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RESPONSE OF SNOWMELT HYDROLOGY TO CLIMATE CHANGE

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Abstract. In mountainous regions where the accumulation and melt of seasonal snow cover are important for runoff production, the timing and quantity of water supply could be strongly affected by regional climate change, particularly altered temperature and precipitation regimes. In this paper, the hydrological response to climate change scenarios is examined using a semi-distributed snowmelt runoff model. The model represents an improvement over simple temperature-based models, in that it incorporates the net radiation into the snowpack. Thus it takes into account the basin's topography and slope orientation when computing snowmelt. In general, a warmer climate is expected to shift snowmelt earlier into the winter and spring, decreasing summer runoff. The effects of other potential climate changes (such as precipitation and cloudiness patterns) are explored. The uncertainties in these predictions are discussed.

Keywords: snowmelt, runoff, net radiation, snow cover, climate change, water supply

1. Introduction

The runoff produced by the melting of seasonal snow cover in mountainous basins is an important water resource in many regions of the world. The occurrence of precipitation as snow — rather than rain — and its accumulation during the cold season provide a natural reservoir that releases its stored water during the summer season, when it is needed for both agriculture and hydropower. The timing and quantity of this water supply could be strongly affected by changes in a region's climate, particularly altered temperature and precipitation regimes.

Sustainable water resource planning requires consideration of possible climatic changes that are relevant to system design (Schultz and Hornbogen, 1995). Currently, much attention is being given to a global warming trend due to an increase of greenhouse gases in the Earth's atmosphere. However, the effects of such large-scale change on particular regions are uncertain. In addition, the general circulation models that are used to make predictions of climate change still do not adequately represent important physical processes (such as clouds) and feedback processes that might either counteract or reinforce the warming trend.

Many factors affect the response of snowmelt hydrology to changes in climate; these are:

- changes in snowfall and accumulation
- changes in the timing and amount of energy to melt the snow.

Experiments with mathematical models of snowmelt-runoff production indicate that a warmer climate — all else being equal — would shift runoff earlier into the winter and

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spring, at the expense of summer runoff. In addition, a greater fraction of the precipitation would occur as rain rather than snow, bypassing the natural reservoir storage of the snowpack. Thus, the effect of temperature change is to shift the timing of runoff; changes in the region's precipitation regime, however, would affect the runoff volume. A warmer temperature could decrease runoff volume through increased evaporation; however, a small increase in precipitation could offset that decrease (Rango, 1992; McCabe and Hay, 1995).

Two questions must be addressed:

- How will a region's climate change in the future?
- How will snowmelt hydrology respond to that change?

Given the current state of knowledge, the first question remains largely hypothetical. Therefore, this paper addresses the second question. The approach is a series of sensitivity studies, that is, experiments that demonstrate the effect of various aspects of regional climate on the basin snowmelt response. A simple snowmelt-runoff model is used to demonstrate some of the complexities of the problem.

2. Snowmelt Runoff Model

The Snowmelt Runoff Model (SRM) (Martinec *et al.*, 1994) is used worldwide for forecasting melt-season runoff in mountain regions. SRM has been developed for microcomputer application and is ideal for use in data-sparse regions (Kumar *et al.*, 1991), due to its simple data requirements and incorporation of remote sensing to determine snow-covered area. SRM has been used successfully to simulate runoff in over 60 basins ranging from 0.76 to 122,000 km^2 in area.

SRM uses a temperature-index (degree-day) approach to melt snow from a basin's elevation zones. Air temperature has been shown to be the best single meteorological variable for predicting snowmelt (Zuzel and Cox, 1975). The degree-day approach has been criticized as lacking a physical basis in comparison to more complete approaches that consider all aspects of the energy exchange. Nonetheless, degree-day methods remain popular in snowmelt modeling, and perform well when properly applied (Rango and Martinec, 1995).

A new version of SRM incorporating net surface radiation is under development (Kustas *et al.*, 1994); depending on data availability, the user could choose between the simple temperature-index or the slightly more complex temperature and radiation versions. In the degree-day version of SRM, the melt depth (M [cm day^{-1}]) is calculated as:

$$M = aT_d \tag{1}$$

where T_d [°C] is the degree-day index and a [cm °C^{-1} day^{-1}] the degree-day coefficient. In the radiation-based version, Equation (1) is expanded to include a net radiation index (R_d [W m^{-2}]),

$$M = m_Q R_d + a_r T_d \tag{2}$$

In Equation (2), m_Q [(cm day$^{-1)}$ (W m^{-2})$^{-1}$] is a physical constant converting energy to water mass or depth, R_d is the radiation index, and a_r [cm day^{-1} °C^{-1}] is the restricted degree-day coefficient, which is not equal to a in Equation (1) but multiplies the same T_d. One advantage of the radiation-based version is that the restricted degree-day coefficient a_r is not as variable in time as the simple degree-day coefficient a. The net radiation component can take actual radiation measurements or can calculate the net radiation based on meteorological data and topography. In addition to altered temperature and precipitation regimes in a hypothetically changed climate, the radiation-based version can account for changes in humidity and cloudiness, which affect the net radiation received at the snow surface.

For the Degree-Day version of SRM, the basin is subdivided into elevation zones, and a lapse rate is applied to base-station temperatures in order to obtain daily-average temperatures for the zones. In the Radiation version, general orientation (aspect) of the hillslope is a major factor in the amount of solar radiation received. Therefore, in this version, the basin is further divided into aspect/elevation zones.

The melt formulas, Equations (1) and (2), are applied only to the snow-covered fraction of each zone. Thus, a measurement or prediction of snow-covered area is a required input to the melt calculation. For simulations, the required snow-cover data are obtained from remote-sensing images. In forecast mode, SRM automatically evaluates the future course of snow-cover depletion by deriving curves of snow-covered-area versus cumulative melt (modified depletion curves) from records of snow-covered area versus time (conventional depletion curves). This procedure is described in Martinec et al., 1994.

3. Net Radiation

The radiation received at a point at the Earth's surface is composed of both shortwave (solar) and longwave (terrestrial) components, as follows:

$$R_{net} = K_{in} - K_{refl} + L_{atm} - L_{surf} \tag{3}$$

where K_{in} represents the incoming shortwave (solar) radiation that reaches the surface after reflection, backscattering, and absorption by clouds, K_{refl} the portion of that incoming energy that is reflected by the surface, L_{atm} the longwave radiation emitted by the overlying atmosphere (both clear sky and clouds), and L_{surf} the longwave radiation emitted by the surface back to the atmosphere. Equation (3) is a general statement of the radiation balance, and does not explicitly account for the radiational effects of vegetation cover. The radiation index R_d in Equation (2) is set equal to R_{net}, if R_{net} is positive (into the snow), and zero otherwise.

4. Study Site

This study focuses on the Dischma basin in the Swiss Alps (area 43.3 km^2, elevation range 1668-3146 meters above sea level). Data from the year 1977 are used for the sensitivity analysis. Information on snow-covered area is obtained from high-quality aerial photographs of the basin. Detailed meteorological data are available from the

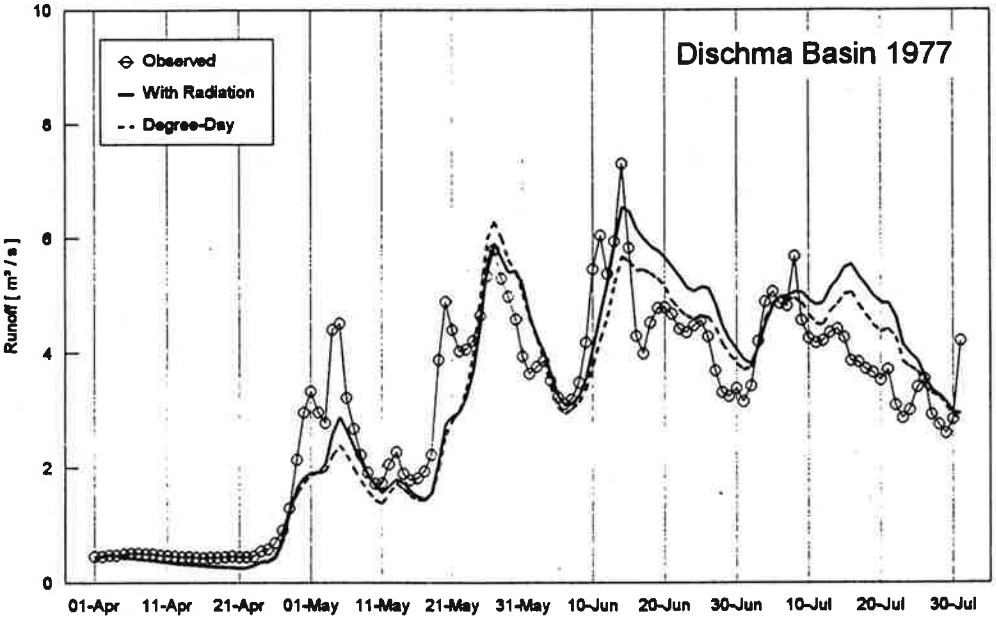

Fig. 1. Observed and model-simulated runoff hydrographs for the Dischma basin, Swiss Alps, in 1977.

Weissfluhjoch research station, allowing fairly accurate estimation of net radiation. The Weissfluhjoch station (elevation 2693 m.a.s.l.) lies near, but not in, the Dischma basin.

5. Snowmelt-Runoff Sensitivity to Climatic Variables

CONTROL (CURRENT CLIMATE) SIMULATIONS

Figure 1 shows model-simulated runoff hydrographs for the Dischma basin, compared to the observed hydrograph for four months of 1977. In the Radiation simulation, the restricted degree-day coefficient was set to a constant value of 0.36 cm $^{\circ}C^{-1}$ day^{-1}, and in the Degree-Day simulation, the coefficient varied from 0.4 on 1 April to 0.55 on 31 July. Both versions of the model succeed in capturing the general shape, but not the details, of the hydrograph. In the interest of consistency, the changed-climate simulations described below are compared to the current-climate simulations rather than the observed runoff.

WARMER TEMPERATURE

Figure 2(a) shows the response of both model versions to an increase of 3°C in daily-average temperature on every day of the melt season, with precipitation, cloud, and relative humidity remaining the same as in the 1977 observations. Because the relative humidity is unchanged and because saturation specific humidity increases with temperature, the volume of water vapor in the air is increased in the warmer climate scenarios, with a resulting increase in atmospheric longwave emissivity. In these simulations, the snow-covered area at the beginning of the melt season (1 April) is assumed to be the same as under the current climate (this last assumption is relaxed in another simulation, described below). As shown in Figure 2(b), the net change in runoff between the warmer and current climate is nearly the same in the two models. In a

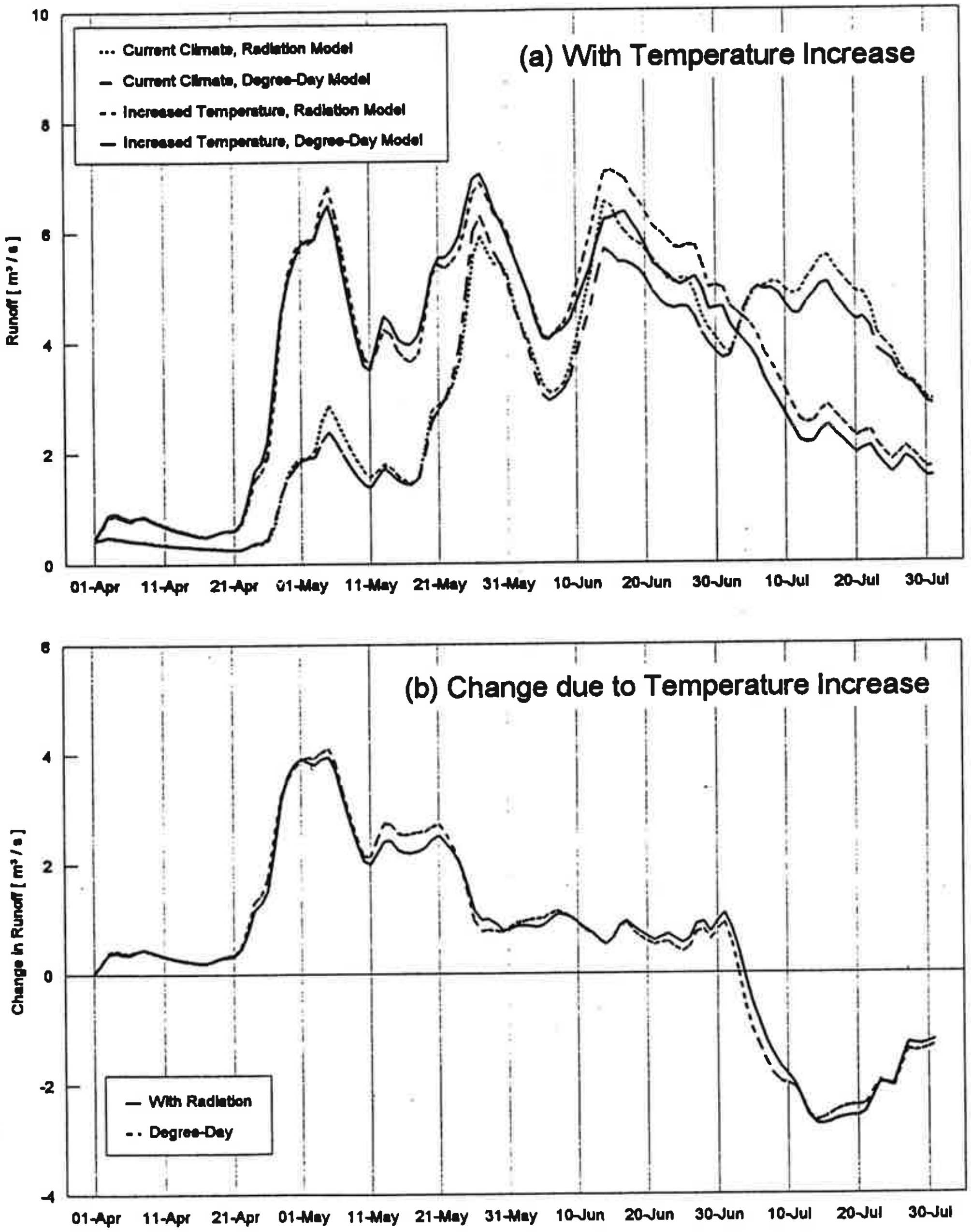

Fig. 2. (a) Simulation hydrographs using two versions of SRM for melt season 1977 in the Dischma basin under current climate conditions and with a 3 °C increase in temperature; (b) the change in runoff due to the increased temperature in both model versions.

warmer climate, the pattern of runoff is shifted, as energy is available for melt earlier in the season. With the snow cover depleted by this earlier runoff, less snow is available for melt in the summer months, with a resulting decrease in runoff during those months. For example, in this experiment, the warmer-climate July runoff represents a 36 percent decrease with respect to the current climate.

POSSIBLE CHANGES IN CLOUDS UNDER A WARMER CLIMATE

A change in the global and regional climate regimes might be accompanied by a change in the cloudiness patterns of the region. The Radiation model includes mathematical expressions for a number of cloud properties, including cloud fraction and cloud optical thickness. Cloud fraction represents the amount of the sky that is covered by clouds. Cloud optical thickness depends both on the physical thickness of the clouds and the frequency distribution of water droplet sizes within the cloud. The distribution of droplet sizes affects how sunlight is transmitted through and reflected from the clouds (Liou, 1992). In the following climate sensitivity experiments, the Radiation version of SRM is used to demonstrate the sensitivity of basin runoff to these cloud properties. In these experiments, the clear-air relative humidity is again held the same as in the current climate, regardless of the changes made to cloud type and amount.

Cloud amount

Figure 3 shows the simulation hydrographs that result when the cloud fraction is increased and decreased by 20% of sky-cover, in addition to the 3 °C temperature change, in the Radiation version of SRM. The model shows some sensitivity to the fraction of sky covered by cloud. It is somewhat surprising that increased cloud cover leads to more

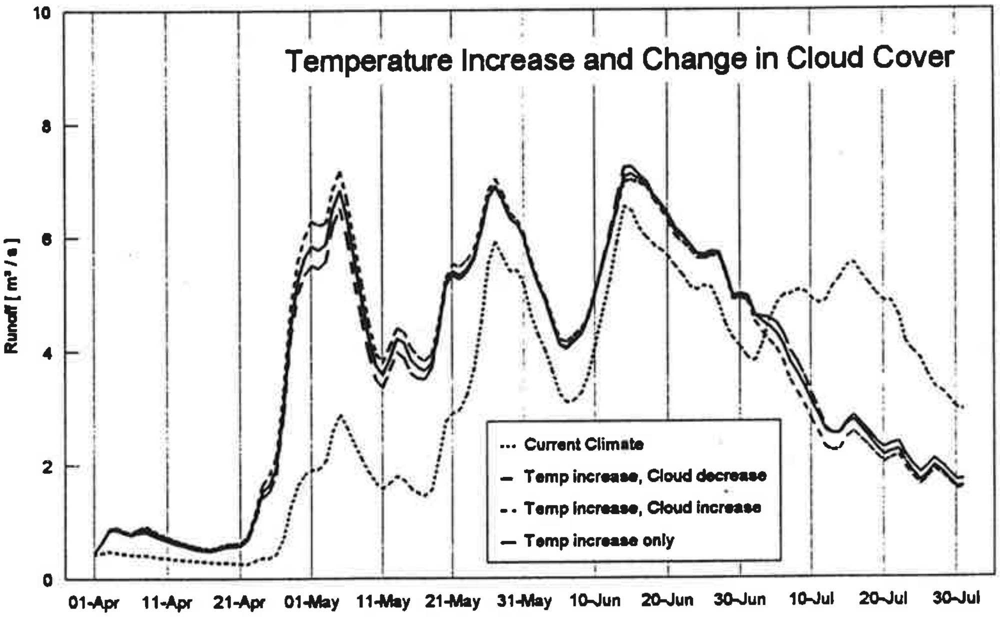

Fig. 3. Model-simulated runoff hydrographs, based on the 1977 melt season in Dischma basin, for the current climate, and a warmed (by 3 °C) climate, with decreased cloud amount, increased cloud amount, and no change in cloud amount.

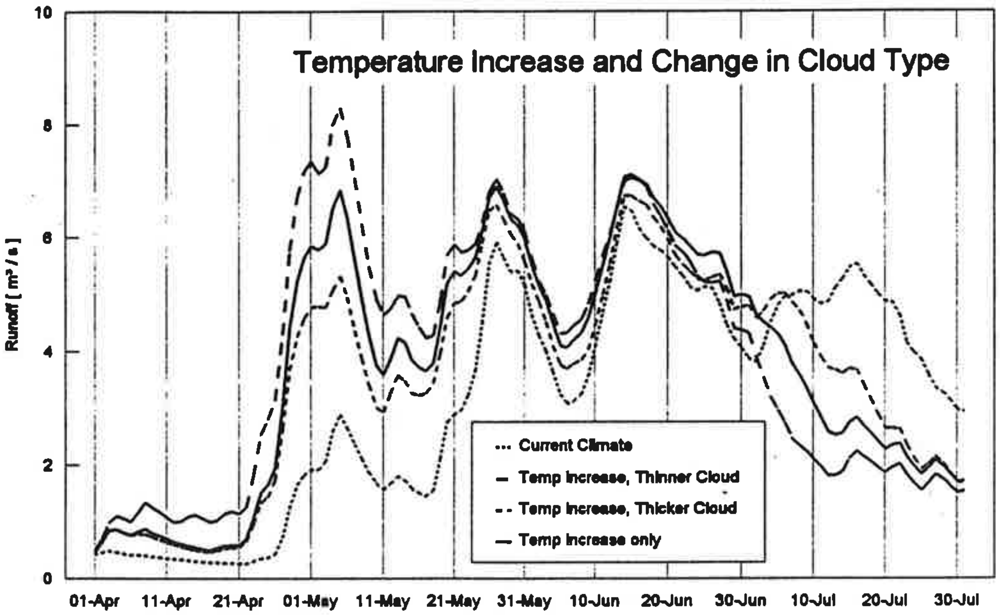

Fig. 4. Simulated climate-change scenarios based on the 1977 melt season in Dischma basin, for a warmer (by 3 °C) climate, with optically thinner, optically thicker, and unchanged clouds.

melt, as reflected by a slightly higher peak in runoff at 4 May. Intuitively, one would expect that as more clouds allow less sunlight, less melt would occur. However, clouds are significant radiators in the longwave, and this unexpected result reflects an increase in the L_{atm} term when cloud cover is increased, offsetting the decrease in the K_{in} term.

Cloud type (thickness)

Cloud type is represented in the SRM Radiation model by a mathematical expression for cloud optical thickness. This term depends on the frequency distribution of water droplet sizes in the cloud (Liou, 1992). Figure 4 shows the simulation results when this expression is changed to represent, respectively, optically thinner clouds (such as low stratus) and optically thicker clouds (such as nimbostratus or fair-weather cumulus), in addition to the 3 °C temperature increase. In these experiments, the cloud-cover fraction is held the same as in the 1977 observations, which is not totally consistent with the assumed change in cloud type. However, the experiment allows us to observe the model's sensitivity to the cloud optical thickness, which affects only the K_{in} term in Equation (4). As expected, optically thinner clouds allow more solar energy to reach the surface, further enhancing the shift in the runoff hydrograph to earlier in the melt season. In the other simulation, optically thicker clouds partially offset the effect of the temperature change.

DECREASED SNOWFALL

Year-round increases in temperature could lead to a greater fraction of winter precipitation falling as rain, rather than snow, and a resulting decrease in the water

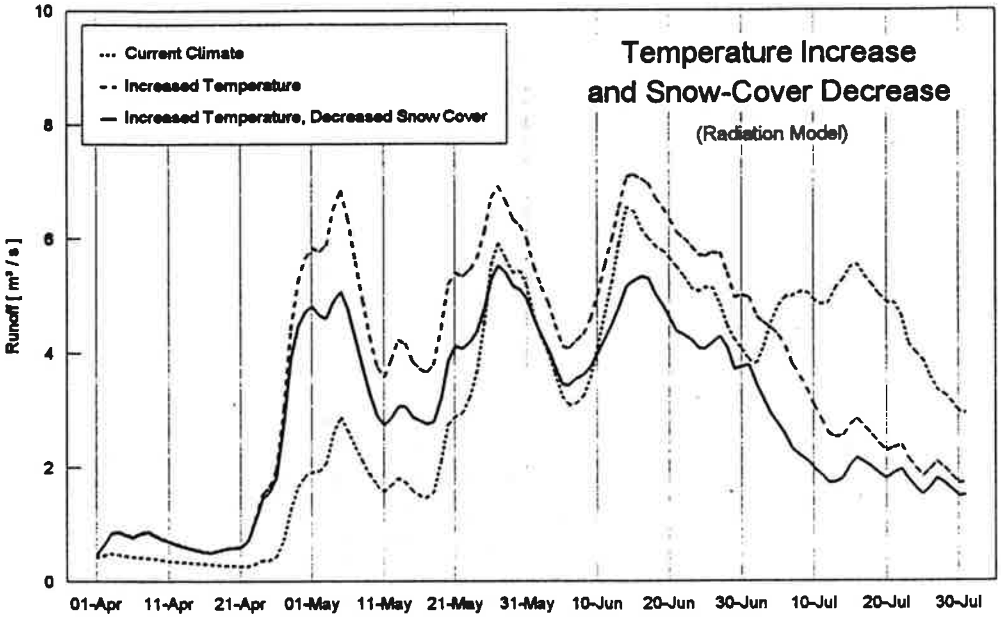

Fig. 5. Simulated runoff hydrographs based on the 1977 melt season for Dischma basin, for current climate and a warmer (by 3 °C) climate with the same and a decreased snowpack at the beginning of the melt season.

equivalent of the snowpack. SRM is not a snow accumulation model, and the simulations described in this paper are seasonal rather than year-round. The response of melt-season runoff to a reduced winter snowpack, in addition to warmer temperatures, is simulated by shifting the observed snow-covered area (SCA) curves to represent a decreased snow-water equivalent at the beginning of the melt season. In this experiment, the curves are simply (and arbitrarily) shifted by one-half month, so that the SCA on 16 April in the current climate becomes the SCA on 1 April in the "changed" climate. The decline of SCA after that date is adjusted by the modified-depletion-curve technique in SRM. Rango and Martinec (1994) describe a more rigorous procedure to estimate the time shift of snow cover, taking into account changes in winter-season precipitation (snowfall) as well as temperature. The result (Figure 5) is a dramatic decrease in the seasonal volume of runoff in response to the warmed climate.

6. Summary

In mountainous regions where snowmelt is a major factor in runoff production, a warmer climate can be expected to shift the runoff hydrograph earlier into the winter and spring at the expense of summer runoff. However, other climatic changes may accompany regional warming, including changes in precipitation and cloudiness patterns. The simulation results presented in this paper are intended as sensitivity studies, and not predictions of basin response; in addition, because the simplified radiation balance does not account for vegetation, these results are not necessarily applicable to forested basins.

Simple experiments based on the 1977 melt season in the Dischma basin, Swiss Alps, demonstrate that, due to the important role of clouds in determining the radiation received at the Earth's surface, changes in cloud amount or type might exacerbate or compensate for temperature-driven changes in runoff, depending on the direction and magnitude of these changes. Improved satellite observations of clouds are becoming available (Simpson and Gobat, 1995), which should allow improvements in radiation-based snowmelt simulation. A better understanding of present cloud climatology and cloud physics will improve the scientific community's ability to predict what changes in regional cloud patterns and precipitation are likely to result from large-scale global warming.

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