Impacts of GISS-modelled climate changes on catchment hydrology

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Abstract The hydrological regime of a mountainous catchment, in this instance the Mesochora catchment in Central Greece, was simulated for altered climates resulting when using the Goddard Institute for Space Studies (GISS) model for carbon dioxide doubling. The catchment snow water equivalent was predicted on the basis of the snow accumulation and ablation model of the US National Weather Service River Forecast System (NWSRFS), while the catchment runoff, as well as actual evapotranspiration and soil moisture storages, were simulated through application of the soil moisture accounting model of NWSRFS. Two scenarios of monthly climate change were drawn from the GISS model, one associated with temperature and precipitation changes, while the other referred to temperature changes alone. A third hypothetical scenario with temperature and precipitation changes similar to those corresponding to the mean monthly GISS scenarios was used to test the sensitivity of the monthly climate change of the hypothetical case on catchment hydrology. All three scenarios projected decreases in average snow accumulations and in spring and summer runoff and soil moisture, as well as increases in winter runoff and soil moisture storage and spring evapotranspiration.

Conséquences sur l'hydrologie d'un bassin des changements climatiques par application du modèle GISS

Résumé Le régime hydrologique d'un bassin montagneux, en l'occurrence le bassin de Mesochora en Grèce Centrale, fut simulé d'après le modèle GISS, cité en rubrique (GISS = Institut Goddard de Recherches Spatiales) pour le doublement du bioxyde de carbone. L'équivalent en eau de la neige du bassin fut prédit selon le modèle d'accumulation de neige et d'ablation du Service National Météo des Etats Unis (NWSRFS), tandis que le drainage du bassin, l'évapotranspiration et l'humidité de sol ont été simulés d'après le modèle d'humidité du sol du susdit NWSRFS. Deux scénarios de changement climatique mensuel furent tirés du modèle GISS, un afférent au changements de la température et du régime des précipitations, l'autre aux changements de température uniquement. On a utilisé un troisième scénario hypothétique afférent aux changements de température et de précipitation, pareil à ceux correspondant au mois moyen des scénarios GISS pour éprouver la sensibilité de l'hydrologie du bassin au changement climatique mensuel du scénario hypothétique. Les trois scénarios ont produit des baisses de l'accumulation moyenne de neige et du drainage et de l'humidité terrestre, ainsi que des hausses en écoulement hivernal, en humidité du sol et en évapotranspiration printanière.

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INTRODUCTION

While climate changes over periods of thousands of years are well documented, hydrologists have been rather reluctant to agree for as long as a decade (1960 to 1970) as to whether changes (signals) within typical water resources systems design periods (100 years or less) can indeed be distinguished from random variations (noise) in a physical hydrological time series (US National Academy of Sciences, 1977). The advent of general circulation models (GCMs) over the last decade and consensus about the direction of future global climate change threw light on the controversial theme, thus making acceptable the aspect that climate change does exist.

The continued burning of fossil fuels, plus deforestation and changes in use of land (converting it to urban and industrial use), let alone the increased use of nitrogen fertilizers, as well as large nuclear eruptions and primarily atmospheric pollution, have increased the concentrations of carbon dioxide and other trace gases (e.g. CH_4, N_2O, CFC-11, CFC-12) by about 20% over the last hundred years (US National Academy of Sciences, 1983; Jager, 1983; USEPA, 1983; Bach, 1984; Palutikof *et al.*, 1984; Houghton, 1991; Siegenthaler & Sanhueza, 1991). It is expected that, during the next fifty to eighty years (until 2070), those activities will result in doubling the concentration of CO_2 in the atmosphere (US National Academy of Sciences, 1983; Manabe & Wetherald 1985; MacCracken & Luther 1986; Mitchell & Qingcun, 1991) and, through a "greenhouse" effect, cause a gradual warming of the Earth. By varying the level of carbon dioxide concentration in GCM simulations, the models can provide quantitative estimates (predictions) of climate and hydrological variables for any level of CO_2.

A general circulation model (GCM) solves numerically equations of mass, energy, momentum and state on a global grid of cells (Hansen *et al.*, 1983, 1988; Mitchell & Qingcun, 1991). However, the spatial scale of GCM outputs is inadequate for catchment hydrological simulation. The GCM predictions are provided as spatial averages over areas of the order of 10^4 to 10^5 km^2 (macro-scale), where the fundamental differential equations of the continuum hydro- and thermodynamics can conserve a real-world validity in contrast to the validity of these equations when they are applied to the hydrological modelling of a catchment (meso- and micro-scale simulation) (Becker & Němec, 1987). Furthermore, it is doubtful if GCM predictions on time scales shorter than one month reflect the natural variability of field data, because such predictions represent grid-cell averages.

The study of the impacts of changes in meteorological inputs to a hydrological system requires these inputs to be specified on a time step appropriate for conceptual catchment simulation of storm events. This is because the transfer function of rainfall to runoff is not linear, and also because the infiltration and evapotranspiration processes that play a major role in catchment runoff determination are highly dependent on the storage and movement of water within the soil during a storm occurrence, as well as on the soil moisture state at the beginning of a storm (the determination of soil moisture capacities).

The operation of a soil moisture system requires daily, hourly or even shorter time scales, depending on the size of the river basin. The GCM outputs can be represented on daily or shorter time steps, but it is not clear whether the results with such short scales properly reflect the short term dynamics of the atmospheric circulation process (Lettenmaier & Gan, 1990).

Since an appropriate space-time coupling between, firstly, GCM results (e.g. temperature, precipitation, potential evaporation etc.) and secondly, hydrological models has yet to be achieved, one resorts, for hydrological use, to scenarios of long-term changes of meteorological variables occurring in space and time based on GCM predictions. However, the latter do not yield the direct GCM outputs for carbon dioxide doubling. Therefore the hydrological findings of this paper have only a descriptive character and are limited to alternative scenarios and to sensitivity analysis of hydrological variables to climate changes.

The objectives of this work are:

(a) to investigate, through a conceptual catchment simulation process, the hydrological impacts of GISS-associated predictions of climate change on a medium-sized (of the order of 100 to 1000 km^2) mountainous catchment. The conceptual catchment simulation comprises the snowmelt hydrology that would result from long term precipitation changes, coupled with changes in temperature and potential evapotranspiration; and

(b) to note possible differences and similarities in the findings between the current and a previous study (Panagoulia, 1990b) that pursued the same aim, and used the same methodology and same catchment, but a different climate change interpretation. In the previous study the precipitation and temperature changes were introduced by a choice from a wide range of hypothetical scenarios.

While a lot of work of this sort has taken place (e.g. Němec & Schaake, 1982; Rosenzweig, 1985; Gleick, 1986, 1987; Cohen, 1986, 1987; Liebscher, 1989; Budyko, 1989; Lins *et al.*, 1991) the ones most similar to the present study (as regards the methodology used and climate change interpretation) are those of Lettenmaier (Lettenmaier *et al.*, 1988 and Lettenmaier & Gan 1990) and an EPA report (USEPA, 1989). Those studies attempted to interpret the hydrological impacts of the Geophysical Fluid Dynamics Laboratory (GFDL), GISS and Oregon State University (OSU) scenarios of climate change in an ensemble of four catchments in the Sacramento-San Joaquin river basin, California. Two of the catchments involved, the Thomas Creek and North Fork American situated in the middle of the part of the Central Valley modelled by Lettenmaier *et al.* (1988), have the latitude of the catchment used in this study. A brief comparison of the several results is attempted.

STUDY CATCHMENT AND CLIMATE CHANGE SCENARIOS

The Mesochora catchment, which is drained by the upper Acheloos river, was selected for study purposes thanks to its geographical and hydrological significance, plus the absence of upstream diversions or flow regulation, as well as to the availability of hydrological and meteorological records. A relatively dense network of hydrometeorological stations is installed (Fig. 1). At the catchment outfall, the river will be partially diverted to irrigate the arid Thessaly Plain and boost the hydropower generation of the surrounding region.

The Mesochora catchment (632.8 km^2, Fig. 1) lies in Central Greece and

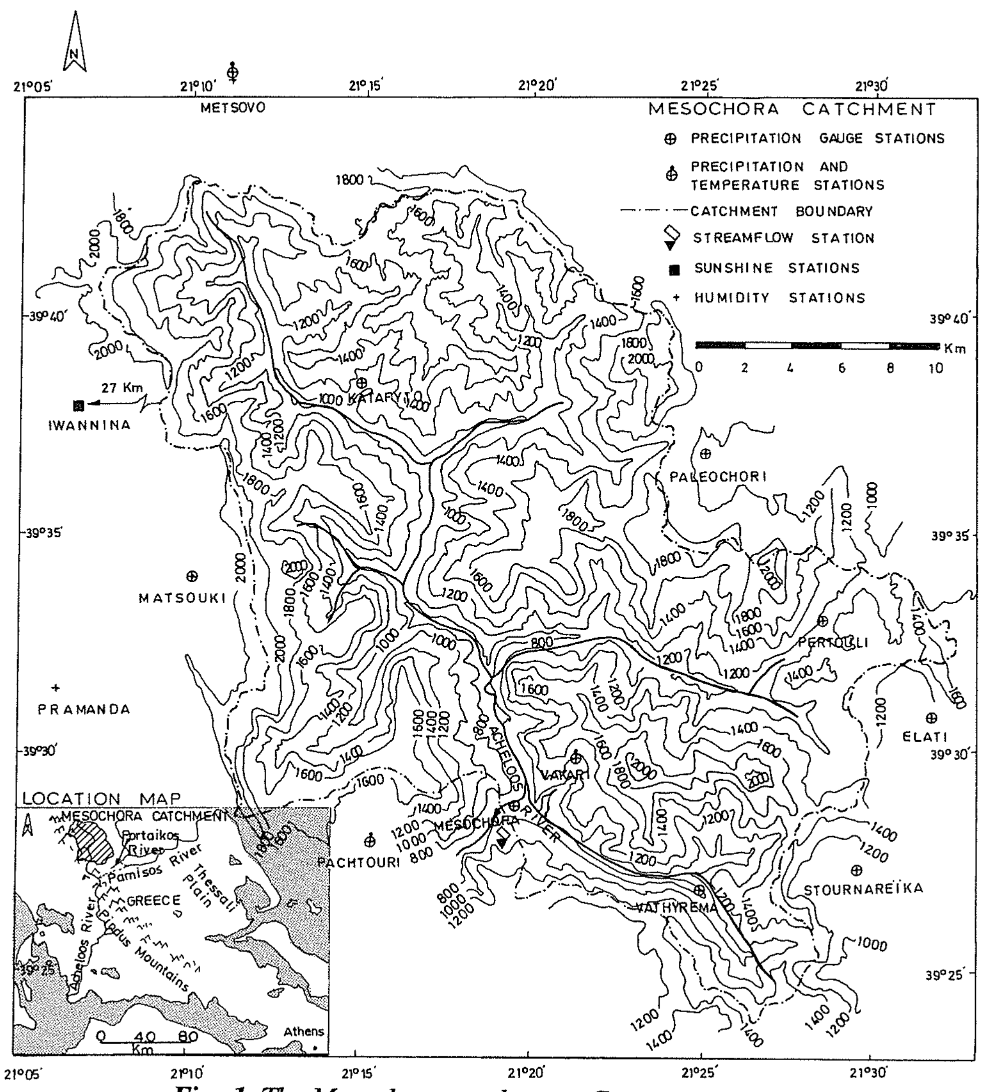

Fig. 1 The Mesochora catchment, Greece: topography and hydrometeorological stations.

extends nearly 32 km from north (39°42′) to south (39°25′) with an average width of about 20 km. A detailed description of the catchment is presented by Panagoulia (1990a). The basic hydrometeorological characteristics of the catchment are assembled in Table 1.

Table 1 *Basic hydrometeorological characteristics of the Mesochora catchment*

Catchment area km^2	Mean annual precipitation mm	Mean annual runoff mm	Mean January daily temperature (°C)			Mean July daily temperature °C		
			Daily average	Minimum	Maximum	Daily average	Minimum	Maximum
632.8	1898	1170	0.10	-3.5	3.7	17.5	11.4	23.6

The catchment hydrological regime, interpreted by snow accumulation and ablation, runoff, soil moisture storages and evapotranspiration, has been investigated for the impacts of hypothetical climate change scenarios (Panagoulia, 1990b). Searching for the same aim, a more realistic climate change scenario has been used, viz. the one resulting from the GISS model for CO_2 doubling. The GISS general circulation model was developed by Hansen *et al.* (1983) of the Goddard Institute for Space Studies (NASA) in the USA and ever since it has been evolving continuously. This global model has realistic topography, 8° × 10° (latitude × longitude) resolution in the horizontal and nine layers in the vertical. The model simulates climate by solving the fundamental equations for conservation of mass, energy, momentum and water. The source terms in these equations incorporate numerical representations of the physical processes of radiation, turbulent transfers at the ground-atmosphere boundary, cloud formation, condensation of rain and transport of heat by ocean boundary currents. A complete description of the model appears in Hansen *et al.* (1983). However, there are many uncertainties in the modelling and parameterization of terms. Various processes, such as cloud feedback, are only crudely modelled. Initial conditions of temperatures and precipitation, i.e. control runs, are difficult to determine at all points. As a result, the model is unable to simulate completely the present climate, especially precipitation. When the initial parameterizations are modified by doubling atmospheric CO_2 concentration, any errors inherent in the initial model runs would probably occur in the 2 × CO_2 simulations. Another problem concerns the relatively coarse resolution of the model outputs (8° × 10°).

Despite the limitations on spatial resolution and on hydrological parameterizations of the model, the outputs of the GISS model, as well as certain other similar models, such as the GFDL, OSU and National Center for Atmospheric Research (NCAR) models, are used for the formation of climate change scenarios for several reasons:

(a) to evaluate the strengths and weaknesses of the hydrological mechanisms used by GCMs;

(b) to study the sensitivity of a watershed hydrological system to changes in meteorological variables; and

(c) to throw light on the information required for an appropriate coupling of physically-based hydrological models and climate models.

The model outputs or grid-cell data used in the study were obtained from the Goddard Institute for Space Studies and include average monthly air temperature and precipitation for a control run (1 × CO_2) and the GISS 2 × CO_2 experiment. The runs were integrated for 35 years and the data provided are the average figures for each month over the last 10 years.

The data are the average values over an 8° × 10° cell, with the data-point references located at the centre of each cell. Data for all cells of the global grid were also obtained as above. Three cells were determined: one lies within Greece, and two surrounding. The centres of the three cells have the coordinates: 34°42′N latitude and 20°0′E longitude; 35°42′N latitude and 21°0′E longitude; and 43°42′N latitude and 20°0′E longitude. The data for the first cell were interpolated, using the centre data of the other two cells, to latitude 39°34′N and longitude 21°19′E, which is approximately the centroid of the Mesochora catchment. The temperature difference between the 2 × CO_2 and control run on a monthly basis yielded the monthly temperature change scenario (Table 2, Fig. 2), while the ratio of the 2 × CO_2 monthly precipitation to the control run monthly precipitation provided the scenario of relative precipitation change. The temperature changes combined with precipitation changes formed the full GISS climate change scenario, while the temperature change alone scenario was characterized as a sensitivity scenario of the hydrological regime of the catchment to the full GISS scenario.

Table 2 *Temperature changes in °C and precipitation scaling factors for GISS model scenario*

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature changes in °C	3.37	4.33	4.09	4.98	4.20	3.47	3.36	4.08	4.51	3.80	4.05	3.09
Precipitation scaling factor	1.029	0.828	1.050	1.089	1.049	0.925	1.204	1.048	0.959	1.487	1.190	1.133

METHODOLOGY AND ALTERED CLIMATE INPUTS

The methodology of conceptual catchment simulation was adopted in this work for reasons of detailed representation of catchment hydrological processes and comparison between the impacts on the hydrological regime that have the hypothetical scenarios of climate change (Panagoulia, 1990b) and those resulting from the GISS model. Actually, the snow accumulation and ablation model (Anderson, 1973) and the soil moisture accounting model (Burnash *et al.*, 1973) of the US National Weather Service river forecast system were used. The minimum and maximum daily temperatures, as well as the daily precipi-

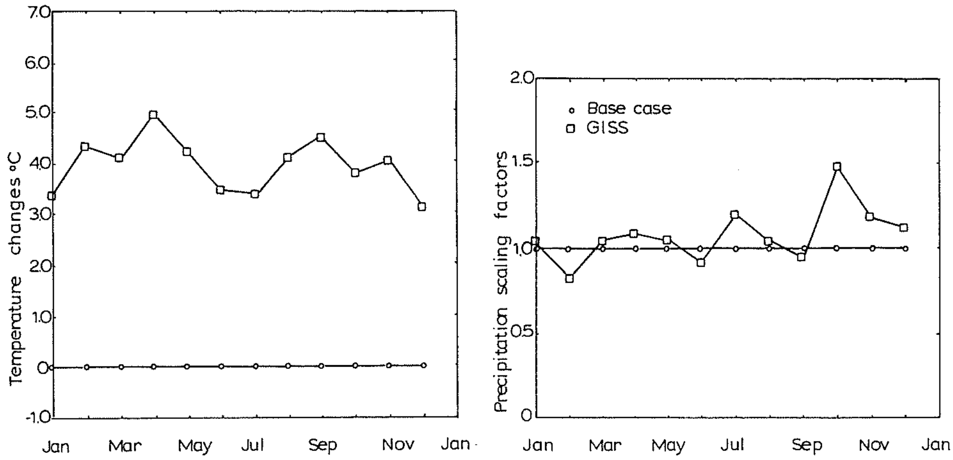

***Fig. 2** Monthly temperature changes and precipitation scaling factors for base case and GISS climate change scenario.*

tation for fifteen consecutive years were used as inputs to the snow accumulation and ablation model. The output of this model, daily rain plus melt, was used as input to the soil moisture accounting model, as also was the monthly long term average catchment potential evapotranspiration, which was computed using the Penman equation (Veihmeyer, 1963). A detailed description of the models, their calibration on the catchment historical data, and their statistical verification is presented by Panagoulia (1990a, 1990b).

The historical input data were adjusted to reflect the altered climates simulated by each of two GISS-conceived scenarios. Thus, all the input precipitation records were multiplied by the monthly precipitation ratio for the CO_2-doubling and control runs. The monthly temperature difference between the CO_2-doubling run and control run was added to the input historical data too. The potential evapotranspiration (*PET*) was computed using the Penman equation for two different sets of monthly temperature data for the CO_2-doubling run and the control run, while all the other variables (wind speed, humidity, solar radiation, etc.) in the Penman equation remained unaltered. The monthly differences in *PET* were computed and the resulting differences were then added to the historic *PET* data used as input to the soil moisture accounting model.

ANALYSIS OF RESULTS

As described previously, the long term hydrological response of the Mesochora catchment was simulated for the current climate conditions (base case), the full GISS climate change scenario (monthly change in precipitation and temperature), and the alternative GISS scenario associated with temperature changes (monthly) only, in order to study the sensitivity of the catchment hydrology to precipitation changes. Because the catchment hydrology was simulated for fifteen years and three alternative climates (one is the base case), a great volume of data was obtained. To simplify the analysis of the results, five variables were selected: monthly average catchment runoff, long term average snow water equivalent over the catchment, monthly average catchment evapotranspiration and monthly average catchment soil moisture storages in the conceptual model zones. For all climate cases, the mean of each variable was computed for the 15-year simulation period.

Before presenting the results, it is important to discuss the climate scenarios in order to highlight their character. Thus, change in temperature consists of average increases for all months with maximum value in April and minimum in December (Table 2, Fig. 2). The precipitation increases in nine months of the year and decreases in the months February, June and December (Table 2, Fig. 2). The largest precipitation increase occurs in October and the largest reduction in February. The mean monthly temperature increase is 3.94°C, practically the same as the temperature increase of 4°C of the hypothetical scenarios (Panagoulia, 1990b). The mean monthly precipitation increases by 8.3% and this value approximates the hypothetical scenario precipitation increase of 10% (Panagoulia, 1990b). Therefore, it is expected that the hydrological results of the GISS scenarios will approach those of the combined hypothetical scenarios of 4°C temperature increase and 10% precipitation increase. This expectation will be tested during analysis of the results for each variable separately.

The full climate change scenario, as well as each of the alternatively generated eight GISS scenarios of the catchment hydrological response (due to eight variables which simulate the catchment hydrology), together with another eight scenarios for the base case, are plotted in Figs 3 to 10 for each variable. The scenarios are described below.

Snow water equivalent

The hydrology of the Mesochora catchment is dominated by high elevation snow accumulation in winter and snowmelt in spring and the first summer month (June). The mean (long term) monthly snow water equivalent over the catchment for the two GISS scenarios and base case are presented in Fig. 3. This Figure shows a large reduction in the average snow water equivalent and a clear change in the timing of snowmelt for both GISS scenarios in relation to that of the base case. The snow water equivalent is maximized in February, one month earlier than the base case maximization, and ceases in May, two months earlier than that of the base case. It comes back in November for all climate cases.

The difference between the two GISS scenarios indicates the sensitivity

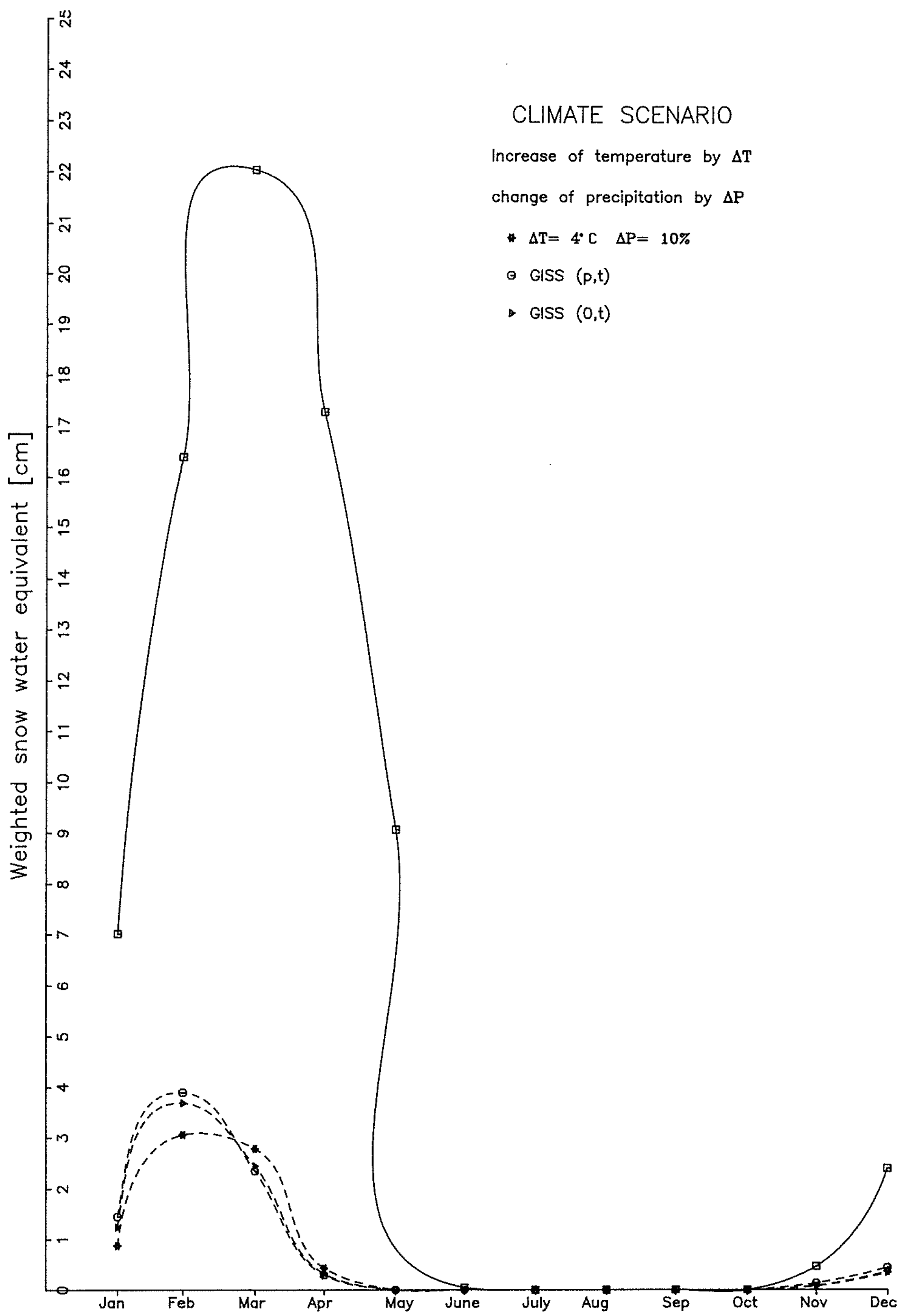

Fig. 3 *Mesochora catchment: monthly mean snow water equivalent for GISS model climate scenarios, hypothetical and base cases.*

of the snow water equivalent to the GISS-predicted temperature changes alone. There are relatively small differences between those two scenarios which confirms the fact that changes in winter snow accumulation are primarily temperature-dependent. As regards the GISS scenarios and the combined hypothetical one (temperature increase by 4°C and precipitation increase by 10%), all scenarios generate similar annual snow water equivalent hydrographs in the same month of snow maximization, extinction and return (Fig. 3). This general picture presents all the hypothetical scenarios that combine the temperature increase of 4°C with the mean annual precipitation changes by ±20%, ±10% and 0 (Panagoulia, 1990b), confirming also the fact that snow accumulation is, above all, temperature-dependent.

Regarding the Lettenmaier *et al.* study (1988), the Thomas Creek catchment presents exactly the same monthly snowmelt patterns and maximum monthly percentage reductions of snow water equivalent (80-85%), compared to those of the present study for full and sensitivity GISS climate change scenarios. For the North Fork American catchment, the results are similar too, with the difference that the snow water equivalent maximization is one month later.

Runoff

Figure 4 shows the changes in the seasonal distribution of Mesochora catchment runoff. Summer (June, July, August) runoff goes down considerably and it falls for GISS scenarios to 35% in relation to the base case. Winter (December, January, February) runoff goes up by 35% for the full GISS scenario and just 22% for the alternative one. The same reduction percentage compared to summer runoff is explained by the fact that the temperature increase is the same for both GISS scenarios, while the precipitation does not play a major role in runoff for the two GISS scenarios is due to a rather high precipitation increase in December. As regards the hypothetical scenario, this decreases the summer runoff by 30% and increases the winter runoff by 40%, percentages that are near those of the full GISS scenario.

Studying the monthly runoff with a full GISS scenario, runoff increases considerably in wet months (October to February) and decreases likewise in spring and summer. Maximum runoff increase occurs in October due to precipitation increase, while maximum runoff decrease is observed in May, having integrated the snowmelt and the shift of runoff to the winter months. The sensitivity GISS scenario reduces the May runoff by a similar percentage and this is to be expected since temperature, which causes snowmelt, is the same. This scenario decreases the runoff in the remaining months of the year, except for the hard winter ones (December, January, February), during which the runoff increases and reaches its maximum in February. The known hypothetical scenario increases the runoff during the period of October-March, a fact that occurs for the full GISS scenario too. For this last scenario, the maximum

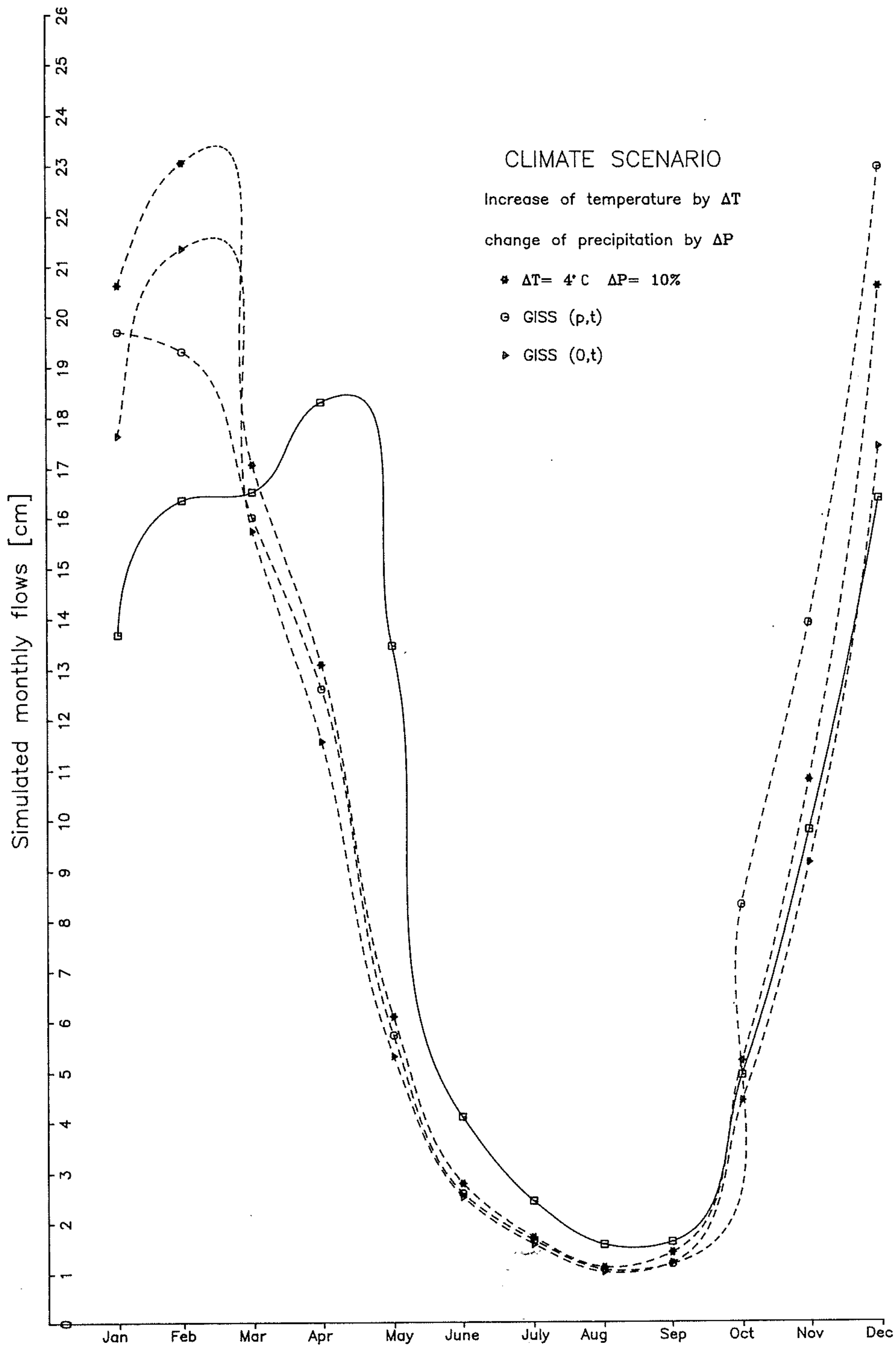

***Fig. 4** Mesochora catchment: monthly mean streamflow for GISS model climate scenarios, hypothetical and base cases.*

runoff increase occurs in January and this is a clear effect of the earlier snowmelt and rainfall augmentation relative to precipitation. The largest decrease in runoff occurs in May, just as it does for the two GISS scenarios.

The predicted changes in annual runoff relative to the base case are 4.9% increase for the full GISS scenario, 8.6% decrease for the alternative GISS scenario and 3.7% increase for the hypothetical scenario. As may be seen, the annual runoff changes are small, their monthly distributions presenting very large changes, as described above.

The effects of reduced snow storage and change in the timing of snowmelt (Fig. 3) are seen clearly in all runoff scenarios. The annual runoff hydrograph peak shifted earlier in the year because of a decrease in the amount of snowfall in relation to rainfall. For the full GISS scenario, the annual hydrograph peak shifted earlier by four months in relation to the peak month of the base case (from April to December), while the runoff peak for the alternative GISS scenario shifted from April to January. Despite the winter runoff differences between the two GISS scenarios, Fig. 4 shows that the profile of monthly runoff distributions is more or less the same due certainly to the same temperature increase which determines whether precipitation falls as snow or rain.

For both GISS scenarios, the catchments in the Central Valley of California present similar monthly runoff patterns to those of Mesochora. For the full GISS scenario, the California catchments present the same month of runoff minimization and one month earlier for the sensitivity GISS case. This difference probably is due to the precipitation falling as rainfall and to the earlier snowmelt due to slightly higher temperatures (mean January temperatures: 1.7 and 4.5°C for the base case) than those of Mesochora. The month of maximum runoff reduction is the same for all three catchments.

Evapotranspiration

As described previously, potential evapotranspiration (*PET*) was computed for the two GISS climate scenarios using the Penman equation with the GISS-predicted temperature changes. The actual evapotranspiration (*ET*) simulated by the soil moisture accounting model depends on soil moisture, as well as on potential evapotranspiration. Therefore, although *PET* was increased for all months in the two GISS scenarios due to temperature increase, the direction of changes in actual evapotranspiration varies from month to month. During the September-October period, the actual *ET* was somewhat affected by precipitation changes, while the same was affected dramatically by high temperature rise in relation to that of the base case (Fig. 5). During the dry summer period (June, July, August), the actual *ET* went down for both GISS scenarios, regardless of precipitation increases.

No doubt the alternative GISS scenario generated larger reductions in actual *ET* because it is associated with temperature changes only. The hypo-

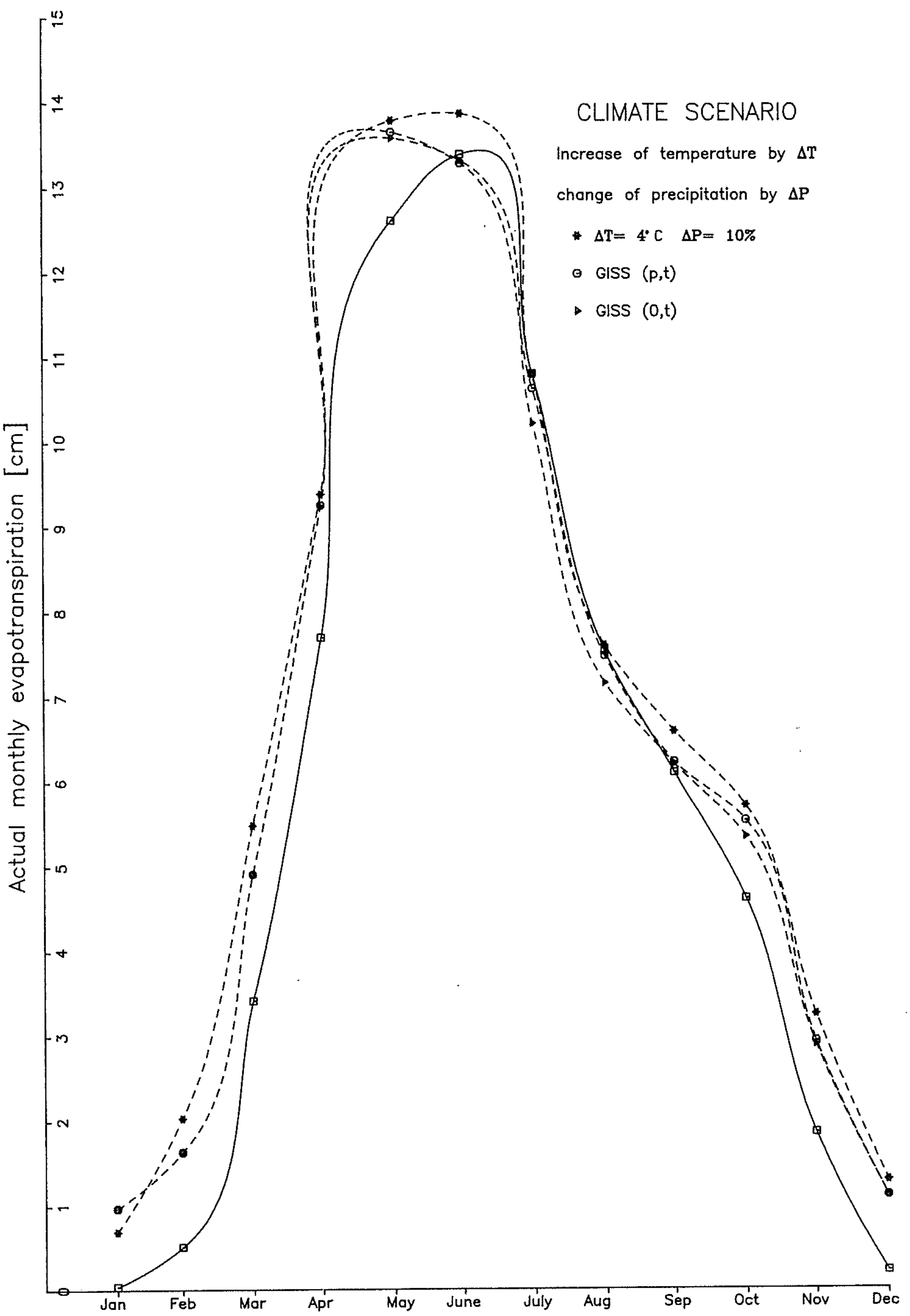

***Fig. 5** Mesochora catchment: monthly mean evapotranspiration for GISS model climate scenarios, hypothetical and base cases.*

thetical climate change scenario presents minor changes (increases) of the actual *ET* in the three summer months, while for the remaining months this scenario gives the same picture relatively of the actual *ET* for the GISS scenarios. The peak of the monthly distribution of actual *ET* occurs in May for both GISS scenarios, while the hypothetical scenario and base case actual *ET* increase markedly in June. All three scenarios of actual *ET* present a flatter crest of the monthly distribution than that of the base case. The GISS scenarios of actual *ET* present the same monthly profile as that of the hypothetical climate change. Despite the changes in monthly distribution of actual *ET*, the changes in annual actual *ET* are small (12.8% for the full GISS scenario, 11.3% for the GISS alternative and 17% for the hypothetical scenario) in relation to the annual actual *ET* of the base case.

The mean monthly evapotranspiration patterns of the California catchments are the same as those of Mesochora for both GISS scenarios, with the same maximization and minimization months of evapotranspiration correspondingly.

Soil moisture storages

By parameterizing the model zone, the soil moisture analysis for the GISS climate change scenarios runs as follows.

The moisture content of the upper tension zone (Fig. 6) is little affected by the GISS climate changes in the winter period (December to February), while all the other months are affected much more. The tension moisture content of that zone is reduced for all months and its maximum fall occurs in May for both GISS scenarios, which yield results similar to the lightly increased reductions of the alternative GISS scenario. The same profile of seasonal tension moisture reduction generates the hypothetical scenario which registers its maximum reduction also in May. The fact of the considerable tension moisture reduction in spring and early summer months is to be attributed to the reduction in snowmelt that contributes to the soil moisture.

The moisture content of the lower tension zone (Fig. 7) shows the same monthly distribution profile for both GISS scenarios and the hypothetical one. The largest reduction in lower tension moisture occurs in October for the two GISS scenarios and in September for the hypothetical one. Generally, the larger lower zone tension moisture reductions appear shifted forward by two or three months compared with these of the upper zone tension moisture storages.

As regards the California catchments, they generally present the same upper and lower tension zone moisture patterns as Mesochora for both GISS scenarios. The only and somewhat remarkable difference is that the California catchments show a flatter crest of the upper tension zone moisture hydrograph (in October-March period) than that of Mesochora.

The free water contents in the other three zones of the model are strongly and erratically influenced by the GISS climate change, not only from month to

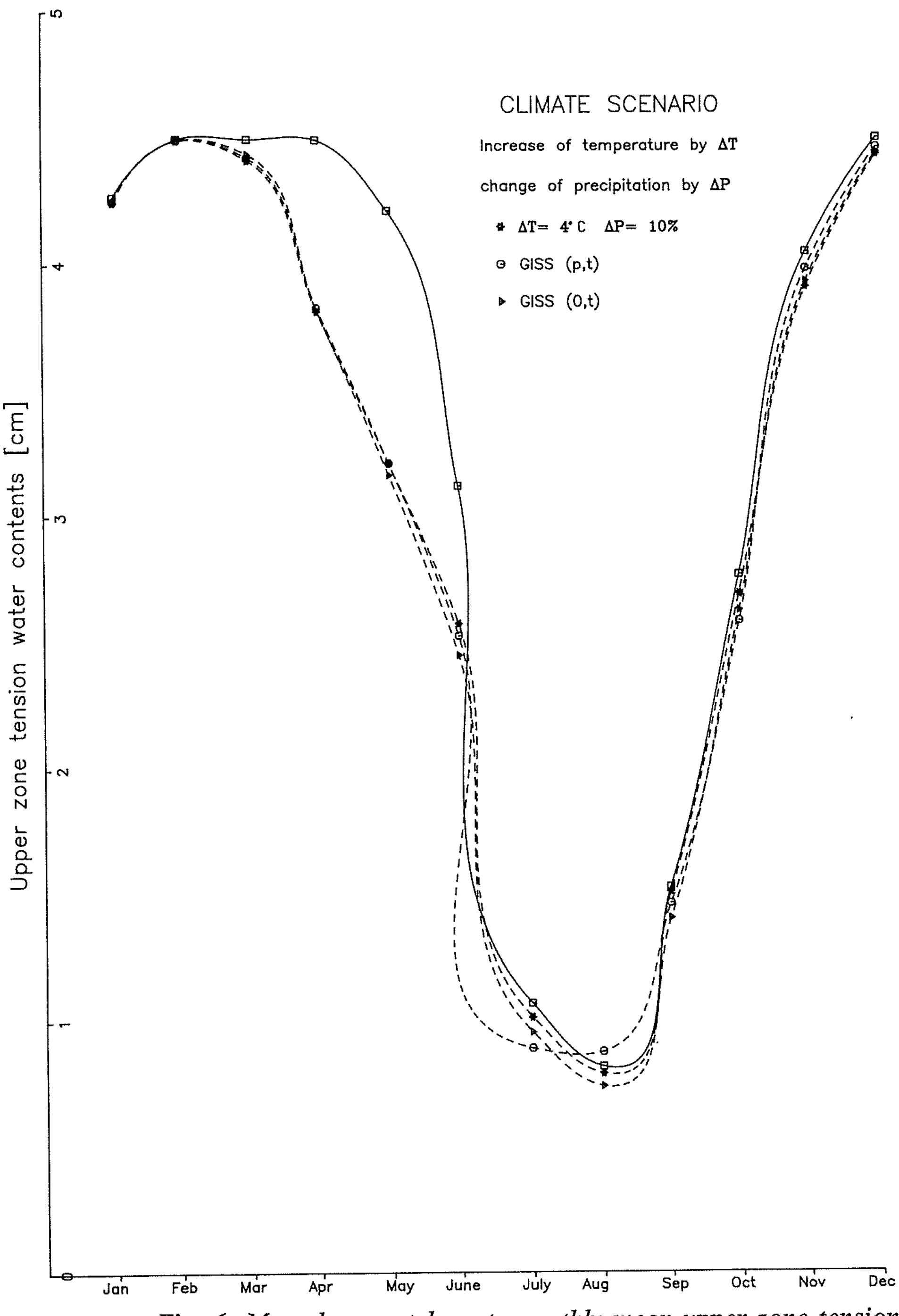

***Fig. 6** Mesochora catchment: monthly mean upper zone tension water for GISS model climate scenarios, hypothetical and base cases.*

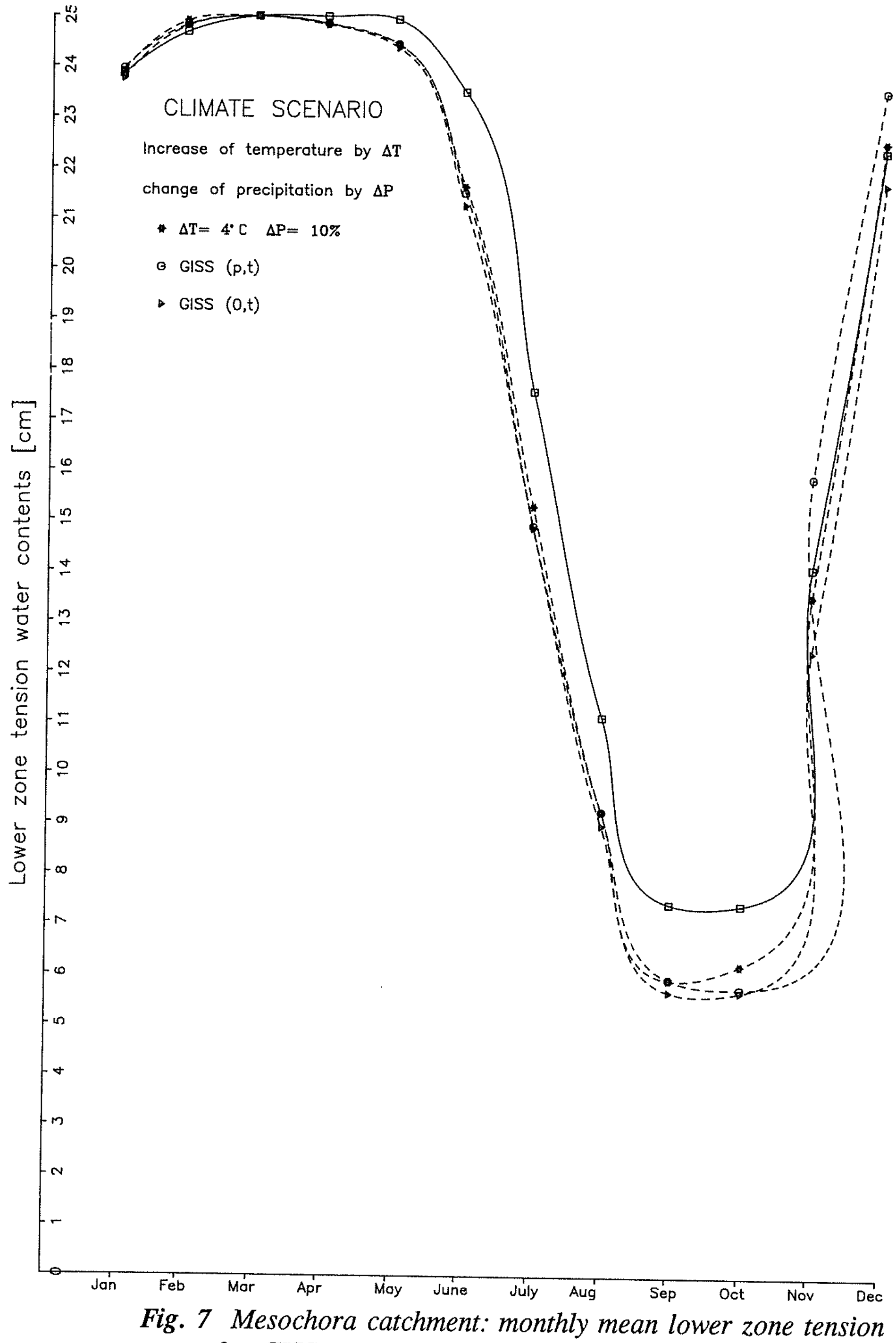

Fig. 7 Mesochora catchment: monthly mean lower zone tension water for GISS model climate scenarios, hypothetical and base cases.

month for the same scenario but from scenario to scenario as well. This picture is reflected in the California catchments too.

The moisture content of the upper free water zone (Fig. 8) shows larger fluctuations than those of the lower free water zone (Figs 9 and 10). It peaks in December for both GISS scenarios, the hypothetical one and the base case, and goes down during the dry July-October period for all cases of climate change.

The free moisture content of the lower primary zone (Fig. 9) peaks in March for both GISS scenarios and the hypothetical one, and it appears shifted earlier by two months from the peak month (May) for the base case. This content is minimized in October for all climate cases.

The free moisture content of the lower supplement zone (Fig. 10) peaks in February for the full GISS scenario, in March for the alternative GISS and hypothetical scenarios, and in April for the base case, presenting for all cases a backward shift of the peak by one or two months. The moisture minimization appears in the dry July-September period for both GISS scenarios and in August for the hypothetical one.

Just as for the hypothetical scenario, so for the other scenarios, there prevails the aspect that soil moisture storages for both GISS and hypothetical scenarios may differ in terms of absolute values, but these appear as monthly distributions with definite changes of profile. This trend is stronger in the free moisture zones than in the tension ones.

From the free water zones, the lower (primary and supplemental) present monthly patterns most similar to those in California for both GISS scenarios. The upper free water zone reflects some differences in months of moisture maximization. Those differences in all likelihood are due to the different geological conditions among the catchments.

CONCLUSIONS

The hydrological regime of the medium-sized mountainous Mesochora catchment was simulated for altered climates using GISS predictions for carbon dioxide doubling. The hydrological impacts of the full GISS scenario including monthly precipitation changes and monthly temperature increase, and the alternative GISS scenario associated with monthly temperature increase only, were investigated. Because both monthly precipitation changes and those of temperature yielded average annual estimates of 8.3% in increased precipitation and 3.94°C in temperature increase, the two GISS scenarios were tested in relation to the hypothetical one of increased precipitation by 10% and temperature by 4°C as given in Panagoulia (1990b).

The conclusions about the impacts of GISS climate change scenarios on snow accumulation and ablation, runoff, actual evapotranspiration and soil moisture storages of the Mesochora catchment are generally the same as those

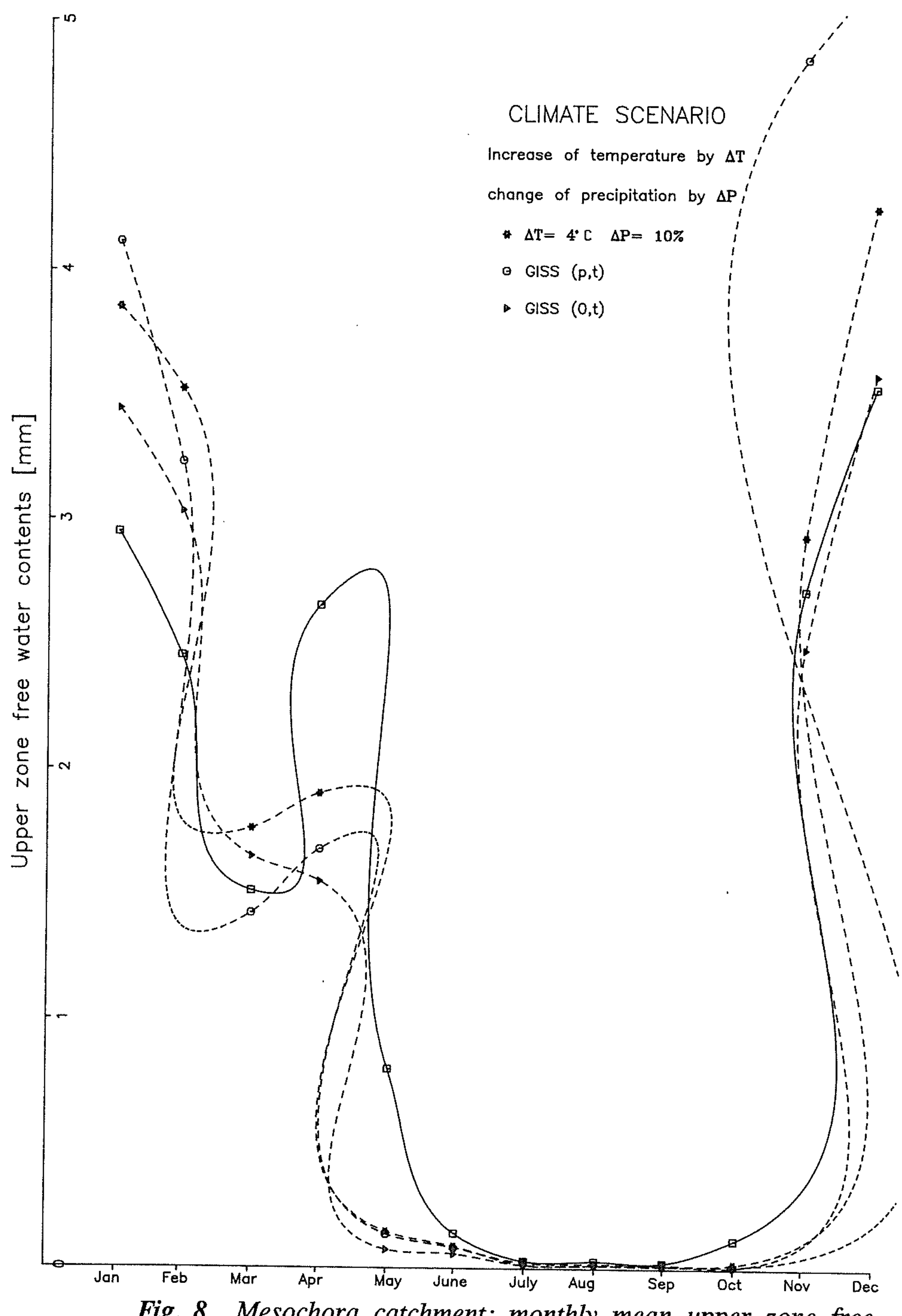

Fig. 8 *Mesochora catchment: monthly mean upper zone free water for GISS model climate scenarios, hypothetical and base cases.*

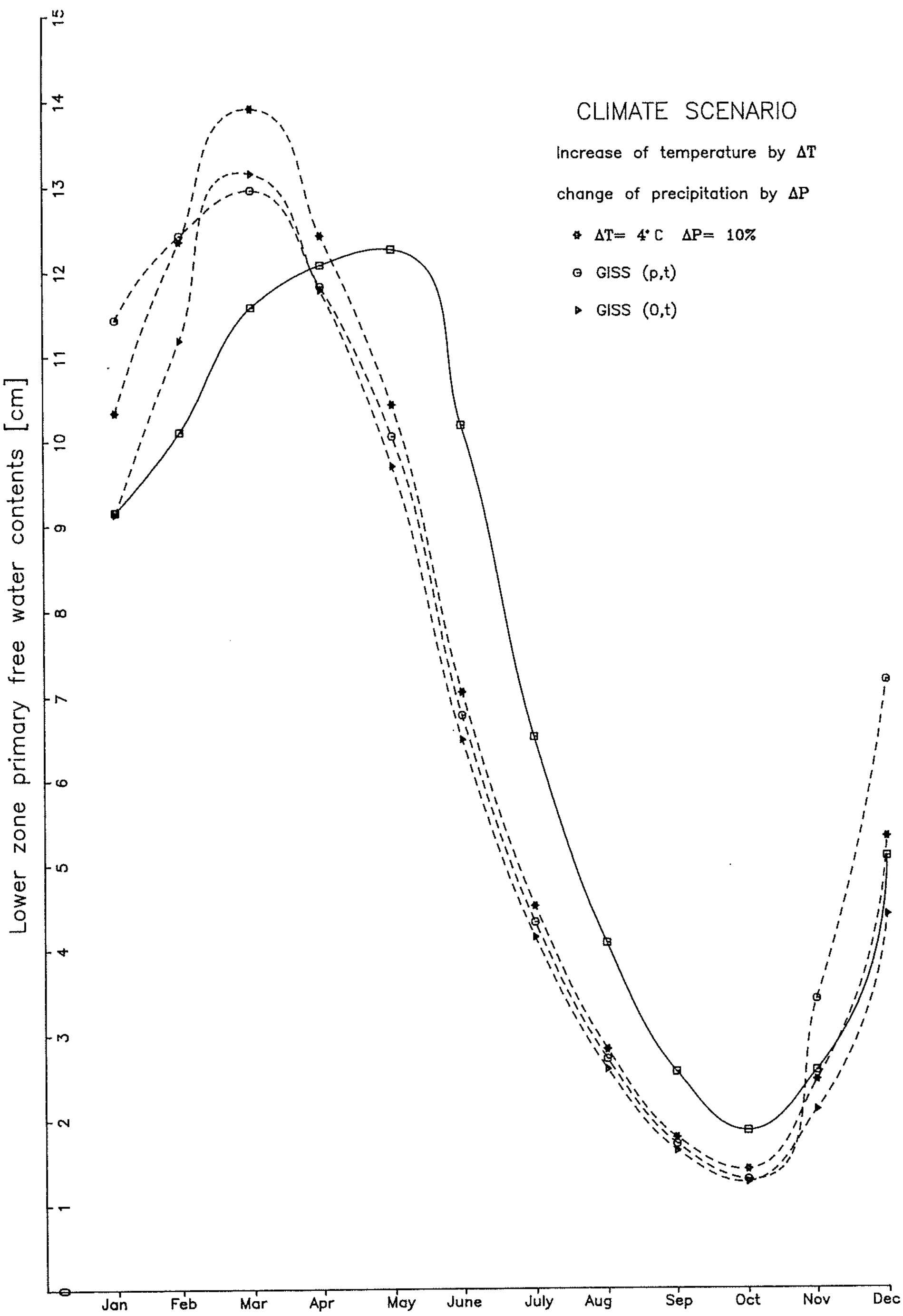

Fig. 9 *Mesochora catchment: monthly mean lower zone free primary water for GISS model climate scenarios, hypothetical and base cases.*

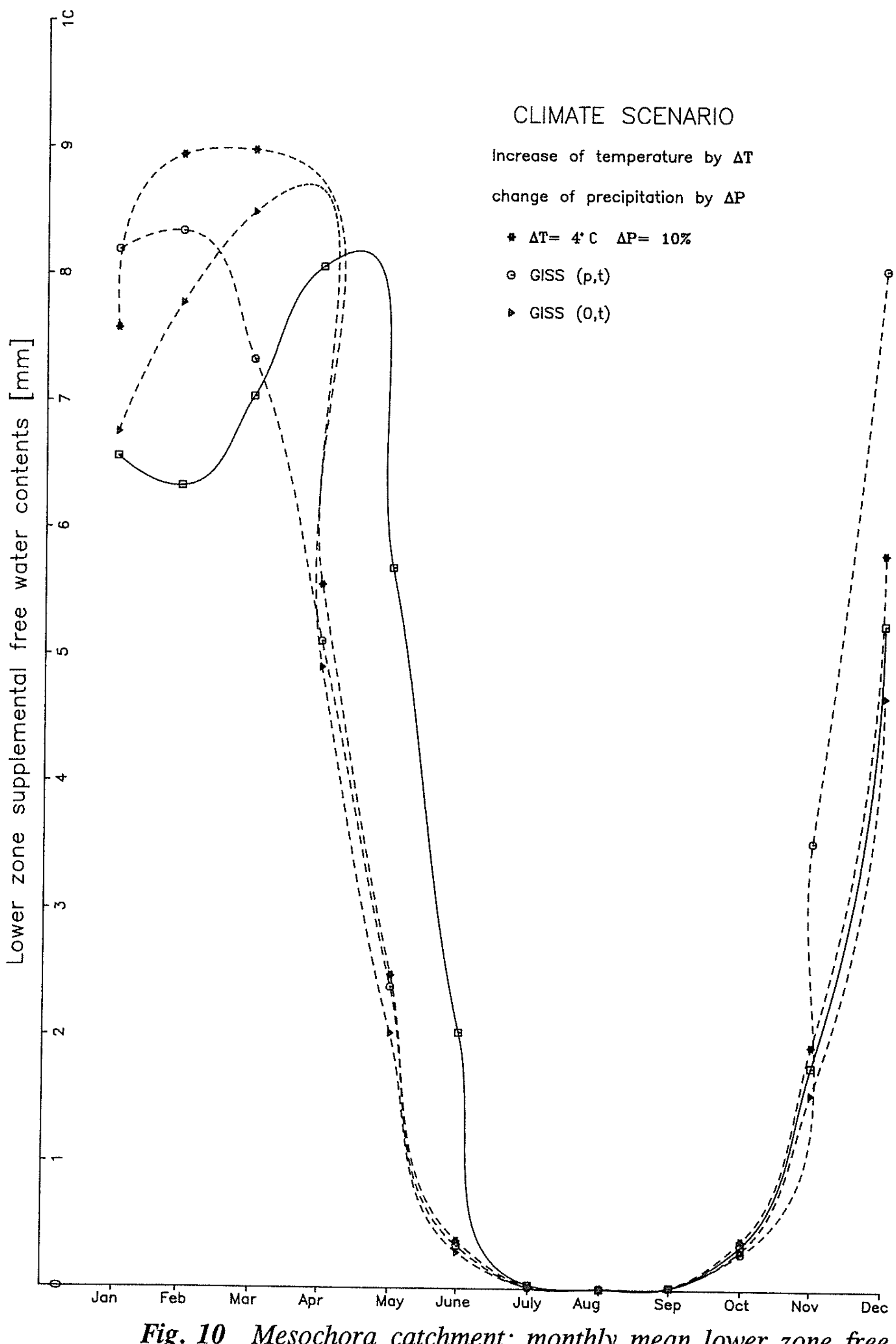

Fig. 10 Mesochora catchment: monthly mean lower zone free supplemental water for GISS model climate scenarios, hypothetical and base cases.

of the hypothetical scenarios (Panagoulia, 1990b) and the same as those of Lettenmaier (Lettenmaier *et al.*, 1988; Lettenmaier & Gan, 1990) for the middle catchments of the Central Valley of California. In other words, the current scenarios also confirm the fact that the increased temperature would reduce considerably the snow accumulation over the study catchment, whereas the decrease in precipitation amount falling as snow would increase the winter runoff and decrease, as well, the spring and summer runoff. Also the increase in precipitation amount falling as rain would increase the winter soil moisture storages, thereby leaving much more moisture for evapotranspiration early in spring. These hydrological results could augment flooding and drought possibilities and hence cause serious problems to the irrigation and hydropower system of the study region.

Differences in results between the two GISS scenarios were observed for hydrological processes that were driven by precipitation or where precipitation change values were very high (e.g. October change value). Inasmuch as the driving mechanism for the snow and accumulation process is the temperature, there was not any remarkable difference in reduction of snow storage for both GISS scenarios. The largest precipitation increases in the winter period (about 50% in October) raised considerably the winter free moisture storages and, as a result, the winter runoff, in relation to that of GISS scenario covering temperature increases only. In contrast, the tension moisture storages remained unaffected by precipitation changes for all months of the year, with the result that the actual evapotranspiration does not substantially differ for both GISS scenarios during winter and spring months.

As regards the hypothetical scenario, it produces a profile of changes in the monthly distributions of hydrological variables similar to those of the GISS scenarios, but yields different numerical results, particularly in winter months, because the GISS precipitation changes were over 10% up.

Searching on a monthly basis for equivalents among GISS scenarios and hypothetical ones (1, 2, 4°C temperature increase and ±20%, ±10%, 0 precipitation changes) (Panagoulia, 1990b), these are reflected in Table 3 through two figures which express, first, temperature increases, and second, precipitation change percentages. The equivalent scenarios of Table 3 are characterized by:

(a) the general temperature increase by 4°C. This value appears to have the higher occurrence probability;

(b) two or more hypothetical scenarios equivalent to a GISS scenario in the same month. The equivalent scenarios 1, -20 and 2, -10 are more often presented; and

(c) the assumption that the October runoff and free moisture of the upper zone resulting from the full GISS scenario cannot be simulated by any combination of hypothetical scenarios due to the high increased precipitation (about 50%).

Table 3 *Equivalent climate scenarios: GISS and hypothetical cases*

	GISS scenario	Hypothetical scenarios (temperature increase (°C), precipitation change (%))											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Snow water equivalent	p,t	4,20	4,20	4,0	4,0	4,all	4,all					2,-20	4,20
	0,t	4,20	4,20	4,0	4,0	4,all	4,all					4,0	4,10
Runoff	p,t	1,20	2,0	1,0 2,0	1,-20	2,-10	2,-10	2,-10 1,-20	2,-10	4,0	None	1,20	1,20
	0,t	1,10	2,10	4,0	4,0	4,0	1,-20	4,0	4,0	1,-10 4,0	4,0	2,0	4,0
Upper zone tension water content	p,t	4,all	4,-10 4,0	4,10	4,10	4,10	2,0	2,-10	1,10	2,0	4,0	1,-20 2,10	2,-10
	0,t	4,all	4,-10 4,0	4,20	4,10	4,0	4,0	1,-10 4,0	4,0	4,0	1,-10 4,0	4,20	2,-20 4,10 4,20
Upper zone free water content	p,t	2,20	4,0	1,0	1,-20	4,-10	2,-10	4,-20	4,-20	4,-20	4,0	None	2,20
	0,t	2,0 4,0	2,0	2,20	4,0	4,-10	2,-10	4,-20	4,-20	4,-20	4,0	4,0	2,0
Lower zone tension water content	p,t	2,10	1,10 4,0	all	4,20	2,-20 4,10 4,20	2,-10	1,-20 2,-10	4,10	4,10	2,-10	4,0	2,20
	0,t	2,10	2,0	all	4,20	4,0 4,10	4,0	2,-10 4,0	1,-20 2,-10	1,-20	2,-10	4,0	2,0
Lower zone primary free water content	p,t	4,20	1,20 4,10	4,0	4,0	2,-10	1,-20 2,-10	1,-20 2,-10	4,0	1,-20 2,10	2,-10	1,20	1,20
	0,t	4,0	4,0	1,10	4,0	4,-10	4,0	4,0	1,-20	4,0	2,-10	4,0	4,0
Lower zone supplemental free water content	p,t	2,10	2,10	1,0 2,0	2,-20	4,10	2,0	1,-10 2,-10	all	1,0	1,-10	none	2,20
	0,t	1,0	1,10	1,10 2,10	2,-20	2,-20 4,0	4,0	2,0 4,0	all	4,0	4,0	4,0	4,0
Actual evapotranspiration	p,t	4,all	4,all	4,-20	4,-20	4,0	1,0	1,0	4,10	4,0	4,0	4,-20	4,all
	0,t	4,all	4,all	4,-20	4,-20	4,0	2,0	4,0	2,0 4,0	4,0	2,20	4,-20	4,all

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