EFFECT OF GLOBAL WARMING ON SIERRA NEVADA MOUNTAIN SNOW STORAGE

by

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INTRODUCTION

Snow is a natural reservoir that accumulates water during the winter and releases it during the late spring and early summer. Irrigation and other human uses rely heavily on the release of water from the snowpack. In addition, the alpine mountains are ecologically sensitive areas and are inhabited by wild animals and unique plants. These animals and plants live in harmony with the seasonal cycle of the alpine mountain climate. The snow season occupies roughly one-third of the cycle in the Sequoia National Forest. Unfortunately, the anthropogenic increase in CO_2 concentration will result in a significant threat to this environment.

In most prior studies of the hydrologic consequences of climatic change, snowmelt runoff is considered to be either a function of temperature or a function of precipitation (Gleick 1987; Lettenmaier and Gan 1990). Nonetheless, the greenhouse effect is expected to be accompanied by changes not only in temperature and precipitation, but also in radiation, wind, humidity, and the snow/rain ratio (Ramanathan 1981; Washington and Meehl 1983; Manabe and Wetherald 1975; Manabe et al. 1981; Schlesinger 1984; Wilson and Mitchell 1987; Schlesinger and Mitchell 1987). This study evaluates the impacts of all of the aforementioned changes. In order to evaluate all these impacts, traditionally used air-temperature-index-based snowmelt runoff models, such as used by Gleick (1989) and Lettenmaier and Gan (1990), cannot be used. These air-temperature-index-based snowmelt runoff models cannot determine the impact of changes in radiation, wind speed, and humidity. Therefore, an energy-based snowmelt runoff model developed by Tsuang (1990) is used for the purpose of this study.

The input data for Tsuang's (1990) model includes atmospheric pressure, solar radiation in the visible band and in the near-infrared band, downward longwave radiation, wind speed, humidity, air temperature, soil temperature, the date, volume and density of snow fall, snow redeposition factor, and initial snow pack temperature, thickness, and density.

The outputs from Tsuang's model are the albedo of snow surface, upward longwave radiation, precipitation temperature, latent heat, sensible heat, conduction energy between soil and snow, advection energy, snow temperature, snow density, snow thickness, snow water equivalent, snowmelt, liquid water content, and the magnitude and timing of snowmelt runoff.

This snowmelt runoff model has five major characteristics that together are structurally unique: 1) a two-layer snowmelt runoff algorithm is developed; 2) the variations in the snow albedo are determined as a function of the snow grain size and the impurities in snow composition; 3) the flux of water in the snow pack is determined by Darcy's law; 4) the snow metamorphism of the snowpack is determined; and 5) the model is structured to be readily used in the analysis of the effects of greenhouse warming on snowmelt runoff. The model is computer time-efficient, and the results indicate that the simulated snow water equivalent and snow temperature are in good agreement with field observations.

Presented at the Western Snow Conference, Washington to Alaska.

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"Reprinted Western Snow Conference 1991"

ENERGY BALANCE

The model uses an energy balance calculation here for the snow surface layer and the snow lower layer. This balance calculates the energy flux between the atmosphere, the snowpack, and the underlying soil.

Energy Balance of the Surface Snow Layer

The mass of the surface snow layer is involved in the calculations of energy transfer with the atmosphere and the snow lower layer. The energy balance of the snow surface layer is obtained from

$$\dot{Q}_s = (1-\alpha_v)R_{s,v} + (1-\alpha_{nir})R_{s,nir} + R_{l\downarrow} - R_{l\uparrow} + H - LE + M - G_{s,l} - LE_{s,l} \quad (1)$$

where $\dot{Q}_s$ = net energy change in the snow surface layer (w/m^2); $R_{s,v}$, $R_{s,nir}$ = visible and near-infrared solar radiation on the snow surface (w/m^2); α_v, α_{nir} = visible and near-infrared albedo of the snow surface; $R_{l\downarrow}$ = downward longwave radiation (w/m^2); $R_{l\uparrow}$ = upward longwave radiation (w/m^2); H = sensible heat transferring into the snow surface (w/m^2); LE = latent heat transferring from the snow surface to the atmosphere (w/m^2); M = advected energy into the snow surface (w/m^2); $G_{s,l}$ = conduction energy from the surface layer to the lower layer of the snow pack (w/m^2); $LE_{s,l}$ = latent heat released from the surface layer to the lower layer (w/m^2).

Energy Balance of Lower Layer

The mass of the lower layer is involved in the calculations of energy transfer with the snow surface layer and the underlying soil. The energy balance of the lower layer of snowpack is obtained from

$$\dot{Q}_l = G_{s,l} + LE_{s,l} - G_{l,g} - LE_{l,g} \quad (2)$$

where $\dot{Q}_l$ = net energy change in the lower layer of snowpack (w/m^2); $G_{s,l}$ = conduction energy exchange between the snow surface layer and the lower layer (w/m^2); $LE_{s,l}$ = latent heat released from the surface layer to the lower layer (w/m^2); $G_{l,g}$ = conduction heat flux to the soil (w/m^2); $LE_{l,g}$ = latent heat released from the lower layer of snowpack to the soil (w/m^2).

CONTROL RUN

Data from the Emerald Lake watershed, Sequoia National Forest, California (Figure 1), during the 1985/1986 snow season, is used as the control run. These data were obtained under studies funded by the California Air Resources Board (Dozier et al. 1988). These data have been measured from 1985 to the present. The measurement site is located at 36°36'N latitude and 118°40'W longitude with an elevation of 2813 m. The data collection procedures are reported in Dozier et al. (1988) and Marks (1988).

Data available from the Emerald Lake watershed includes all of the model inputs except for the snow redeposition factors. Snow redeposition is important in the Emerald Lake basin during storm events. During those storms, significant redeposition occurred due to avalanches and wind scour (Dozier, et al. 1988; Marks 1988). These snow redeposition effects were not measured. Therefore, it is required that a snow redeposition factor be determined by calibrating the snow water equivalent. The snow redeposition factor was calibrated to be 0.22 cm of snow water equivalent per day. Figure *2* shows simulated and observed snow water equivalents.

Figure *3* shows simulated and observed daily average snow temperatures. The simulated snow temperature varies from a low of -8 °C during the accumulation period to a high of 0 °C during the melt period. The comparison with the observed values is quite satisfactory as verified by Tsuang (1990).

GREENHOUSE SCENARIOS

Climatologists agree that a doubling of the present-day atmospheric CO_2, which increases downward long-wave radiation, would cause an increase in surface air temperature and would accelerate the processes within the hydrologic cycle, causing increases in precipitation, evaporation, humidity, and cloud cover (Schneider et al. 1990). Therefore, to assess the implications of the greenhouse effect for snowmelt runoff, regional-scale details of future changes are needed for temperature, precipitation, wind speed, humidity, radiation, and other hydrometeorological variables. Scenarios for the California region are summarized by Lettenmaier and Gan (1990), who compiled monthly scenarios. Their scenarios, regarding potential changes in precipitation and air temperature, are derived from three GCM results (the models of the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute for Space Studies (GISS), and the Oregon State University Department of Meteorology (OSU)). Other than precipitation and air temperature, other climatic factors, especially humidity and downward thermal radiation, may also have profound impacts on the snowmelt runoff pattern. Unfortunately, these data are not available in the Lettenmaier and Gan (1990) study, and are not available in most published GCM results.

In order to assess Lettenmaier's and Gan's (1990) scenarios, several assumptions are made for the purpose of this study. Although in doubled CO_2 experiments, absolute humidity is found to increase substantially, by 40% in the experiment of Wilson and Mitchell (1987), relative humidity is typically assumed to be invariant. According to Manabe and Wetherald (1975), the zonal surface relative humidity varies from -1% to 8%, with 0% variation at a latitude of 35°. Therefore, the relative humidity is assumed to be invariant in this study. The relative humidity was also assumed to be invariant by Bultot et al. (1988). The increase in the downward thermal radiation is assumed to have a global value of 15.5 w/m^2, out of which 1.2 w/m^2 is due to direct heating of doubled CO_2 (Ramanathan 1981). The decrease in solar radiation is estimated to be 0.5 w/m^2 (Ramanathan 1981). Note that the estimation of the decrease in solar radiation does not consider the cloud feedback. The wind speed is assumed to be invariant since not all of the GCMs produce compatible estimates (Lettenmaier and Gan 1990). The temperature differences and precipitation adjustment ratios are summarized in Table *1* and Table *2*, respectively. The annual average temperature differences are 4.48 °C using the GFDL scenario, 4.78 °C using the GISS scenario, and 2.12 °C using the OSU scenario. The annual average precipitation decreases by 10.5% using the GFDL scenario, increases by 8.3% using the GISS scenario, and increases by 0.3% using the OSU scenario.

Table 1
Temperature Shifts in °C for Alternative Climate Scenarios
(after Lettenmaier and Gan, 1990)

Case	J	F	M	A	M	J	J	A	S	O	N	D	avg.
GFDL	3.50	4.35	4.50	4.55	5.70	6.10	4.35	3.90	4.90	4.30	4.10	3.45	4.48
GISS	5.90	4.60	4.60	5.40	3.10	4.10	3.90	5.50	7.20	5.30	3.40	4.40	4.78
OSU	0.55	2.03	1.31	2.08	1.97	2.68	2.12	3.12	2.39	1.58	3.08	2.57	2.12

Table 2
Precipitation Shifts in % for Alternative Climate Scenarios
(after Lettenmaier and Gan, 1990)

Case	J	F	M	A	M	J	J	A	S	O	N	D	avg.
GFDL	-6.4	13.0	-7.6	-8.9	-29.0	-5.3	-89.0	-11.1	-18.2	8.4	18.9	9.6	-10.5
GISS	21.0	6.0	34.0	-23.6	-2.4	28.0	-34.5	26.0	-23.5	30.0	24.0	15.0	8.3
OSU	3.0	13.0	4.0	36.0	-7.0	5.0	1.0	-12.0	7.0	-11.0	-24.0	-11.0	0.3

GREENHOUSE ANALYSIS RESULTS

Model input for the snowmelt runoff simulations under three GCM scenarios is constructed by adjusting the temperature of the study site by the GCM-simulated temperature shift from Table *1*. Station precipitation is adjusted by the factors listed in Table *2*. Relative humidity and wind speed are assumed to be invariant for all three scenarios. Station downward longwave radiation is adjusted by adding 15.5 w/m^2. Station solar radiation is adjusted by subtracting 0.5 w/m^2.

Snow/Precipitation Ratio

Figure *4* indicates the simulated distribution of precipitation temperatures at the study site for the 1985-1986 climatic conditions and for the scenarios of GFDL, GISS, and OSU. In the control run, the temperatures for all of the precipitation events are below -2 °C. All three scenarios show increases in precipitation temperatures. The GFDL scenario indicates that 43% of the precipitation events have precipitation temperatures larger than 0 °C. For the GISS scenario, it is 36%. As a consequence, the snow/precipitation ratio decreases. The snow/precipitation ratios (by weight) are 66% using the GFDL scenario, and 69% using the GISS scenario. However, the OSU scenario indicates that although the precipitation temperatures increase somewhat, precipitation temperatures are still below 0 °C and the snow/precipitation ratio remains the same.

In the control run, the temperatures of all the precipitation events are below -2 °C. The study site is located at an elevation of 2800 m. At lower altitudes, where air temperature is about 2 °C higher and humidity is 20% higher, the snow/precipitation ratio would change dramatically due to a small perturbation in air temperature and humidity. If a lapse rate of 4 °C/km is used, as measured in the Emerald Lake Basin, the snow/precipitation ratio at an elevation below 2300 m would change significantly.

Snow Water Equivalent

Figure *5* shows the simulated daily snow water equivalents. In the control run, the snow water equivalent is 1.39 m, and the snow season lasts 262 days. The marked reduction in average snow water equivalent for all the climate scenarios is striking. Although the general change in the snow water equivalent is consistent in all the cases, case-specific changes are observed as well. The changes are more significant using the GFDL and GISS scenarios, which cause a significant change in the snow/precipitation ratio. The GFDL scenario suggests that the snow season would end 65 days earlier, and the average snow water equivalent for the period of the snow season in the control run decreases to 0.63 m, which corresponds to a 44% reduction in the snow water equivalent. The GISS scenario suggests that the snow season would end 68 days earlier, and the average snow water equivalent decreases to 0.53 m, which corresponds to a 60% reduction in the snow water equivalent. The OSU scenario is more modest. Nonetheless, it suggests that the snow season would end 26 days earlier, and the average snow water equivalent decreases to 1.19 m, which corresponds to a 14% reduction in the snow water equivalent.

It should be noted that the shorter snow season decreases the albedo of land surface, since the albedo of snow is much higher than that of vegetation or soil. The decrease in the albedo implies that there is more solar radiation absorbed in the land surface. The extra land-absorbed energy would eventually be released into the atmosphere, in the forms of upward longwave radiation, sensible heat, and latent heat. As a consequence, there would be more upward longwave radiation, sensible heat and latent heat in the atmosphere. These energies would increase air temperature, enhancing the regional warming. This effect is called the snow albedo feedback. Similar snow and sea-ice feedbacks have been identified at high latitudes (Dickinson et al. 1987; Harvey 1988). In addition, changes in the duration of snow storage may affect the climate in a very remote regions (Dickson 1984; Barnett et al. 1988, 1989; Sikka 1985; Yamazaki 1989).

Snowmelt Runoff

Figure 6 shows the simulated changes in the daily distribution of snowmelt runoff. The effect of reduced snow storage is immediately apparent; in all cases the centroid of the hydrograph shifts to earlier in the year. This is due to the decrease in the amount of snowfall in relation to rainfall. Runoff increases markedly in all cases for the winter months and decreases substantially in the late spring and summer. Although the general shifts in the annual snowmelt runoff hydrograph are consistent in all the cases, case-specific change is observed as well. The phase shifts are substantial in the cases of the GFDL and the GISS scenarios, because the simulated temperature increases are above 0 °C. Some spikes in the hydrograph are observed. These spikes are caused by rain instead of snow, and they pose a possibility of flash flooding during the winter months. The phase shift is less in the case of the OSU scenario because the simulated temperature increase is more modest than for the other two scenarios. It should be noted that the shift in the annual distribution of runoff will be critical for water resource management. That is, for controlled surface water reservoir storage volumes, the seasonal distribution of runoff, and its variability, is more important than the changes in the total annual runoff.

CONCLUSION

An energy-based snowmelt runoff model is used to study the sensitivity of snowmelt runoff to climatic variations. An alpine climatic site with an elevation of 2813 m in the Sequoia National Forest, California, was chosen for the case study. The results indicate that under global warming scenarios derived from three GCM simulations, the hydrograph of snowmelt runoff shifts between 19 and 93 days earlier and the snow season would end between 25 to 68 days earlier at the alpine climatic site. The most striking change is the decrease in the snow/precipitation ratio. There would be more precipitation occurring as rain, resulting in flash floods during the winter months and the shift in the hydrograph. Elevations below 2300 m would suffer a major impact because a small increase in air temperature would cause significant amounts of snow to occur as rain.

The decrease in the duration of the snow season will further modify the climate regionally and globally through the so-called snow albedo feedback. However, this effect cannot be resolved by running a snowmelt runoff model alone. In order to obtain this feedback between the atmosphere and the snowpack a climatic model such as a GCM or a mesoscale model should be coupled to this type of a snowmelt runoff model.

Note that this study uses greenhouse scenarios derived from GCMs. However, current GCMs do not have good cloud parameterization (Schlesinger and Mitchell 1987). The greenhouse effect may increase water vapor supply to the atmosphere, thus increasing clouds. Clouds will block solar radiation but will enhance longwave radiation. The net radiation feedback of the clouds is expected to mitigate the total increase in radiation energy (Ramanathan et al. 1989a, 1989b). The magnitude of cloud feedback, however, continues to be a major source of uncertainty. The exact climatic change due to the greenhouse effect cannot be determined until the cloud feedback analysis is quantified (Schlesinger and Mitchell 1987). In addition, the three GCMs do not have detailed formulation of land surface terrain. Therefore, the regional climatic change can not be identified until a more detailed formulation of land surface terrain is completed (Gleick 1989; Verstraete 1989; Avissar and Verstraete 1990).

ACKNOWLEDGEMENT

This study was supported by the University of California Water Resources Center, under grant number W-751. The authors would like to especially thank Drs. Danny Marks and Jeff Dozier, University of California, Santa Barbara, for their efforts in obtaining the valuable data set at the Emerald Lake Basin. Their work was funded by the California State Air Resources Board, whose generous support is acknowledged under grant number A3-106-32.

BIBLIOGRAPHY

Avissar, R. and M.M. Verstraete, 1990, The Representation of Continental Surface Processes in Atmospheric Models, *Reviews of Geophysics*, 28, 1, pp. 35-52.

Barnett, T.P., L. Dumenil, U. Schlese and E. Roeckner, 1988, The Effect of Eurasian Snow Cover on Global Climate, *Science*, Vol. 239, pp. 504-507.

Barnett, T.P., L. Dumenil, U. Schlese, E. Roeckner, and M. Latif, 1989, The Effect of Eurasian Snow Cover on Regional and Global Climate Variations, *Journal of the Atmospheric Sciences*, Vol. 46, No. 5, pp. 661-685.

Bultot, F., G.L. Dupriez and D. Gellens, 1988, Estimated Annual Regime of Energy-Balance Components, Evapotranspiration and Soil Moisture for a Drainage Basin in the Case of a CO_2 Doubling, *Climatic Change*, Vol. 12, pp. 39-56.

Dickinson, R.E., G.A. Meehl and W.M. Washington, 1987, Ice-Albedo Feedback in a CO_2-Doubling Simulation, *Climatic Change*, 10, pp. 241-248.

Dickson, R.R., 1984, Eurasian Snow Cover vs. Indian Monsoon Rainfall. An Extension of Hahn-Shukla Results, *J. Climat. and Appl. Meteorol., 23*, pp. 171-173.

Dozier, J., J.M. Melack, D. Marks, K. Elder, R. Kattleman, and M. Williams, 1988, Snow Deposition, Melt, Runoff, and Chemistry in a Small Alpine Watershed, Emerald Lake Basin, Sequoia National Park, *Final Report, CARB Contract A3-106-32*, 367 pp., Computer Systems Laboratory, University of California, Santa Barbara, CA.

Gleick P.H., 1987, Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases, *Climatic Change*, 10, 137-161.

Gleick P.H., 1989, Climate Change, Hydrology, and Water Resources, *Reviews of Geophysics*, 27, 3, pp. 329-344.

Harvey, L.D.D., 1988, On the Role of High Latitude Ice, Snow, and Vegetation Feedbacks in the Climatic Response to External Forcing Changes, *Climatic Change*, Vol. 13, pp. 191-224.

Lettenmaier D.P. and T.Y. Gan, 1990, Hydrologic Sensitivities of the Sacramento-San Joaquin River Basin, California, to Global Warming, *Water Resources Research*, Vol. 26, No. 1, pp. 69-86.

Manabe,S., and R.T. Wetherald, 1975, The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, pp. 3-15.

Manabe, S., R.T. Wetherald and R.J. Stouffer, 1981, Summer Dryness Due To An Increase of Atmpospheric CO_2 Concentration, *Climatic Change*, 3, 347-386.

Marks, D., 1988, *Climate, Energy Exchange, and Snowmelt in Emerald Lake Watershed, Sierra Nevada*, Ph.D. Dissertation, Remote Sensing Hydrology, University of California, Santa Barbara, 158 pp.

Ramanathan, V., 1981, The Role of Ocean-Atmosphere Interactions in the CO_2 Climate Problem, *Journal of The Atmospheric Sciences*, Vol. 38, pp. 918-930.

Ramanathan, V., et al., 1989a, Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment, *Science*, Vol. 243, pp 57-63, 6 January.

Ramanathan, V., et al., 1989b, Climate and the Earth's Radiation Budget, *Physics Today*, May, pp. 22-32.

Schlesinger, M.E., 1984, Climate Model Simulations of CO_2-Induced Climate Change, *Advances in Geophysics*, Vol. 26, pp. 141-235.

Schlesinger, M.E. and J.F.B. Mitchell, 1987, Climate Model Simulations of the Equilibrium Climatic Response to Increased Carbon Dioxide, *Review of Geophysics*, Vol. 25, No. 4, pp. 760-798.

Schneider, S.H., P.H. Gleick and L.O. Mearns, 1990, Prospects for Climate Change, Chapt. 3 in *Climate Change and U.S. Water Resources*, (Ed) Waggoner, P.E., J. Wiley and Sons, N.Y.

Sikka, D.R., 1985, Impact of Winter and Spring Time Snow Cover Over Eurasia on the Short-Term Climatic Fluctuations of the Summer Monsoon over India, pp. 47-60, in *Proceedings of the First National Symposium on Seasonal Snow Cover, 28-30 April, 1983, New Delhi*, organized by Snow & Avalanche Study Establishment, Manali, India.

Tsuang, B.J., 1990, *Climate Processes of Lake Evaporation and Snowmelt Runoff: Part I. Evaporation Rates from Temperature-Stratified Saline Lakes- Mono Lake as a Case Study; Part II. Snowmelt Runoff and Climate Change- Emerald Lake as a Case Study*, Ph.D. Dissertation, Civil Engineering Department, University of California, Los Angeles, 364 pp.

Verstraete, M.M., 1989, Land Surface Processes in Climate Models: Status and Propects, in *Climate and Geo-Sciences*, edited by A. Berger, pp. 312-340.

Washington, W.M. and G.A. Meehl, 1983, General Circulation Model Experiments on the Climatic Effects Due to a Doubling and Quadrupling of Carbon Dioxide Concentration, *Journal of Geophysical Research*, Vol. 88, No. C11, pp. 6,600-6,610.

Washington, W.M. and G.A. Meehl, 1984, Seasonal Cycle Experiment on the Climate Sensitivity Due to a Doubling of CO^2 with an Atmospheric General Circulation Model Coupled to a Simple Mixed-Layer Ocean Model, *Journal of Geophysical Research*, Vol. 89, pp. 9,475-9,503.

Wilson C.A. and J.F.B. Mitchell, 1987, A Doubled CO_2 Climate Sensitivity Experiment With a Global Climate Model Including a Simple Ocean, *Journal of Geophysical Research*, Vol. 92, No. D11, pp. 13,315-13,343.

Yamazaki, K., 1989, A Study of the Impact of Soil Moisture and Surface Albedo Changes on Global Climate Using the MRI-GCM-I, *Journal of the Meteorological Society of Japan*, Vol. 67, No. 1, pp. 123-146.

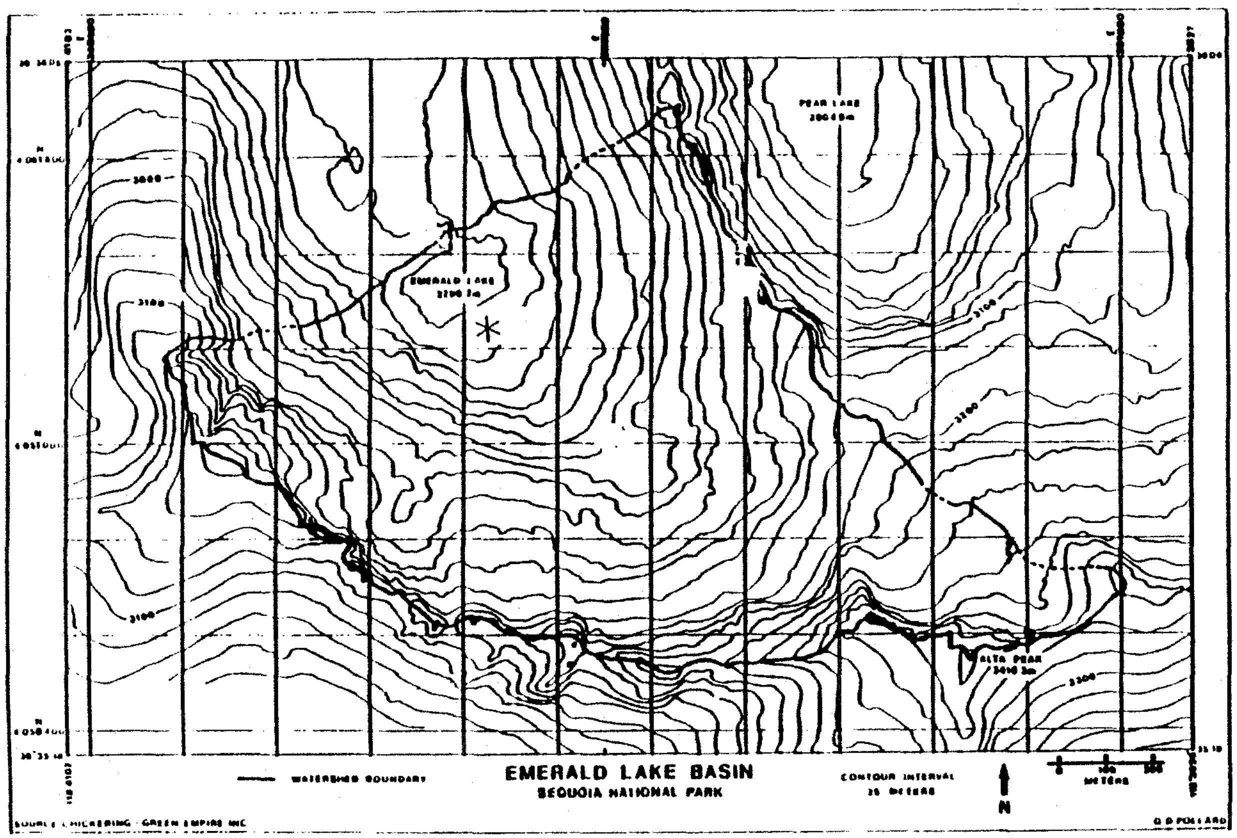

Figure 1. Topographic map of Emerald Lake watershed and surrounding area. The study site is shown by a star. The site is located at the inflow to the lake (Lake site) (from Marks, 1988).

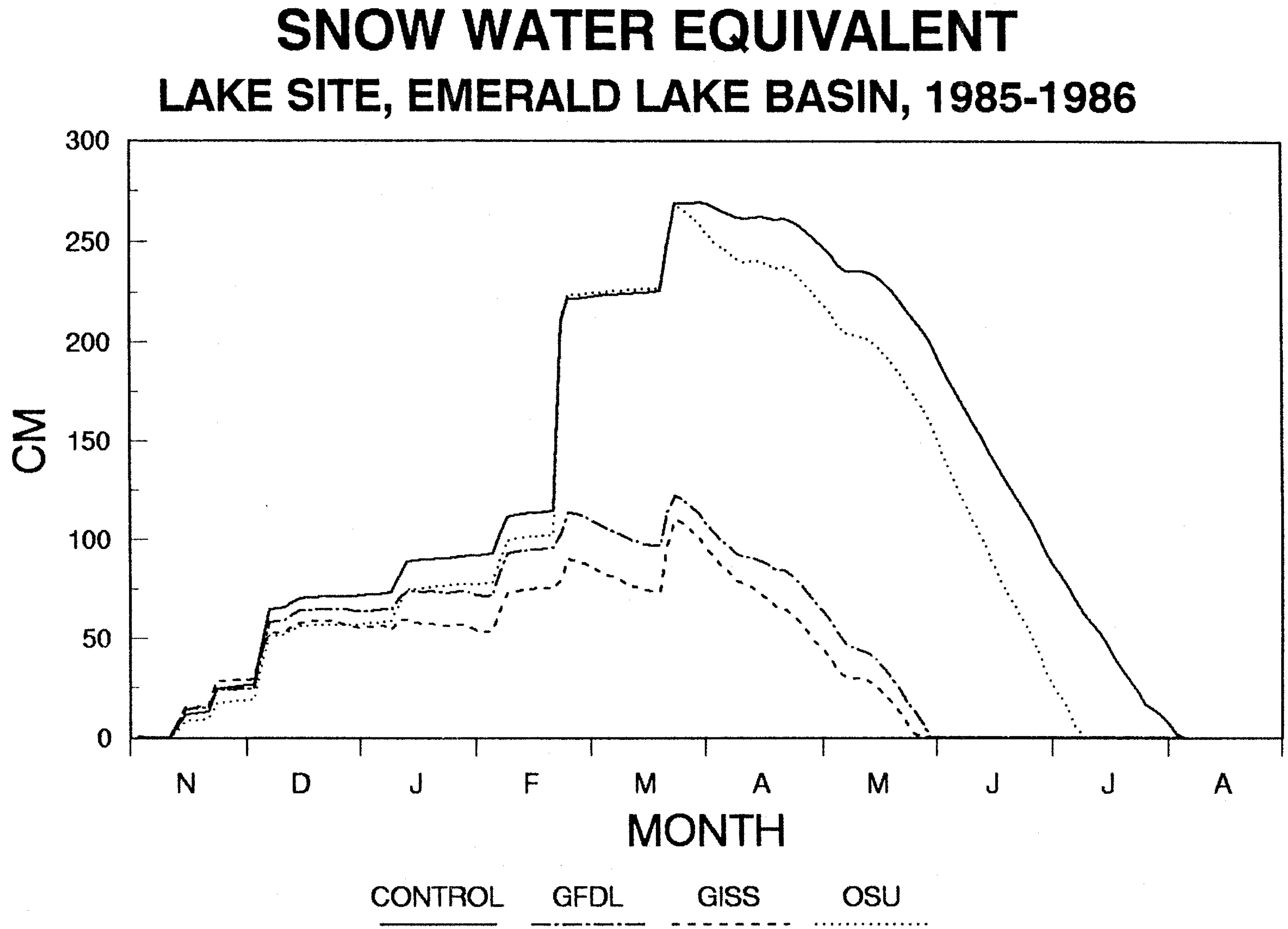

Figure 2. Snow water equivalent at the lake site, Emerald Lake watershed, 1985/1986 snow season, where observed data are in circles, simulated results are in solid line.

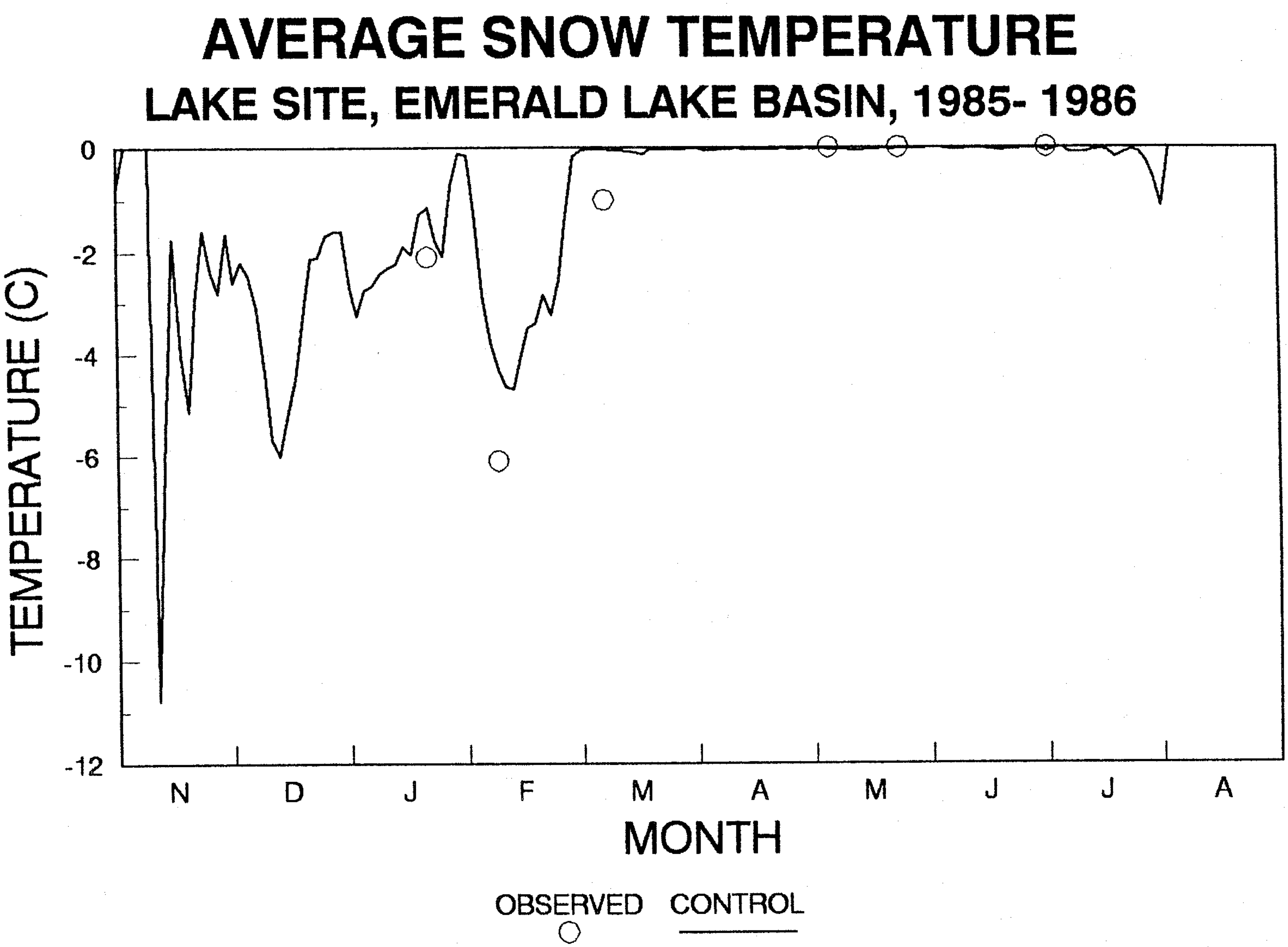

Figure 3. Daily average snow temperature at the lake site, Emerald Lake watershed, 1985/1986 snow season, where observed data are in circles, simulated results are in solid line.

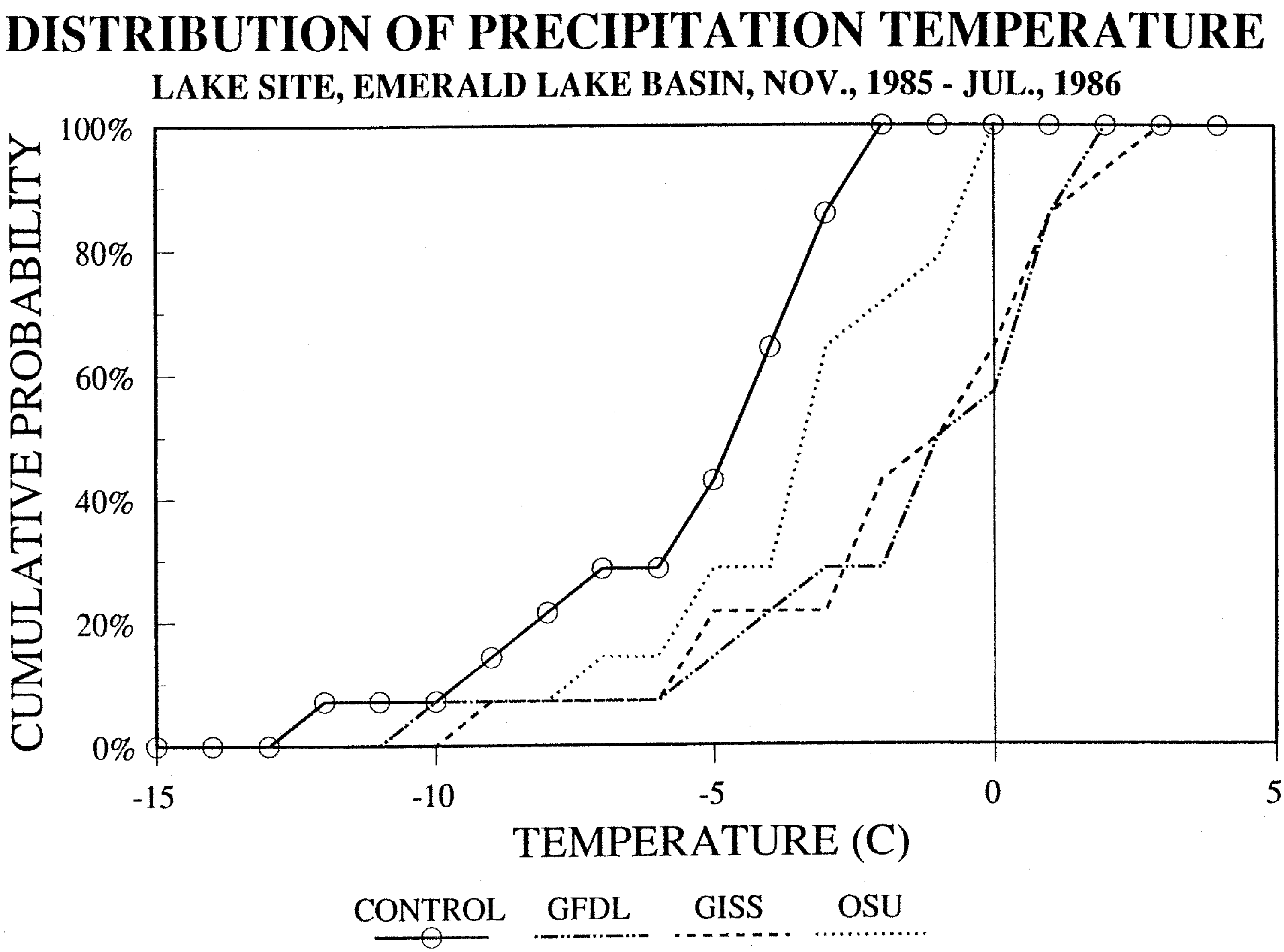

Figure 4. Simulated distribution of precipitation temperatures under climatic scenarios at the lake site, Emerald Lake Basin, 1985- 1986.

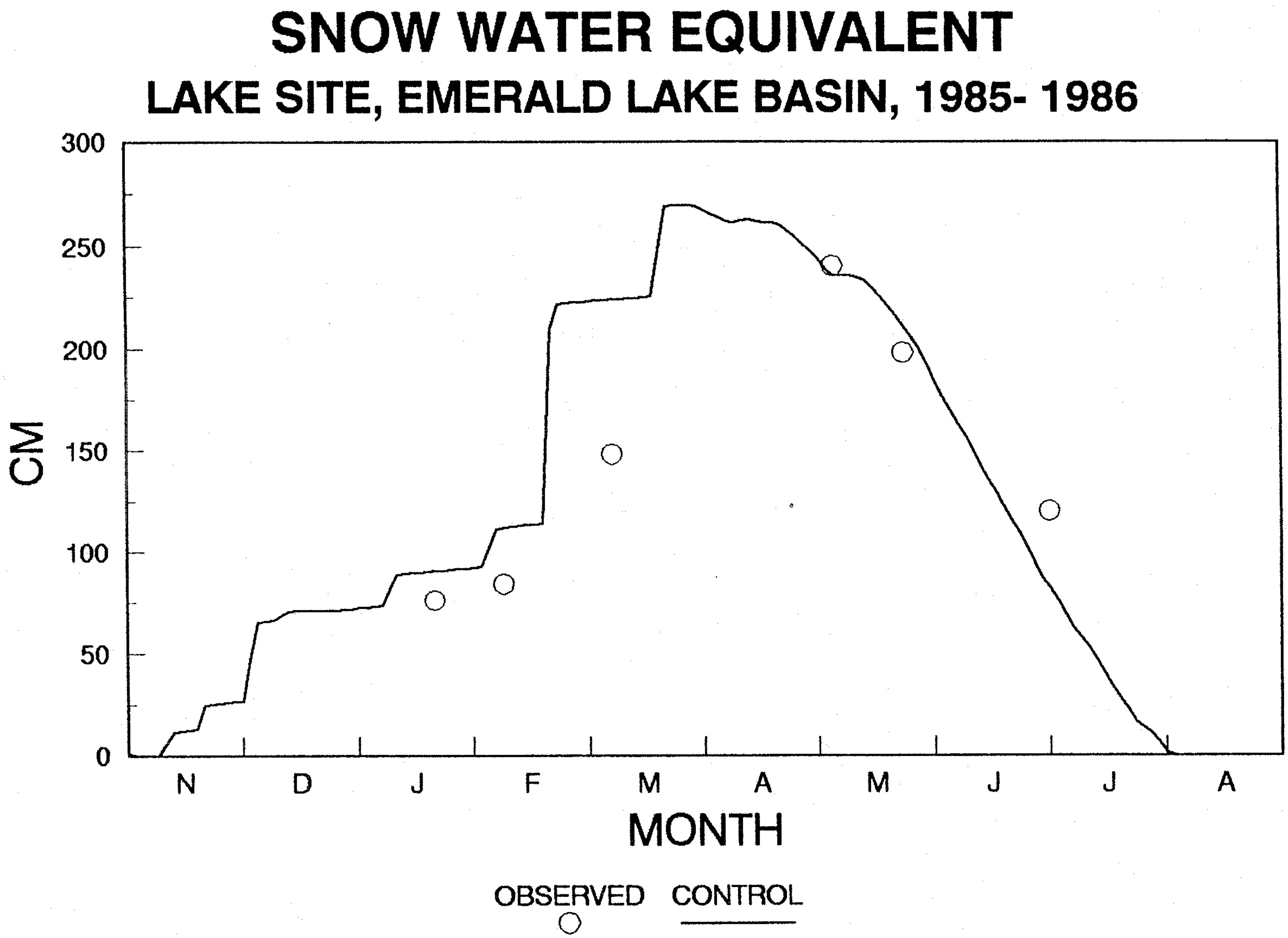

Figure 5. Simulated daily snow water equivalents under climatic scenarios at the lake site, Emerald Lake Basin, 1985-1986.

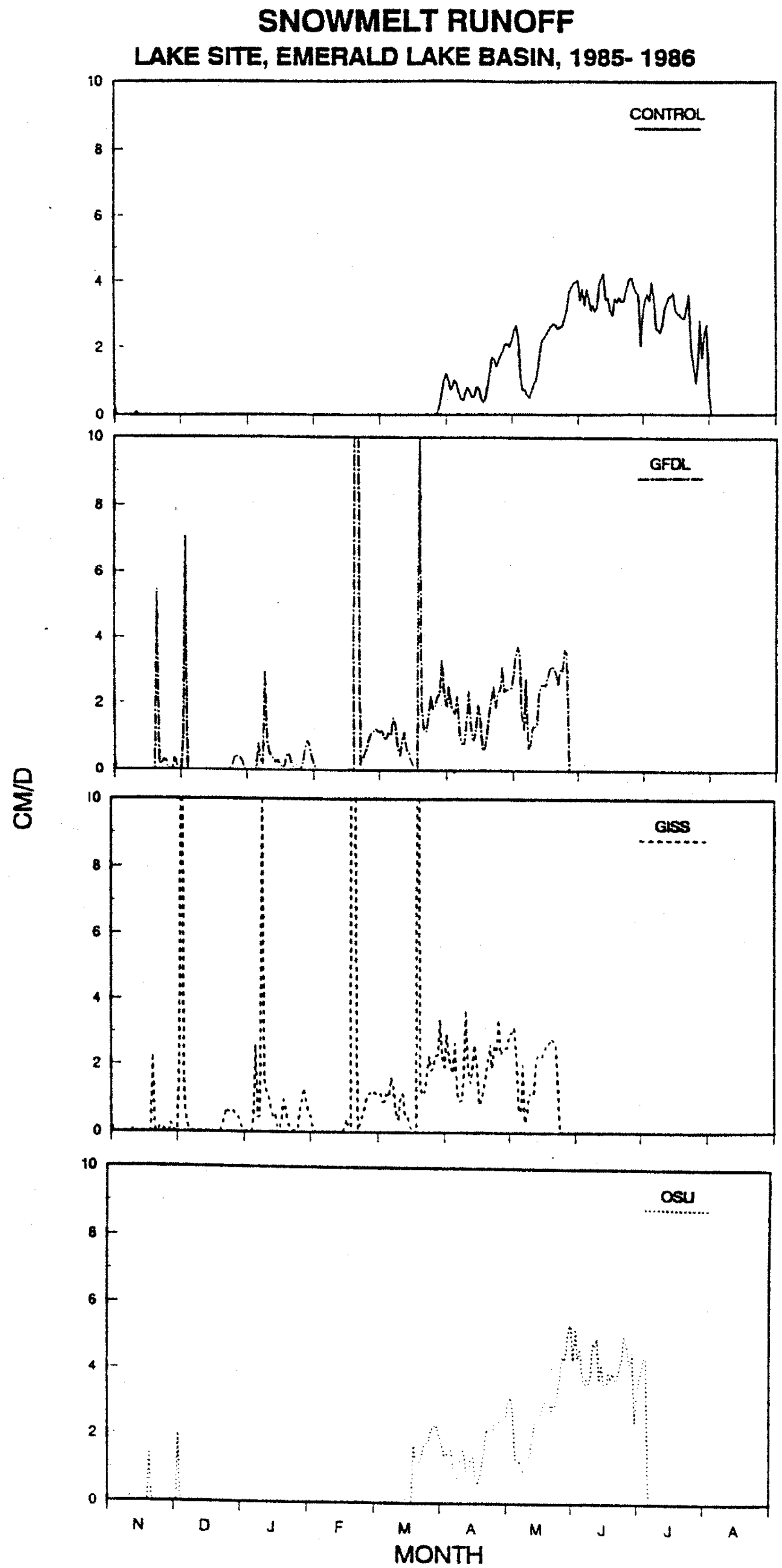

Figure 6. Simulated daily snowmelt runoff under climatic scenarios at the lake site, Emerald Lake Basin, 1985- 1986, where (a) is the results of the control run, (b) by using the GFDL scenario, (c) by using the GISS scenario and (d) by using the OSU scenario.