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

Project Report No. 411

Observed and Simulated Ice Characteristics of Five Freshwater Lakes and Extrapolation to a Projected 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
Mid-Continent Ecology Division
Duluth, Minnesota

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ABSTRACT

The MINLAKE97 model was employed to simulated ice-on and ice-off dates, ice cover duration and ice thicknesses for four lakes in the US and one lake in Canada. MINLAKE97 is a one dimensional, year-round, deterministic water quality model which simulates vertical temperature and dissolved oxygen profiles in lakes and has the ability to simulate ice on-dates, ice growth, ice decay and ice-off dates. A new ice and snow albedo submodel was incorporated into the MINLAKE96 model to produce MINLAKE97. The average standard errors between simulated and measured values were 10 days, 9 days and 11 days for ice on-dates, ice-off dates and ice cover duration, respectively, without calibrating the model.

The model was also employed to simulate the effect of a projected $2xCO_2$ climate scenario on the ice characteristics of the same five lakes. To illustrate the climate change effect, time series for the ice-on dates, ice-off dates, ice cover duration and maximum ice thicknesses under past and $2xCO_2$ climate scenarios were simulated. The root mean square of changes for ice-on dates, ice-off dates, ice cover duration and maximum ice thicknesses between past and $2xCO_2$ climate scenarios were projected to be 13 days, 21 days, 31 days and 0.27 m, respectively. Under the $2xCO_2$ climate scenario the average ice-on dates are 7 days to 12 days later; the average ice-off dates are 15 days to 23 days earlier; the ice cover durations are 25 days to 33 days shorter; and the maximum ice thicknesses are 0.18 m to 0.30 m thinner.

The results were compared with empirical projections by Adams and Stefan (1997). The two models gave similar results for the projected changes of ice-on and ice-off dates between $2xCO_2$ and past conditions, but gave different results for the projected changes of ice cover duration.

The overall conclusion is that a doubling of atmospheric carbon dioxide ($2xCO_2$) would have a significant effect on lake ice characteristics.

ACKNOWLEDGMENTS

The investigation described herein was conducted for the U.S. Environmental Protection Agency as part of a research project to anticipate the possible effects of projected climate change on water resource and ecosystems. Barbara M. Levinson (Office of Research and Development, Washington, D.C.) was project officer.

Data were provided by the following: John Magnuson and Barbara Benson, North Temperate Lakes Long-Term Ecological Research Project, Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin; Susan Kasian, Database Manager, Experimental Lakes Area, Department of Fisheries and Oceans, Winnipeg, Canada; and Steve Kahl, Director, Water Research Institute, University of Maine, Orono, Maine. We are grateful to these individuals for providing the data.

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1. INTRODUCTION

MINLAKE96 is a one-dimensional, deterministic water quality model which simulates vertical temperature and dissolved oxygen profiles in lakes year-round. The model has the ability to simulate ice-on dates, ice growth, ice decay and ice-off dates. Development and applications of the model have been summarized in several reports, e.g. by Fang and Stefan (1996).

The model was modified by incorporating a new ice and snow albedo submodel which was developed by Henneman and Stefan (1997). The modified model (MINLAKE97) was then applied to four lakes in the US and one lake in Canada, and model results were compared with observations of ice-on dates, ice-off dates and ice cover duration assembled by Adams and Stefan (1997). Statistics for the goodness of fit are presented in this report.

The modified model was also employed to simulate the effect of a $2xCO_2$ climate scenario on ice characteristics of the five lakes. To illustrate the potential climate change effects, the plots of time series for the ice-on dates, ice-off dates, ice cover duration and maximum ice thicknesses under past and $2xCO_2$ climate scenarios are presented in this report.

The simulation results were compared with empirical projections by Adams and Stefan (1997). The two models gave similar results for the projected change from past to $2xCO_2$ conditions of ice-on and ice-off dates, but gave different results for the change of ice cover duration.

2. MODEL MODIFICATION

Albedo is the ratio of upwelling to incoming solar radiation at a surface. In the winter season ice and snow thicknesses, ice-off and snow-off dates, water temperatures and DO concentrations in a lake are all functions of ice and snow albedos.

A field study set up to measure snow and ice albedos was conducted on Ryan Lake in Minneapolis, Minnesota by Henneman from December 17, 1996 to March 21, 1997. Average daily albedos were calculated, and the variations in albedo were studied. An empirical model was developed to predict snow and ice albedos (Henneman and Stefan, 1997) as follows.

The minimum daily albedo value α_{min} for a lake ice or snow cover is

$$\alpha_{min} = 0.38 \tag{1}$$

On snowfall days the daily albedo α is

$$\alpha = 0.83 \tag{2}$$

During nonmelt periods

$$\alpha = -0.011d + 0.83 \tag{3}$$

During melt periods

$$\alpha = -0.17 + \alpha_{i-1} \qquad \text{for } T_{air} > 0^{\circ}\text{C} \tag{4}$$

$$\alpha = -0.013 + \alpha_{i-1} \qquad \text{for } T_{air} \le 0^{\circ}\text{C} \tag{5}$$

where

α = daily albedo
α_{min} = minimum daily albedo
α_{i-1} = albedo from previous day
T_{air} = average daily air temperature (°C)
d = number of days after snowfall

Melt periods start after incoming solar radiation has been larger than 10 MJ m^{-2} day^{-1} for more than two days and $T_{air} > 0^{\circ}$C. Nonmelt periods start after $T_{air} < 0^{\circ}$C for three consecutive days.

3. BATHYMETRIC CHARACTERISTICS OF THE LAKES

The lakes simulated for ice-on dates, ice-off dates, ice cover durations and ice thicknesses are Lake 239 of the Experimental Lakes Area (ELA) near Kenora, Ontario, Canada; Allequash Lake, Crystal Lake and Trout Lake in northern Wisconsin and Moosehead Lake in Maine. In Table 3.1 a summary of physical characteristics of the lakes is provided. The surface areas range from 0.367 km^2 for Crystal Lake to 331 km^2 for Moosehead Lake. Maximum depths range from 8.0 m for Allequash Lake to 75.0 m for Moosehead Lake. There is no substantial difference in the topographic elevation of the lakes which ranges from 319 m for Moosehead Lake to 502 m for Crystal Lake. The Wisconsin lakes (Allequash Lake, Crystal Lake and Trout Lake) are headwater lakes and have significant connections to ground water. The ELA Lake 239 is in a forested watershed. Bathymetric maps of the lakes are given in Appendix C.

Table 3.1. Summary of Physical Lake Characteristics.

Lake Name	Location	Latitude	Longitude	Surface Area (km^2)	Max Depth (m)	Mean Depth (m)	Elevation (m)
Lake 239, ELA*	Near Kenora, Ontario	49°40′ N	93°44′ W	0.561	30.4	10.5	425
Allequash Lake	Near Boulder Junction, Wisconsin	46°02′ N	89°37′ W	1.684	8.0	2.9	494
Crystal Lake	Near Boulder Junction, Wisconsin	46°00′ N	89°37′ W	0.367	20.4	10.4	502
Trout Lake	Near Boulder Junction, Wisconsin	46°02′ N	89°40′ W	16.079	35.7	14.6	492
Moosehead Lake	Near Greenville, Maine	45°45′ N	69°45′ W	331.000	75.0	16.6	319

* Experimental Lakes Area

4. DATA

4.1 Lake Ice Data

Data of ice-in dates, ice-off dates and ice cover duration for the five lakes were assembled by Adams (1997). The data were provided by individuals and organizations which are listed in the Acknowledgment section.

Tables 4.1 to 4.5 give the observed ice-on and ice-off dates for ELA Lake 239 from 1969 to 1995, Allequash Lake from 1981 to 1990, Crystal Lake from 1981 to 1990, and Trout Lake from 1981 to 1990, and the ice-off dates for Moosehead Lake from 1948 to 1988.

4.2 Weather Data

To run the simulation model, daily weather data are required as input. Unfortunately on-site weather data are not available, and off-site data have to be used in the simulations. Weather data were compiled by the National Climate Data Center obtained from the Solar And Meteorological Surface Observation Network (SAMSON) for the years 1961 to 1990. Two weather stations in Minnesota (International Falls and Duluth) and one in Maine (Caribou) were used in this study. Table 4.6 gives the names and locations of the weather stations used for the simulation of each lake.

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 choice of weather stations was mainly determined by the distance from the lake to the weather station. The station nearest the lake was used for simulation. If the lake was located approximately midway between two stations, simulations with data from both stations were made and the one giving the smallest standard error between simulation results and observed data was retained.

The projected climate changes under a doubling of atmospheric carbon dioxide ($2xCO_2$) were obtained from the Canadian Climate Center General Circulation Model (CCC-GCM). Monthly average changes in air temperature, dew point temperature, wind speed, solar radiation and precipitation which were used to specify the $2xCO_2$ climate scenario are given in Tables 4.7 to 4.9 for International Falls, MN, Duluth, MN and Caribou, ME, respectively.

Table 4.1. Observed ice-on and ice-off dates for Lake 239 of the Experimental Lakes Area, Canada

Year	Ice-off (Date)	Ice-off (Julian day)	Ice-on (Date)	Ice-on (Julian day)
1969	Apr. 27	117	Nov. 16	320
1970	May 16	136	Nov. 15	319
1971	May 01	121	Nov. 10	314
1972	May 05	126	Nov. 14	319
1973	May 01	121	Nov. 18	322
1974	May 09	124	Nov. 15	319
1975	May 07	127	Nov. 23	327
1976	Apr. 23	114	Nov. 08	313
1977	Apr. 27	117	Nov. 22	326
1978	May 06	126	Nov. 19	323
1979	May 13	133	Nov. 11	315
1980	Apr. 26	117	Nov. 21	326
1981	Apr. 20	110	Nov. 20	324
1982	May 02	122	Nov. 21	325
1983	May 05	125	Dec. 01	335
1984	Apr. 24	115	Nov. 15	320
1985	Apr. 24	114	Nov. 21	325
1986	Apr. 21	111	Nov. 11	315
1987	Apr. 17	107	Nov. 21	325
1988	Apr. 30	121	Nov. 23	328
1989	May 11	131	Nov. 17	321
1990	Apr. 26	116	Nov. 19	323
1991	Apr. 28	118	Nov. 04	308
1992	May 09	130	Nov. 15	320
1993	Apr. 29	115	Nov. 06	310
1994	Apr. 23	113	Nov. 23	327
1995	Apr. 30	120	Nov. 08	312

Table 4.2. Observed ice-on and ice-off dates for Allequash Lake, Wisconsin

Year	Ice-off (Date)	Ice-off (Julian day)	Ice-on (Date)	Ice-on (Julian day)
1981	--	--	Dec. 09	343
1982	May 01	121	Nov. 22	326
1983	Apr. 27	117	Nov. 28	332
1984	Apr. 21	112	Nov. 09	314
1985	Apr. 21	111	Nov. 25	329
1986	Apr. 12	102	Nov. 14	318
1987	Apr. 10	100	Nov. 23	327
1988	Apr. 12	103	Nov. 30	335
1989	Apr. 26	116	Nov. 22	326
1990	Apr. 17	107	Dec. 03	337

Table 4.3. Observed ice-on and ice-off dates for Crystal Lake, Wisconsin

Year	Ice-off (Date)	Ice-off (Julian day)	Ice-on (Date)	Ice-on (Julian day)
1981	--	--	Dec. 11	345
1982	May 03	123	Dec. 07	341
1983	Apr. 29	119	Dec. 03	337
1984	Apr. 20	111	Dec. 01	336
1985	Apr. 23	113	Nov. 25	329
1986	Apr. 13	103	Nov. 19	323
1987	Apr. 09	99	Dec. 03	337
1988	Apr. 15	106	Dec. 01	336
1989	Apr. 27	117	Nov. 22	326
1990	Apr. 16	106	Dec. 03	337

Table 4.4. Observed ice-on and ice-off dates for Trout Lake, Wisconsin

Year	Ice-off (Date)	Ice-off (Julian day)	Ice-on (Date)	Ice-on (Julian day)
1981	--	--	Dec. 20	354
1982	May 04	124	Dec. 13	347
1983	May 02	122	Dec. 03	337
1984	Apr. 26	117	Dec 18	353
1985	Apr. 24	114	Dec 04	338
1986	Apr. 15	105	Dec 07	341
1987	Apr. 16	106	Dec 22	356
1988	Apr. 27	118	Dec 12	347
1989	May 03	123	Dec 01	335
1990	Apr. 23	113	Dec 14	348

Table 4.5. Observed ice-off dates for Moosehead Lake, Maine

Year	Date	Julian Day
1848	Apr. 30	121
1849	May 12	132
1850	May 09	129
1851	May 14	134
1852	May 17	138
1853	May 11	131
1854	May 20	140
1855	May 17	137
1856	May 09	130
1857	May 12	132
1858	May 13	133
1859	May 14	134
1860	May 11	132
1861	May 12	132
1862	May 18	138
1863	May 18	138
1864	May 06	127
1865	May 04	124
1866	May 11	131
1867	May 19	139
1868	May 18	139
1869	May 10	130
1870	May 04	124
1871	May 13	133
1872	May 11	132
1873	May 16	136
1874	May 26	146
1875	May 24	144
1876	May 23	144
1877	May 06	126
1878	May 29	149
1879	May 14	134
1880	May 06	127
1881	May 09	129
1882	May 18	138
1883	May 13	133
1884	May 08	129
1885	May 16	136
1886	May 02	122

Year	Date	Julian Year
1887	May 13	133
1888	May 22	143
1889	Apr. 30	120
1890	May 09	129
1891	May 14	134
1892	May 04	125
1893	May 18	138
1894	May 01	121
1895	May 06	126
1896	May 08	129
1897	May 08	128
1898	May 04	124
1899	May 07	127
1900	May 11	132
1901	May 29	149
1902	May 28	148
1903	May 28	148
1904	May 10	131
1905	May 02	122
1906	May 13	133
1907	May 14	134
1908	May 11	132
1909	May 15	135
1910	May 20	110
1911	May 13	133
1912	May 08	129
1913	May 02	122
1914	May 15	135
1915	May 01	121
1916	May 04	125
1917	May 14	134
1918	May 01	121
1919	May 03	123
1920	May 14	135
1921	Apr. 22	112
1922	May 01	121
1923	May 10	130
1924	May 09	130
1925	Apr. 28	118

Table 4.5 (Cont'd)

1926	May 18	138
1927	Apr. 25	115
1928	May 12	133
1929	May 08	128
1930	May 05	125
1931	Apr. 24	114
1932	May 05	126
1933	May 04	124
1934	May 04	124
1935	May 10	130
1936	May 02	123
1937	May 10	130
1938	Apr. 29	119
1939	May 17	137
1940	May 17	138
1941	Apr. 29	119
1942	May 05	125
1943	May 18	138
1944	May 14	135
1945	Apr. 14	104
1946	May 06	126
1947	May 13	133
1948	May 04	125
1949	Apr. 23	113
1950	May 07	127
1951	Apr. 29	119
1952	Apr. 30	121
1953	Apr. 24	114
1954	May 02	122
1955	May 04	124
1956	May 15	136
1957	May 02	122
1958	May 02	122
1959	May 09	129
1960	May 06	127
1961	May 17	137
1962	May 18	138
1963	May 07	127
1964	May 07	128
1965	May 07	127
1966	May 06	126
1967	May 08	128
1968	Apr. 25	116
1969	May 13	133
1970	May 16	136
1971	May 14	134
1972	May 22	143
1973	May 05	125
1974	May 16	136
1975	May 12	132
1976	May 01	122
1977	May 06	126
1978	May 15	135
1979	May 01	121
1980	May 02	123
1981	Apr. 27	117
1982	May 13	133
1983	May 02	122
1984	May 06	127
1985	May 03	123
1986	May 28	148
1987	May 21	141
1988	May 03	124

Table 4.6. Summary of the weather stations used in the simulations

Lake Name	Station Name	Latitude	Longitude	Elevation (m)	Distance to lake (km)
Lake 239	International Falls, MN	48°34′ N	93°23′ W	361.0	124.8
Allequash Lake	Duluth, MN	46°50′ N	92°11′ W	432.0	215.3
Crystal Lake	Duluth, MN	46°50′ N	92°11′ W	432.0	216.7
Trout Lake	Duluth, MN	46°50′ N	92°11′ W	432.0	211.8
Moosehead Lake	Caribou, ME	46°52′ N	68°01′ W	190.0	182.0

Table 4.7 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 = $2xCO_2 - 1xCO_2$

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

Table 4.8 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 = $2xCO_2 - 1xCO_2$
[2] ratio = $2xCO_2/1xCO_2$

Table 4.9 CCC-GCM $2xCO_2$ climate scenario for Caribou, Maine.

Month	Air temp. difference[1] (°C)	Specific humidity ratio[2]	Wind speed ratio	Solar radiation ratio	Precipitation ratio
Jan	7.17	1.53	1.05	0.94	1.03
Feb	7.25	1.72	1.12	0.94	1.29
Mar	4.11	1.40	0.93	0.97	1.02
Apr	3.16	1.34	1.00	0.97	1.11
May	4.21	1.32	1.01	1.02	0.97
Jun	4.46	1.36	0.91	0.98	0.93
Jul	4.20	1.31	0.88	0.94	1.12
Aug	3.92	1.30	0.90	0.97	0.89
Sep	3.93	1.31	0.93	0.97	1.26
Oct	3.28	1.27	0.90	0.99	0.93
Nov	1.86	1.17	0.95	0.99	0.91
Dec	1.03	1.15	0.88	1.00	1.07

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

5. MODEL APPLICATION

5.1 Results for Past Climate Conditions

The model was applied to each of the five lakes with the appropriate weather data input, and without calibration. Simulated and observed average values of the ice-on date, ice-off date, ice cover duration and their standard deviations are summarized in Tables 5.1 to 5.5 for ELA Lake 239, Allequash Lake, Crystal Lake, Trout Lake and Moosehead Lake, respectively. The average values are over periods ranging from 10 to 27 years. The average standard errors between simulated and observed ice-on dates, ice-off dates and ice cover durations after removal of bias are 7 days, 6 days and 10 days, respectively.

5.1.1 Ice on dates

The observed ice-on dates range from calendar day 322 for ELA Lake 239 to calendar day 346 for Trout Lake; the ice-off dates range from calendar day 110 for Allequash Lake to calendar day 129 for Moosehead Lake. The differences may have several causes. First, the lakes are located in regions with different meteorological conditions. Second, the morphometry differs from lake to lake. Depth of a lake is an important factor in determining the ice-on date. Finally, wind has an effect on ice formation and wind sheltering is affected by topography and lake surface area.

Time series of the simulated and observed ice-on dates for ELA Lake 239, Allequash Lake, Crystal Lake and Trout Lake, respectively, are shown in Figs. 5.1 to 5.4. The simulated ice-on date is the date at which a lake's ice cover is finally completely formed. We can see that the simulated ice-on dates are several days earlier than the observed ones for most of the simulated years. The bias given in Tables 5.1 to 5.4 is from -2 to 11 days. It is larger for the lakes with larger surface area. This would suggest a wind effect. The exact reason is not known. Possible reasons are: (1) Ground water effect. Ground water inflow delays the formation of an ice cover. The model does not simulate ground water inflow. (2) Wind effect. During several days after ice cover formation, ice can be only a few millimeters to several centimeters thick. Winds may be able to break up the ice cover and delay the date of complete ice cover formation. The model does not include ice break-up by wind. The difference between simulated and observed ice-on dates for Trout Lake is bigger than for the other two Wisconsin lakes and may be due to the larger wind fetch of Trout Lake. Trout Lake has a larger surface area. (3) Measurement errors. An ice cover may form several times under the effect of alternating cold and warm weather. It is unclear whether the observed data were obtained at the first or the last freeze-over. (4) Meteorological data. The meteorological data used in the simulation were not on-site data. In late fall or early winter, northwest winds bring warm air from Lake Superior to northern Wisconsin. At the weather station in Duluth,

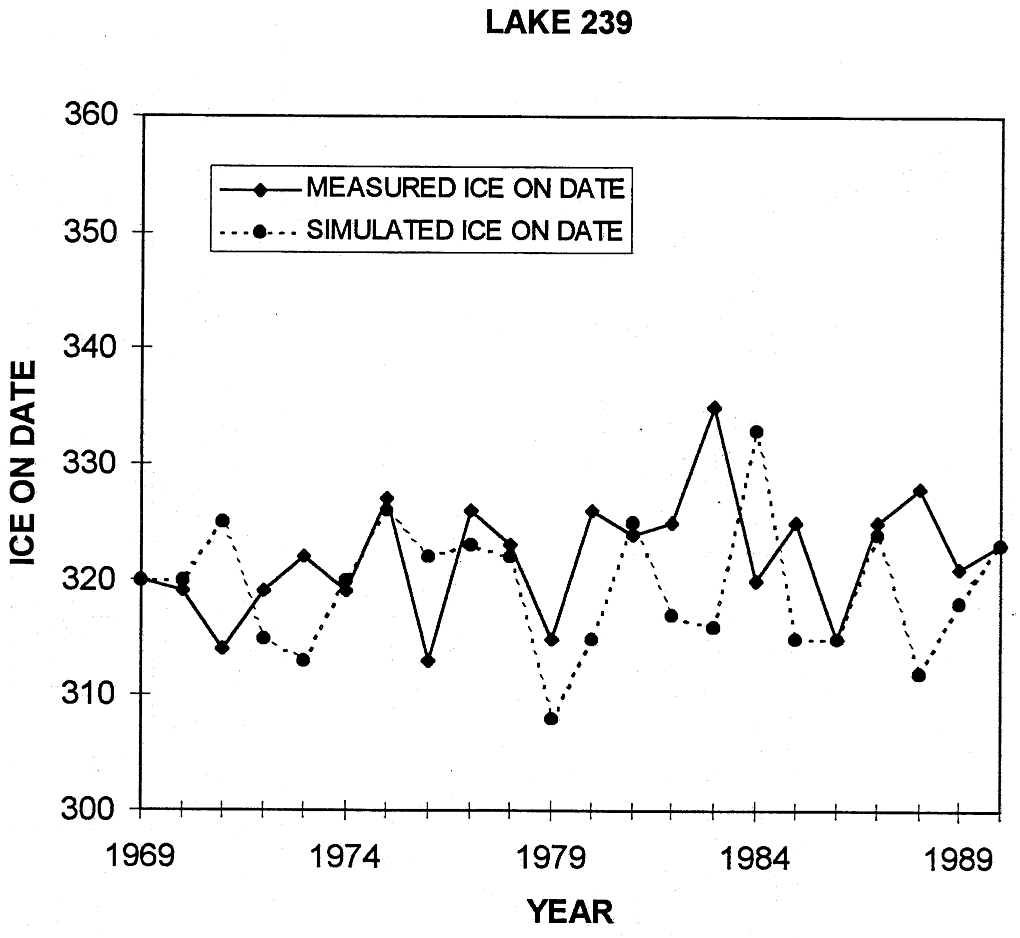

Fig. 5.1. Simulated and observed ice-on dates for ELA Lake 239

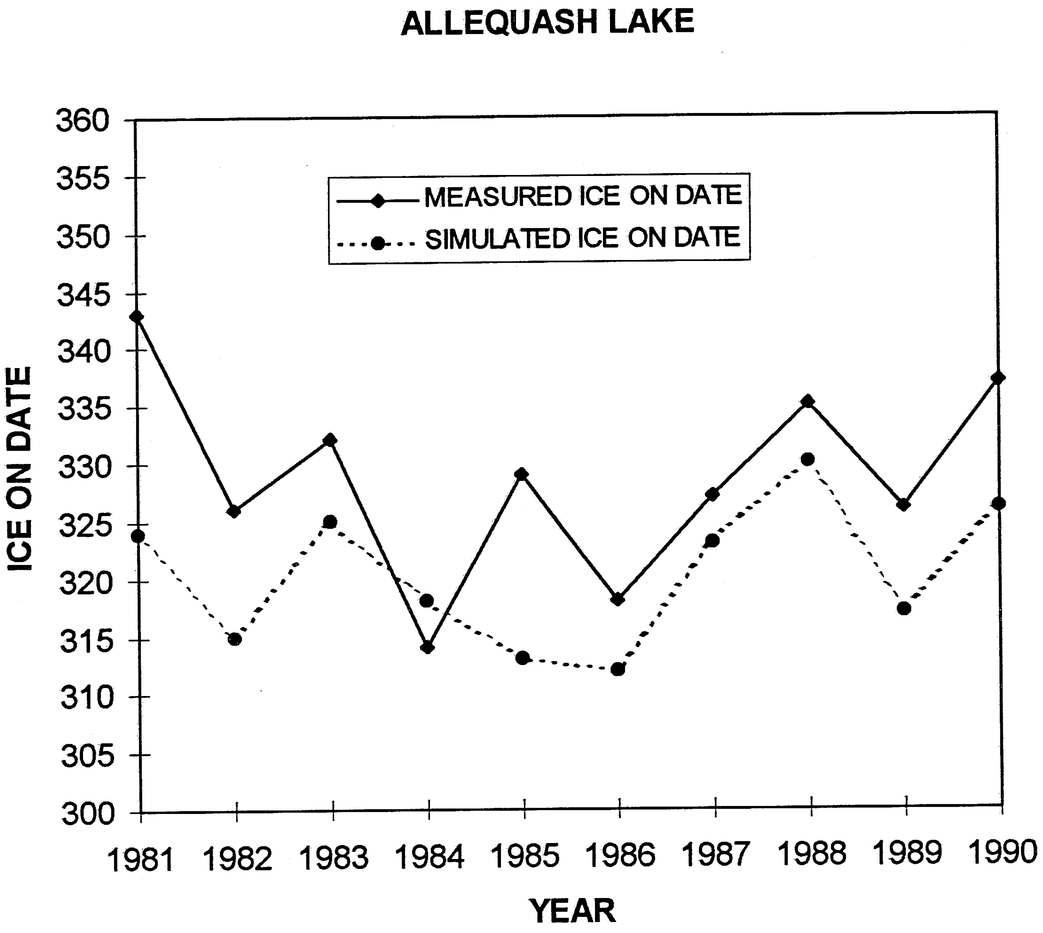

Fig. 5.2. Simulated and observed ice-on dates for Allequash Lake

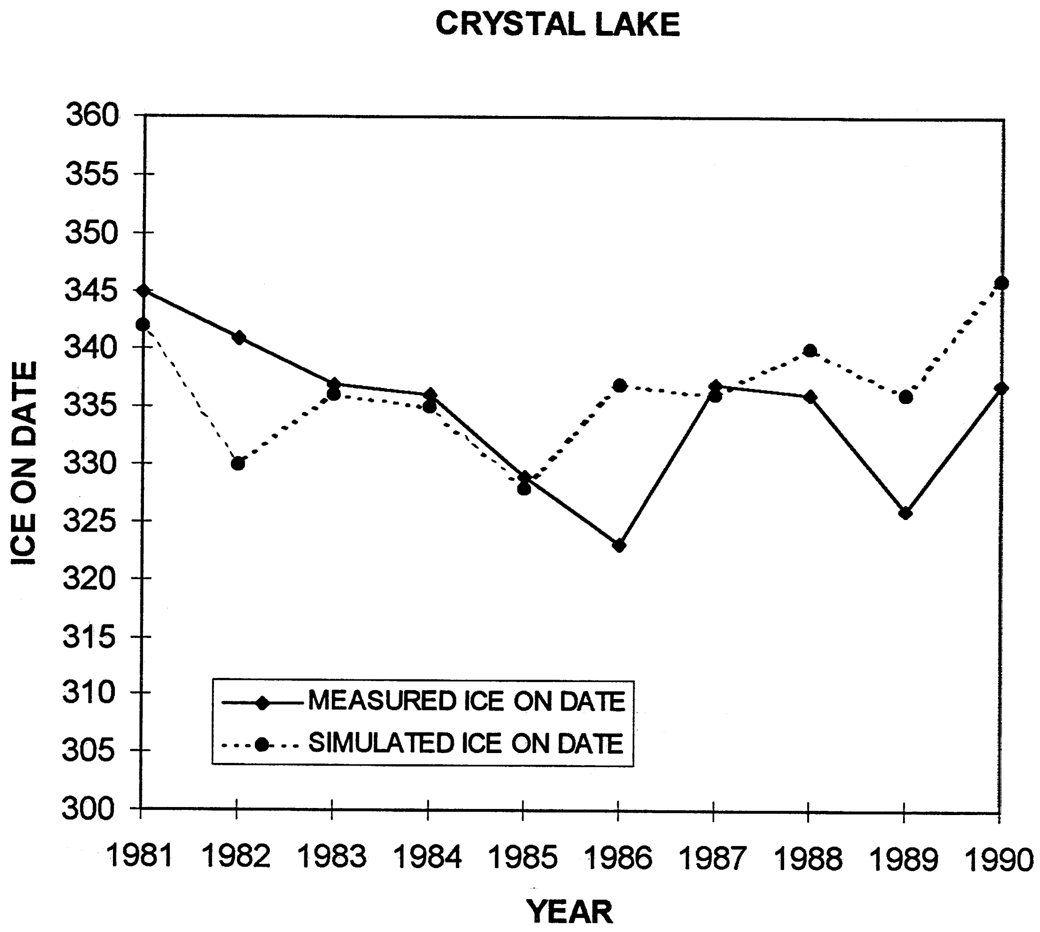

Fig. 5.3. Simulated and observed ice-on dates for Crystal Lake

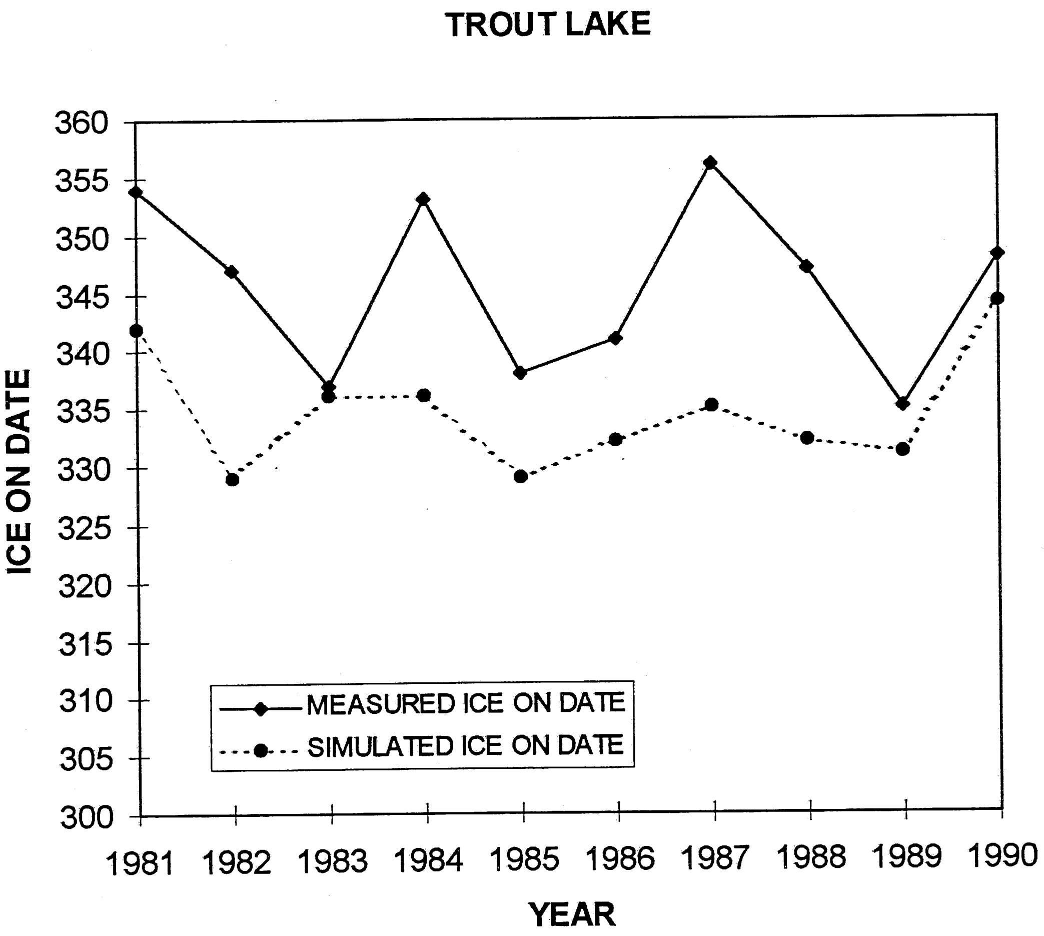

Fig. 5.4. Simulated and observed ice-on dates for Trout Lake

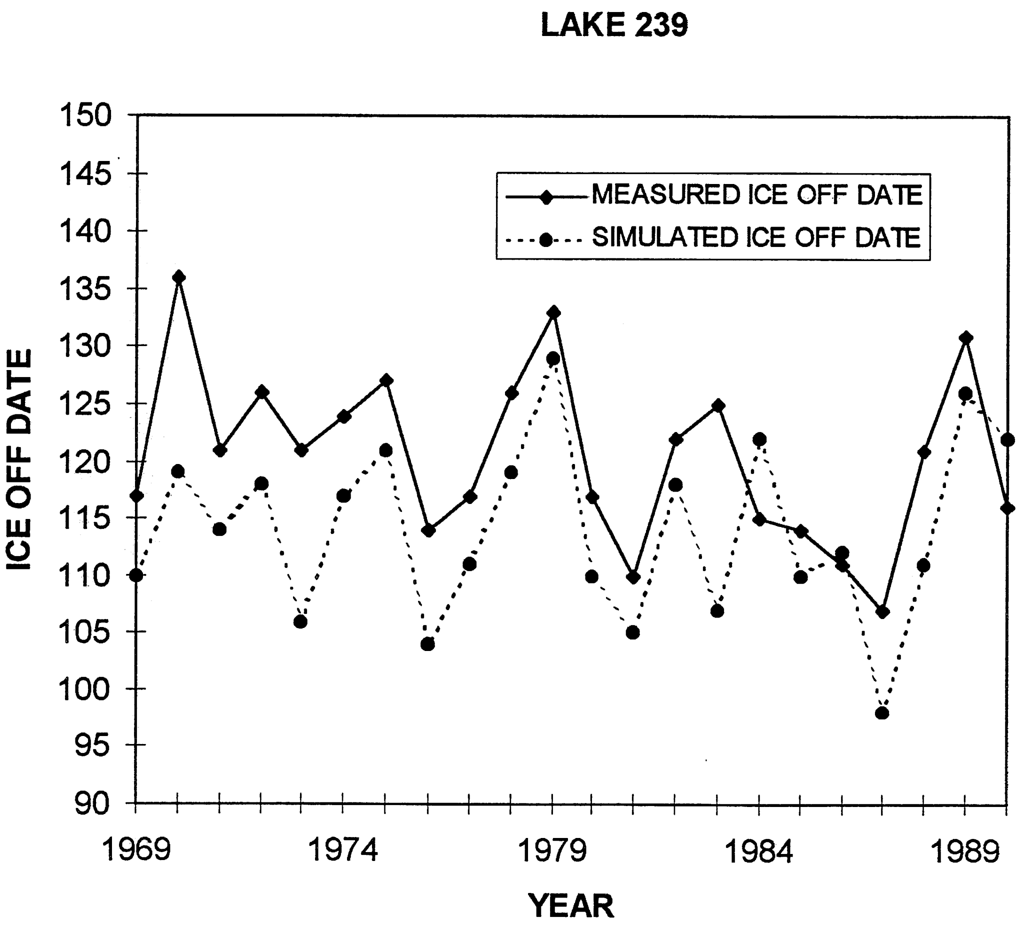

Fig. 5.5. Simulated and observed ice-off dates for ELA Lake 239

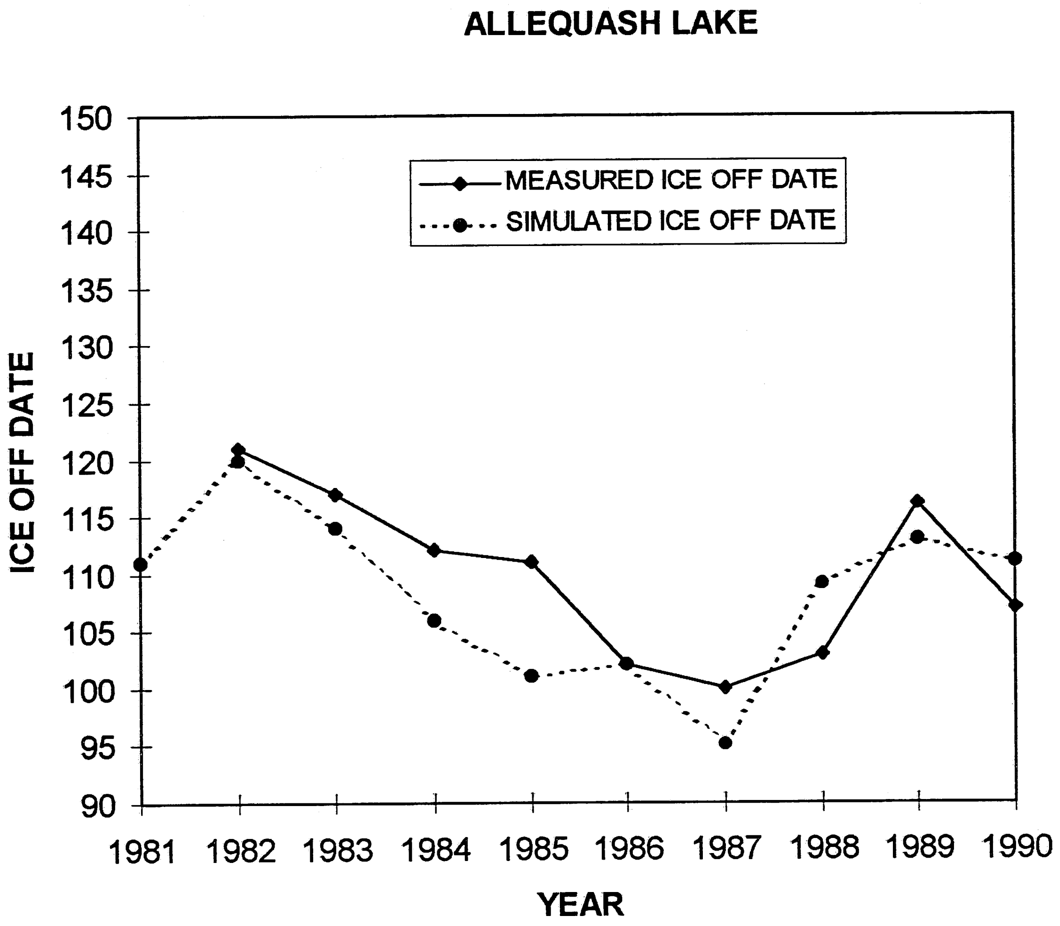

Fig. 5.6. Simulated and observed ice-off dates for Allequash Lake

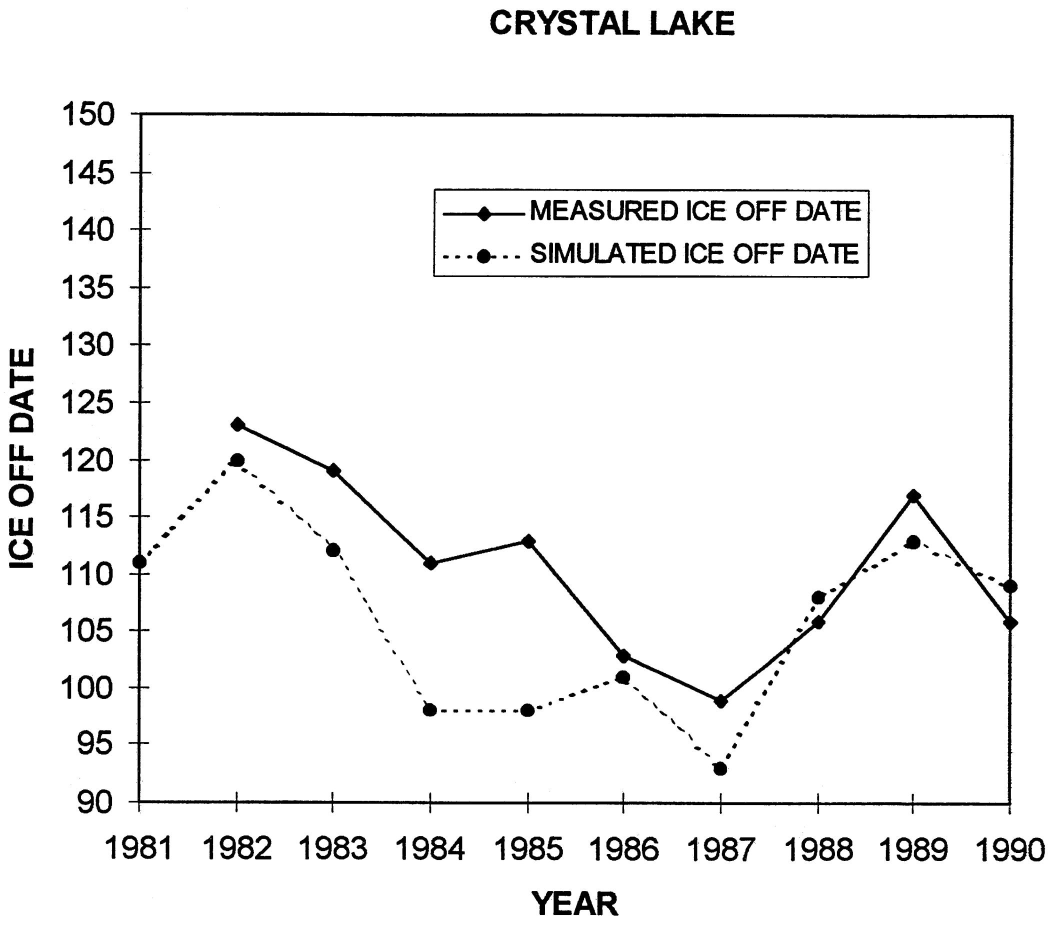

Fig. 5.7. Simulated and observed ice-off dates for Crystal Lake

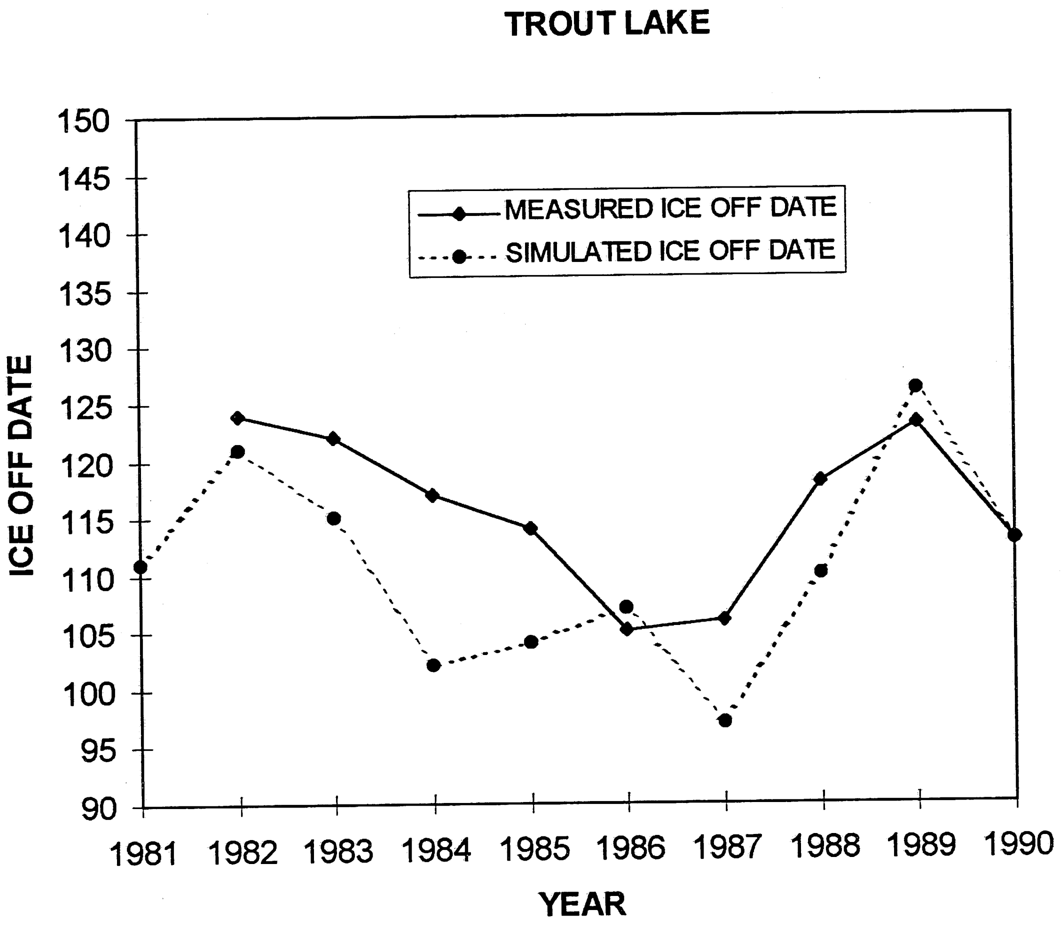

Fig. 5.8. Simulated and observed ice-off dates for Trout Lake

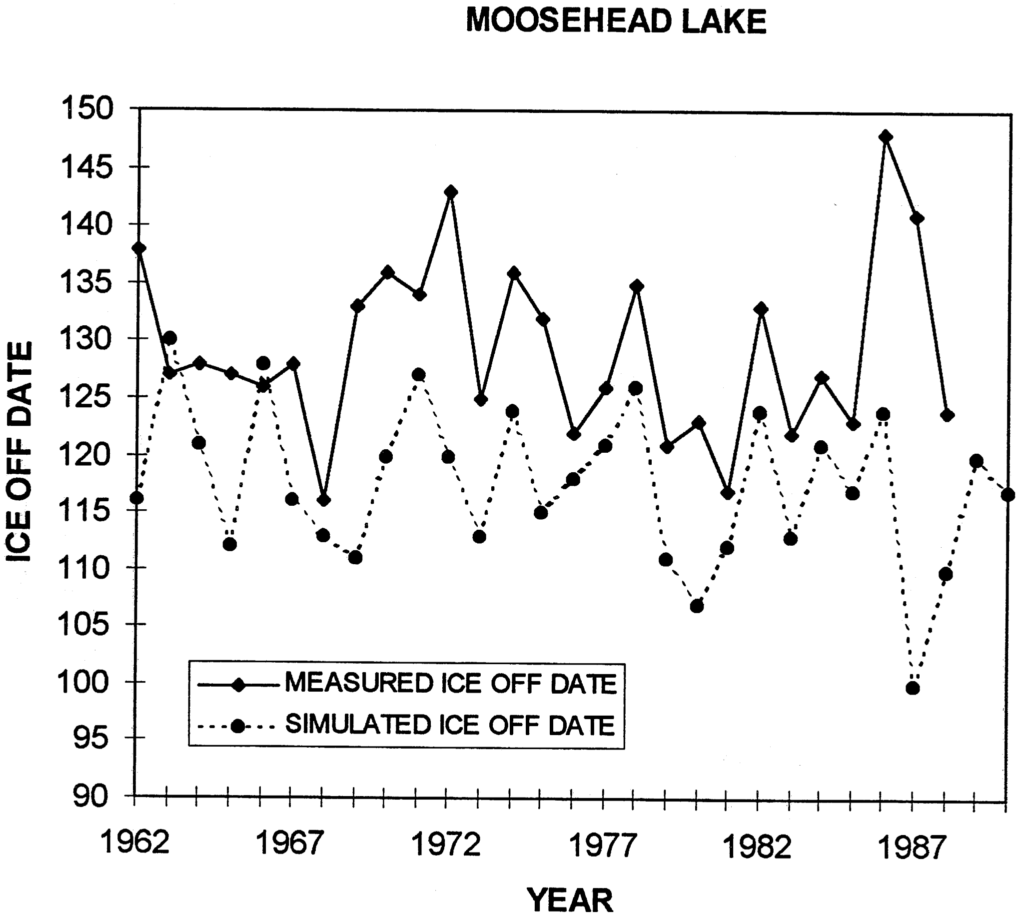

Fig. 5.9. Simulated and observed ice-off dates for Moosehead Lake

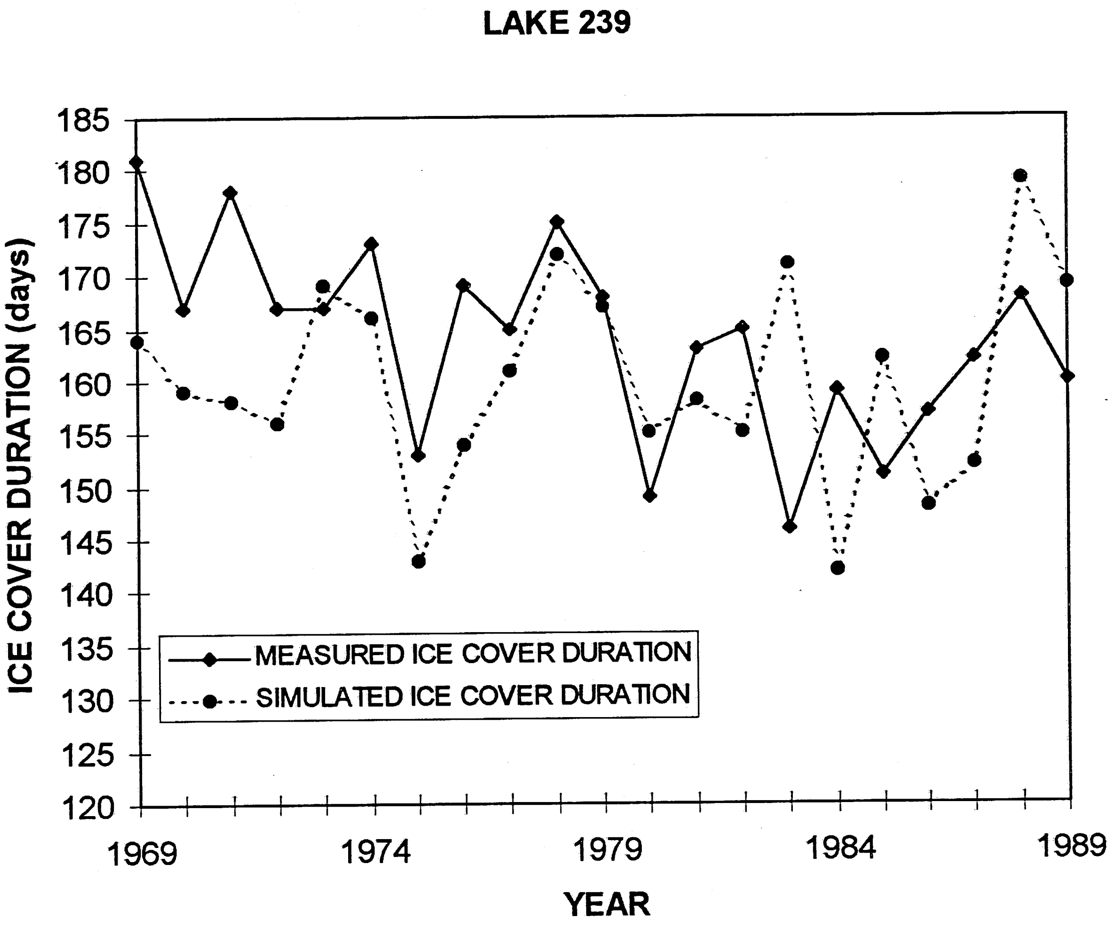

Fig. 5.10. Simulated and observed ice cover durations for ELA Lake 239

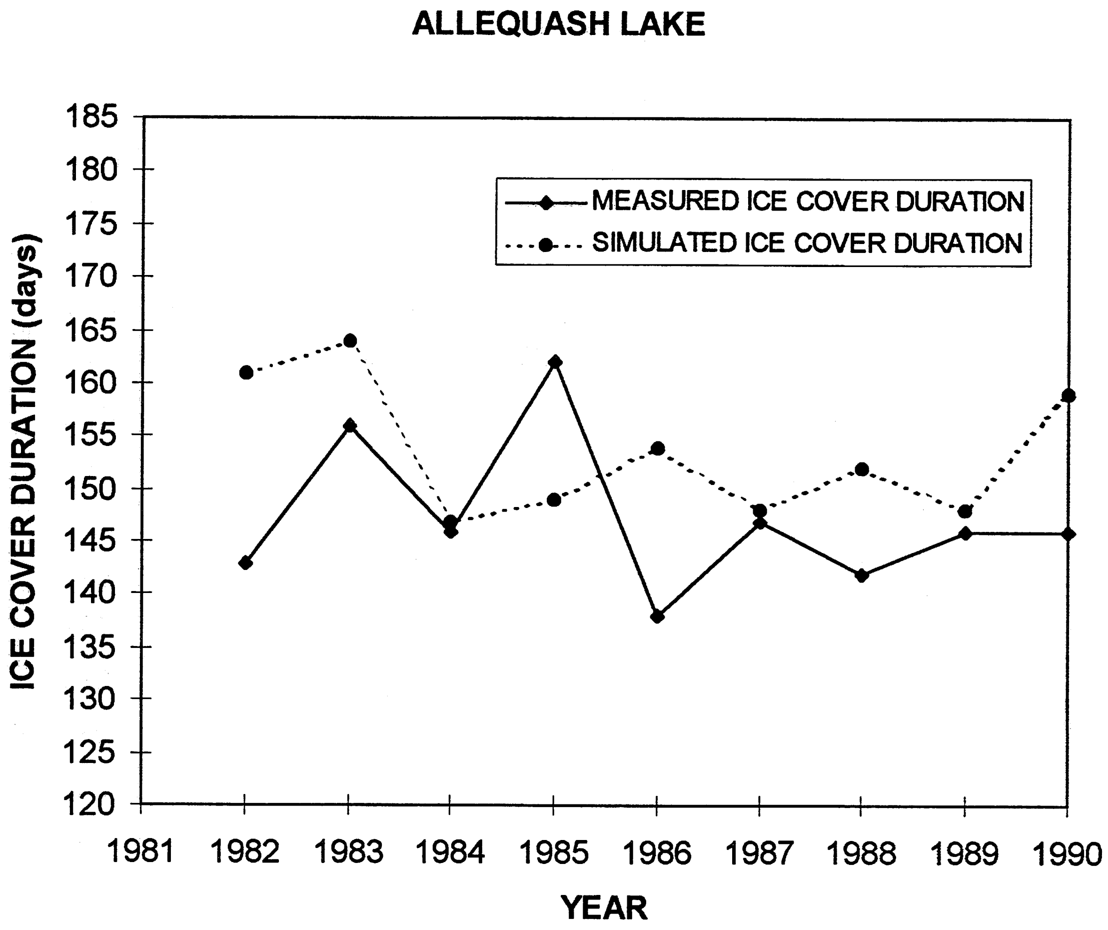

Fig. 5.11. Simulated and observed ice cover durations for Allequash Lake

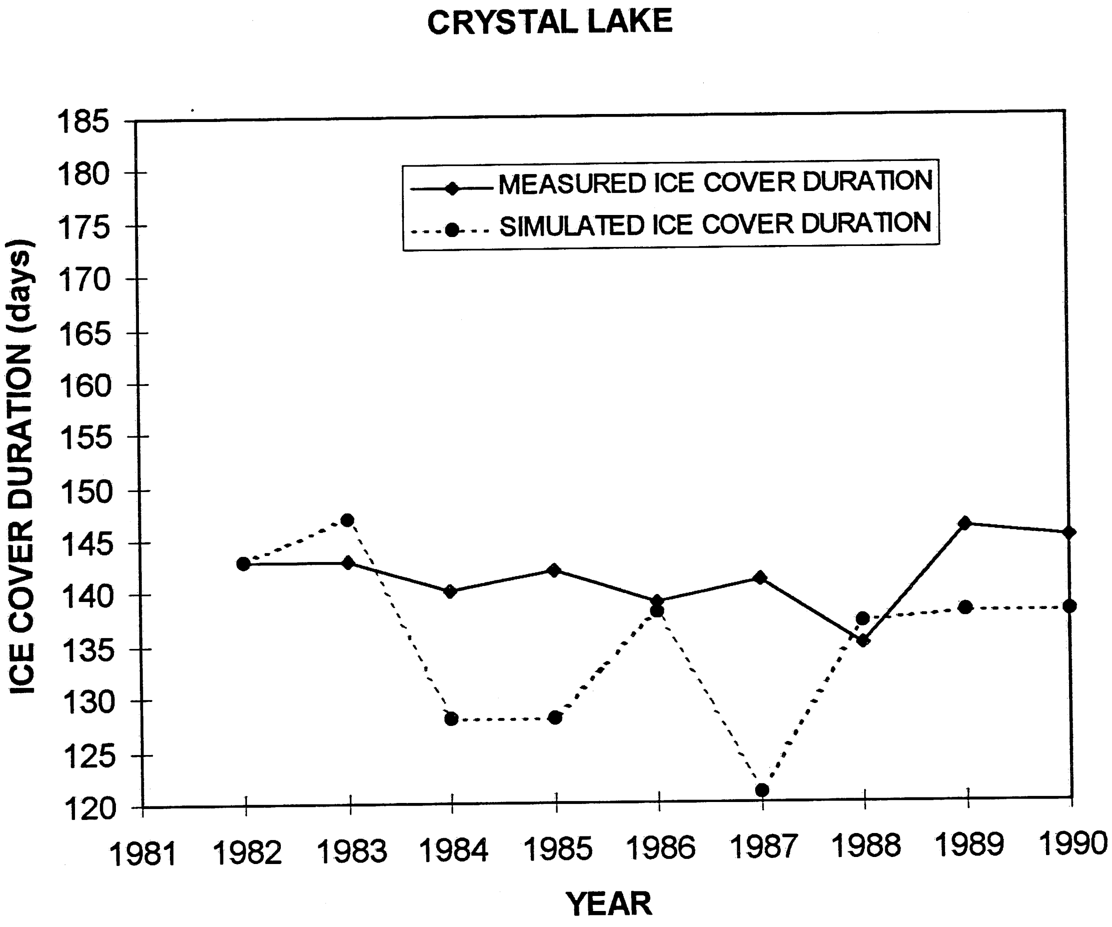

Fig. 5.12. Simulated and observed ice cover durations for Crystal Lake

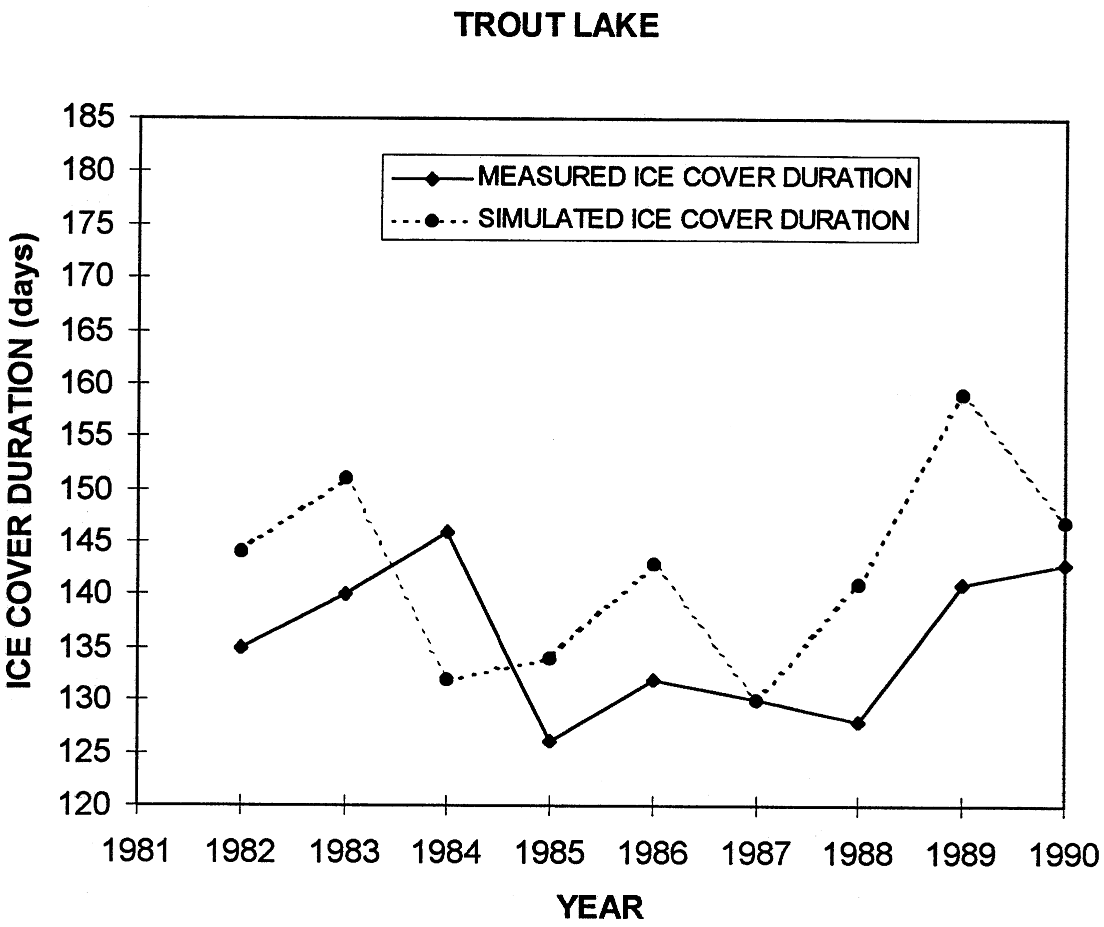

Fig. 5.13. Simulated and observed ice cover durations for Trout Lake

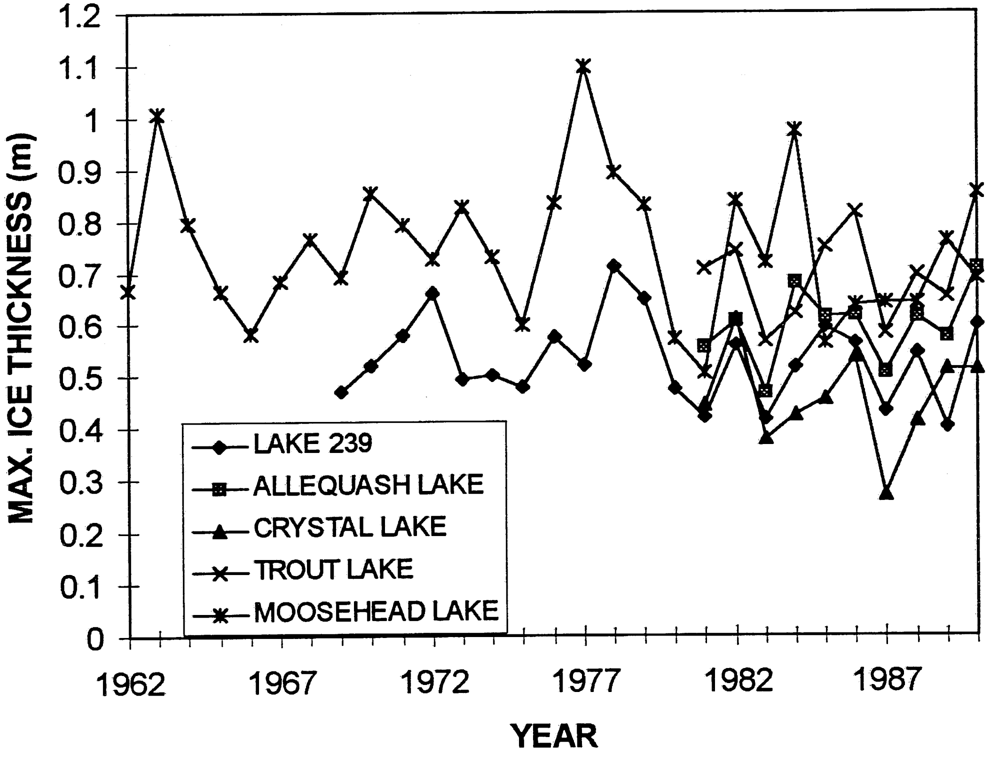

Fig. 5.14. Simulated maximum ice thicknesses for the five lakes

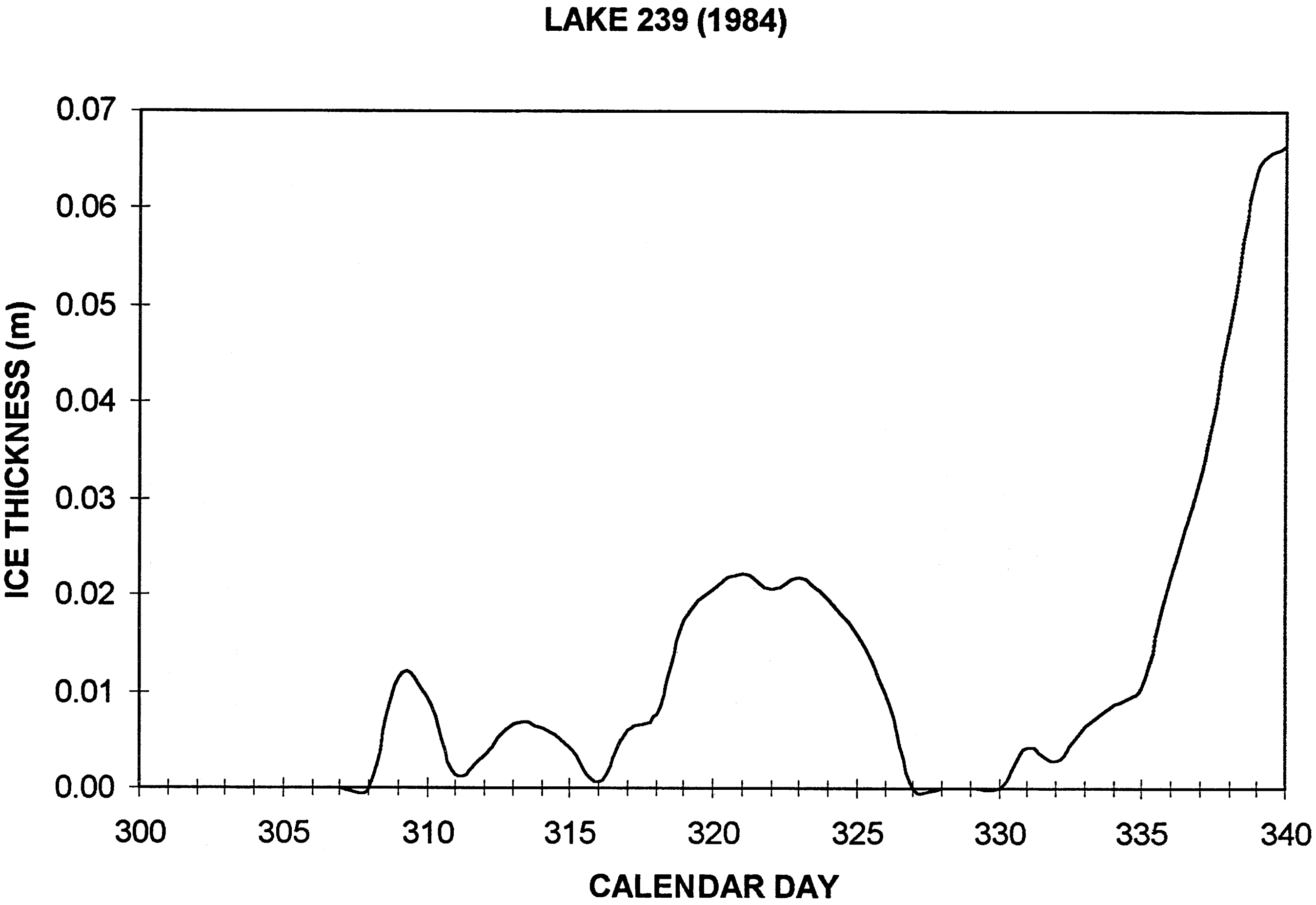

Fig. 5.15. Ice thicknesses at the beginning of the winter season for ELA Lake 239 in 1984

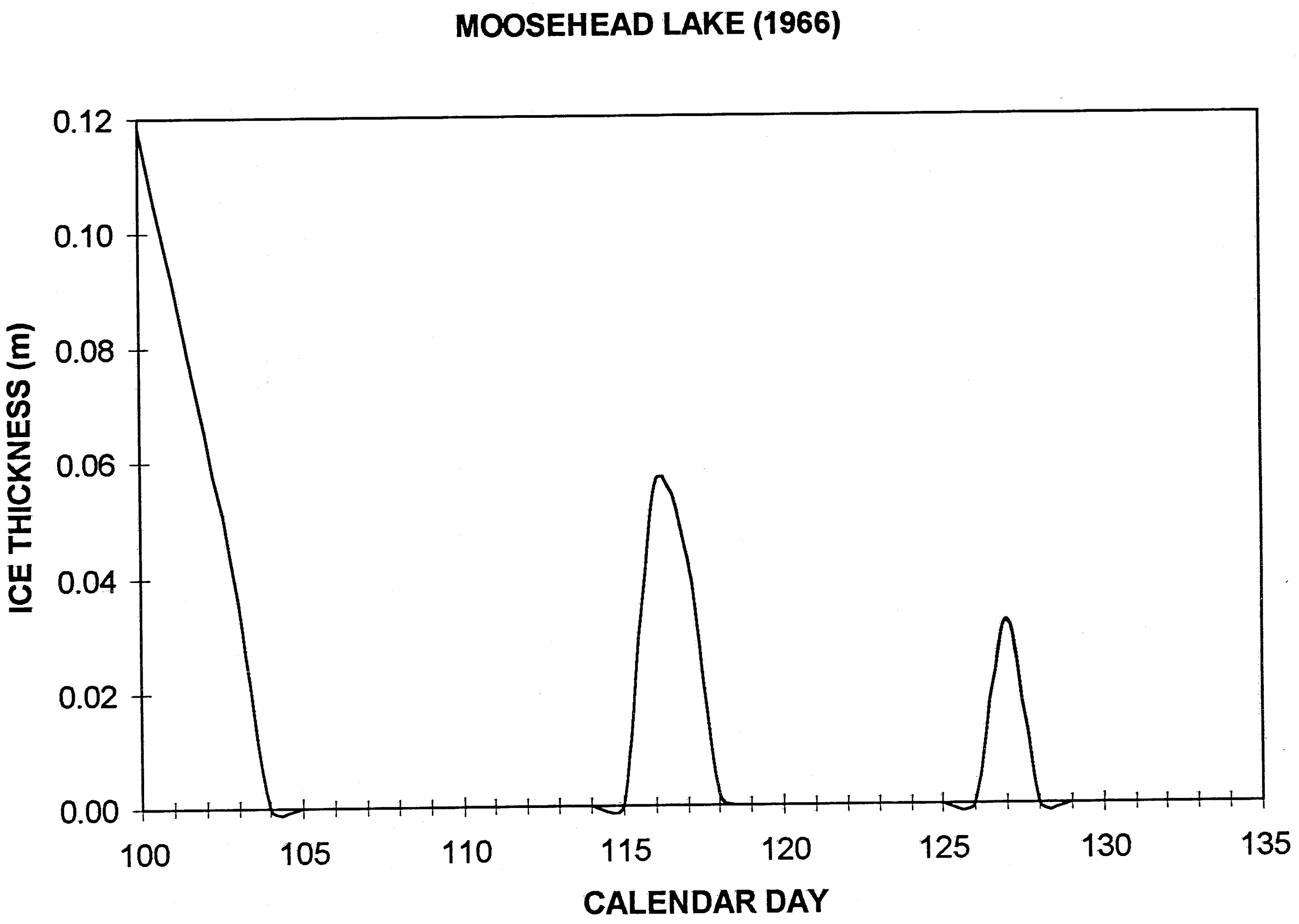

Fig. 5.16. Ice thicknesses at the end of the winter season for Moosehead Lake in 1966

Table 5.9. Simulated ice-on date, ice-off date, ice cover duration and maximum ice thickness for Trout Lake under past and $2xCO_2$ climate scenarios

	Past Average[1]	Past STD[2]	$2xCO_2$ Average[1]	$2xCO_2$ STD[2]	RMS[3]	DELTA[4]
Ice-on date (Julian day)	335	5	347	8	13	12
Ice-off date (Julian day)	111	9	88	8	24	-23
Ice cover duration (days)	142	9	109	11	35	-33
Max ice thickness (m)	0.70	0.09	0.40	0.11	0.31	-0.30

Note: [1]-Average from year 1969 to 1990
[2]-Standard deviation from its average (STD)
[3]-Root mean square of change from past to $2xCO_2$ climate scenario
[4]-Difference of averages ($2xCO_2$ average - Past average)

Table 5.10. Simulated ice-on date, ice-off date, ice cover duration and maximum ice thickness for Moosehead Lake under past and $2xCO_2$ climate scenarios

	Past Average[1]	Past STD[2]	$2xCO_2$ Average[1]	$2xCO_2$ STD[2]	RMS[3]	DELTA[4]
Ice-on date (Julian day)	337	5	344	4	9	7
Ice-off date (Julian day)	117	7	98	8	22	-19
Ice cover duration (days)	146	8	120	9	29	-26
Max ice thickness (m)	0.74	0.14	0.46	0.12	0.31	-0.28

Note: [1]-Average from year 1969 to 1990
[2]-Standard deviation from its average (STD)
[3]-Root mean square of change from past to $2xCO_2$ climate scenario
[4]-Difference of averages ($2xCO_2$ average - Past average)

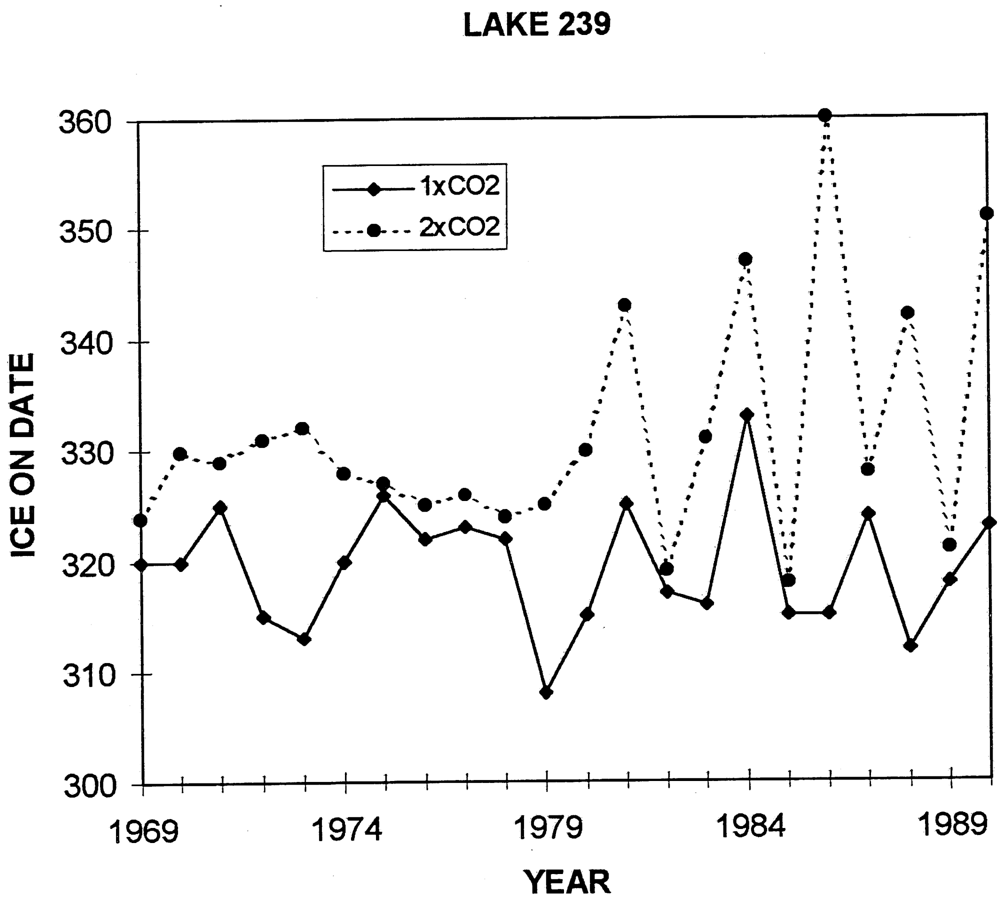

Fig. 5.17. Simulated ice-on dates for ELA Lake 239 under past and 2xCO_2 climate scenarios

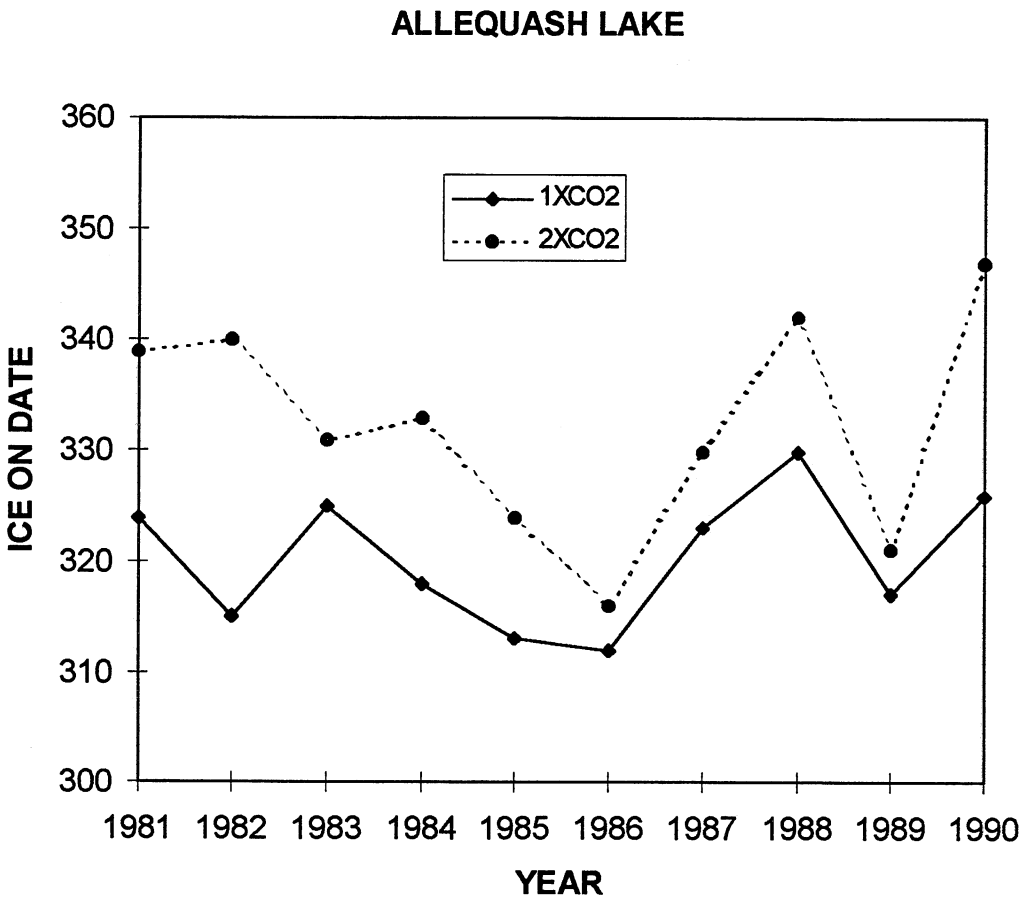

Fig. 5.18. Simulated ice-on dates for Allequash Lake under past and $2xCO_2$ climate scenarios

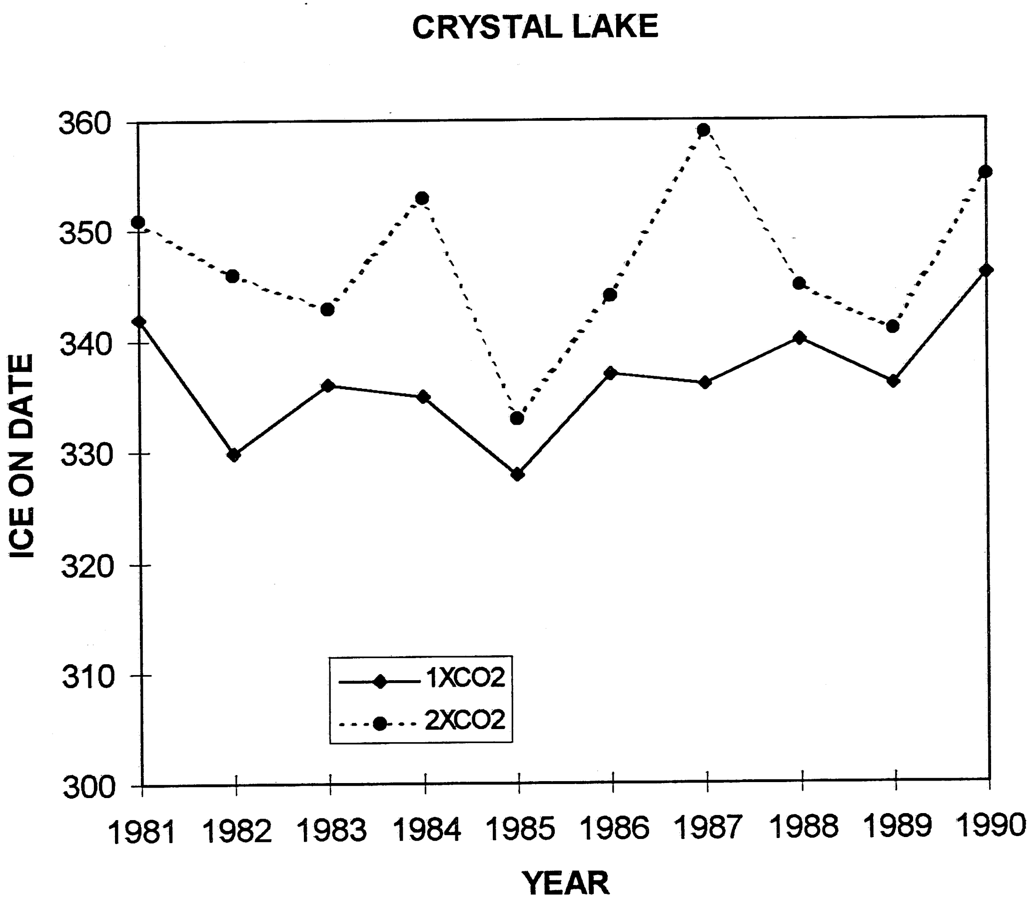

Fig. 5.19. Simulated ice-on dates for Crystal Lake under past and $2xCO_2$ climate scenarios

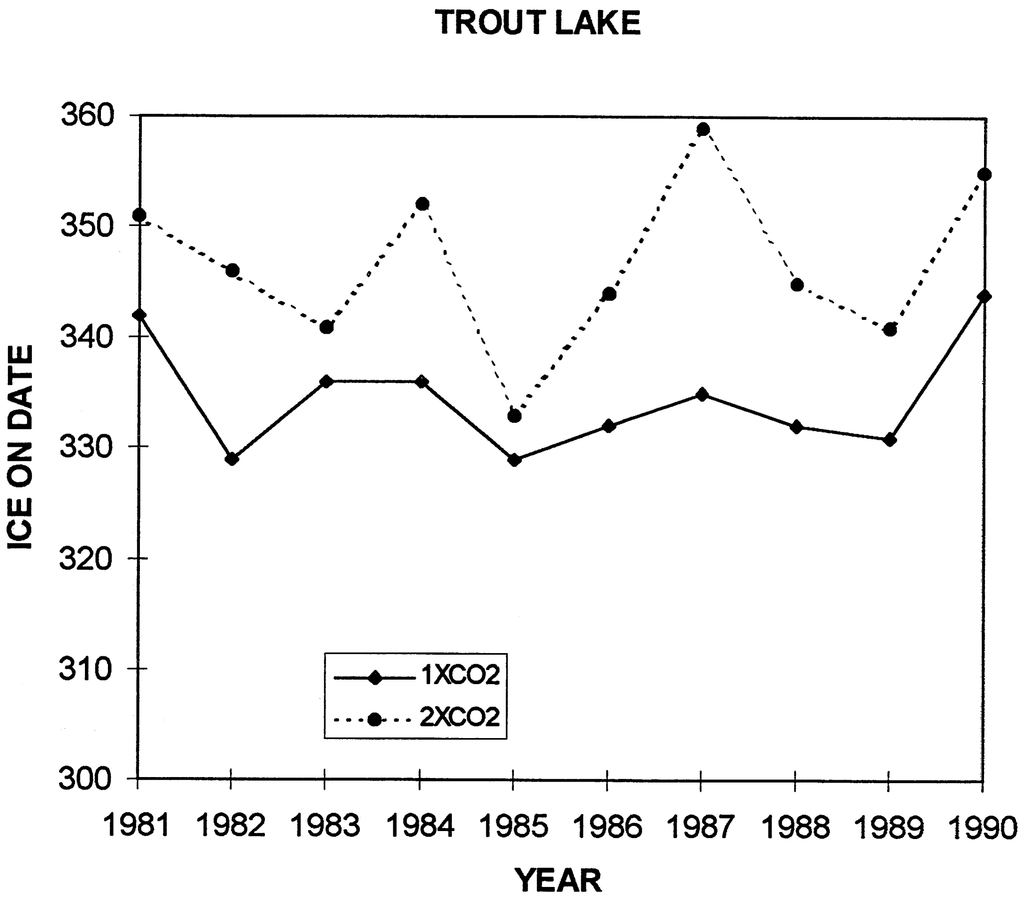

Fig. 5.20. Simulated ice-on dates for Trout Lake under past and $2xCO_2$ climate scenarios

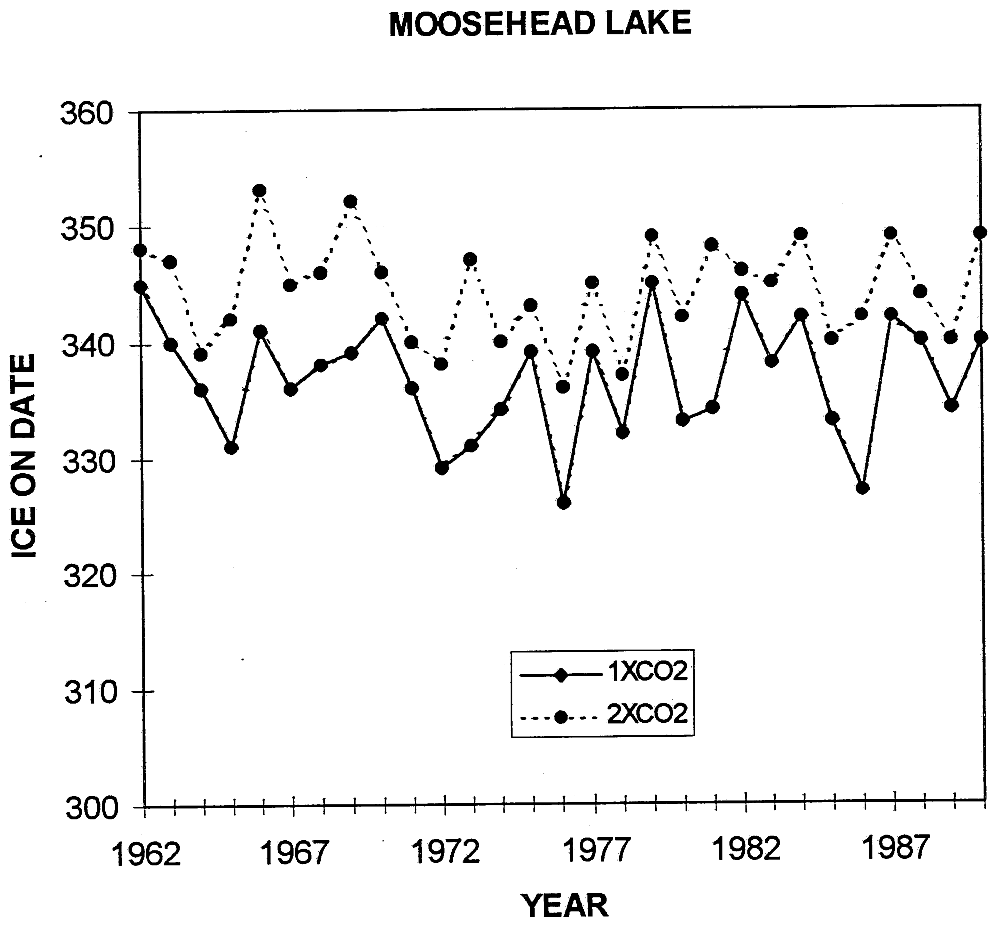

Fig. 5.21. Simulated ice-on dates for Moosehead Lake under past and $2xCO_2$ climate scenarios

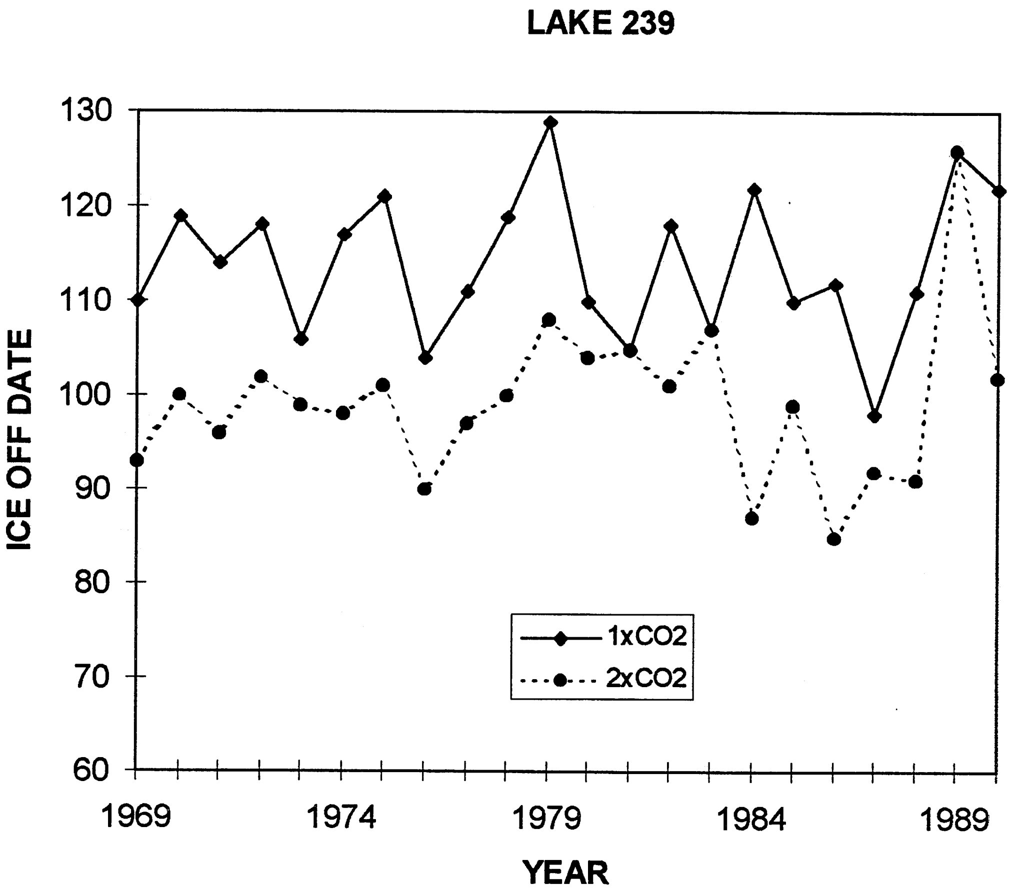

Fig. 5.22. Simulated ice-off dates for ELA Lake 239 under past and $2xCO_2$ climate scenarios

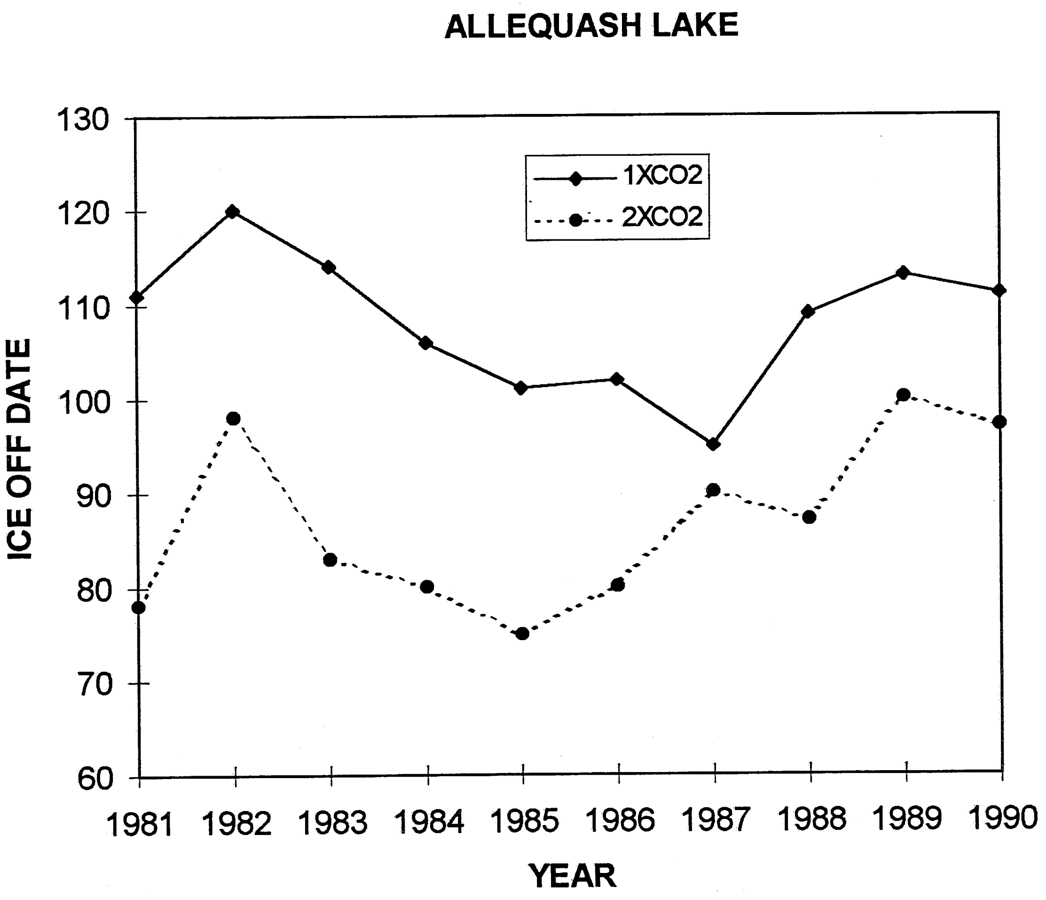

Fig. 5.23. Simulated ice-off dates for Allequash Lake under past and $2xCO_2$ climate scenarios

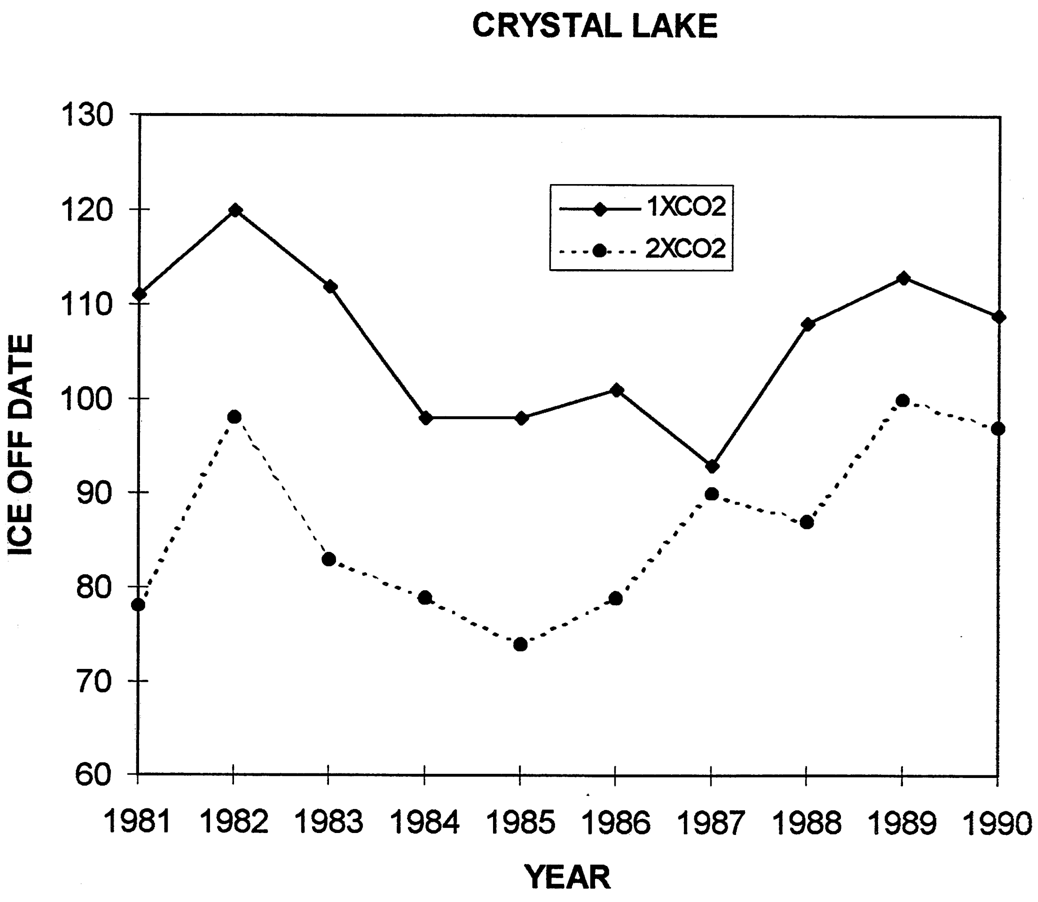

Fig. 5.24. Simulated ice-off dates for Crystal Lake under past and $2xCO_2$ climate scenarios

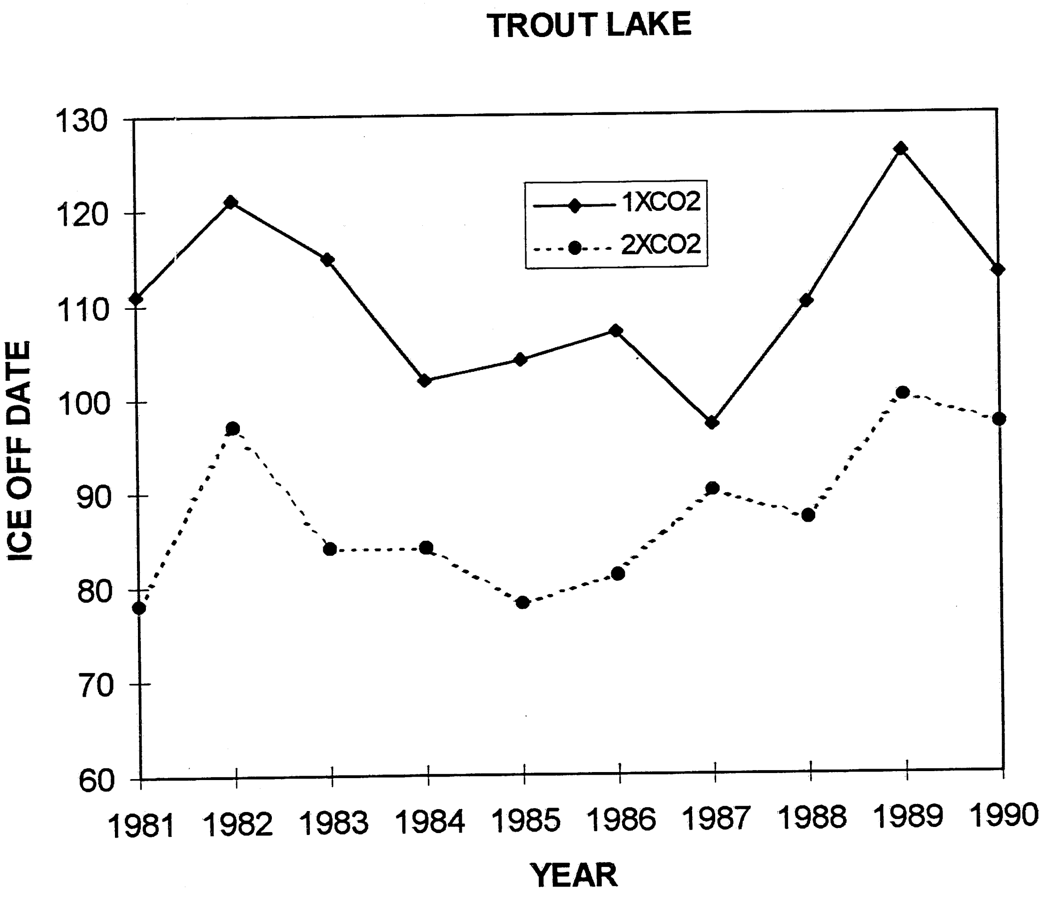

Fig. 5.25. Simulated ice-off dates for Trout Lake under past and $2xCO_2$ climate scenarios

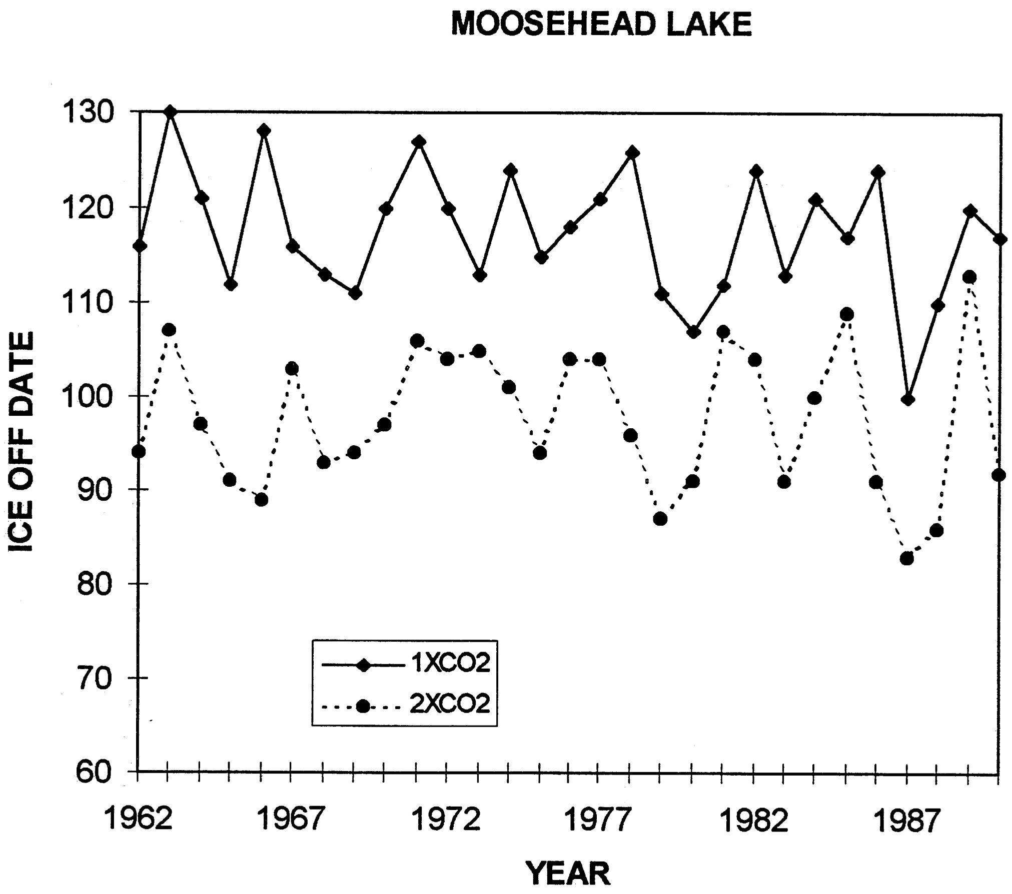

Fig. 5.26. Simulated ice-off dates for Moosehead Lake under past and $2xCO_2$ climate scenarios

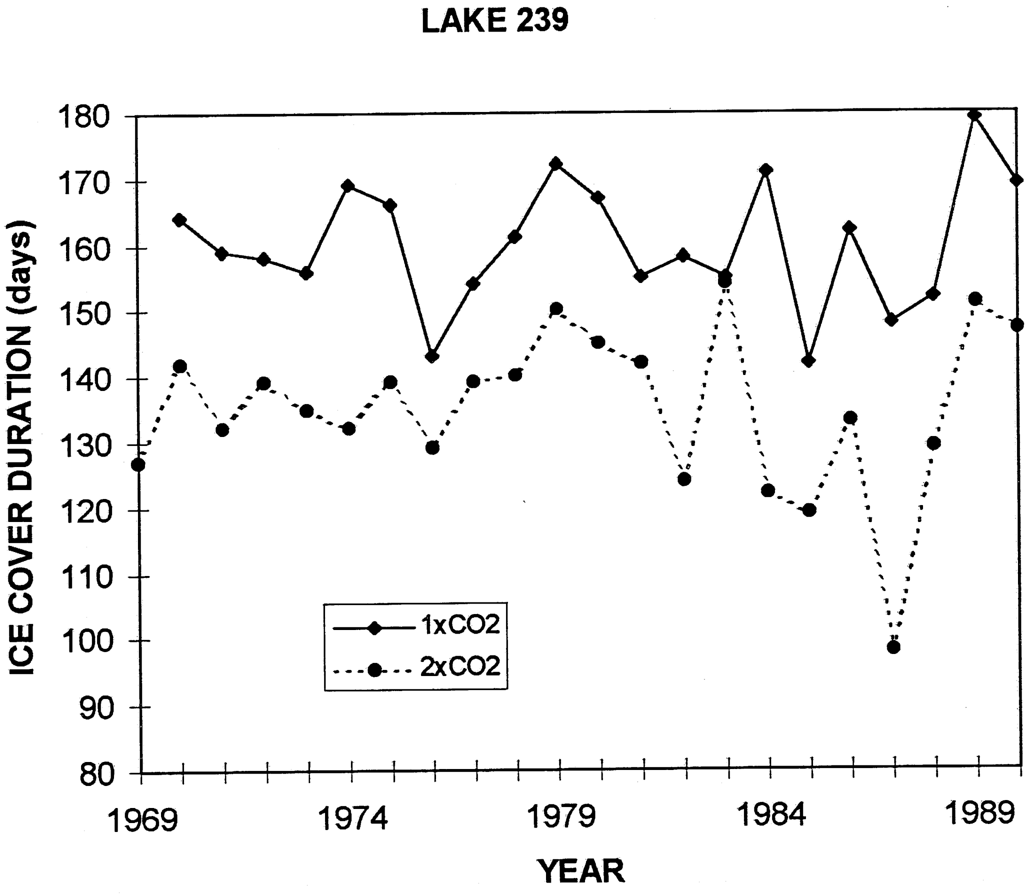

Fig. 5.27. Simulated ice cover durations for ELA Lake 239 under past and $2xCO_2$ climate scenarios

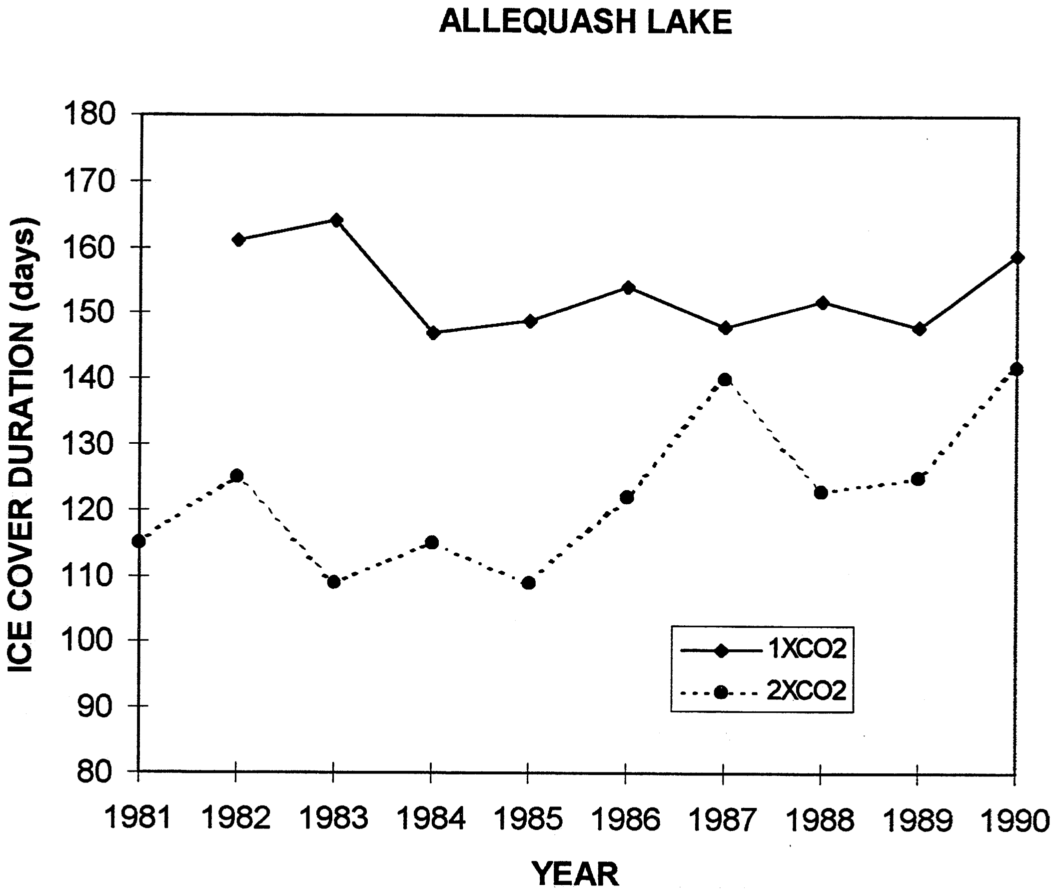

Fig. 5.28. Simulated ice cover durations for Allequash Lake under past and $2xCO_2$ climate scenarios

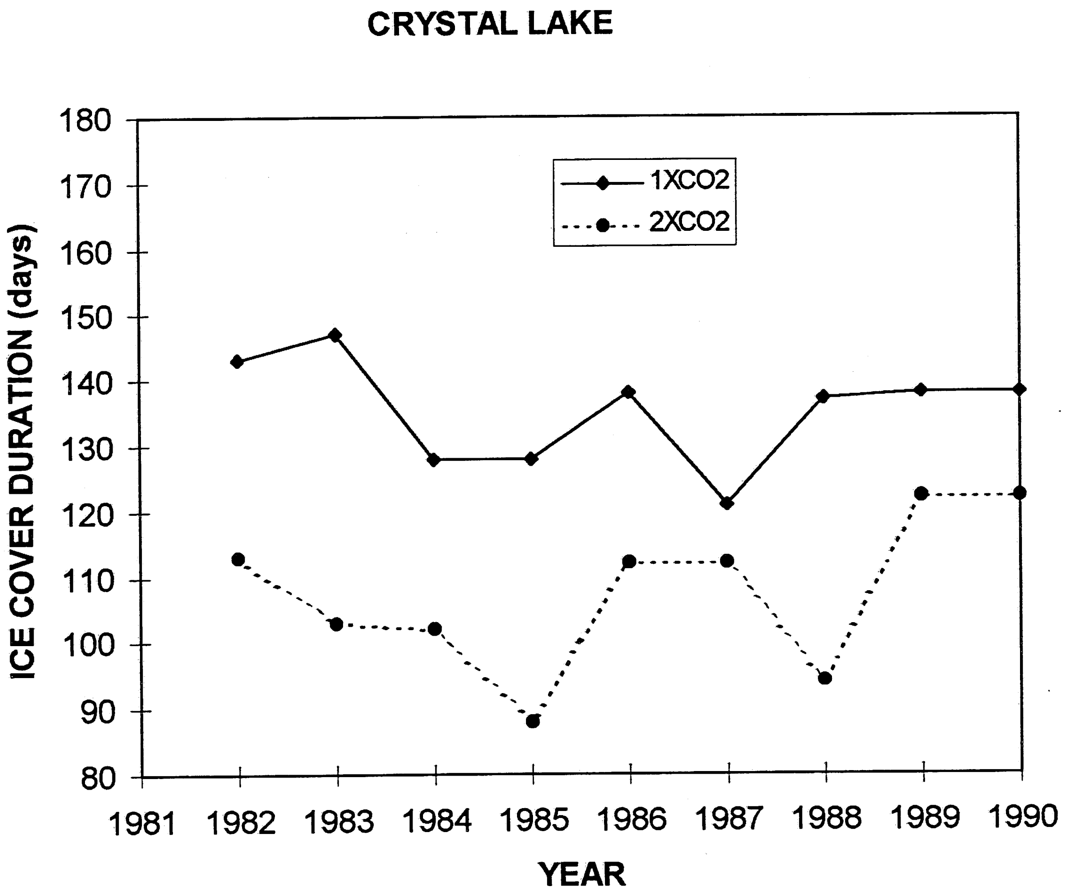

Fig. 5.29. Simulated ice cover durations for Crystal Lake under past and $2xCO_2$ climate scenarios

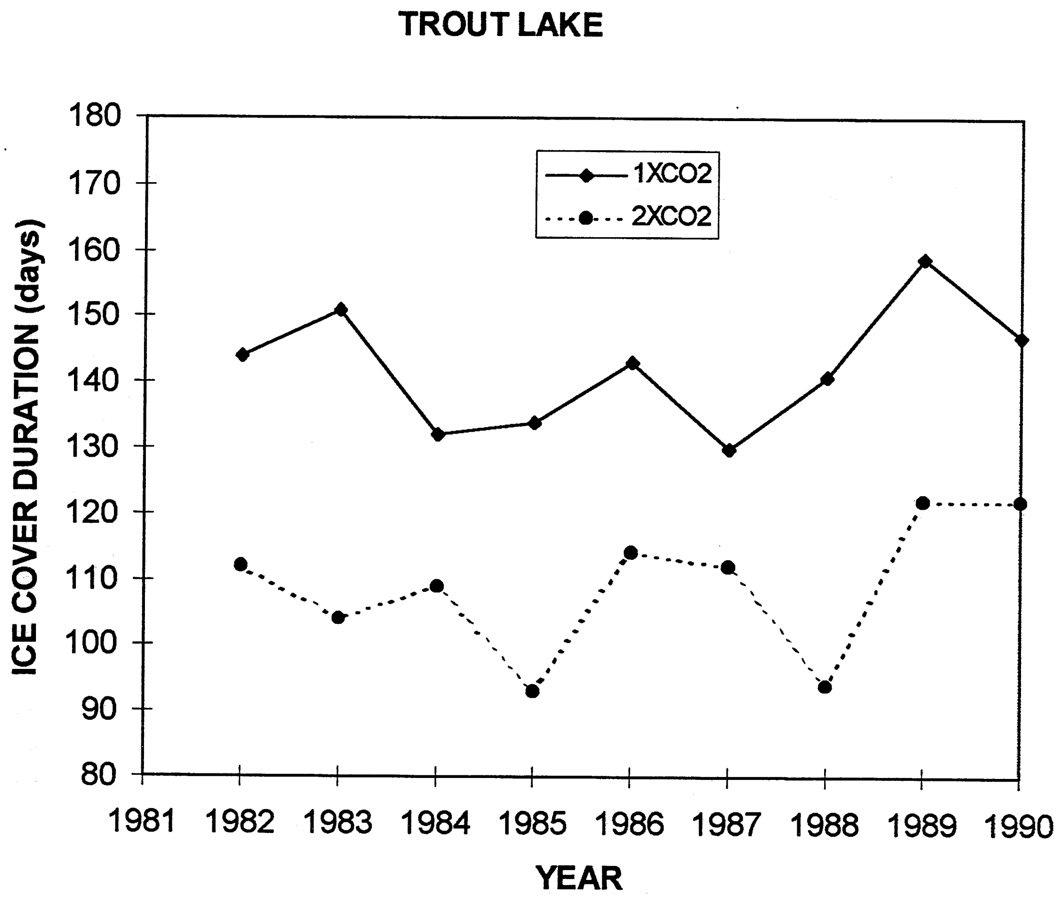

Fig. 5.30. Simulated ice cover durations for Trout Lake under past and $2xCO_2$ climate scenarios

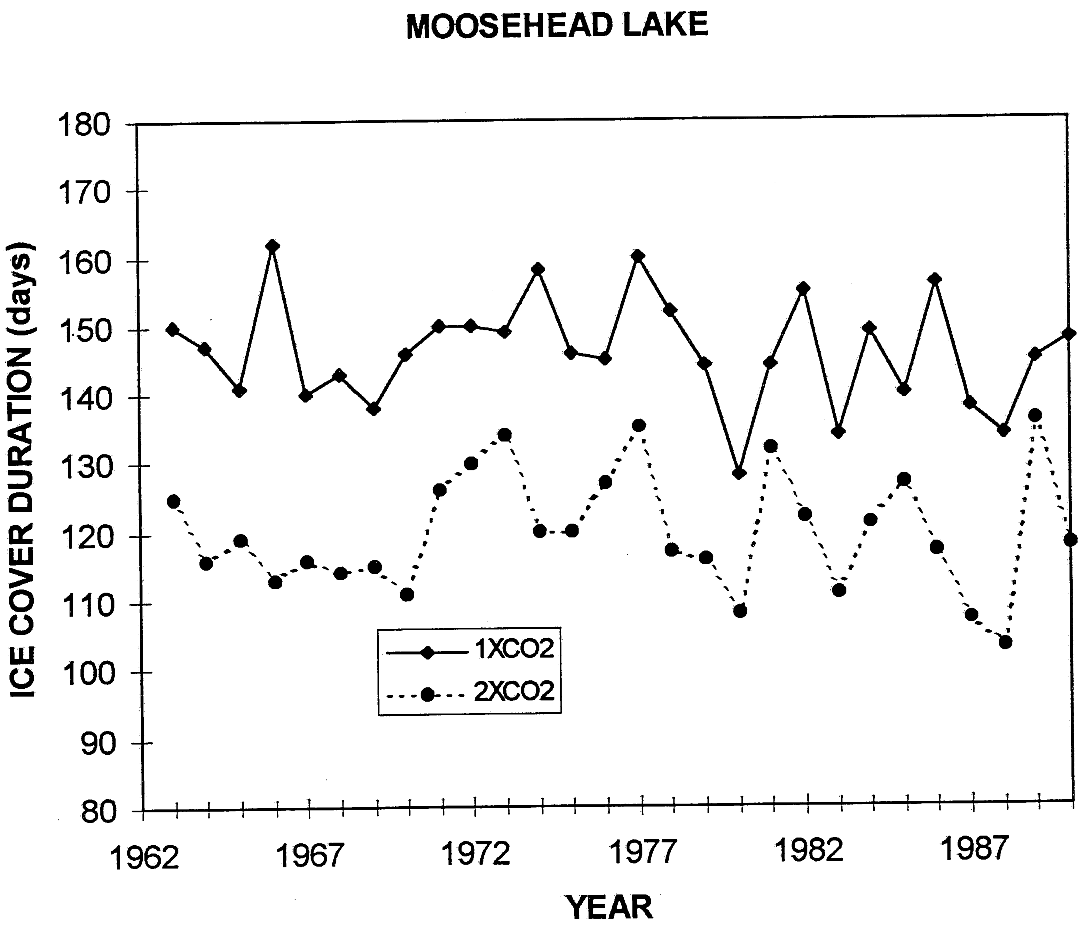

Fig. 5.31. Simulated ice cover durations for Moosehead Lake under past and $2xCO_2$ climate scenarios

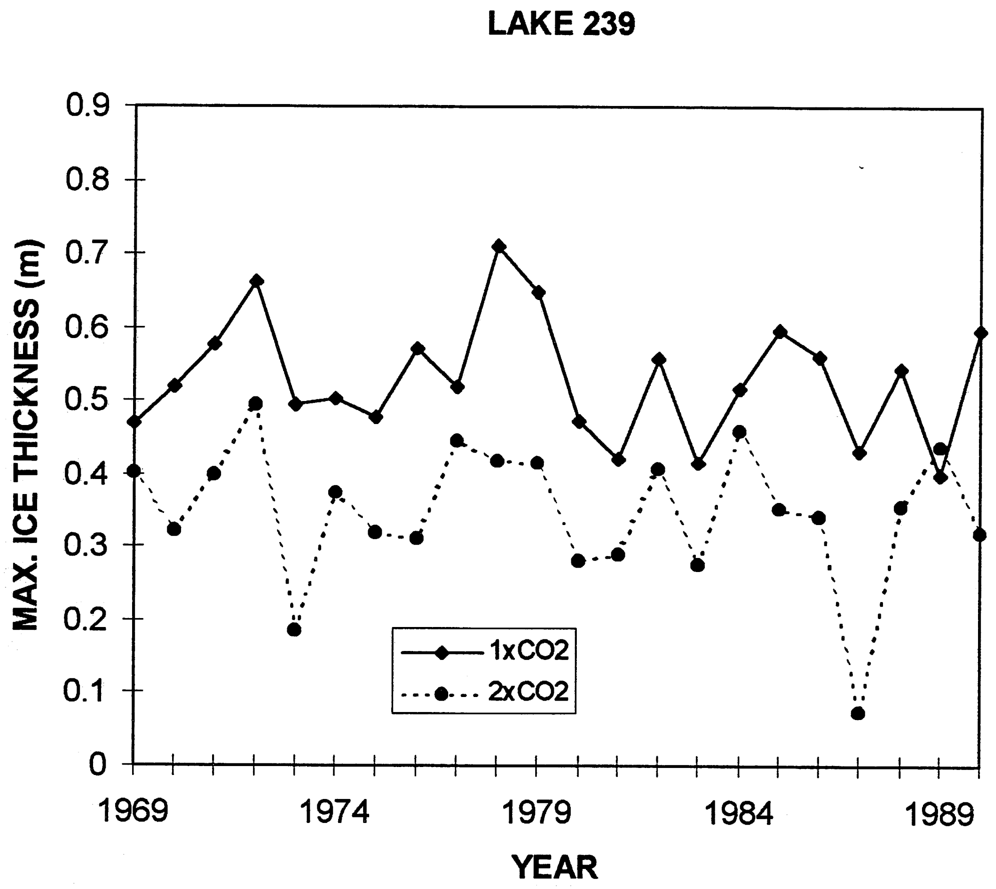

Fig. 5.32. Simulated maximum ice thicknesses for ELA Lake 239 under past and $2xCO_2$ climate scenarios

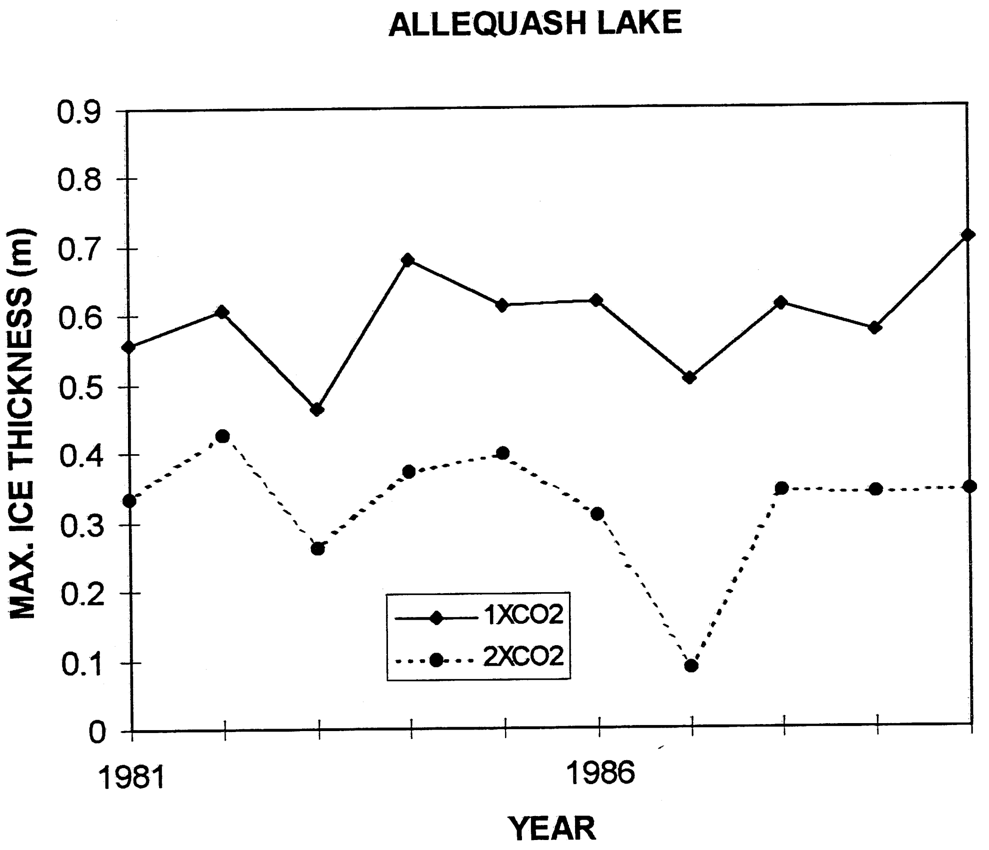

Fig. 5.33. Simulated maximum ice thicknesses for Allequash Lake under past and $2xCO_2$ climate scenarios

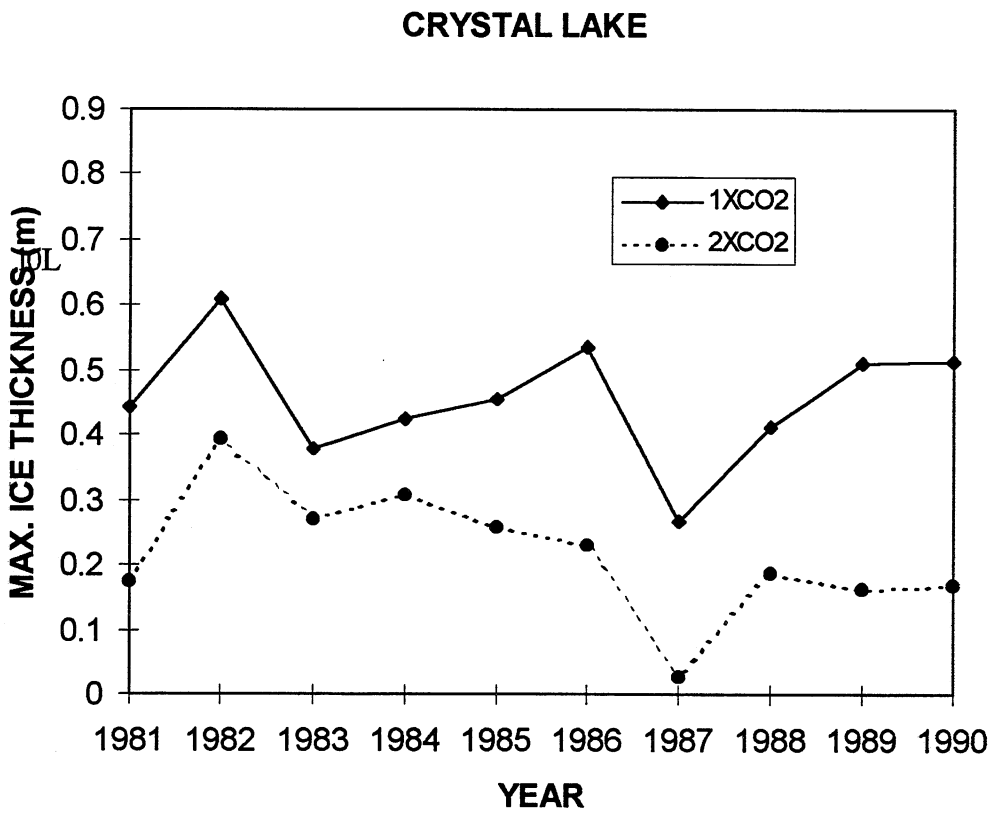

Fig. 5.34. Simulated maximum ice thicknesses for Crystal Lake under past and 2xCO$_2$ climate scenarios

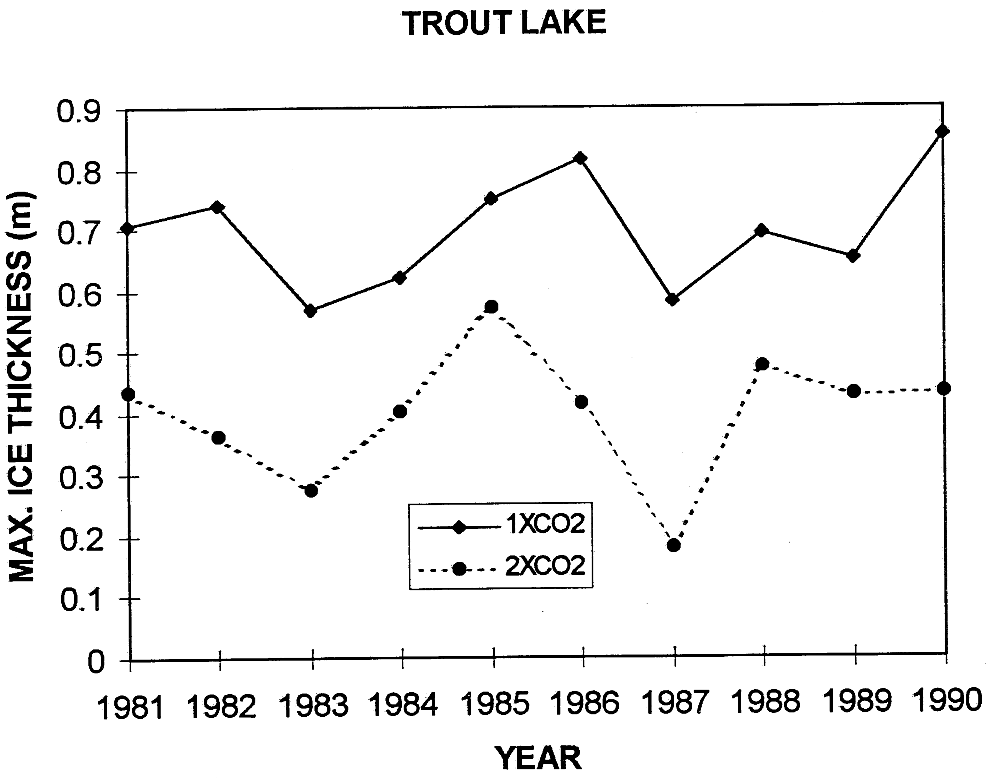

Fig. 5.35. Simulated maximum ice thicknesses for Trout Lake under past and $2xCO_2$ climate scenarios

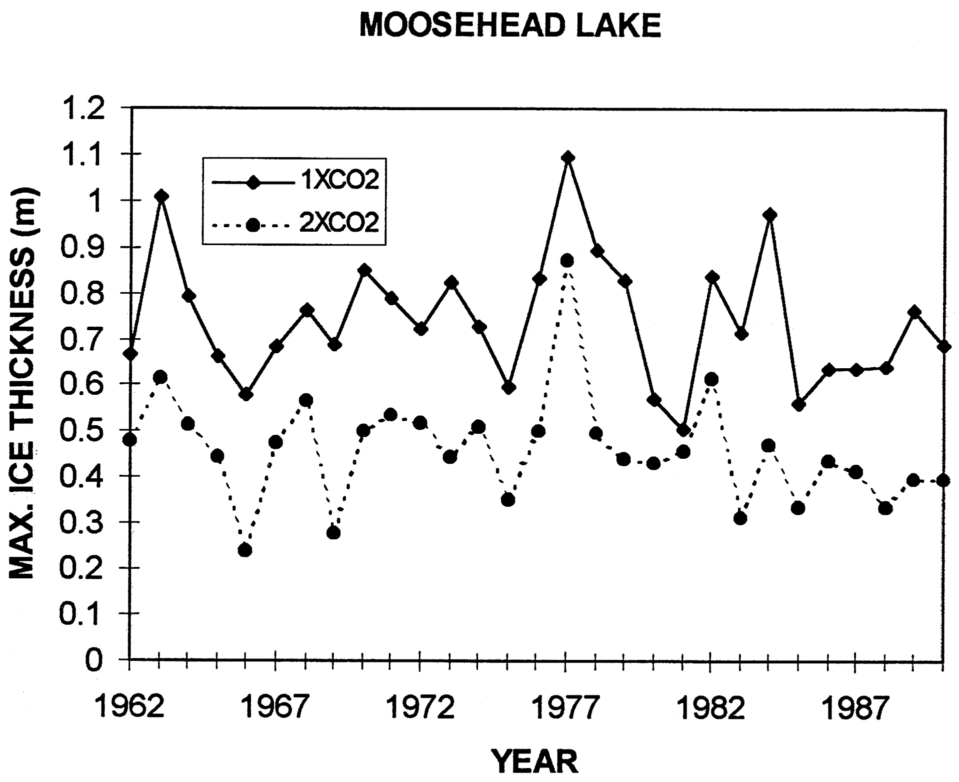

Fig. 5.36. Simulated maximum ice thicknesses for Moosehead Lake under past and $2xCO_2$ climate scenarios

6. COMPARISON OF MODEL RESULTS WITH EMPIRICAL PROJECTIONS

Adams and Stefan (1997) assembled available lake ice data for some freshwater lakes in the United States and Canada including the five lakes studied herein. A multiple variable linear regression was performed for the ice-on dates, ice-off dates and ice cover duration. Using these equations, projections under a $2xCO_2$ climate scenario (CCC-GCM) were made.

The equations used by Adams and Stefan (1997) are:

For ice-on dates $$IID = 322.2 + 5.259 * T1 + 1.407 * M \quad (1)$$

For ice-off dates $$IOD = 174.7 - 4.807 * T2 \quad (2)$$

For ice cover duration $$ICD = 221 - 11.83 * T3 \quad (3)$$

IID = ice-on date (Julian day)
T1 = mean air temperature for Oct., Nov. and Dec. (^oC)
MD = mean depth (m)
IOD= ice-off date (Julian day)
T2 = mean air temperature for April, May and June (^oC)
ICD= ice cover duration (days)
T3 = mean annual air temperature (^oC)

Projections of ice-on dates, ice-off dates and ice cover duration by the deterministic model and the empirical model are given in Table 6.1. Table 6.2 gives the differences between projected and past climate conditions for ice-on dates, ice-off dates and ice cover duration calculated by MINLAKE97 and the above empirical equations. The differences between the two models are 3 to 11 days for the changes of ice-on date, 1 to 4 days for the changes of ice-off date and 22 to 31 days for the changes of ice cover duration. The average differences are 6 days for the change of ice-on date, 1 day for the change of ice-off days and 26 days for the changes of ice cover duration.

For the changes of ice-off dates, the two models give almost the same results. The average difference between the two models is only 1 day. The difference between the two models for the projected change of ice-on date is larger. The average difference between the two models is 6 days. For the change of ice cover duration the two models give very different values. The average difference between the two models is 26 days. Adams' equation for predicting ice cover duration only has one parameter (mean annual air temperature). This simple equation can not take into account many factors which affect ice cover duration in a lake, e.g. lake depth or size and snow depth. This may be one reason why the two models give such different results for ice cover duration.

If we ignore Equation (3), and calculate ice cover duration with Equations (1) and (2), the results are much closer to those obtained by MINLAKE97. The difference between the two models then is 4 to 17 days for ice cover duration. The average difference is 9 days.

Table 6.1 Comparison of ice characteristics projected by the deterministic model and the empirical model under the 2xCO$_2$ climate scenario

	Ice-on date (Julian day)		Ice-off date (Julian day)		Ice cover duration (days)	
	Adams	Minlake97	Adams	Minlake97	Adams	Minlake97
ELA Lake 239	341	331	103	99	108 (126)*	135
Allequash Lake	341	332	90	87	88 (114)*	123
Crystal Lake	352	347	90	87	88 (103)*	108
Trout Lake	358	347	90	88	88 (97)*	109
Moosehead Lake	N/A	344	108	98	N/A	120

* Calculated by Equations (1) and (2)

Table 6.2 Comparison of changes projected by the deterministic model MINLAKE97 and the empirical model by Adams and Stefan (1997)

	Change of ice-on dates ($2xCO_2$ - past)			Change of ice-off dates ($2xCO_2$ - past)			Change of ice cover duration ($2xCO_2$ - past)		
	Adams	Minlake97	Difference[1]	Adams	Minlake97	Difference[1]	Adams	Minlake97	Difference[1]
ELA Lake 239	23	12	11	-19	-15	-4	-56 (-42)*	-25	-31 (-17)*
Allequash Lake	15	12	3	-22	-21	-1	-55 (-37)*	-31	-24 (-6)*
Crystal Lake	15	10	5	-22	-19	-3	-55 (-37)*	-27	-28 (-10)*
Trout Lake	15	12	3	-22	-23	1	-55 (-37)*	-33	-22 (-4)*
Moosehead Lake	N/A	7	N/A	-18	-19	1	N/A	-26	N/A

[1] Difference = Adams - Minlake 97

* Calculated by Equations (1) and (2)

7. SUMMARY AND CONCLUSIONS

Ice-on and ice-off dates, ice cover duration and ice thicknesses for four lakes in the US and one lake in Canada were simulated. Simulations were made with the model MINLAKE97. Prior to its application, a new ice and snow albedo submodel had been incorporated into the model. Data on observed ice-on dates, ice-off dates and ice cover duration were available for periods of 10 to 27 years. It was therefore possible to study the differences between the simulation results and measurements. The simulated average ice-in dates were 3 days to 11 days earlier than the observed ones. It is believed that the potential causes for this difference are ground water effects, wind effects, poor representation of the off-site meteorological data and observation inconsistencies. The average standard errors were 10 days, 9 days and 11 days for ice on dates, ice off dates and ice cover duration, respectively, without calibrating the model. The simulated average ice-off dates were 2 days to 11 days earlier than the observed ones. Possible reasons for the difference are weaknesses in the snow submodel and observation errors.

The effects of a projected 2xCO_2 climate scenario on lake ice characteristics for the five lakes were also simulated. Under a 2xCO_2 climate scenario the average ice-on dates are projected to be 7 days to 12 days later; the average ice-off dates are projected to be 15 days to 23 days earlier; the ice cover durations are 25 days to 33 days shorter; the maximum ice thicknesses are projected to be 0.18 m to 0.30 m thinner. Climate change to a 2xCO_2 scenario is therefore projected to have a significant effect on lake ice characteristics.

The results were compared with empirical projections by Adams and Stefan (1997). The two models gave similar results for the projected changes of ice-on and ice-off dates between 2xCO_2 and past conditions, but gave very different results for the projected changes of ice cover duration. Possible reason is that Adam's empirical equation for ice cover duration has only one parameter (mean annual air temperature). It can not take into account many other factors which affect ice cover duration in a lake.

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APPENDICES

Appendix A: Comparison of MINLAKE96 and MINLAKE 97 Results

Appendix B: Sensitivity of Lake Ice Characteristics to Meteorological Parameters

Appendix C: Bathymetric Lake Maps

APPENDIX A: COMPARISON OF MINLAKE96 AND MINLAKE 97 RESULTS

MINLAKE96 was modified by incorporating a new ice and snow albedo submodel, which was developed by Henneman and Stefan (1997), to produce MINLAKE97. To compare their ability to simulate ice characteristics, both models were used to simulated ice-on dates, ice-off dates and maximum ice thicknesses from 1968 to 1990 for ELA Lake 239.

Fig. A1 shows time series of simulated and observed ice-on dates. As expected the two models give identical results for ice-on dates. For ice-off dates (Fig. A2) the differences between results obtained by the two models are very small. Maximum difference is only one day.

Fig. A3 shows simulated maximum ice thicknesses by both models. The two models gave slightly different results. The difference is less than 0.06 m.

Overall, the two models give similar results for ice-on dates, ice-off dates and maximum ice thicknesses. Therefore, MINLAKE97 is not better than MINLAKE96 in simulating ice characteristics.

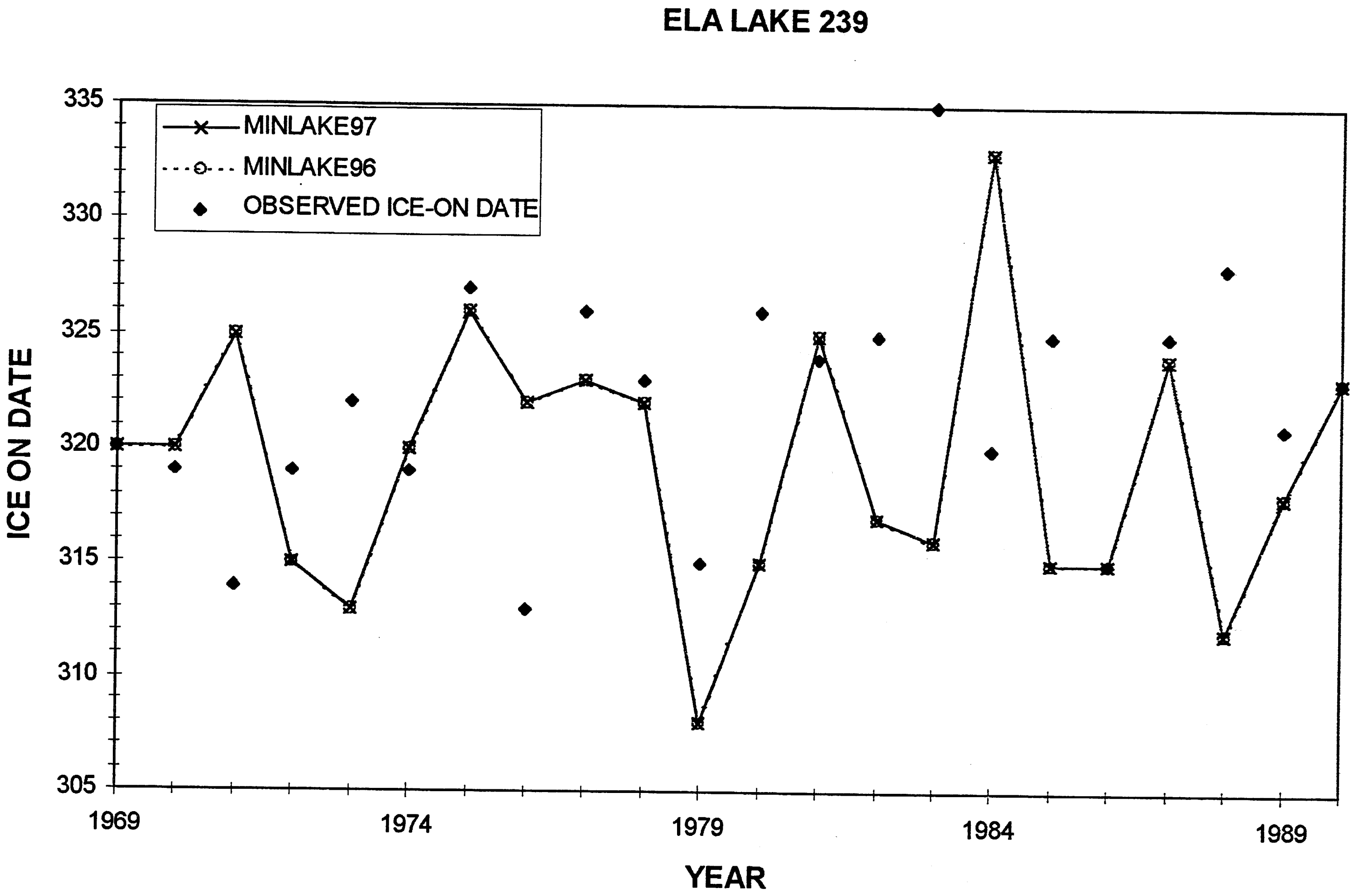


Fig. A1 Observed and simulated ice-on dates by MINLAKE96 and MINLAKE97 for ELA Lake 239

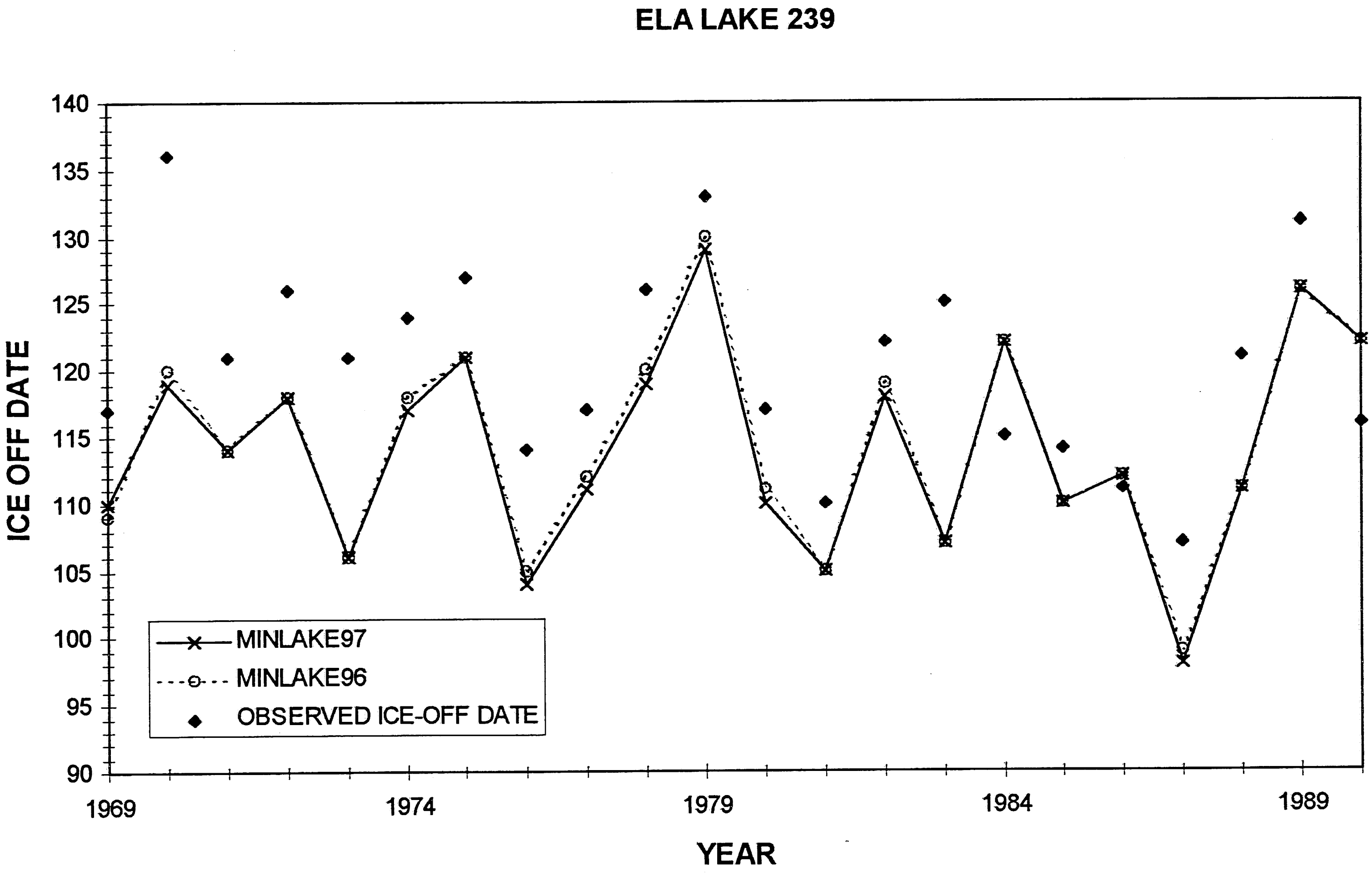


Fig. A2 Observed and simulated ice-off dates by MINLAKE96 and MINLAKE97 for ELA Lake 239

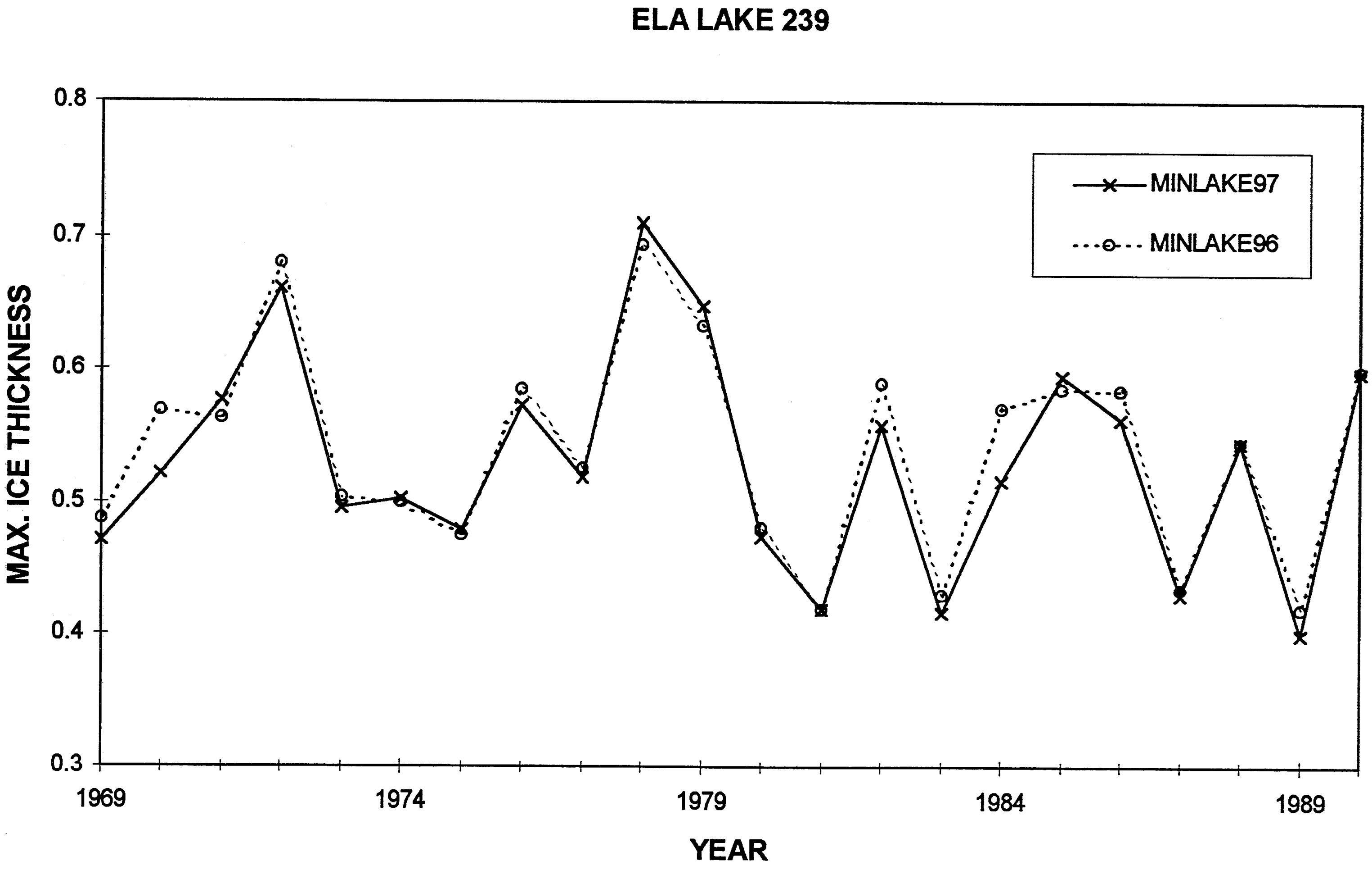


Fig. A3 Observed and simulated maximum ice thicknesses by MINLAKE96 and MINLAKE97 for ELA Lake 239

APPENDIX B: SENSITIVITY OF LAKE ICE CHARACTERISTICS TO METEOROLOGICAL PARAMETERS

The sensitivity of lake ice characteristics to different meteorological parameters was investigated for ELA Lake 239. The lake was simulated with MINLAKE96 from 1969 to 1990 and values of meteorological parameters were changed by increasing or decreasing air temperatures and dew point temperatures by ±5°C, solar radiation, wind speed and snowfall by ±20%. The magnitude of these changes is in the range projected for a $2xCO_2$ climate scenario. The change was applied to each daily value of a meteorological parameter. Table B1 gives average values (1969 - 1990) of the meteorological parameters for International Falls, Minnesota, from which the meteorological date used for simulation came.

Figures B1 to B15 show simulated time series of ice-on dates, ice-off dates and maximum ice thicknesses under both unchanged and changed meteorological conditions. Average values for the simulation period (1969 - 1990), standard deviations from average values and root mean square differences between unchanged and changed meteorological conditions are given in Table B2.

Lake ice characteristics are most sensitive to air temperature (Table B2). Increasing air temperature by 5°C delayed ice-on date by 15 days, advanced ice-off date by 22 days, and reduced ice thickness by 0.19 m. Decreasing air temperature by 5°C advanced ice-on date by 12 days, delayed ice-off date by 20 days, and increased ice thickness by 0.21 m. Ice-off dates are more sensitive to air temperature than ice-on dates.

Lake ice characteristics are least sensitive to snowfall changes. Increasing or decreasing snowfall by 20% produced no significant changes. Ice-on date does not change with the changing of snowfall. Ice-off date changes only one day. Maximum ice thickness changes about 4 to 5 cm.

For the other three meteorological parameters, root mean square differences between unchanged and changed meteorological conditions were about 4 to 7 days for ice-on date, 1 to 4 days for ice-off date and 3 to 7 cm for maximum ice thickness.

Air temperature is the most important factor in determining lake ice characteristics. Lake ice characteristics are most sensitive to air temperature. This is the reason why empirical models for lake ice characteristics can be developed with only one meteorological parameter, air temperature.

There are some points in the figures which call for an explanation. For example in Fig. B3 when air temperature decreased by 5°C, maximum ice thickness increased for all the simulation year except for 1978. The decrease of air temperature causes a significant increase of snow depth in that year, and the increase of snow depth tends to decrease ice thickness. This completely offsets the effect of lower air temperature on ice thickness which tends to increases the ice thickness. In other years the increase of snow depth only partly offset the lower air temperature effect on ice thickness.

When dew point temperature is increased by 5°C, the ice-on date should be later due to less heat loss by evaporation. The reason why in 1976 ice-on date became earlier (Fig. B4) is that the ice-on date was defined as latest ice-on date. If we examine the simulation carefully, we find that the earliest ice-on date did come later. Under the unchanged climate conditions ice formed, melted and formed again. This made the latest ice-on date under the increased dew point temperature earlier in 1976.

Another example is in Fig. B15. Increasing snow fall usually tends to decrease ice thickness. In some years, however, the maximum ice thicknesses increased when snow fall increased because the snow cover exceeded a critical depth which depends on the densities of ice and snow and the ice thickness. This lead to the conversion of part of the snow into gray ice, and the decreased snow depth further increased the ice thickness.

Other discrepancies be explained in similar ways.

Table B1 Average values (1969 - 1990) of some meteorological parameters for International Falls, Minnesota

Month	Air Temp. (°C)	Dew Point Temp. (°C)	Solar Radiation (langley day^{-1})	Wind Speed (mph)	Snow Fall (mm)
Jan	-16.3	-20.4	122.9	8.6	19.1
Feb	-12.3	-17.2	207.4	8.5	18.3
Mar	-5.0	-11.1	317.9	9.3	23.4
Apr	4.4	-3.8	415.6	9.5	25.9
May	12.0	3.4	473.2	9.0	23.2
Jun	16.6	9.8	497.9	8.4	0.0
Jul	19.6	13.4	503.0	7.7	0.0
Aug	17.8	12.6	423.6	7.6	0.0
Sep	11.9	7.5	297.3	8.6	0.0
Oct	5.3	0.6	188.0	9.2	20.2
Nov	-3.9	-7.4	118.0	9.0	28.3
Dec	-13.3	-16.6	96.1	8.5	16.4

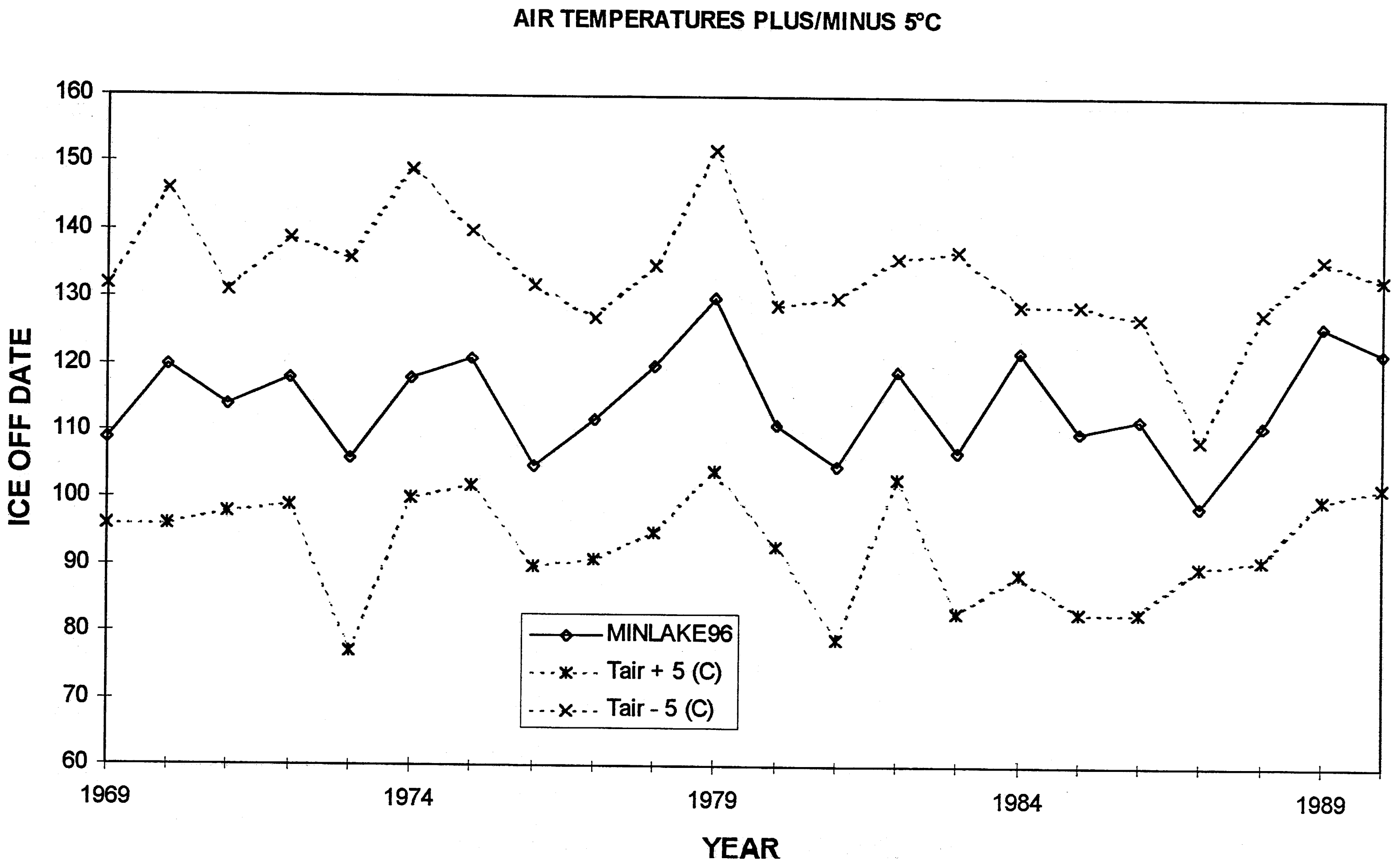


Fig. B2 Sensitivity of ice-off date to air temperature

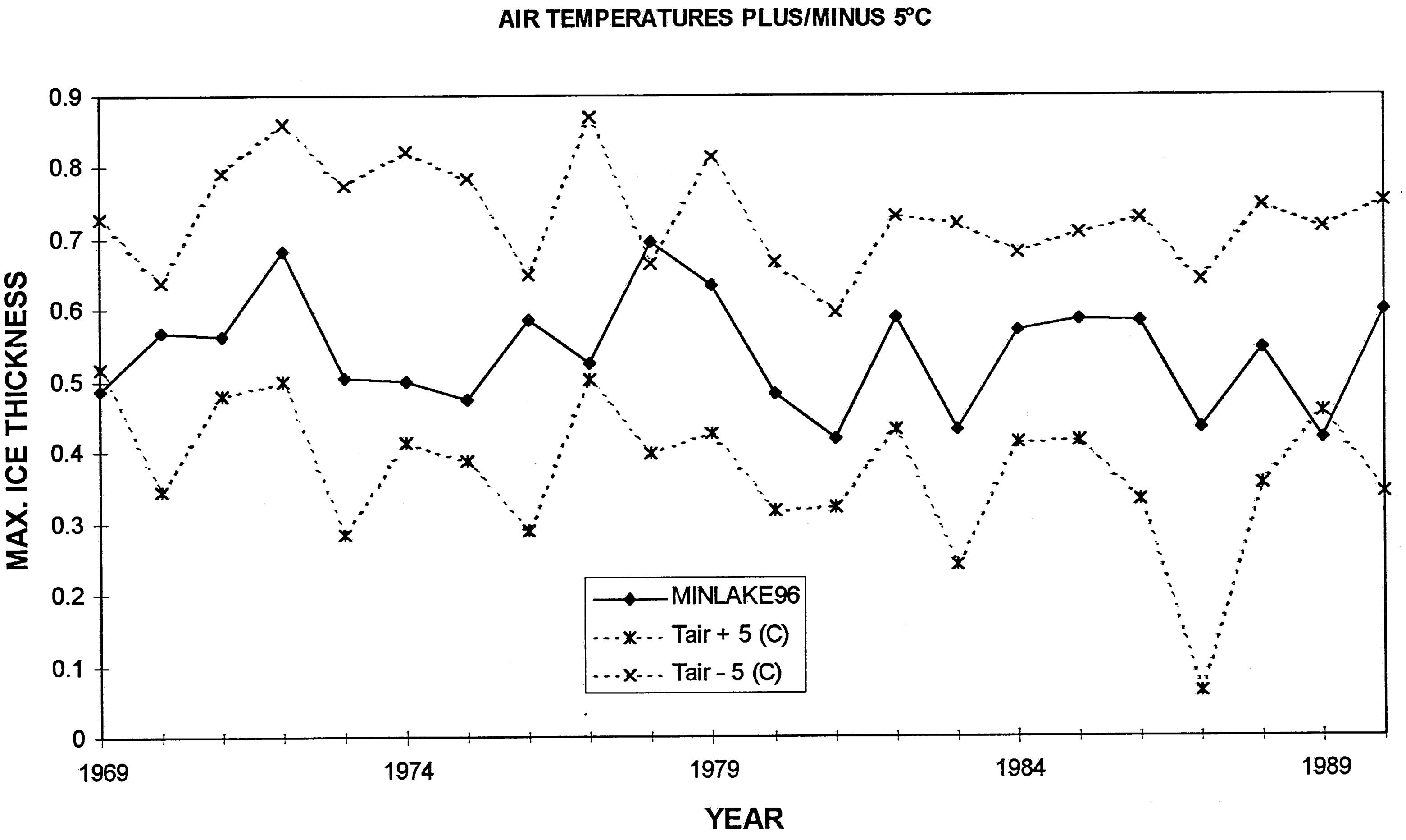


Fig. B3 Sensitivity of maximum ice thickness to air temperature

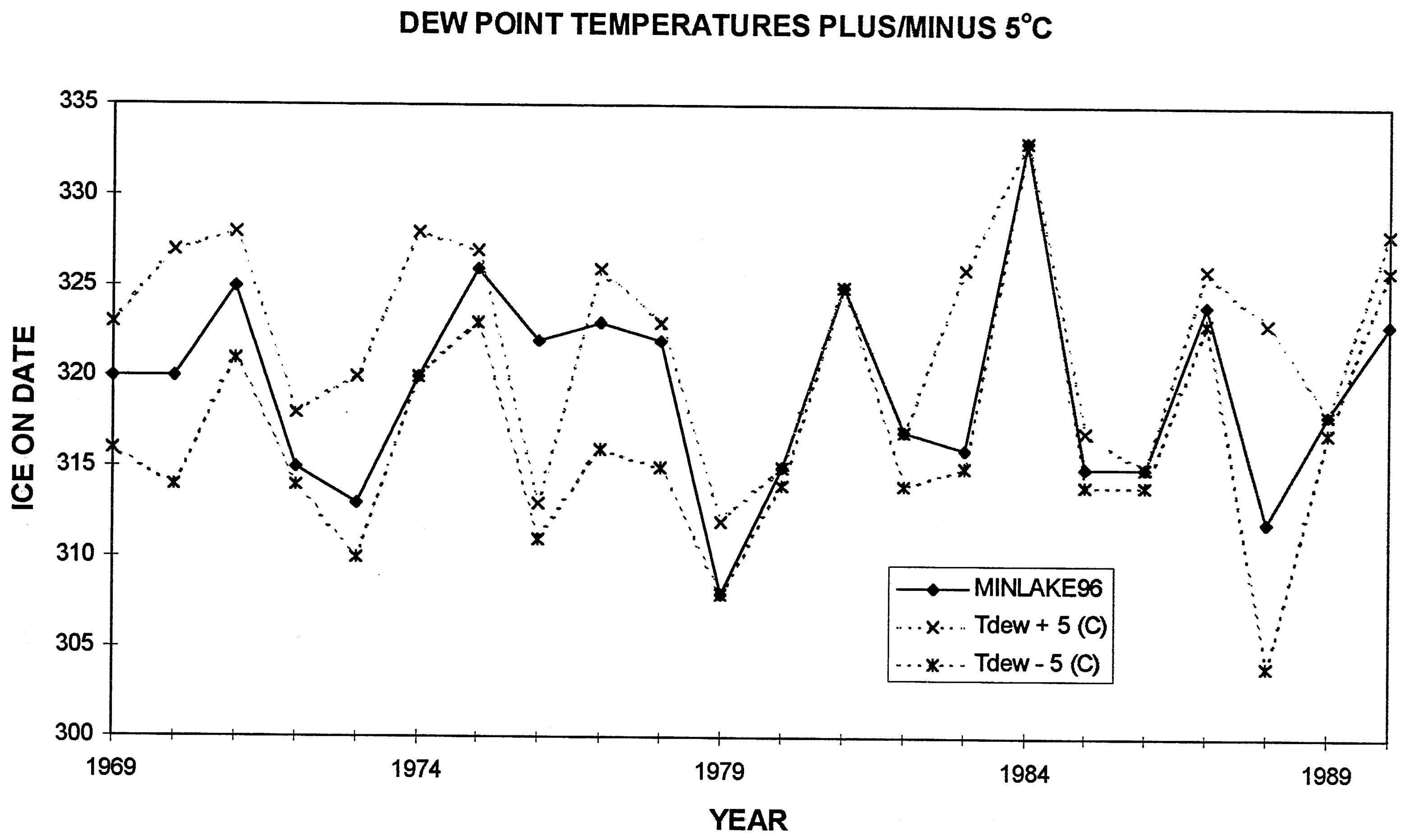


Fig. B4 Sensitivity of ice-on date to dew point temperature

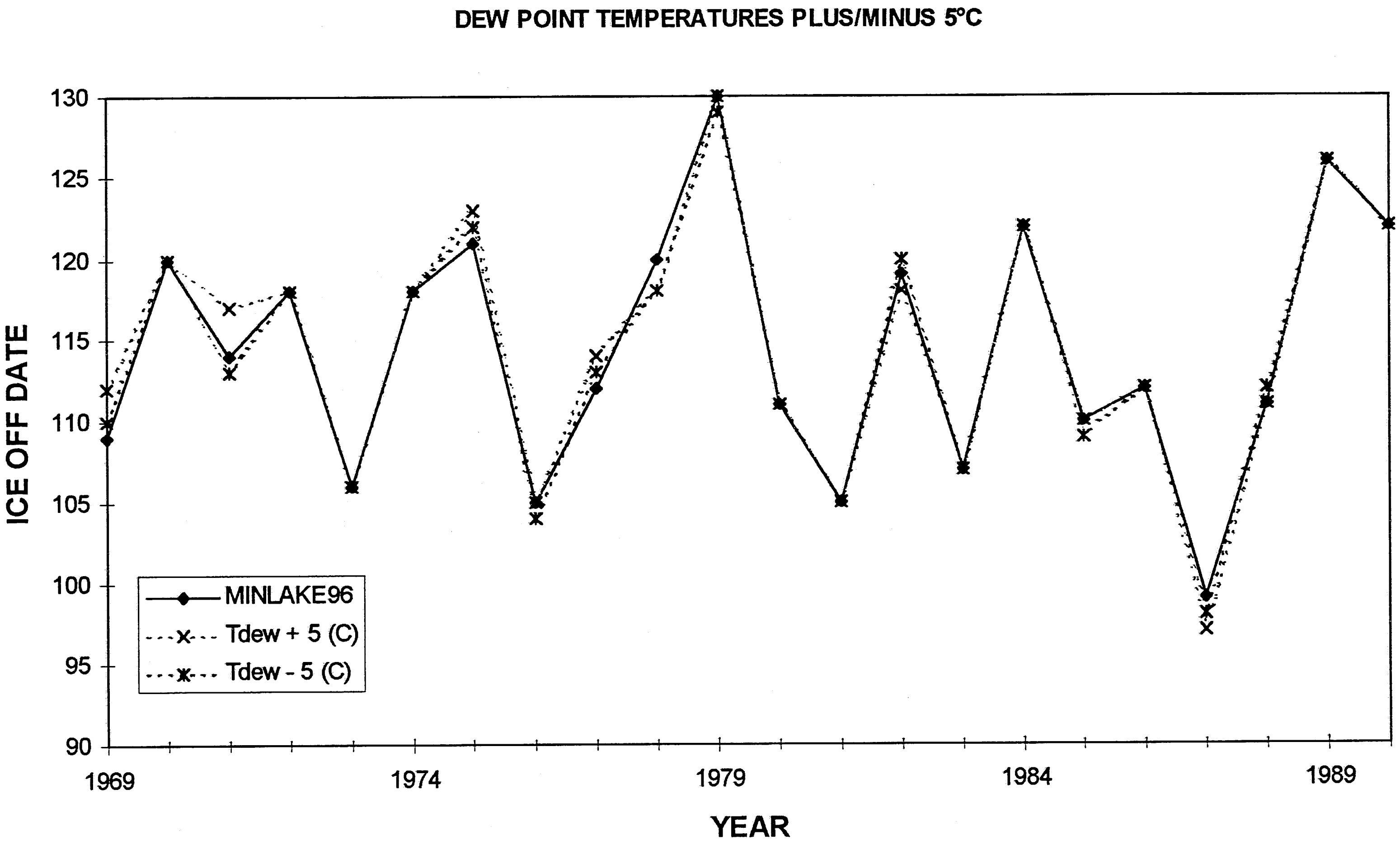


Fig. B5 Sensitivity of ice-off date to dew point temperature

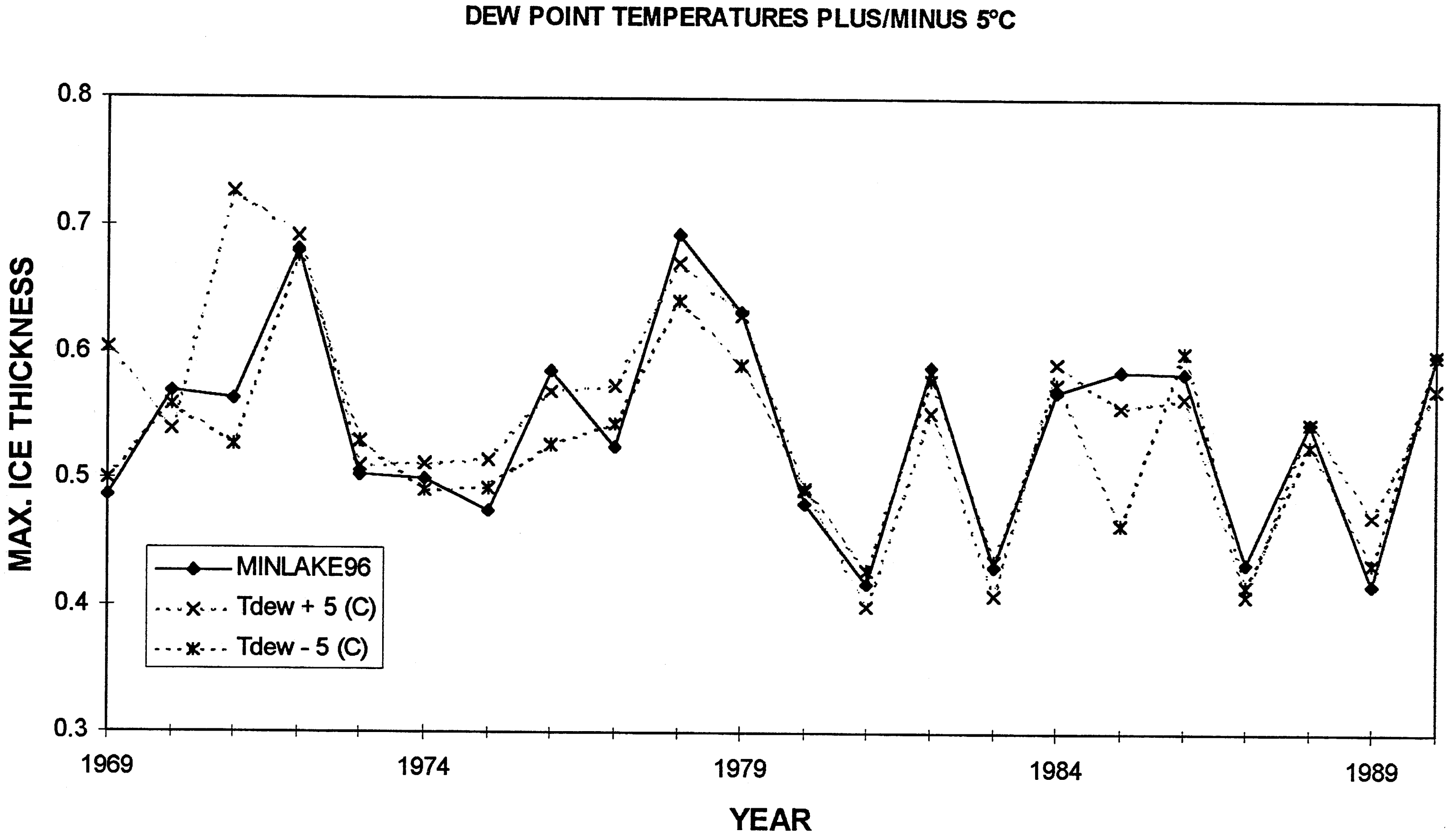


Fig. B6 Sensitivity of maximum ice thickness to dew point temperature

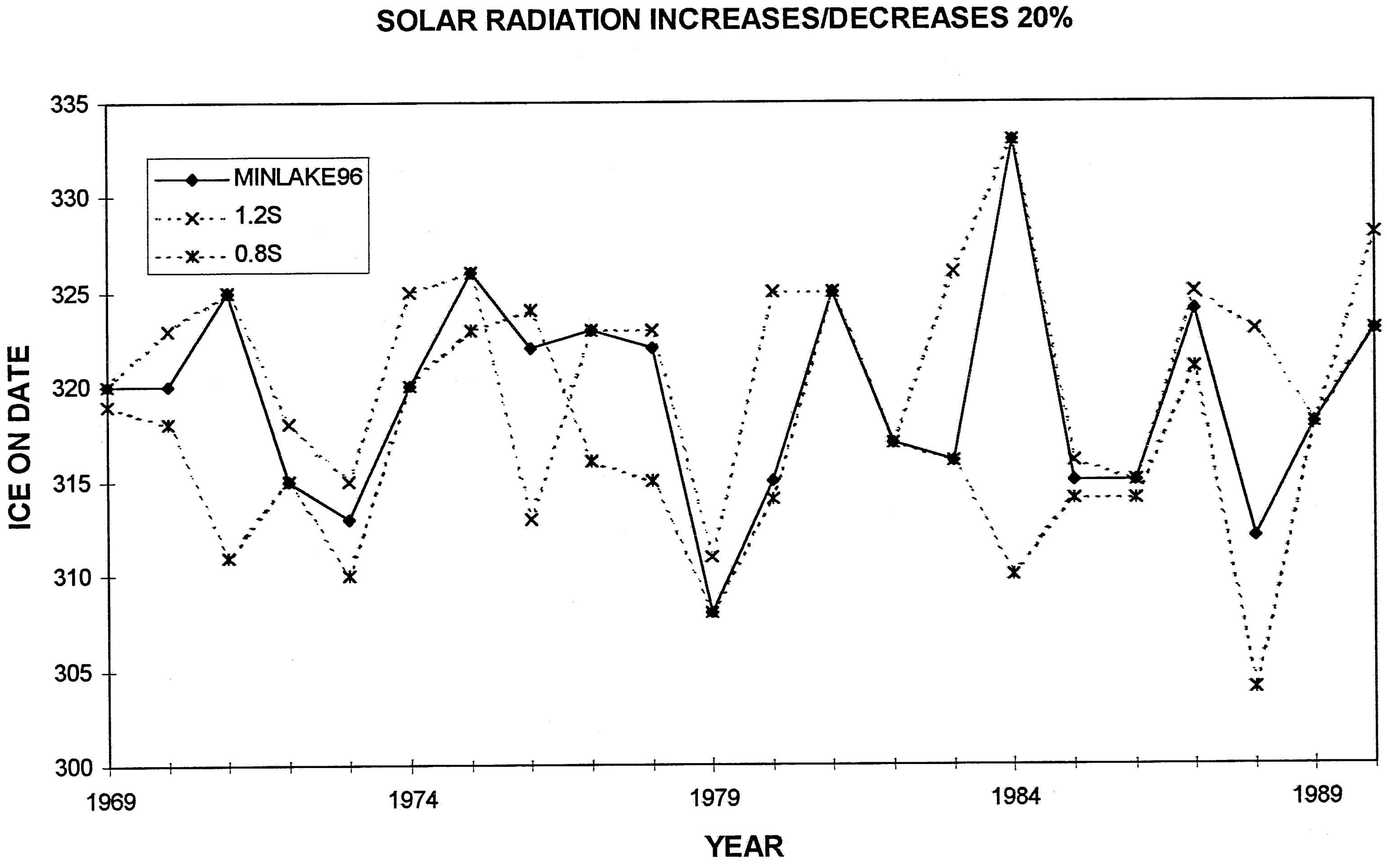


Fig. B7 Sensitivity of ice-on date to solar radiation

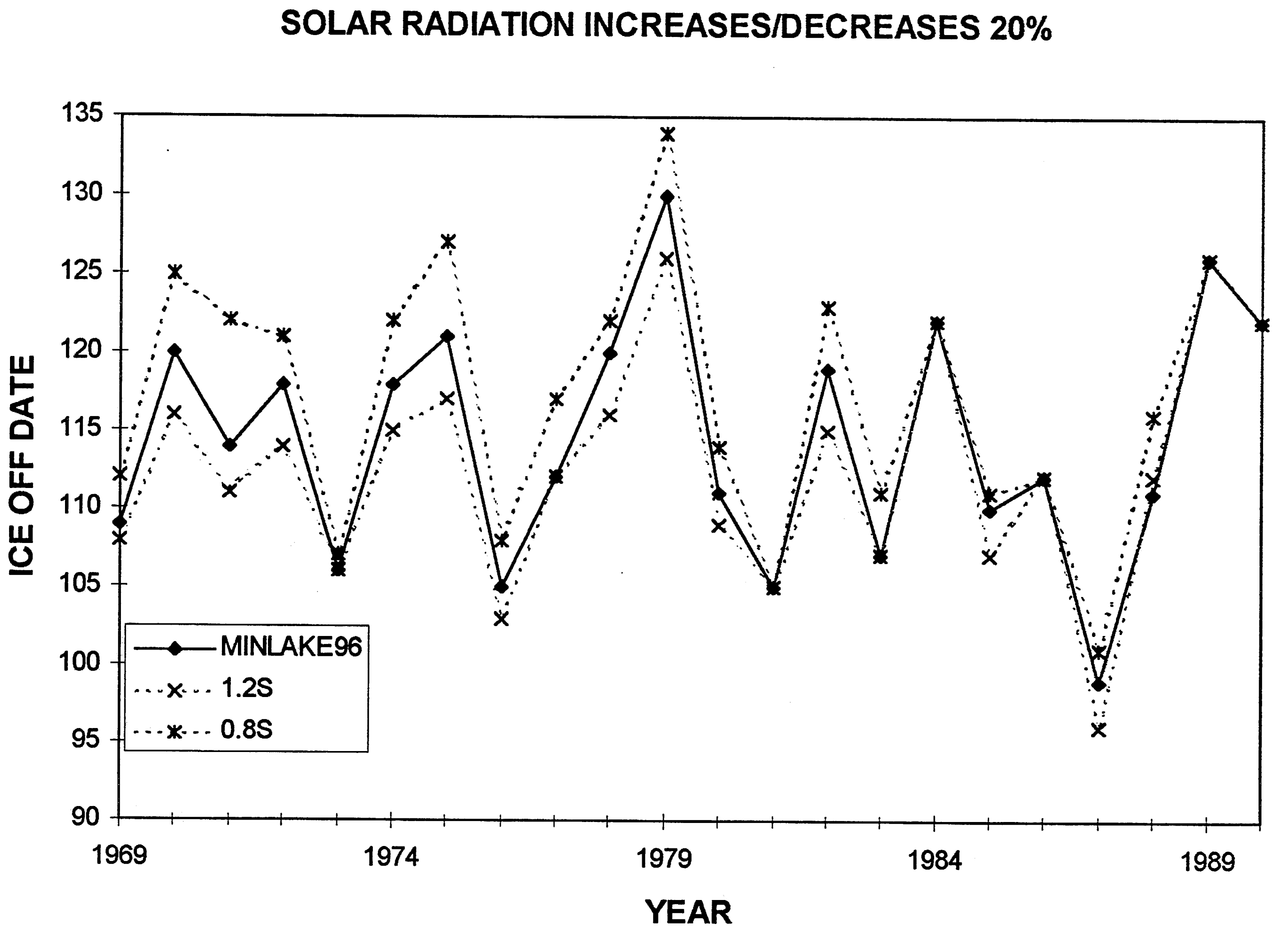


Fig. B8 Sensitivity of ice-off date to solar radiation

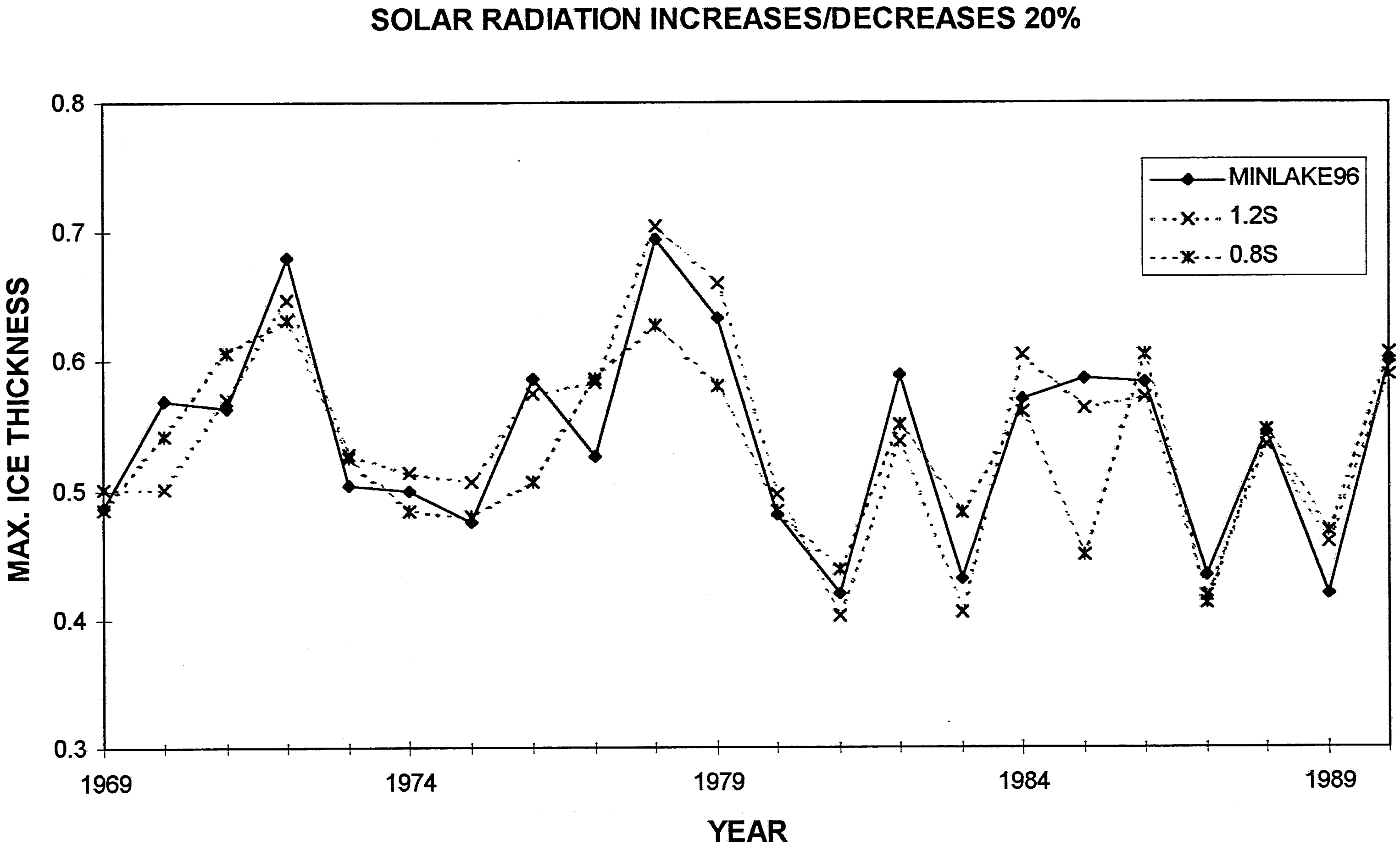


Fig. B9 Sensitivity of maximum ice thickness to solar radiation

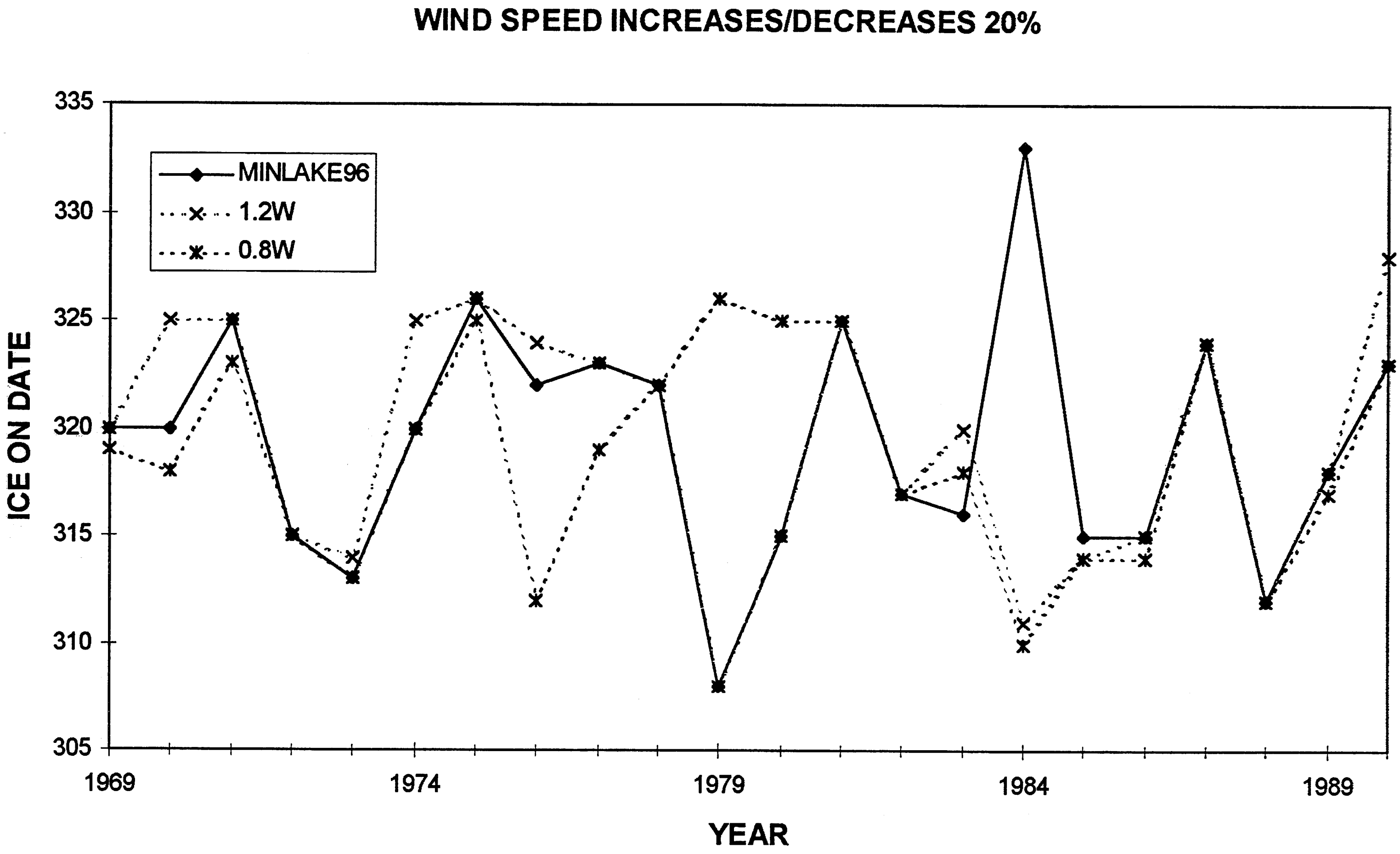


Fig. B10 Sensitivity of ice-on date to wind speed

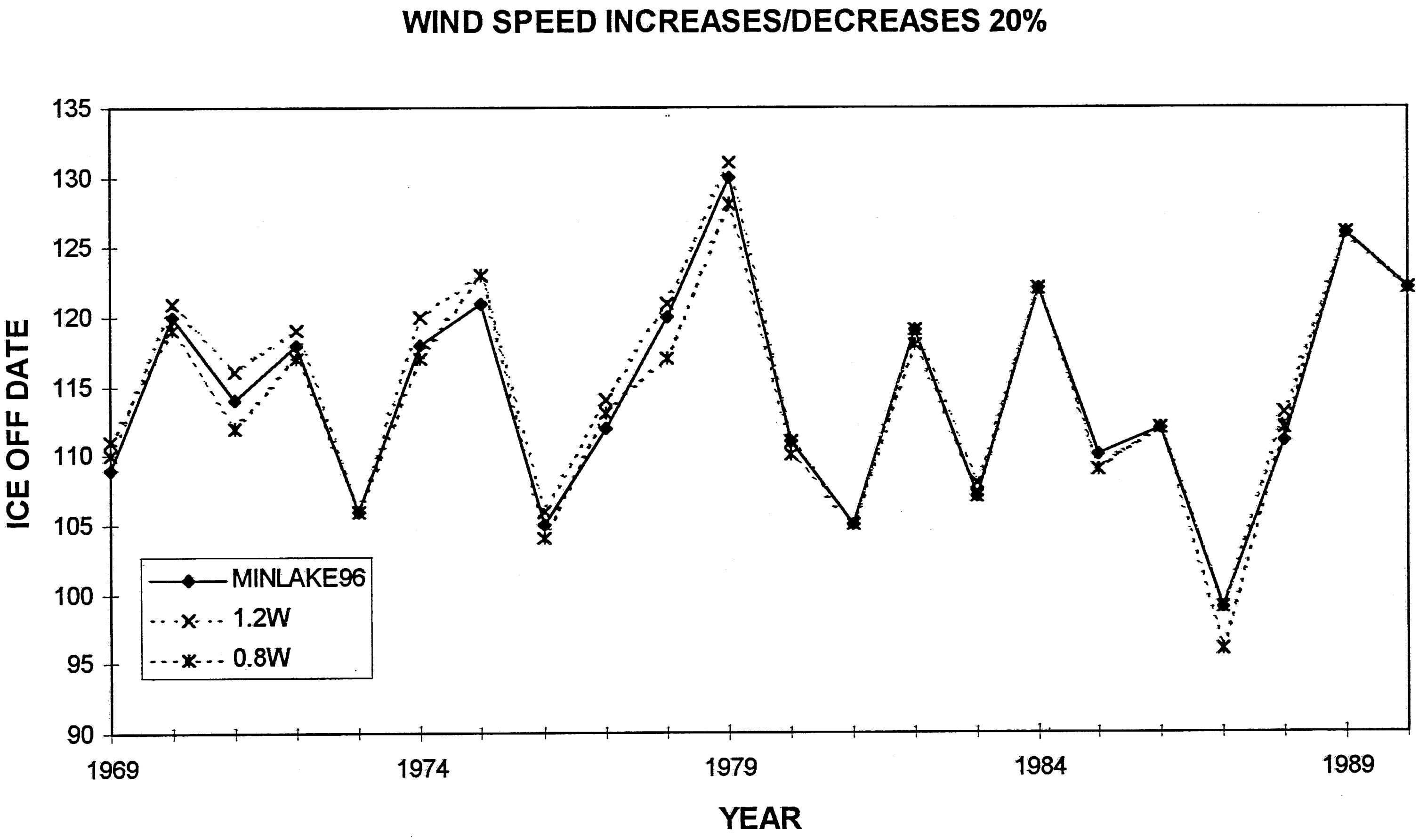


Fig. B11 Sensitivity of ice-off date to wind speed

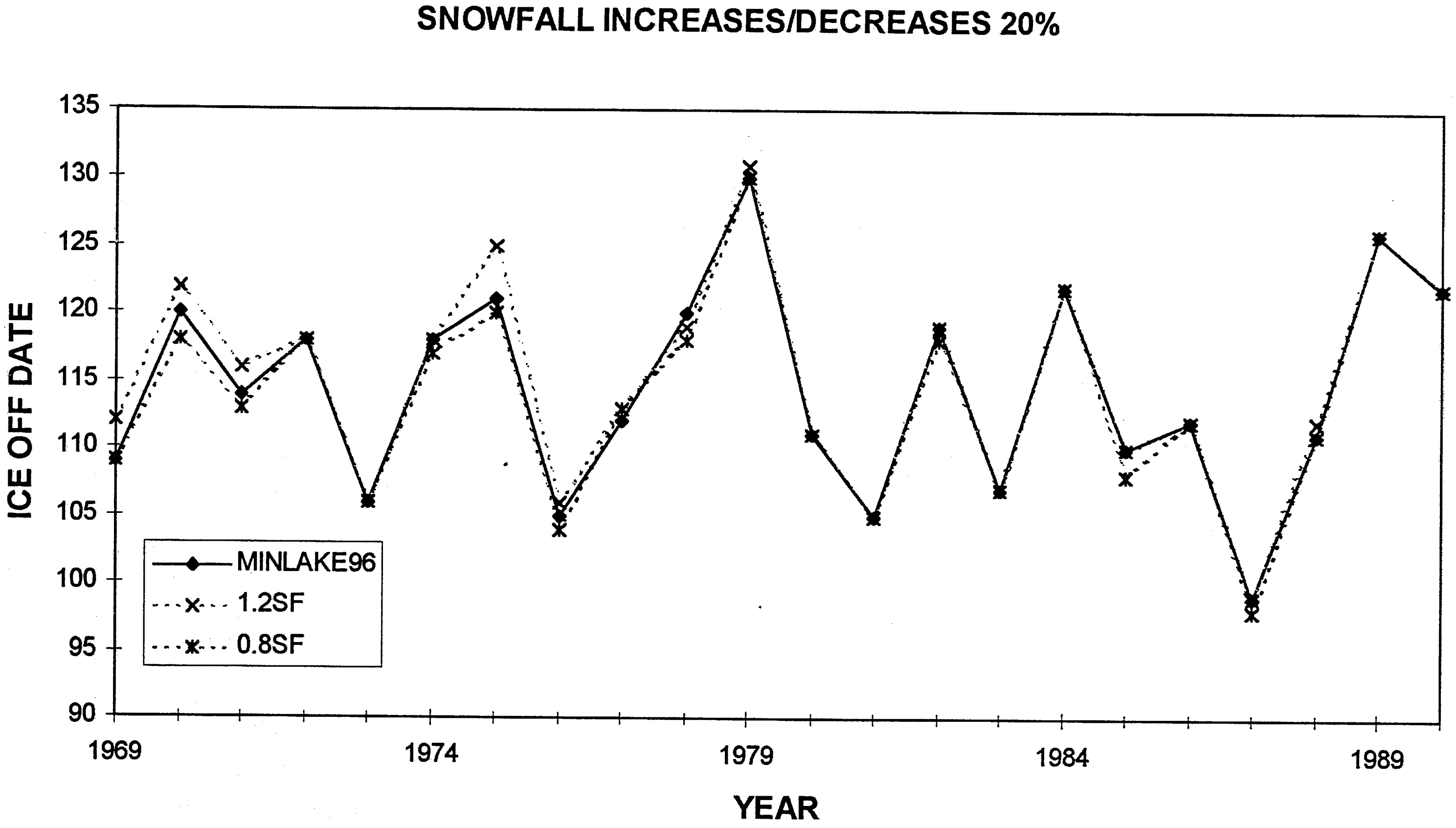


Fig. B14 Sensitivity of ice-off date to snowfall

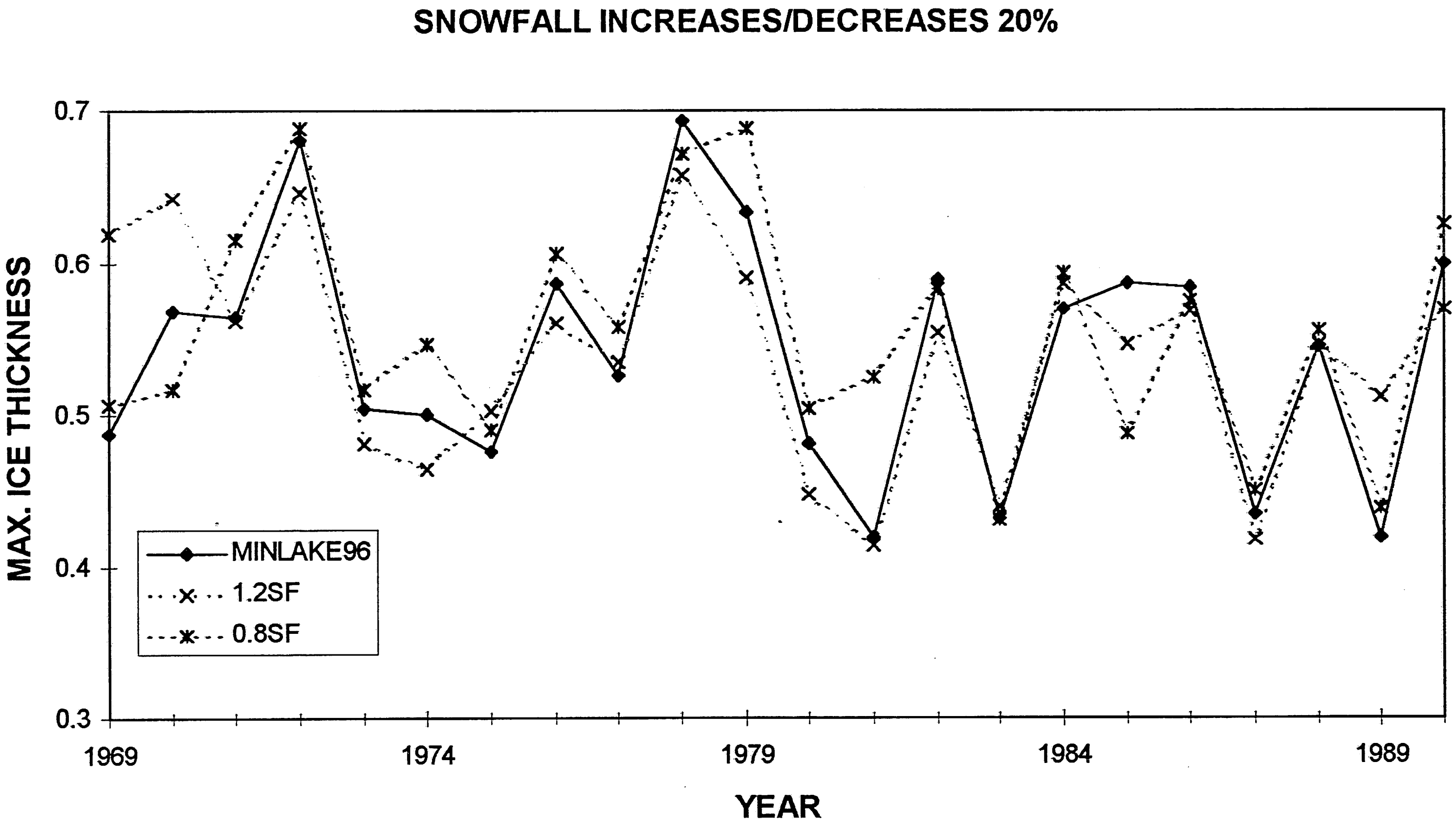
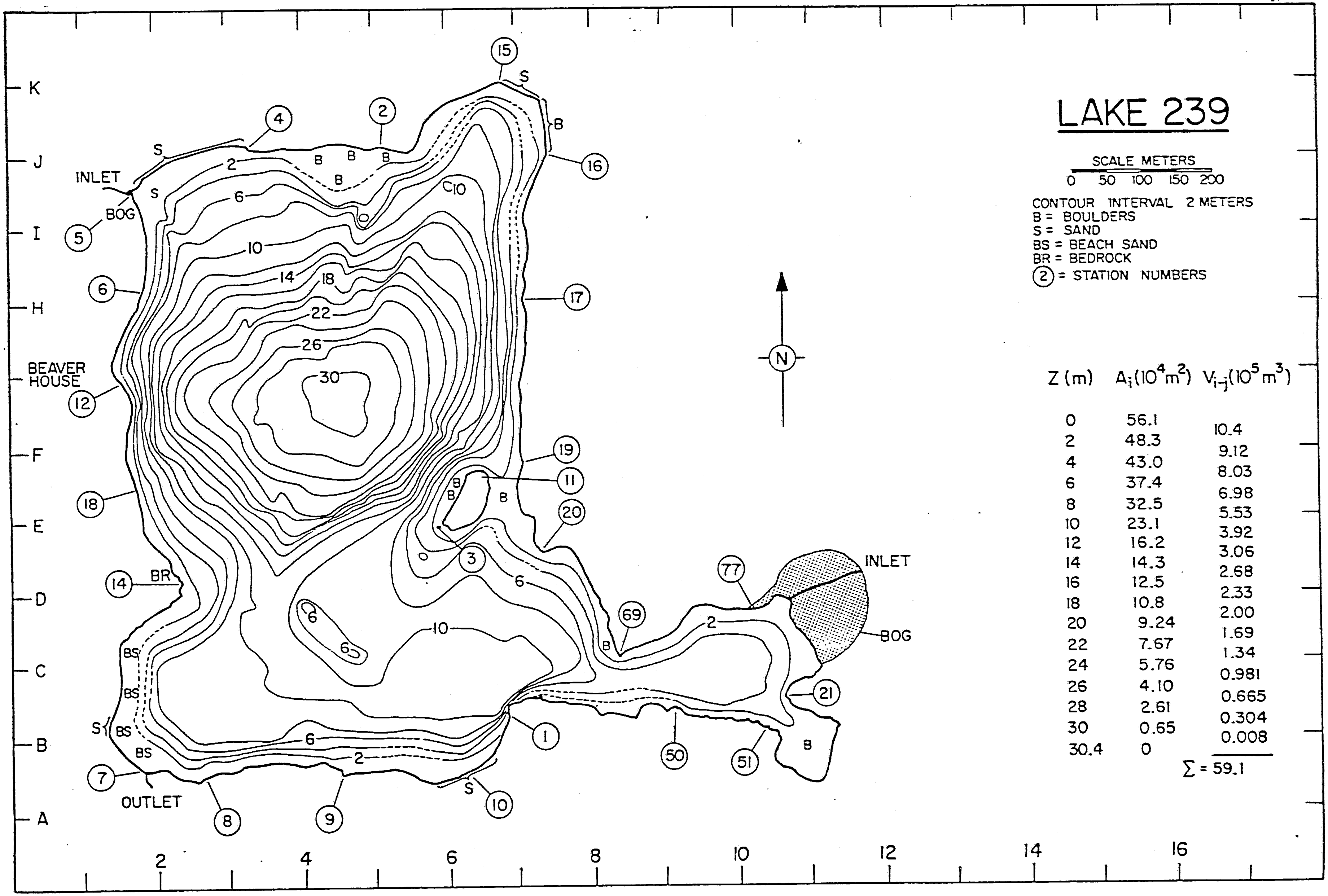
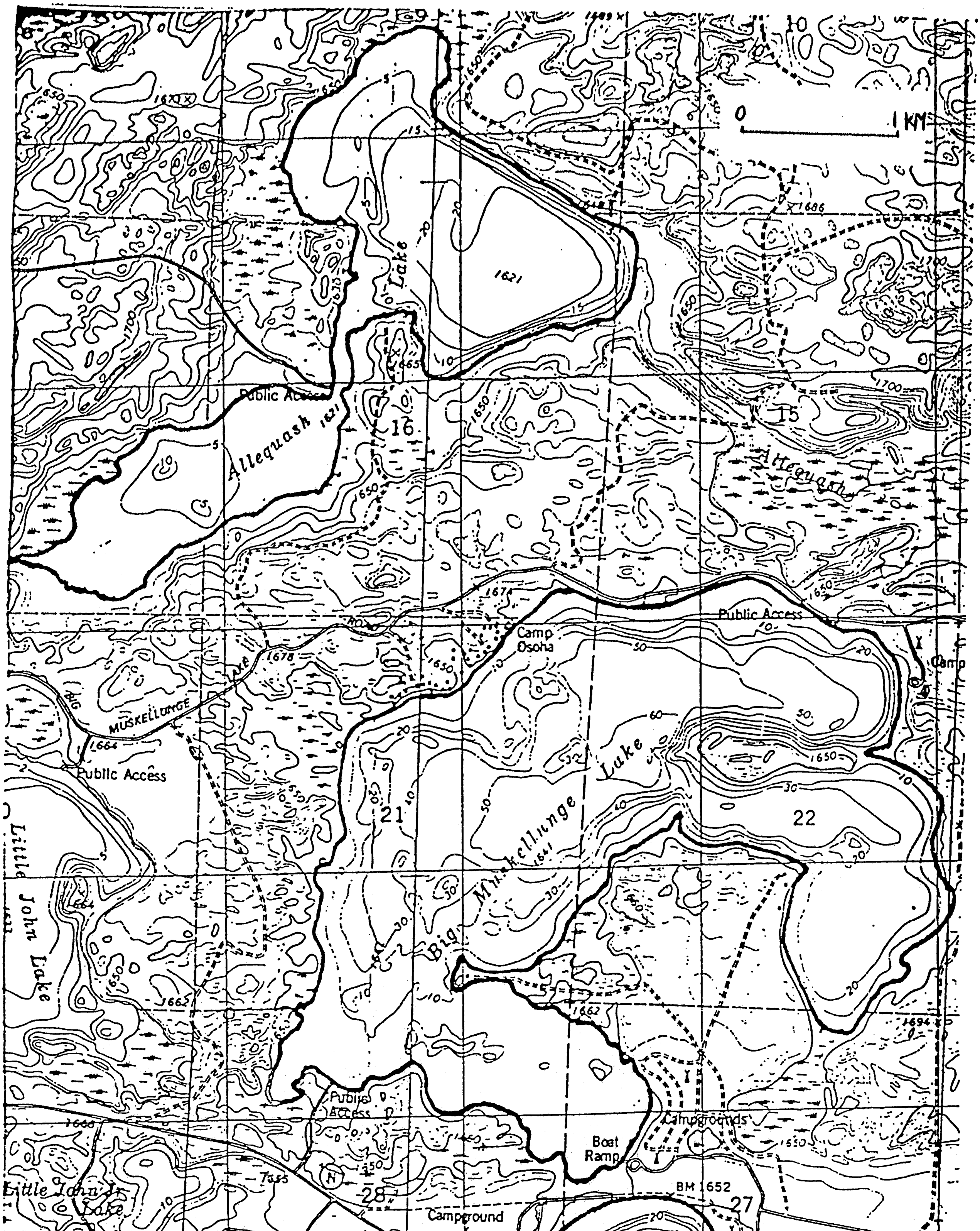


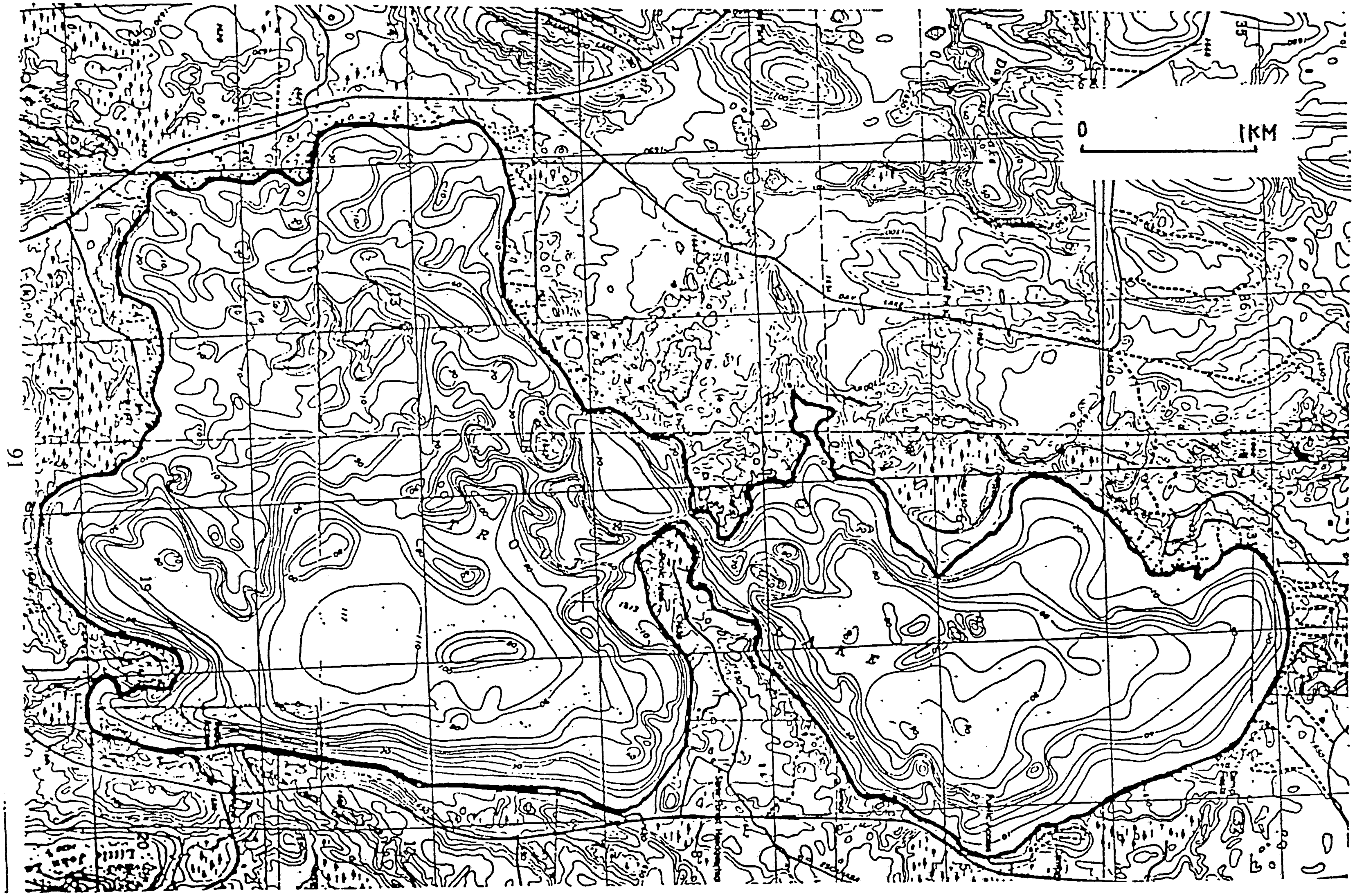
Fig. B15 Sensitivity of maximum ice thickness to snowfall

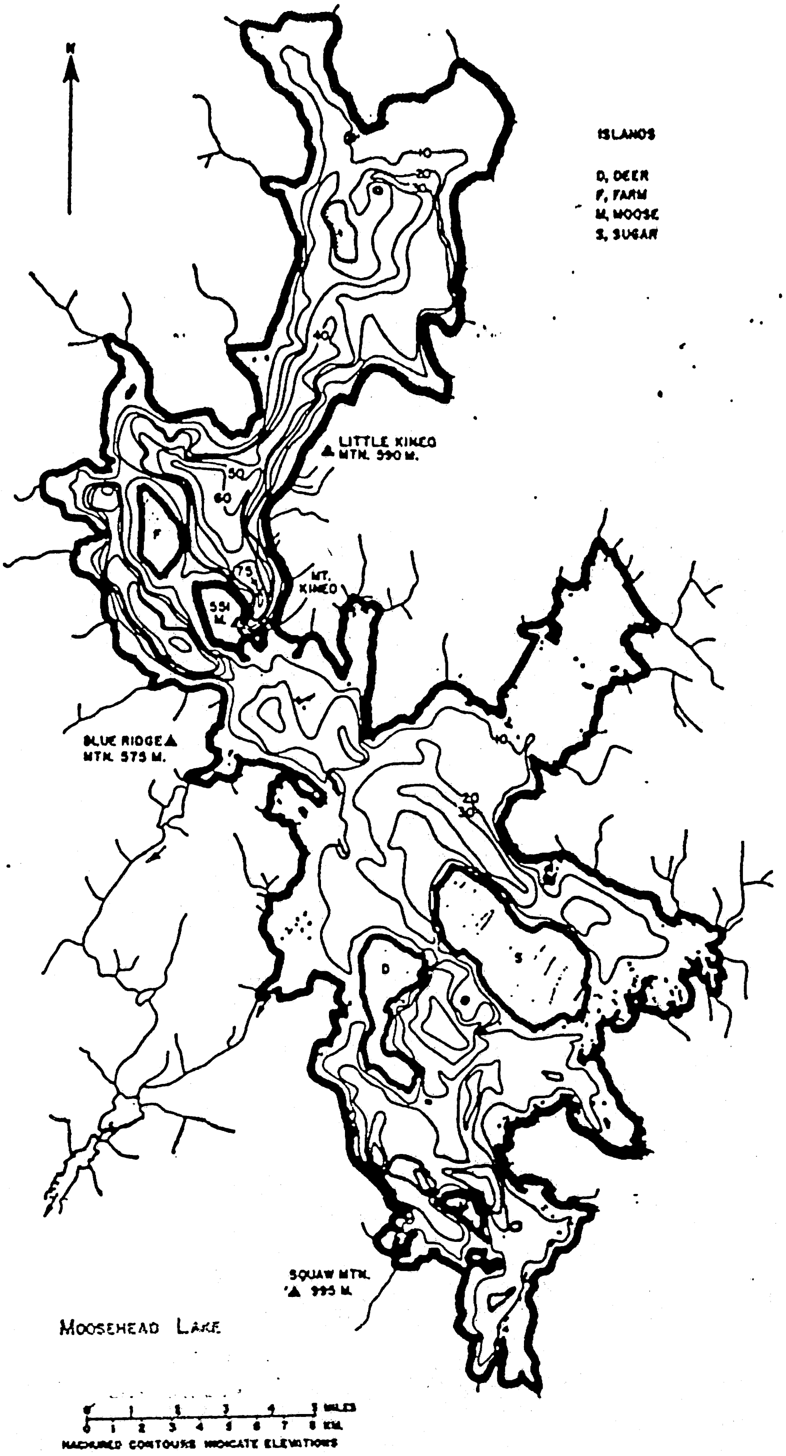
APPENDIX C: BATHYMETRIC LAKE MAPS



Z (m)	$A_i (10^4 m^2)$	$V_{i-j} (10^5 m^3)$
0	56.1	10.4
2	48.3	9.12
4	43.0	8.03
6	37.4	6.98
8	32.5	5.53
10	23.1	3.92
12	16.2	3.06
14	14.3	2.68
16	12.5	2.33
18	10.8	2.00
20	9.24	1.69
22	7.67	1.34
24	5.76	0.981
26	4.10	0.665
28	2.61	0.304
30	0.65	0.008
30.4	0	
		$\Sigma = 59.1$


0 1 KM
10
1621
Lake
Allequash 1621
Public Access
16
15
Allequash
1700
1650
1686
Camp Osoha
Public Access
Camp
Big Muskellunge Lake
1641
Big Muskellunge Lake
1678
1664
Public Access
21
22
Little John Lake
1662
1694
Public
Access
Boat Ramp
Campgrounds
Little John Jr. Lake
28
BM 1652
27
Campground
Picnic Area
Crystal Lake
1647
Campground
Firefly Lake
Public
Campground


0
1KM



Bathymetric map of Moosehead Lake, Piscataquis County, Maine. Approximate bottom contours drawn from soundings given on map in Cooper and Fuller, 1945.