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

Project Report No. 459

Daily Water Temperature Simulations for Lake Mille Lacs

(1983-2002)

by

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Prepared for

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Abstract

Each year the Minnesota Department of Natural Resources (MNDNR), Division of Fisheries, assesses the walleye population in Mille Lacs Lake to provide a forecast for the upcoming fishing season. Water temperature is a controlling factor in the estimate. Because water temperature measurements in Mille Lacs Lake are only available for recent years, the MNDNR requested simulations of daily water temperatures for Mille Lacs Lake from 1983 - 2002. Temperatures in September and October were of particular interest.

MINLAKE 96, a one dimensional, unsteady water quality model was employed to simulate the water temperatures. Weather data from Brainerd and Duluth, were used as input. Water temperature measurements from 2000 to 2002 were used to validate the simulations.

It was determined that the weather data from Brainerd provided the best simulation for the summer, fall and winter. However, the Duluth data offered a better estimate for the spring.

Since the walleye assessment takes place in September of each year, the Brainerd simulation should provide the best water temperature estimates. For the years when the Brainerd data is not available, the Duluth measurements can be used with a correction factor.

Acknowledgments

This project was completed in response to a request by Dr. Don Pereira, Fisheries Research Supervisor of the Minnesota Department of Natural Resources. The water temperature simulation was completed by Dr. Xing Fang, of Lamar University in cooperation with the University of Minnesota. The weather data was provided by Greg Spoden, Associate State Climatologist. Mr. Dehui Su at Lamar University helped in reorganizing weather data for model simulations. Mr. Jennings of the Minnesota Department of Natural Resources provided the lake temperature measurements. The work was coordinated by Dr. Heinz G. Stefan and this report was assembled by Mr. William Matzek.

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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. The heat exchange between sediment and water is calculated for all water layers simulated.

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

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

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)

Standard errors for water temperature between simulated and measured data were 0.95°C for Mille Lacs Lake (Gao and Stefan, 1997).

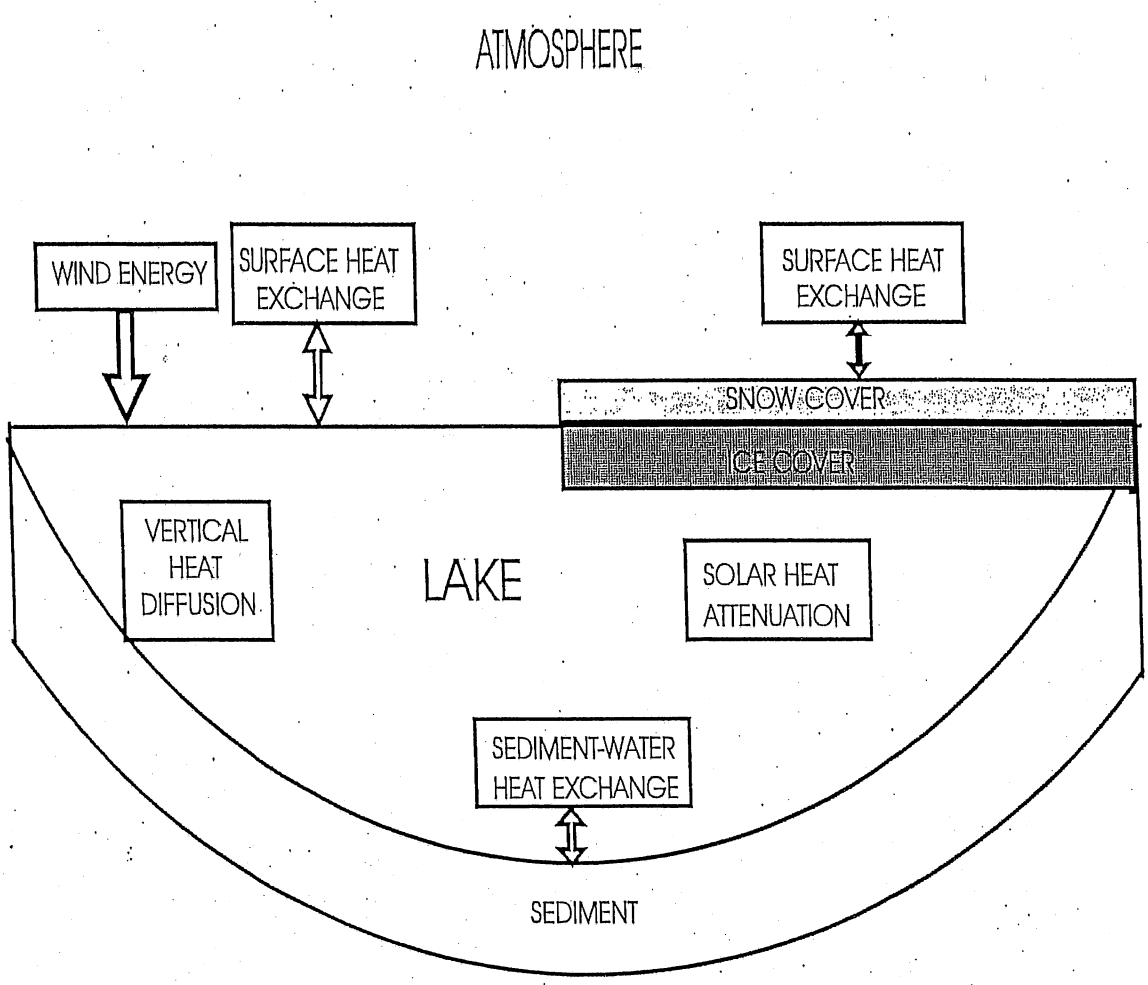


Figure 2.1 Graphical representation of heat transfer processes in MINLAKE 96

3. Input Data

In order to determine how accurate the MINLAKE 96 water temperature simulations are, the model output is compared to actual lake water temperatures. At three different locations data was recorded during 2000, 2001, and 2002. The data plots for Site 1, which is located in the south central portion of the lake, can be found in Figure 3.1. Water temperatures were recorded at three different depths. At six feet deep measurements were taken from 6/8/2000 to 9/30/2000 and from 5/10/2001 to 3/6/2002. At a depth of 14 feet, data was recorded from 4/11/2000 to 9/30/2000. At 21.5 feet deep measurements were taken from 6/8/2000 to 3/4/2001.

For Site 2, located in the NE quadrant of Mille Lacs, data was collected at a depth of 6 feet from 3/9/2001 to 3/6/2002. The Site 2 plot can be found in Figure 3.2. At Site 50, which is in the north shore sands, data was collected at 2.5 feet depth from 4/4/2000 to 11/9/2000 and from 5/3/2001 to 11/29/2001. Figure 3.3 displays the Site 50 data plots. In Figure 3.4 there is a plot of all the data from all three sites. A map of Lake Mille Lacs is provided in Appendix A.

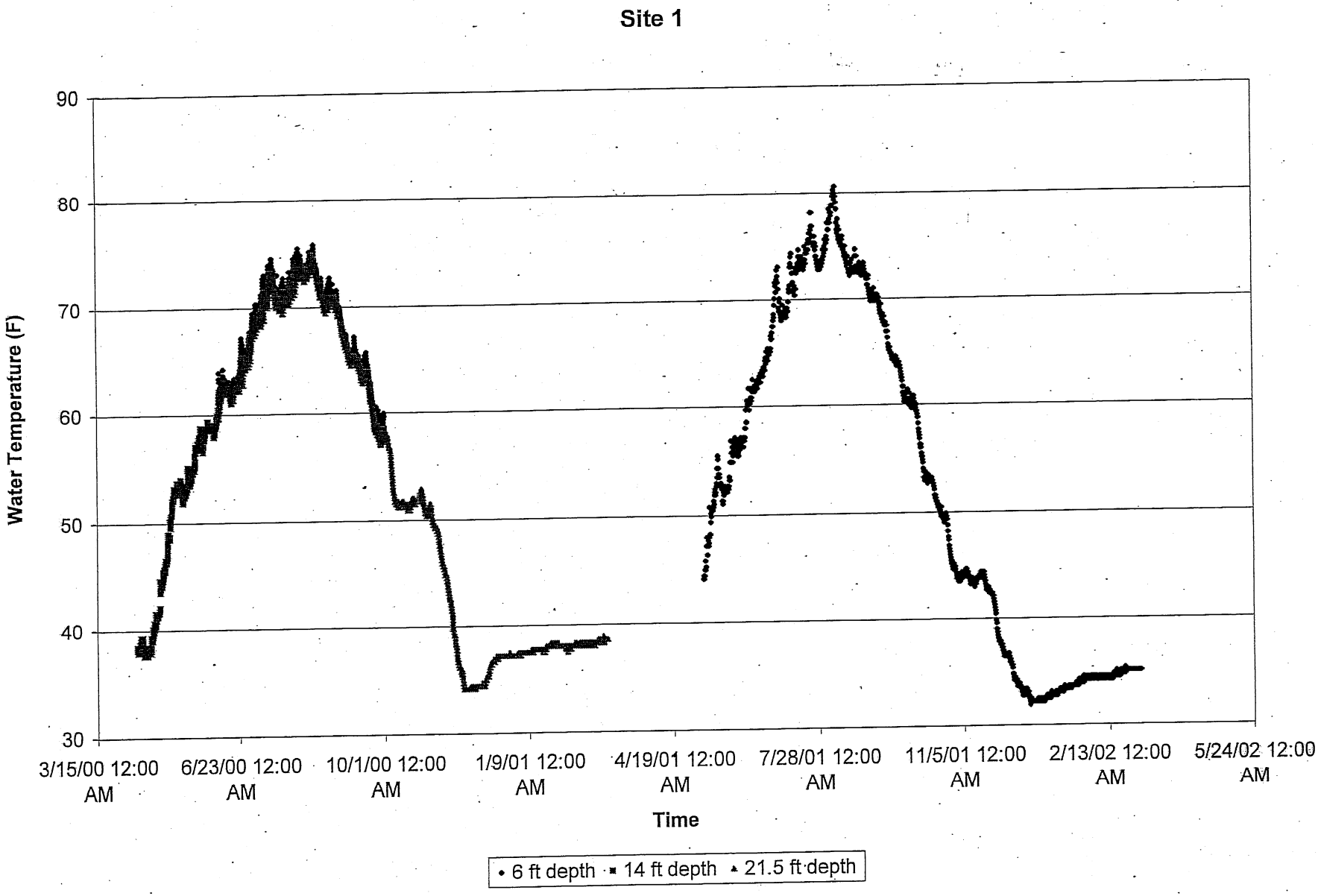


Figure 3.1 Field measurements from Site 1

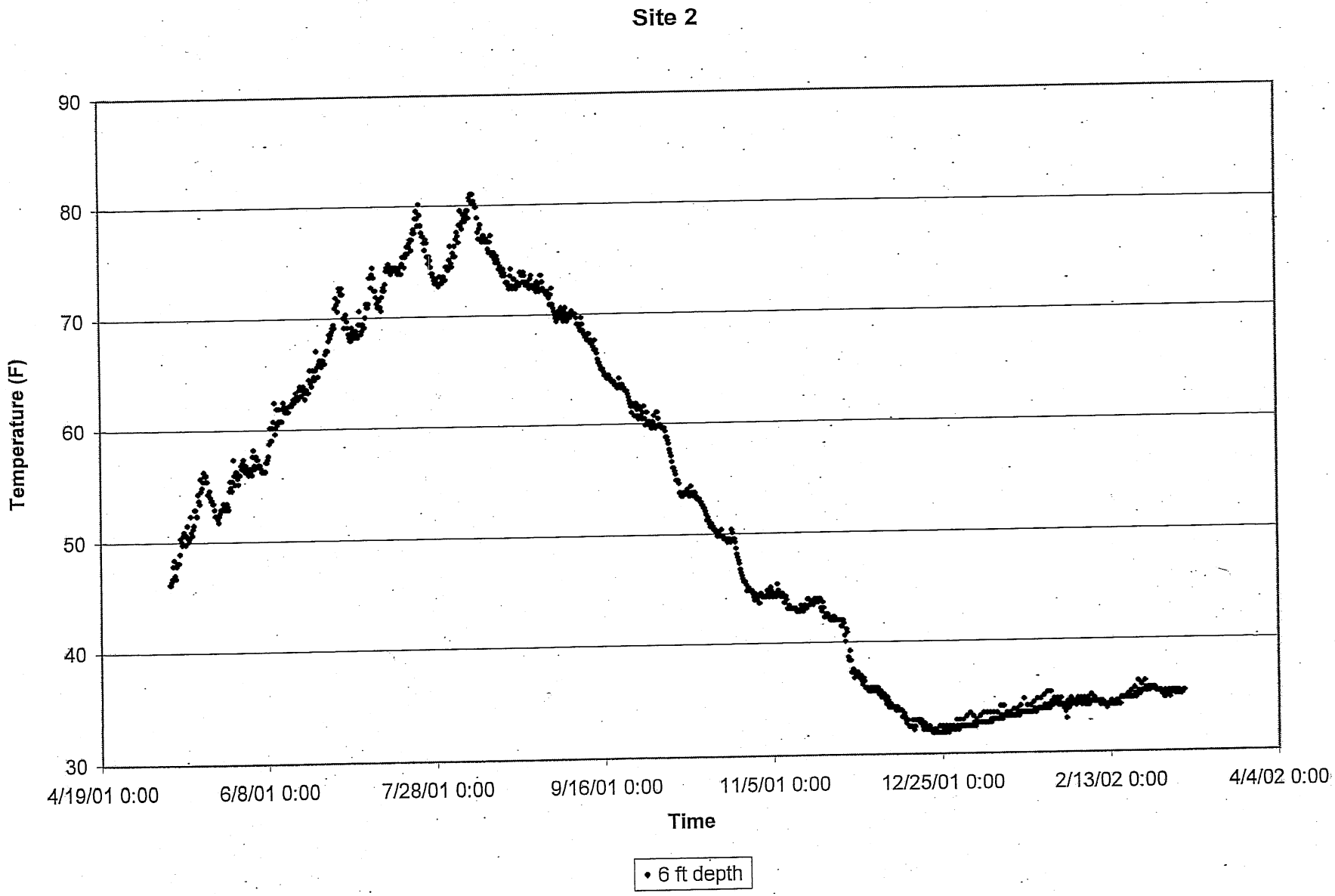


Figure 3.2 Field measurements from Site 2

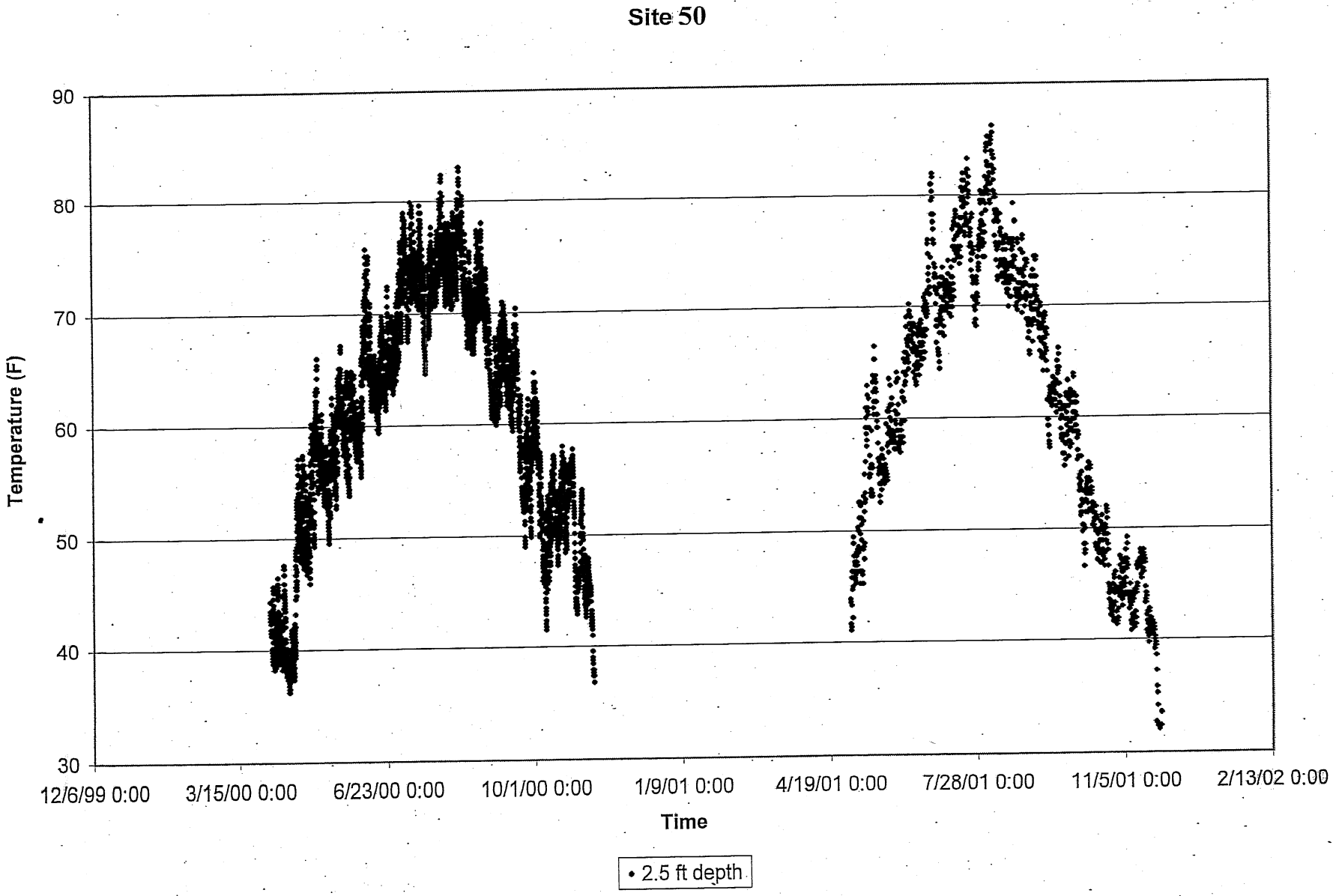


Figure 3.3 Field measurements from Site 50

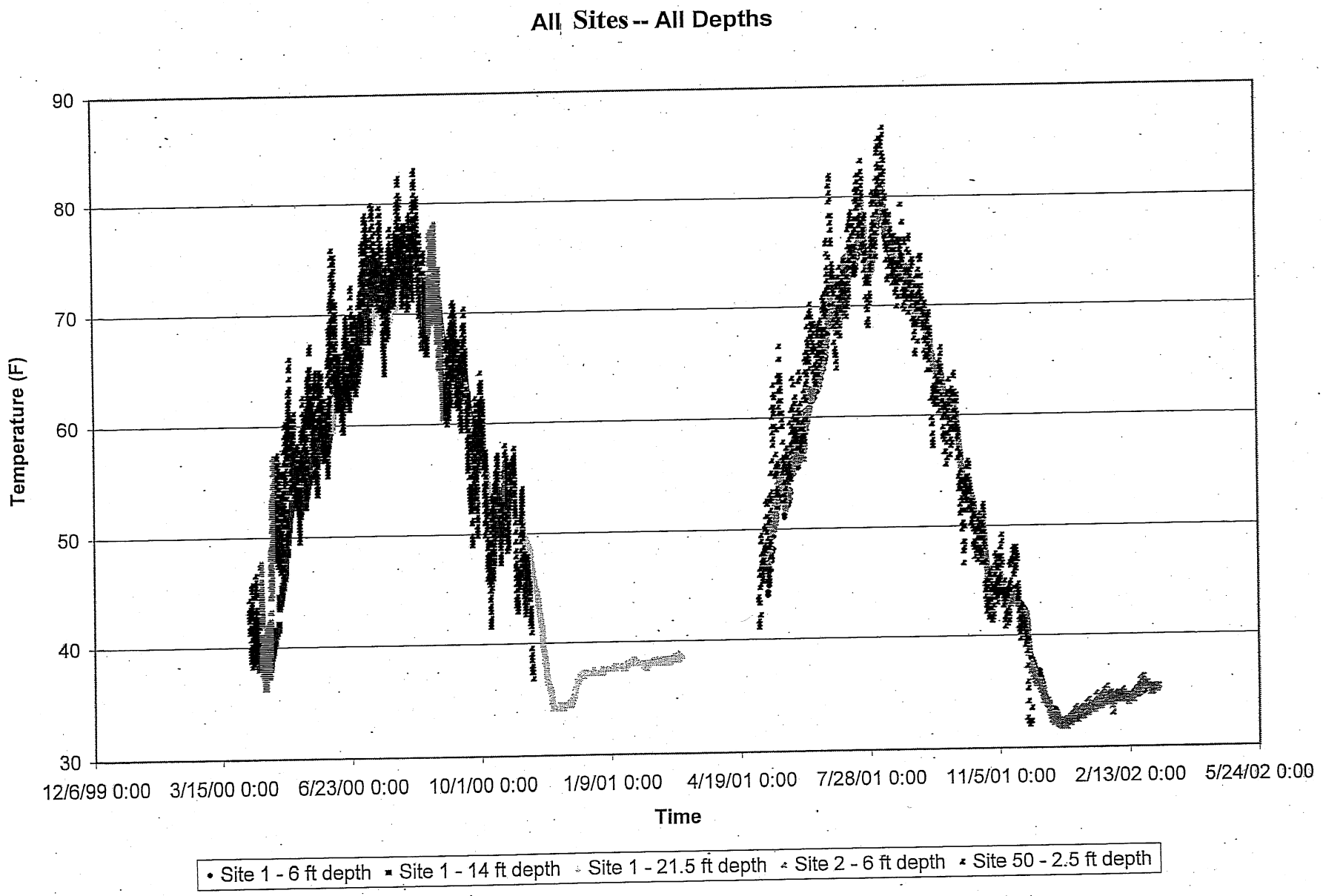


Figure 3.4 Field measurements from all sites

4. Simulation Results

Simulations of water temperatures for Lake Mille Lacs were completed using both the Brainerd and Duluth weather. For each case, the simulation results were recorded in text (ASCII) data files. The data output formats can be found in Appendix B and C. Appendix B is a data format for both the Brainerd and Duluth simulations. Appendix C is a data format for the more relevant months for gillnetting of September and October.

4.1 Results simulated with Brainerd weather data

Figures 4.1 to 4.8 graphically show the simulation results of water temperature vs. time for the Brainerd weather data. Figure 4.1 shows the available data points plotted on the simulation results for 1996 to 2002. Figures 4.2 through 4.8 show the simulation for the individual years, with the available field data points plotted for the years 2002, 2001, and 2000.

Figures 4.9 to 4.14 give the water temperatures on graphs of depth vs. time. These figures show the more relevant months of September and October that are vital to the study. These plots show that water temperatures generally stay constant with depth. This lack of stratification is due to the fact that Mille Lacs is a relatively shallow and large lake.

4.2 Results simulated with Duluth weather data

The remaining figures are for the water temperature simulation with weather data from Duluth. These figures are plotted in the same manner as the preceding figures. Figures 4.15 to 4.35 show the timeseries plots for the years 1983 to 2002. Figures 4.36 to 4.55 show isotherms for the months of September and October.

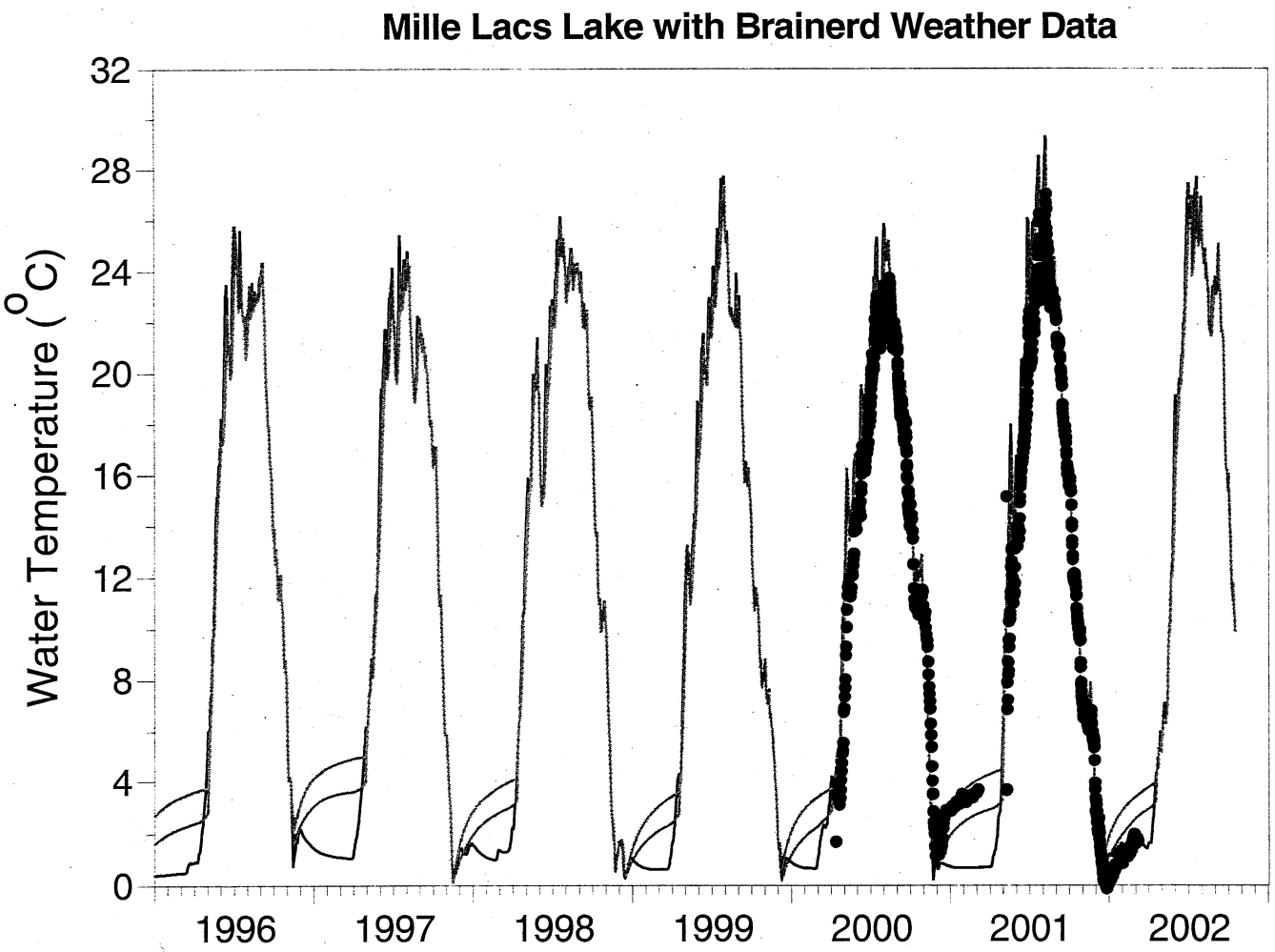


Figure 4.1 Simulation Results with Brainerd Weather Data for 2002

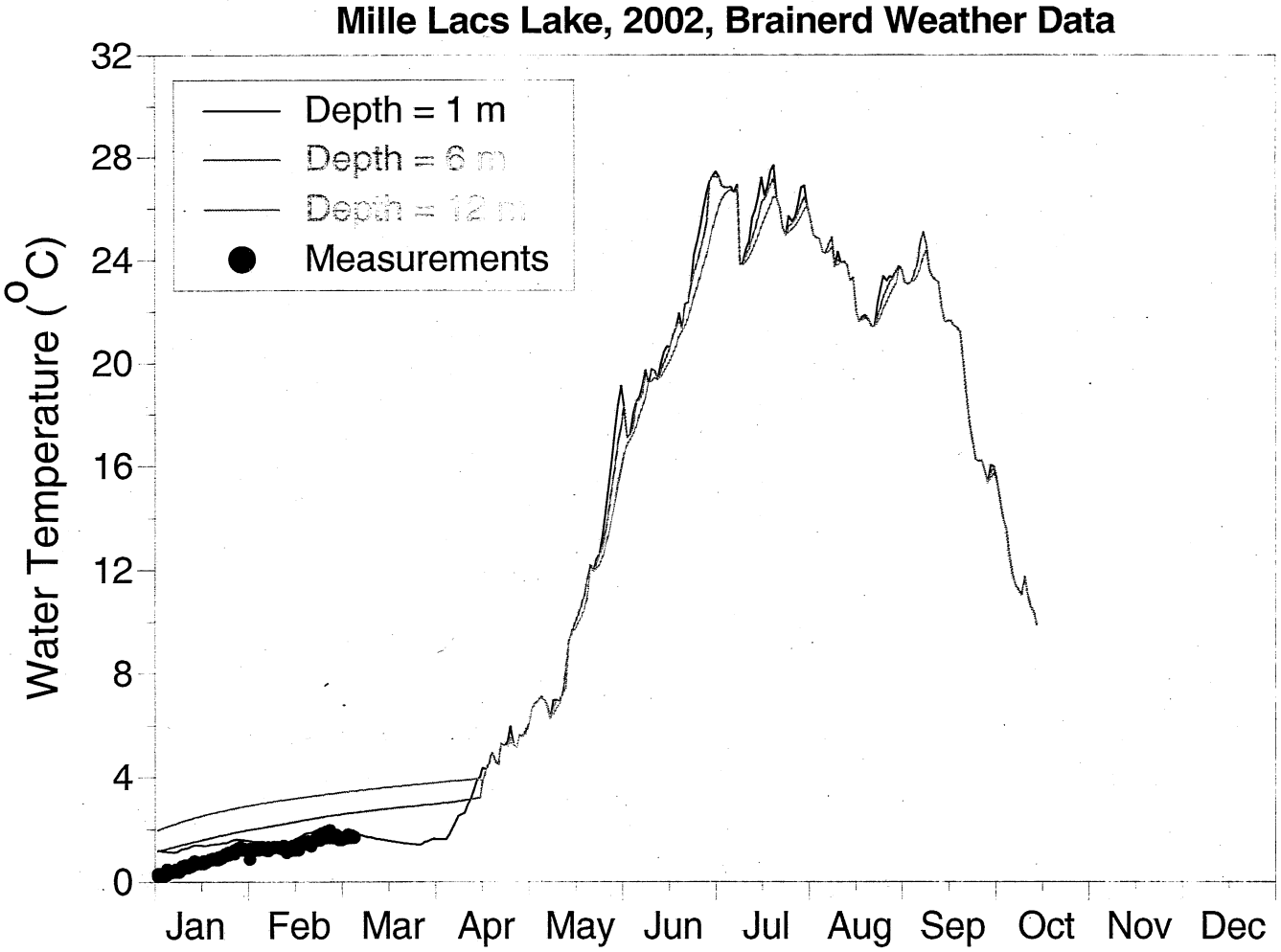


Figure 4.2 Simulation Results with Brainerd Weather Data for 2002

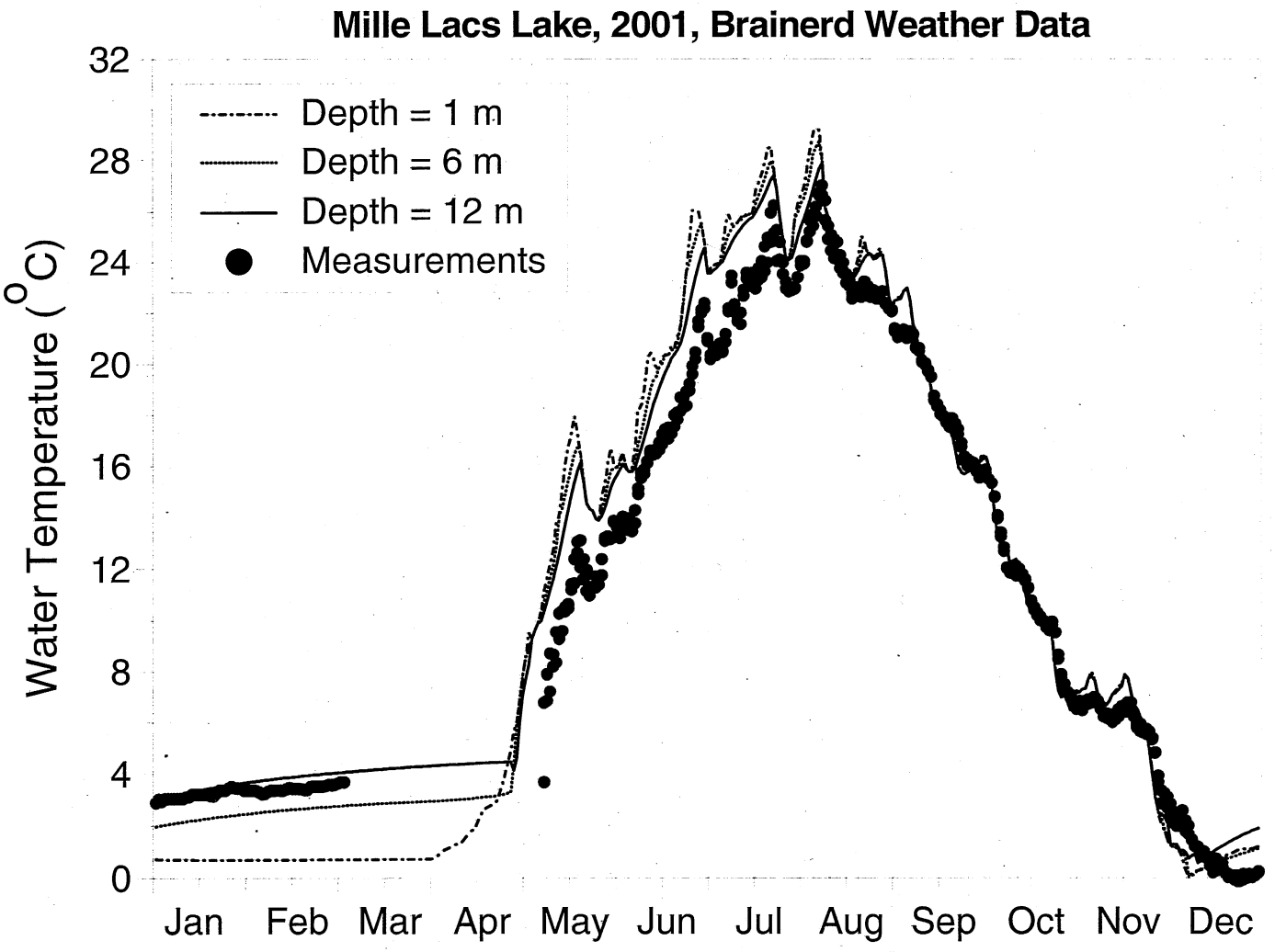


Figure 4.3 Simulation Results with Brainerd Weather Data for 2001

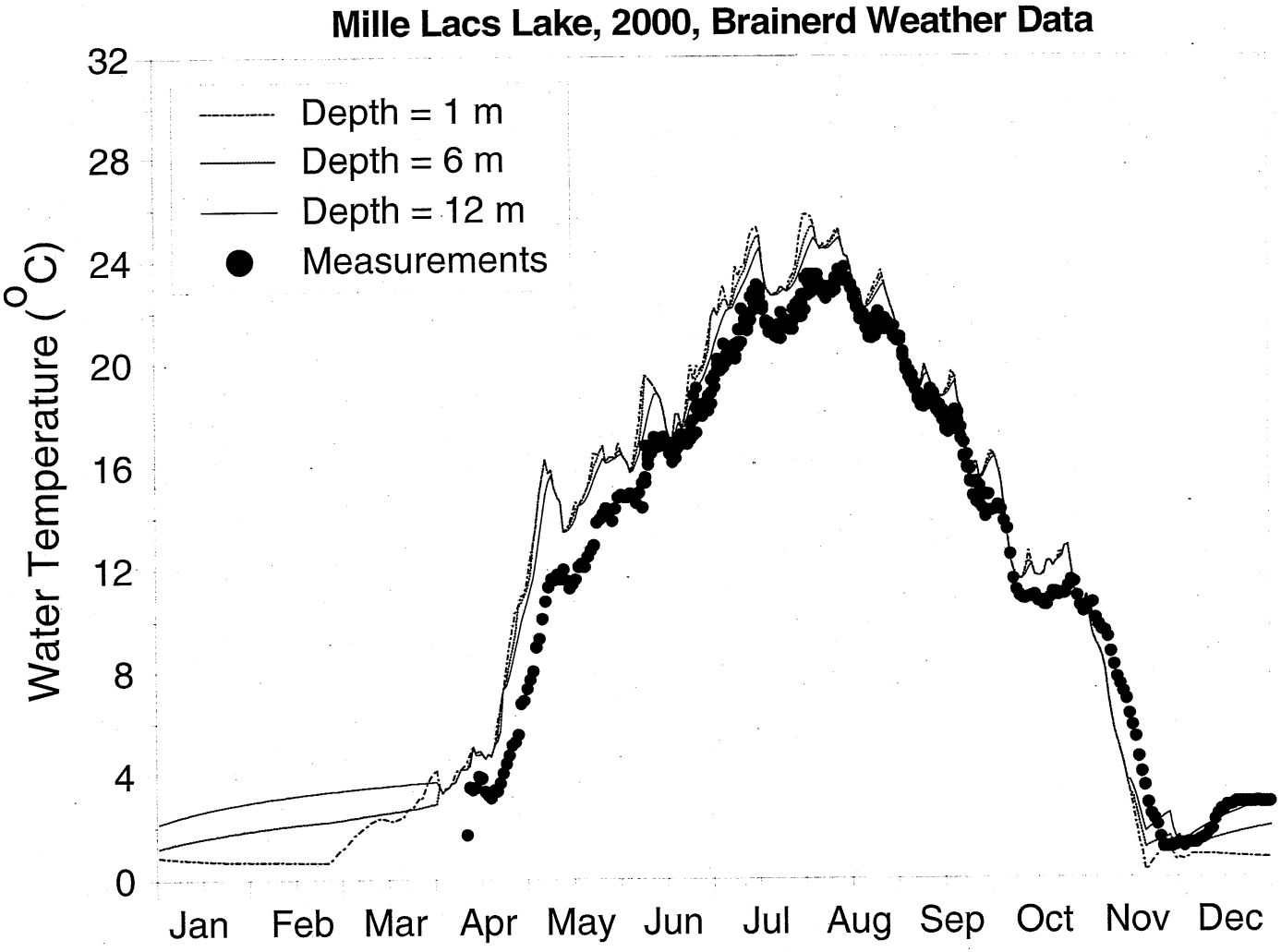
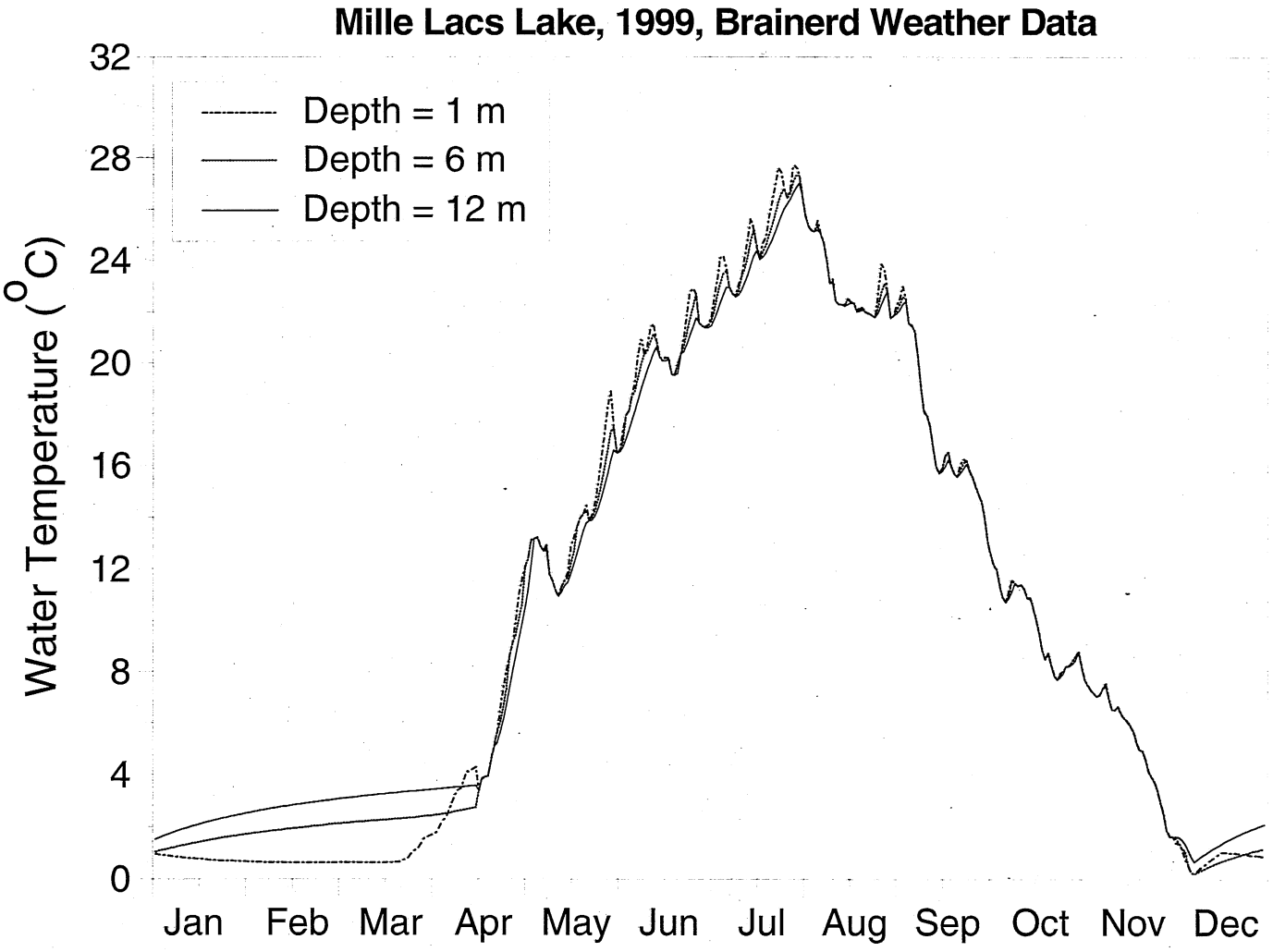


Figure 4.4 Simulation Results with Brainerd Weather Data for 2000



Figuure 4.5 Simulation Results with Brainerd Weather Data for 1999

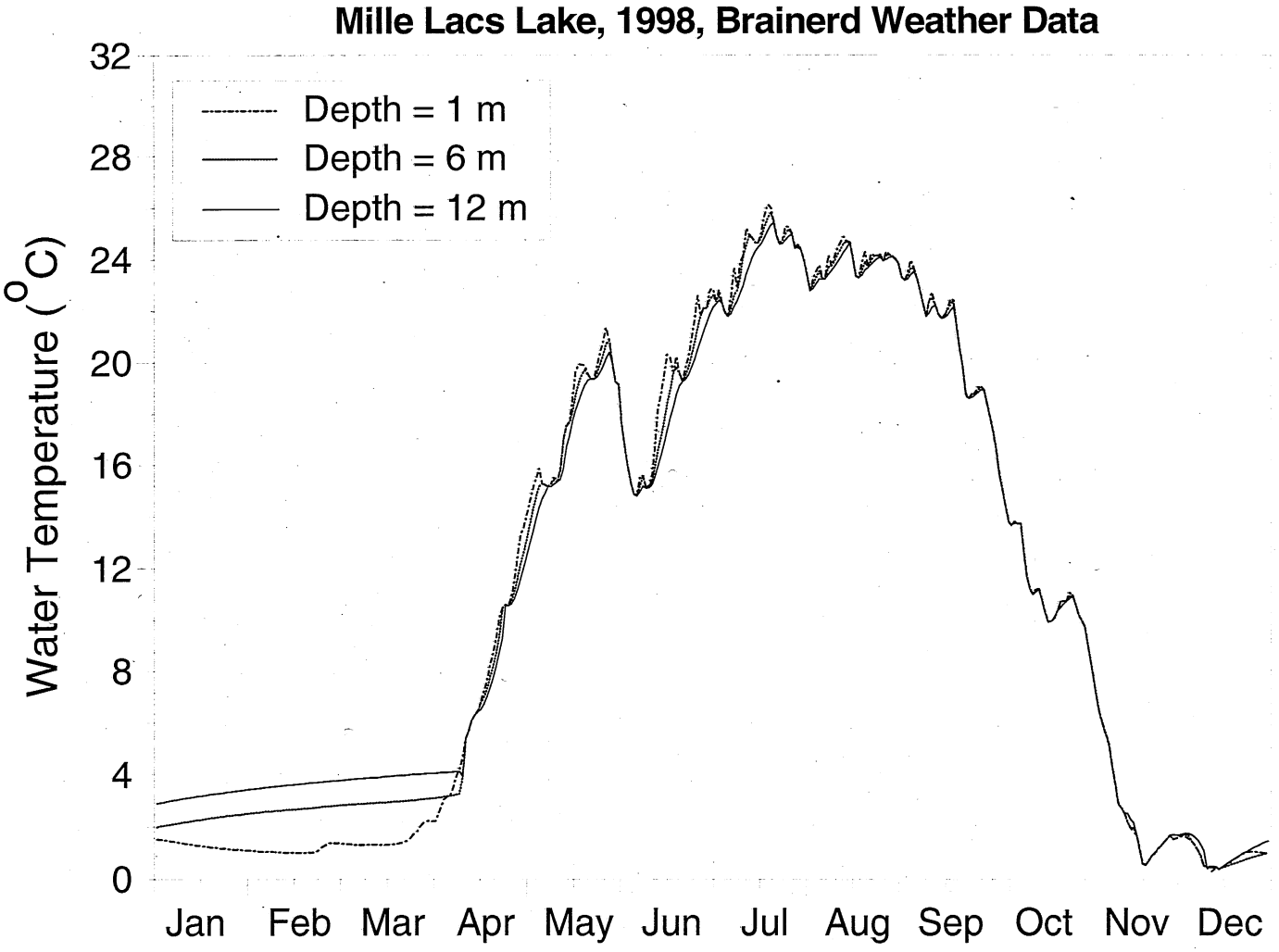


Figure 4.6 Simulation Results with Brainerd Weather data for 1998

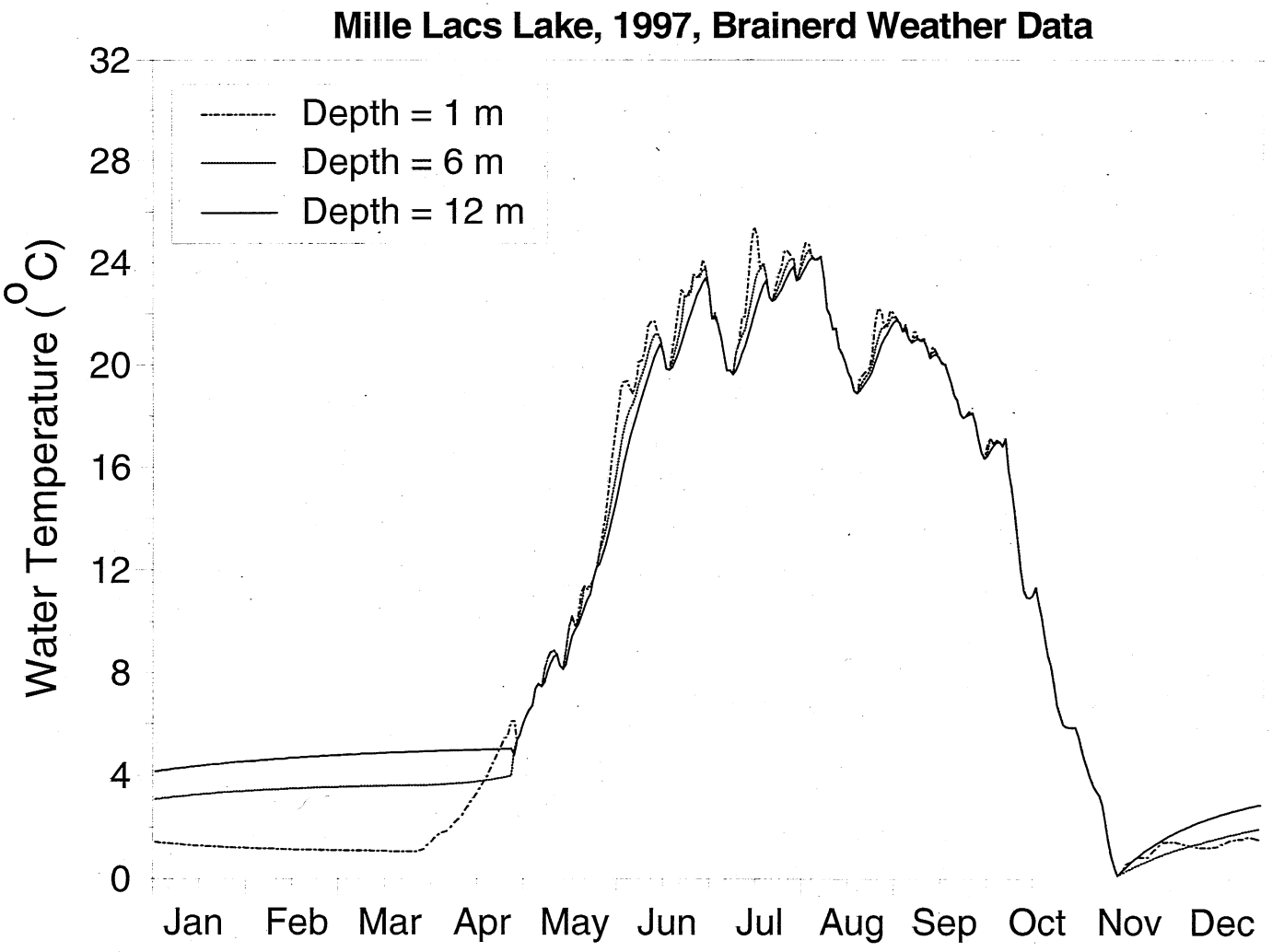


Figure 4.7 Simulation Results with Brainerd Weather Data for 1997

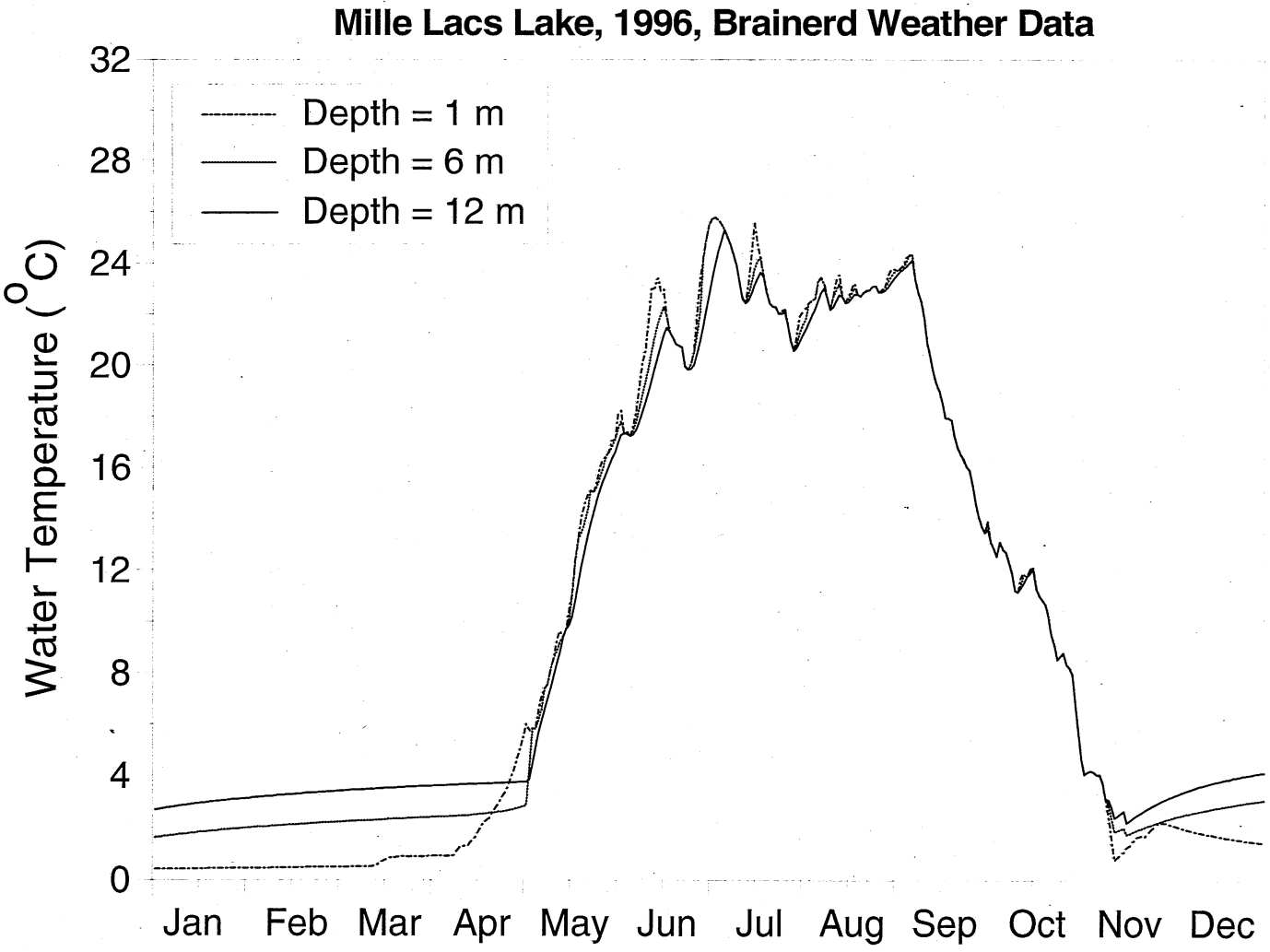


Figure 4.8 Simulation Results with Brainerd Weather Data for 1996

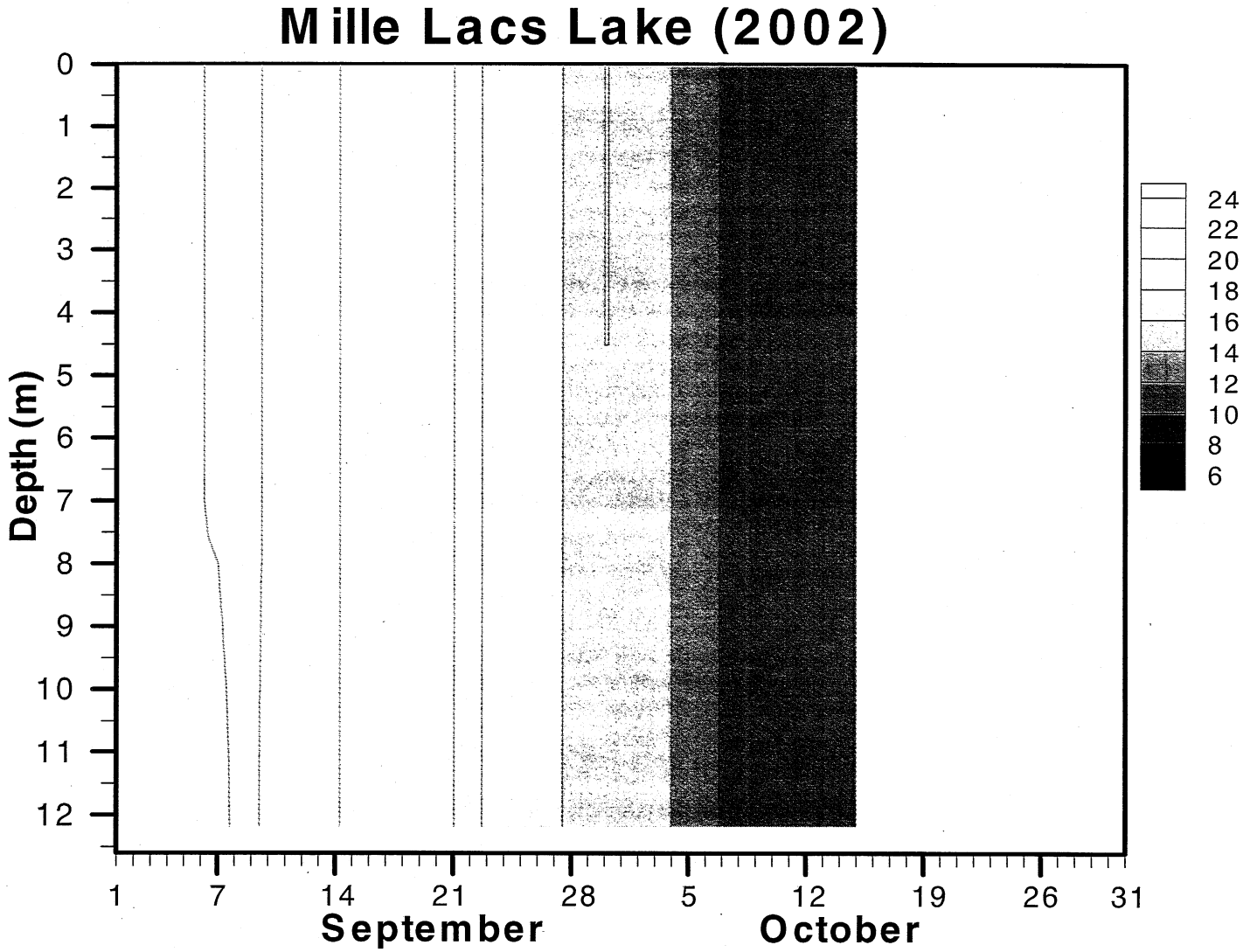


Figure 4.9 Simulation Results with Brainerd Weather Data for Sept. and Oct. 2002

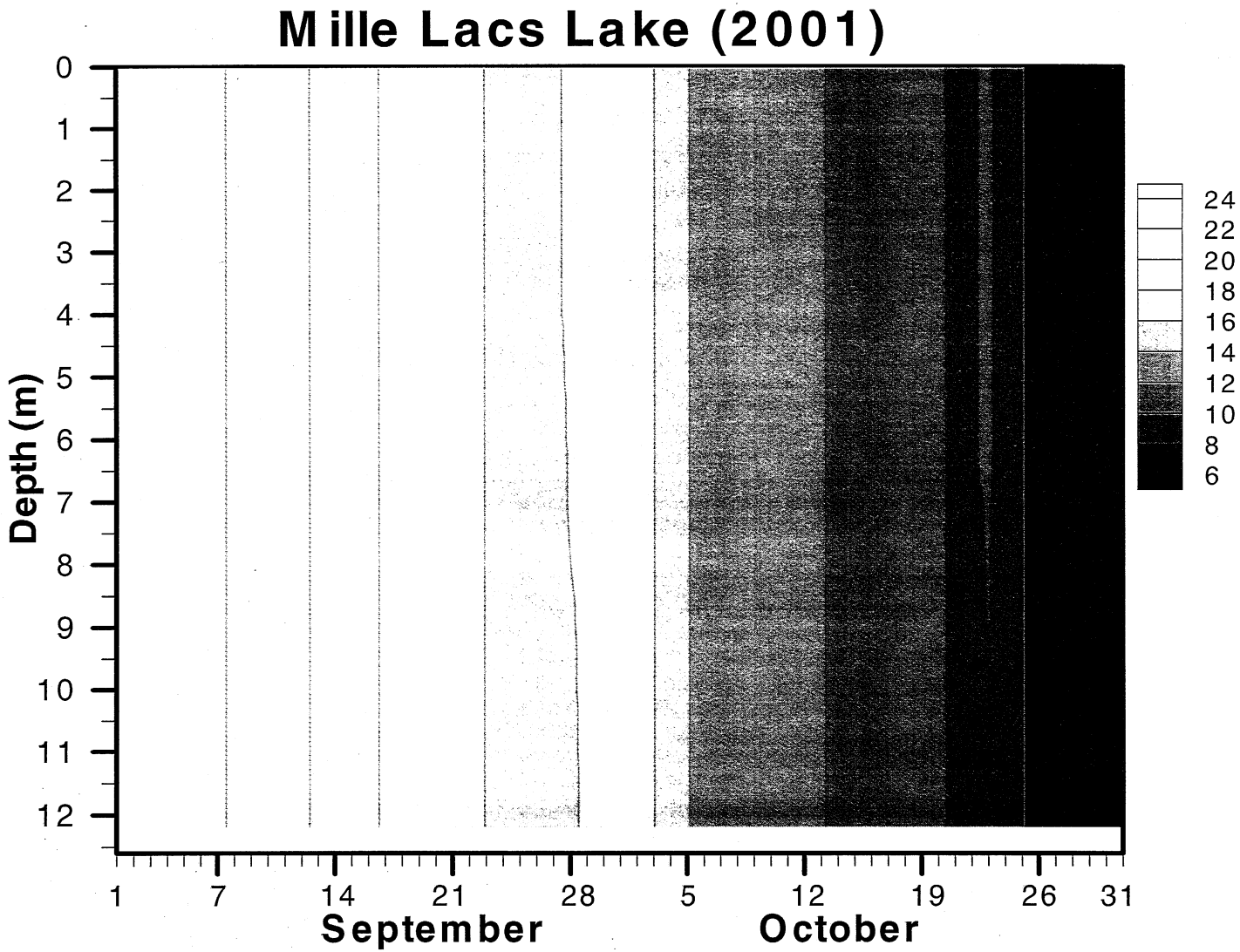


Figure 4.10 Simulation Results with Brainerd Weather Data for Sept. and Oct. 2001

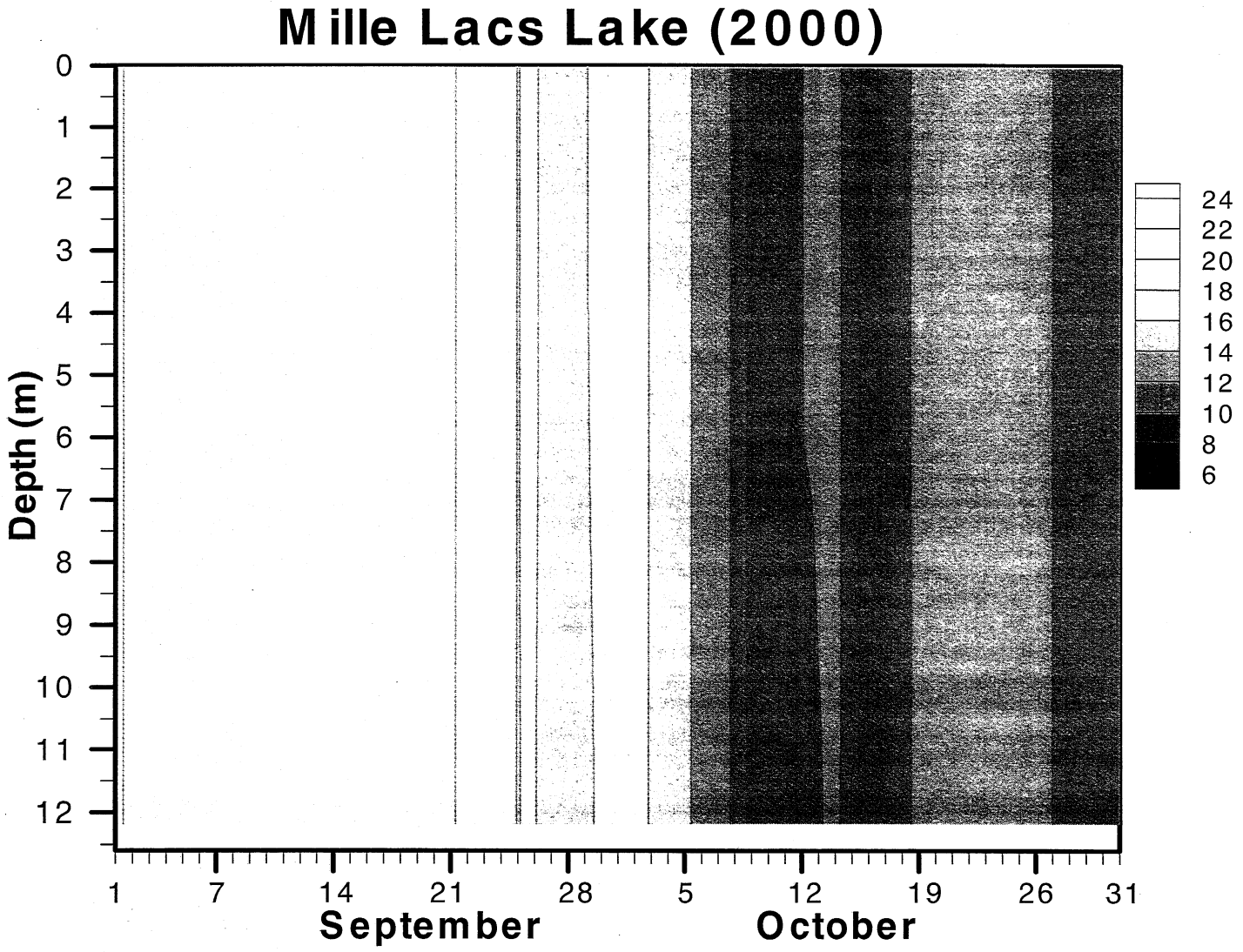


Figure 4.11 Simulation Results with Brainerd Weather Data for Sept. and Oct. 2000

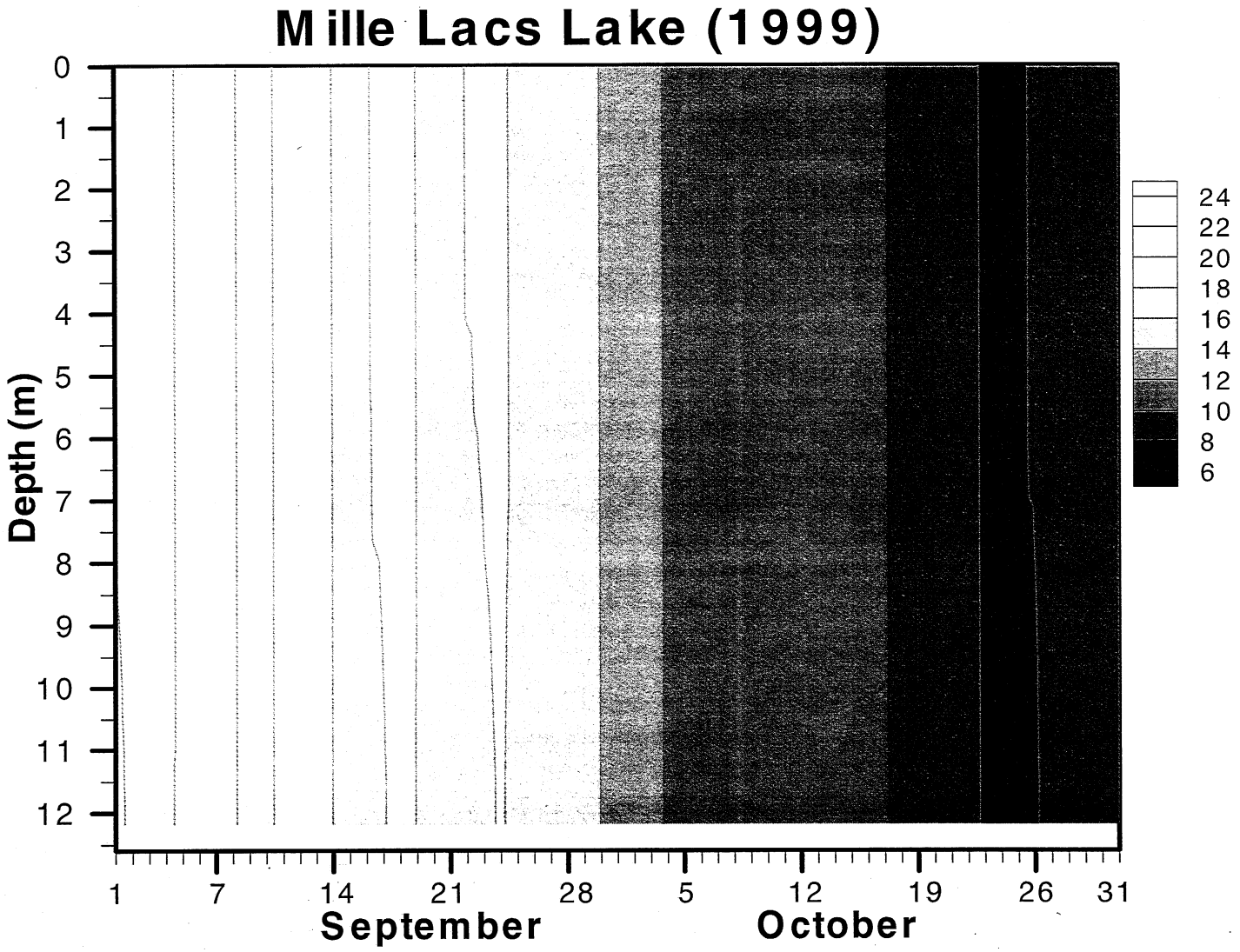


Figure 4.12 Simulation Results with Brainerd Weather Data for Sept. and Oct.1999

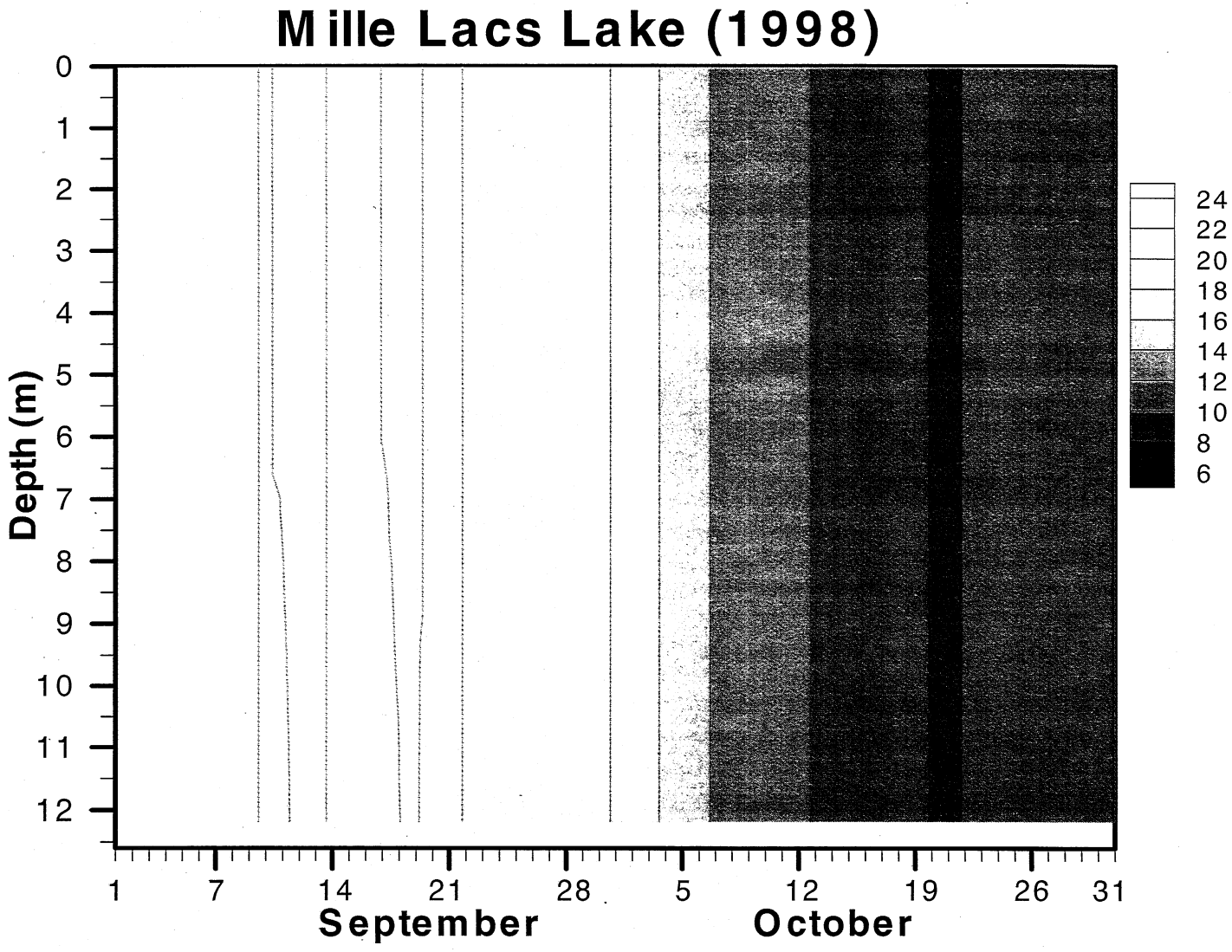


Figure 4.13 Simulation Results with Brainerd Weather Data for Sept. and Oct. 1998

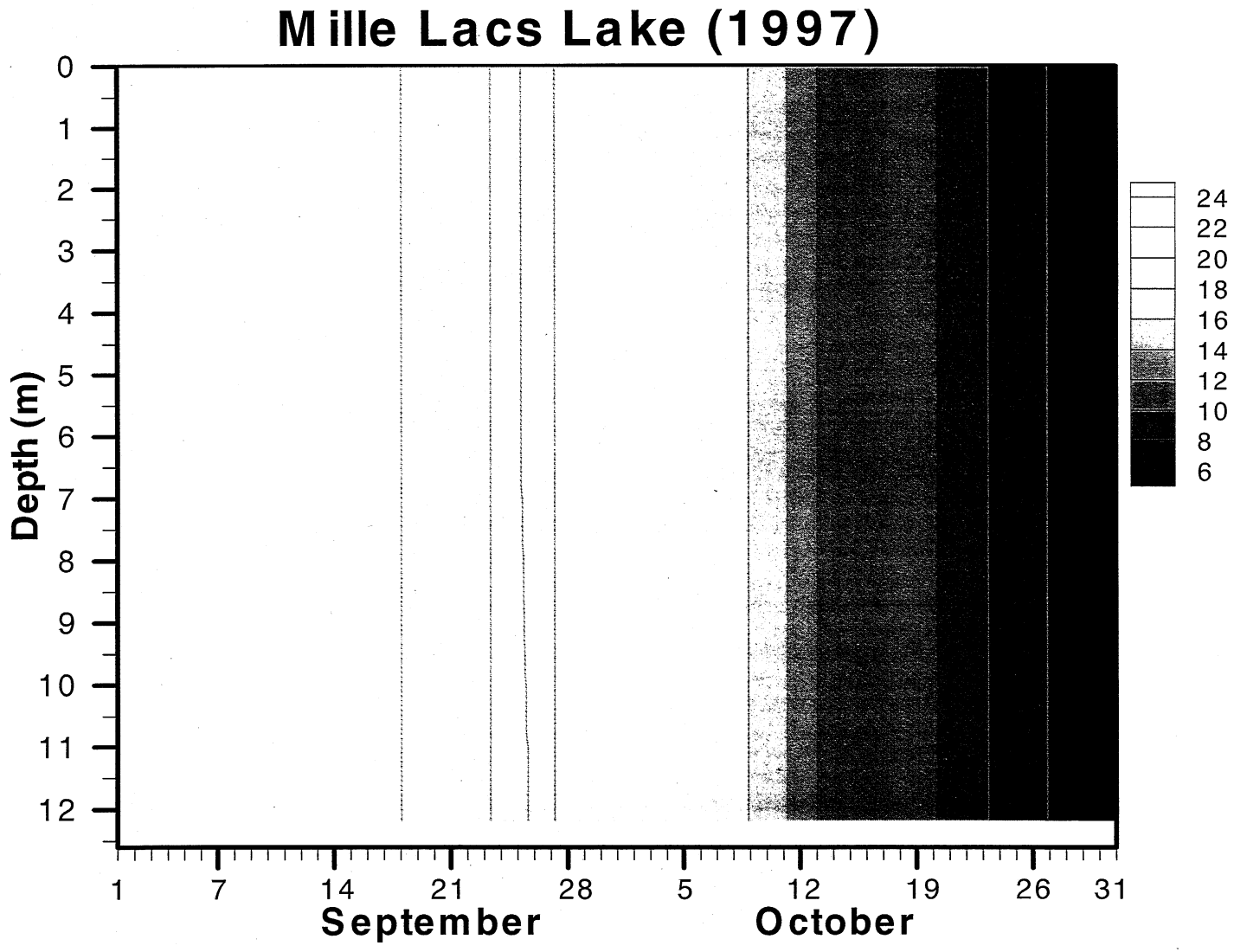


Figure 4.14 Simulation Results with Brainerd Weather Data for Sept. and Oct. 1997

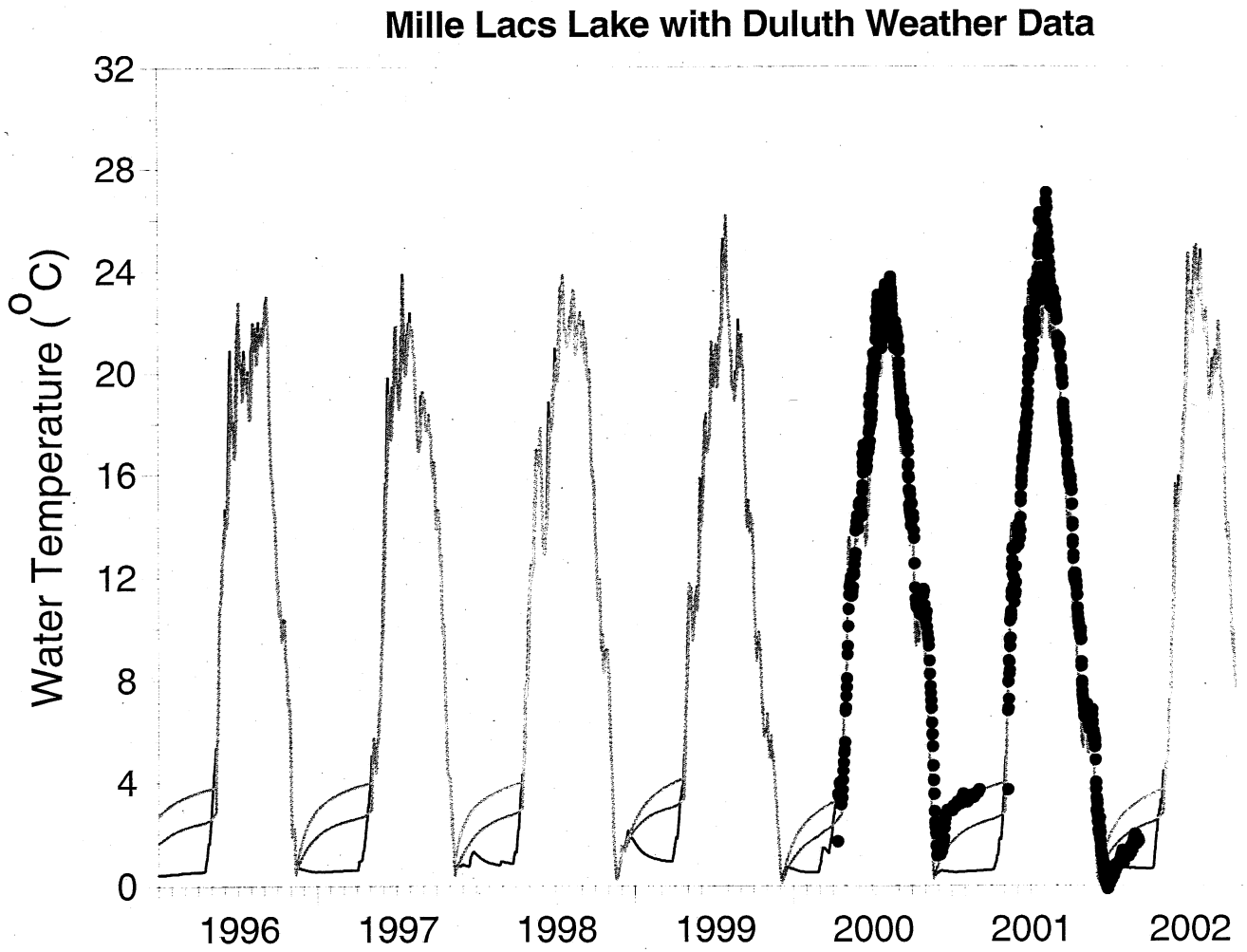


Figure 4.1 Simulation Results with Brainerd Weather Data for 2002

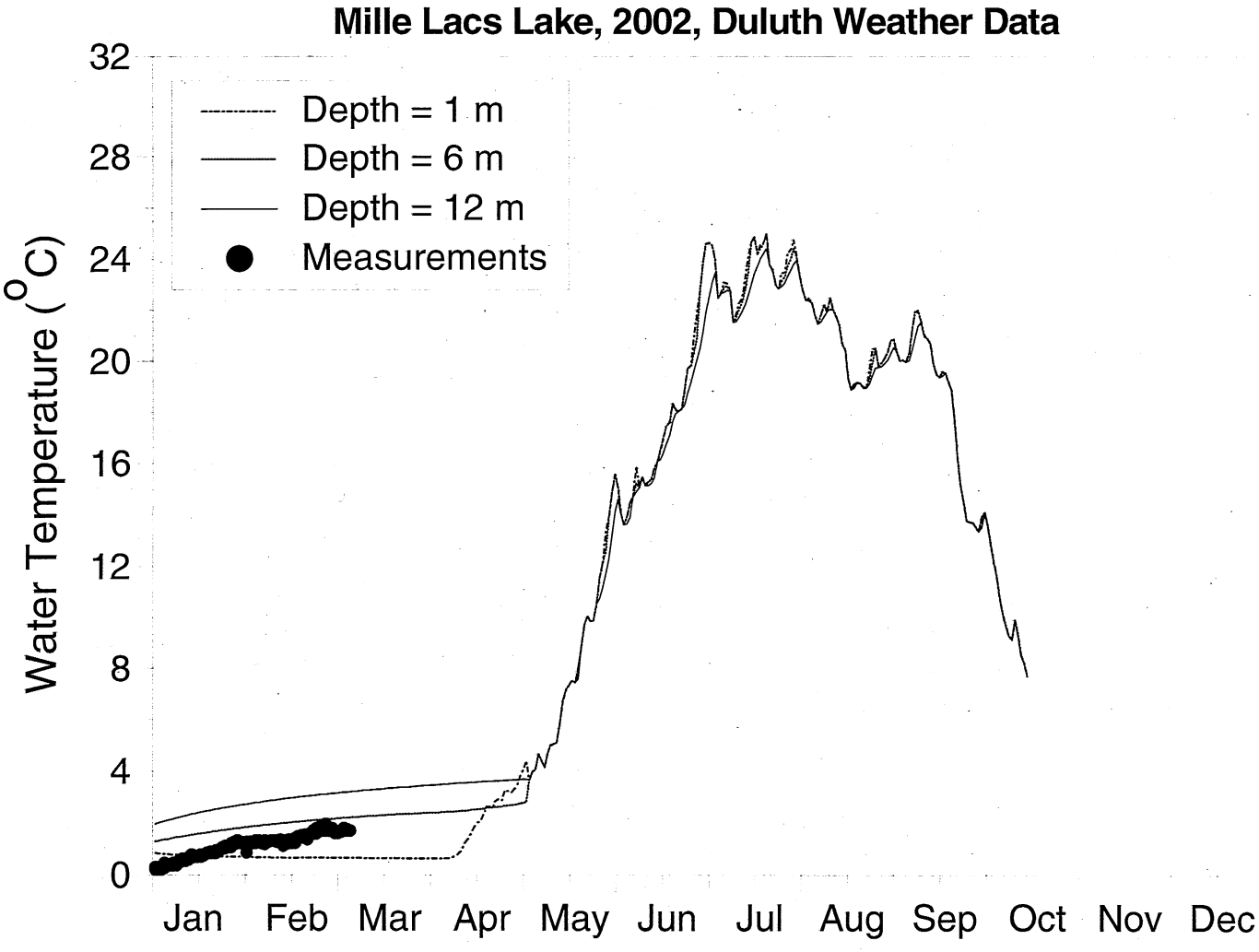


Figure 4.16 Simulation Results with Duluth Weather Data for 2002

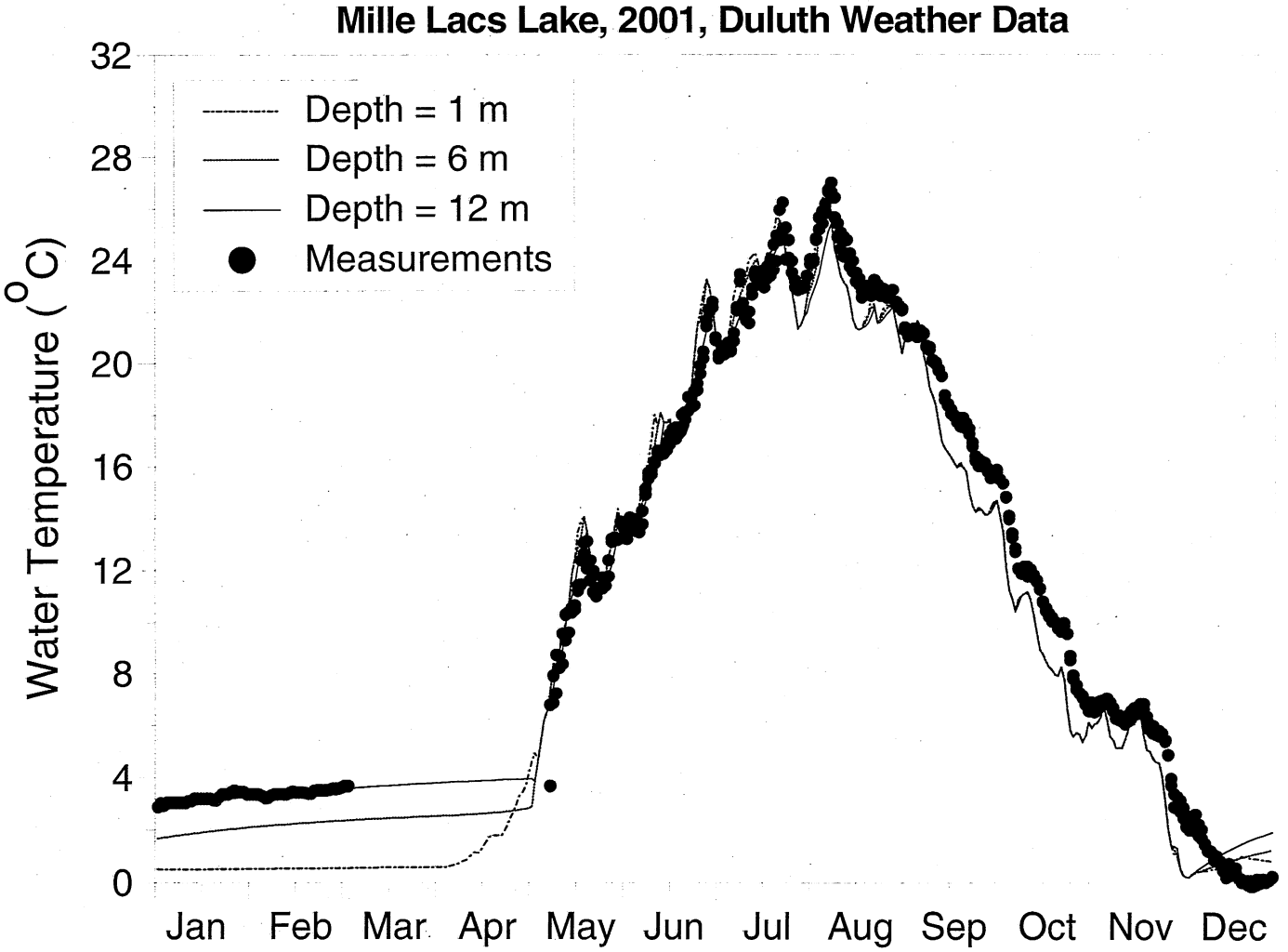


Figure 4.17 Simulation Results with Duluth Weather Data for 2001

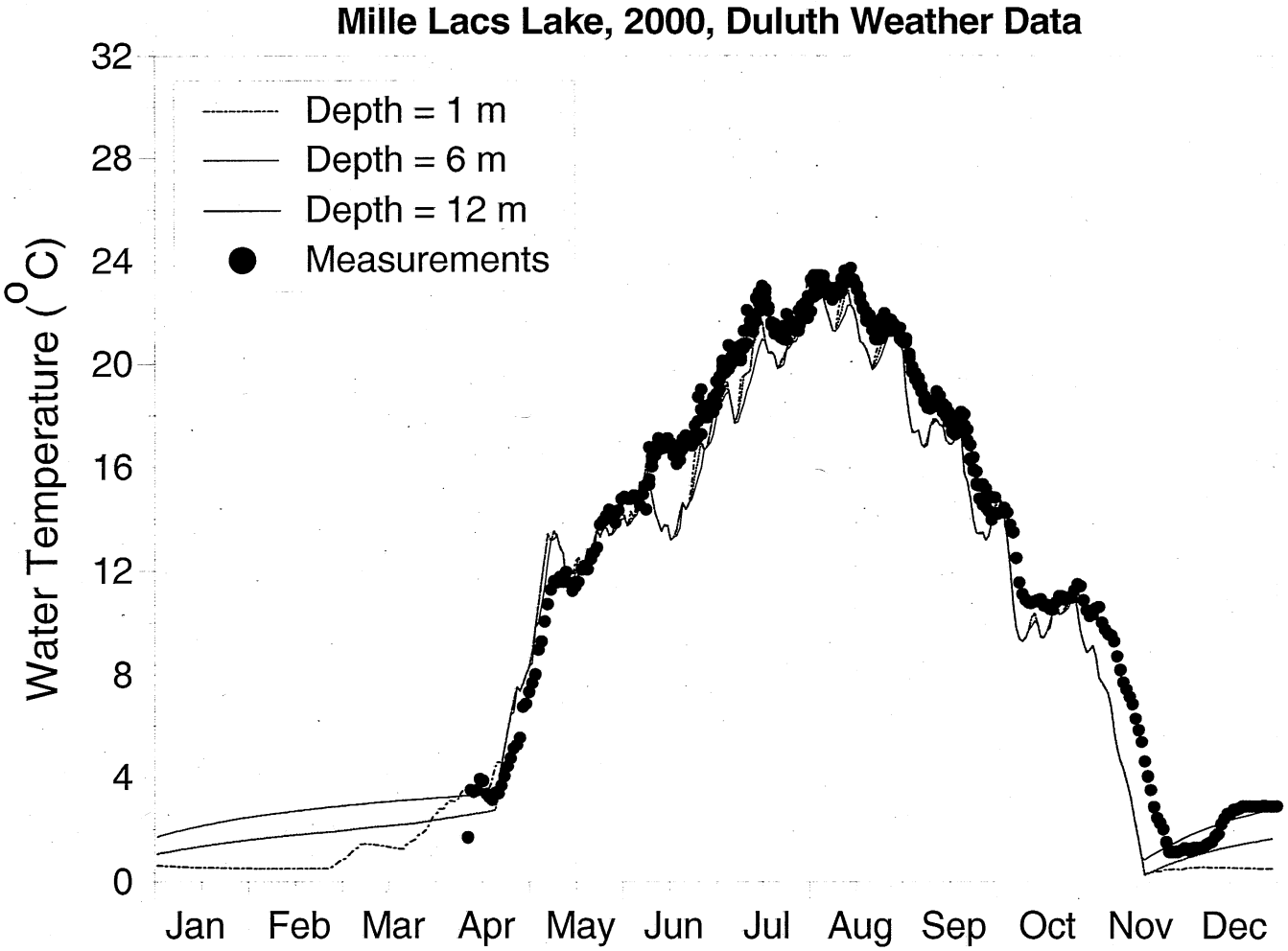


Figure 4.18 Simulation Results with Duluth Weather Data for 2000

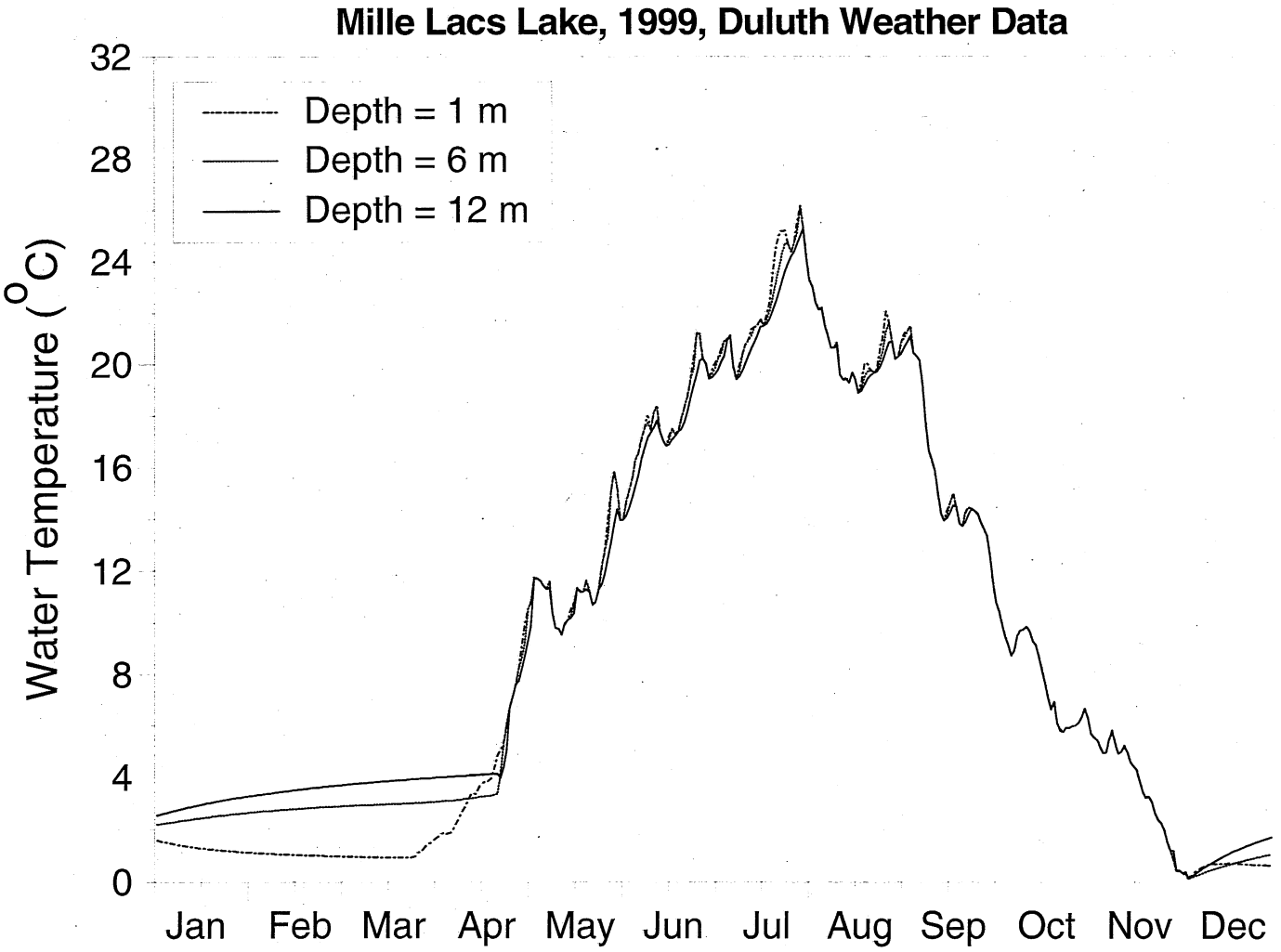


Figure 4.19 Simulation Results with Duluth Weather Data for 1999

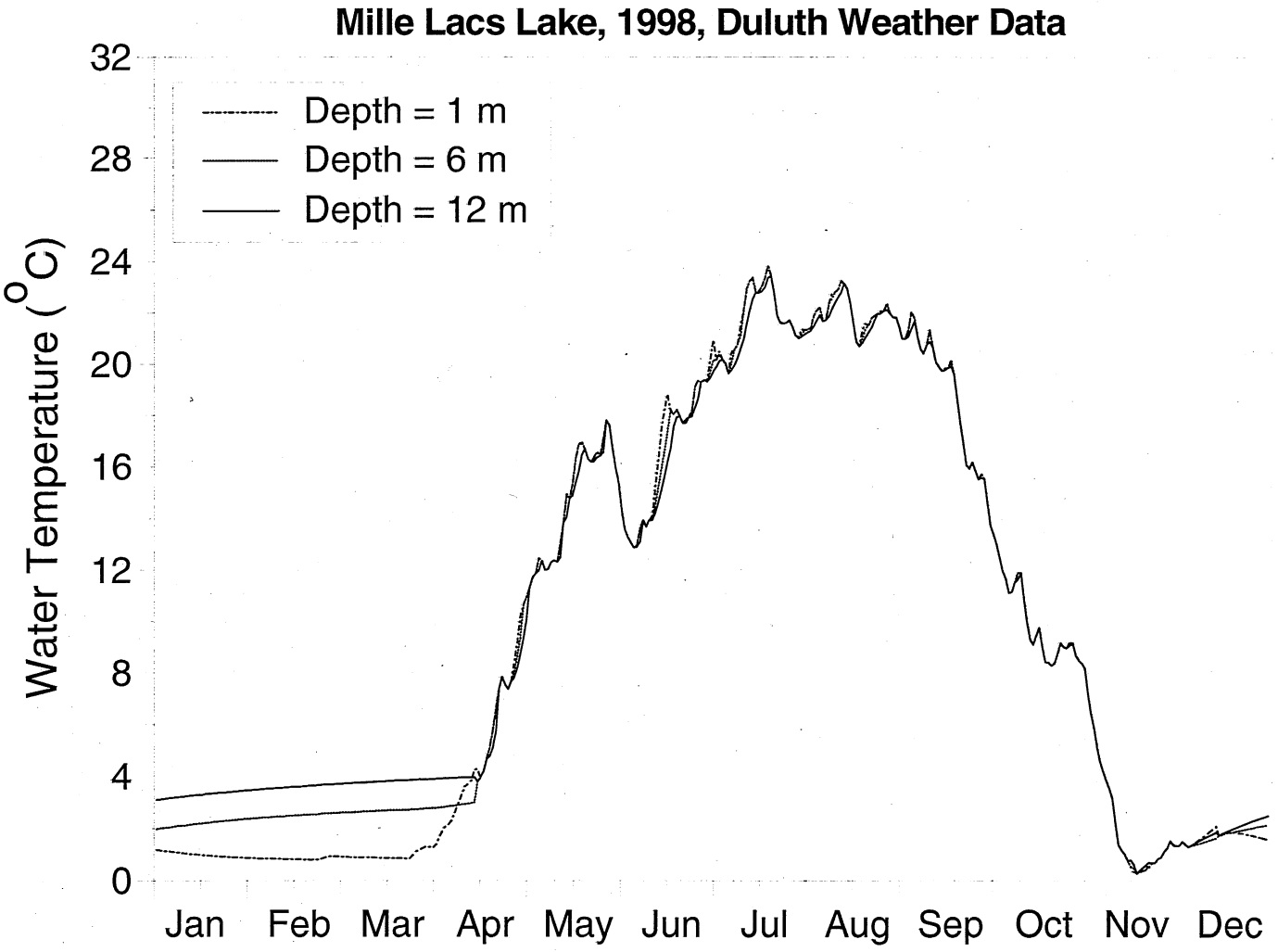


Figure 4.20 Simulation Results with Duluth Weather Data for 1998

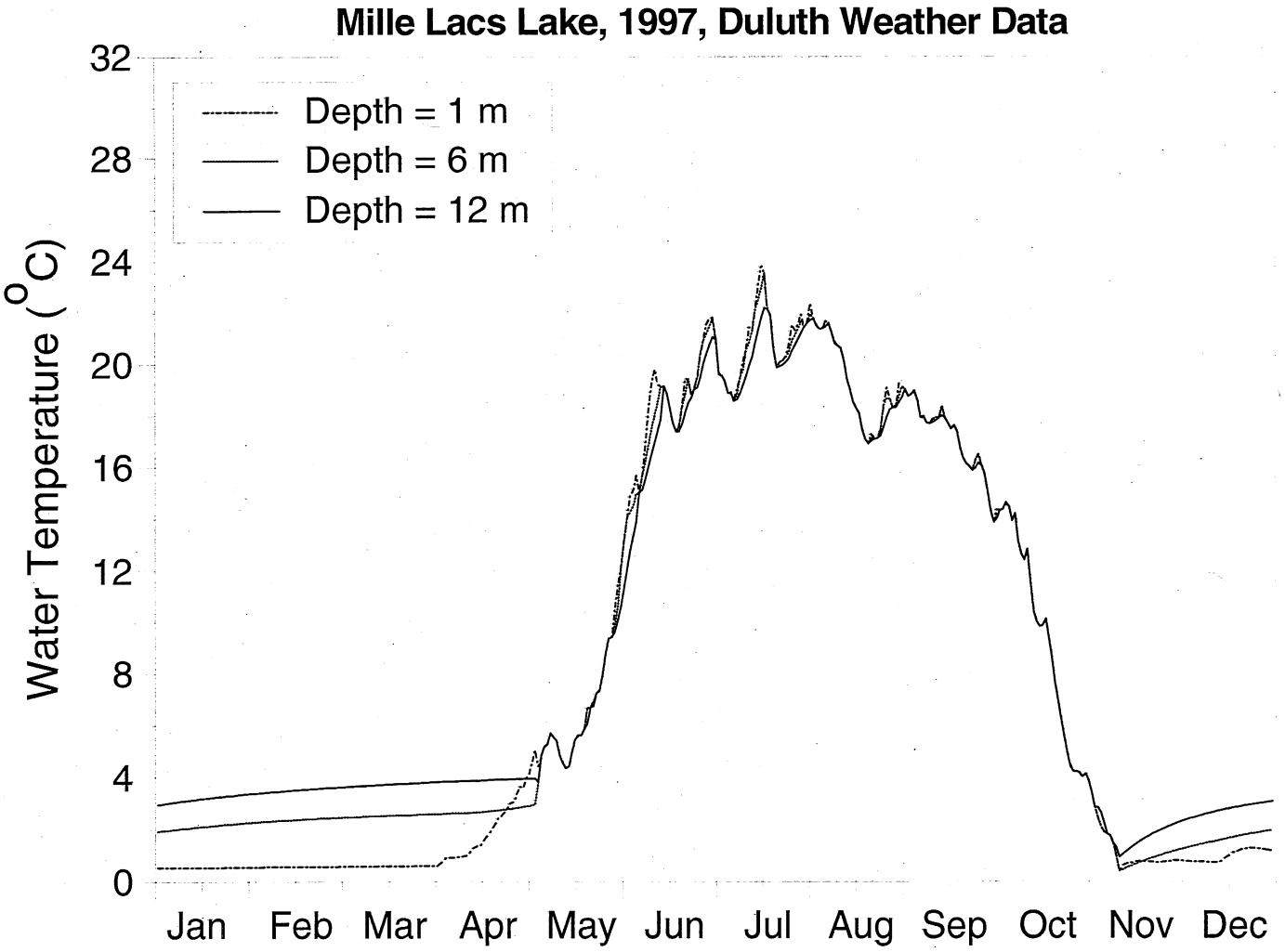


Figure 4.21 Simulation Results with Duluth Weather Data for 1997

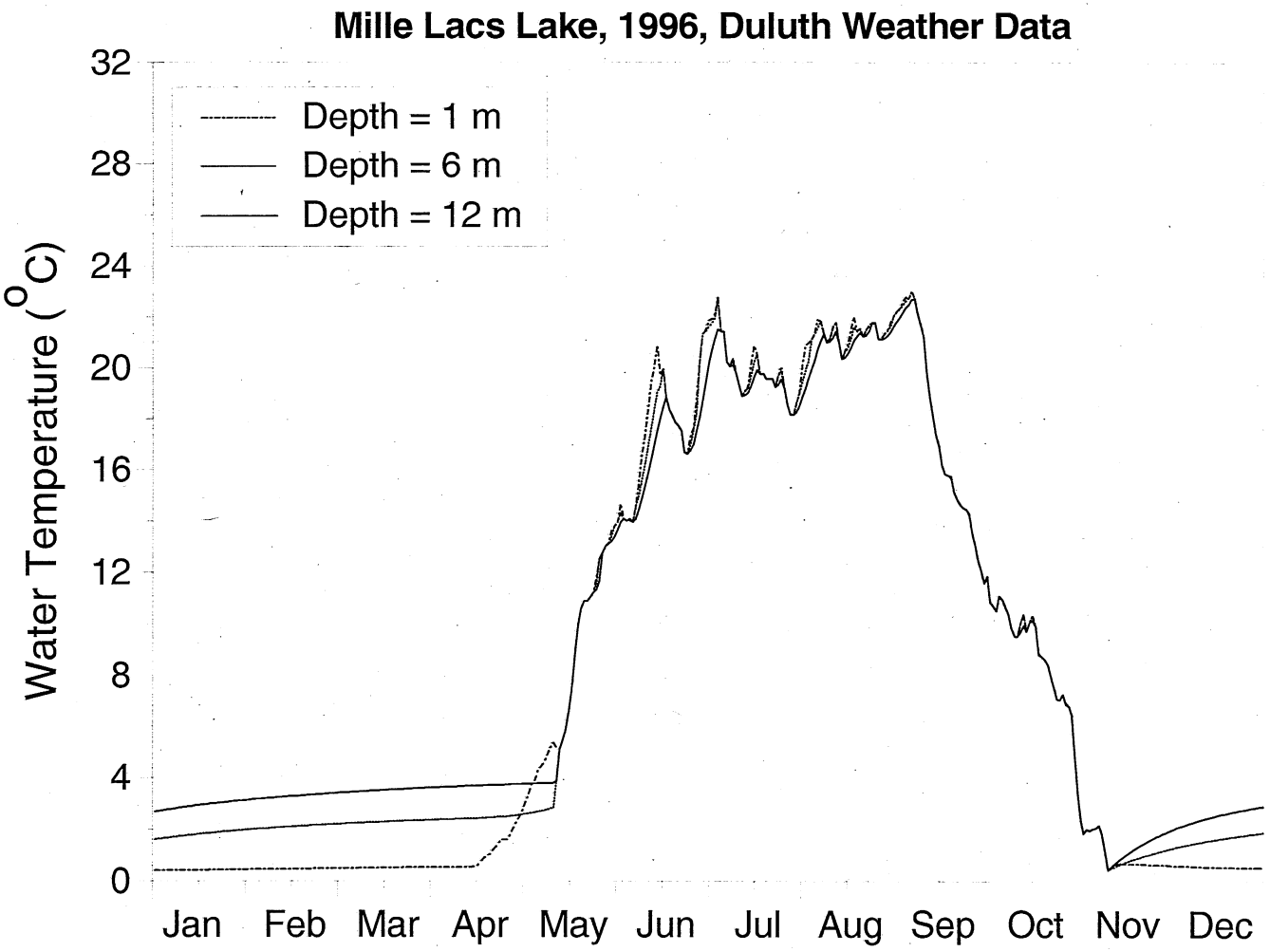


Figure 4.22 Simulation Results with Duluth Weather Data for 1996

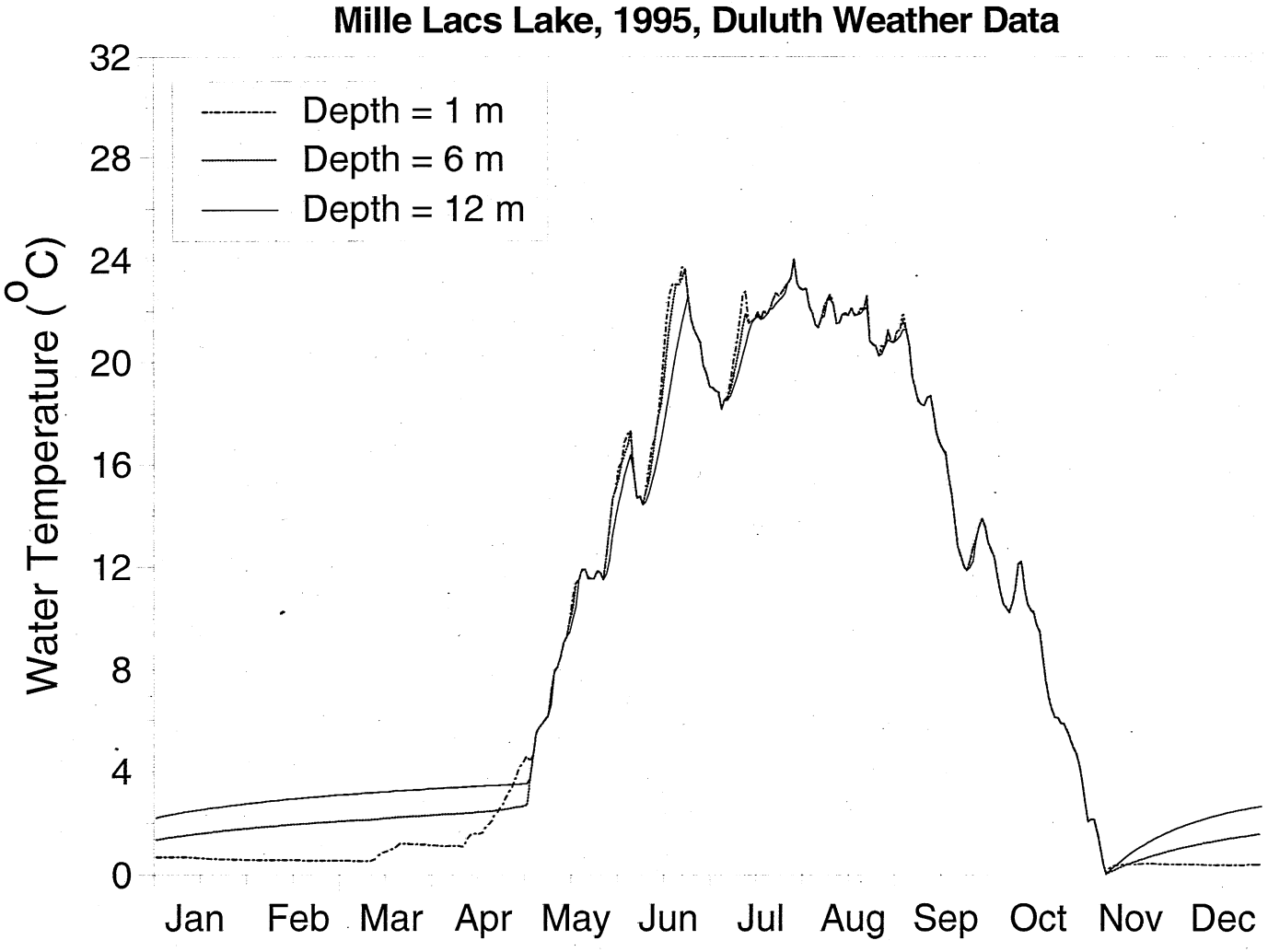


Figure 4.23 Simulation Results with Duluth Weather Data for 1995

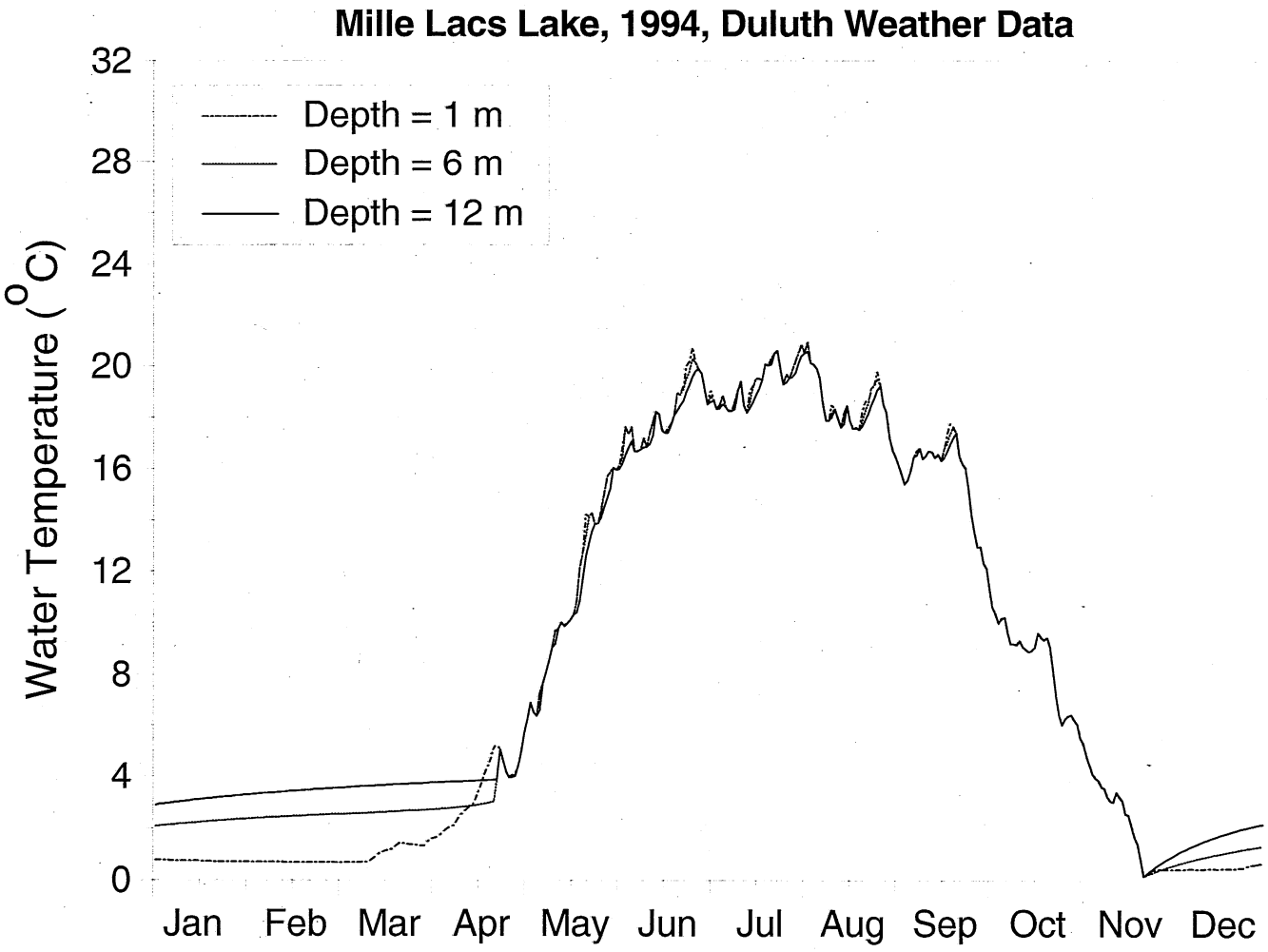


Figure 4.24 Simulation Results with Duluth Weather Data for 1994

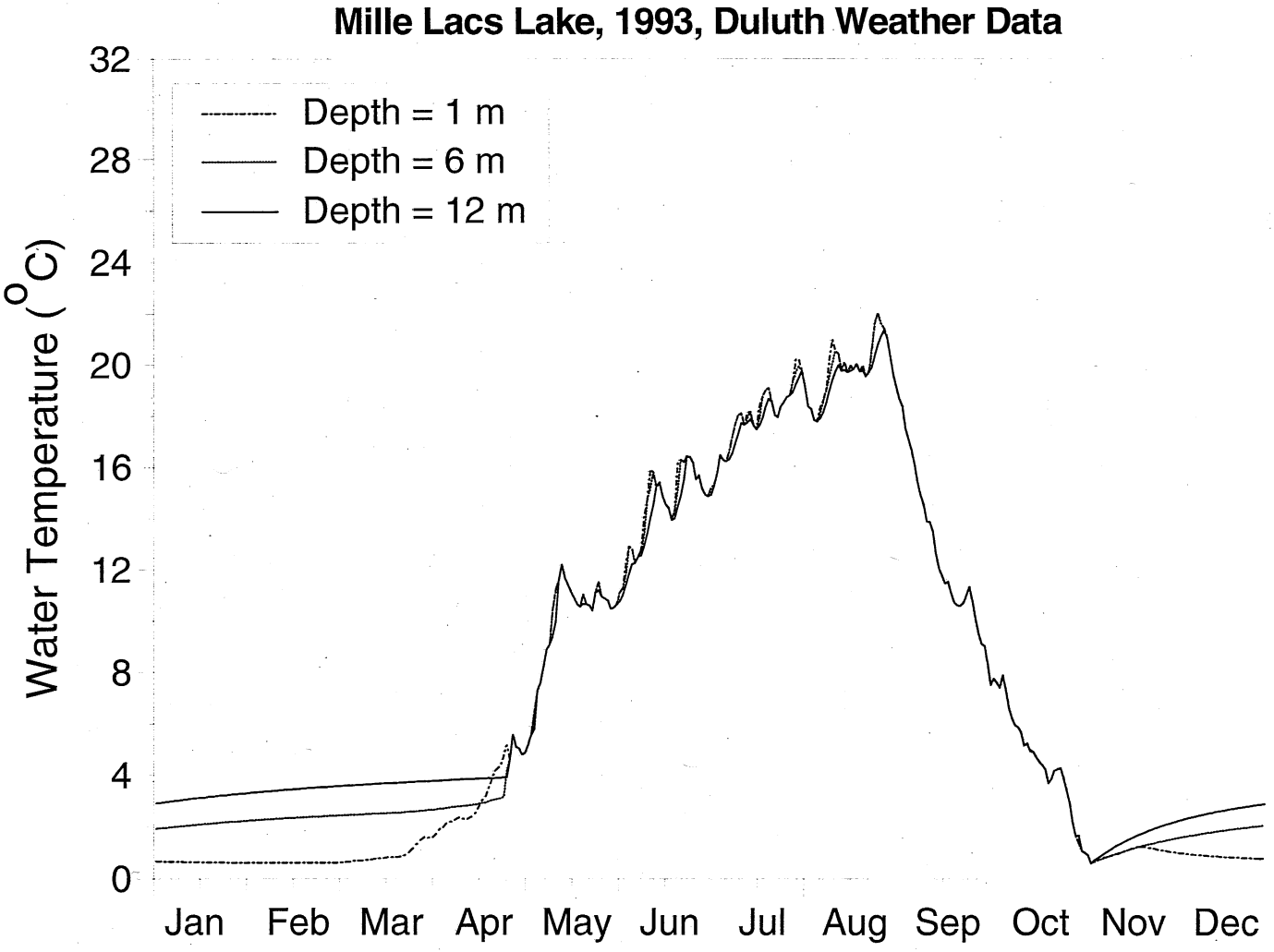


Figure 4.25 Simulation Results with Duluth Weather Data for 1993

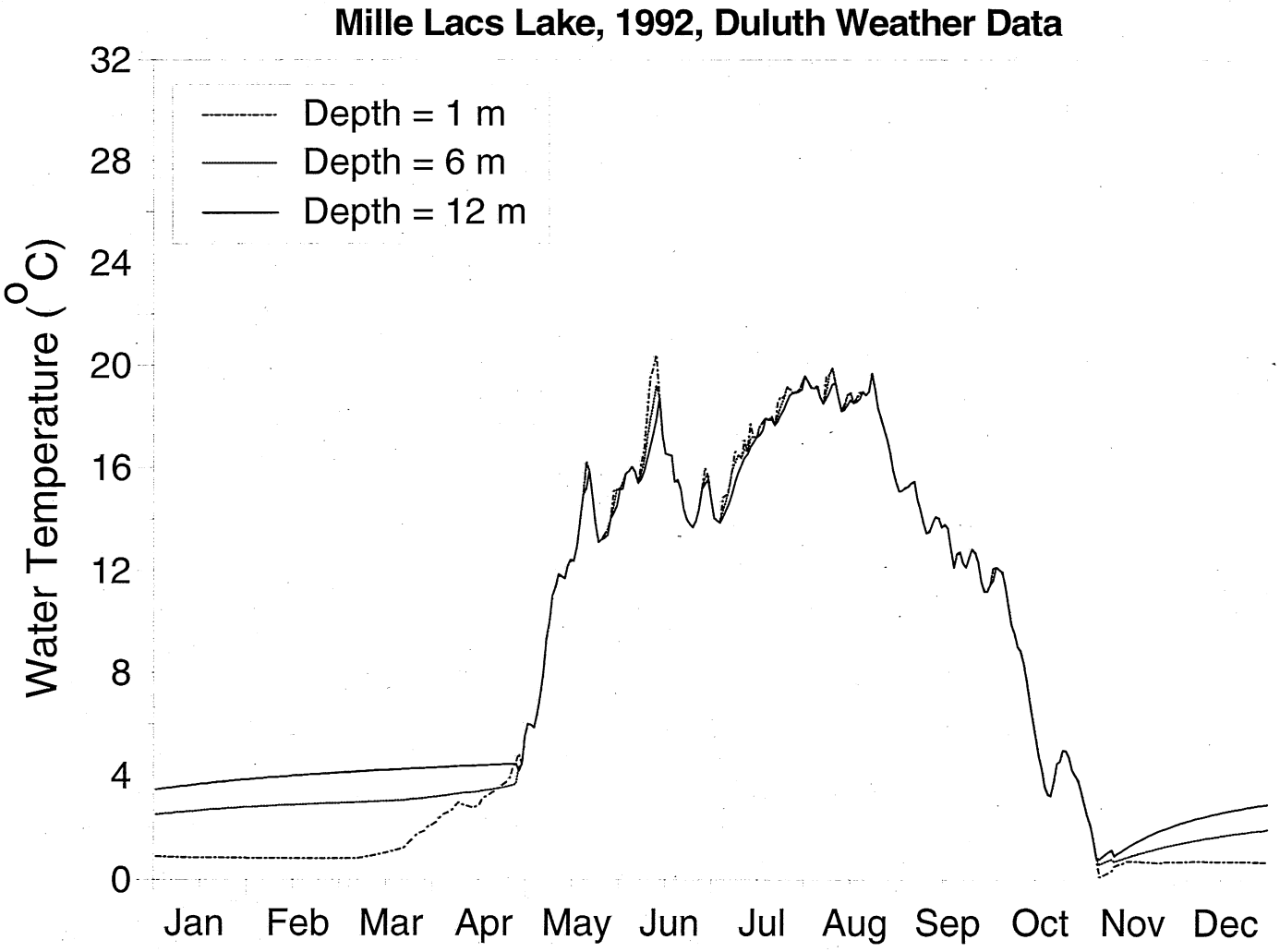


Figure 4.26 Simulation Results with Duluth Weather Data for 1992

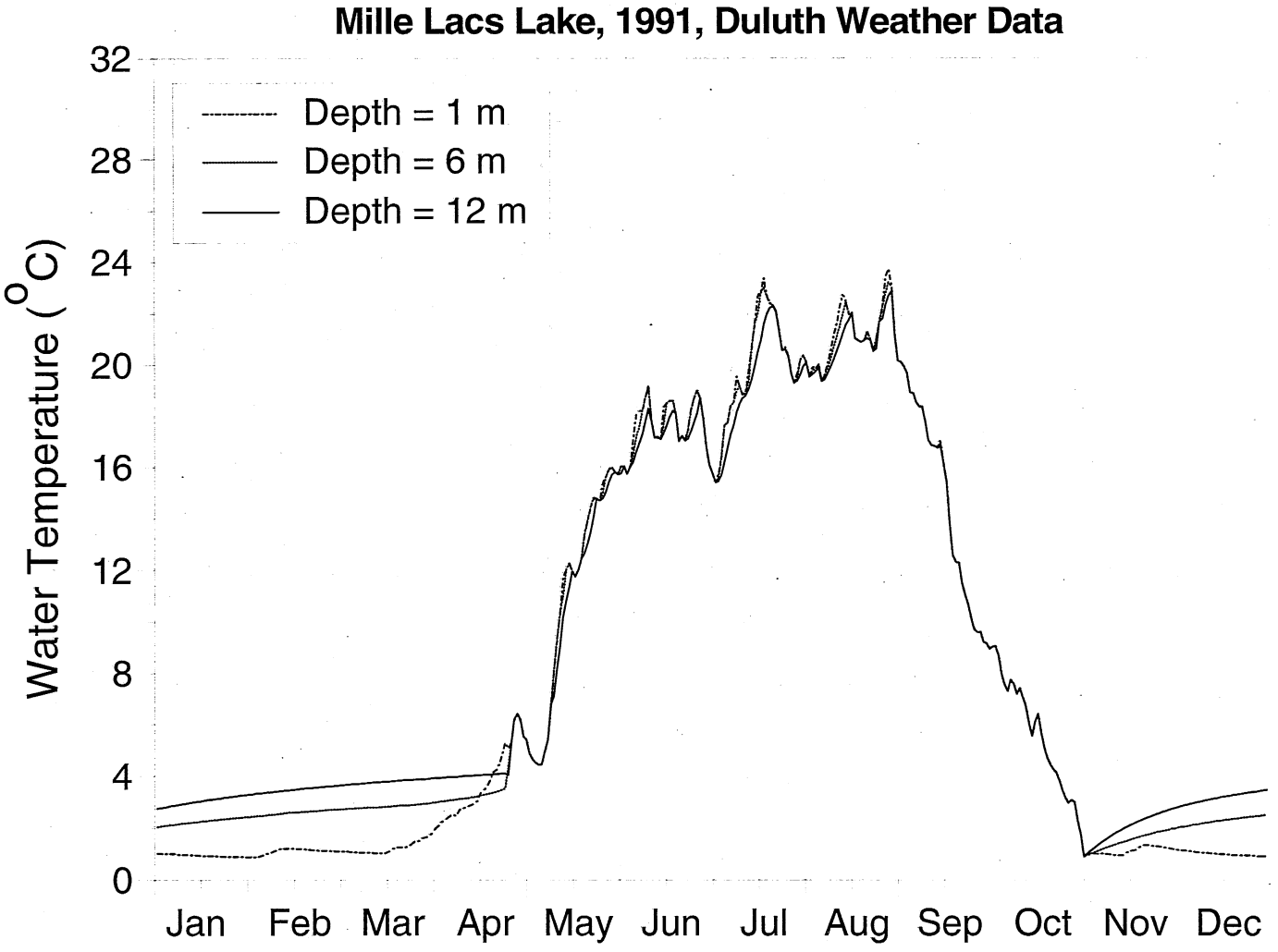


Figure 4.27 Simulation Results with Duluth Weather Data for 1991

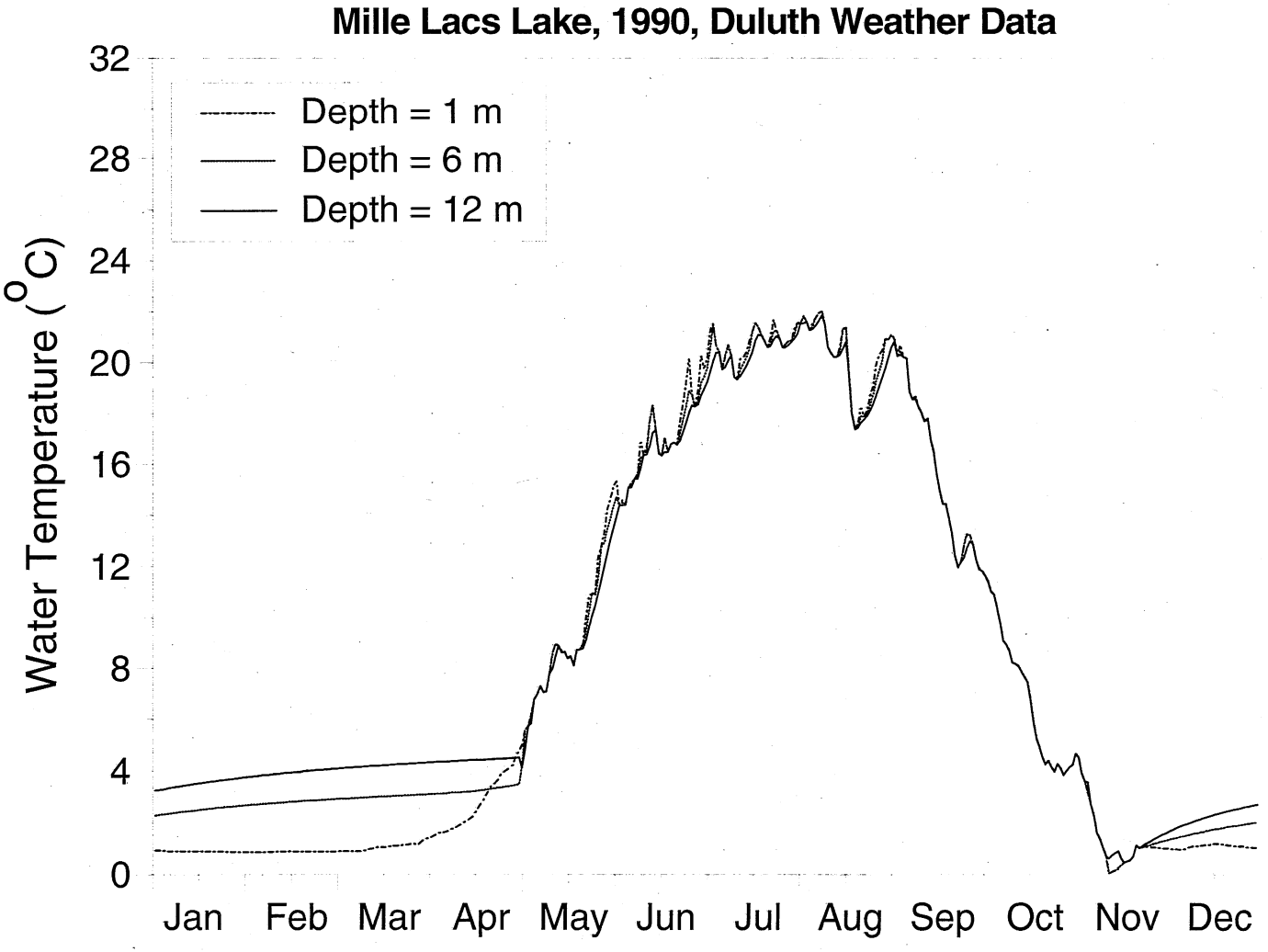


Figure 4.28 Simulation Results with Duluth Weather Data for 1990

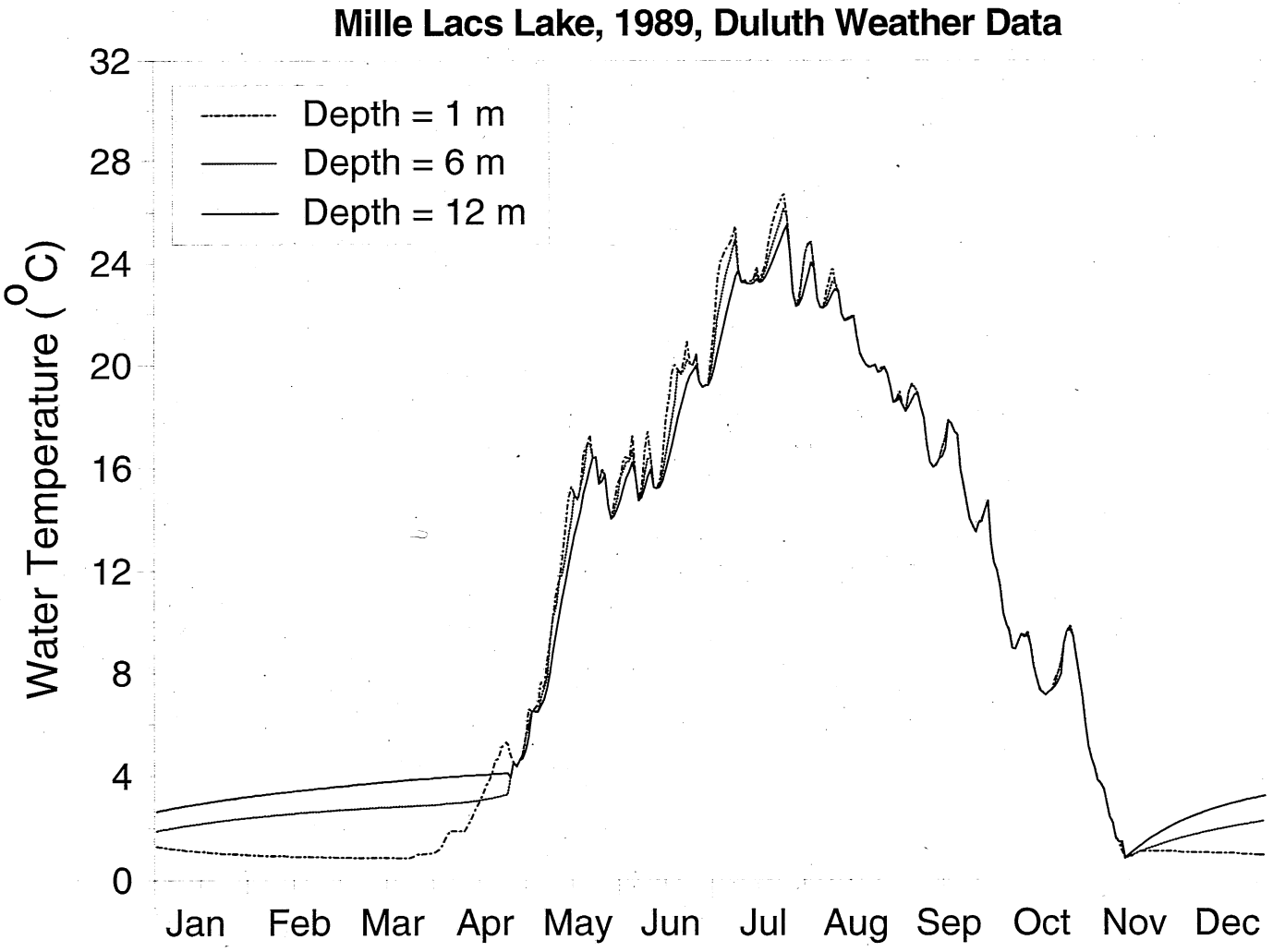


Figure 4.29 Simulation Results with Duluth Weather Data for 1989

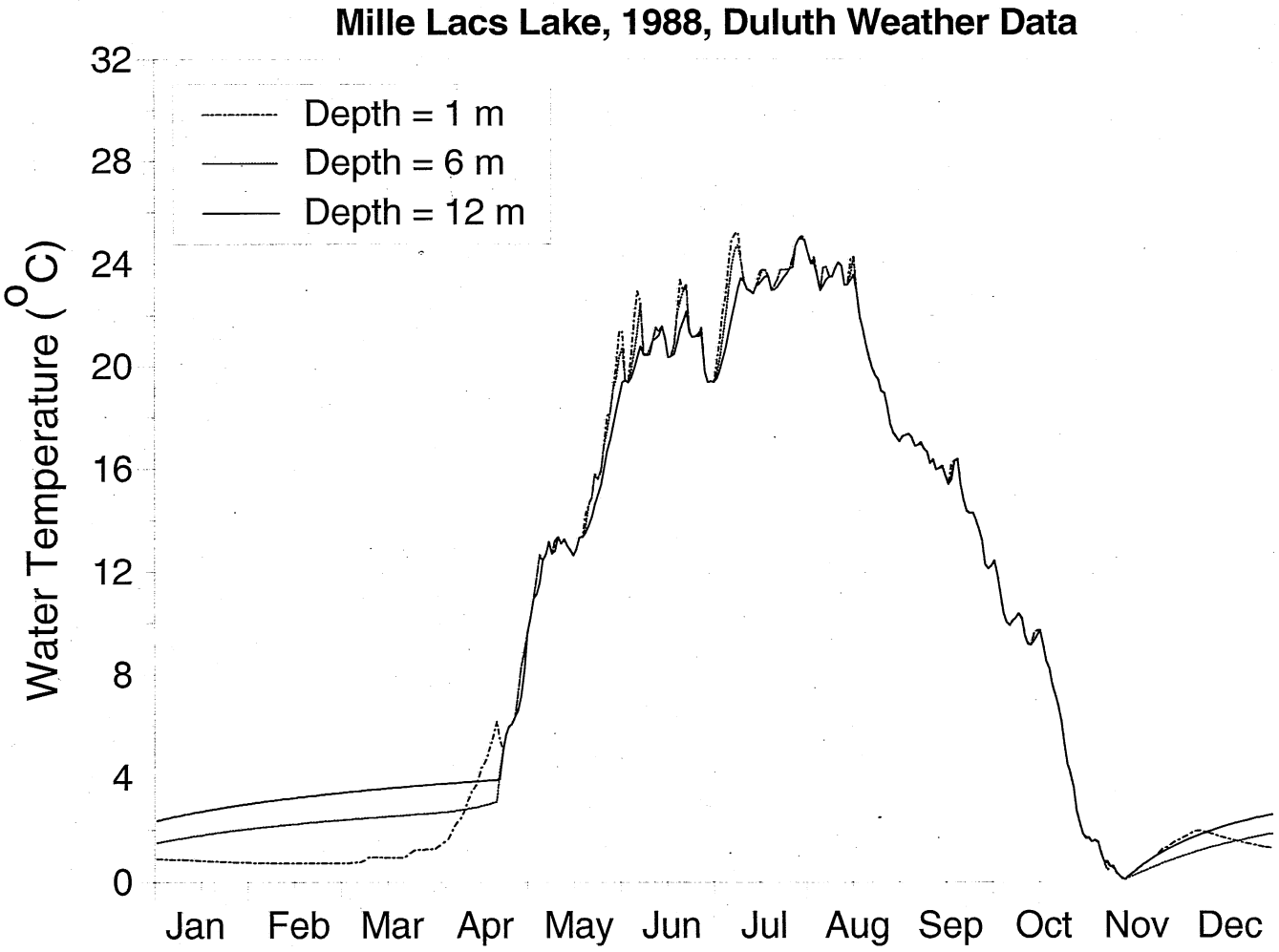


Figure 4.30 Simulation Results with Duluth Weather Data for 1988

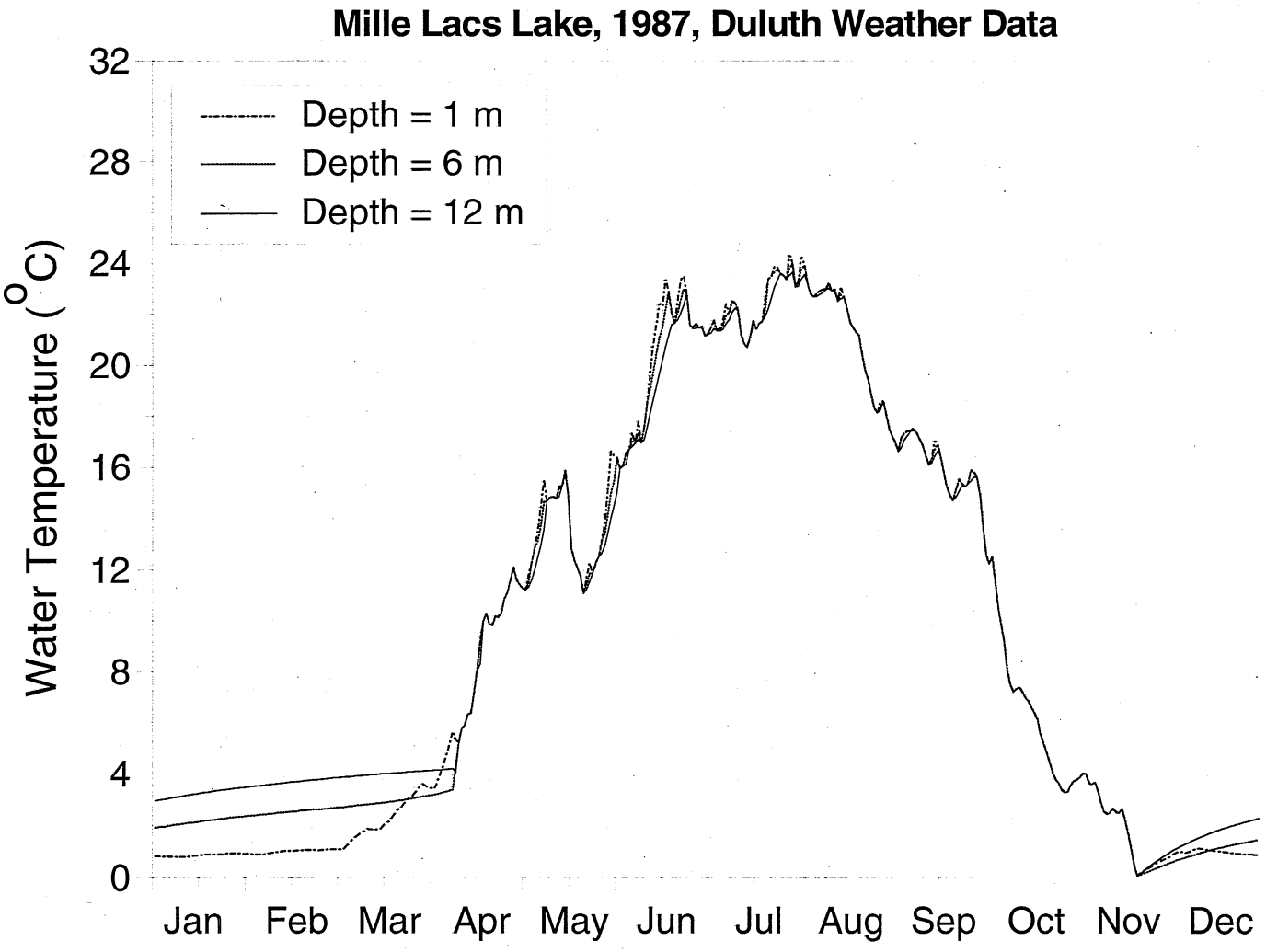


Figure 4.31 Simulation Results with Duluth Weather Data for 1987

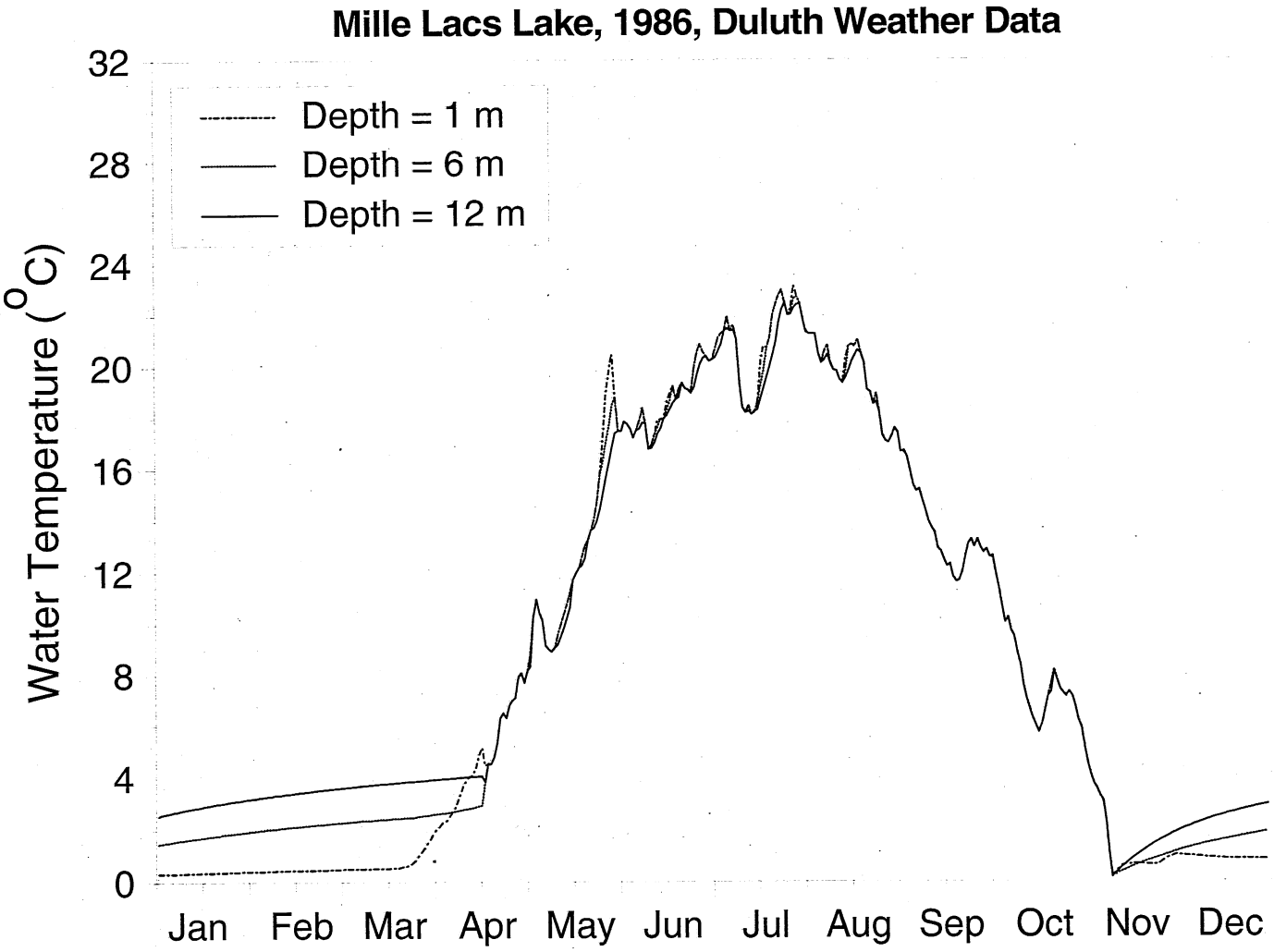


Figure 4.32 Simulation Results with Duluth Weather Data for 1986

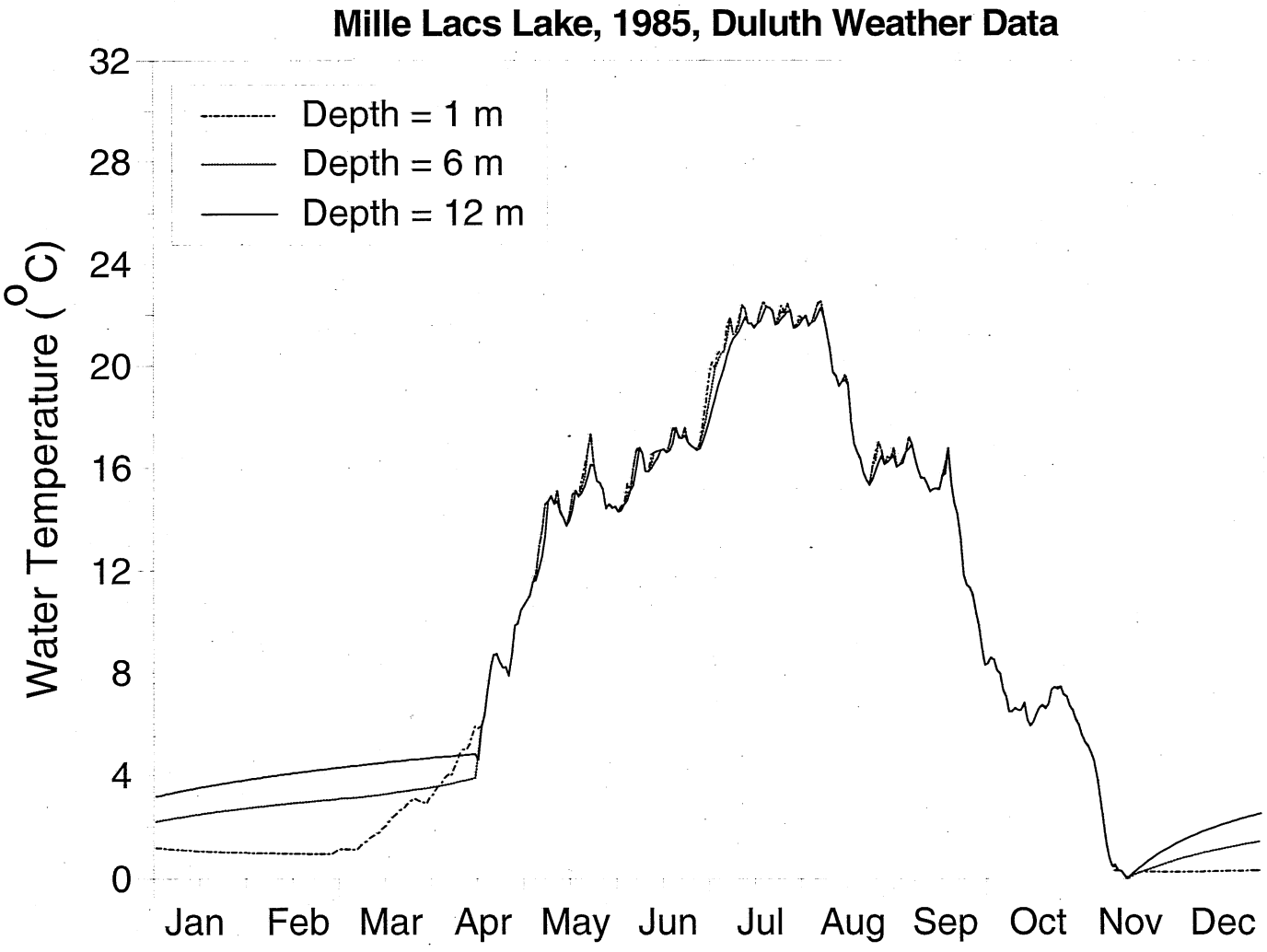


Figure 4.33 Simulation Results with Duluth Weather Data for 1985

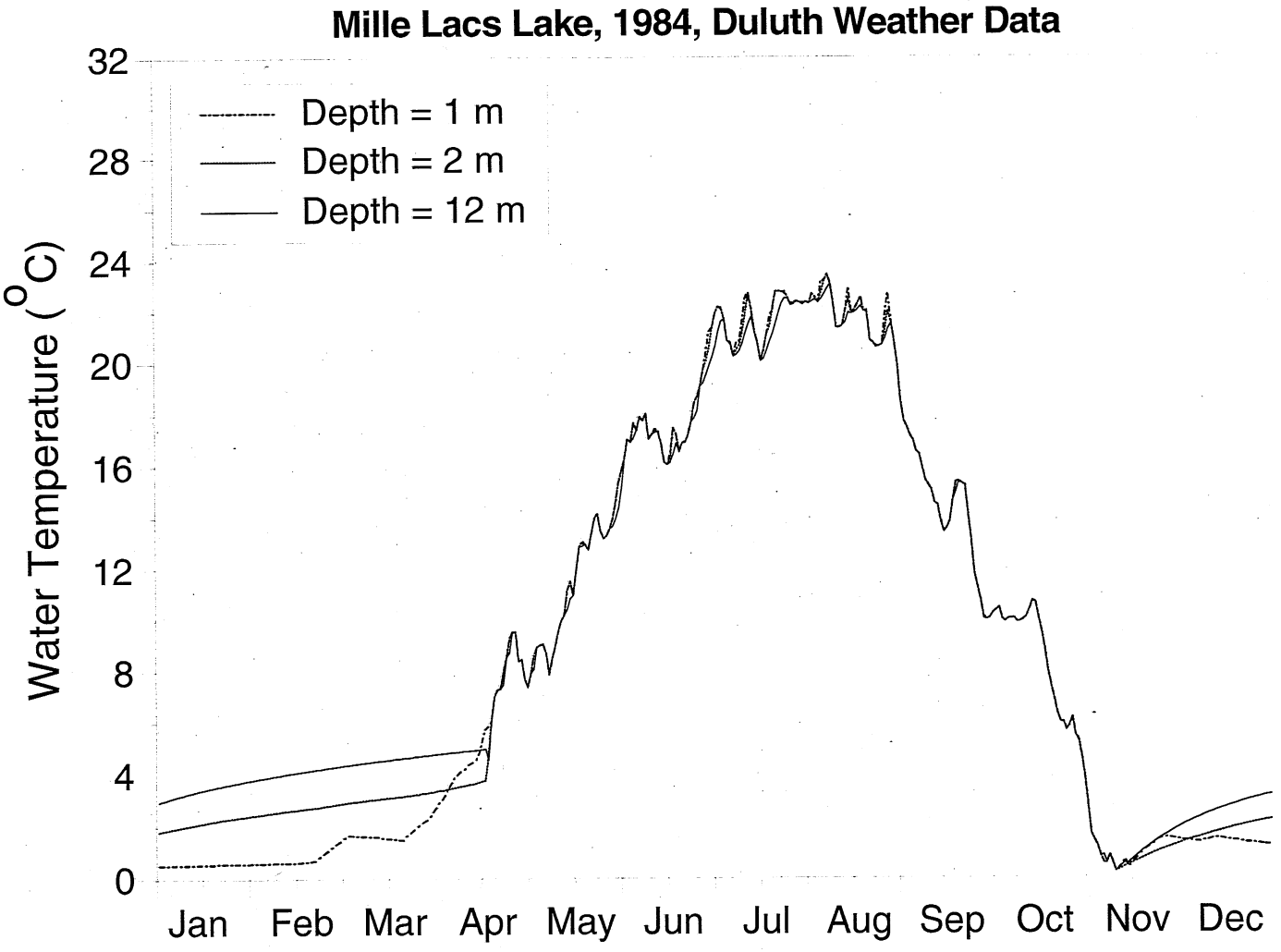


Figure 4.34 Simulation Results with DUluth Weather Data for 1984

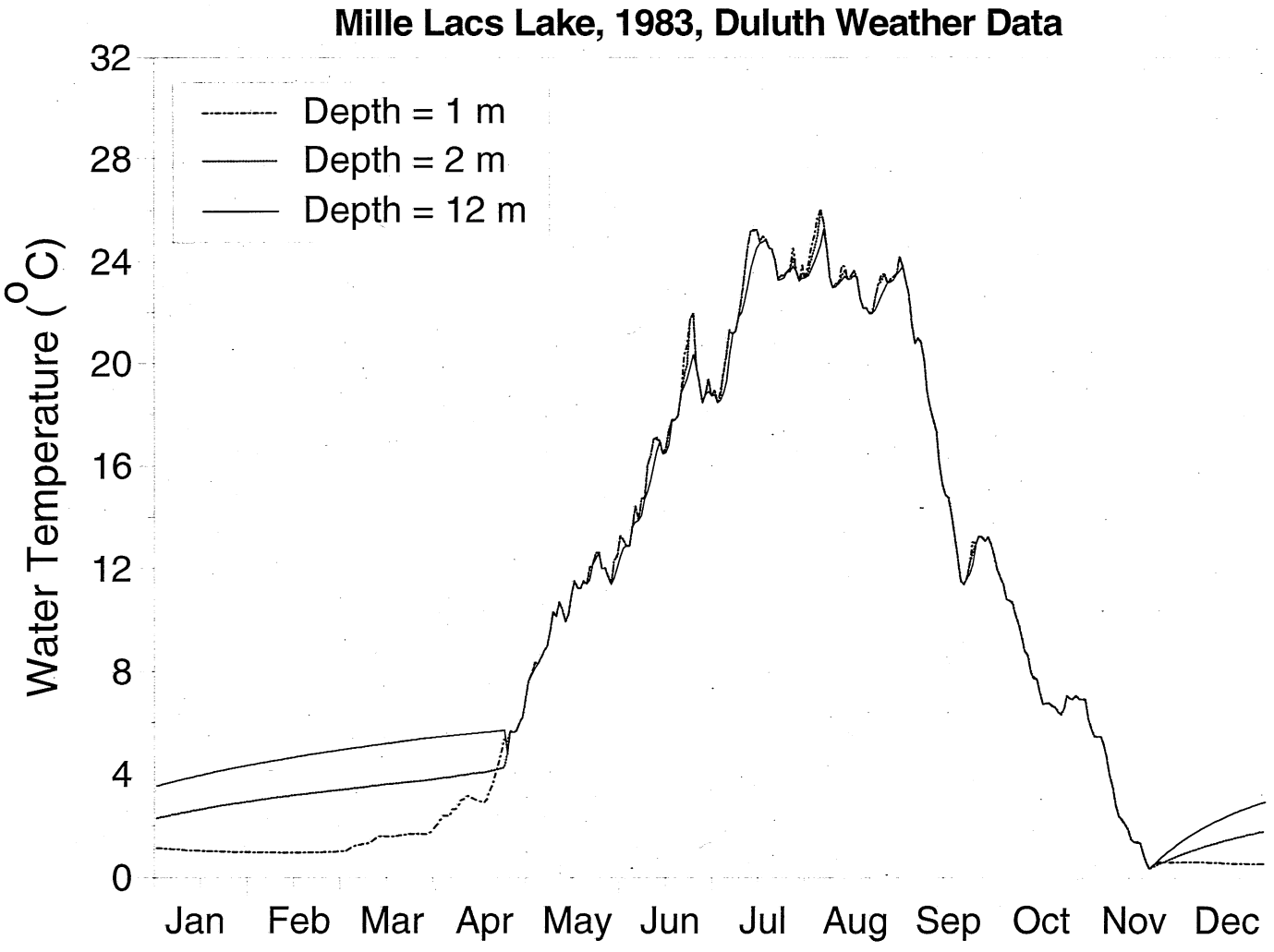


Figure 4.35 Simulation Results with Duluth Weather Data for 1983

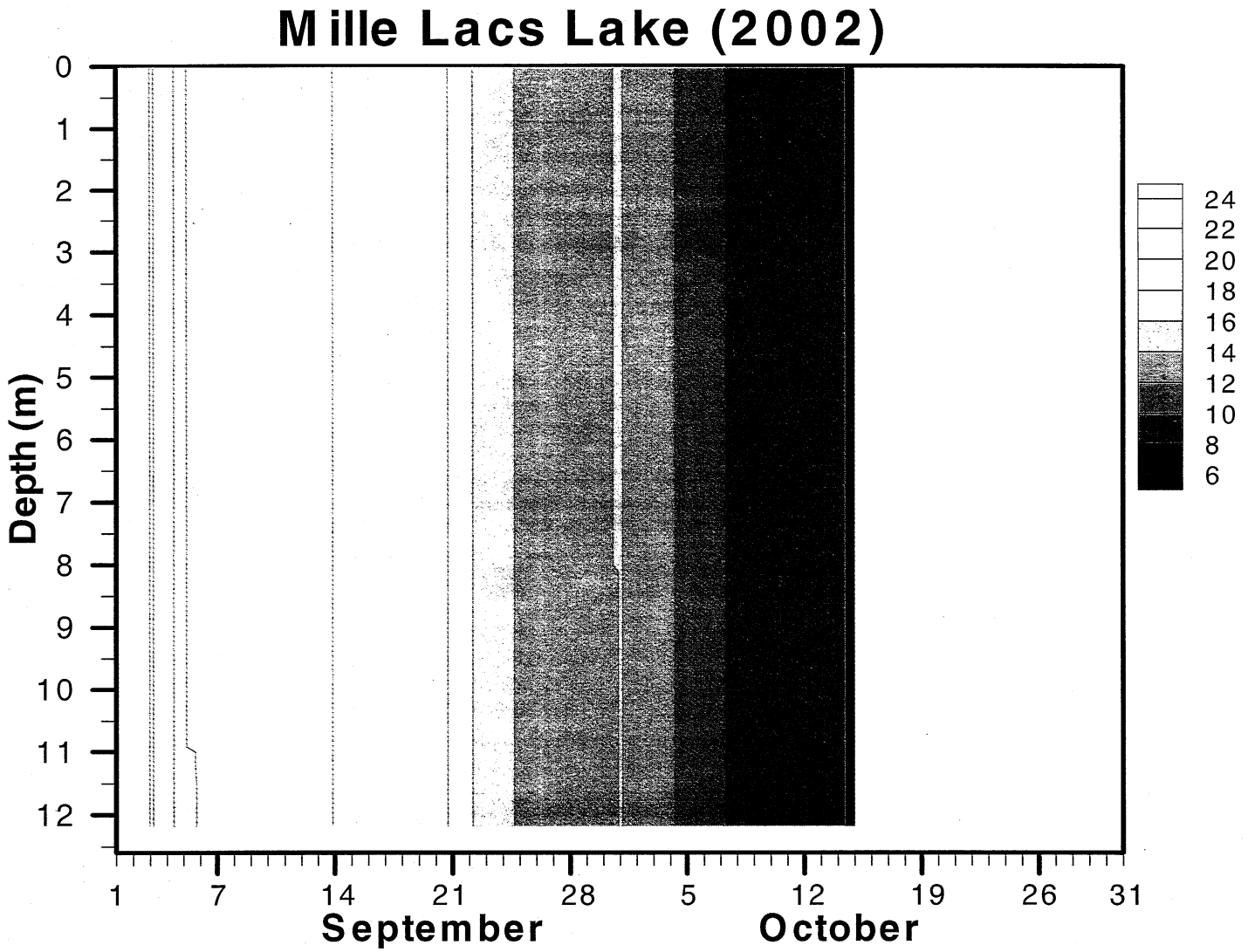


Figure 4.36 Simulation Results with Duluth Weather Data for Sept. and Oct. 2002

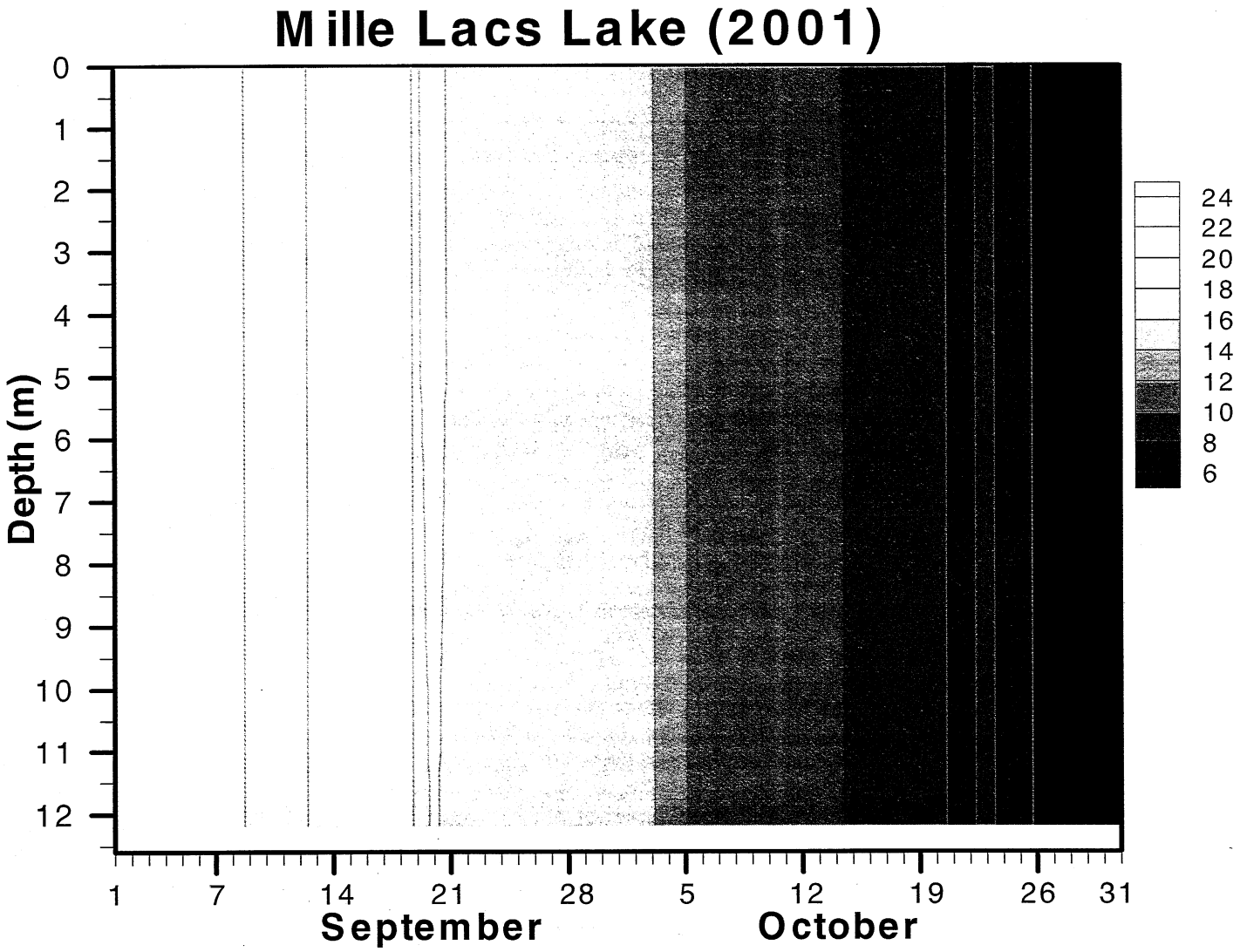


Figure 4.37 Simulation Results with Duluth Weather Data for Sept. and Oct. 2001

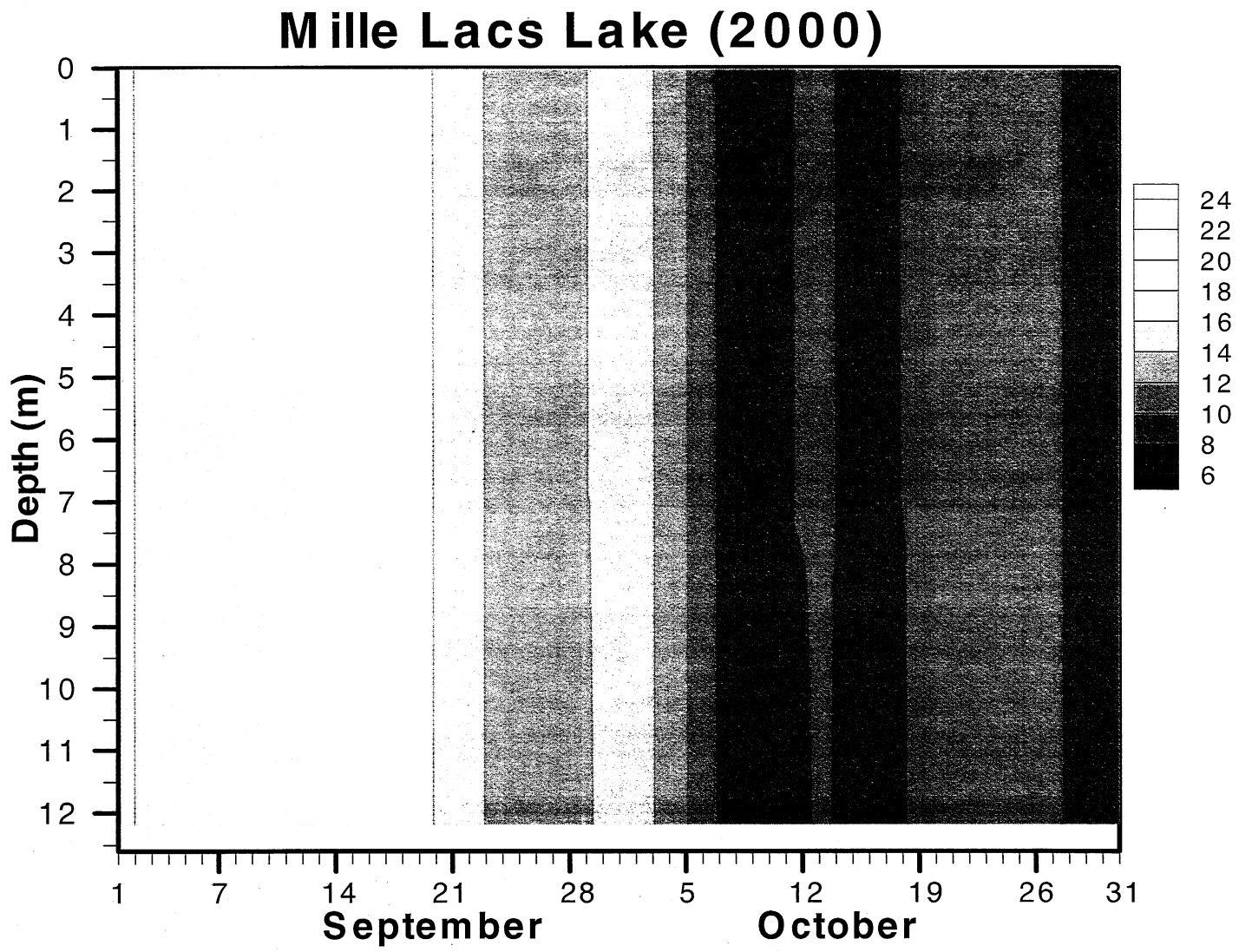


Figure 4.38 Simulation Results with Duluth Weather Data for Sept. and Oct. 2000

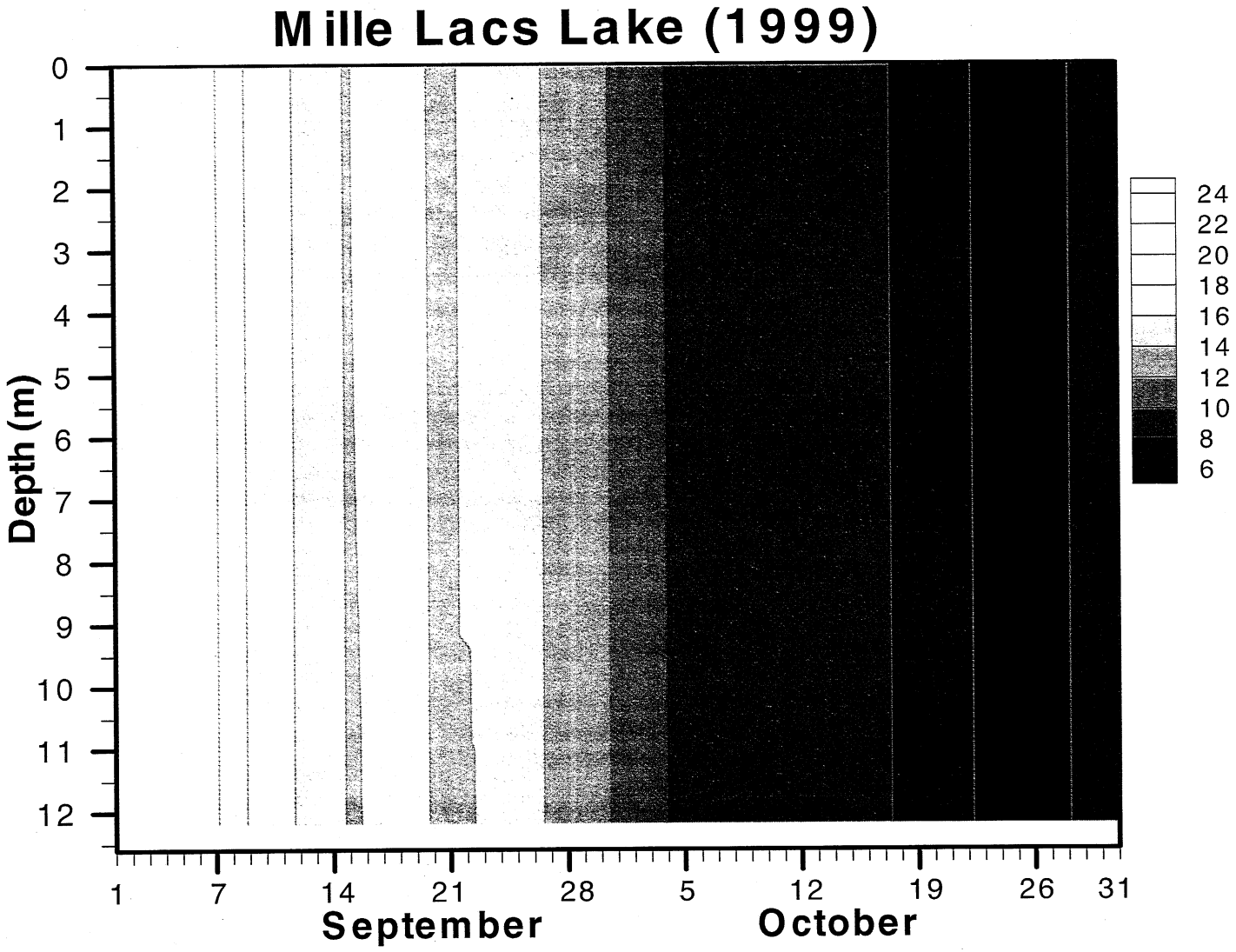


Figure 4.39 Simulation Results with Duluth Weather Data for Sept. and Oct. 1999

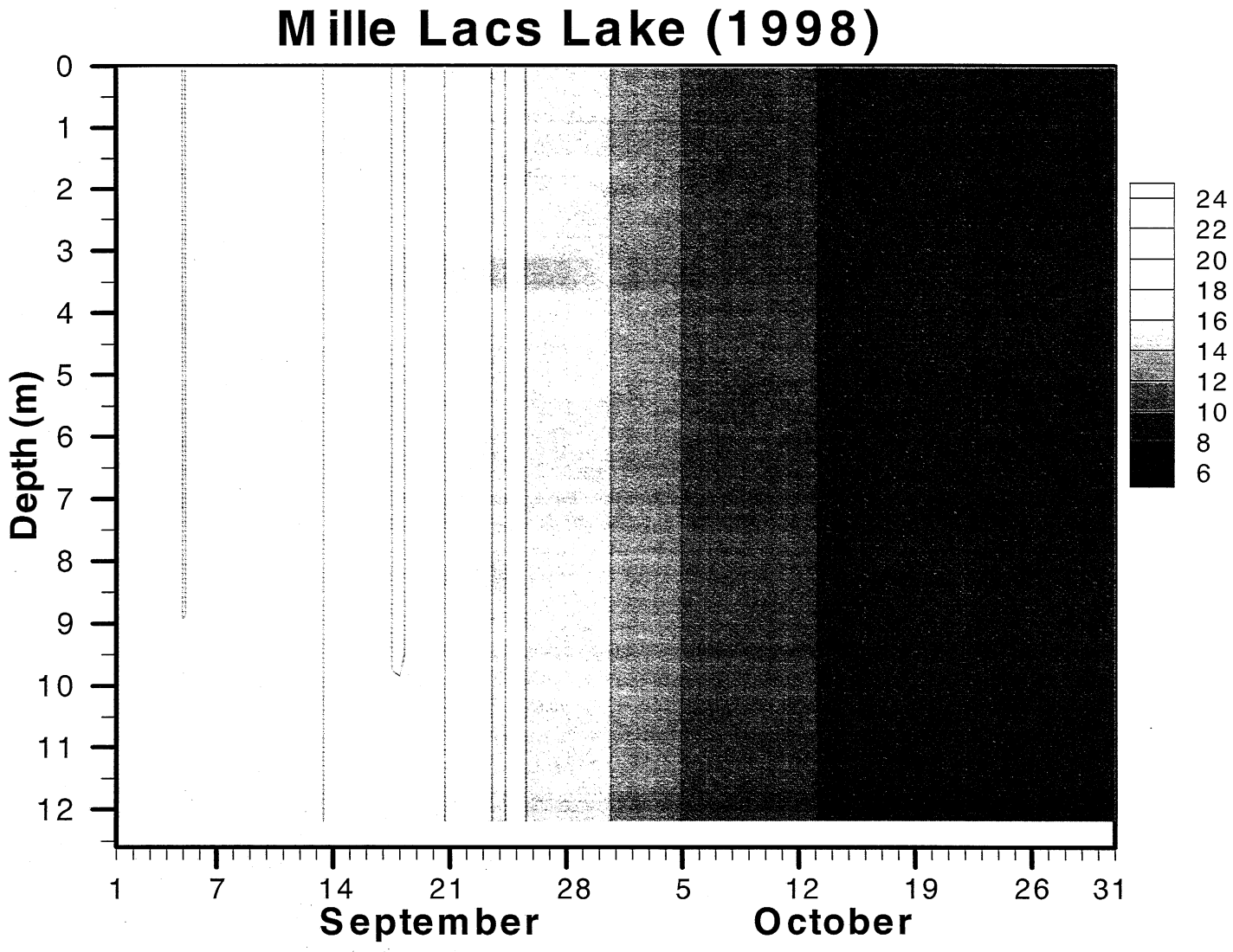


Figure 4.40 Simulation Results with Duluth Weather Data for Sept. and Oct. 1998

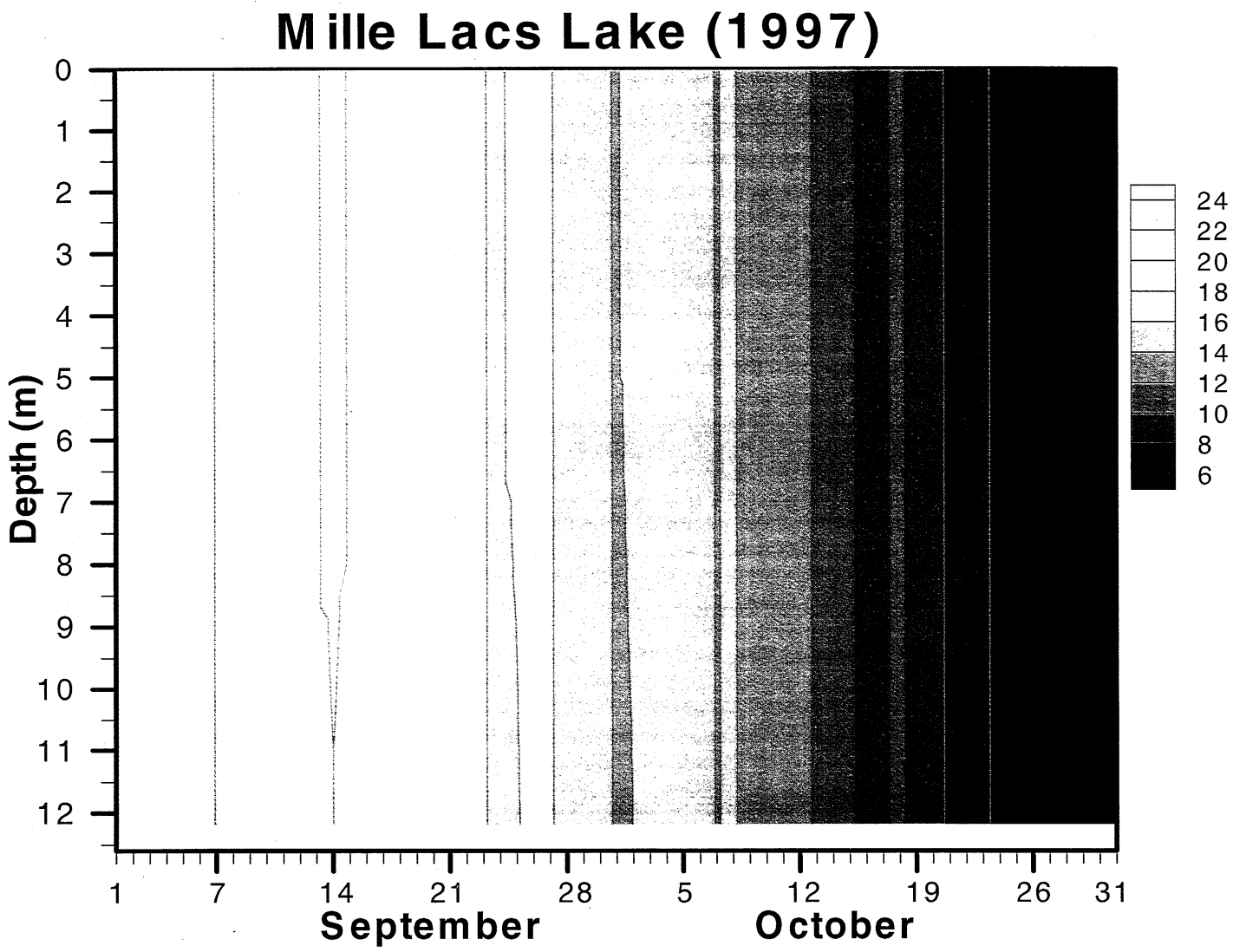


Figure 4.41 Simulation Results with Duluth Weather Data for Sept. and Oct. 1997

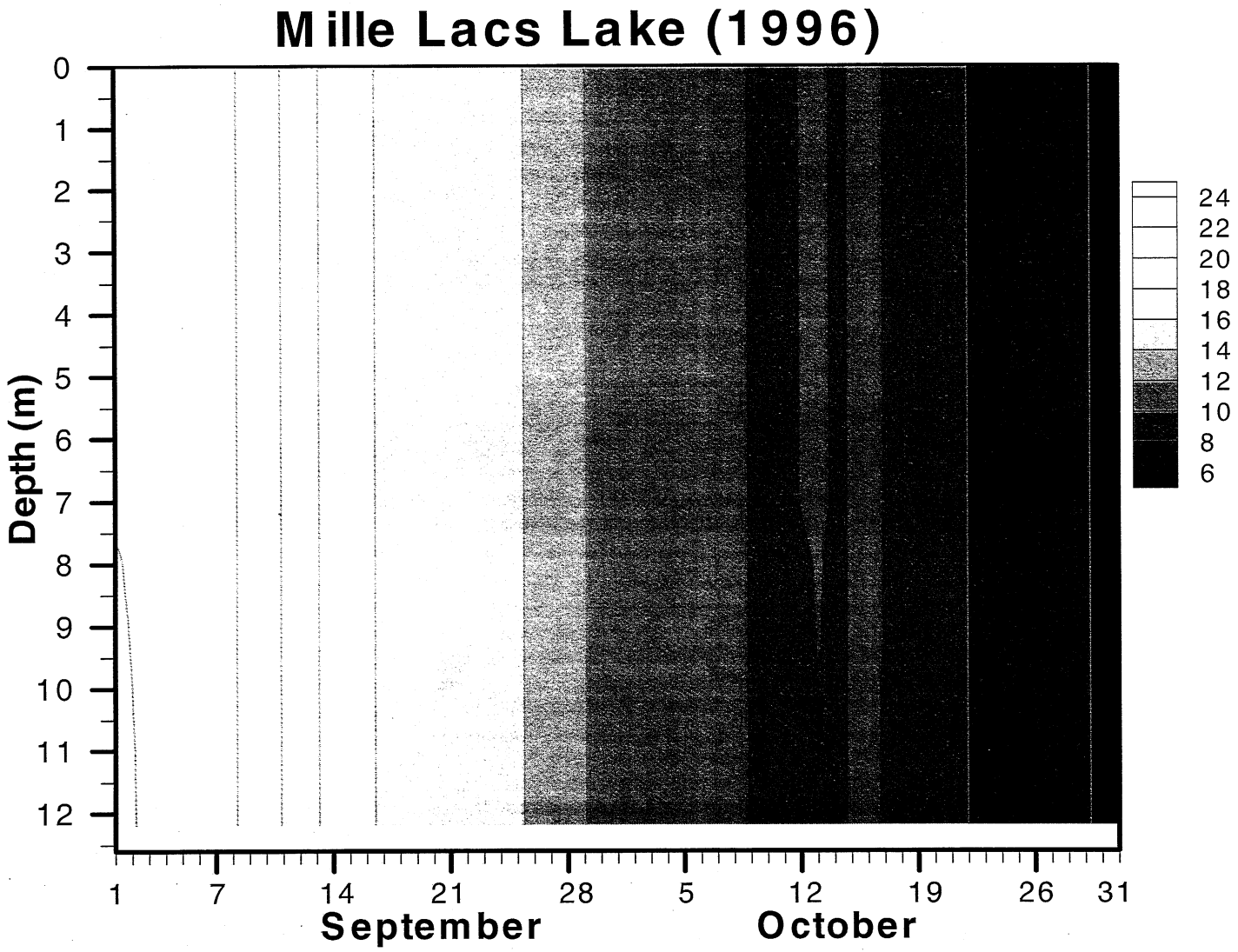


Figure 4.42 Simulation Results with Duluth Weather Data for Sept. and Oct. 1996

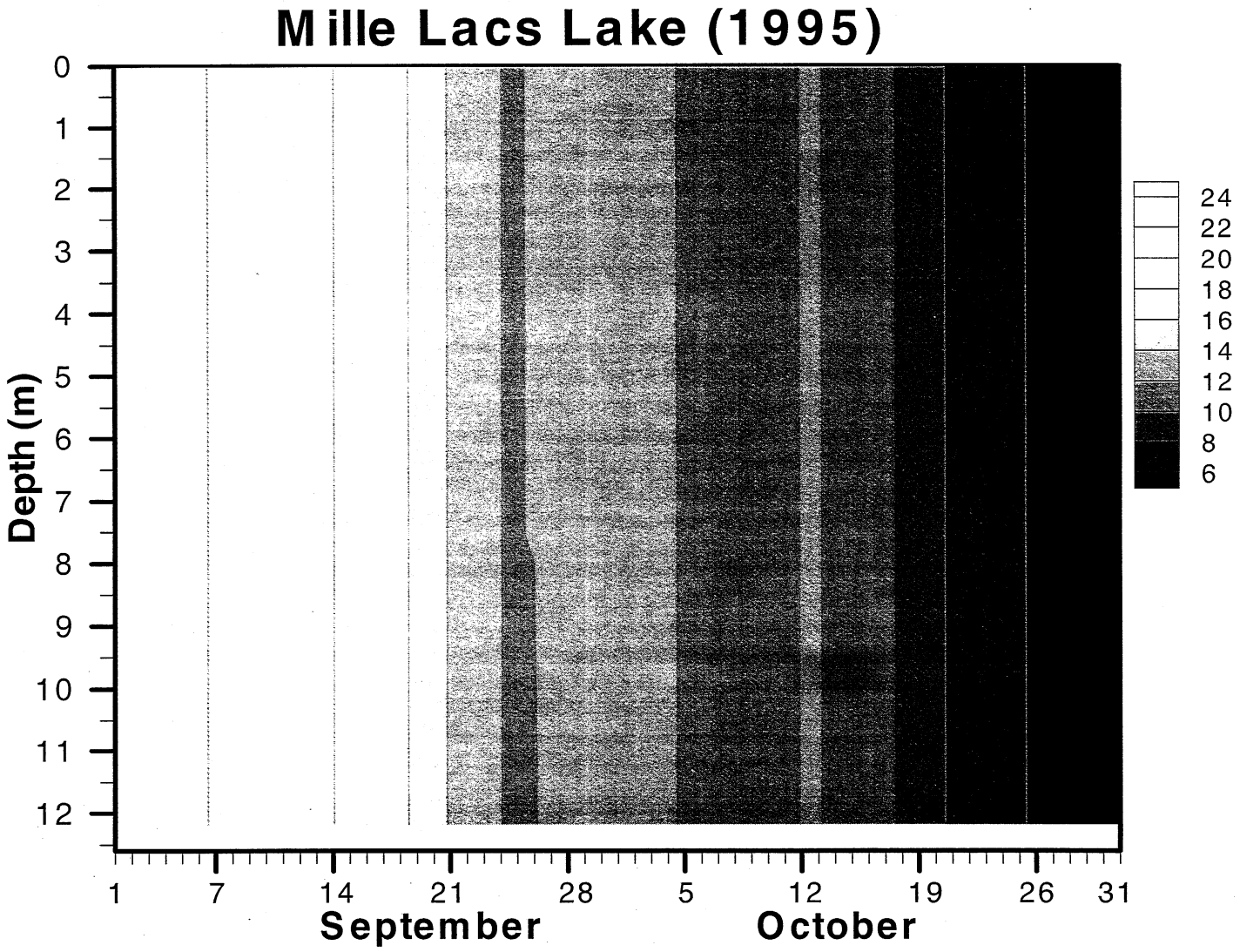


Figure 4.43 Simulation Results with Duluth Weather Data for Sept. and Oct. 1995

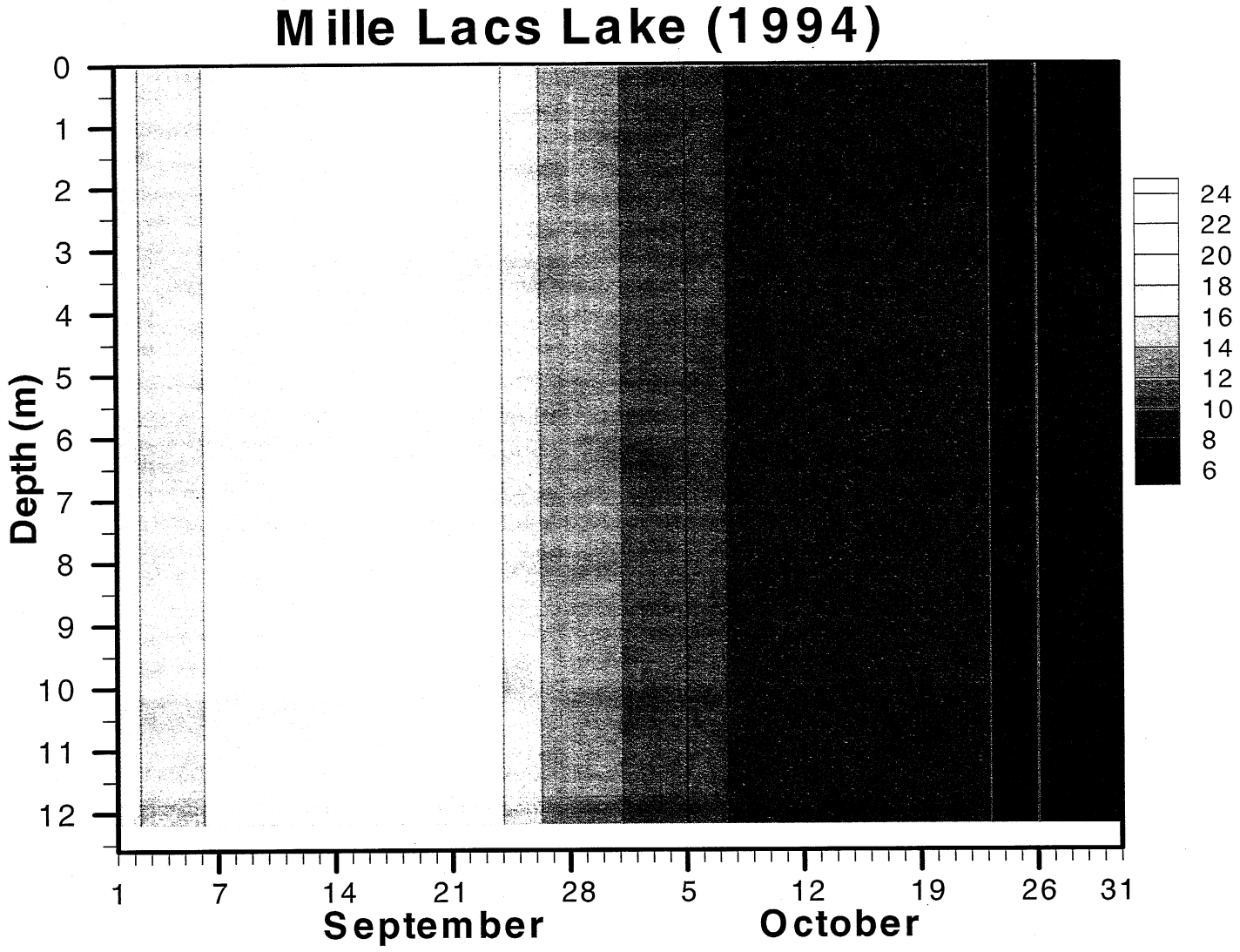


Figure 4.44 Simulation Results with Duluth Weather Data for Sept. and Oct. 1994

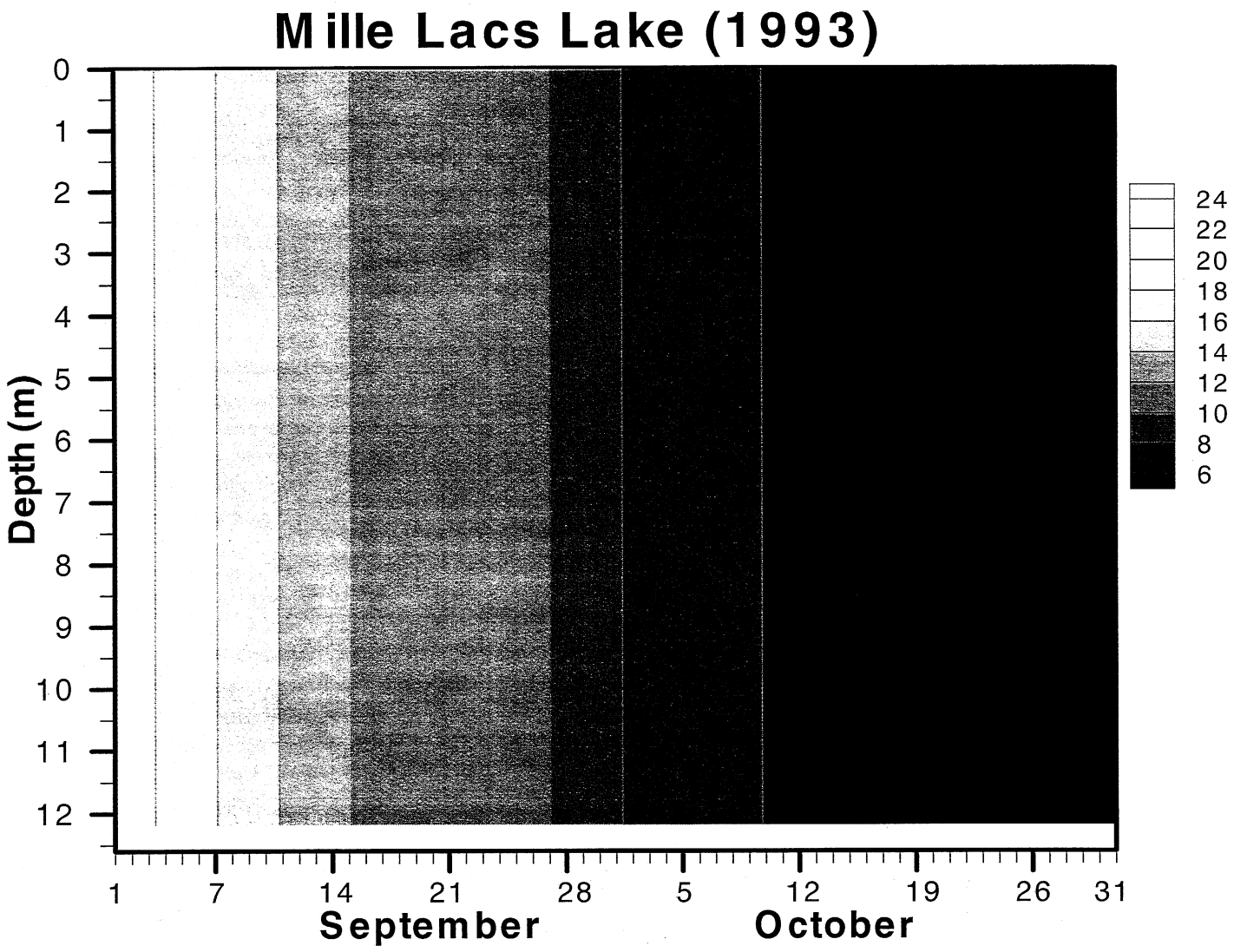


Figure 4.45 Simulation Results with Duluth Weather Data for Sept. and Oct. 1993

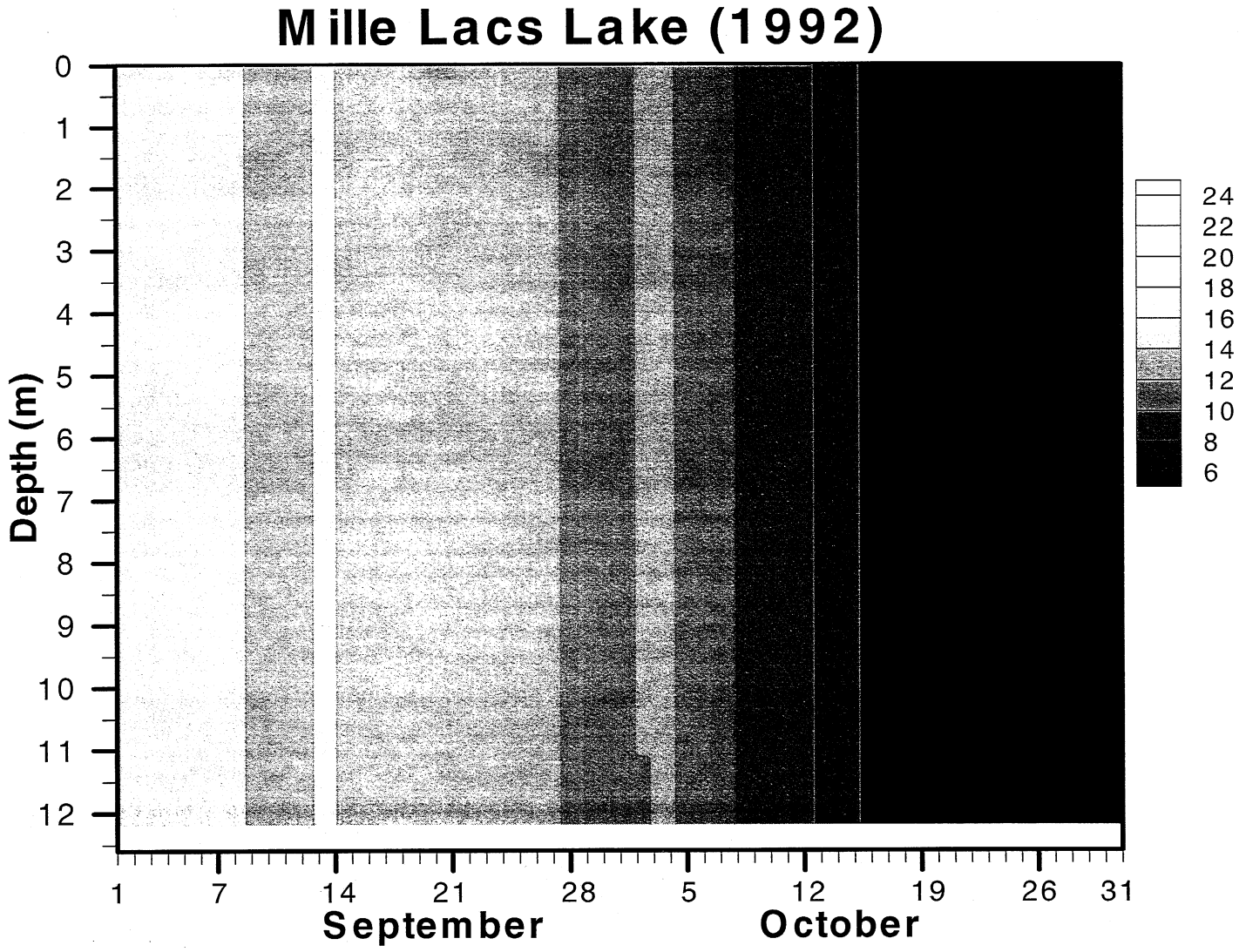


Figure 4.46 Simulation Results with Duluth Weather Data for Sept. and Oct. 1992

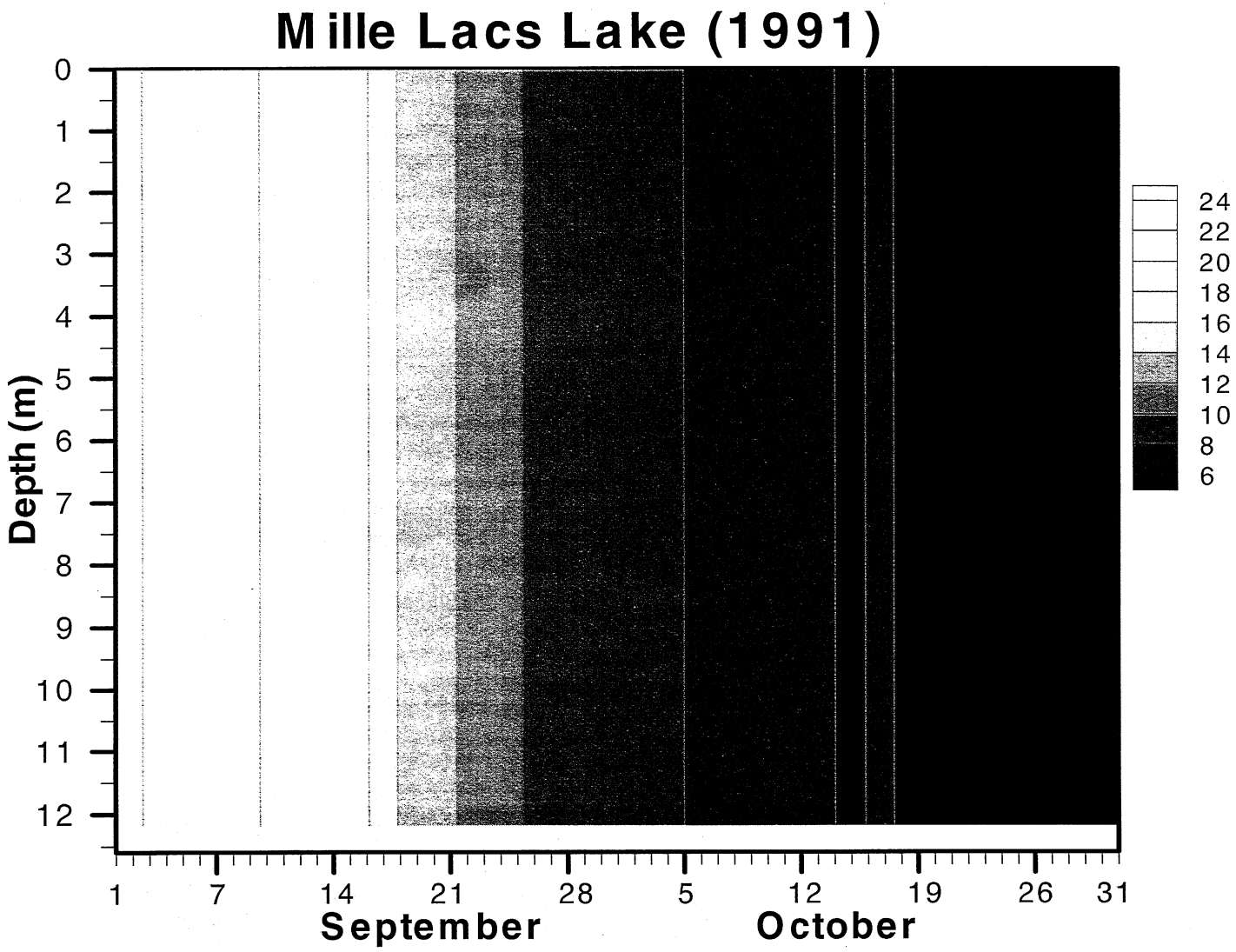


Figure 4.47 Simulation Results with Duluth Weather Data for Sept. and Oct. 1991

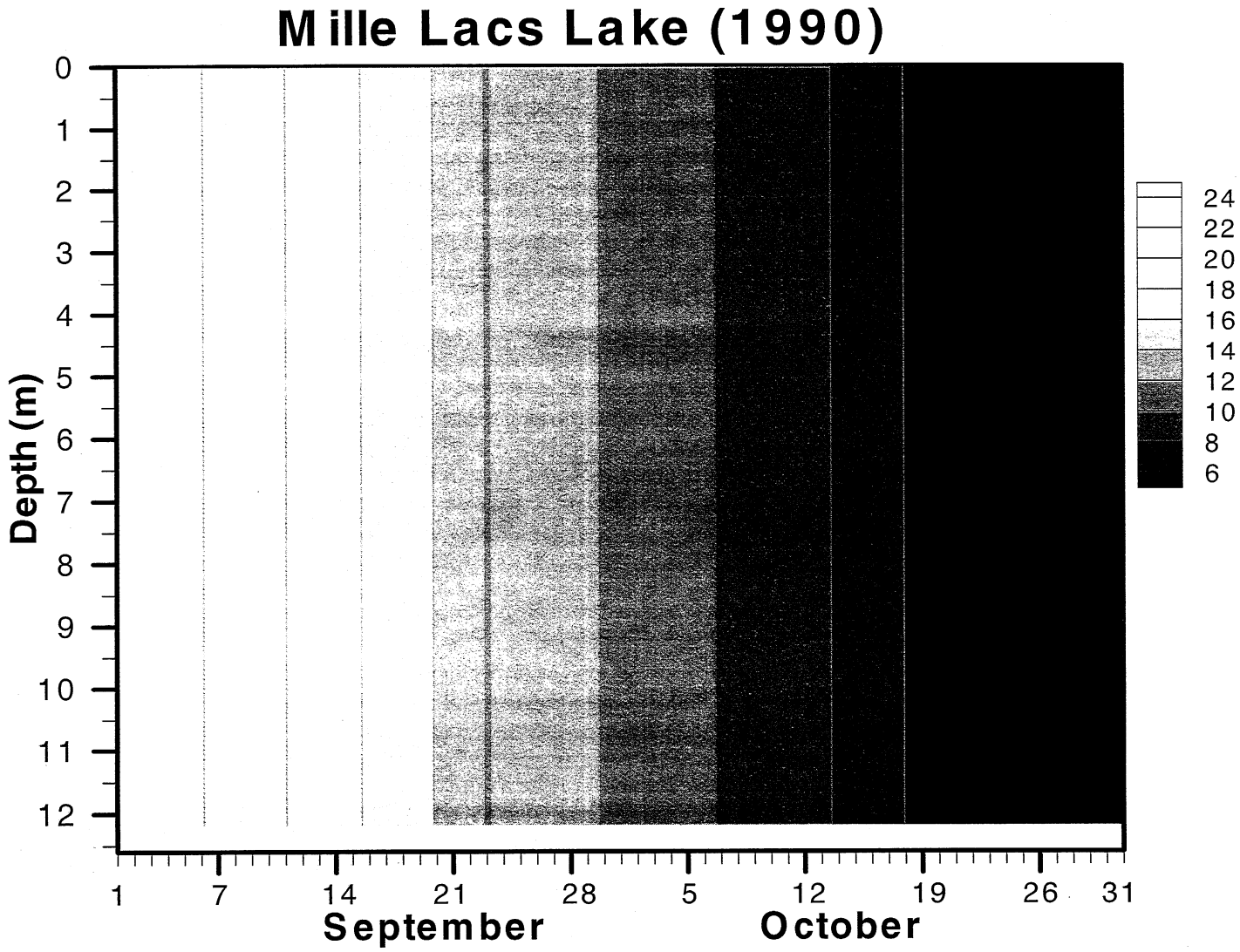


Figure 4.48 Simulation Results with Duluth Weather Data for Sept. and Oct. 1990

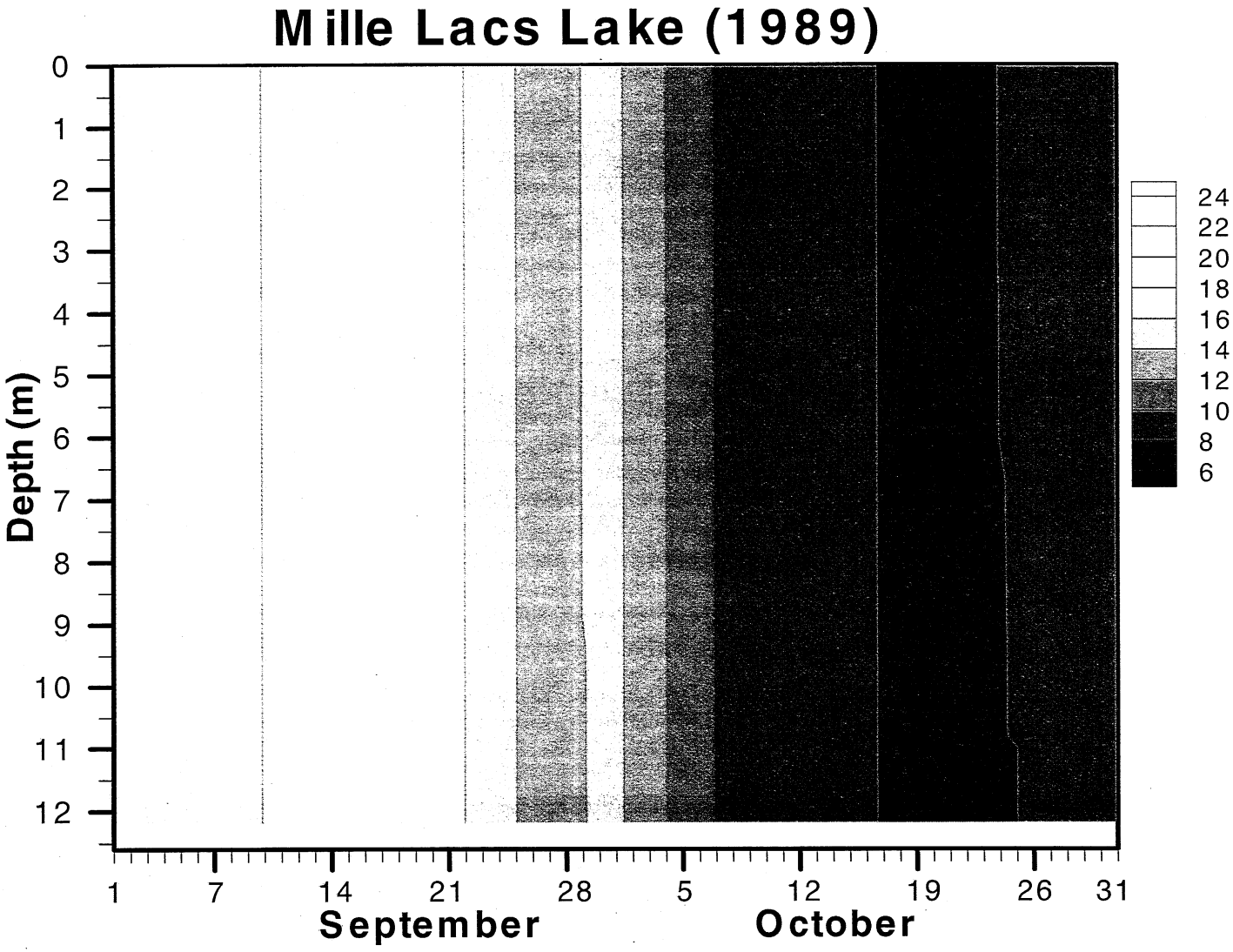


Figure 4.49 Simulation Results with Duluth Weather Data for Sept. and Oct. 1989

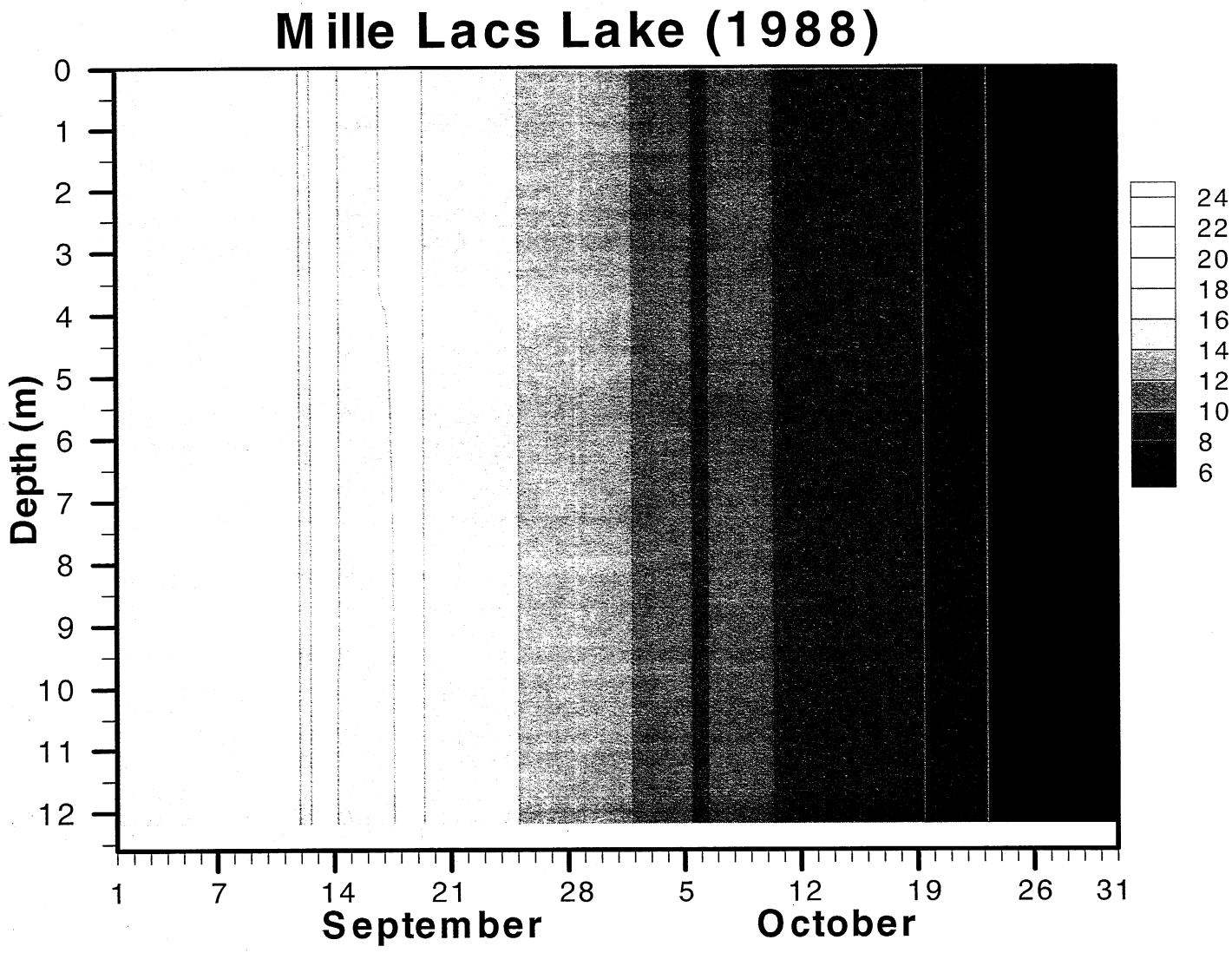


Figure 4.50 Simulation Results with Duluth Weather Data for Sept. and Oct. 1988

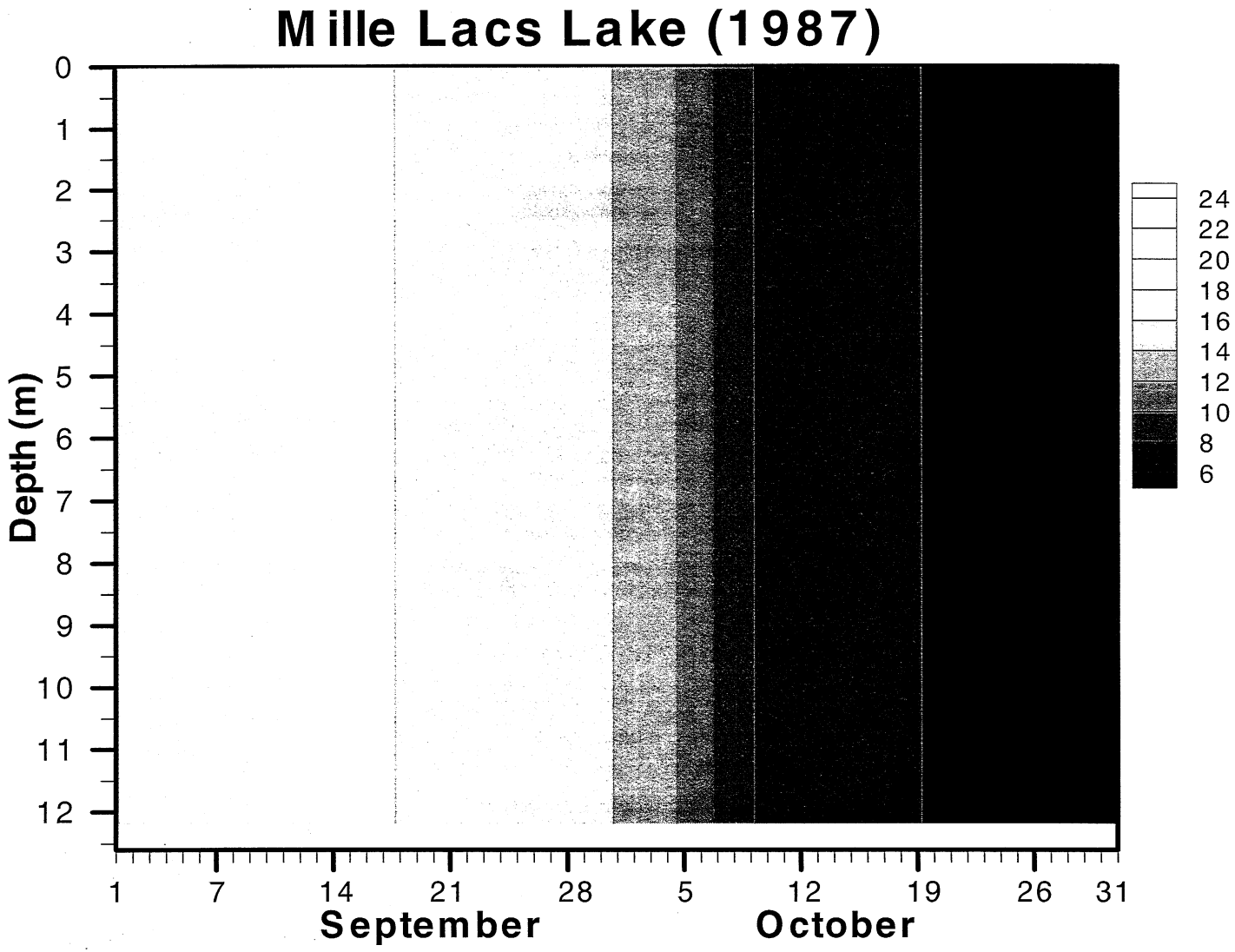


Figure 4.51 Simulation Results with Duluth Weather Data for Sept. and Oct. 1987

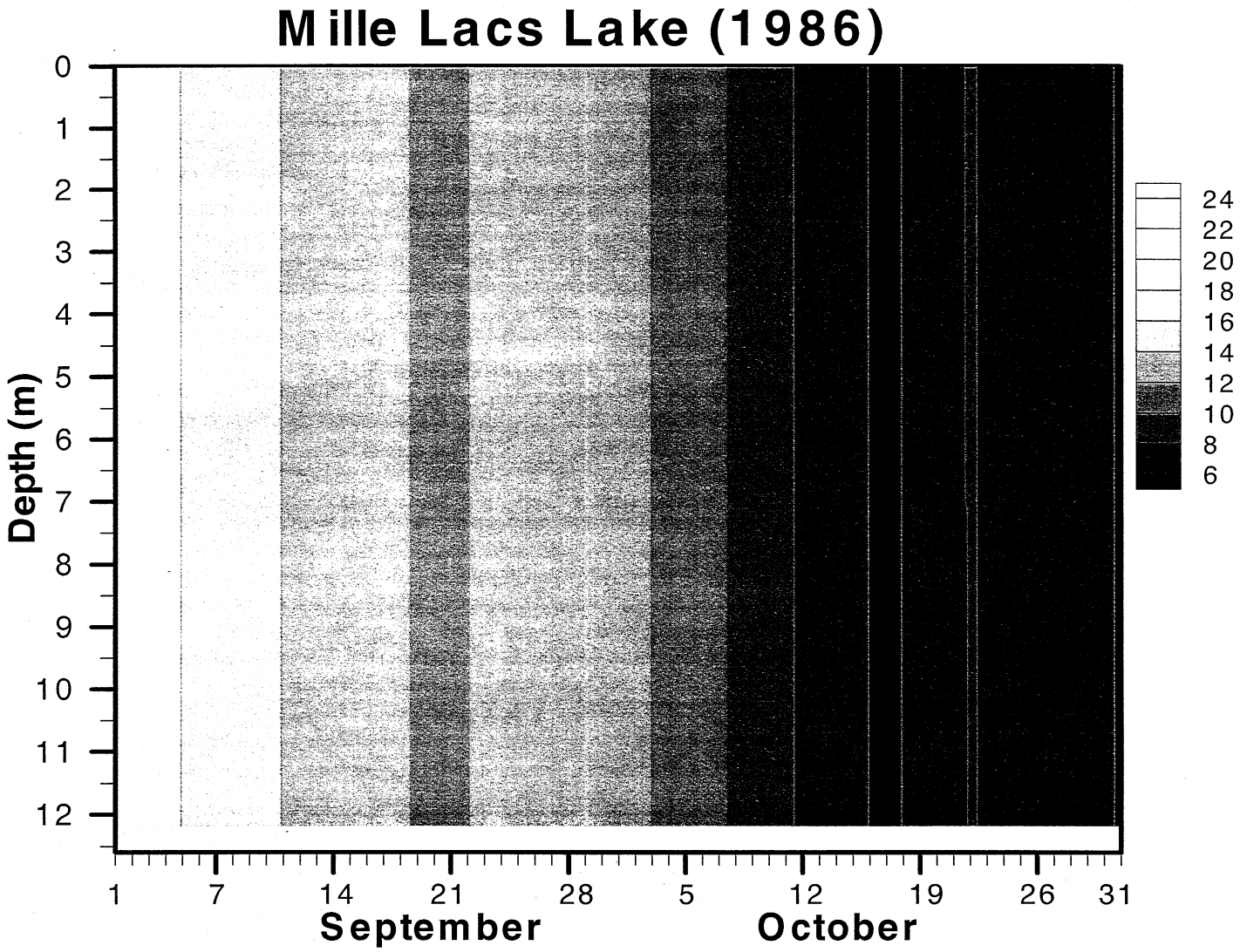


Figure 4.52 Simulation Results with Duluth Weather Data for Sept. and Oct. 1986

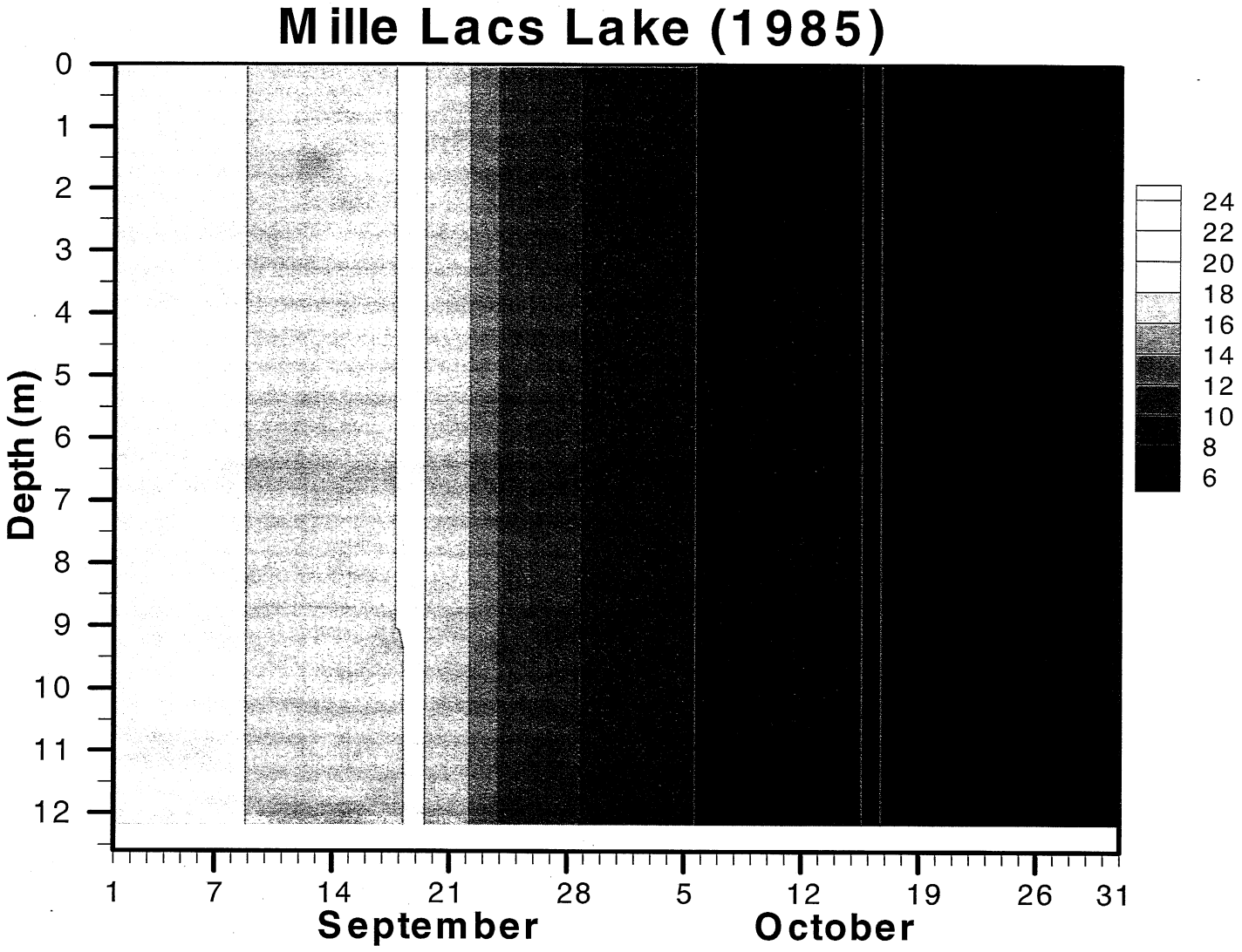


Figure 4.53 Simulation Results with Duluth Weather Data for Sept. and Oct. 1985

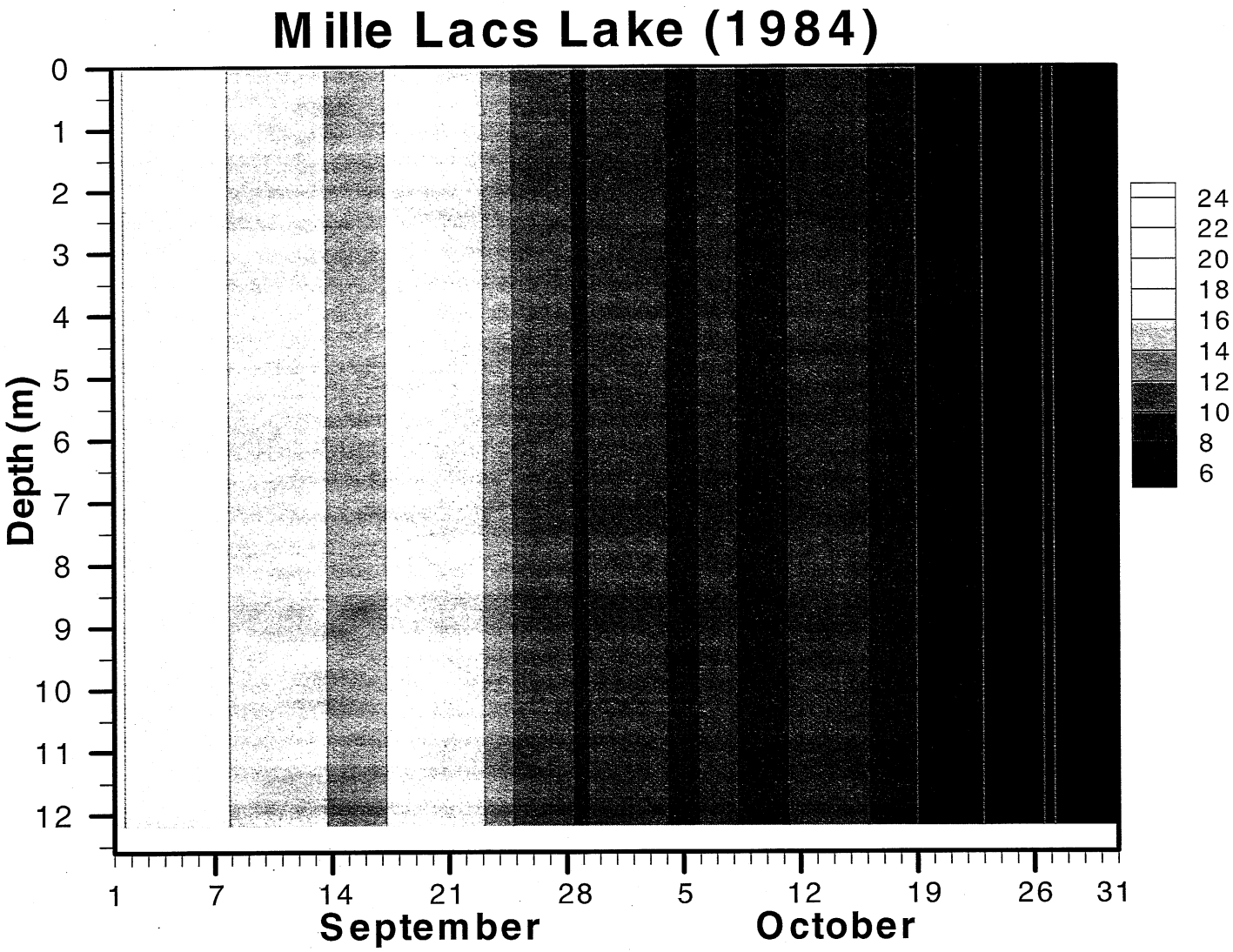


Figure 4.54 Simulation Results with Duluth Weather Data for Sept. and Oct. 1984

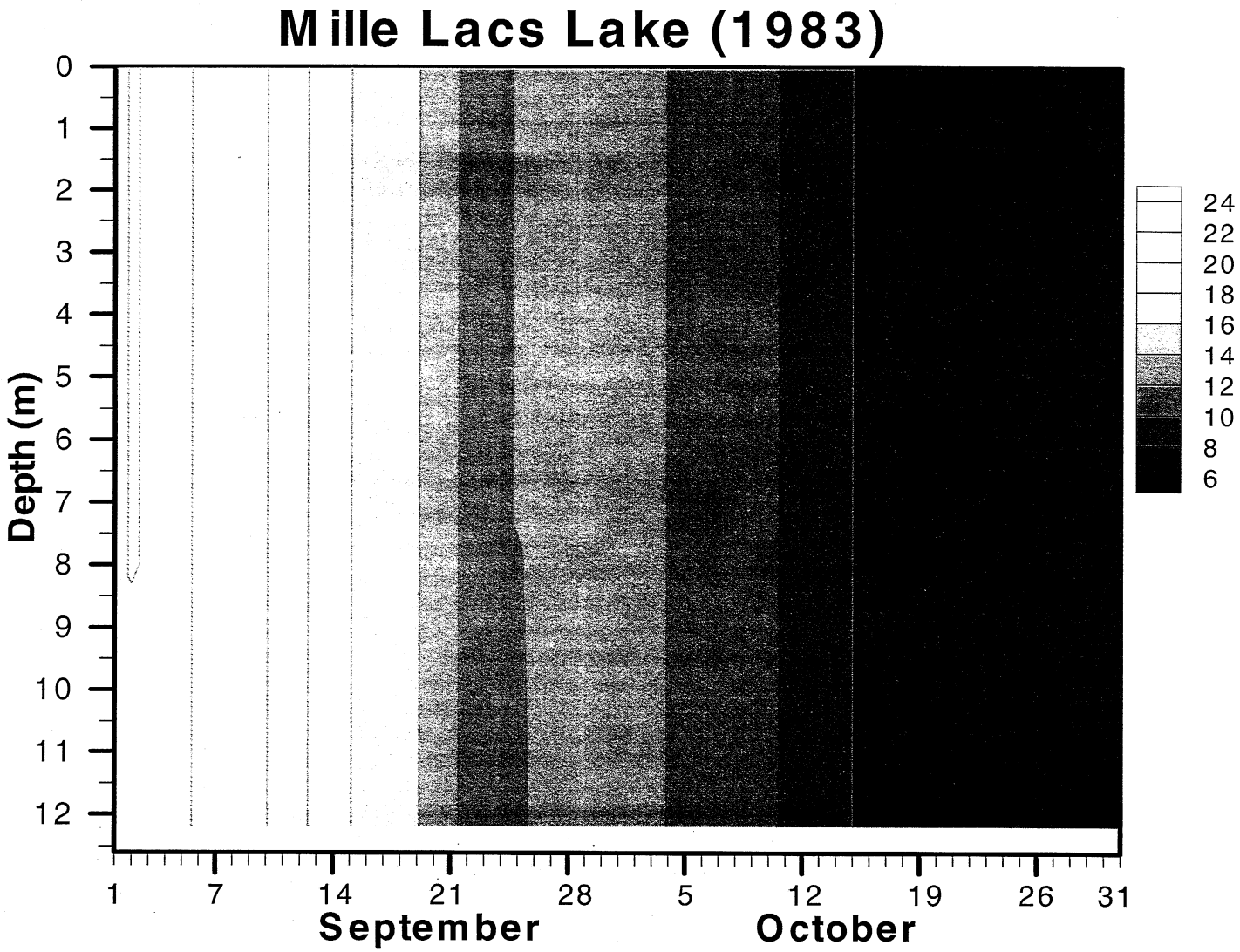


Figure 4.55 Simulation Results with Duluth Weather Data for Sept. and Oct. 1983

5. Analysis

By using weather data from Brainerd and Duluth, the MINLAKE 96 Model was able to predict the Lake Mille Lacs water temperatures well. As seen in Figures 4.3 and 4.4, the model accurately simulated the water temperatures in the summer, fall, and winter with weather input data from Brainerd. However, the calculated temperatures in the spring are greater than the observed. With Duluth weather as input, the model was more accurate in the spring and less accurate the remainder of the year as shown in Figures 4.17 and 4.18.

Since the model simulations with weather data from Brainerd give more accurate results during the summer, fall, and winter, it is recommended that this simulation be used in the walleye assessment. The specific time for the gillnetting process is September, and the model will provide the best results with Brainerd weather data for that time. That model yields a more rapid heating in the spring than is indicated by the lake data. However, this is only a minor concern since spring temperatures have a negligible affect on the water temperatures in September. If for some reason spring water temperatures are needed, the model should be run with Duluth weather data.

The main drawback of using weather data from Brainerd is that these measurements are available only after 1996. This shortcoming can be remedied by applying a correction to the simulation results obtained with Duluth data. The correction can be the daily average between the model outputs in September and October for Duluth and Brainerd daily weather data input from 1996 to 2001. This average adjustment can then be applied to the simulations with Duluth weather data for the years prior to 1996.

Figures 5.1, 5.2, and 5.3 give average simulated daily water temperatures in September, in October, and in September and October, respectively, from 1996 to 2001. Time series of average daily water temperatures simulated with Brainerd and Duluth weather data have a very similar pattern from 1996 to 2001, but those simulated with Brainerd weather data are always higher than ones simulated with Duluth weather data. These simulated daily water temperatures from 1996 to 2001 have been further averaged over 6 years (Figures 5.1 to 5.3). The average adjustments for September, October, and September plus October are 1.85 ^{o}C, 1.93 ^{o}C, and 1.89 ^{o}C, respectively. Since differences among the above average adjustments are very small, we can apply a correction of 1.9 ^{o}C to the September and October simulations with Duluth weather data for the years prior to 1996.

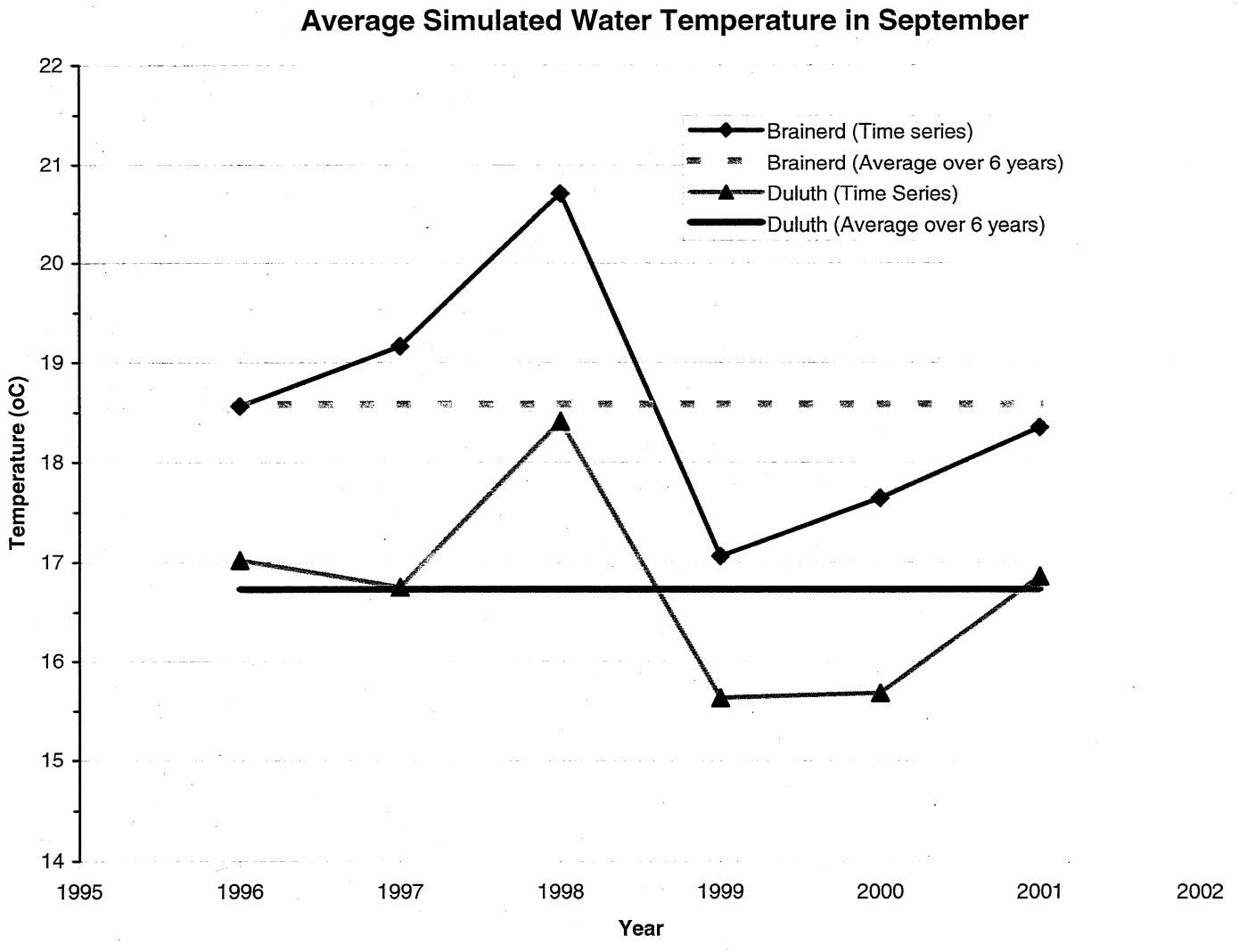


Figure 5.1 Average Simulated Water Temperature in September from 1996 to 2001

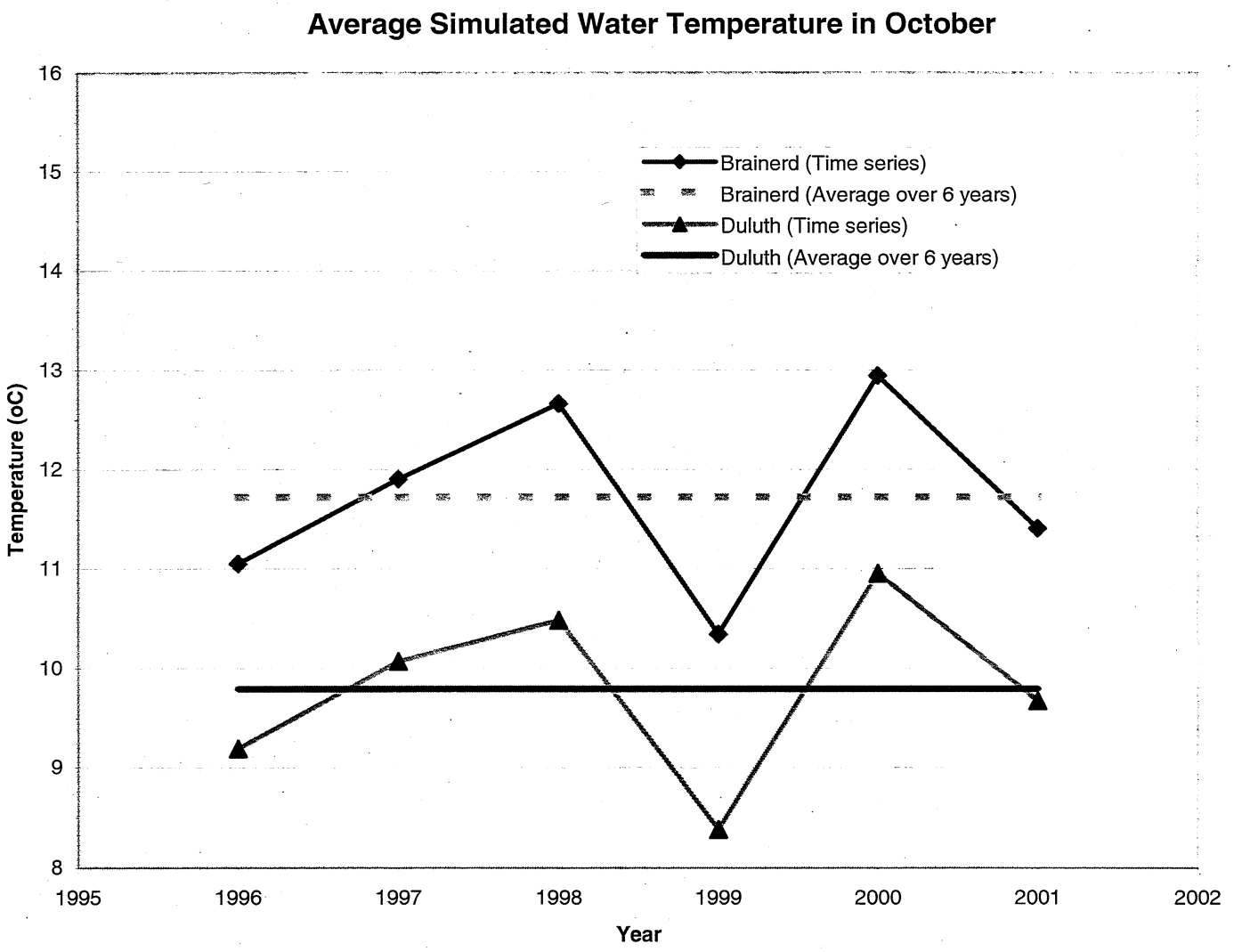


Figure 5.2 Average Simulated Water Temperature in October from 1996 to 2001

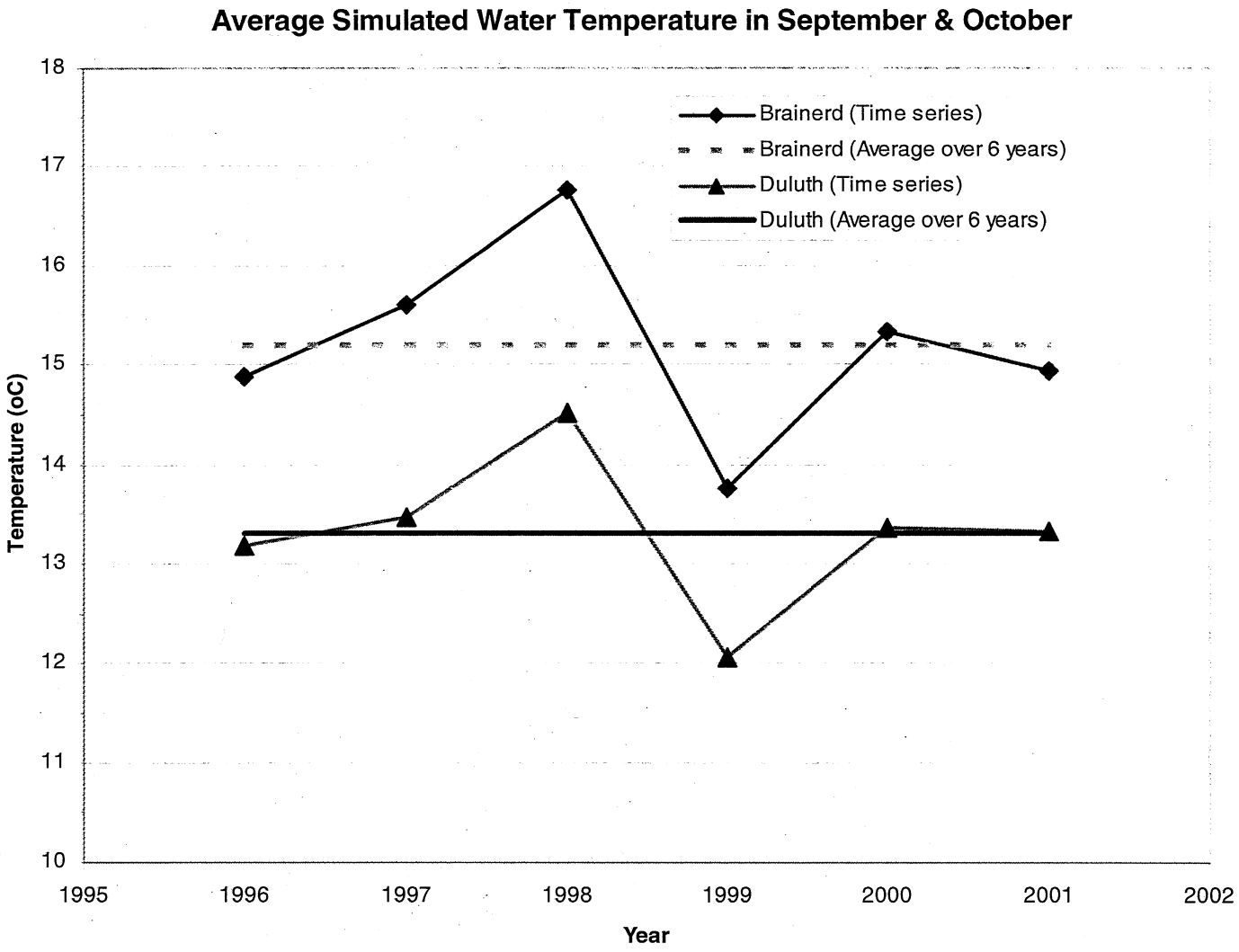


Figure 5.3 Average Simulated Water Temperature in Sept. and Oct. from 1996 to 2001

6. Conclusions

The MINLAKE 96 simulation has provided fairly accurate results for predicting Lake Mille Lacs temperatures by using data from the Brainerd and Duluth weather stations. These simulation results should help the Minnesota Department of Natural Resources Division of Fisheries provide a relative walleye abundance estimate for the coming (2003) fishing season. The simulation results were transmitted electronically in October for immediate use by the MNDNR.

References

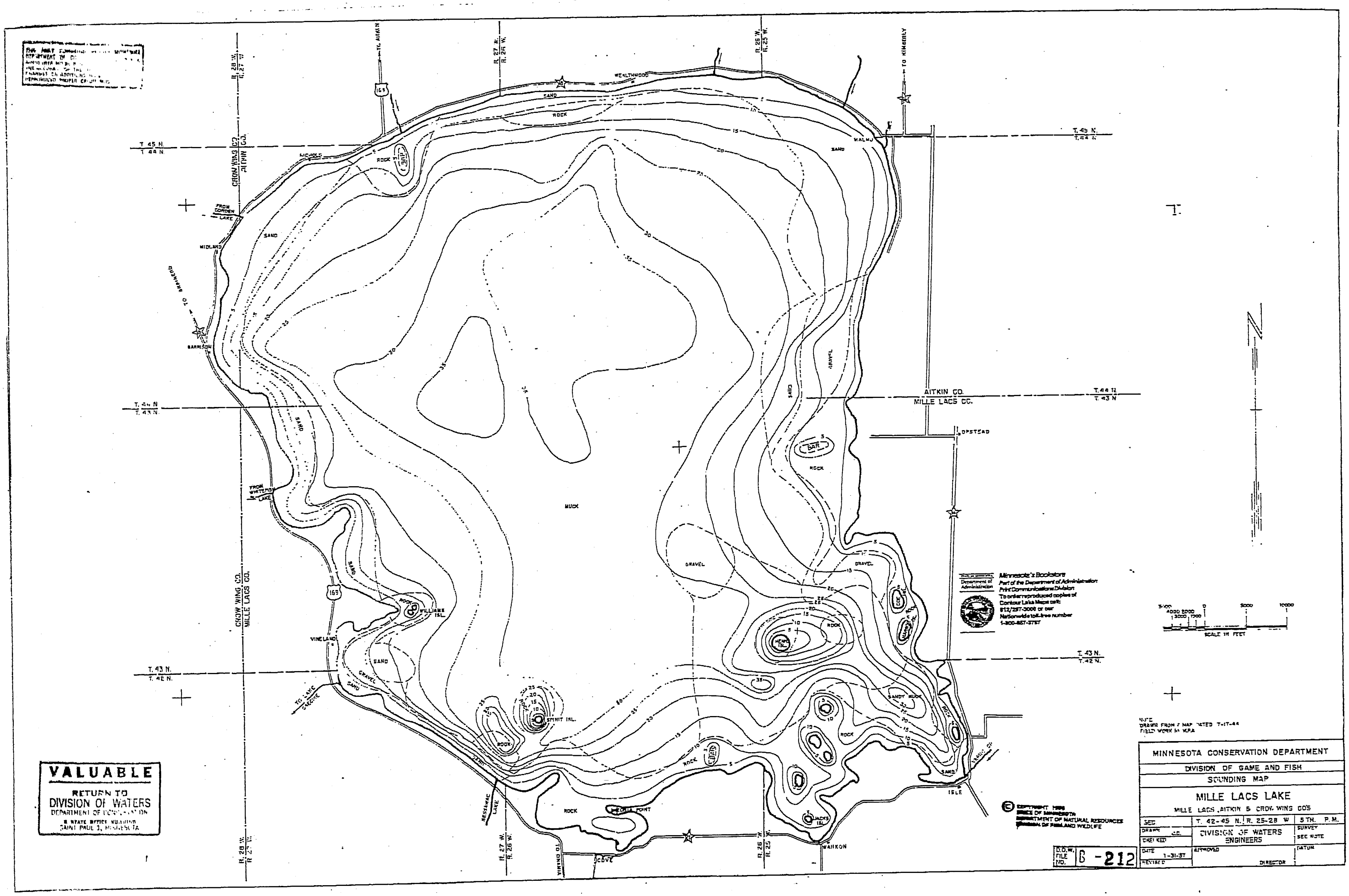
Fang, S. and H.G. Stefan, Development and validation of the water quality model MINLAKE 96 with winter data, Project Report 390, Saint Anthony Falls Laboratory, University of Minnesota, 1996.

Gao, S. and H.G. Stefan, Projections of seasonal water temperature cycles and stratification in five large lakes in Minnesota under a $2xCO_2$ Climate Scenario, Project Report 423, Saint Anthony Falls Laboratory, University of Minnesota, 1998.

Hondzo, M. and H.G. Stefan, Water temperature characteristics of lakes subjected to climate change, Project Report 329, Saint Anthony Falls Laboratory, University of Minnesota, 1998.

Hondzo, M. and H.G. Stefan, Lake water temperature simulation model. *J. Hydraulic Engineering*, ASCE Vol. 119 No. 11, Nov. 1993.

Appendix A



MINNESOTA CONSERVATION DEPARTMENT
DIVISION OF GAME AND FISH
SOUNDING MAP
MILLE LACS LAKE
T. 42-45 N. R. 25-28 W 5TH. P.M.
DIVISION OF WATERS ENGINEERS
DATE 1-31-57
DIRECTOR
SURVEY
SEE NOTE
DATUM
D.O.W. FILE NO. 6-212
VALUABLE
RETURN TO
DIVISION OF WATERS
AITKIN CO.
MILLE LACS CO.
CROW WING CO.
AITKIN CO.
T. 45 N.
T. 44 N.
T. 43 N.
T. 42 N.
WEALTHWOOD
MALMO
MIDLAND
GARRISON
VINELAND
WAHKON
ISLE
COVE
SPIRIT ISL.
WILLIAMS ISL.
HENNEPIN ISL.
JACKS ISL.
MUCK
SAND
ROCK
GRAVEL
TO KIMBERLY
TO BRAINERD
SCALE IN FEET

Appendix B

Simulated Water Temperature by Using Brainerd and Duluth Weather Data

Description of Data Format

1. **File name convention**
   Simulated water temperatures are organized year by year, and these are text (ASCII) data file, which can be opened by Notepad and WordPad. Their file names start "PMN" (past weather data, MN simulation) plus "DULU" for Duluth, or "BRAI" for Brainerd (first four letters of weather station), then plus the last two digits for simulation year, e.g., "99", with extension ".TEP" (stands for temperature). Therefore PMNDULU96.TEP and PMNBRAI02.TEP stand for water temperature simulated for 1996 with Duluth weather data, and for 2002 with Brainerd weather data.

2. **Data Format**
   Data is then organized month-by-month, and day-by-day (see partial data below). The **first** line of each month gives the month (e.g., 1 – January for the data below), starting date (1, first date of the month), ending date (31, last date of the month), simulation year (2002), number of depths which water temperatures were simulated (24 depths). The **next three** lines give water depths where water temperatures were simulated (e.g., form 0.019 to 12.175, and those very small depths are necessary to simulate ice-in and ice-out dates in the model). After the fourth line, the file gives water temperatures simulated for those 24 corresponding water depths for the starting date to the ending date (each line contact maximum ten values). ***This format repeats for each month of the year.***

   Original example data:

```
1  1 31 2002 24
 0.019  0.056  0.112  0.275  0.600  1.025  1.500  2.000  2.500  3.000
 3.500  4.000  4.500  5.125  6.000  7.000  8.000  8.875  9.500 10.000
10.500 11.000 11.500 12.175
 0.148  0.256  0.396  0.714  1.054  1.192  1.209  1.179  1.146  1.119
 1.129  1.172  1.188  1.185  1.159  1.118  1.128  1.227  1.406  1.636
 1.788  1.880  1.938  1.982
 0.147  0.240  0.367  0.673  1.027  1.182  1.212  1.193  1.166  1.144
 1.156  1.199  1.216  1.216  1.191  1.150  1.161  1.261  1.442  1.674
 1.828  1.923  1.983  2.028
```

   Data format with explanation of text insert:

```
 1 (month)  1 (starting date) 31 (ending date of the month) 2002 (year) 24
(number of depths which water temperatures were simulated)
 0.019  0.056  0.112  0.275  0.600  1.025  1.500  2.000  2.500  3.000
 3.500  4.000  4.500  5.125  6.000  7.000  8.000  8.875  9.500 10.000
10.500 11.000 11.500 12.175 (24 water depths)
```

0.148 0.256 0.396 0.714 1.054 1.192 1.209 1.179 1.146 1.119
1.129 1.172 1.188 1.185 1.159 1.118 1.128 1.227 1.406 1.636
1.788 1.880 1.938 1.982 (24 simulated water temperatures for day 1)
0.147 0.240 0.367 0.673 1.027 1.182 1.212 1.193 1.166 1.144
1.156 1.199 1.216 1.216 1.191 1.150 1.161 1.261 1.442 1.674
1.828 1.923 1.983 2.028 (24 simulated water temperatures for day 2)

Appendix C

Simulated Water Temperature by Using Brainerd and Duluth Weather Data

Description of Data Format for September and October

1. **File name convention**
   Simulated water temperatures are organized year by year, and these are text (ASCII) data file, which can be opened by Notepad and WordPad. Their file names start "PMN" (past weather data, MN simulation) plus "DULU" for Duluth, or "BRAI" for Brainerd (first four letters of weather station), then plus the last two digits for simulation year, e.g., "99", with extension ".SDF" (stands for temperature). Therefore PMNDULU96.SDF and PMNBRAI02.SDF stand for September and October water temperatures simulated for 1996 with Duluth weather data, and for 2002 with Brainerd weather data.

2. **Data Format**
   Data is organized day-by-day (see partial data below). The **first** column is a numerical date (day 1 is for September 1, day 30 is for September 30, and day 31 will be for October 1), and the **second** column gives 24 water depths where water temperatures were simulated. The **third** column gives 24 water temperatures simulated for 24 corresponding water depths. ***This format repeats for each date of September and October.***

1	0.02	23.62
1	0.06	23.62
1	0.11	23.62
1	0.28	23.62
1	0.60	23.62
1	1.02	23.62
1	1.50	23.62
1	2.00	23.62
1	2.50	23.62
1	3.00	23.62
1	3.50	23.62
1	4.00	23.62
1	4.50	23.62
1	5.12	23.62
1	6.00	23.62
1	7.00	23.62
1	8.00	23.62
1	8.88	23.62
1	9.50	23.62
1	10.00	23.62
1	10.50	23.62
1	11.00	23.62

1	11.50	23.62
1	12.18	23.62
2	0.02	23.11
2	0.06	23.11
2	0.11	23.11
2	0.28	23.11
2	0.60	23.11