Exchange Processes at the Land Surface for a Range of Space and Time Scales

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Catchment hydrological responses to climate changes calculated from incomplete climatological data

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Abstract The long-term hydrological responses of the medium-sized mountainous Mesochora catchment to climate changes were extensively analysed. The climate changes were imposed with a set of hypothetical and monthly GISS (Goddard Institute for Space Studies) scenarios of temperature increases, coupled with precipitation changes. The US National Weather Service snowmelt and rainfall-runoff models used in this study, were accepted as input historical climatological data which were integrated over area and elevation range from incomplete point records. Both sets of climate change scenarios resulted in decreases in snow accumulation and in spring and summer runoff, as well as increases in winter runoff and spring evapotranspiration. Differences in hydrological numerical results among all climate cases were due to the wide range of changes in the climate variables.

INTRODUCTION

Present general circulation models (GCMs) can only grossly simulate the observed large-scale features of the climate, as well as the long-term seasonal circulation. Much more, they cannot simulate accurately observed regional or local climatic features (temperature, precipitation, etc) that are needed for making detailed assessments and predictions of hydrological, ecological, agricultural, and societal impacts. Therefore, the few attempts to validate GCM simulations of present surface climatological conditions using observed surface climatological data are limited only to long-term climatic averages over large areas (Wallis *et al.*, 1991).

Thus, for hydrological design areas (basins, sub-basins, etc) the coupling of GCM predictions and hydrological models is achieved through the adjustment of present day surface climatological data, to account for climate change scenarios. Yet, any calibration for climate studies demands accurate and physical climatic information (Hutchinson, 1990; Wallis *et al.*, 1991). This information is not so easy to obtain in mountainous regions where the high slopes and strong wind affect the measurement of true precipitation. In addition, the harsh conditions cause instruments to malfunction more frequently, thereby leading to gaps in the records, as well as to non-homogeneity when instruments have to be replaced or recalibrated.

This paper deals with the long-term hydrological responses (snow water equivalent, runoff and actual evapotranspiration) of a medium-sized mountainous catchment to hypothetical and GISS (Goddard Institute for Space Studies) modelled climate changes. The climatological data used in the study included incomplete point values of daily precipitation and minimum/maximum temperature. In order to preserve the physical nature of climatic information and avoid the errors caused by the interpolation techniques (Georgakakos & Krajewski, 1991; Wallis *et al.*, 1991), we did not estimate the unavailable values, but integrated instead the existing ones for areal variation and change with elevation.

HYDROLOGICAL DESIGN

We selected the Mesochora catchment of the Acheloos River in Central Greece for an analysis of the hydrological responses to global climate changes (Panagoulia, 1990). The basic criterion for this selection was its geographical and hydrological significance due to the partial diversion of the river for irrigation and hydropower purposes. The part of the river which drains the Mesochora catchment flows freely (no upstream diversions or flow regulations). The network of meteorological stations installed in and around the catchment is relatively dense, but 3.5% of daily precipitation values and 15.5% of daily min-and-max temperature values were missing for the 15-year period used in this study (1972-1986). The climate in the Mesochora catchment is elevation-dependent, with hot summers and mild winters at low elevations and mild summers and cold winters at high elevations. Because of its high mean elevation (1390 m), its hydrology is controlled by snowfall and snowmelt.

The catchment area is 632.8 km^2, its annual precipitation is 189.8 cm and its runoff is 117.0 cm. A more detailed description of the catchment has been presented by Panagoulia (1991a, 1992a, 1992b).

The methodology of conceptual hydrological simulation was adopted in this study for reasons of detailed representation of a medium-sized catchment. Two hydrological models were used : the snow accumulation and ablation model of Anderson (1973) and the soil moisture accounting model of Burnash *et al.* (1973). The snowmelt model describes the change in storage of water and heat in the snowpack, based on six-hourly precipitation and temperature data. The runoff model accounts for the flux of soil moisture between five conceptual storages zones. The runoff model accepts as inputs the snowmelt model output "daily rain plus melt" and long-term average monthly potential evapotranspiration, which in this study was estimated from the Penman equation (Veihmeyer, 1964).

For better performance of the snowmelt model, the catchment was divided into three elevation zones (about 30% of total area for each of the upper and middle zones and 40% for the lower zone). Eleven precipitation stations and three temperature stations were operated. Because the daily precipitation records were incomplete, the zone areal precipitation was assessed through the Thiessen method for all the combinations of zone stations which were yielding data for that particular day. The estimated zone areal precipitation was corrected for the median zone elevation. The above mentioned combination technique was also used to estimate the zone areal daily max-and-min temperature (Panagoulia, 1992a). The study catchment mean areal precipitation (MAP) was taken as the average of the snowmelt output over the elevation zones (the weighting was proportional to the elevation zone areas). The MAP was then used as input to soil moisture accounting model.

The calibration period was 15 years for both models. The models were manually calibrated (Peck, 1976) and their final parameter estimates were obtained through a trial-and-error approach, which was carried out concurrently for both models. The typical monthly simulation errors (monthly differences between simulated and observed streamflows), expressed as a percentage of observed flows, were of the order of 10-15% (except for the August and September runoff which reached 23%). The plot of the long term annual mean catchment pseudo-precipitation (rain plus melt) over 15 years showed three distinct periods with different climate conditions. A modified differential split sample test was implemented in order to verify the ability of the soil moisture accounting model (and hence the snowmelt model) to respond to the three different climate periods. Details of the development, calibration, and statistical verification of the models are presented in Panagoulia (1990, 1992a).

The historical input data were adjusted to reflect the altered climates simulated by (a) fifteen hypothetical scenarios denoted as HYPO(âT,âP), where âT is temperature increase by 1,2,4 C and âP is precipitation change by 0, ±10, ±20%, and (b) two GISS-predicted scenarios (with both monthly precipitation and temperature changes GISS(t,p), and with monthly temperature changes alone GISS(t,0)) (Panagoulia 1992b). Thus, all the input precipitation time series were multiplied for the HYPO cases by a uniform factor and the GISS cases by the monthly precipitation ratio (the ratio of monthly precipitation for CO-doubling to the control run, ranging from 0.925 to 1.487) applied for the centre of the catchment (39°34'N latitude and 21°19'E longitude). The HYPO temperature increases were applied uniformly to all daily values of the historical input series, while the GISS-predicted monthly temperature differences (ranging from 3.37 to 4.98 C) between the CO-doubling and control run were added to the input historical data as well.

For the HYPO cases the potential evapotranspiration (PET) was computed using the Penman equation with the indicated temperature increases, which were applied uniformly to the historical monthly temperature data. For the GISS cases, the PET was also computed with the same equation for the monthly temperature data for the CO-doubling and the control run. The monthly differences in PET were computed and these differences were then added to the historical PET data. The other variables (wind speed, humidity, solar radiation, etc) remained unaltered in the Penman equation for both HYPO and GISS cases.

HYDROLOGICAL RESPONSES

Because the catchment hydrology was simulated for 15 years and 18 alternative climates (one is the base case), large amounts of computer output were generated. This paper restricts the analysis of the hydrological responses to three variables: monthly mean snow water equivalent over the catchment, monthly mean catchment runoff (streamflow), and monthly mean catchment evapotranspiration. The monthly mean soil moisture storages in the five conceptual storage zones are excluded from this paper. They are described in other studies (Panagoulia, 1991a,b). The hydrological scenarios of the above three variables are plotted in Figs 1-3 and a brief interpretation of these figures follows.

Snow water equivalent

The long-term monthly snow water equivalent over the study catchment for all alternative climates is presented in Fig. 1. There was a marked reduction in average snow water equivalent for all alternative scenarios. The GISS scenarios and the HYPO(4,all) produced the maximum reduction in snow water equivalent. They

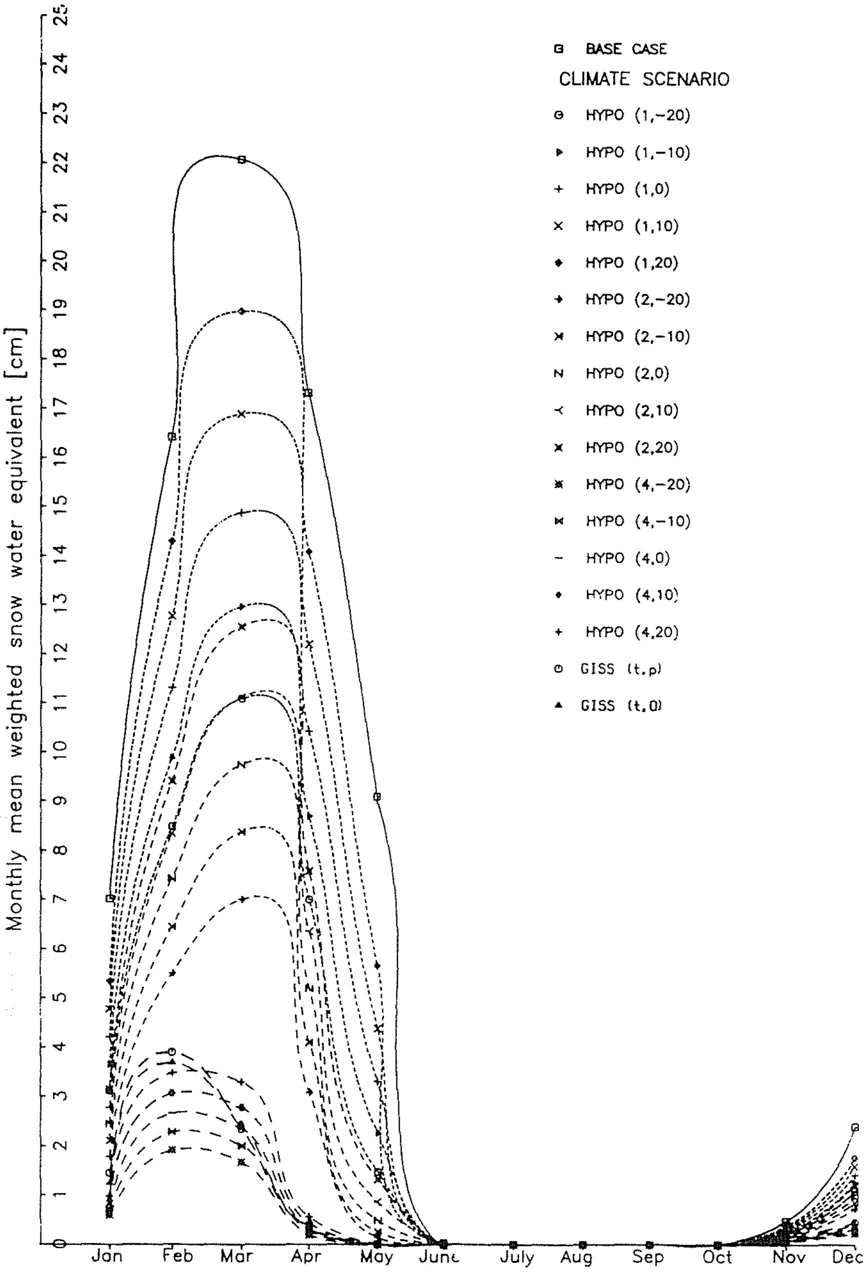

Fig. 1 Mesochora catchment monthly mean snow water equivalent for the HYPO, GISS and base case climate scenarios.

generally generated similar annual snow water equivalent hydrographs in the same month of snow maximization, extinction and return. But there is a difference in snow water profiles: the HYPO(4,all) cases yielded hydrographs with obviously flatter crest than that of GISS ones. This is because the GISS-predicted climate changes have different monthly values, while those of HYPO are the same within the month. Searching, on a monthly basis, for equivalencies among all the scenarios, those characterized by 4°C increase appeared to be more similar. This is perhaps due to the fact that the average of the GISS monthly temperature increases is 3.94°C, a value which is approximately the same with that of HYPO(4,all) scenarios.

Runoff

Figure 2 shows significant changes in the seasonal distribution of Mesochora catchment runoff for all 17 climate scenarios. The effect of reduced snow storages and change in the timing of snowmelt (Fig. 1) are seen clearly in all runoff responses. The annual hydrograph peak shifted to earlier in the year because of a decrease in the amount of snowfall in relation to rainfall. The summer runoff went down considerably in GISS scenarios and 14 of the 15 HYPO cases. The summer runoff resulting from the scenarios HYPO(1,20) went up a little due to the small increase of the temperature and large precipitation increase. The winter runoff increased in the two GISS scenarios and 10 of the 15 HYPO cases. It decreased in the case of the climate scenarios HYPO(1,10), HYPO(2,10) and HYPO(all,20). For the April to August period the scenarios of HYPO(1,-20) and HYPO(2,-10) are similar to GISS(t,p).

Evapotranspiration

The actual evapotranspiration (ET) simulated by the soil moisture accounting model depends on soil moisture status, as well as on PET. Therefore, although PET increased for all months and climates (HYPO and GISS) due to temperature rise, the direction of change in ET varied from season to season. During the wet November-April period, ET remained unaffected by precipitation changes (Fig. 3), but increased in relation to base case ET. During the dry May-October period ET increased with precipitation increase and decreased with precipitation reduction.

The peak value of monthly ET occurred in June for the base case and 9 of the 15 HYPO scenarios, while the other 6 scenarios (characterized by precipitation reduction), as well as the GISS climates peaked in May. The GISS scenarios as well as those of HYPO ones with minor precipitation reduction showed a flatter crest in the monthly distribution of ET. For the winter months the GISS scenarios are similar to HYPO(4,all).

CONCLUSIONS

The main conclusions from the present study are as follows:

— The monthly distribution patterns of the catchment hydrological variables for

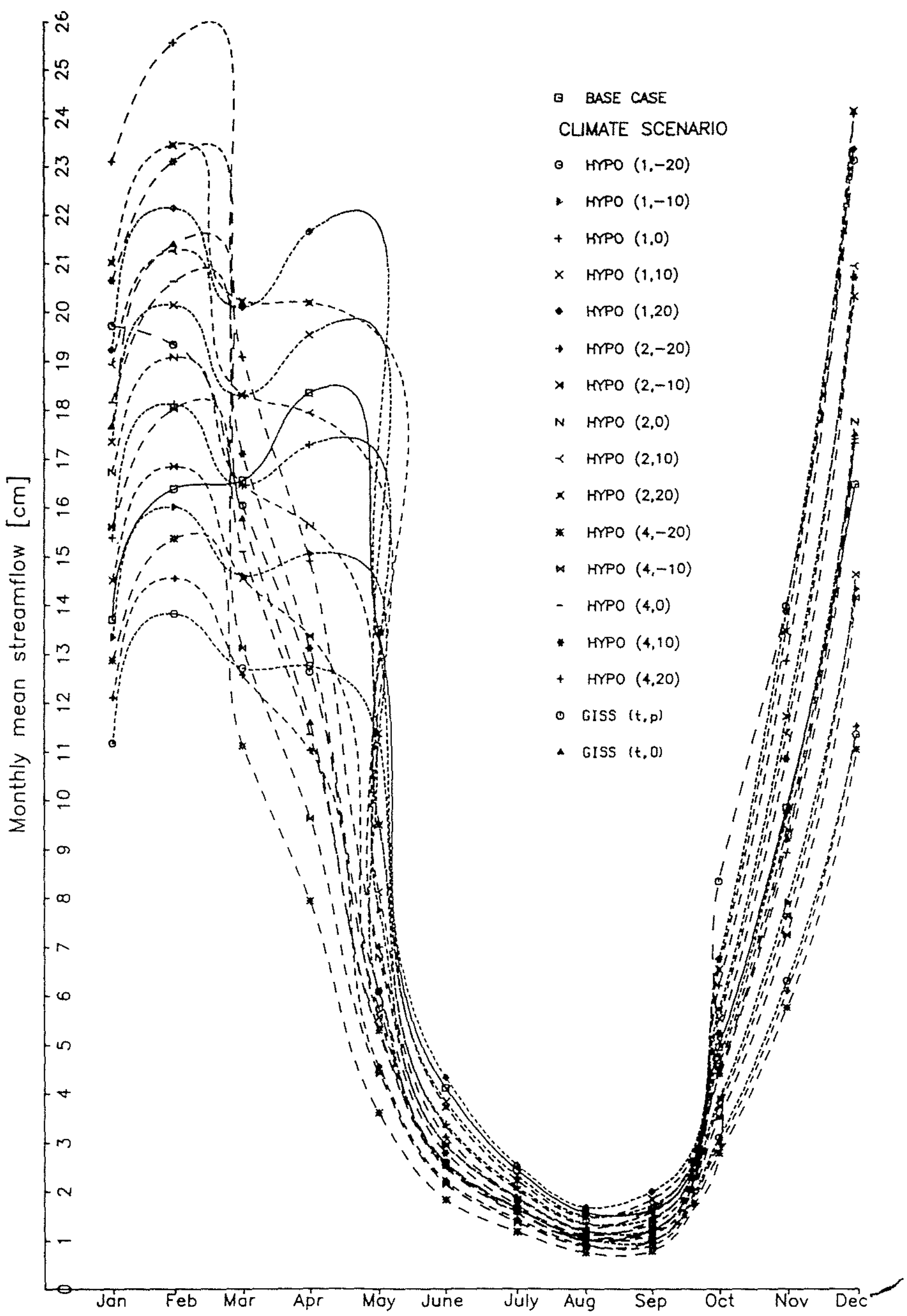

Fig. 2 Mesochora catchment monthly mean runoff for the HYPO, GISS and base case climate scenarios.

HYPO and GISS climate scenarios are very similar. Both cases showed that increased temperature would reduce considerably the snow accumulation over the study catchment.The decrease in the precipitation falling as snow would increase the winter runoff and decrease, as well, the spring and summer runoff. Also the

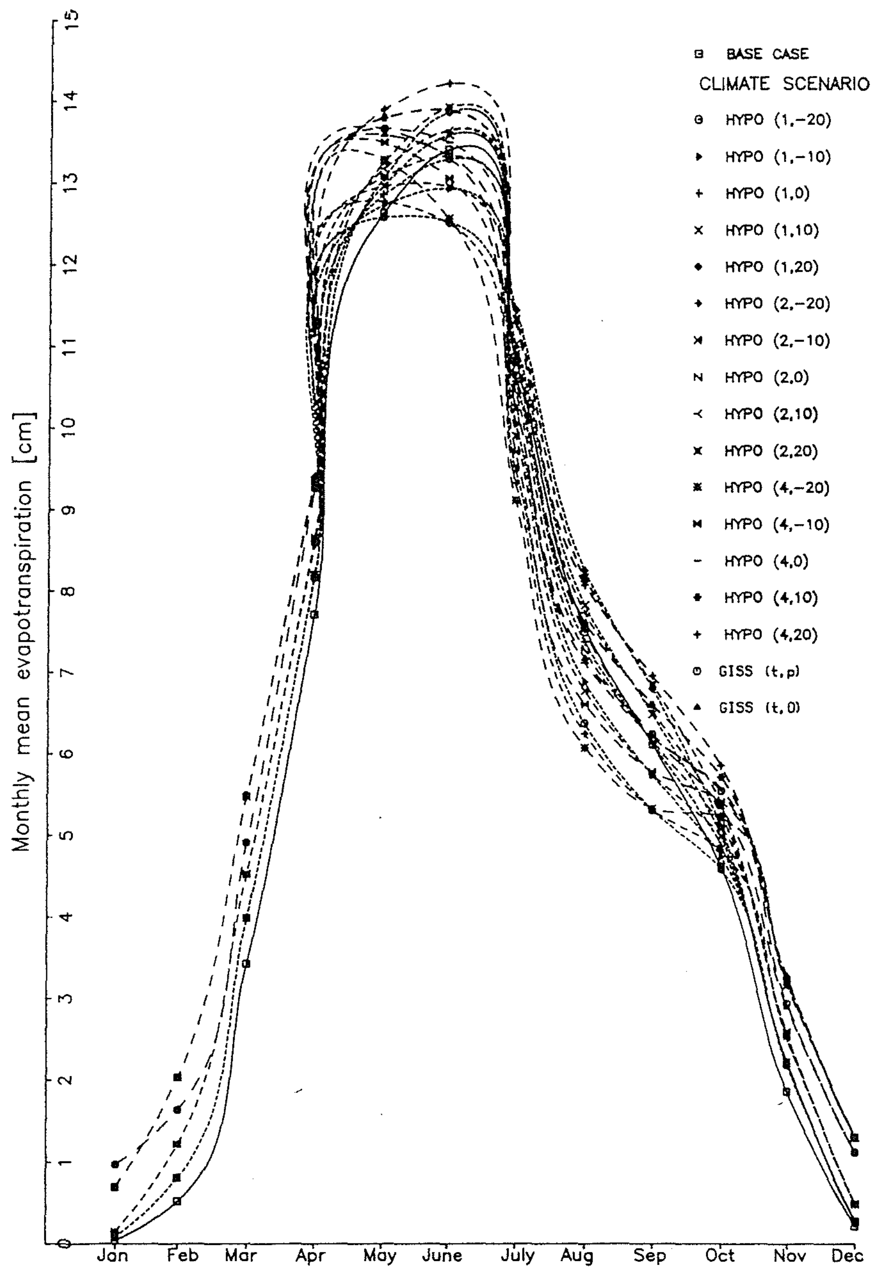

Fig. 3 Mesochora catchment monthly mean evapotranspiration for the HYPO, GISS and base case climate scenarios.

increase in precipitation amount falling as rain would increase the winter soil moisture, thereby leaving much more moisture for evapotranspiration early in the spring.

– Significant differences were noted in hydrological numerical results among the two GISS scenarios and HYPO scenarios due to the wide range of the climate variables changes (e.g. the GISS precipitation increase in October was up 50%).

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