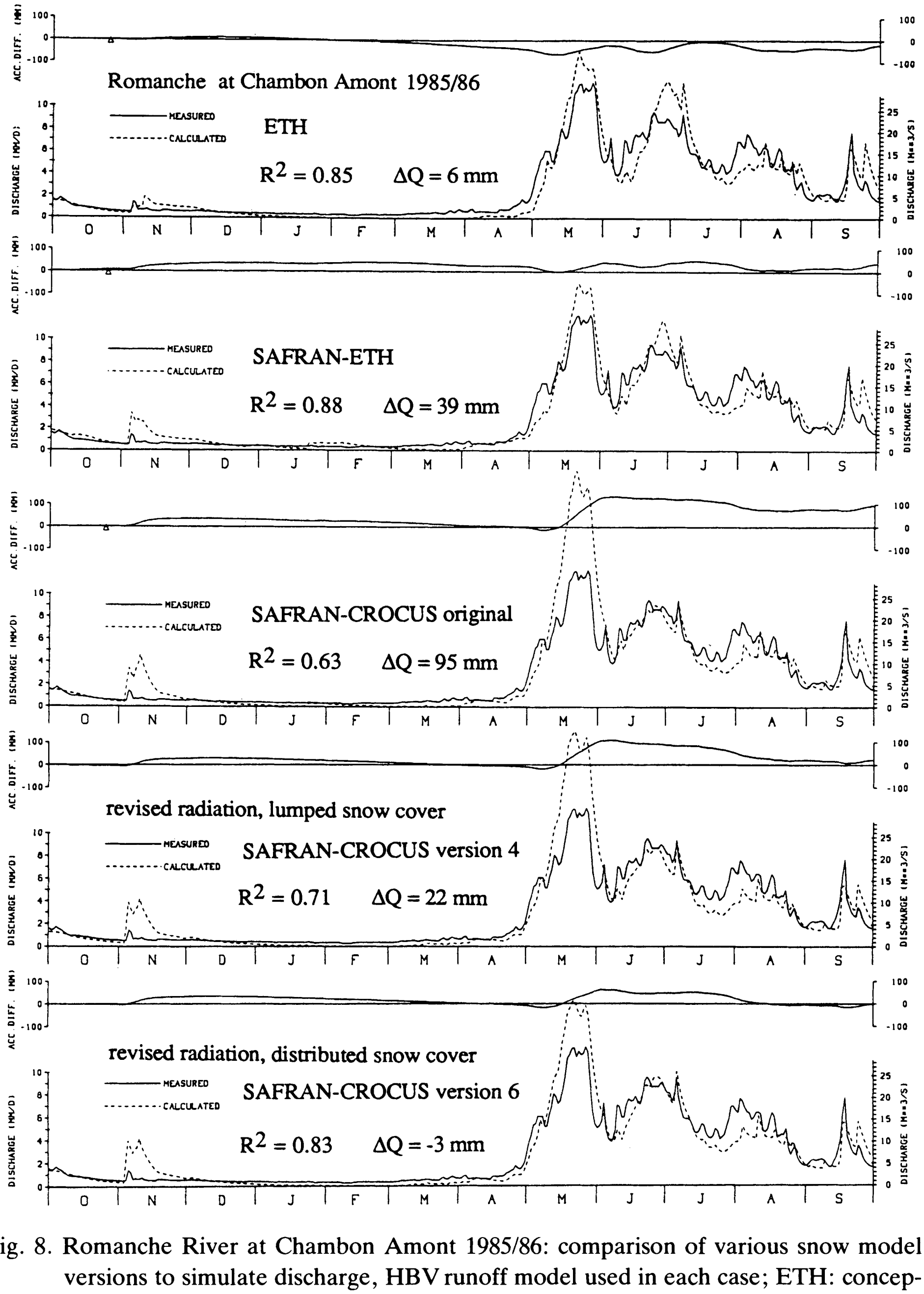

Fig. 8. Romanche River at Chambon Amont 1985/86: comparison of various snow model versions to simulate discharge, HBV runoff model used in each case; ETH: conceptual snow model (temperature-index), simple distribution of air temperature and precipitation; SAFRAN-ETH: same conceptual snow model, but with sophisticated distribution of air temperature and precipitation; SAFRAN-CROCUS: various versions of the physically-based approach.

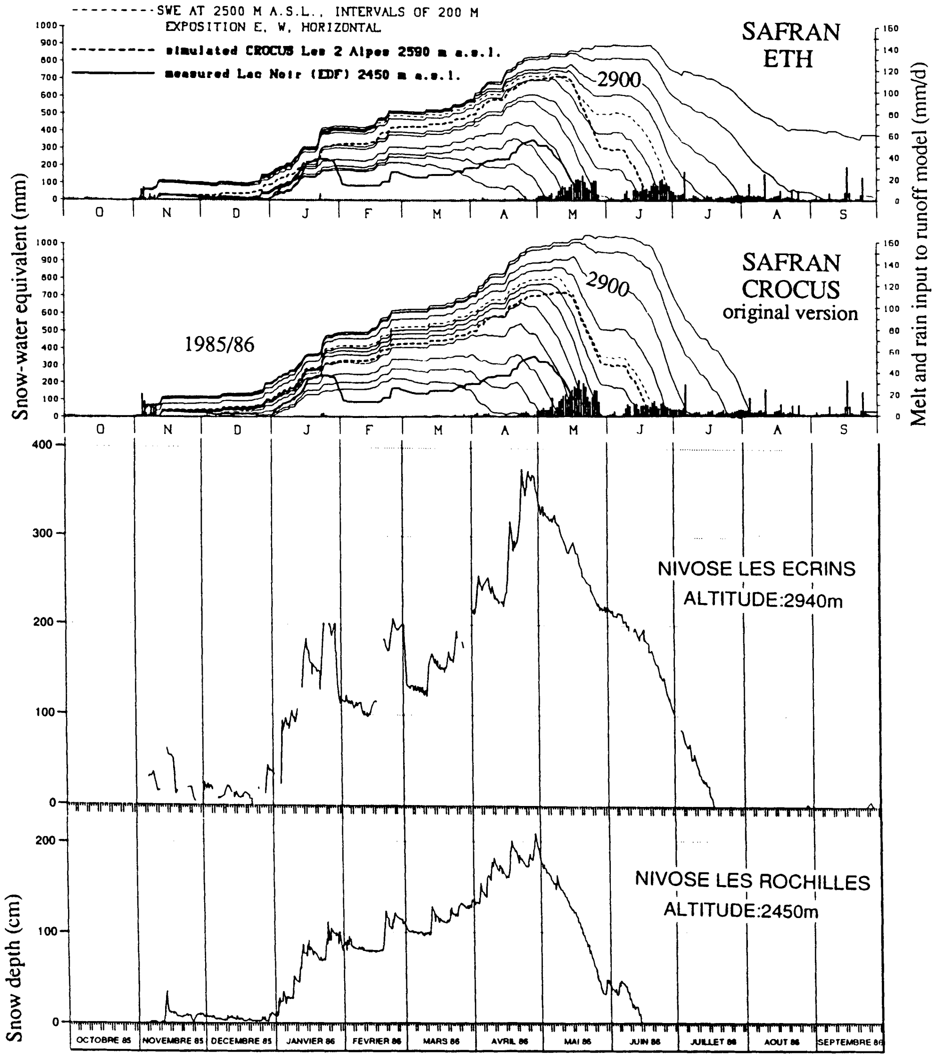

Fig. 9. Case 1985/86, upper two graphs: simulated snow-water equivalent and input to the runoff model resulting from melt and rain for the conceptual (ETH) and physically-based (CROCUS) snow models. Comparisons with the measured values at Lac Noir (snow-water equivalent, EDF, 2,400 m a.s.l.) and previous CROCUS model validation for Les 2 Alpes (Nivo-Meteo Station); lower to graphs: measured snow depth and Nivose stations Les Ecrins and Les Rochilles (locations see Fig. 4).

melt rates as given by CROCUS are in fact more typical than the conceptual model values. It appears that the high melt values of CROCUS are realistic, but if applied over the total area of the corresponding sub-unit, a strong overestimation of melt runoff occurs. The following two factors may be responsible for this effect:

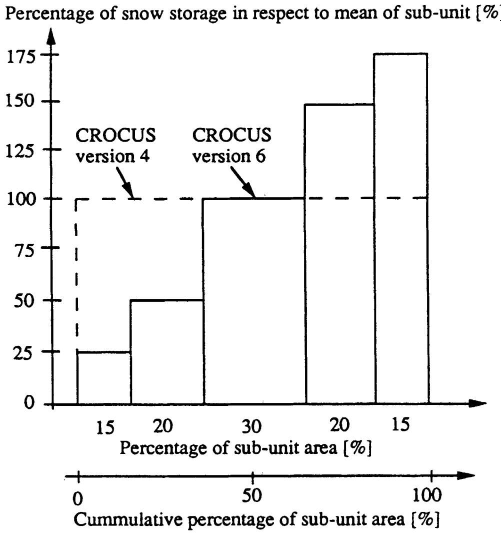

Fig. 10.
Distribution of the snow-water equivalent as simulated by CROCUS (version 6) in each sub-unit.

- Snow storage is not evenly distributed in the sub-units considered, and a more realistic distribution may reduce the initial overestimation of melt runoff by taking into account areas that are bare or melt out quickly, and by prolonging the melt season due to the persistence of snow patches late into the summer;
- Not all areas where melt occurs contribute directly to streamflow. It may well be that groundwater storage takes on values that are much higher than modelled to date, maintaining a rather high discharge during the cold winter months, which, up to now, has been underestimated consistently (see Fig. 8).

Consequently, the simulated snow-water equivalents were distributed within each subunit in a first step as shown in Fig. 10, which resulted in a further improvement of discharge simulations (SAFRAN-CROCUS version 6). In comparison to the lumped model version 4, the distributed snow cover has the effect of reducing discharge during the main melt season (gradual melt-out of each sub-unit) despite the high CROCUS melt rates found to be realistic point values.

Hydrological Consequences of Climatic Change as Assessed by Various Models

Previous studies (*e.g.* Braun, Grabs, and Rana 1993) have shown that various conceptual snowmelt-runoff models give quite different answers in respect to the hydrological consequences of climatic changes. Therefore, a comparison was made between the conceptual ETH snow and glacier melt model, and the SAFRAN-CROCUS physically-based snow model. In the first case, the climate change scenario consisted in an increase in air temperature by 2°C, in the second case it was chosen according to previous studies simulating a doubling of CO_2 employing the EMERAUDE model (Mahfouf 1992). Here, the climatic change scenario consisted of an increase in air temperature by 1.8°C, of an increase of incoming long-

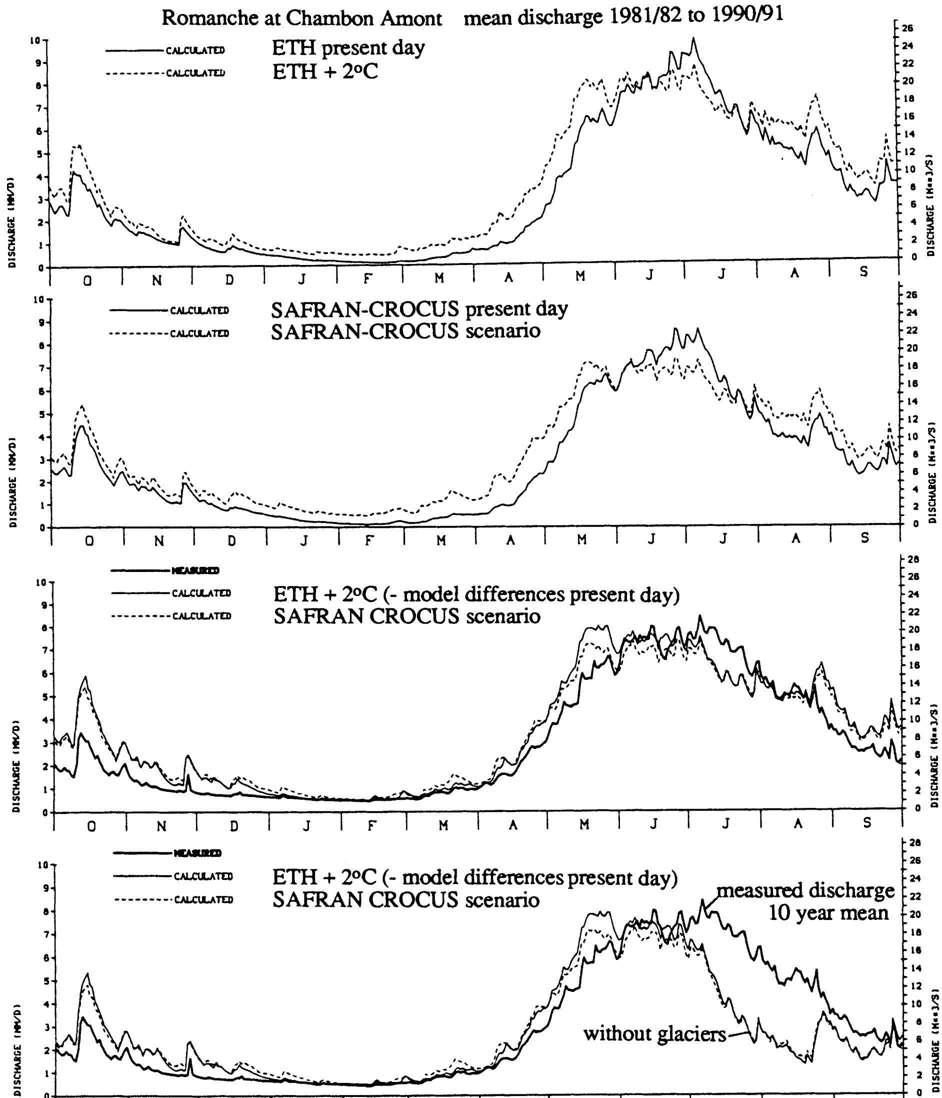

Fig. 11. Mean discharge of the Romanche River over 10 years (1981/82 to 1990/91) under present day conditions and with a changed climate calculated by two modelling approaches ETH and SAFRAN-CROCUS.

wave radiation by 3 %, an increase in incoming direct short-wave radiation by 10 %, and a diminuation in the incoming diffuse short-wave radiation by 10 % (these latter terms as a result of reduced cloud cover at hight elevations). Fig. 11 shows the simulation of mean discharge over the 10-year period 1981/82 to 1990/91 under present-day conditions and under above mentioned climatic scenarios. Both model types show higher melt rates over the winter period, increased snowmelt runoff during the onset of the melt season, less discharge in June/July, and increased glacier melt runoff in August/September (upper two graphs). If we remove the present-day model differences of simulated discharge and compare the model results with measured mean discharge, one can conclude that the response of the two models to these climatic scenarios is surprisingly similar (second graph from the bottom). On the average, annual discharge (presently at 1,050 mm/y) is increased by some 200 mm/y, which is primarily contributed by increased glacier runoff. Under these simulated climatic conditions (no increase in precipitation assumed!) the glaciers would disappear to a large extent (a 3°C increase in air temperature would cause some 75 % of the glacierized surfaces to disappear according to VAW 1990). If all glaciers were absent, July and August discharges would be reduced to about half the present values, and mean annual discharge would take on a value of about 1,000 mm/y under the climatic scenarios.

Summary and Conclusions

The results and conclusions can be summarized as follows:

1) Conceptual models of snow and glacier melt runoff can be regarded as efficient and robust tools to simulate daily discharge of high alpine basins. Due to their modest need for input data they can be used effectively to assess the water balances over many years, provided that model calibration can be achieved via discharge and preferably supported by glacier mass balance and snow cover data. Quite often, however, simple conceptual models miss the onset of the melt period, and a clear improvement in modelling performance is achieved if a sophisticated meteorological data distribution is employed instead of fixed gradients of air temperature and precipitation.
2) In the application of the conceptual snowmelt-runoff model as reported here (Romanche basin, area = 224 km^2, 12.5 % glacierized), a more detailed basin discretization according to aspect did not improve simulations.
3) Validation of the SAFRAN-CROCUS physically-based snow model via daily discharge was a worthwhile undertaking. A revised model version employing a new radiation routine and a realistic distribution of snow cover in each sub-unit resulted in an overall performance comparable with the calibrated conceptual modelling approach. One of the advantages of using the physically-based approach is the built-in ability to use a shorter time step, and its capability to deal with incomplete input data series, points which are advantageous when operational forecasting of streamflow is required.
4) Sensitivity analyses of the various snow models investigating the possible hydrological consequences of climate changes show surprisingly similar results.

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