UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 423

Projections of Seasonal Water Temperature Cycles and Stratification in Five Large Lakes in Minnesota under a $2xCO_2$ Climate Scenario

by

Shaobai Gao and Heinz G. Stefan

Prepared for

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, D. C.
and
MINNESOTA DEPARTMENT OF NATURAL RESOURCES
St. Paul, Minnesota

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ABSTRACT

The objective of this study was to simulate seasonal water temperature cycles and stratification in five large lakes in Minnesota under a $2xCO_2$ climate warming scenario and to compare the results with those under the present (1983 - 1990) climate. The five lakes studied were Mille Lacs Lake, Upper Red Lake, Lake Vermillion, Lake Pepin and Rainy Lake. MINLAKE 96, a one dimensional, unsteady water quality model, was employed.

The values of some parameters which describe lake water temperature and ice characteristics are extracted from the simulation results for both present and 2xCO2 climate scenarios. Results are presented for surface temperatures, bottom temperatures, and differences between surface and bottom water temperatures under the two climate scenarios. Time series for ice thickness are also presented.

During the open water season, water temperatures are projected to increase in the entire lake. The maximum increase is usually in early spring.

In the ice cover season, water temperatures may decrease slightly with climate change, especially near the lake bottom. In deep Rainy Lake the decrease is more than in the shallow Upper Red Lake.

Bottom temperatures less than 8 ^{o}C are found during a shorter period under a $2xCO_2$ climate scenario. This will affect the growth of fish.

During the ice cover season the climate change tends to weaken the inverse stratification. In the open water season climate change strengthens stratification.

Ice is thinner under a $2xCO_2$ climate scenario most of the time, but not all the time. Thicker ice cover is caused by absence of snow. Snowfall and snow depths are smaller under a $2xCO_2$ climate scenario.

Ice-in dates are later and ice-out dates are earlier under a $2xCO_2$ climate scenario. Thus ice cover duration is shorter by an average of 49 days (range from 34 to 73 days). Ice cover also becomes less continuous. The shorter ice cover duration will decrease the possibility of anoxic conditions (winterkill) in lakes during the ice cover season. Earlier ice-out leads to earlier spring overturn.

ACKNOWLEDGMENTS

The investigation described herein was conducted for the Minnesota Department of Natural Resource. Some data used to calibrate the numerical model were provided by Nancy M. Flandrick, Minnesota Pollution Control Agency. Others were provided by Don Pereira, Senior Fisheries Biologist, and Staff of the Minnesota Department of Natural Resources. The work was partially supported by the U.S. Environmental Protection Agency, Office of Research and Development, Washington D.C.. Barbara M. Levinson was project officer.

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1. INTRODUCTION

The importance of temperature as a controlling variable at all levels of ecological systems is well known (Christie et al., 1988). Temperature is one of the most significant factors to determine where fishes can live and thrive. Pending other conditions being favorable (food, dissolved oxygen, etc.), fish will select temperatures near their growth optimum to inhabit most of the time. Each species has a temperature tolerance range (Eaton et al., 1995). If water temperatures are in excess of this range fish will not survive. In temperature stratified lakes fish are therefore forced to find water layers where their requirements are met. It is also known that temperature is a major controlling factor affecting the growth rate of fishes. Different species of fish have different optimum temperature for growth. This means that the pattern of environmental temperature in lakes affects the production and yield of individual species populations. Projected climate change is expected to change water temperature in lakes to some degree. Therefore correctly simulating temperature change in lakes due to climate change is important for projecting changes of optimal thermal habitat and yields for fish species.

The purpose of this study is to simulate seasonal water temperature cycles and stratification under a 2xCO_2 (doubling of atmospheric carbon dioxide) climate scenario in five large lakes in Minnesota, including Mille Lacs Lake, Upper Red Lake, Lake Vermilion (Big Bay), Lake Pepin and Rainy Lake, and to compare the results with those obtained under present climate scenario by Gao and Stefan (1997).

The model used in this study was MINLAKE96, the same model employed to obtain the results under present climate.

Monthly climate parameter increments obtained from the Canadian Climate Center Global Circulation Model (CCC-GCM) were applied to present climate conditions (1982-1990) to generate the projected 2xCO_2 climate scenario. Then the generated weather data were used as input for MINLAKE96 to simulate water temperature in the five lakes.

Simulation results are averaged for 8 years. Averaged isotherms under both present and 2xCO_2 climate scenarios and temperature changes from present to 2xCO_2 climate scenario are presented in this report. Time series of surface temperature, bottom temperature, difference between surface and bottom temperature, ice thickness and snow depth, and their difference between present and 2xCO_2 climate scenarios are also given.

2. MINLAKE 96 MODEL

The model employed for the water temperature simulations is MINLAKE 96. MINLAKE 96 is a one-dimensional, deterministic water quality model which simulates daily temperature and dissolved oxygen profiles in lakes. The model accounts for the heat transfer processes shown in Fig. 2.1. The mechanisms used in the modeling of water temperature in the open water season are wind mixing, surface heat exchange, vertical diffusion in the water, heat absorption from solar radiation and sediment-water heat exchange. For ice-covered lakes the model includes simulations of the onset of ice cover, ice growth and decay, snow accumulation and snow melt, heat transfer through ice and snow, water mixing below the ice cover and heat exchange between sediment and water.

MINLAKE 96 is a modified version of the water quality model MINLAKE 95. Modifications made include the decay of albedo of the winter snow cover after snowfall and ice growth upwards from the ice surface caused by refreezing of water coming through cracks in the ice cover and of snowmelt water.

The general, one-dimensional, unsteady heat transport equation used for the water temperature simulation in MINLAKE 96 is

$$\frac{\partial T}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z}\left[K_z A \frac{\partial T}{\partial z}\right] + \frac{H}{\rho c_p} \tag{2.1}$$

where $T(z,t)$ = water temperature, °C

z = depth, m

t = time, day

A = horizontal area as a function of depth, m^2

K_z = vertical turbulent heat diffusion coefficient, m^2/day

c_p = specific heat, J/(kg.°C)

H = heat source or sink strength per unit volume, J/(m^3.day)

The model was calibrated for four of the five lakes (Gao and Stefan, 1997). Standard errors for water temperature between simulated and measured data were 0.95°C for Mille Lacs Lake, 1.79°C for Upper Red Lake, 0.74°C for Lake Vermilion, and 0.93°C for Lake Pepin. Accuracy of the model for snow depth and ice thickness was 0.07 m and 0.12 m for Thrush Lake, Minnesota, and Little Rock Lake, Wisconsin (Fang and Stefan, 1996). The difference between simulated and observed ice-on date was less than 6 days for nine Minnesota lakes (Fang et al., 1996), and the average differences for ice-on date, ice-off date and ice cover duration were 10 days, 9 days and 12 days for three lakes in Wisconsin, one lake in Maine and one lake in Canada (Gao and Stefan, 1998).

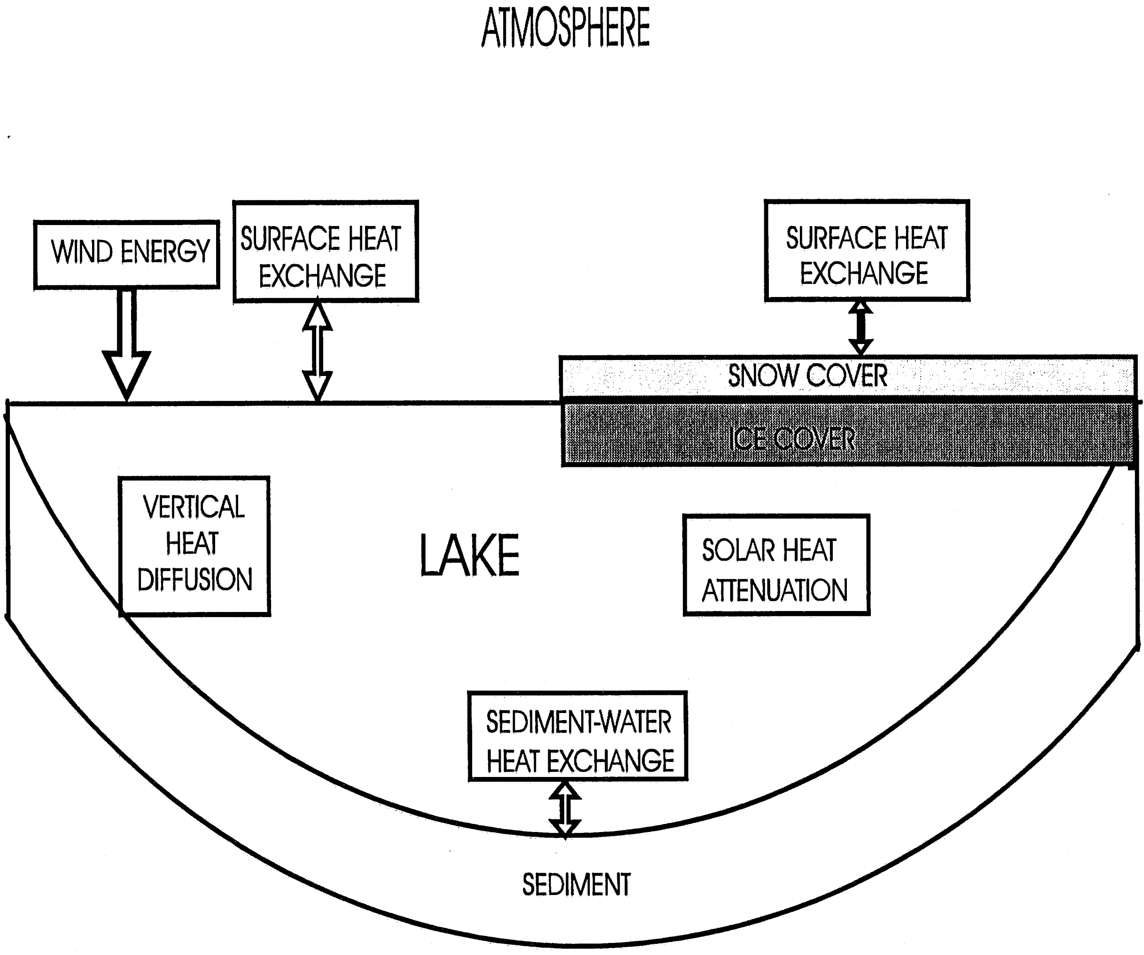

Fig. 2.1 Heat transfer processes represented in MINLAKE 96

3 BATHYMETRIC CHARACTERISTICS OF THE LAKES AND WEATHER DATA

3.1 Bathymetric Characteristics of the Lakes

The five large lakes simulated are Mille Lacs Lake, Upper Red Lake, Lake Vermilion, Lake Pepin and Rainy Lake. The locations of the five lakes are given in Fig. 3.1. The lake surface areas range from 101.4 km^2 to 893.6 km^2 and the maximum depths from 6.1 m to 49.1 m. Table 3.1 shows surface areas, maximum depths, weather stations from which meteorological data came, and the lake geometry ratio $A^{0.25}/H_{max}$ which can be used to determine whether a lake will be strongly stratified in summer. Mille Lacs Lake and Upper Red Lake are expected to be polymictic lakes; Lake Vermillion and Lake Pepin are expected to be weakly stratified lakes; Rainy Lake is expected to be the most strongly stratified of the five lakes. This will be confirmed by the simulation results.

3.2 Weather Data

Weather data for the present climate (1982 - 1990) were obtained from the Solar And Meteorological Surface Observation Network (SAMSON), compiled by the National Climatic Data Center. Three weather stations in Minnesota (Duluth, International Falls, Rochester) were used in this study.

The meteorological data needed in the simulations are the daily values of air temperature, dew point temperature, precipitation, wind speed, sunshine percentage and solar radiation.

The projected climate changes for a doubling of atmospheric carbon dioxide (2xCO_2) were obtained from the Canadian Climate Center General Circulation Model (CCC-GCM). Monthly averaged changes in air temperature, dew point temperature, wind speed, solar radiation and precipitation are given in Tables 2.2 to 2.4 for International Falls, Duluth and Rochester, respectively.

The projected monthly climate changes were added to the present climate condition (1982 - 1990) to generate 2xCO_2 climate scenario.

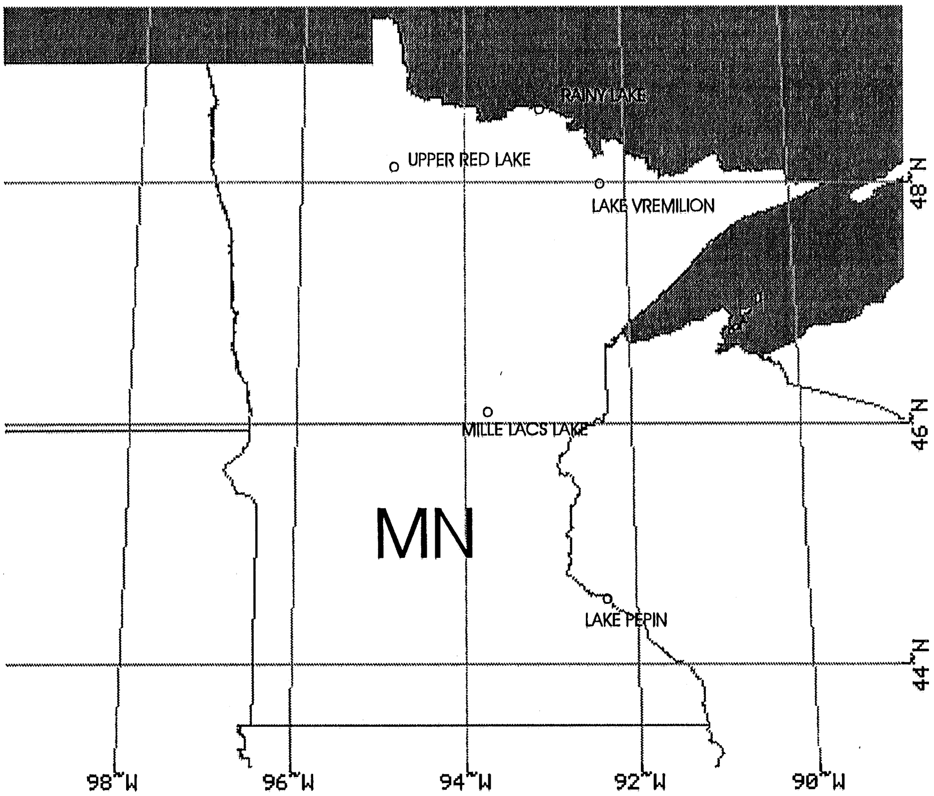

Fig. 3.1 Locations of the five investigated lakes

Table 3.1 Surface Areas, Maximum Depths and Weather Stations used for the Five Lakes

Lake Name	Weather Station	Latitude	Surface Area A_s (km^2)	Max. Depth H_{max} (m)	$A_s^{0.5}/H_{max}$ (m$^{-0.5}$)
Mille Lacs lake	Duluth	46°50"	536.3	11.3	13.5
Upper red lake	Inter. Falls	48°34"	436.3	6.1	23.7
L. Vermilion	Duluth	46°50"	198.7	17.4	6.82
Lake Pepin	Rochester	43°55"	101.4	18.3	5.48
Rainy lake	Inter. Falls	48°34"	893.6	49.1	3.52

Note: Surface areas and maximum depths are obtained from bathymetric maps or provided by the Minnesota Department of Natural Resources

Table 3.2 CCC-GCM $2xCO_2$ Climate Scenario for International Falls, Minnesota.

Month	Air temp. difference[1] (°C)	Specific humidity ratio[2]	Wind speed ratio	Solar radiation ratio	Precipitation ratio
Jan	6.24	1.68	1.22	0.95	1.38
Feb	6.28	1.67	1.10	0.97	1.14
Mar	4.28	1.37	0.96	0.96	0.82
Apr	2.91	1.40	0.99	0.97	1.20
May	4.61	1.39	0.94	0.98	1.32
Jun	4.53	1.33	0.87	0.96	0.89
Jul	4.02	1.19	0.90	0.99	0.60
Aug	5.76	1.29	0.90	1.05	0.97
Sep	4.87	1.24	1.03	1.02	1.56
Oct	2.88	1.16	1.08	1.00	1.20
Nov	2.99	1.24	1.02	1.01	1.35
Dec	7.42	1.50	1.22	0.99	1.27

[1] difference = $2xCO_2$ - $1xCO_2$, $1xCO_2$ = 1982 - 1990

[2] ratio = $2xCO_2/1xCO_2$

Table 3.3 CCC-GCM 2xCO$_2$ Climate Scenario for Duluth, Minnesota.

Month	Air temp. difference[1] (°C)	Specific humidity ratio[2]	Wind speed ratio	Solar radiation ratio	Precipitation ratio
Jan	8.17	1.85	1.08	0.94	1.23
Feb	8.50	1.94	1.10	0.92	1.26
Mar	4.37	1.53	0.88	0.95	1.22
Apr	5.76	1.78	1.01	0.95	1.50
May	5.39	1.46	0.97	0.97	1.05
Jun	4.27	1.32	0.85	0.96	0.99
Jul	3.54	1.23	0.80	0.96	0.87
Aug	5.24	1.35	0.83	0.99	0.87
Sep	4.51	1.29	0.90	0.99	0.79
Oct	2.71	1.19	1.01	0.98	0.96
Nov	2.90	1.29	1.02	1.01	0.96
Dec	4.38	1.25	0.91	1.00	0.97

[1] difference = 2xCO$_2$ - 1xCO$_2$, 1xCO$_2$ = 1982 - 1990

[2] ratio = 2xCO$_2$/1xCO$_2$

Table 3.4 CCC-GCM $2xCO_2$ Climate Scenario for Rochester, Minnesota.

Month	Air temp. difference[1] (°C)	Specific humidity ratio[2]	Wind speed ratio	Solar radiation ratio	Precipitation ratio
Jan	10.09	1.67	0.97	0.91	0.87
Feb	12.98	1.94	1.26	0.89	1.57
Mar	8.67	1.66	1.16	0.93	1.25
Apr	7.62	1.55	1.09	0.94	0.99
May	5.20	1.37	0.95	0.97	1.01
Jun	4.61	1.27	0.90	0.99	1.20
Jul	4.93	1.23	0.78	1.00	0.95
Aug	5.51	1.18	0.79	1.02	0.79
Sep	5.44	1.24	0.92	0.96	1.08
Oct	3.33	1.14	1.00	0.99	1.07
Nov	3.40	1.21	1.07	0.98	0.85
Dec	3.54	1.15	0.82	0.99	1.02

[1] difference = $2xCO_2$ - $1xCO_2$, $1xCO_2$ = 1982 - 1990
[2] ratio = $2xCO_2/1xCO_2$

4. SIMULATION RESULTS FOR THE $2xCO_2$ CLIMATE SCENARIO

4.1 Mille Lacs Lake

Mille Lacs Lake in central Minnesota has a surface area of 536.3 km^2 and a maximum depth of 11.3m. A bathymetric map of the lake is given in Appendix A. Meteorological data (1982 - 1990) from Duluth were used to generate the $2xCO_2$ climate scenario. The lake was simulated for nine years. To eliminate possible error caused by inappropriate initial conditions, results for the first year were excluded. Results were averaged for the remaining eight years.

Figures 4.1.1 and 4.1.2 show isotherms interpolated from averaged simulation results of daily water temperature profiles under present and the $2xCO_2$ climate scenarios. Fig. 4.1.3 gives the water temperature increase from present to the $2xCO_2$ climate scenario. Maximum projected water temperature increase reaches 7^oC; this happens in early spring. Water temperature increases are almost the same from surface to bottom during the open water season.

Figures. 4.1.4 and 4.1.5 show, respectively, time series for average surface water temperature (1 m below water surface) and bottom water temperature (1 m above the deepest point of the lake) under the present and $2xCO_2$ climate scenarios, as well as differences between the results under the two climate scenarios. Both surface temperatures and bottom temperatures increase from the present to the $2xCO_2$ climate scenario, except for a period in early winter during which the surface and bottom water temperatures slightly decrease. This is because ice-in dates are different under the two climate conditions. In shallow lakes such as Mille Lacs Lake, water temperatures reach their annual minimum just before ice-in. After ice cover formation water temperatures increase gradually. Water temperatures begin to increase earlier under present climate condition because the ice cover forms earlier.

Fig. 4.1.6 shows temperature difference between surface water temperature and bottom water temperature under the two climate scenarios. This difference indicates the strength of stratification. In the open water season stratification is very weak. It will increase very slightly under the $2xCO_2$ climate scenario. In the ice cover season stratification is projected to become weaker.

Figures 4.1.7 and 4.1.8 show time series for simulated ice thickness and snow depth under the two climate scenarios. Both ice thicknesses and snow depths decrease from present to the $2xCO_2$ climate scenario. Maximum ice thickness decreases from an average 0.73 m to 0.44 m. The figure also shows that ice-in dates become later and ice-out dates become earlier from present to the $2xCO_2$ climate scenario. The ice-in date

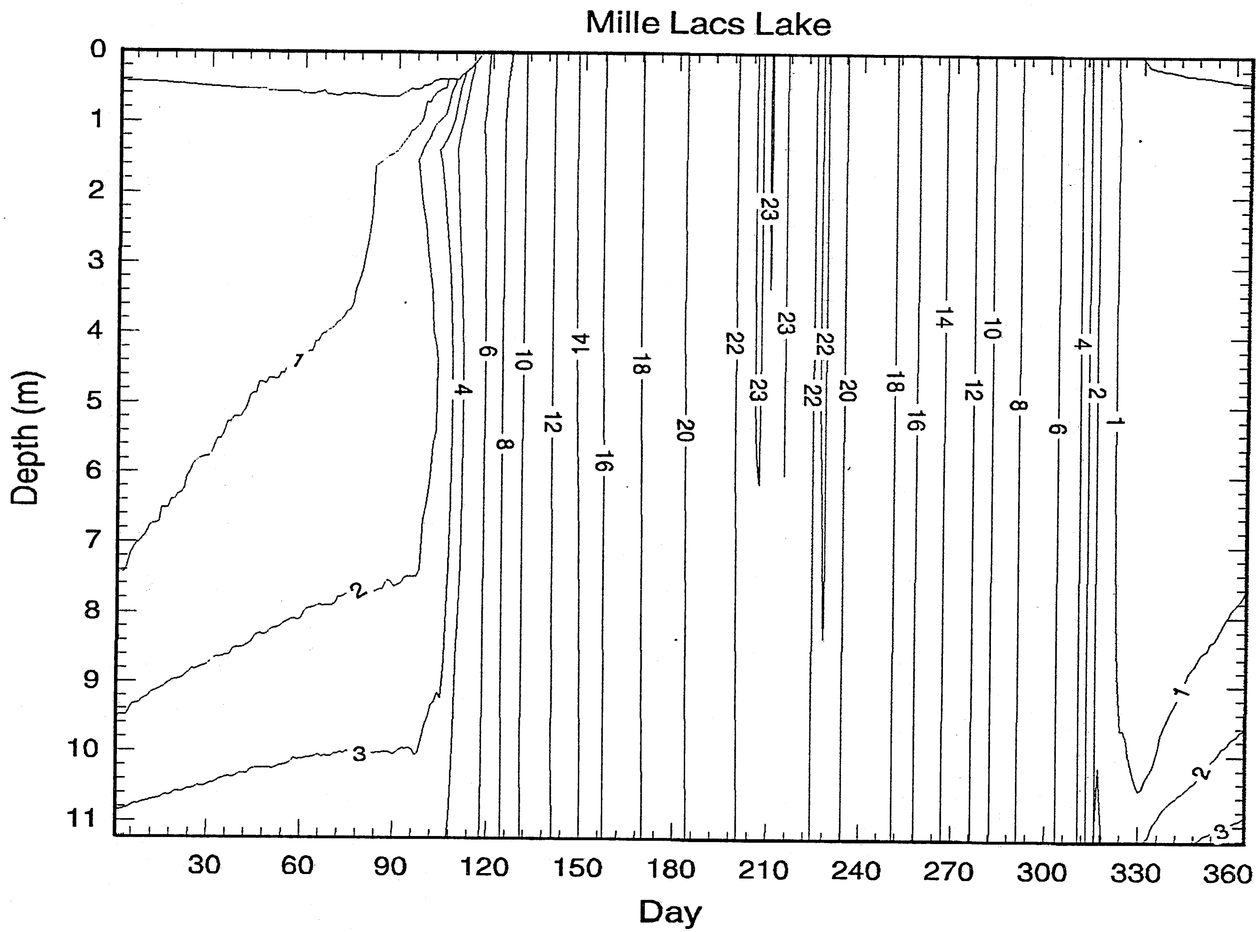

Fig. 4.1.1 Isotherms for Mille Lacs Lake under present (1983 - 1990) climate

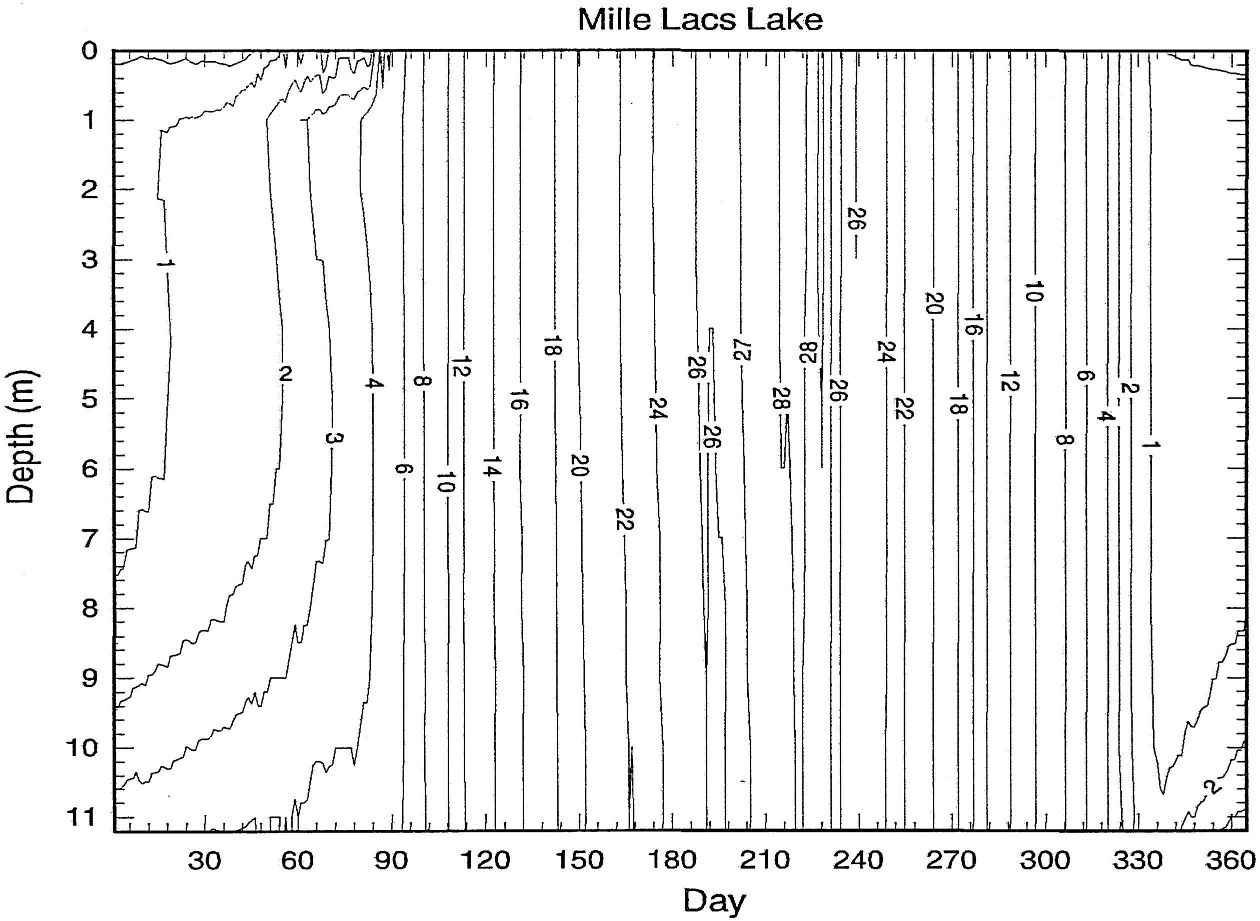

Fig. 4.1.2 Isotherms for Mille Lacs Lake under the $2xCO_2$ climate scenario

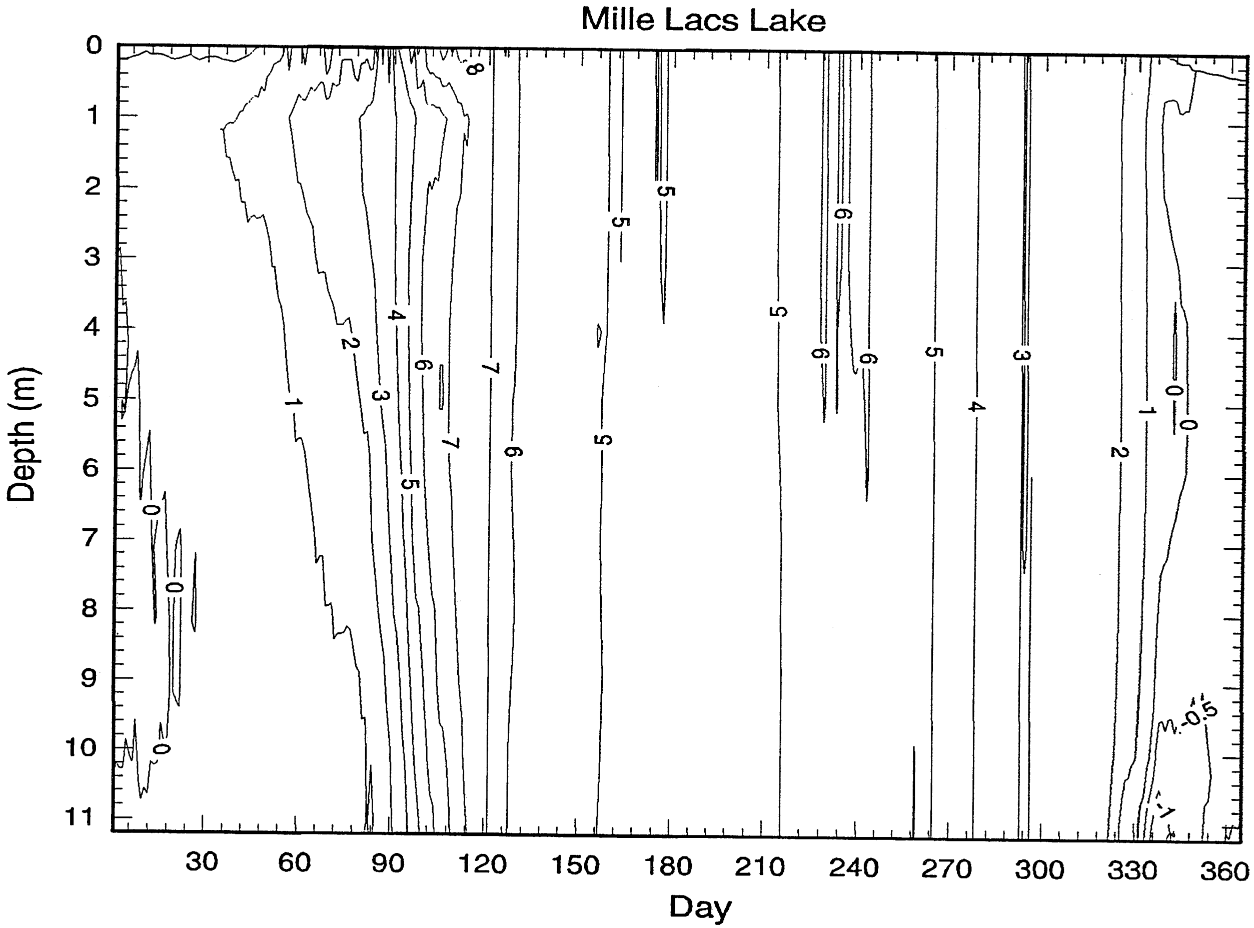

Fig. 4.1.3 Water temperature increase in Mille Lacs Lake from present (1983 - 1990) to the 2xCO$_2$ climate scenario

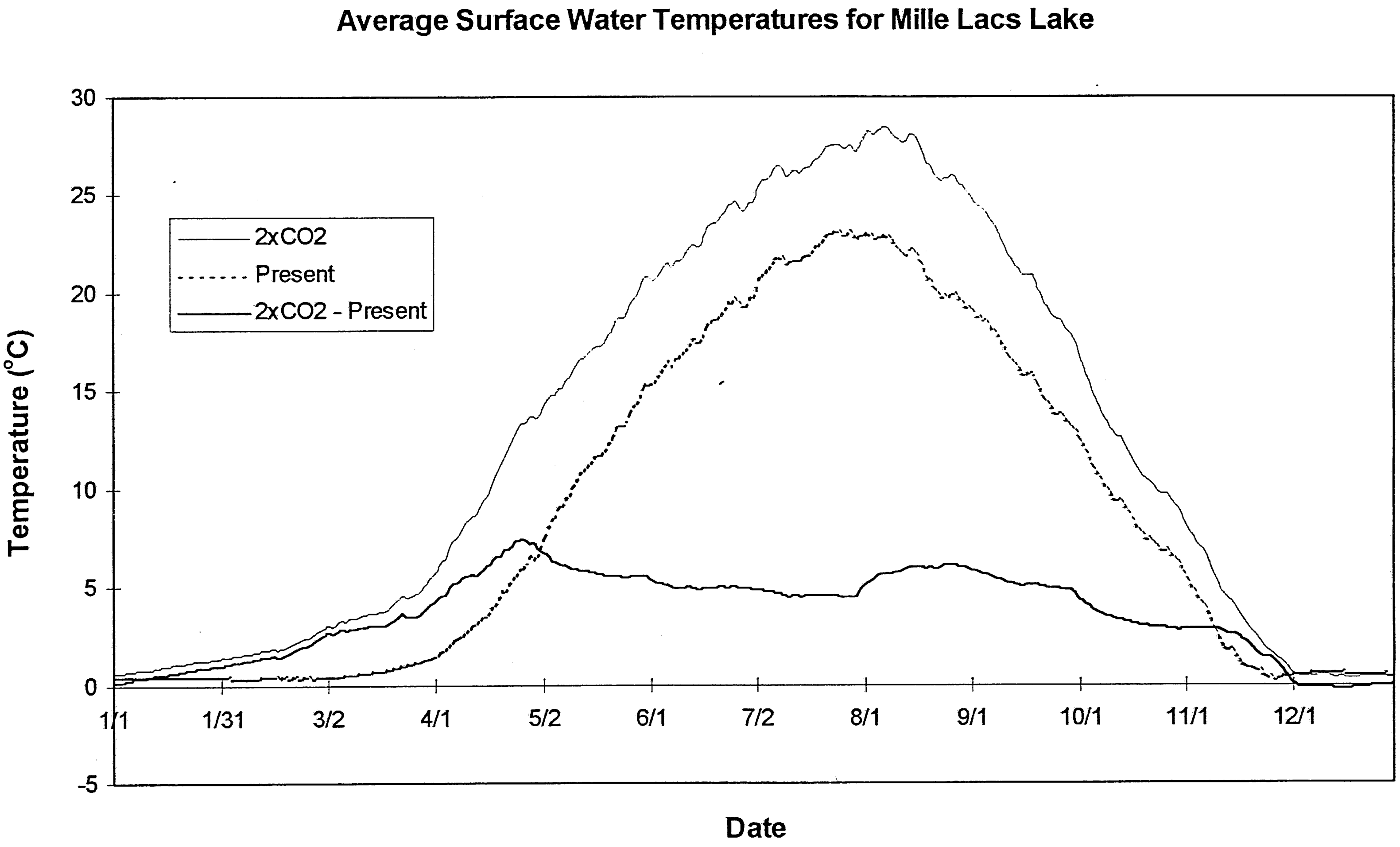

Fig. 4.1.4 Average surface water temperatures in Mille Lacs Lake under present (1983 - 1990) and the 2xCO_2 climate scenario

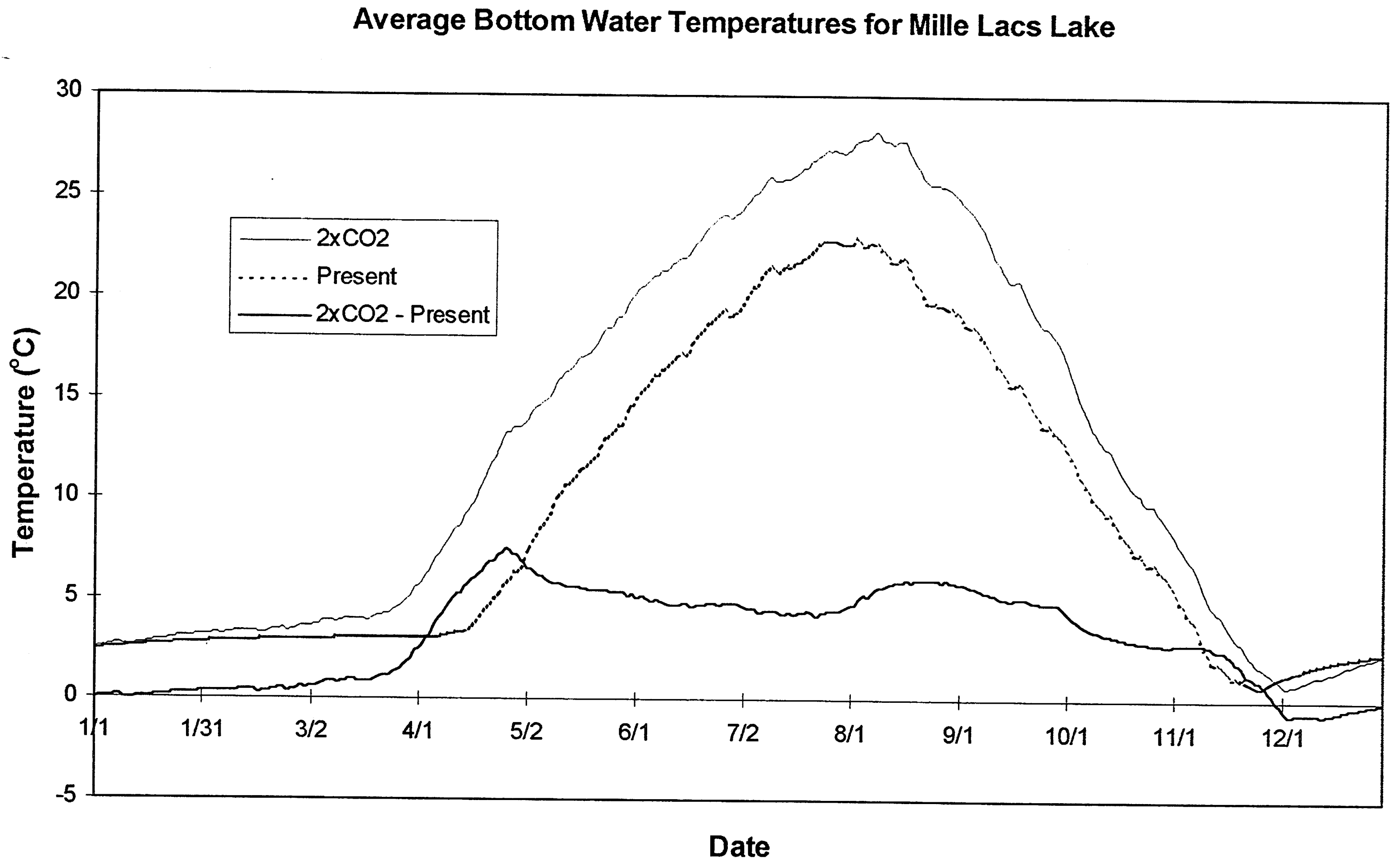

Fig. 4.1.5 Average bottom water temperatures in Mille Lacs Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

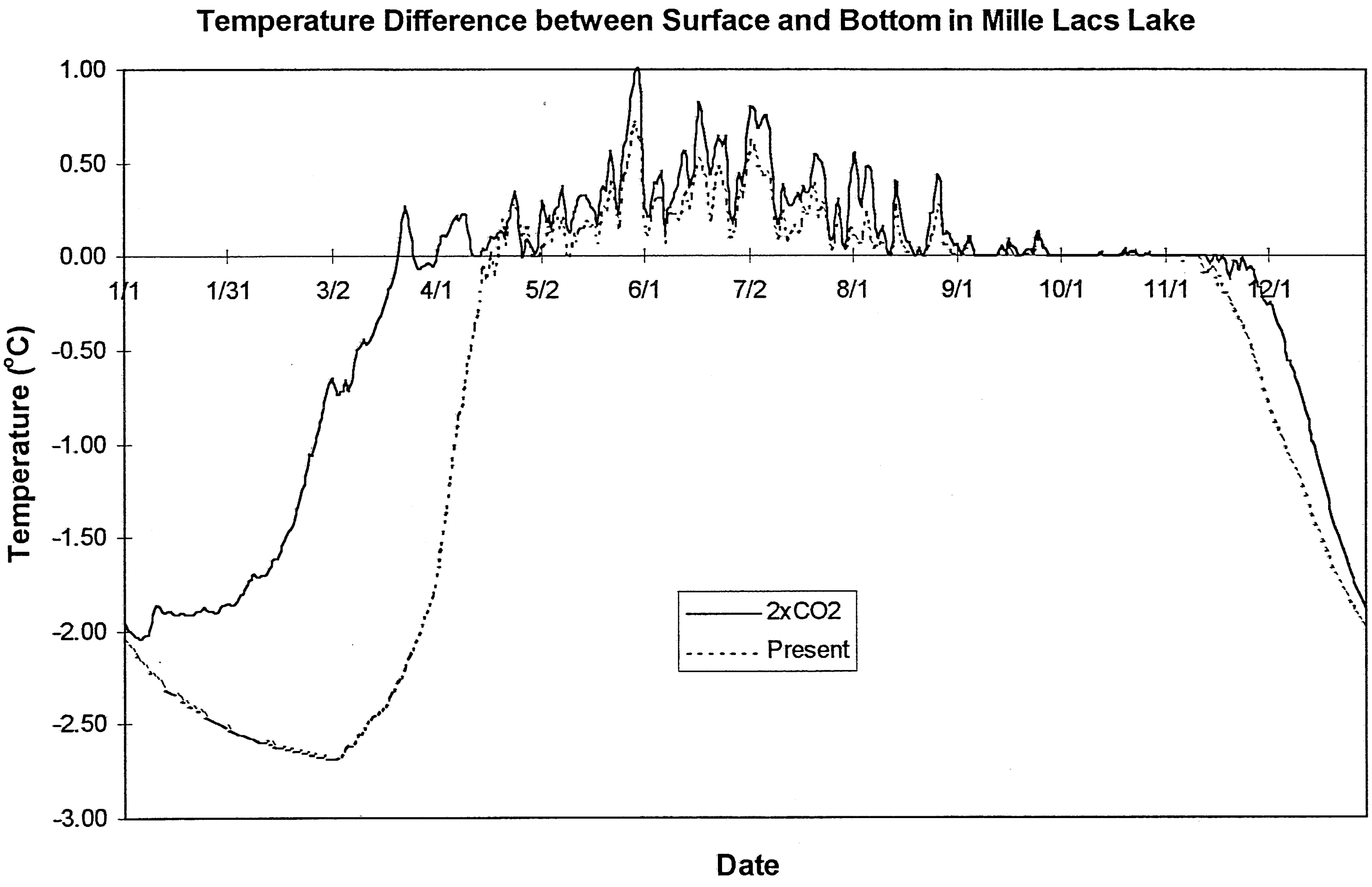

Fig. 4.1.6 Average difference between surface and bottom water temperatures in Mille Lacs Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

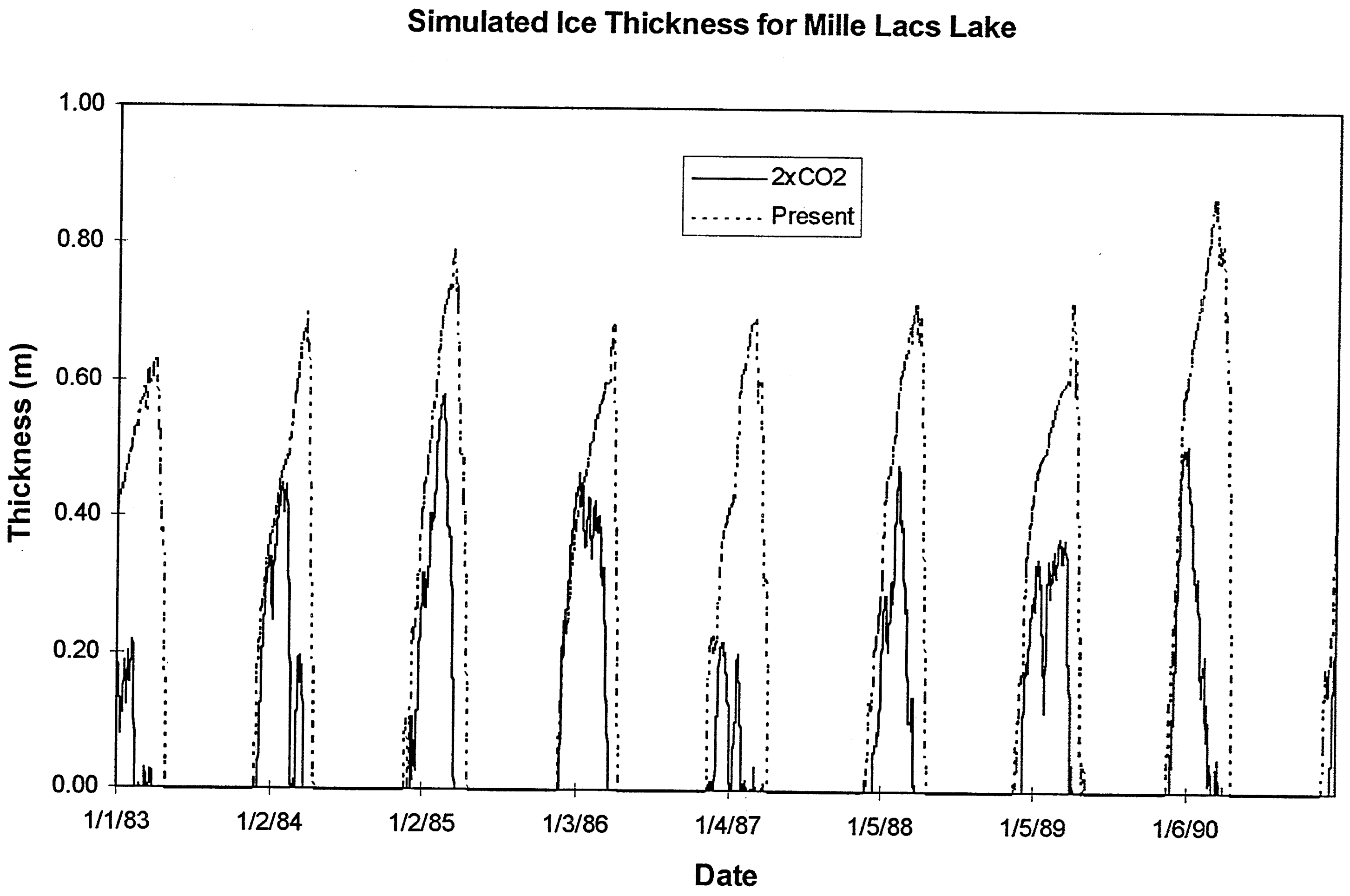

Fig. 4.1.7 Simulated ice thicknesses for Mille Lacs Lake under present (1983 - 1990) and the 2xCO_2 climate scenario

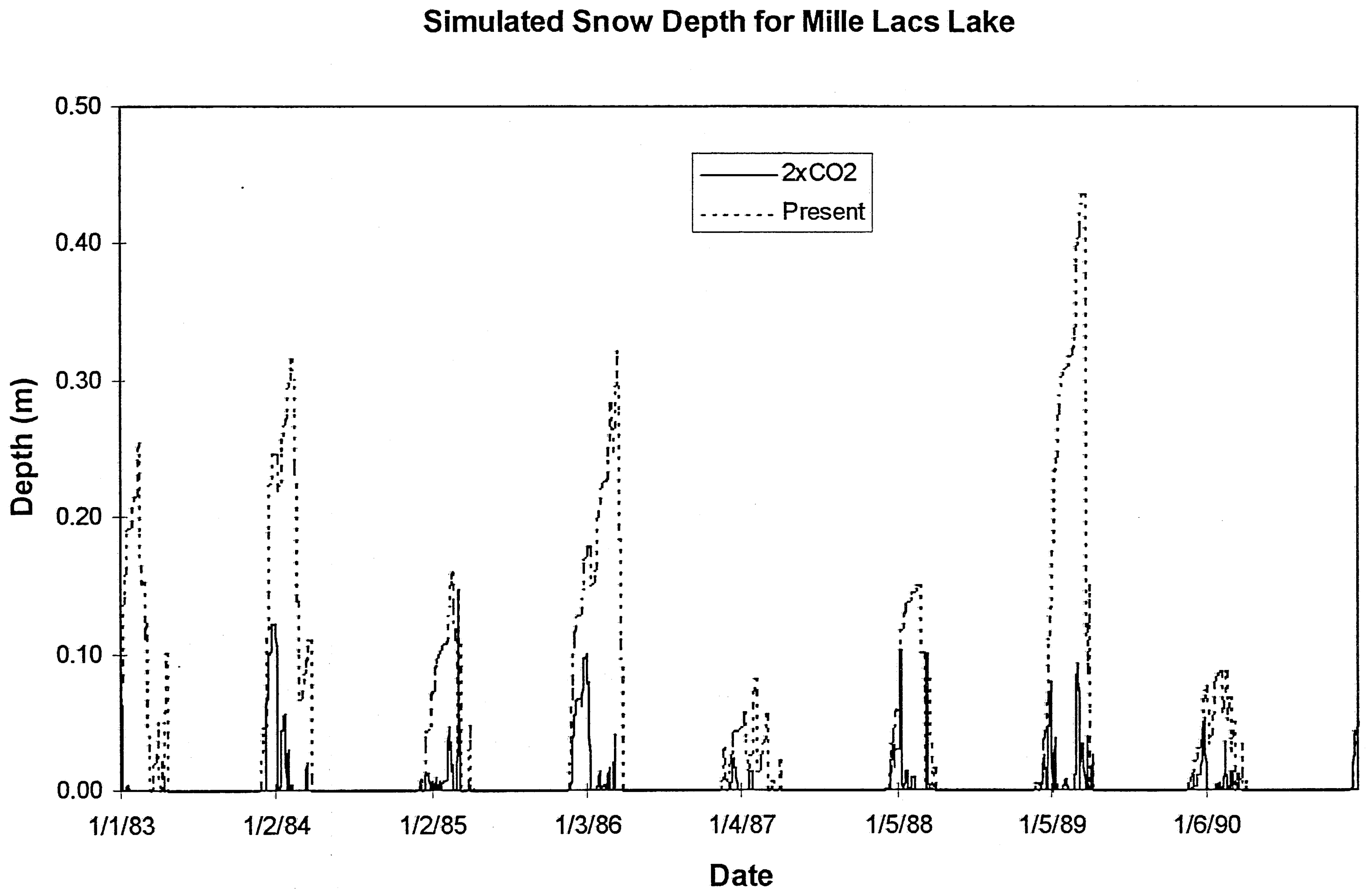

Fig. 4.1.8 Simulated snow depths for Mille Lacs Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

changes on average from November 22 to December 6, and average ice-out date changes from April 21 to March 6. Obviously ice-out date is affected more by climate change than ice-in date.

4.2 Upper Red Lake

Upper Red Lake in northern Minnesota has a surface area of 436.3 km^2 and a maximum depth of only 6.1 m. Meteorological data (1982 - 1990) from International Falls were used to simulate lake temperatures. To eliminate errors caused by inappropriate initial conditions, results for 1982 were excluded. The results for the remaining eight years were averaged.

Figures 4.2.1 and 4.2.2 give isotherms interpolated from average simulated daily water temperature profiles under present (1983 - 1990) and the $2xCO_2$ climate scenarios. Fig. 4.2.3 shows the water temperature increase from present to the $2xCO_2$ climate scenario. The projected maximum water temperature increase reaches 6°C. Because the lake is well mixed, the increases are almost the same from surface to bottom during the open water season. In winter water temperatures are projected to increase by much less than in summer, and the increase is not uniform from surface to bottom. In early winter, water temperatures are projected to decrease by up to about 0.5°C under the $2xCO_2$ climate scenario.

Figures 4.2.4 and 4.2.5 show time series for average surface water temperature (1 m below water surface) and bottom water temperature (1 m above the deepest point of lake bottom) under the present and the $2xCO_2$ climate scenarios, as well as differences between the results under the two climate scenarios. Water temperatures increase from the present to the $2xCO_2$ climate scenario, except for a period in early winter during which water temperatures slightly decrease, because of the different ice-in dates.

Fig. 4.2.6 shows the difference between surface water temperature and bottom water temperature under the two climate scenarios. This difference indicates the strength of stratification. In the open water season the stratification tends to be stronger under the $2xCO_2$ climate scenario than under present climate except during a short period in spring. In the ice cover season the inverse temperature stratification becomes weaker.

Figures 4.2.7 and 4.2.8 show time series for simulated ice thickness and snow depth under the two climate scenarios. In all simulated years snow depths decrease from present to the $2xCO_2$ climate scenario. For most of the years ice thicknesses also decrease, but for two years maximum ice thicknesses under the $2xCO_2$ climate scenario are about the same as those under present climate. This is because under the $2xCO_2$ climate scenario snow depth decreases, and less snow cover causes an increase in the heat transfer from the ice to the atmosphere. This completely offsets the effect of higher air temperature in those two years. In other years the decrease in available snow depth only offsets part of the effect of higher air temperature. Maximum ice thickness decreases from an average 0.76 m to 0.53 m, as climate changes from 1983 - 1990 conditions to the $2xCO_2$ climate scenario. Ice-in is later and ice-out is earlier from present to the $2xCO_2$ climate scenario. Average ice-in date changes from November 10 to November 27, and

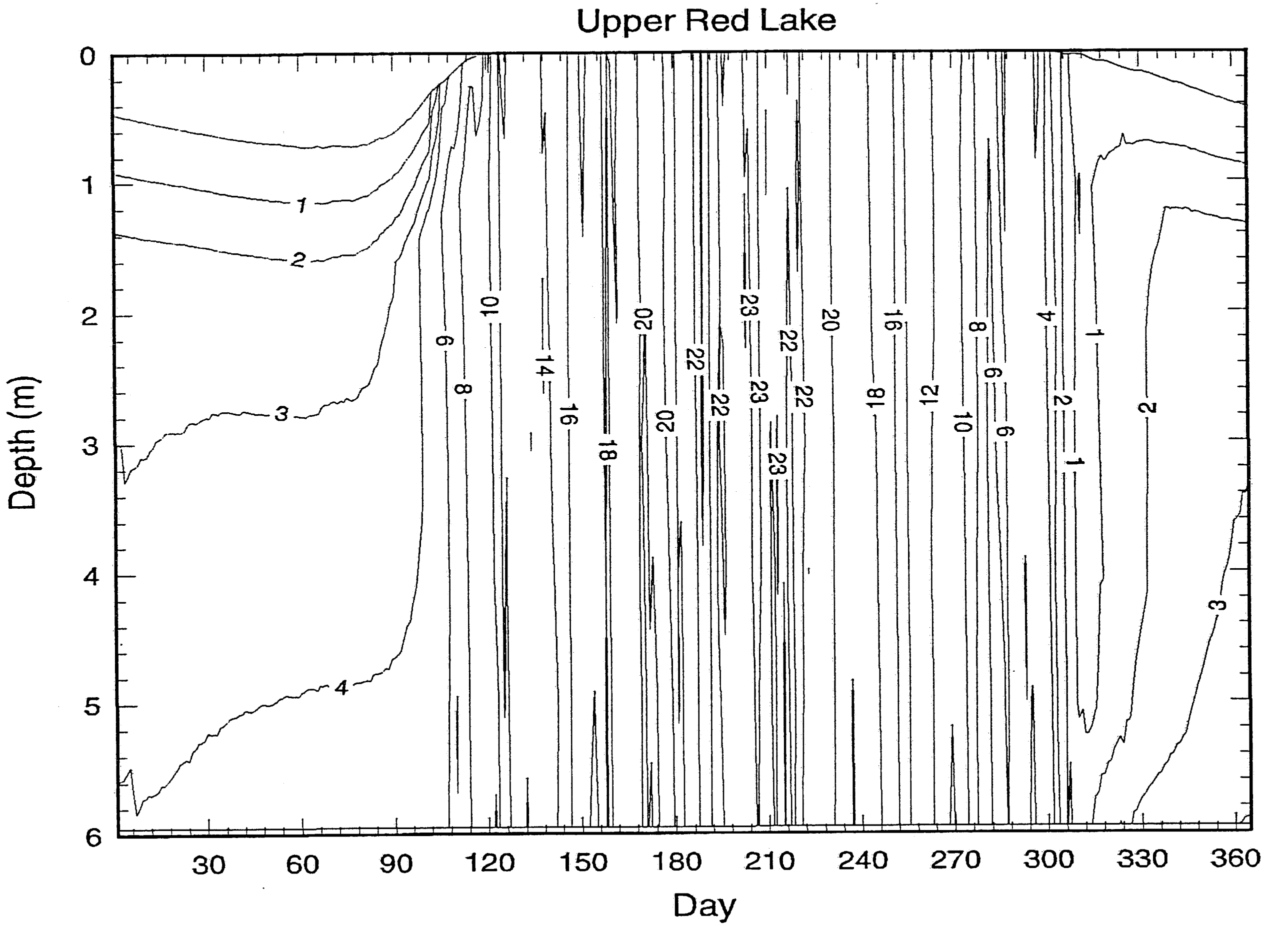

Fig. 4.2.1 Isotherms for Upper Red Lake under present (1983 - 1990) climate

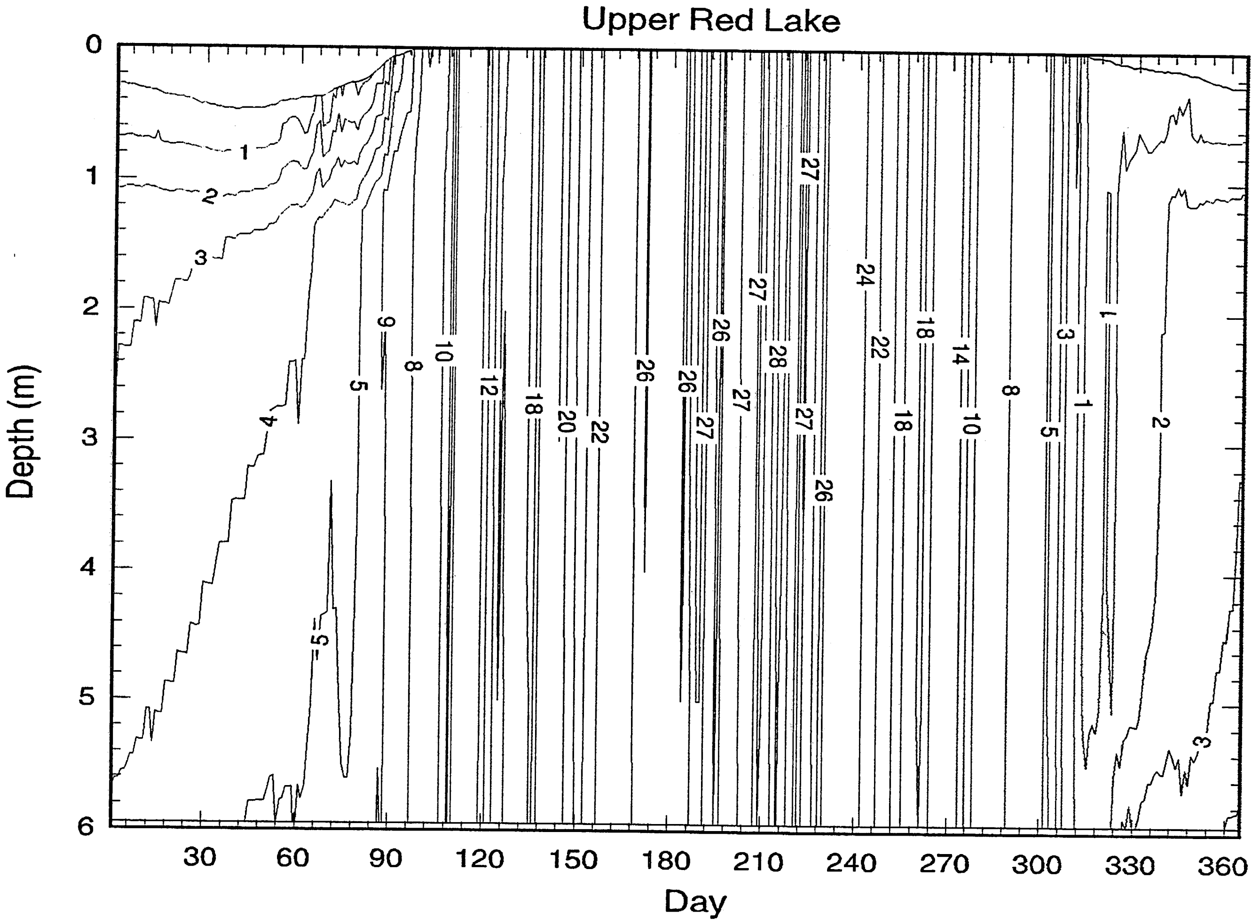

Fig. 4.2.2 Isotherms for Upper Red Lake under the 2xCO$_2$ climate scenario

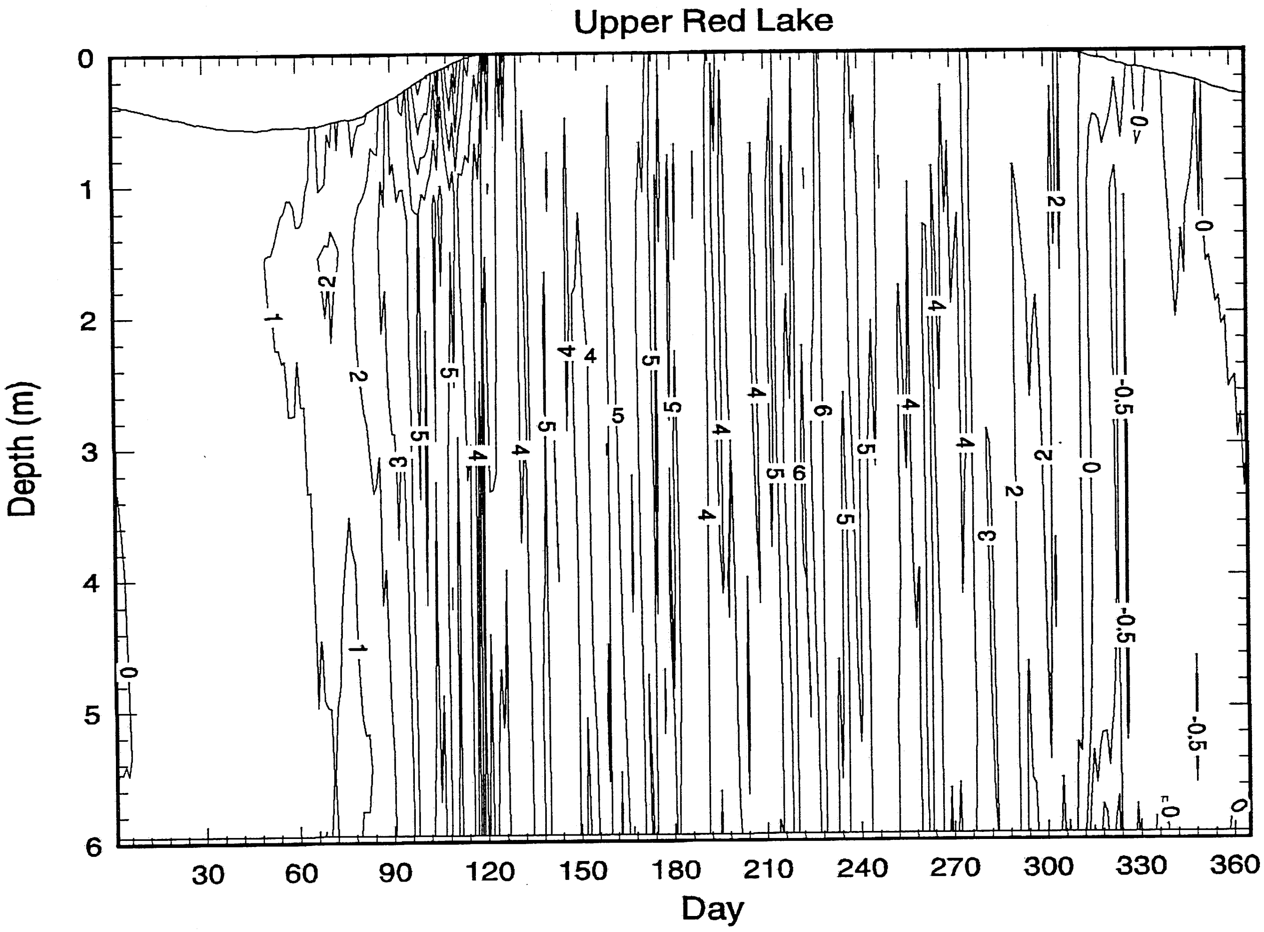

Fig. 4.2.3 Water temperature increase for Upper Red Lake from present (1983 - 1990) to the 2xCO$_2$ climate scenario

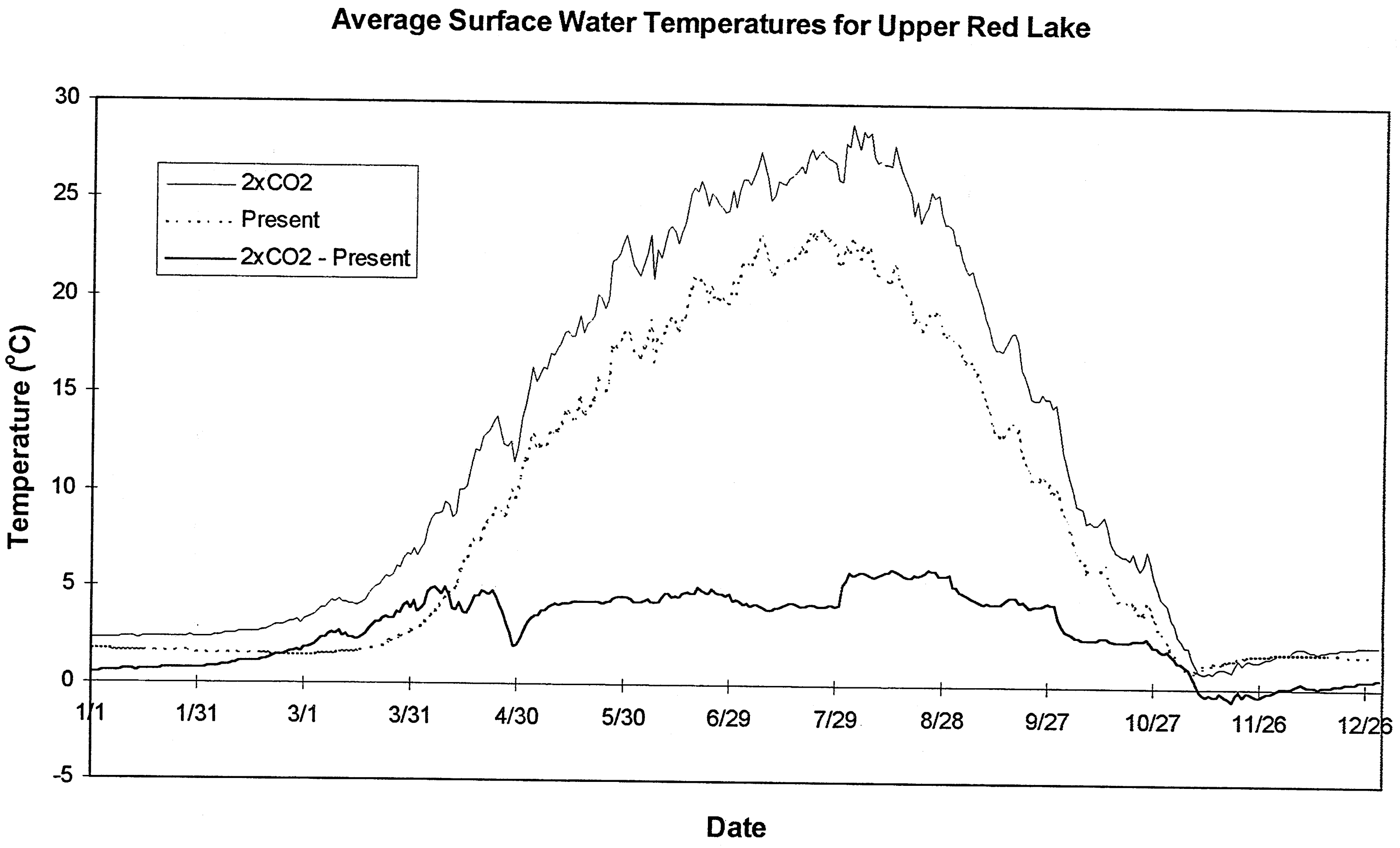

Fig. 4.2.4 Average surface water temperatures in Upper Red Lake under present (1983 - 1990) and the 2xCO$_2$ climate scenario

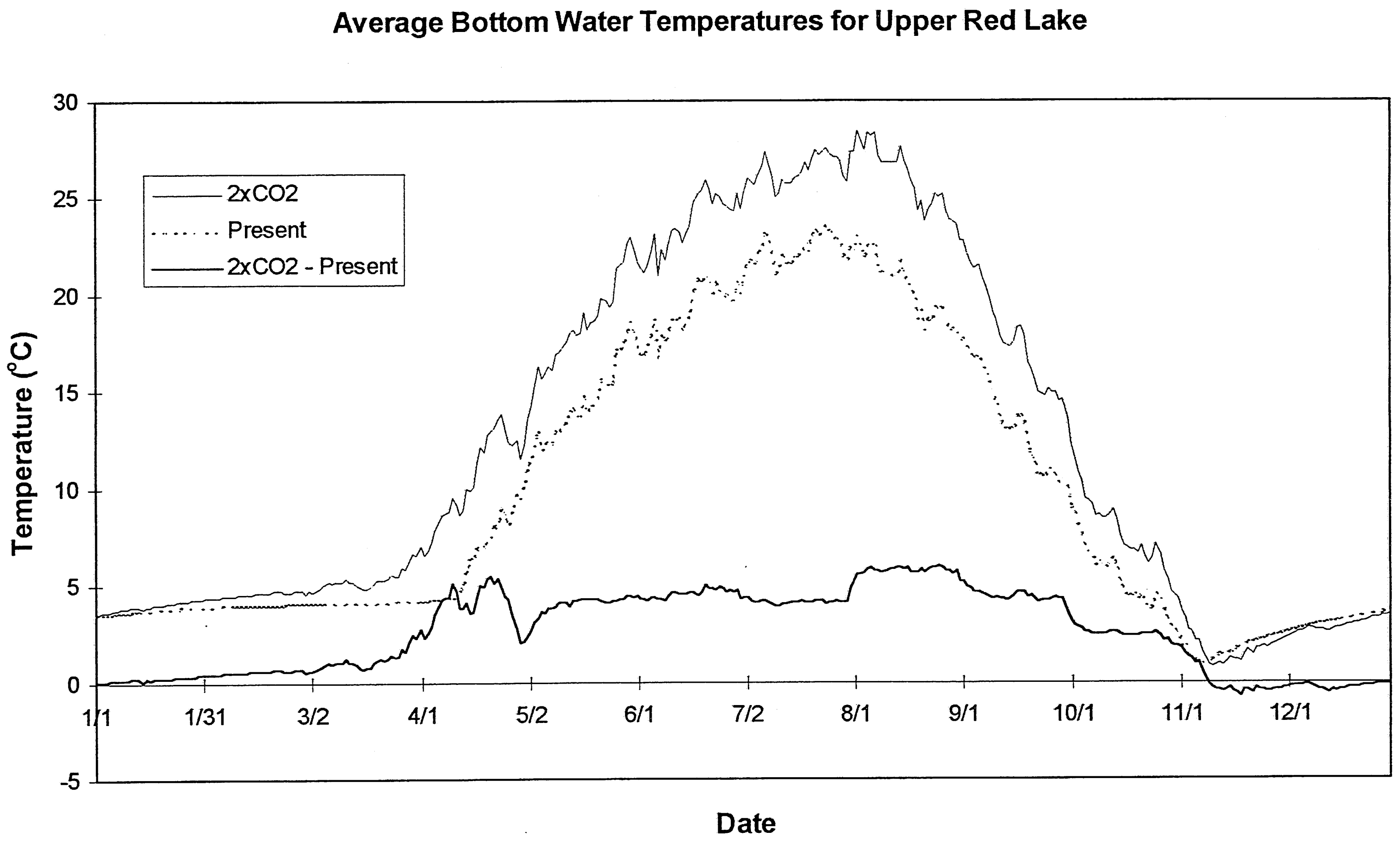

Fig. 4.2.5 Average bottom water temperatures in Upper Red Lake under present (1983 - 1990) and the 2xCO$_2$ climate scenario

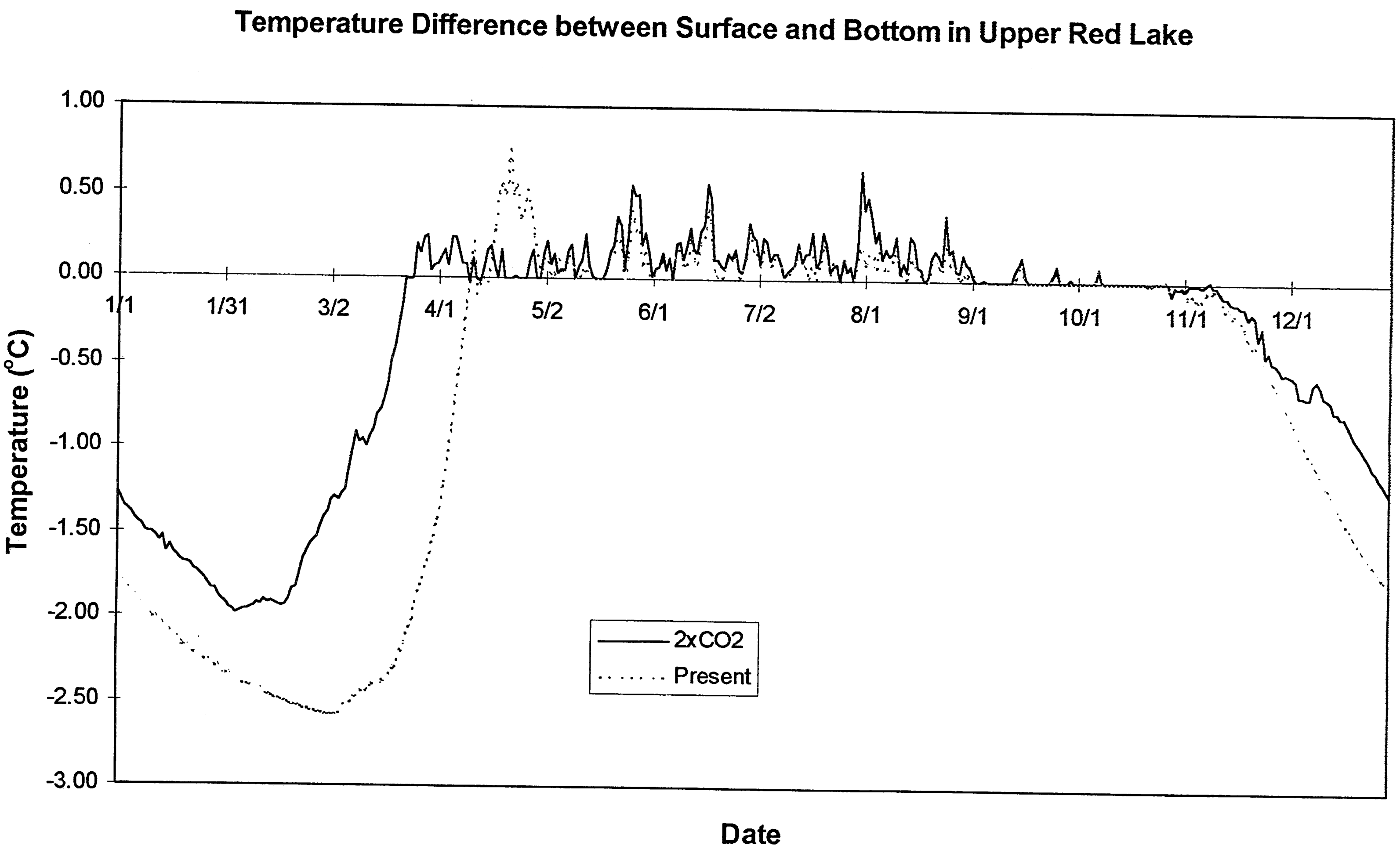

Fig. 4.2.6 Average difference between surface and bottom water temperatures in Upper Red Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

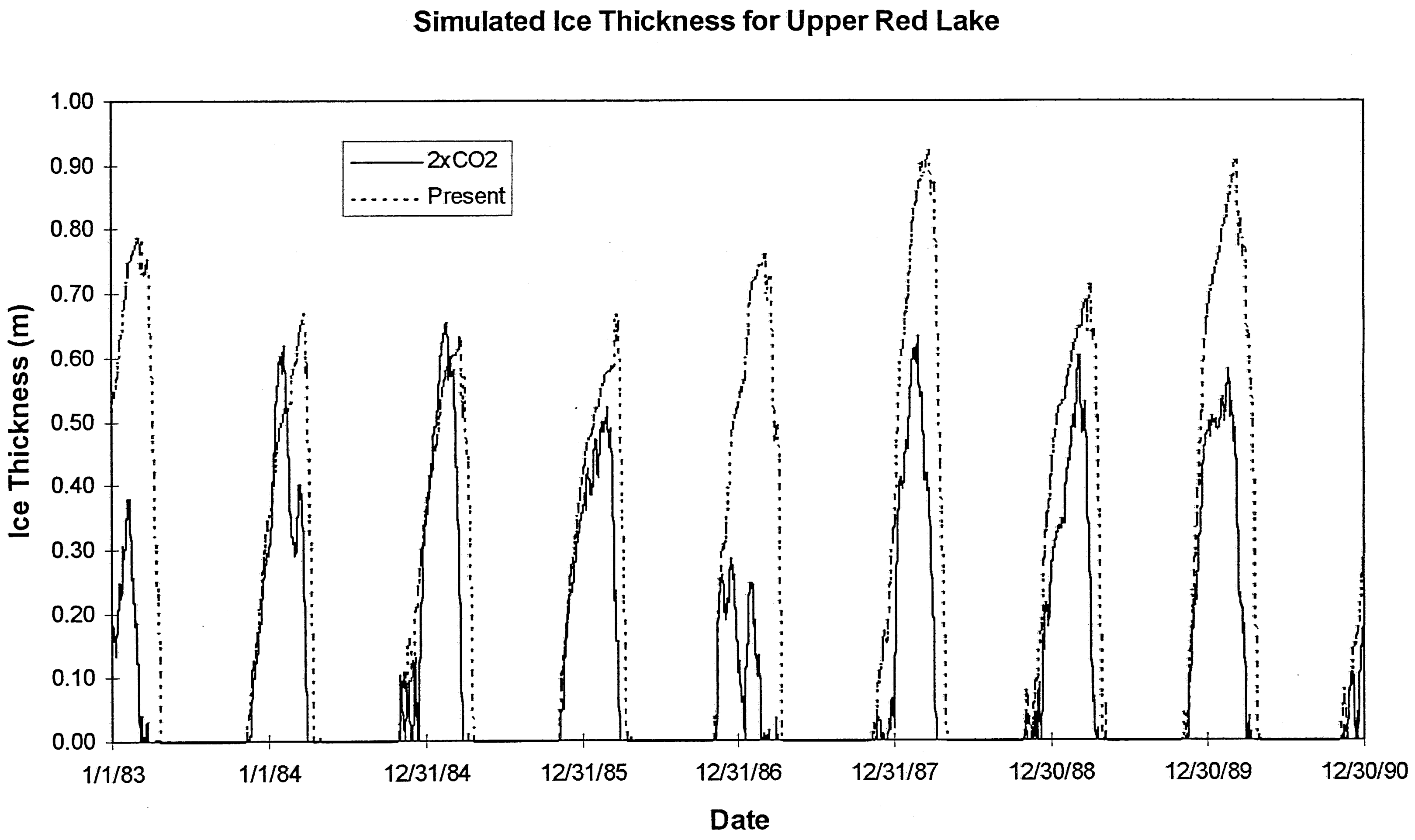

Fig. 4.2.7 Simulated ice thicknesses for Upper Red Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

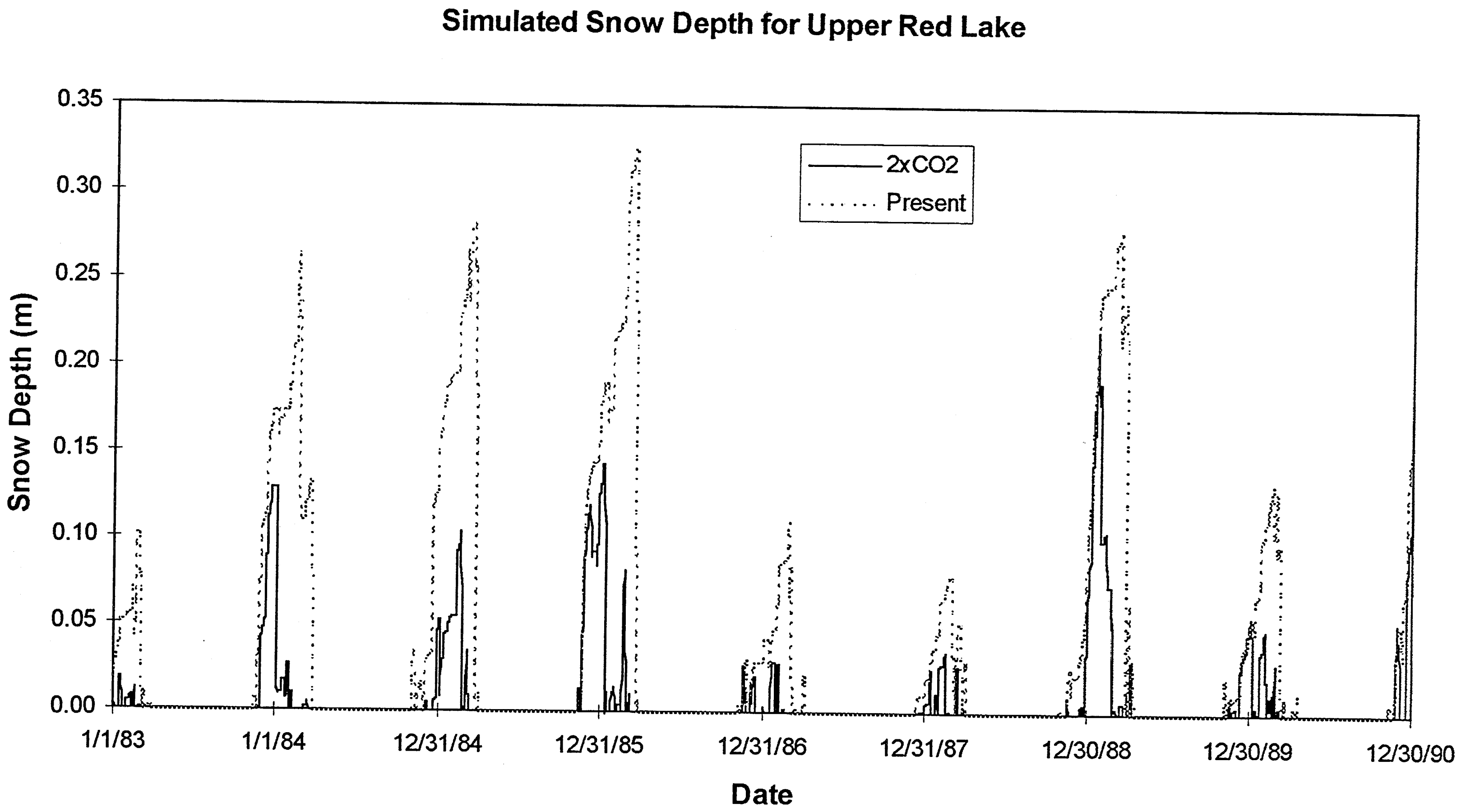

Fig. 4.2.8 Simulated snow depths for Upper Red Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

ice-out date changes from April 21 to March 20. The ice-out date is affected more by climate change than the ice-in date.

4.3 Lake Vermilion

Lake Vermilion in northern Minnesota has several basins separated by shoals which significantly restrict horizontal water exchange between basins. Only the largest basin, Big Bay, was simulated. Big Bay has a surface area of 61.1 km^2 and a maximum depth of 23.2 m. Meteorological data (1982 - 1990) from Duluth were used to simulate lake temperatures. To eliminate errors caused by inappropriate initial conditions, results for 1982 were excluded. The results for the remaining eight years were averaged.

Figures 4.3.1 and 4.3.2 give isotherms interpolated from average simulated daily water temperature profiles under present (1983 - 1990) and the $2xCO_2$ climate scenarios. Fig. 4.2.3 shows the water temperature increase from the present to the $2xCO_2$ climate scenario. The projected maximum water temperature increase reaches 8^oC in early spring. In summer surface water temperatures increase about 4 to 5 ^oC. The increases are not uniform from surface to bottom. Surface water temperatures increase about 1^oC more than bottom water temperatures. This is because Lake Vermilion is slightly stratified during the open water season.

Figures 4.3.4 and 4.3.5 show time series for average surface water temperature (1 m below water surface) and bottom water temperature (1 m above the deepest point of lake bottom) under present and $2xCO_2$ climate scenarios, as well as differences between the results under the two climate scenarios. Both surface temperatures and bottom temperatures increase from present to the $2xCO_2$ climate scenario except for a short period in early winter during which water temperatures slightly decrease because of the difference in ice-in dates.

Fig. 4.3.6 shows the difference between surface water temperature and bottom water temperature under the two climate scenarios. This difference indicates the strength of stratification. In the open water season the stratification tends to be stronger under the $2xCO_2$ climate scenario than under present climate scenario. In the ice cover season the inverse temperature stratification becomes weaker most of the time except in early winter during which the stratification becomes stronger.

Figures 4.3.7 and 4.3.8 show time series for simulated ice thickness and snow depth under the two climate scenarios. In all simulated years maximum ice thicknesses and snow depths decrease from present to the $2xCO_2$ climate scenario. In early winter of one year ice thicknesses are thicker under the $2xCO_2$ climate scenario. As discussed in the previous section for Upper Red Lake, this is because of the decrease of snow depth under the $2xCO_2$ climate scenario. Maximum ice thickness decreases from an average 0.73 m to 0.45 m, as climate changes from 1983 - 1990 conditions to a $2xCO_2$ climate scenario. Ice-in is later and ice-out is earlier from present to the $2xCO_2$ climate scenario. Average ice-in date changes from November 22 to December 5, and ice-out date changes from April 21 to March 7. Ice-out date is affected more by climate change than ice-in date.

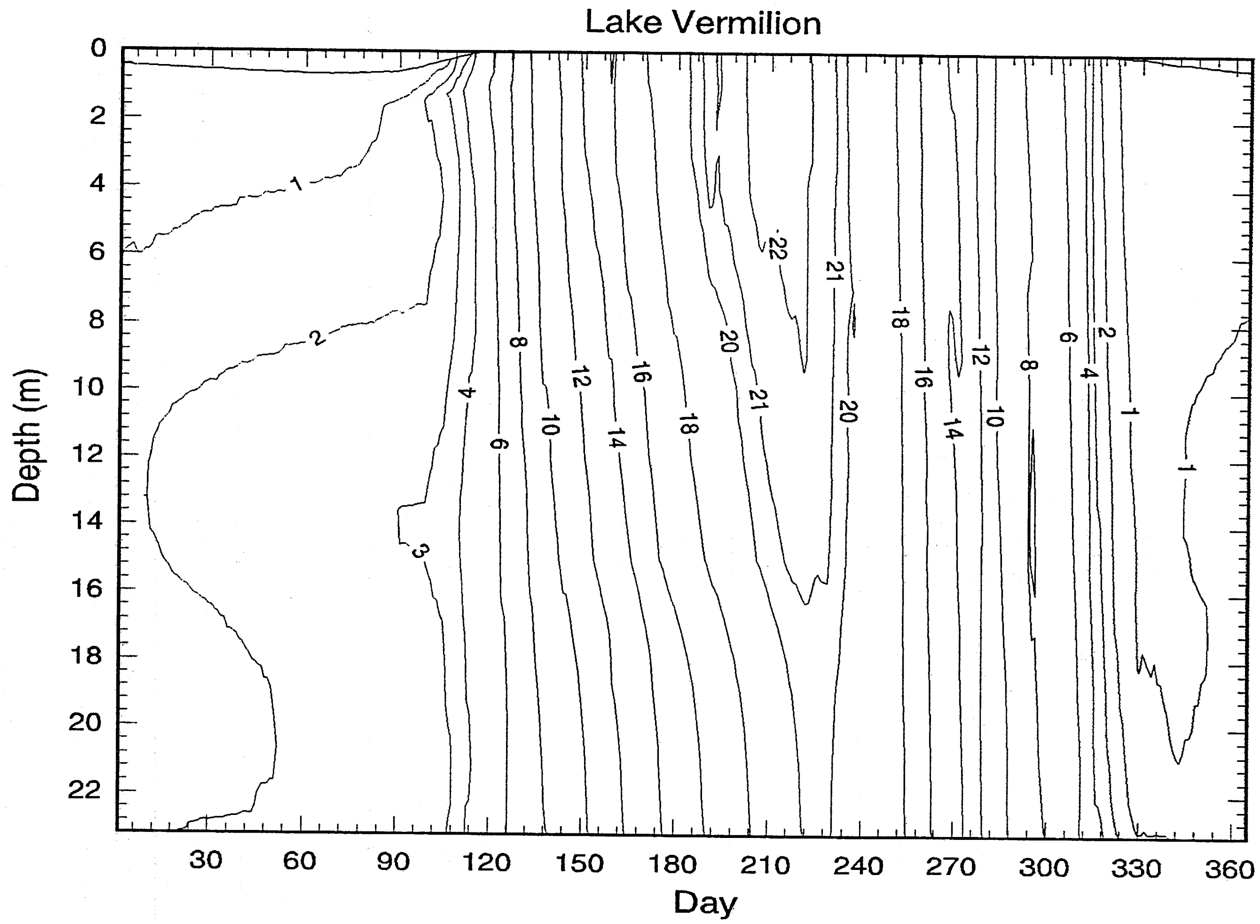

Fig. 4.3.1 Isotherms for Lake Vermilion under present (1983 - 1990) climate

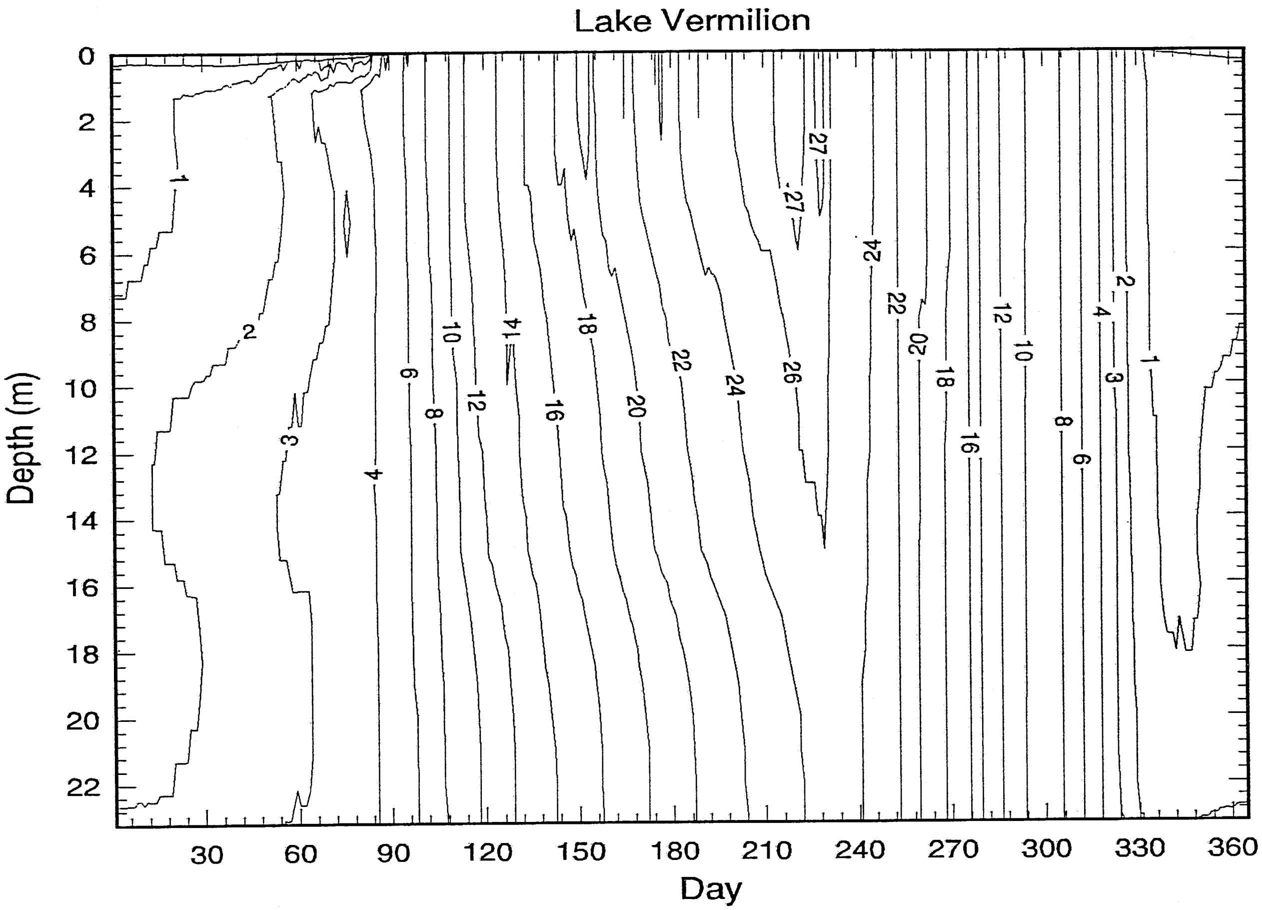

Fig. 4.3.2 Isotherms for Lake Vermilion under the 2xCO$_2$ climate scenario

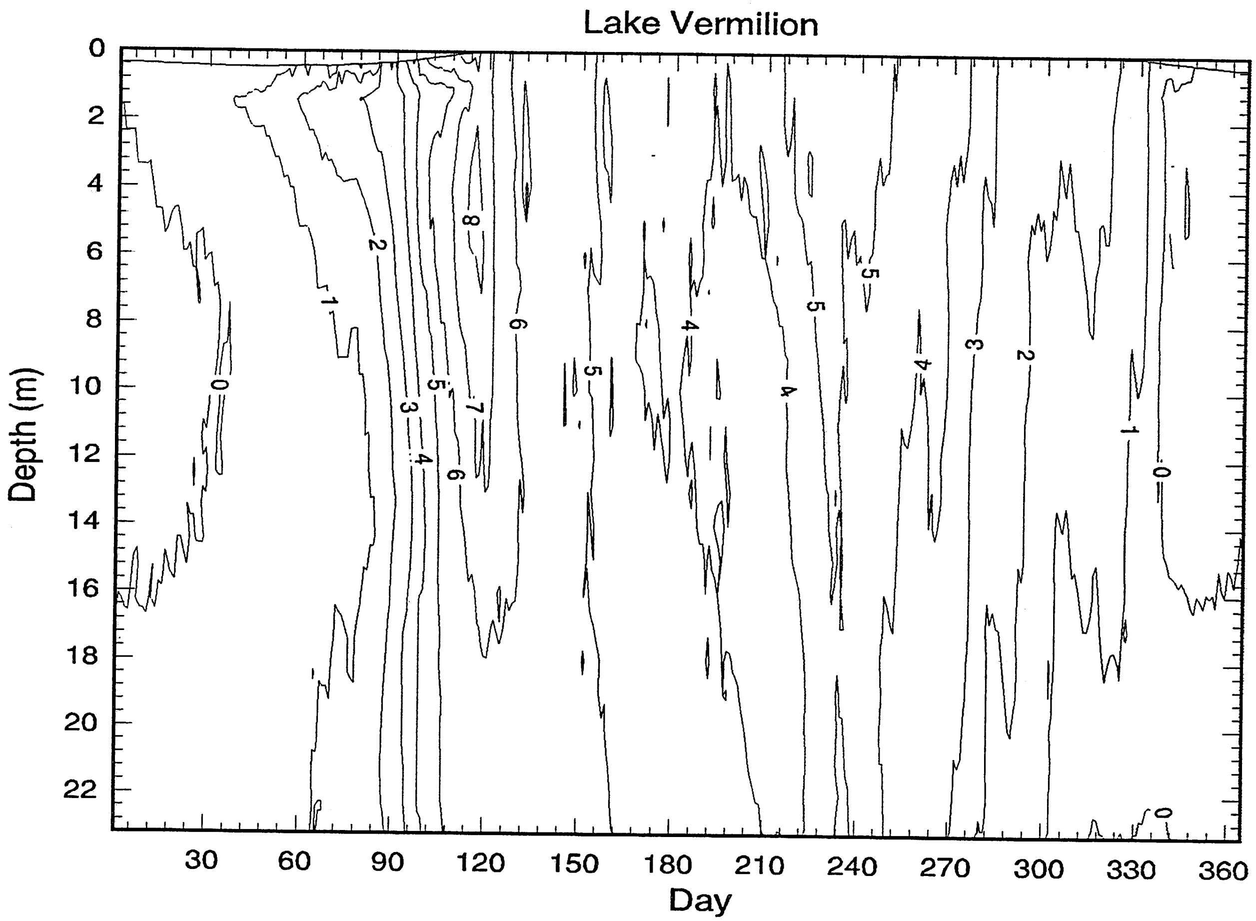

Fig. 4.3.3 Water temperature increase for Lake Vermilion from present (1983 - 1990) to the $2xCO_2$ climate scenario

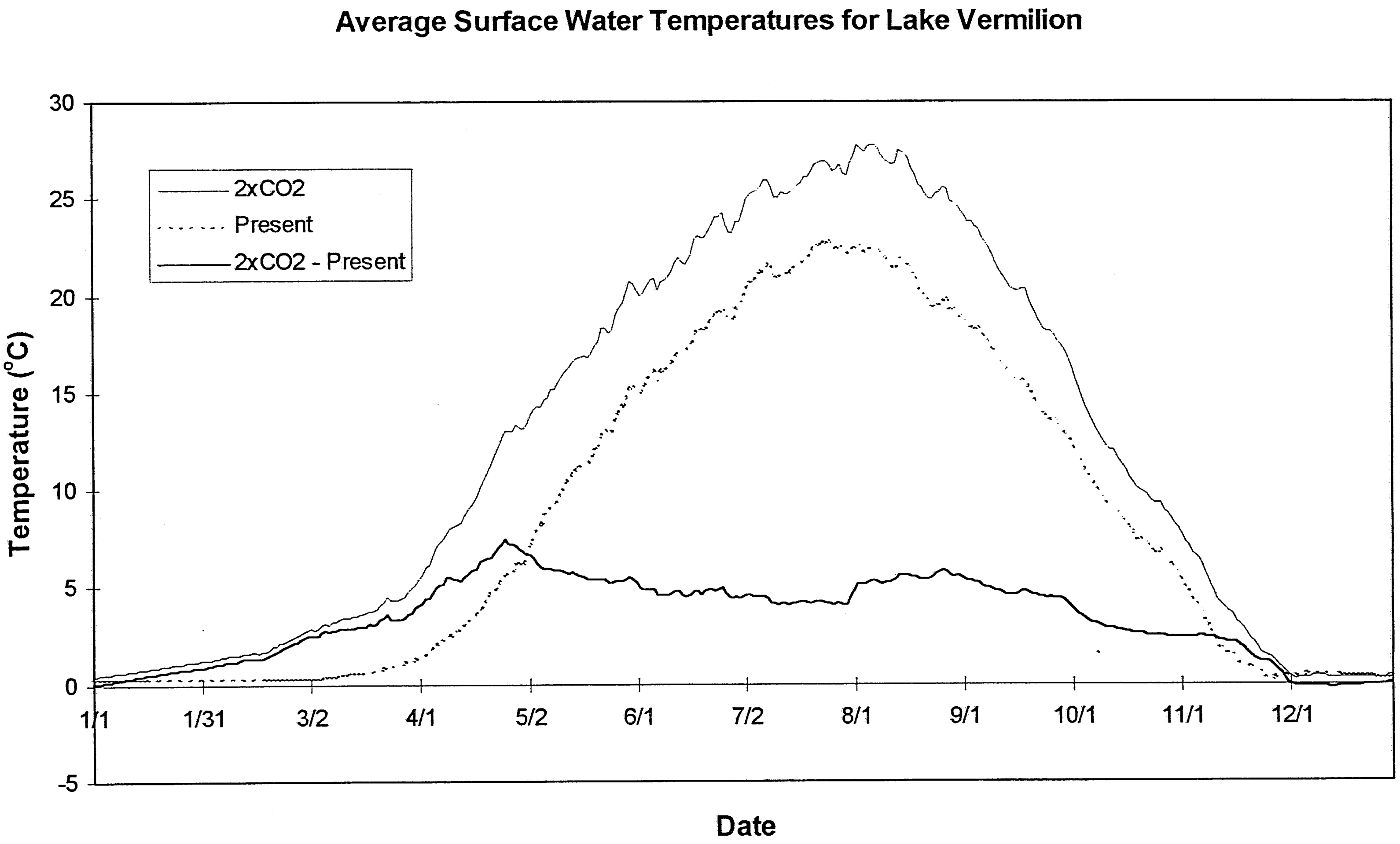

Fig. 4.3.4 Average surface water temperatures in Lake Vermilion under present (1983 - 1990) and the 2xCO_2 climate scenario

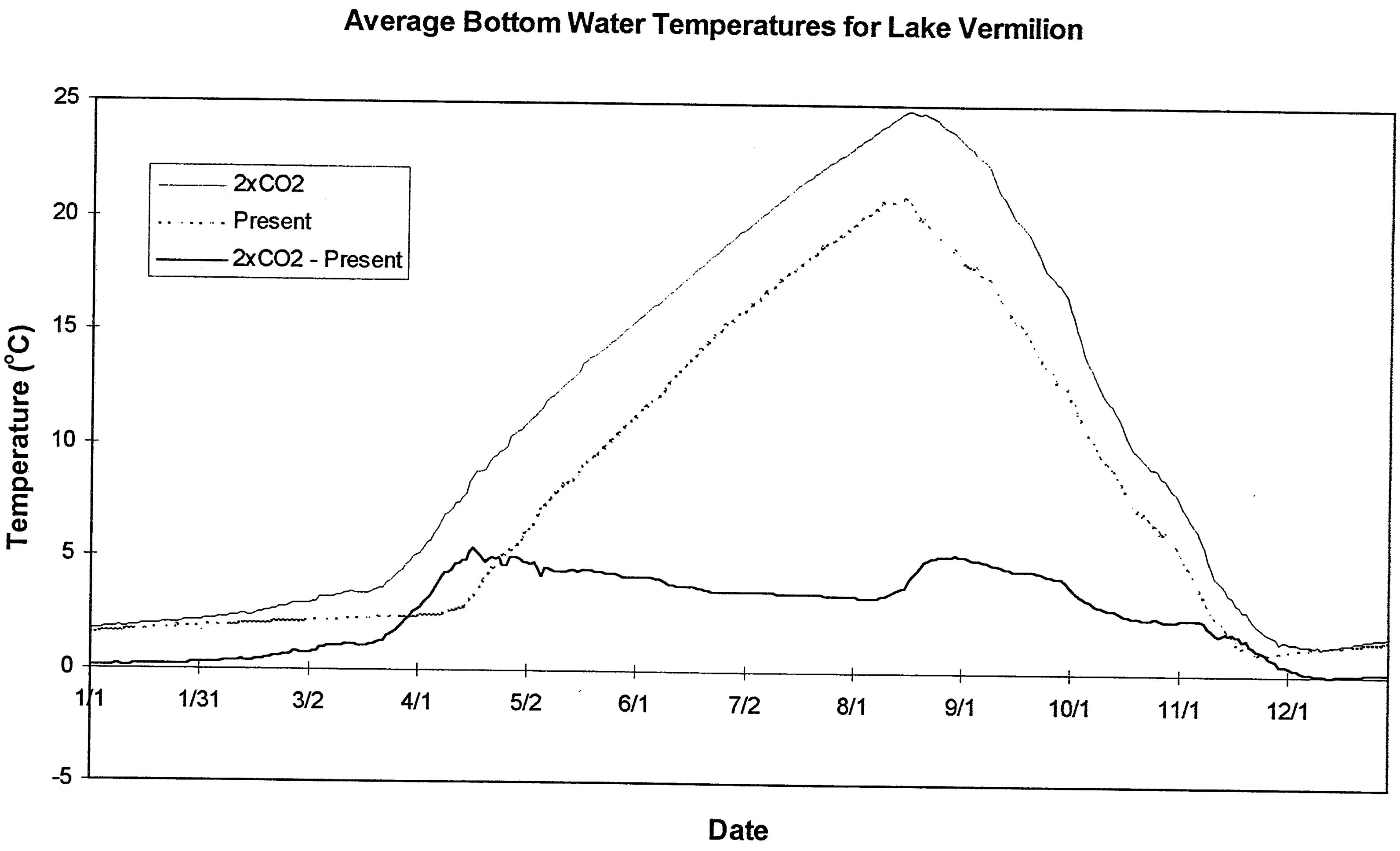

Fig. 4.3.5 Average bottom water temperatures in Lake Vermilion under present (1983 - 1990) and the 2xCO_2 climate scenario

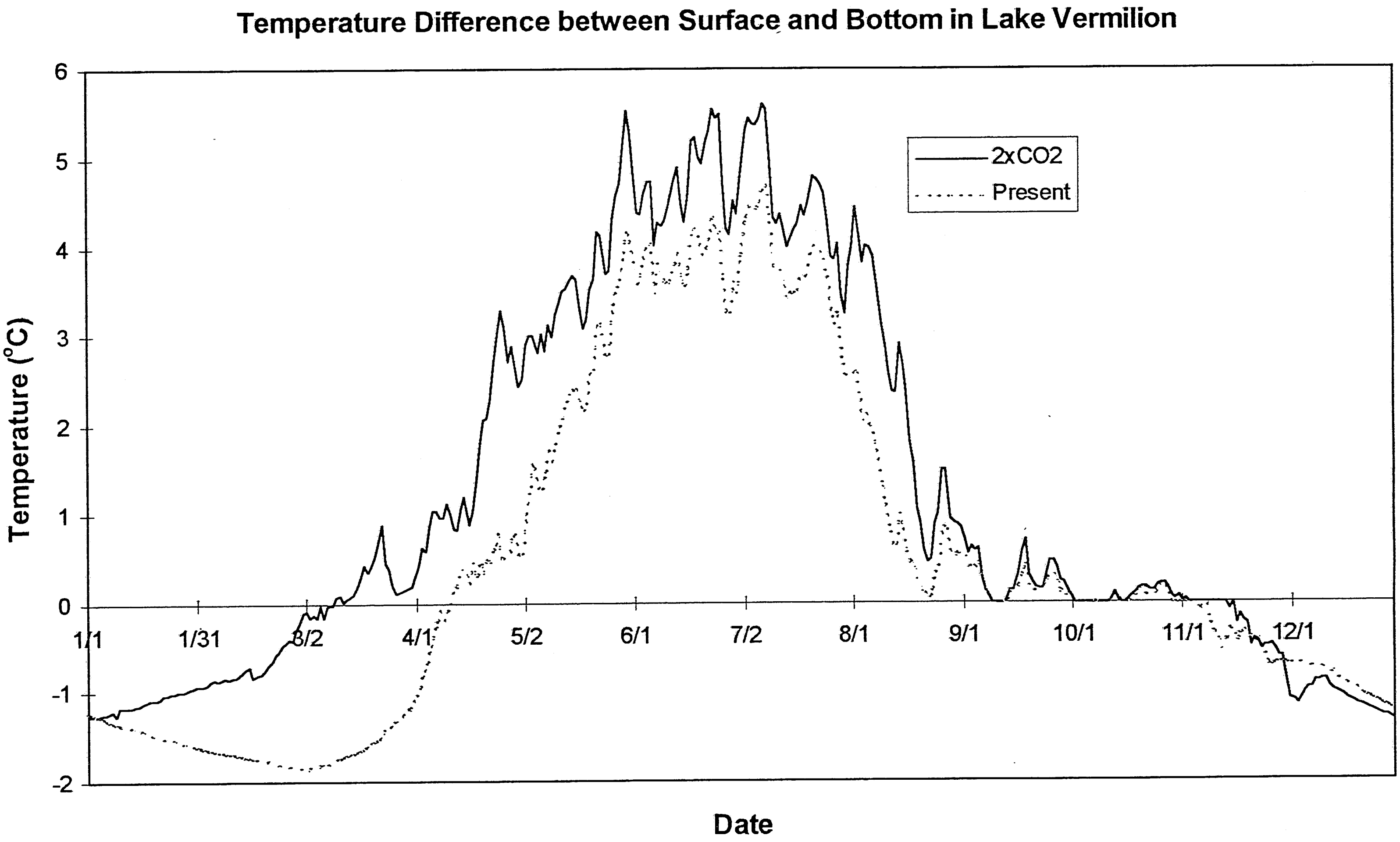

Fig. 4.3.6 Average difference between surface and bottom water temperatures in Lake Vermilion under present (1983 - 1990) and the $2xCO_2$ climate scenario

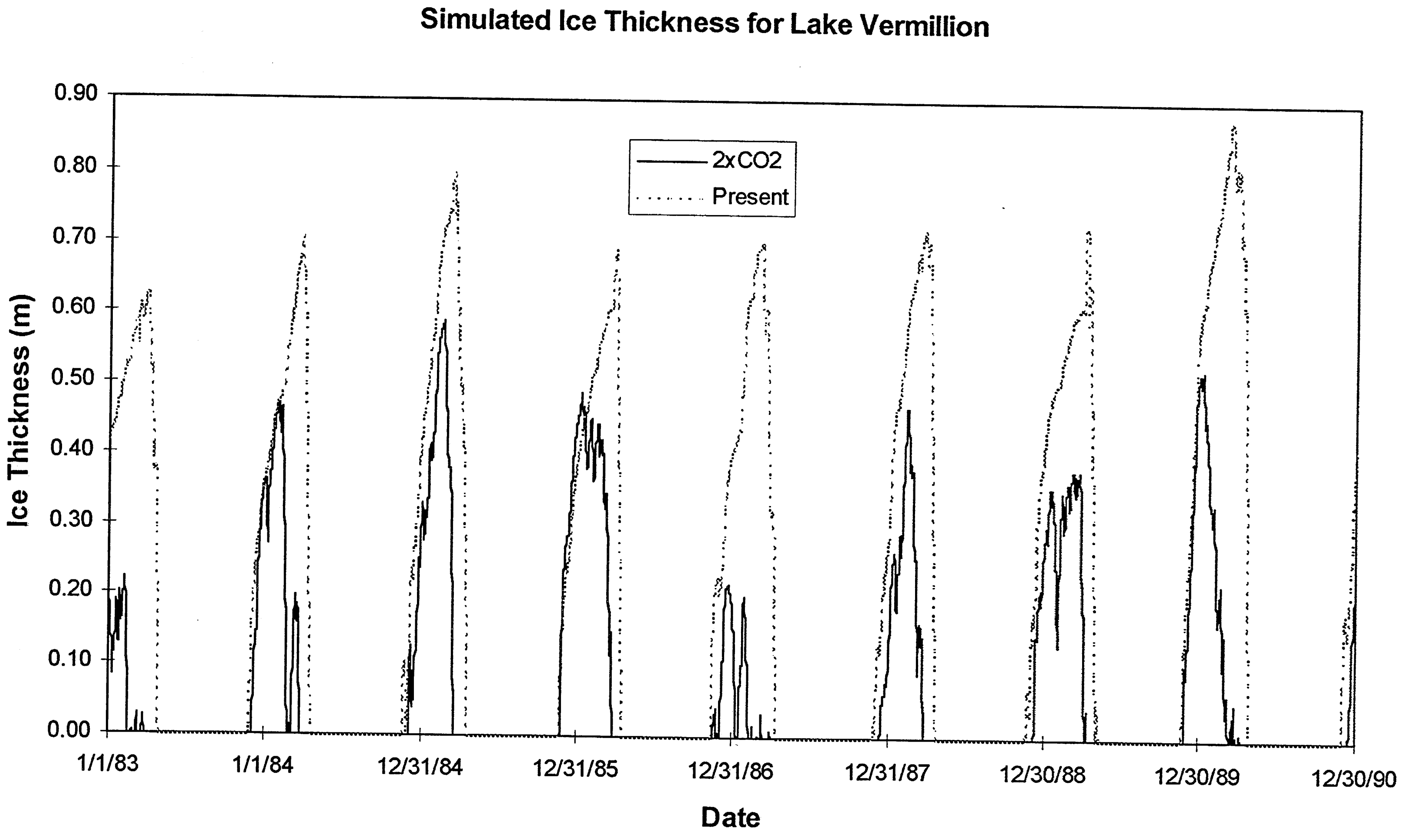

Fig. 4.3.7 Simulated ice thicknesses for Lake Vermilion under present (1983 - 1990) and the 2xCO$_2$ climate scenario

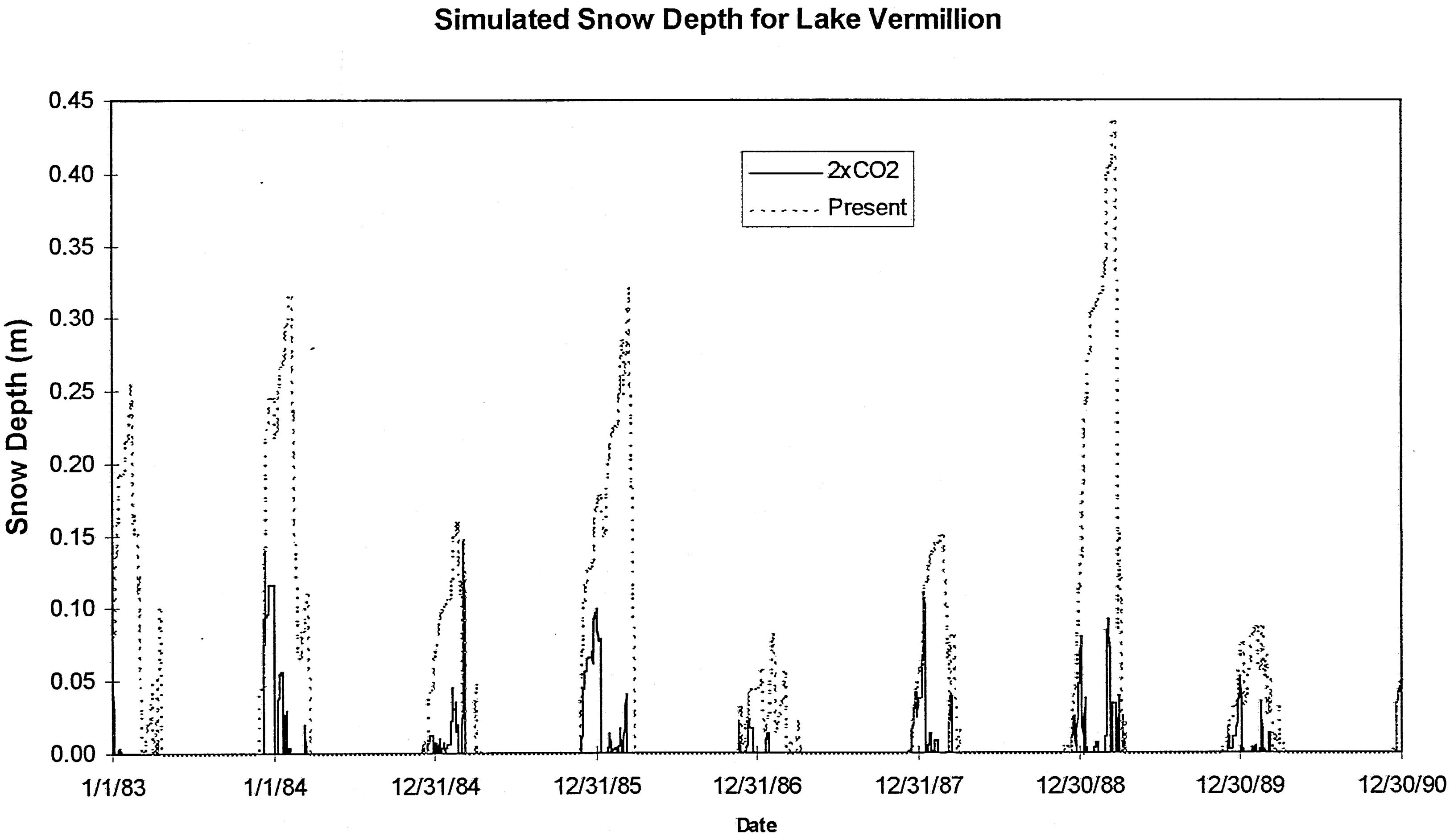

Fig. 4.3.8 Simulated snow depths for Lake Vermilion under present (1983 - 1990) and the $2xCO_2$ climate scenario

4.4 Lake Pepin

Lake Pepin is located in southeastern Minnesota. The lake is an enlargement of the Mississippi River. It has a surface area of 101.4 km^2 and a maximum depth of 18.3 m. A bathymetric map of the lake is given in Appendix A. Meteorological data (1982 - 1990) from Rochester were used to simulate lake temperatures. To eliminate errors caused by inappropriate initial conditions, results for 1982 were excluded. The results for the remaining eight years were averaged.

Figures 4.4.1 and 4.4.2 give isotherms interpolated from average simulated daily water temperature profiles under the present (1983 - 1990) and the 2xCO_2 climate scenarios. Fig. 4.4.3 shows the water temperature increase from present to the 2xCO_2 climate scenario. The projected maximum water temperature increase reaches 8°C in spring. In summer surface water temperatures increase about 5°C. The increases are not uniform from surface to bottom. Surface water temperatures increase about 1°C more than bottom water temperatures. This is because Pepin Lake is slightly stratified during the open water season.

Figures 4.4.4 and 4.4.5 show time series for average surface water temperature (1 m below water surface) and bottom water temperature (1 m above the deepest point of lake bottom) under present and 2xCO_2 climate scenarios as well as differences between the results under the two climate scenarios. Both surface temperatures and bottom temperatures increase from present to the 2xCO_2 climate scenario during open the water season. Bottom water temperatures are slightly lower under the 2xCO_2 climate scenario during the entire ice cover season.

Fig. 4.4.6 shows the difference between surface water temperature and bottom water temperature under the two climate scenarios. This difference indicates the strength of stratification. In the open water season the stratification tends to be stronger under the 2xCO_2 climate scenario than under the present climate scenario. In the ice cover season the inverse temperature stratification becomes weaker.

Figures 4.4.7 and 4.4.8 show time series for simulated ice thickness and snow depth under the two climate scenarios. In all simulated years ice thicknesses and snow depths decrease from present to the 2xCO_2 climate scenario. Maximum ice thickness decreases from an average 0.65 m to 0.34 m, as climate changes from 1983 - 1990 conditions to the 2xCO_2 scenario. Ice-in is later and ice-out is earlier from present to the 2xCO_2 climate scenario. Average ice-in date changes from November 30 to December 10, and ice-out date changes from April 8 to January 26. Ice-out date is affected more by climate change than ice-in date.

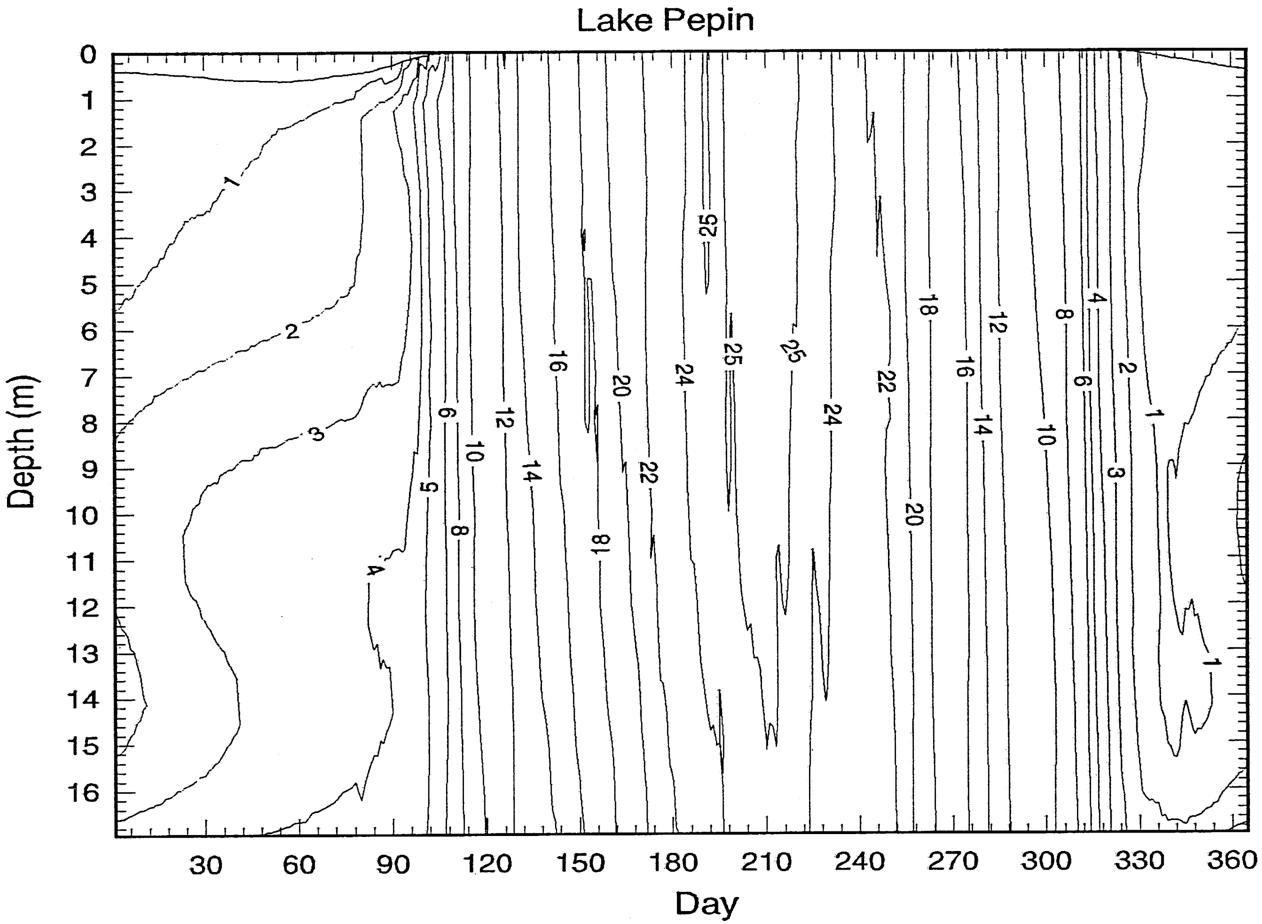

Fig. 4.4.1 Isotherms for Lake Pepin under present (1983 - 1990) climate

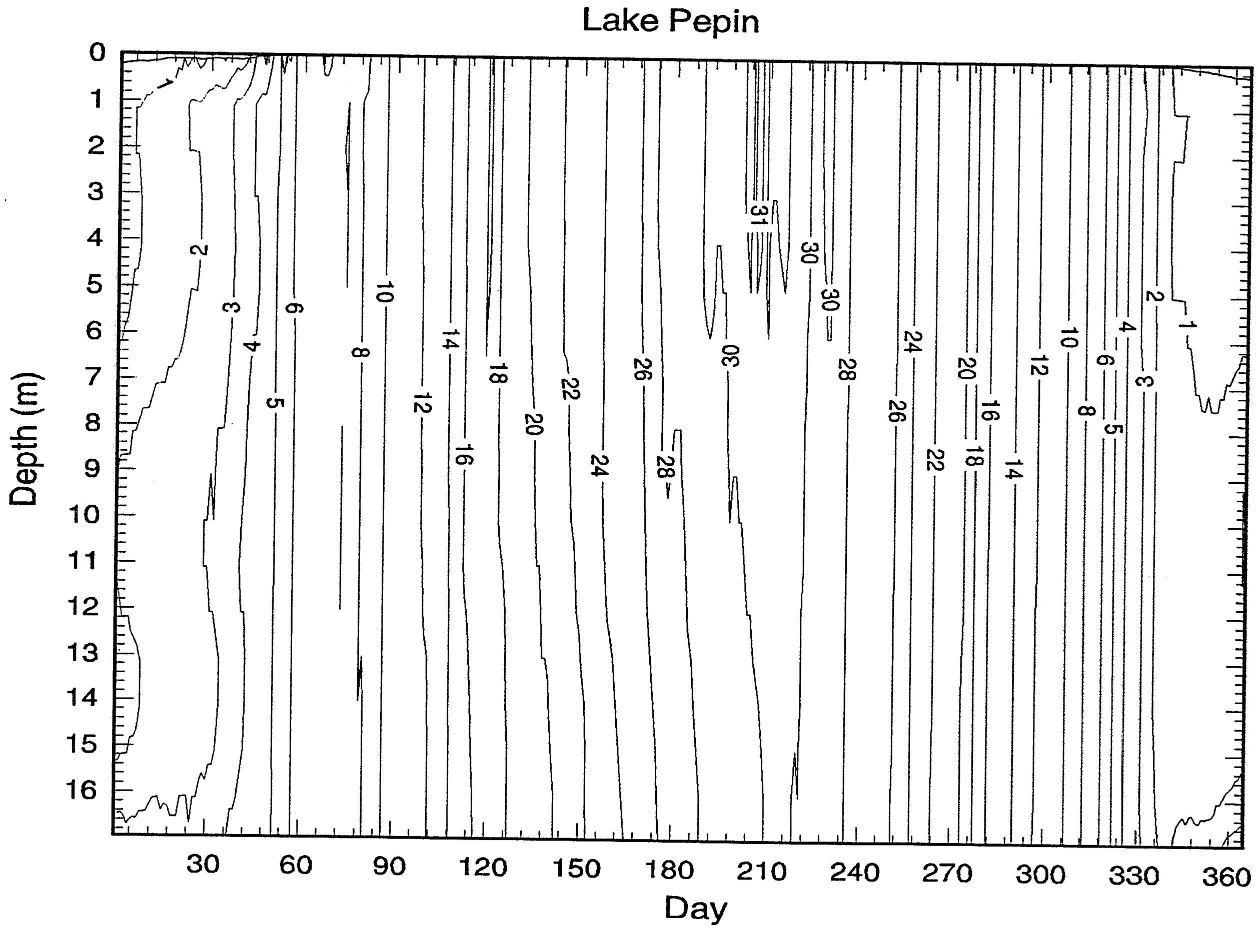

Fig. 4.4.2 Isotherms for Lake Pepin under the 2xCO$_2$ climate scenario

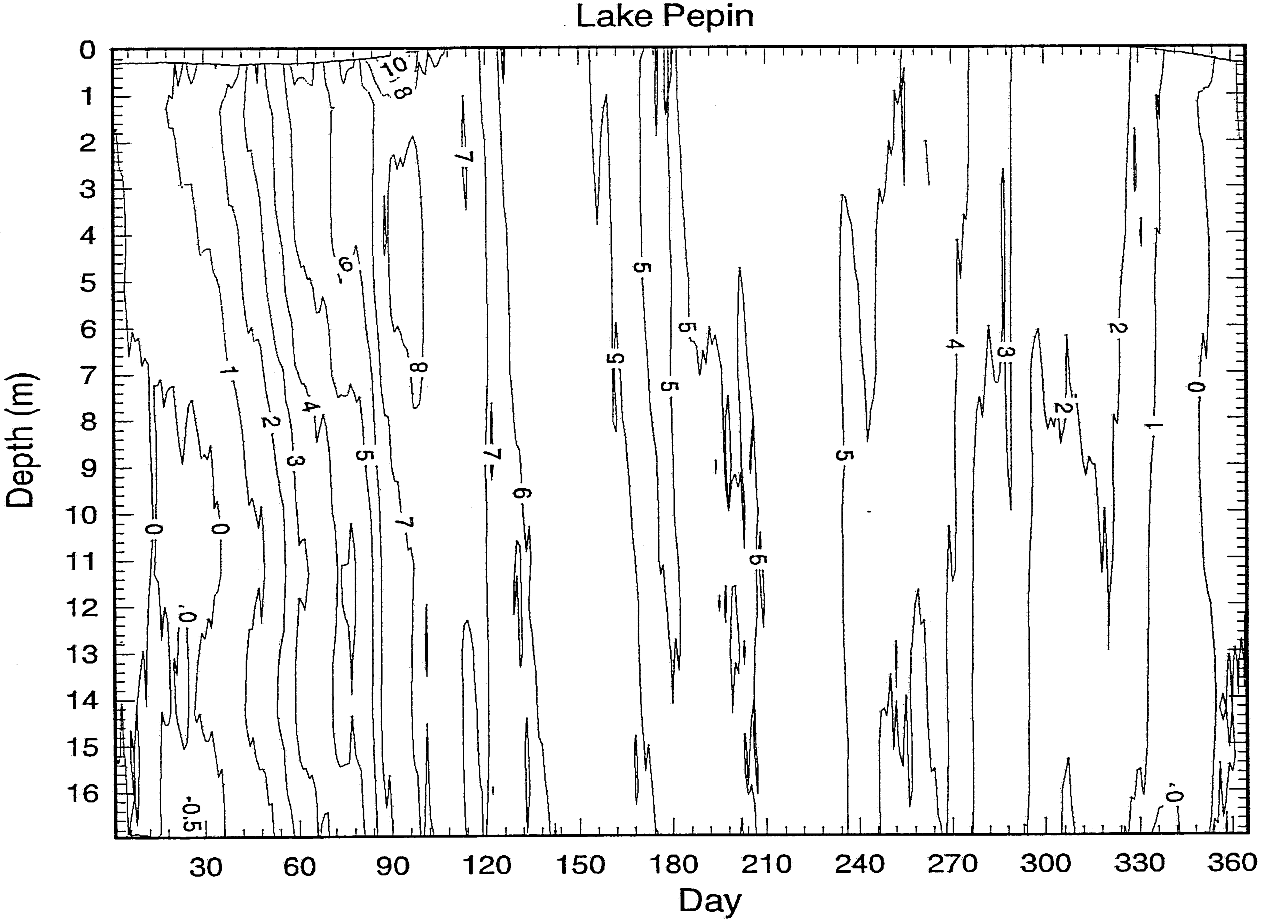

Fig. 4.4.3 Water temperature increase for Lake Pepin from present (1983 - 1990) to the $2xCO_2$ climate scenario

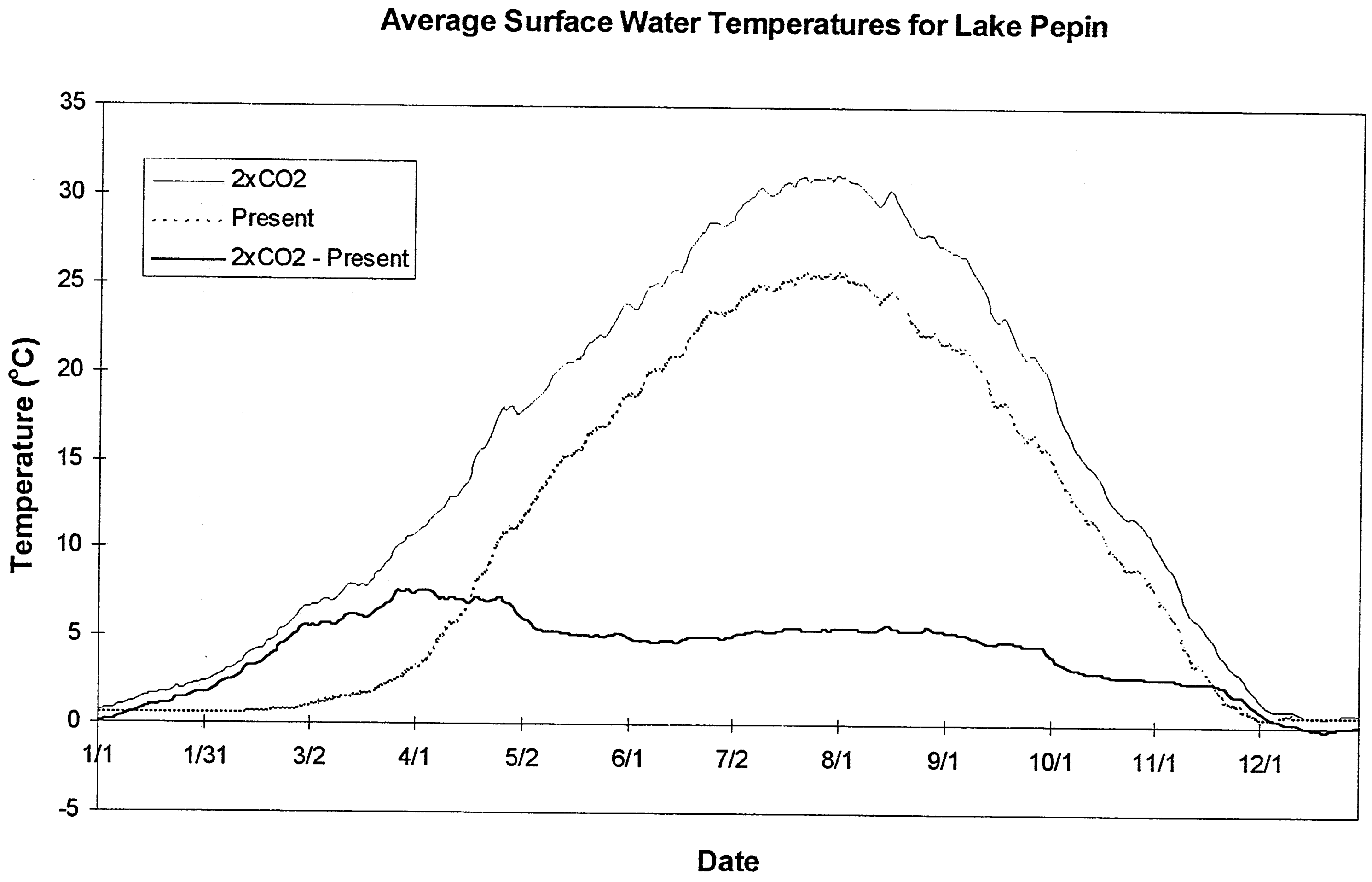

Fig. 4.4.4 Average surface water temperatures in Lake Pepin under present (1983 - 1990) and the $2xCO_2$ climate scenario

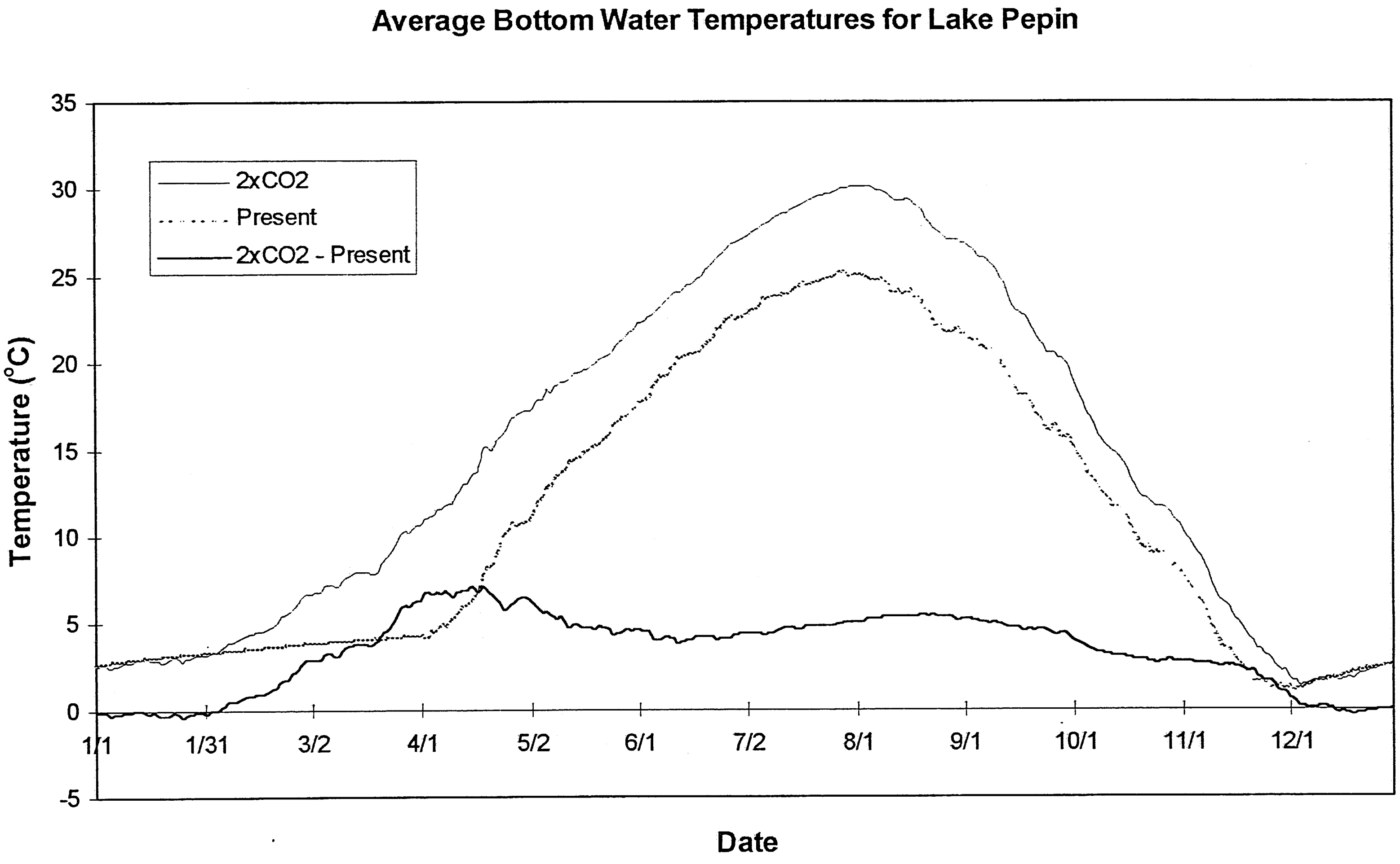

Fig. 4.4.5 Average bottom water temperatures in Lake Pepin under present (1983 - 1990) and the 2xCO_2 climate scenario

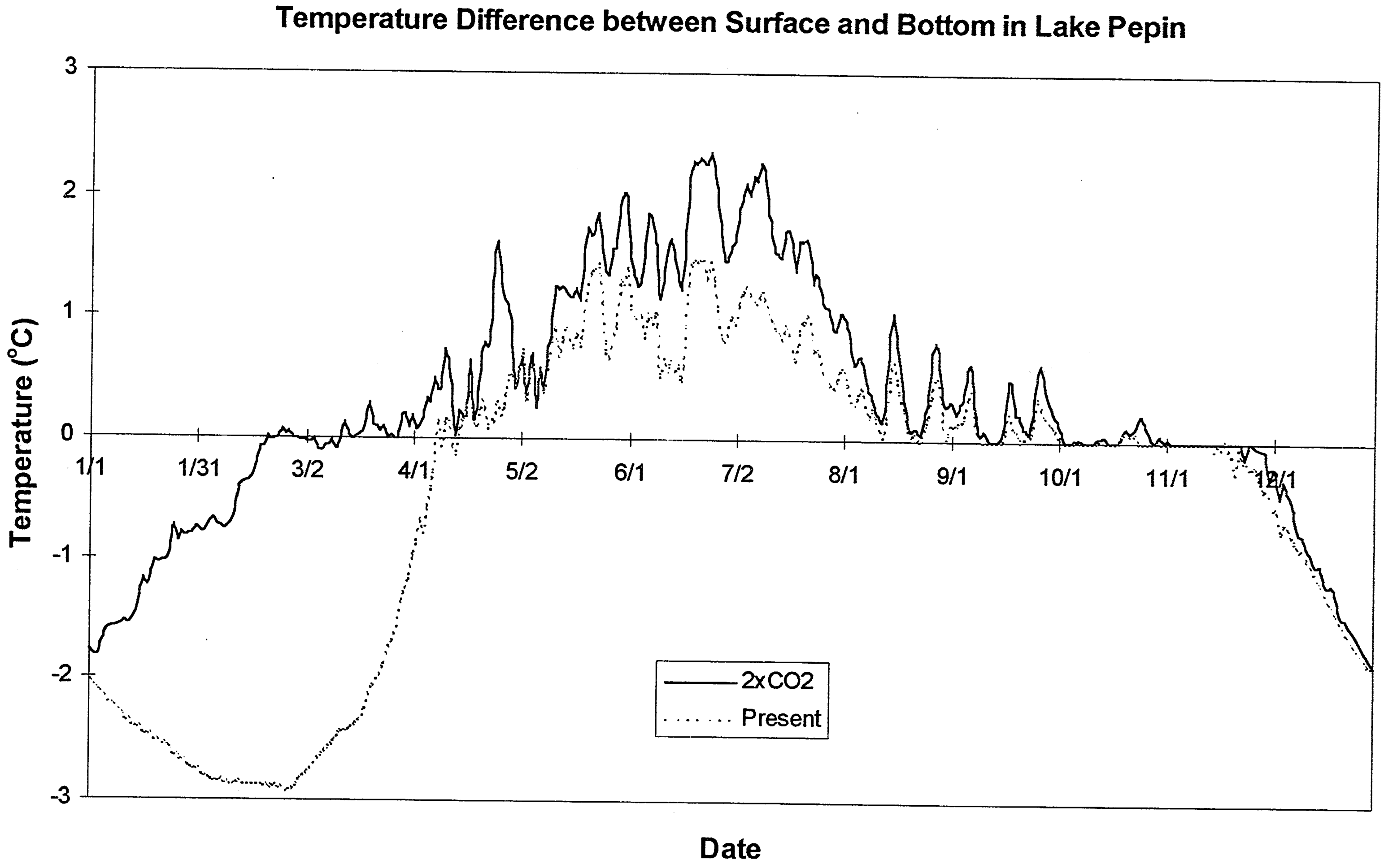

Fig. 4.4.6 Average difference between surface and bottom water temperatures in Lake Pepin under present (1983 - 1990) and the $2xCO_2$ climate scenario

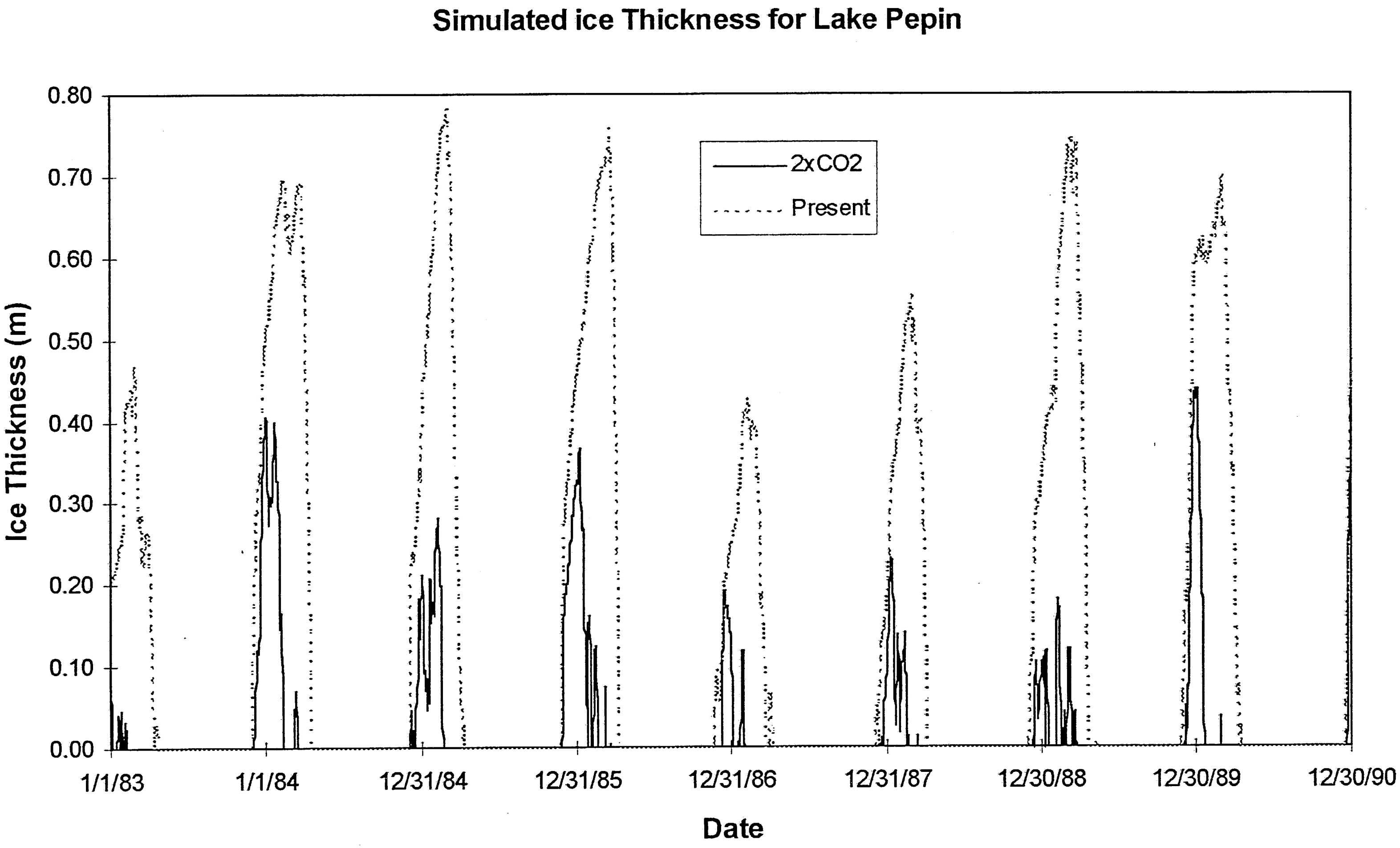

Fig. 4.4.7 Simulated ice thicknesses for Lake Pepin under present (1983 - 1990) and the 2xCO$_2$ climate scenario

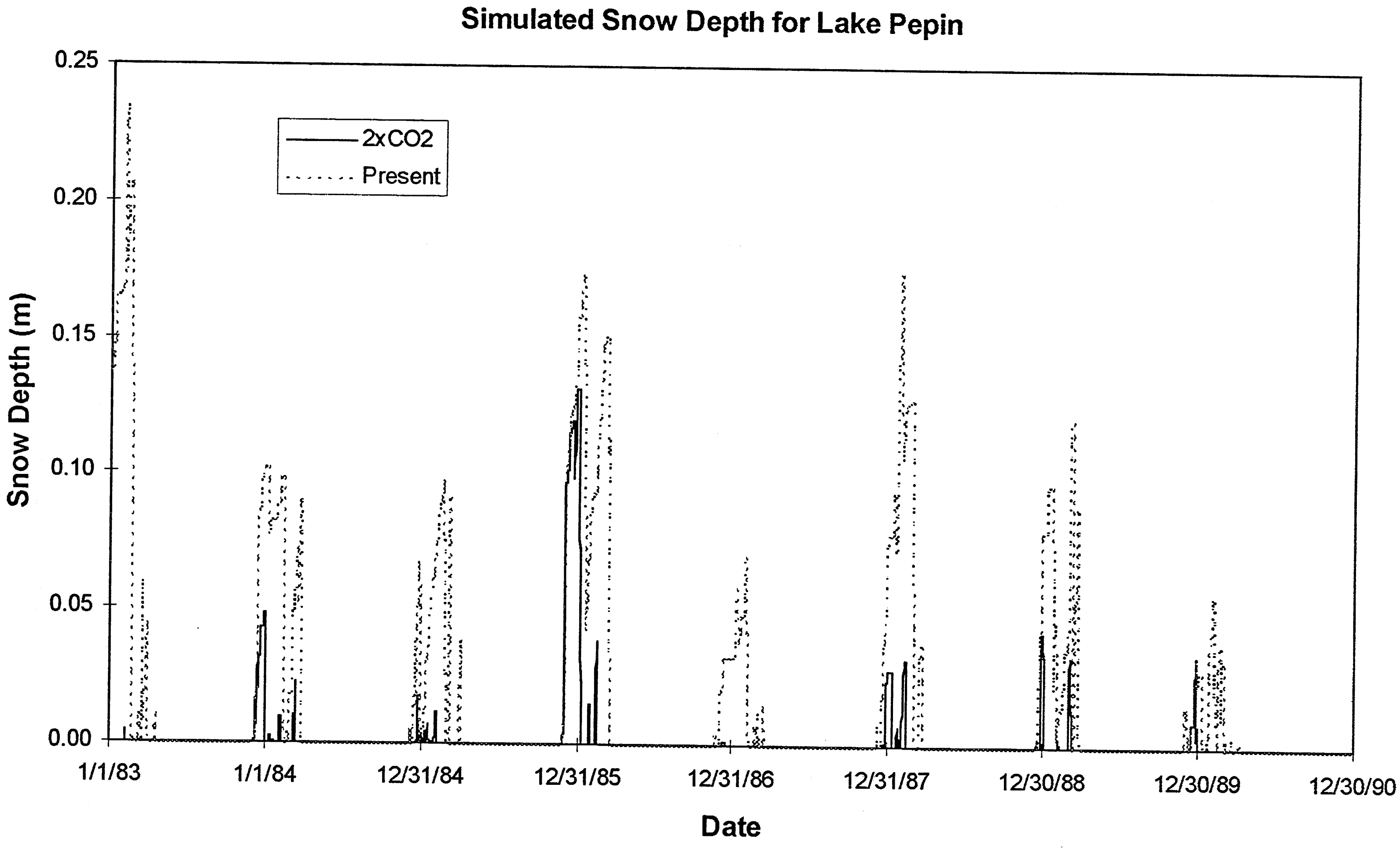

Fig. 4.4.8 Simulated snow depths for Lake Pepin under present (1983 - 1990) and the $2xCO_2$ climate scenario

4.5 Rainy Lake

Rainy Lake at the northern border of Minnesota has a surface area of 893.6 km^2 and a maximum depth of 49.1 m. Meteorological data (1982 - 1990) from International Falls were used to simulate lake temperatures. To eliminate errors caused by inappropriate initial conditions, results for 1982 were excluded. The results for the remaining eight years were averaged.

Figures 4.3.1 and 4.3.2 give isotherms interpolated from average simulated daily water temperature profiles under present (1983 - 1990) and the 2xCO$_2$ climate scenarios. Fig. 4.2.3 shows the water temperature increase from present to the 2xCO$_2$ climate scenario. The projected maximum water temperature increase reaches 7°C. The increases are not uniform from surface to bottom except in fall. During the ice cover season water temperatures decrease in most of the lake. The decrease is projected to be up to 1°C.

Figures 4.5.4 and 4.5.5 show time series for average surface water temperature (1 m below water surface) and bottom water temperature (1 m above the deepest point of lake bottom) under present and 2xCO$_2$ climate scenarios as well as differences between the results under the two climate scenarios. Both surface temperatures and bottom temperatures increase from the present to the 2xCO$_2$ climate scenario during the open water season. Bottom water temperatures are lower under the 2xCO$_2$ climate in all of the ice cover season.

Figure 4.5.6 shows the difference between surface water temperature and bottom water temperature under the two climate scenarios. This difference indicates the strength of stratification. In the open water season the stratification tends to be stronger under the 2xCO$_2$ climate scenario than under the present climate scenario. In the ice cover season the inverse temperature stratification becomes weaker.

Figures 4.5.7 and 4.5.8 show time series for simulated ice thickness and snow depth under the two climate scenarios. In all simulated years maximum ice thicknesses and snow depths decrease from present to the 2xCO$_2$ climate scenario. Maximum ice thickness decreases from an average 0.85 m to 0.56 m as climate changes from 1983 - 1990 conditions to the 2xCO$_2$ scenario. Ice-in is later and ice-out is earlier under the 2xCO$_2$ climate scenario. Average ice-in date changes from December 6 to December 15, and ice-out date changes from April 24 to March 28. Ice-out date is affected more by climate change than ice-in date.

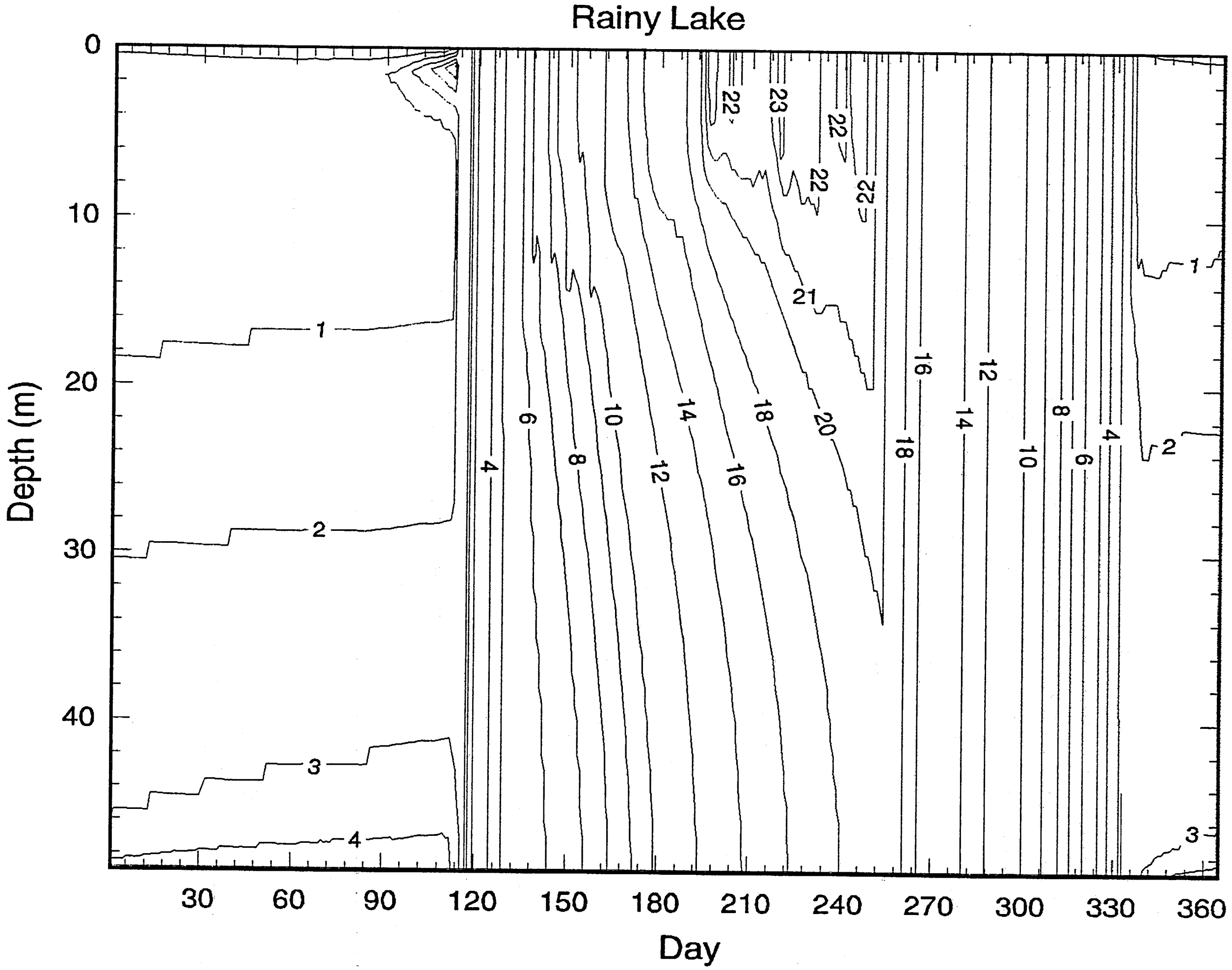

Fig. 4.5.1 Isotherms for Rainy Lake under present (1983 - 1990) climate

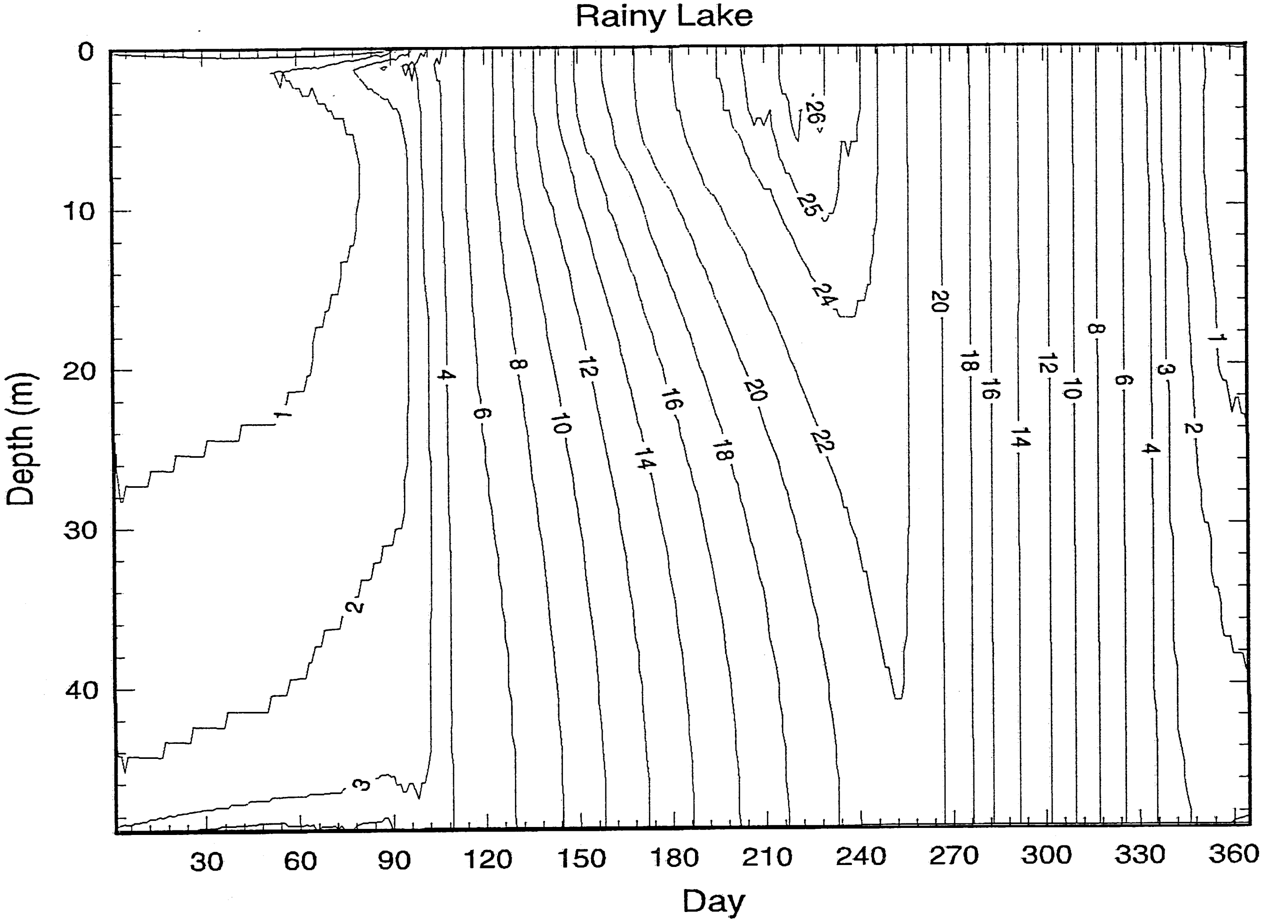

Fig. 4.5.2 Isotherms for Rainy Lake under the $2xCO_2$ climate scenario

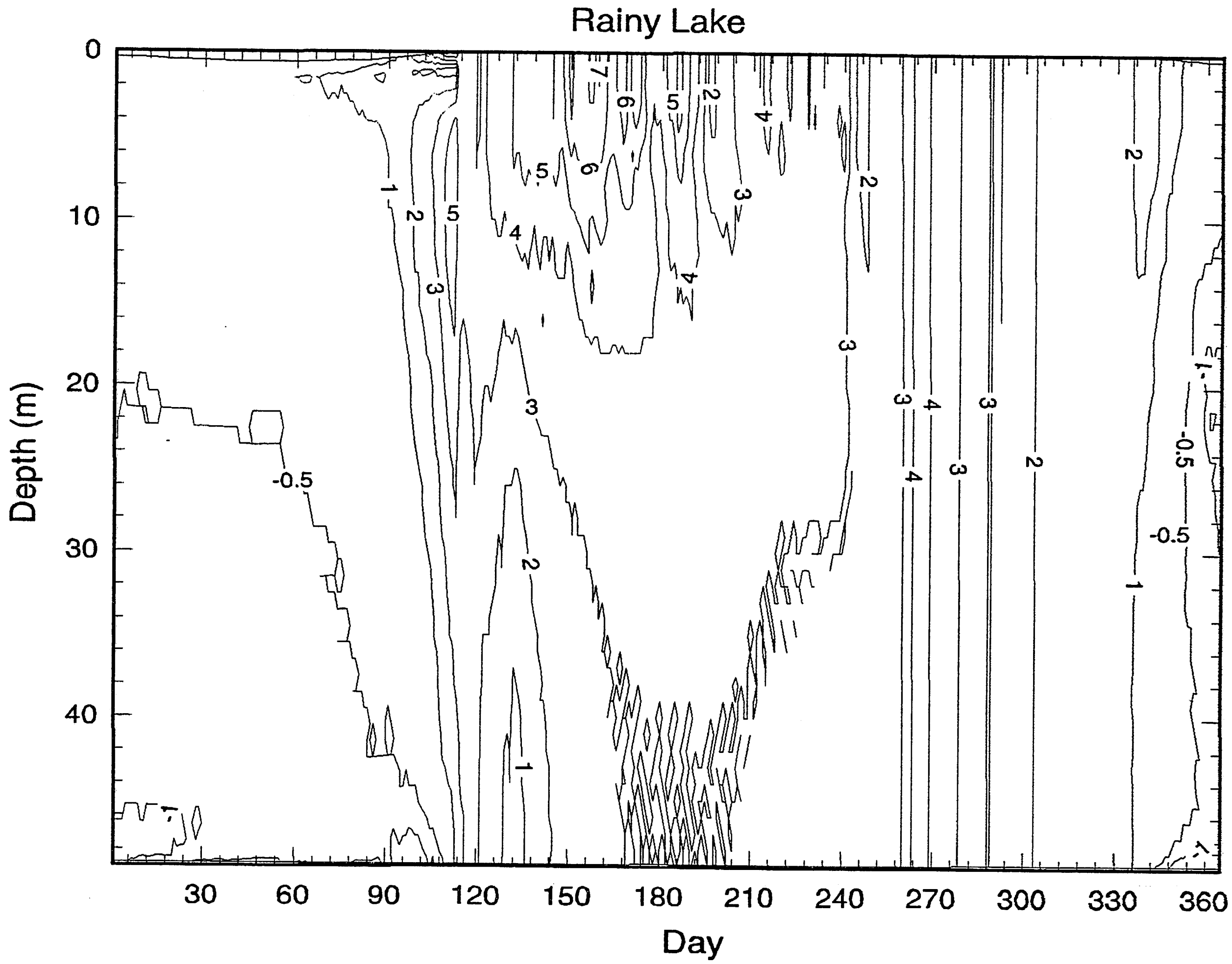

Fig. 4.5.3 Water temperature increase for Rainy Lake from present (1983 - 1990) to the 2xCO$_2$ climate scenario

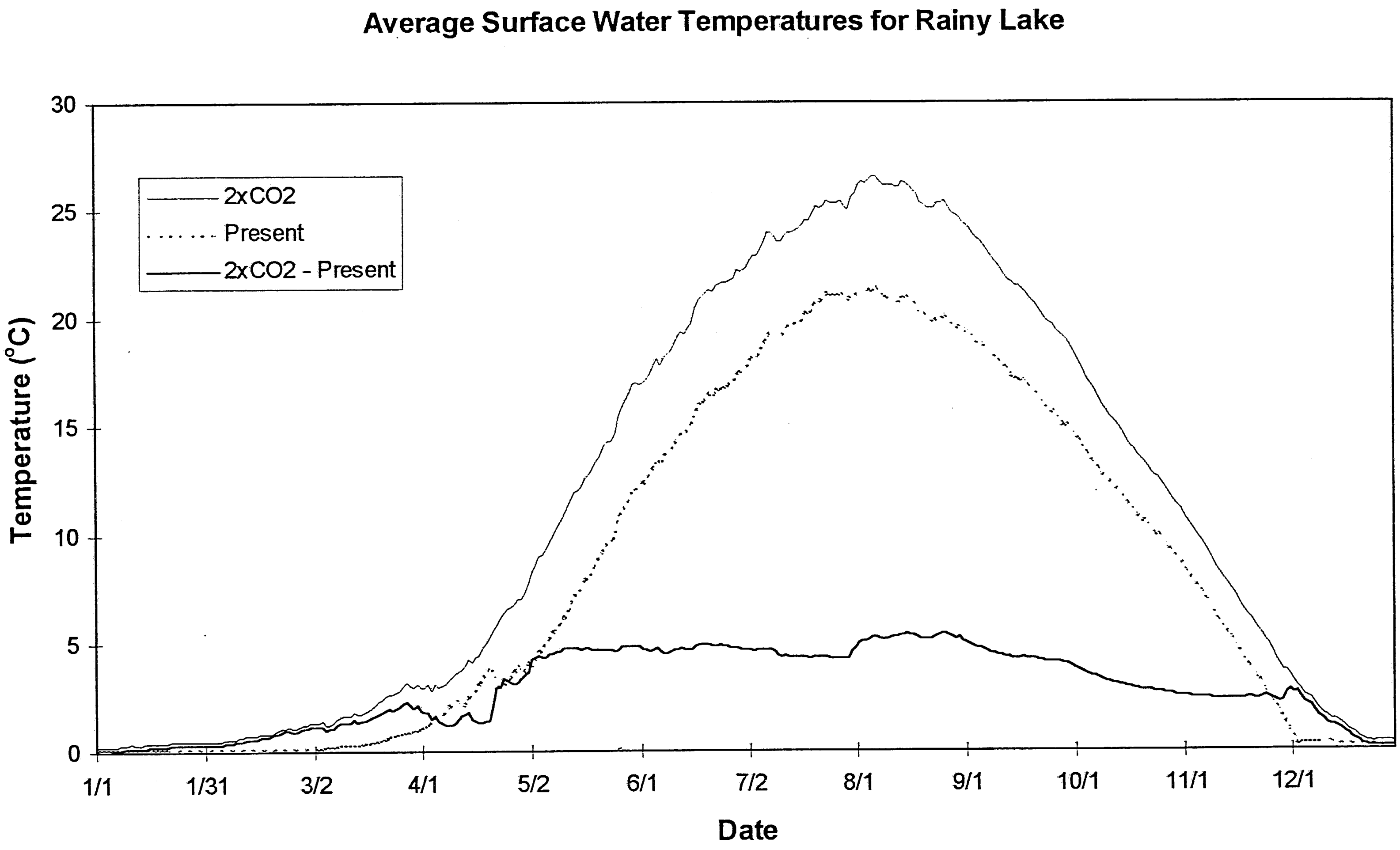

Fig. 4.5.4 Average surface water temperatures in Rainy Lake under present (1983 - 1990) and the 2xCO_2 climate scenario

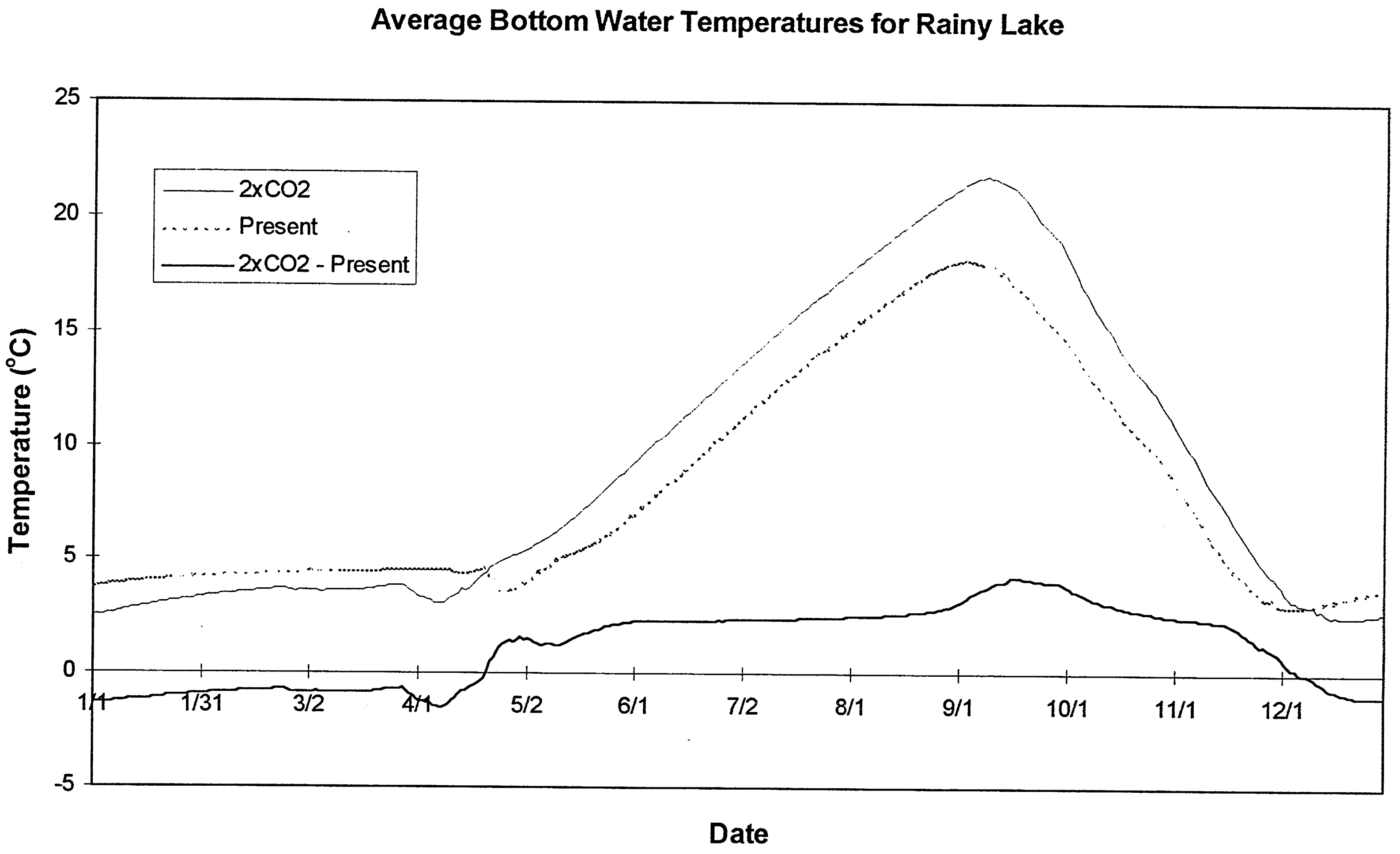

Fig. 4.5.5 Average bottom water temperatures in Rainy Lake under present (1983 - 1990) and the 2xCO_2 climate scenario

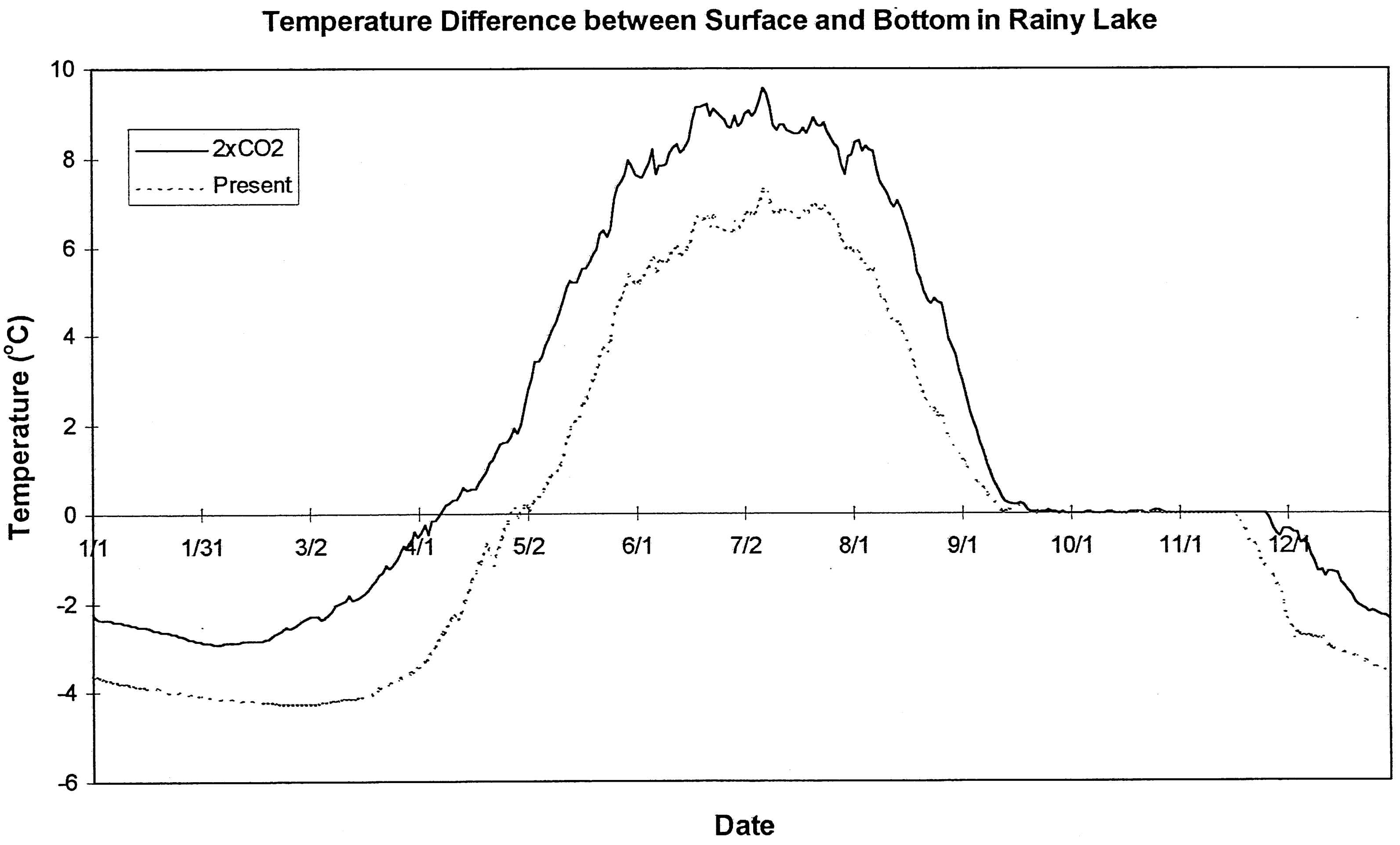

Fig. 4.5.6 Average difference between surface and bottom water temperatures in Rainy Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

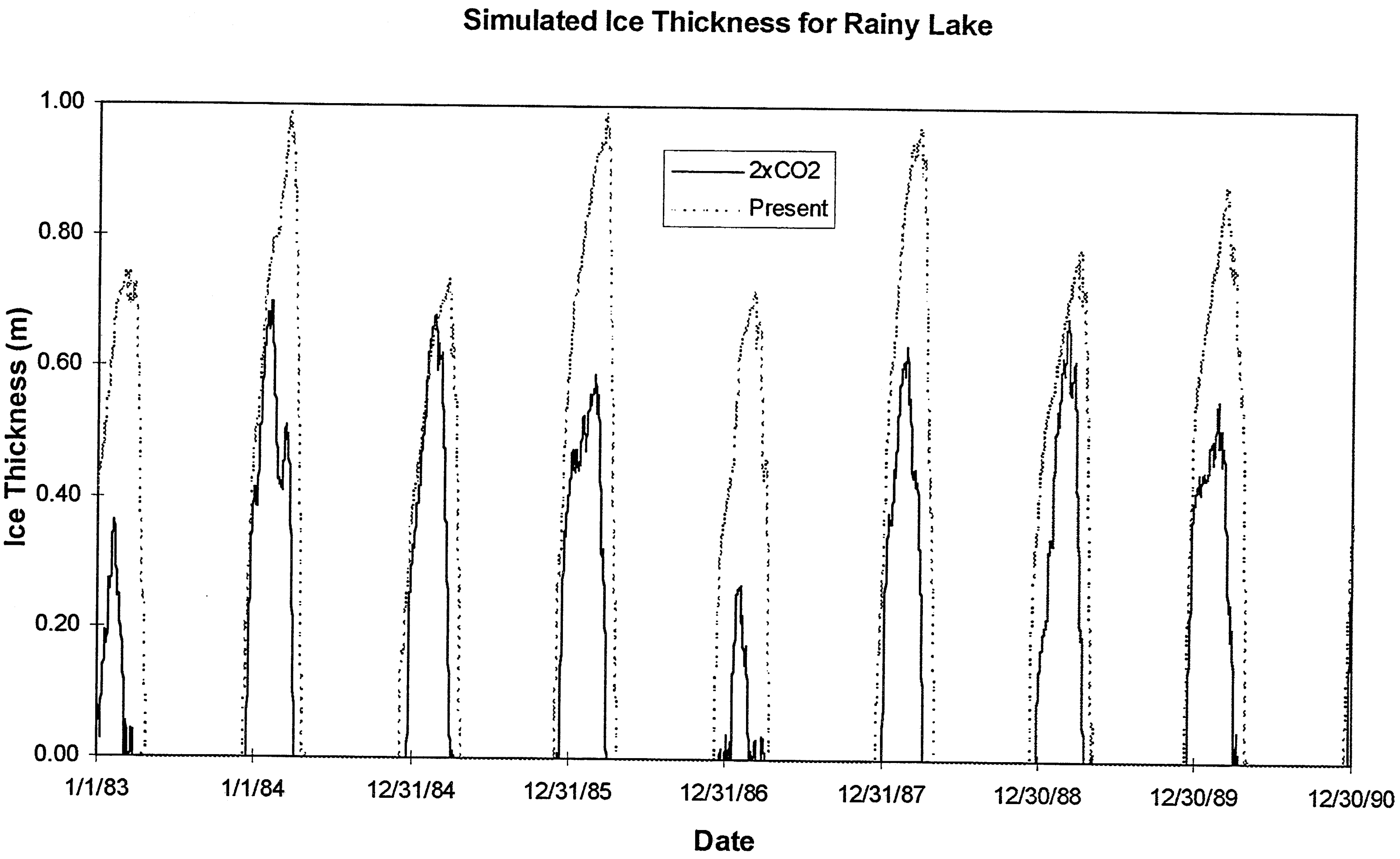

Fig. 4.5.7 Simulated ice thicknesses for Rainy Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

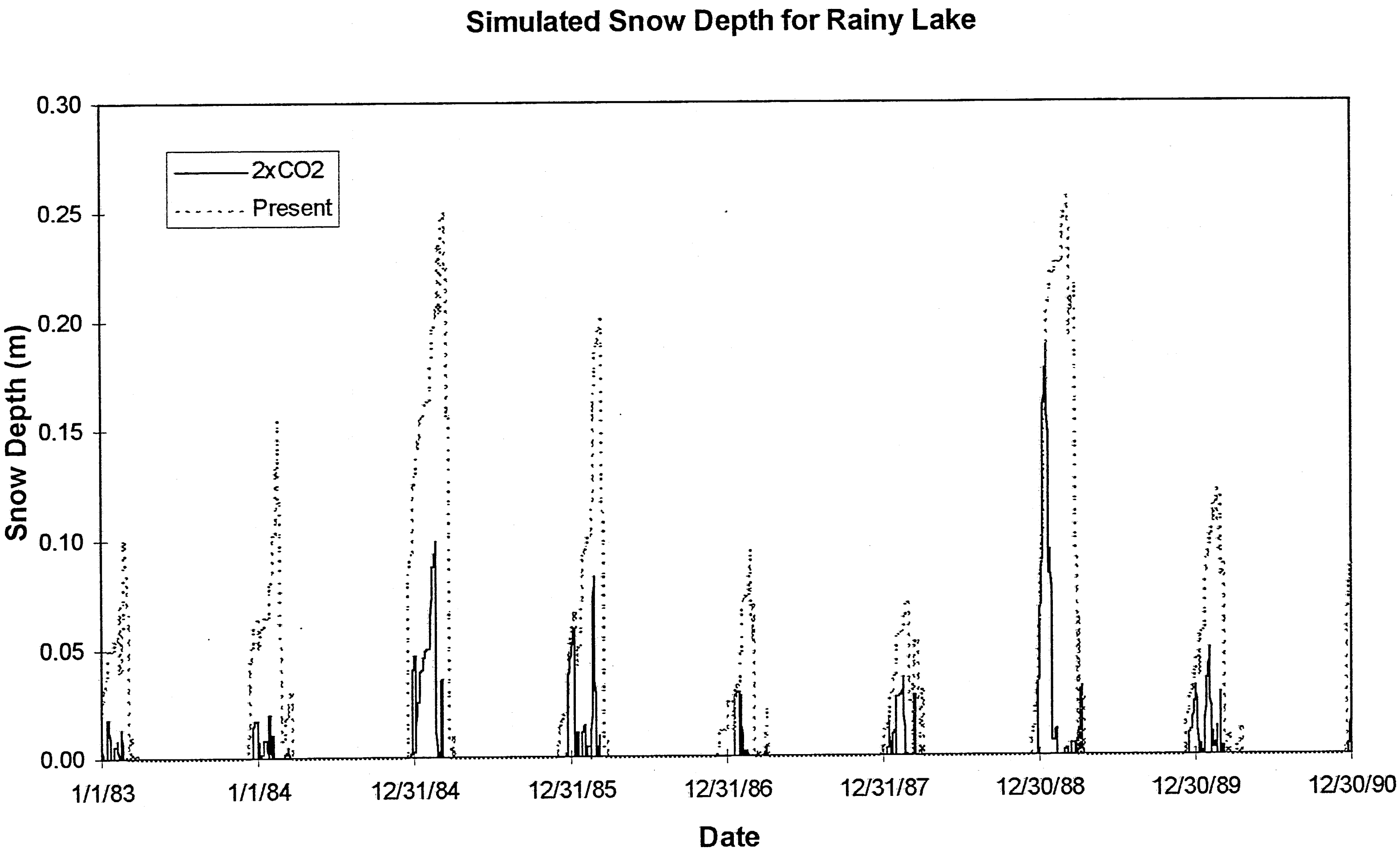

Fig. 4.5.8 Simulated snow depths for Rainy Lake under present (1983 - 1990) and the $2xCO_2$ climate scenario

Table 5.1 Parameters used to Define Temperature Characteristics.

Parameter	Description	Formulation/Definition
Max. surface temperature (°C)	Maximum daily temperature at 1.0 m below the lake surface (T_s)	$\mathrm{Max}[T_s(t), t=1,365]$
Min. surface temperature (°C)	Minimum daily temperature at 1.0 m below the lake surface (T_s)	$\mathrm{Min}[T_s(t), t=1,365]$
Max. bottom temperature (°C)	Maximum daily temperature at 1.0 m above the lake bottom = deepest point of lake (T_b)	$\mathrm{Max}[T_b(t), t=1,365]$
Min. bottom temperature (°C)	Minimum daily temperature at 1.0 m above the lake bottom = deepest point of lake (T_b)	$\mathrm{Min}[T_b(t), t=1,365]$
Maximum temperature difference (°C)	Maximum daily difference between surface water temperature and bottom water temperature	$\mathrm{Max}\{[T_s(t)-T_b(t)], t=1,365\}$
Open-water stratification ratio	Total number of days during the open-water season (surface water temperature > 4°C) when difference between surface and bottom temperature is greater than 1°C divided by 365.	$\mathrm{OSR} = \dfrac{\sum_{1}^{365} t\{[T_s(t) - T_b(t)] \geq 1^\circ \mathrm{C}\}}{365}$ $T_s(t) > 4^\circ \mathrm{C}$
Duration of low bottom temperature (days)	Total number of days in a year when bottom temperature T_b less than 2 and 8 °C	$D_n = \sum_{1}^{365} t[T_b(t) \leq n^\circ \mathrm{C}] \qquad n=2, 8$

Table 5.2 Parameters used to Define Winter Ice and Snow Cover Characteristics.

Parameter	**Description**	**Formulation/ Definition**
Earliest ice-in date	First day with ice cover in fall, but ice may melt out (t_{ei})	
Latest ice-in date	Last day with open water in fall; followed by ice growth and winter ice cover	
Earliest ice-out date	First day without ice cover in spring, but ice cover may form again	
Latest ice-out date	Last day with ice cover in spring; followed by open water season (t_{io})	
Duration of ice cover (days)	Total number of days with lake ice cover (D_{ice})	
Total period of ice cover (days)	Days between earliest ice-in and latest ice-out dates	$t_{io}-t_{ei}$
Continuous ice cover ratio	Duration of ice cover divided by total period of ice cover	$\frac{D_{ice}}{t_{io}-t_{ei}}$
Maximum ice thickness (m)	Maximum ice thickness over winter ice cover period	$\mathrm{Max}[\delta_i, t=1,365]$
Average snow depth (m)	Sum of clarity snow depths on ice divided by duration of ice cover	$\frac{\sum d_{snow}}{D_{ice}}$
Continuous snow cover ratio	Number of days with snow cover divided by duration of ice cover	$\frac{\sum_{t_{io}}^{t_{ei}} t[d_{snow}>0]}{D_{ice}}$

Table 5.3 Average Values of Water Temperature Characteristics under Present (1983 - 1990) Climate Scenario

Lake Name	Max. Surface Temperature (°C)	Min. Surface Temperature (°C)	Max. Bottom Temperature (°C)	Min. Bottom Temperature (°C)	Max. Temperature Difference (°C)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	23.8	0.0	23.6	0.00	1.8	0.025	198	33
Upper Red Lake	26.7	0.0	26.3	0.00	2.1	0.018	201	23
Lake Vermilion	23.7	0.0	21.2	0.65	7.3	0.278	205	91
Lake Pepin	27.3	0.0	26.0	0.02	3.1	0.119	172	26
Rainy Lake	22.4	0.0	18.5	2.65	9.1	0.306	218	0
Average	24.8	0.0	23.1	0.66	4.7	0.149	199	35
Standard Deviation	2.1	0.0	3.3	1.14	3.3	0.137	17	34

Table 5.4 Standard Deviations of Water Temperature Characteristics under Present (1983 - 1990) Climate Scenario

Lake Name	Max. Surface Temperature (°C)	Min. Surface Temperature (°C)	Max. Bottom Temperature (°C)	Min. Bottom Temperature (°C)	Max. Temperature Difference (°C)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	1.4	0.0	1.3	0.00	0.4	0.021	7	10
Upper Red Lake	1.9	0.0	1.8	0.00	0.7	0.009	9	8
Lake Vermilion	1.4	0.0	1.0	0.70	1.8	0.023	6	53
Lake Pepin	1.6	0.0	1.3	0.04	0.7	0.023	6	6
Rainy Lake	1.5	0.0	0.9	0.24	1.9	0.016	7	0

Table 5.5 Average Values of Water Temperature Characteristics under $2xCO_2$ Climate Scenario

Lake Name	Max. Surface Temperature (°C)	Min. Surface Temperature (°C)	Max. Bottom Temperature (°C)	Min. Bottom Temperature (°C)	Max. Temperature Difference (°C)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	29.3	0.0	28.5	0.00	2.1	0.044	161	31
Upper Red Lake	31.6	0.0	31.1	0.00	1.8	0.017	178	25
Lake Vermilion	29.1	0.0	25.4	0.79	8.9	0.360	167	57
Lake Pepin	33.3	0.0	31.1	0.38	4.4	0.190	126	27
Rainy Lake	27.6	0.0	22.1	1.54	11.9	0.377	192	18
Average	30.2	0.0	27.6	0.54	5.8	0.198	165	32
Standard Deviation	2.3	0.0	3.9	0.65	4.4	0.169	25	15

Table 5.6 Standard Deviations of Water Temperature Characteristics under $2xCO_2$ Climate Scenario

Lake Name	Max. Surface Temperature (°C)	Min. Surface Temperature (°C)	Max. Bottom Temperature (°C)	Min. Bottom Temperature (°C)	Max. Temperature Difference (°C)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	1.5	0.0	1.2	0.00	0.5	0.029	4	9
Upper Red Lake	1.9	0.0	1.7	0.00	0.4	0.010	9	9
Lake Vermilion	1.5	0.0	0.9	0.36	1.8	0.030	5	27
Lake Pepin	2.0	0.0	1.5	0.46	1.0	0.024	15	9
Rainy Lake	1.6	0.0	0.7	0.51	2.0	0.025	8	20

Table 5.7 Changes of Values of Water Temperature Characteristics from Present to $2xCO_2$ Climate Scenario

Lake Name	Max. Surface Temperature (°C)	Min. Surface Temperature (°C)	Max. Bottom Temperature (°C)	Min. Bottom Temperature (°C)	Max. Temperature Difference (°C)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	5.5	0.0	4.9	0.00	0.3	0.019	-37	-2
Upper Red Lake	4.9	0.0	4.8	0.00	-0.3	-0.001	-23	2
Lake Vermilion	5.4	0.0	4.2	0.14	1.6	0.082	-38	-34
Lake Pepin	6.0	0.0	5.1	0.36	1.3	0.071	-46	1
Rainy Lake	5.2	0.0	3.6	-1.11	2.8	0.071	-26	18
Average	5.4	0.0	4.5	-0.12	1.1	0.048	-34	-3
Standard Deviation	0.4	0.0	0.6	0.57	1.2	0.037	9	19

Table 5.8 Average Values of Ice and Snow Characteristics under Present (1983 - 1990) Climate Scenario

Lake Name	Earliest Ice-in Date	Latest Ice-In Date	Earliest Ice-out Date	Latest Ice-out Date	Max. Ice Thickness (m)	Duration of Ice Cover (days)	Total Period of Ice Cover (days)	Continuous Ice Cover Ratio	Average Snow Depth (m)	Continuous Snow Cover Ratio
Mille Lacs Lake	325	326	111	112	0.73	152	152	0.995	0.091	0.772
Upper Red Lake	308	314	111	116	0.76	168	173	0.970	0.081	0.771
Lake Vermilion	325	326	111	112	0.73	152	153	0.995	0.091	0.770
Lake Pepin	333	334	98	104	0.65	132	136	0.968	0.047	0.690
Rainy Lake	340	340	114	117	0.85	140	142	0.989	0.036	0.743
Average	326	328	109	112	0.74	149	151	0.983	0.069	0.749
Standard Deviation	12	10	6	5	0.07	14	14	0.013	0.026	0.035

Table 5.9 Standard Deviations of Ice and Snow Characteristics under Present (1983 - 1990) Climate Scenario

Lake Name	Earliest Ice-in Date	Latest Ice-In Date	Earliest Ice-out Date	Latest Ice-out Date	Max. Ice Thickness (m)	Duration of Ice Cover (days)	Total Period of Ice Cover (days)	Continuous Ice Cover Ratio	Average Snow Depth (m)	Continuous Snow Cover Ratio
Mille Lacs Lake	5	6	7	8	0.07	8	10	0.011	0.050	0.065
Upper Red Lake	5	8	7	8	0.11	11	12	0.027	0.043	0.068
Lake Vermilion	5	6	7	8	0.08	9	9	0.009	0.050	0.066
Lake Pepin	8	9	9	11	0.13	13	15	0.042	0.023	0.108
Rainy Lake	6	6	6	8	0.12	10	11	0.018	0.036	0.042

Table 5.10 Average Values of Ice and Snow Characteristics under $2xCO_2$ Climate Scenario

Lake Name	**Earliest Ice-in Date**	**Latest Ice-In Date**	**Earliest Ice-out Date**	**Latest Ice-out Date**	**Max. Ice Thickness (m)**	**Duration of Ice Cover (days)**	**Total Period of Ice Cover (days)**	**Continuous Ice Cover Ratio**	**Average Snow Depth (m)**	**Continuous Snow Cover Ratio**
Mille Lacs Lake	338	340	65	88	0.44	101	115	0.872	0.016	0.493
Upper Red Lake	313	331	79	100	0.53	134	152	0.880	0.023	0.559
Lake Vermilion	337	339	66	88	0.45	103	117	0.877	0.016	0.489
Lake Pepin	342	344	26	61	0.34	59	84	0.704	0.012	0.406
Rainy Lake	354	357	87	101	0.56	100	113	0.819	0.013	0.513
Average	337	342	65	88	0.46	99	116	0.830	0.016	0.492
Standard Deviation	15	10	23	16	0.09	27	24	0.075	0.004	0.056

Table 5.11 Standard Deviations of Ice and Snow Characteristics under $2xCO_2$ Climate Scenario

Lake Name	**Earliest Ice-in Date**	**Latest Ice-In Date**	**Earliest Ice-out Date**	**Latest Ice-out Date**	**Max. Ice Thickness (m)**	**Duration of Ice Cover (days)**	**Total Period of Ice Cover (days)**	**Continuous Ice Cover Ratio**	**Average Snow Depth (m)**	**Continuous Snow Cover Ratio**
Mille Lacs Lake	10	8	28	7	0.12	23	9	0.160	0.009	0.143
Upper Red Lake	7	17	28	12	0.14	18	13	0.091	0.019	0.151
Lake Vermilion	10	7	28	7	0.12	23	9	0.162	0.009	0.134
Lake Pepin	8	9	19	20	0.11	21	23	0.151	0.014	0.208
Rainy Lake	9	12	17	11	0.15	18	17	0.282	0.010	0.092

Table 5.12 Changes of Values of Ice and Snow Characteristics from Present to $2xCO_2$ Climate Scenario

Lake Name	Earliest Ice-in Date	Latest Ice-In Date	Earliest Ice-out Date	Latest Ice-out Date	Max. Ice Thickness (m)	Duration of Ice Cover (days)	Total Period of Ice Cover (days)	Continuous Ice Cover Ratio	Average Snow Depth (m)	Continuous Snow Cover Ratio
Mille Lacs Lake	13	14	-46	-24	-0.29	-51	-37	-0.123	-0.075	-0.279
Upper Red Lake	5	17	-32	-16	-0.23	-34	-21	-0.090	-0.058	-0.212
Lake Vermilion	12	13	-45	-24	-0.28	-49	-36	-0.118	-0.075	-0.281
Lake Pepin	9	10	-72	-43	-0.31	-73	-52	-0.264	-0.035	-0.284
Rainy Lake	14	17	-27	-16	-0.29	-40	-29	-0.170	-0.046	-0.230
Average	11	14	-44	-25	-0.28	-49	-35	-0.153	-0.058	-0.257
Standard Deviation	4	3	17	11	0.03	15	11	0.068	0.018	0.034

6. SUMMARY AND CONCLUSIONS

The objective of this study was to simulate seasonal water temperature cycles and stratification in five large lakes in Minnesota under a $2xCO_2$ climate scenario and compare the results with those under the present climate scenario. The five lakes studied were Mille Lacs Lake, Upper Red Lake, Lake Vermillion, Lake Pepin and Rainy Lake. MINLAKE 96, a one dimensional, unsteady water quality model, was employed.

Results are presented herein for surface temperatures, bottom temperatures, and differences between surface and bottom water temperature under the two climate scenarios. Time series for ice thickness are also presented. The values of some parameters (Table 6.1 and 6.2) which describe lake water temperature and ice characteristics are extracted from the simulation results for both present and $2xCO_2$ climate scenarios.

During the open water season, water temperatures are projected to increase in the entire lake for all five lakes from present to the $2xCO_2$ climate scenarios. Maximum surface water temperatures increase from 4.9°C for Upper Red Lake to 6.0°C for Lake Pepin. Average increase for the five lakes is 5.4°C. Maximum bottom temperatures are projected to increase from 3.6°C (Rainy Lake) to 5.1°C (Lake Pepin). Average increase for the five lakes is 4.5°C.

In the ice cover season, water temperatures may decrease slightly with climate change, especially near the lake bottom. The decrease is projected to be up to 1°C.

Bottom temperatures less than 8 °C are found during a shorter period under a $2xCO_2$ climate scenario for all the five lakes. The period shortens by 23 days for Upper Red Lake to 46 days for Lake Pepin. Average change is 34 days. This will affect the survival and growth of fish.

Open water stratification ratios are projected to increase for four lakes and to remain the same for the other lake (Upper Red Lake). The strength of stratification during the open water season is projected to be stronger for all the five lakes under the $2xCO_2$ climate scenario. During the ice cover season the climate change tends to weaken the inverse stratification.

Ice is thinner under a $2xCO_2$ climate scenario most of the time, but not all the time. Thicker ice is caused by absence of snow. Average maximum ice thickness for the five lakes changes from 0.74 m to 0.46 m. Snowfall and snow depths are smaller under a $2xCO_2$ climate scenario.

Ice-in dates are later and ice-out dates are earlier under a $2xCO_2$ climate scenario. Thus ice cover duration is shorter. Average changes are 14 days, 44 days, and 49 days for latest ice-in date, earliest ice-out date and duration of ice cover. Ice cover also becomes less continuous. The shorter ice cover duration will decrease the possibility of anoxic conditions (winterkill) in lakes during the ice cover season. Earlier ice-out leads to earlier spring overturn.

Comparing the results with those for small lakes obtained by Fang et al. (1997), large lakes respond to the projected climate change in a way similar to small lakes. One difference is that surface water temperatures increase more in large lakes than in small lakes from present climate to $2xCO_2$ climate scenario.

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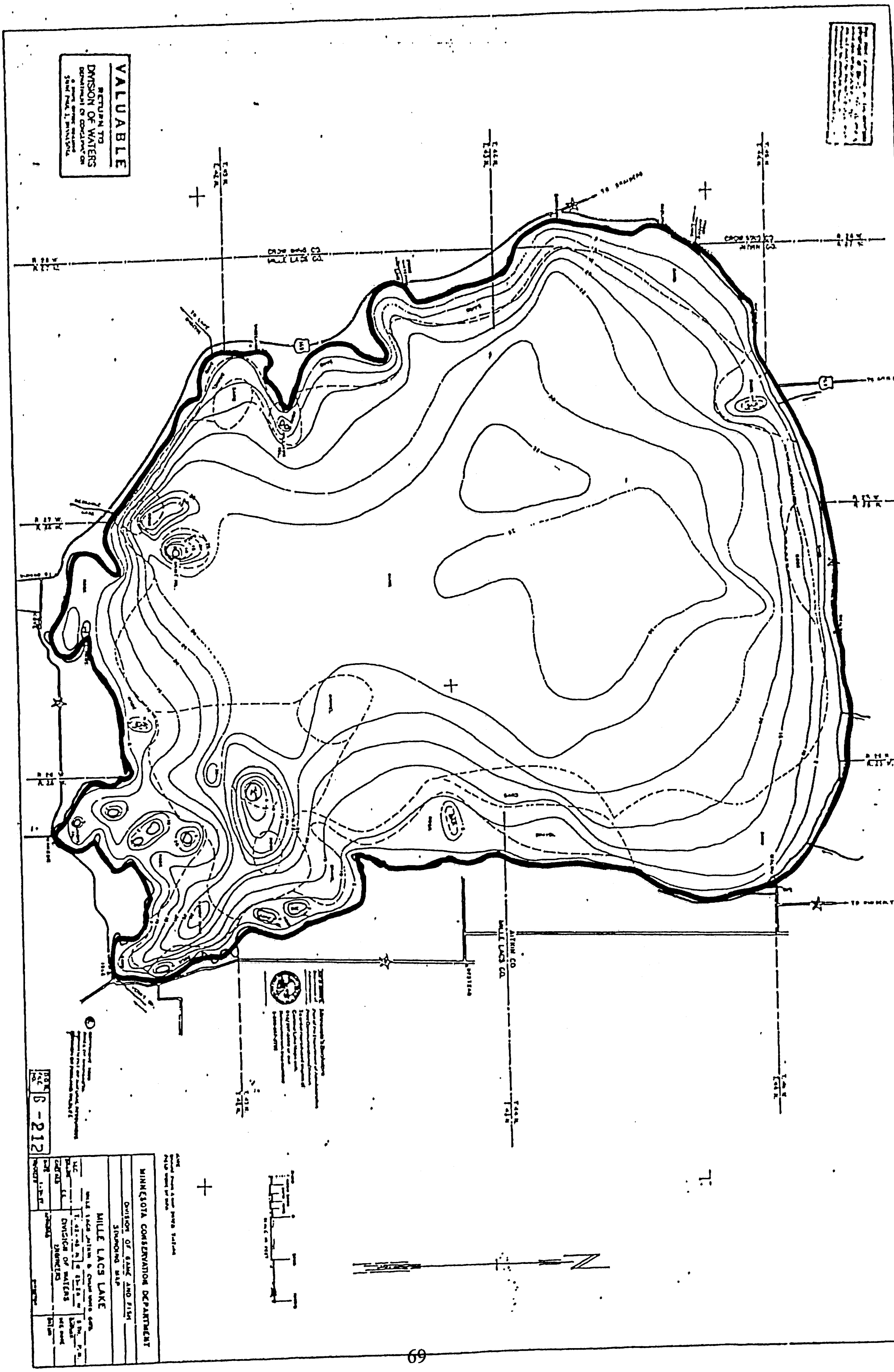
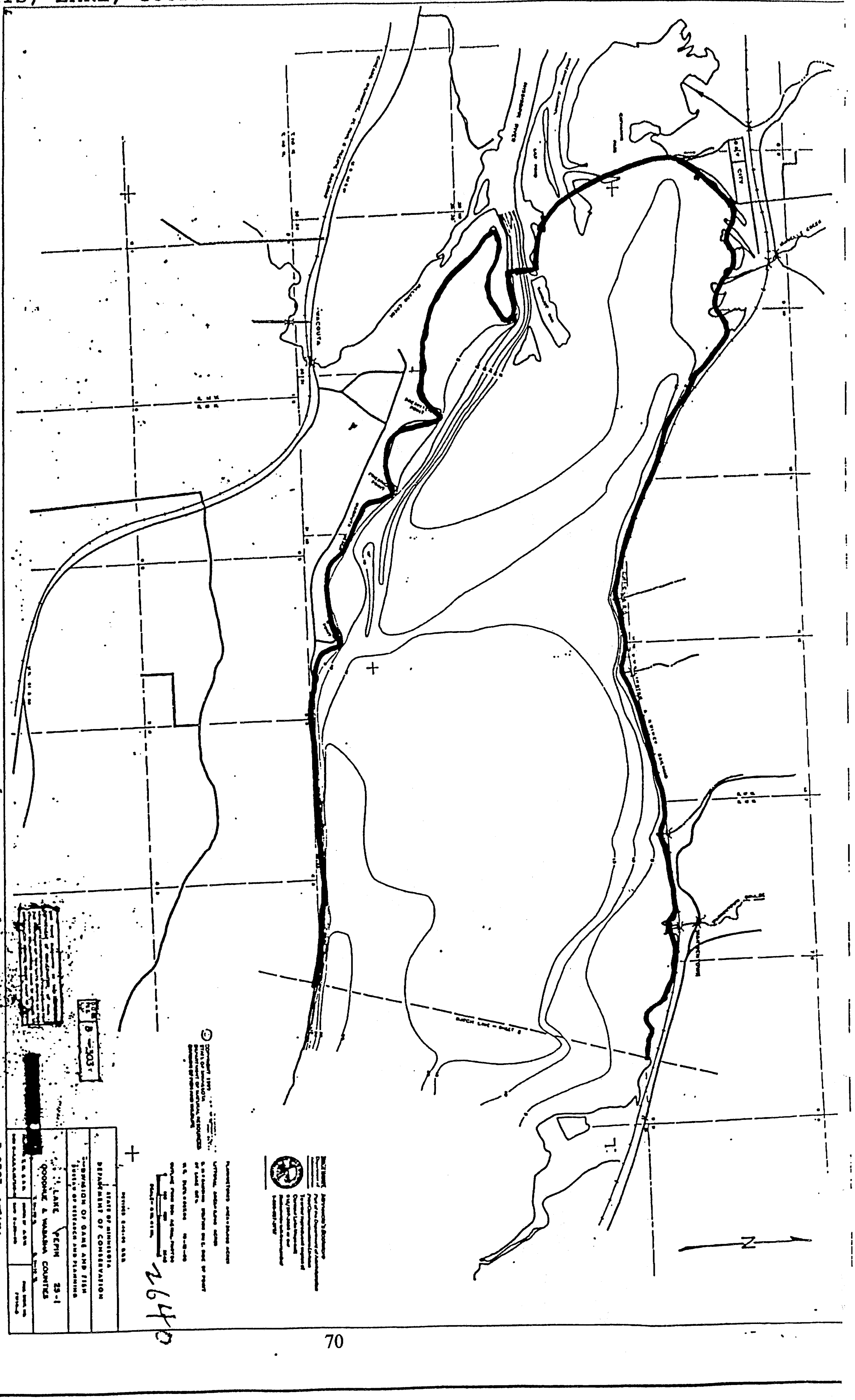
APPENDIX A: BATHYMETRIC LAKE MAPS

Sample Lake Map
MILLE LACS LAKE, MILLE LACS COUNTY
MnDNR 1994



Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994

For Pepin Lake, I simulate the whole lake.



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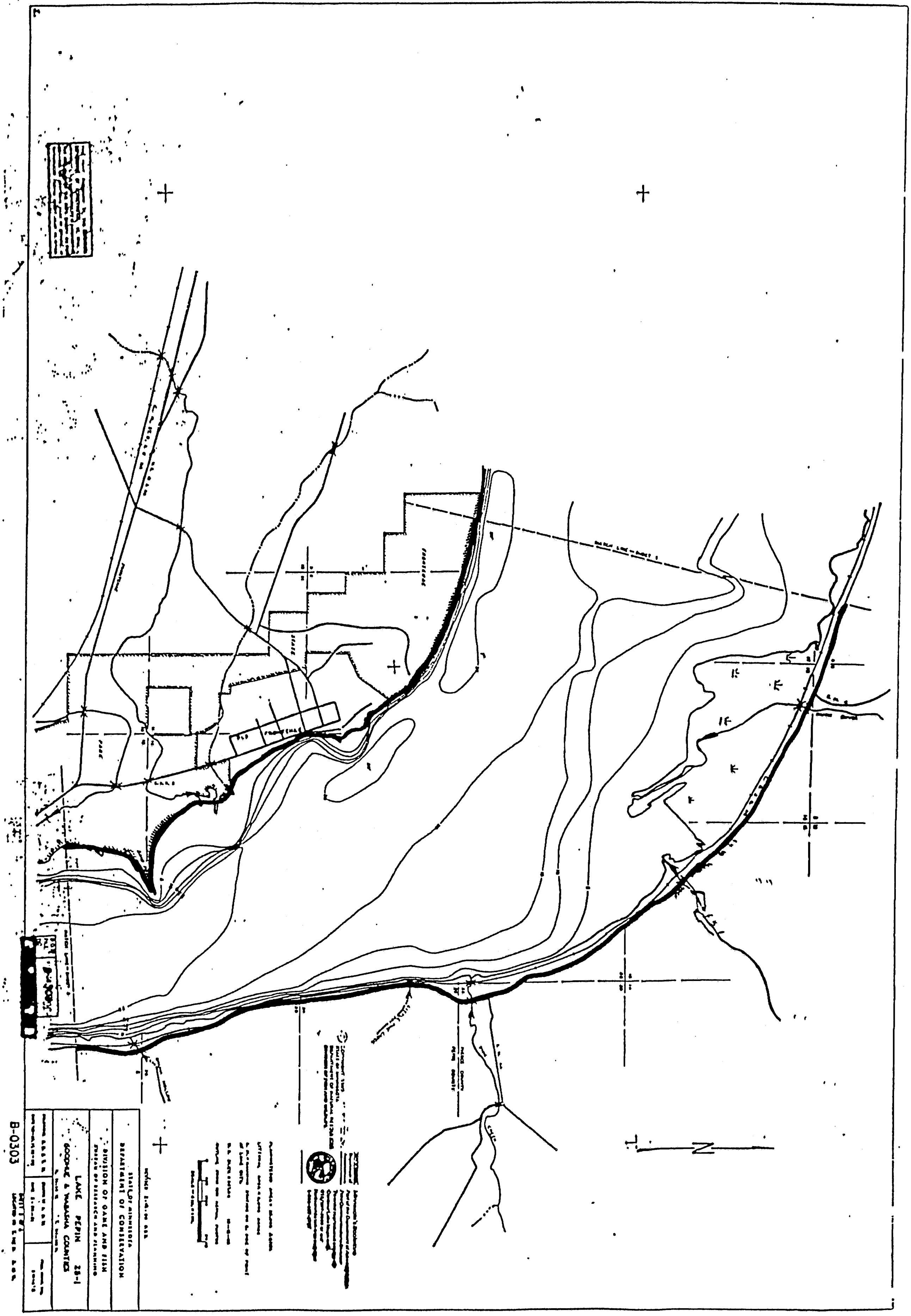
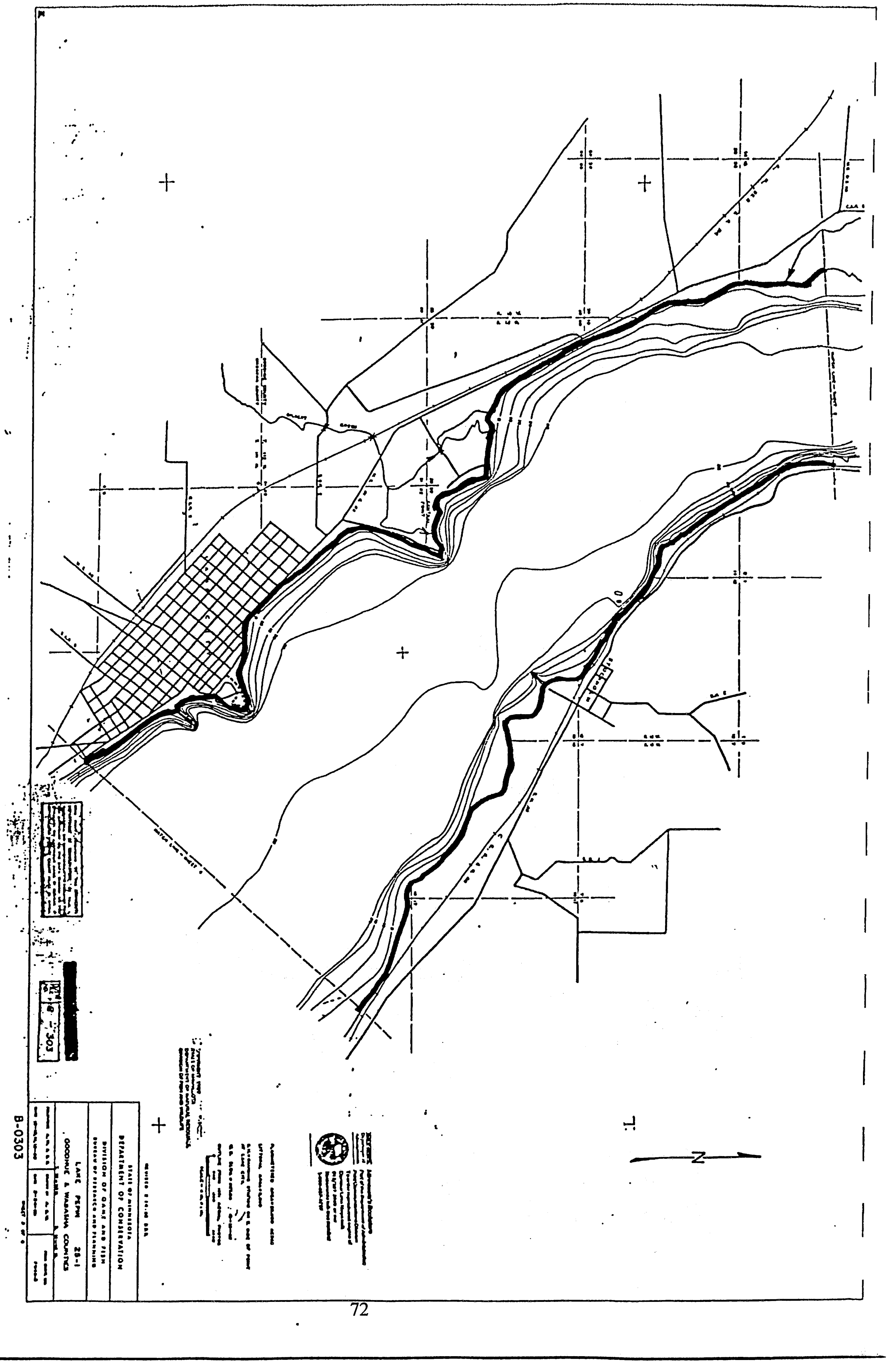
ple Lake Map
IN (FOUR PARTS) LAKE, GOODHUE COUNTY
DNR 1994



Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994



Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994