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Simulations of Cisco Fish Habitat in Minnesota Lakes under Future Climate Scenarios

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Abstract

This report makes projections of potential (refuge) habitat for cisco, a coldwater fish, in Minnesota lakes under projected warmer climate scenarios. It is about the identification and selection of potential refuge lakes for cisco under future climate scenarios in Minnesota. This is the third and final project report in a series that describes computer model simulations of cisco (tullibee) lakes for the Minnesota Department of Natural Resources (DNR). The first report gave an overview of the characteristics of cisco lakes in Minnesota, the second gave results of water quality (temperature and dissolved oxygen, DO) model simulations for selected Minnesota cisco lakes, and this third report identifies and quantifies in which Minnesota lakes cisco habitat is most likely to continue to exist under global warming scenarios.

Cisco habitat simulations were first made for continuous, year-round weather time series from 1962 to 2008 (47 years) at the daily time scale. Simulations were then extended to projected future climate scenarios. A year-round water quality model MINLAKE 2010, that had previously been calibrated against 7384 pairs of temperature and DO data points measured in 28 lakes between 1979 and 2008 with overall standard errors of 1.47 °C for water temperature, and 1.50 mg/L for DO, was used in all cisco habitat simulations (Fang et al. 2010).

Adult cisco habitat is limited by critical water temperature and DO conditions in different strata of a cisco lake. The selection was based on the oxythermal parameter TDO3, which relates to the survival stress of adult cisco. The lower the TDO3 is, the lower the stress is to cisco. TDO3 is a water temperature that occurs where DO = 3 mg/L and was used as the oxythermal parameter to select suitable habitat for adult cisco (Jacobson et al. 2010). Twelve TDO3 parameters ranging from single-day values to multi-year averages, and from extreme values to mean values, were defined in Table 3.1 and calculated from simulated daily temperature and DO profiles. The multi-year values AvgATDO3_{FB} and AvgATDO3_{VB} were ultimately chosen from Table 3.1, lines 6 and 12, for the selection of cisco refuge lakes. Each of these two TDO3 parameters is calculated over the length of a 31-day benchmark period; one uses a fixed benchmark period from DOY 209 to DOY 239 (July 28 to August 27); the other uses a variable (sliding) benchmark period of 31 days.

In this report time-series of the TDO3 parameters and ranges of TDO3 parameter values in selected lakes are analyzed. The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to 2008 were used. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles and associated AvgTDO3_{FB} and AvgTDO3_{VB} for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes.

One associated weather station had to be selected for the simulation of each lake, but data from only three Class I NWS weather stations were useful and available. Three options (methods) were used to pair each lake with one of the three weather stations: (1) by shortest

distance, (2) by latitude, (3) one single weather station for all lakes simulated. Refuge lakes were determined using each of the three options.

The pool of 620 Minnesota cisco lakes was divided into three tiers. Tier 1 for a TDO3 $\leq 11^{\circ}\text{C}$, Tier 2 for the range $11^{\circ}\text{C} < \text{TDO3} \leq 17^{\circ}\text{C}$, and Tier 3 for $\text{TDO3} > 17^{\circ}\text{C}$. Tier 1 and Tier 2 were identified as cisco refuge lakes, Tier 3 as non-refuge lakes for cisco. This decision was based on Jacobson et al. (2010). Tier 1 lakes have the most suitable coldwater fish habitat, Tier 2 lakes have a suitable coldwater fish habitat, and Tier 3 lakes are marginal or unsuitable for cisco. Tier 1 and Tier 2 refuge lakes identified may be called viable cisco lakes where cisco is capable of living, developing, or spawning under favorable conditions. Cisco can still persist in lakes with TDO3 values greater than 17°C but at a reduced probability of occurrence.

Results are presented in tables and in graphical form as isolines of TDO3-values in a diagram of Secchi depth (as an indicator of lake trophic state) vs. lake geometry ratio (as an indicator of lake stratification and mixing dynamics). These contour plots of selected TDO3 parameters were interpolated from data points for 21 cisco study lakes and 30 virtual cisco lakes for both past and two future climate scenarios. Cisco refuge lakes in Minnesota were selected based on limiting values or TDO3-criteria for two future climate scenarios: CGCM 3.1 and MIROC 3.2 (IPCC DDC 2010).

The number of lakes that qualify as cisco refuge lakes depends, of course, on the assumptions and choices made in the method of selection and the climate scenarios. Of the 16 study lakes with adult cisco mortality in 2006, none was identified as a Tier 1 refuge lakes by any of the five methods. All five reference lakes that did not experience adult cisco mortality in 2006, were identified as either Tier 1 or Tier 2 refuge lakes by all of the five methods (Table 5.14). These are remarkable agreements between model predictions of refuge lakes and observed adult cisco mortality events in 2006.

The number of Tier 1 and Tier 2 cisco refuge lakes determined for the future climate scenario MIROC 3.2, varies depending on the selection method used (Tables 5.3 to 5.12). Although the numbers are different, the individual lakes identified by name in Tier 1 or Tier 2 of each of the Tables overlap strongly. Therefore, refuge lakes were listed by name and geographic coordinates in Table 5.16 for Tier 1 and Table E.1 (Appendix E) for Tier 1 plus Tier 2. They are ordered by the number of times that they were found by multiple methods. Lakes that appear most often are on top of the list. These two lists give recommended cisco refuge lakes independent of method used for their determination. The lakes on the list have been plotted on a map of Minnesota in Figures 5.22 and 5.23.

Ultimately 620 cisco lakes in Minnesota were listed by name and location from the most likely refuge lake to the least likely (Tables F.1 and G.1 in Appendixes F and G). Most are located in northeastern Minnesota. A frequency analysis of lake characteristic parameters for the selected refuge lakes was conducted. The results indicate that refuge lakes (Tier 1 plus Tier 2) selected under the future climate scenario MIROC 3.2 have Secchi depths greater than ≈ 2.5 m (Fig. 5.18), lake geometry ratio less than $\approx 2.5 \text{ m}^{-0.5}$ (Fig. 5.19), maximum depths greater than ≈ 15 m (Fig. 5.20), and surface area less than $\approx 30 \text{ km}^2$ (Fig. 5.21).

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Chapter 1 Introduction

Freshwater fish habitat is constrained by several physical and biological parameters that relate to water quality, food supply, and human interference. Channel geometry and streamflow are important to fish habitat in streams (Rundquist and Baldrige 1990). In lakes, water temperature and dissolved oxygen (DO) concentrations are two of the most significant water quality parameters affecting survival and growth of fishes (Fry 1971; Magnuson et al. 1979; Coutant 1985, 1987; Christie and Regier 1988). Climate warming has the potential to reduce coldwater fish habitat in lakes by direct warming of the water, and by increased hypolimnetic oxygen depletion during periods of stratification and thermocline deepening (Schindler et al. 1996; Stefan et al. 1996; Magnuson et al. 1997; Fang et al. 2004). Cisco is the most common coldwater stenothermal fish in Minnesota lakes. The Minnesota Department of Natural Resources (MN DNR) has sampled cisco from 648 lakes in netting assessments since 1946 (Minnesota DNR files). The lakes are scattered throughout much of the central and northern portions of the state and cross several ecoregions (boreal forest, hardwood forest, and prairie) and land uses (agricultural, urban, and forested). The wide distribution suggests that cisco are somewhat more eurythermal than other native, lentic coldwater stenotherms such as lake whitefish *Coregonus clupeaformis* (sampled in 155 lakes), lake trout *Salvelinus namaycush* (124 lakes) and burbot *Lota lota* (233 lakes). The combination of a wide distribution and a requirement for cold, oxygenated water, make cisco an excellent “canary in a mineshaft” species that is a sensitive indicator of climate change.

This report is the third in a series of three reports that describe model simulations of cisco (tullibee) lakes for the Minnesota Department of Natural Resources. In anticipation of possible future climate warming, possible cisco refuge lakes in Minnesota are identified in this report.

As discussed in Project Report 2 (Fang et al. 2010) of this study, 15 study lakes were selected in the first phase of this study for model calibration of the MINLAKE 2010 model that was used to simulate daily temperature and dissolved oxygen (DO) profiles and associated cisco habitat in Minnesota lakes. Eight of the 15 selected study lakes were known to have cisco-habitat, and seven were non-cisco lakes.

In the second phase of the study an additional 13 cisco-habitat lakes were chosen for additional model calibration. To identify cisco refuge lakes (Chapters 3 and 4), MINLAKE2010 simulation results for 21 cisco-habitat lakes (8 cisco lakes selected at the first phase and 13 cisco lakes selected at the second phase) were used.

1.1 Two approaches to evaluate cisco habitat

In this study, two approaches were explored to determine if cisco habitat existed in a Minnesota lake. The first approach was to determine whether or not cisco can survive in a lake based on separate dissolved oxygen (DO) and water temperature constraints; this approach had previously been used to examine the potential impact of future climate warming on cold-, cool-,

and warm-water fish species (guilds) in small lakes in the contiguous United States (Stefan et al. 2001). If cisco cannot survive under certain environmental conditions, it is assumed that fish kill occurs in a lake. The term “fish kill” is applied to a localized die-off of fish populations which may also be associated with more generalized mortality of aquatic life (Wikipedia 2010). According to Wikipedia fish kill may have a variety of causes including drought, disease, oil or chemical spill, hazardous waste spill, ecological hypoxia caused by sewage or organic matter such as leachate or silage liquor, algae blooms, seaquakes, unusual weather conditions, inappropriate re-stocking of fish, underwater explosions, and other catastrophic events that can perturb a normally stable aquatic population. Figure 1.1 shows a cisco killed in a Minnesota lake in July 2006 when unusual warm weather resulted in unfavorable environment conditions in the lake so that cisco could not survive. In this study thermal DO habitat of cisco was determined in 15 study lakes; this means that observed or projected water temperature and DO were compared separately to requirements for fish survival. This is called “fish kill” approach. The fish kill in this case is only due to unfavorable temperature (thermal) and/or DO conditions but not due to other factors listed above. Background information and results of the fish kill approach are given in Appendix A of the report.



Figure 1.1 A cisco kill event: picture of a dead cisco fish taken from a Minnesota lake during the summer of 2006.

The second approach is to use a single oxythermal habitat variable to define suitable or unsuitable fish habitat. Jacobson et al. (2010) studied coldwater fish oxythermal habitat in Minnesota lakes. They used a generalized oxythermal habitat variable, TDO3, called “temperature at 3.0 mg/L DO” and determined by interpolating the water temperature at a benchmark oxygen concentration (i.e., 3.0 mg/L) from vertical temperature and DO profiles in a

lake. DO = 3 mg/L is an oxygen concentration limit that is probably lethal or nearly so for many coldwater species (Frey 1955; US EPA 1986; Evans 2007). They found that TDO3 has a strong connection with four coldwater taxa (lake trout, cisco, whitefish, and burbot). Cisco were present in lakes with a broad range of maximum TDO3 values, with central borders of 4.0 to 16.9 °C (Jacobson et al. 2010). TDO3 allows to evaluate or quantify which lake has better environmental conditions to support cisco habitat, or to determine which lake is a better refuge lake for cisco under a future climate scenario. This second approach is called “TDO3 approach” in this study.

1.2 Twenty-one cisco study lakes and thirty virtual cisco lakes

In previous studies, 27 regional lake classes or types were used to study cold-, cool- and warm-water fish habitat under past and future climate scenarios (Stefan et al., 1996; Stefan et al. 2001, Fang et al. 2004). For the previous lake classification, lake surface areas A_s chosen were 0.2, 1.7 and 10.0 km² for small, medium, and large lakes, respectively; maximum depths H_{max} chosen were 4.0, 13.0 and 24.0 m for shallow, medium-depth, and deep lakes, respectively (Stefan et al. 1992). Secchi depths (SD) of 1.2, 2.5, and 4.5 m were selected for eutrophic, mesotrophic, and oligotrophic lakes using Carlson’s trophic state index (Carlson 1977), respectively. More important than the individual numbers, is the observation that the likelihood of a strong or weak stratification in a lake can be related to the lake geometry ratio, $GR = A_s^{0.25}/H_{max}$ (Gorham and Boyce 1989). The above nine (9) types of lakes cover geometry ratios from 0.9 to 14.1. According to Gorham and Boyce (1989) polymictic lakes have the highest numbers, while strongly stratified dimictic lakes occur at the lowest numbers. The transition occurs between 3 and 5. Hence, the full range of stratification behavior is included in the 27 lake types.

In the first of our three project reports (Fang et al 2009), we determined that 620 documented cisco lakes in Minnesota are relative deep mesotrophic or oligotrophic lakes. Twenty-one (21) cisco lakes were selected as study lakes because they had measured water temperature and DO profiles that could be used for model calibration of MINLAKE2010. Table 1.1 lists characteristics of these 21 cisco study lakes. The calibrated MINLAKE2010 model, discussed and summarized in project report 2 (Fang et al. 2010), generated simulated daily water temperature and DO profiles from which the oxythermal parameter TDO3 could be extracted. Figure 1.2 shows the distribution of the 21 study lakes and the 620 cisco lakes in Minnesota on a plot of Secchi Depth, SD, (m) versus Lake Geometry Ratio, GR, (m^{-0.5}). It can be seen that the 21 cisco study lakes are not well distributed on the plot, and this may create a problem when contour maps of TDO3 parameters are developed from point values, which will be demonstrated and discussed in Chapter 4.

The highest SD value used in previous studies of regional lakes was 4.5 m. For this cisco lakes study higher SD values and lower GR values are required to fill the gaps in Figure 1.2. Therefore, a new set of virtual cisco lakes with SD values ranging from 1.2 m to 8.5 m and GR values ranging from 0.74 to 3.5 m^{-0.5} was introduced and used. The set of virtual cisco lakes includes 30 different types of lake (named LakeC01 to LakeC30; the letter “C” stands for “cisco”

to distinguish the set from the previous lake types named Lake01 to Lake27). The set of 30 virtual cisco lakes comprises lakes with five different SD values (1.2 m, 2.5 m, 4.5 m, 7.0 m and 8.5 m) and six different surface areas (0.1 km², 0.5 km², 1.5 km², 5.5 km², 13.5 km², and 15.5 km²). The maximum depth of all 30 virtual lakes is set at 24 m, because cisco lakes are relatively deep (see Project Report 1; Fang et al. 2009). Combinations of the maximum depth and surface areas give six different geometry ratios for the 30 virtual lakes, i.e. 0.74 m^{-0.5}, 1.11 m^{-0.5}, 1.36 m^{-0.5}, 1.97 m^{-0.5}, 2.50 m^{-0.5}, and 3.50 m^{-0.5}. These and other characteristics of the 30 virtual cisco lakes (or lake classes) used in this study are summarized in Table 1.2.

Table 1.1 Characteristics of the 21 cisco study lakes used for MINLAKE2010 model calibration. These lakes have measured water temperature and DO profiles.

Lake	Surface area (km ²)	Maximum depth (m)	Geometry Ratio (m ^{-0.5})	Mean Secchi depth (m)	Mean chlorophyll a (mg/L)	Trophic status ¹
Big Trout	5.43	39.01	1.24	4.78	0.00336	O
Blue	0.71	14.63	2.04	6.76	0.00280	O
Burntside	28.90	38.40	1.91	5.80	0.00286	O
Carlos	10.20	50.00	1.13	3.27	0.00500	M
Cedar	0.98	26.80	1.17	3.56	0.00480	M
Elk	1.10	28.00	1.16	2.57	0.00480	M
Fish Hook	6.61	23.16	2.19	3.44	0.00400	M
Greenwood	8.18	34.14	1.57	5.46	0.00255	O
Grindstone	2.13	46.63	0.82	2.88	0.00637	M
Kabekona	9.12	41.00	1.34	4.03	0.00320	M
Little Sand	1.56	24.38	1.45	5.22	0.00231	O
Little Trout	0.97	28.95	1.08	6.33	0.00073	O
Mukooda	3.05	23.77	1.76	5.12	0.00115	O
Siseebakwet	5.29	32.00	1.5	3.89	0.00205	M
Six	0.76	42.67	0.69	3.94	0.00445	M
Snowbank	17.30	45.72	1.41	5.28	0.00271	O
South Twin	4.52	8.80	5.22	2.78	0.00340	M
Ten Mile	18.90	63.00	1.05	5.54	0.00250	O
Trout (Cook)	1.04	23.00	1.39	5.40	0.00140	O
Trout (St. Louis)	30.94	29.87	2.50	4.71	0.00247	O
White Iron	13.88	14.30	4.26	1.44	0.00520	E

¹ E = Eutrophic, M = Mesotrophic, O = Oligotrophic.

Even though the selection of lake bathymetry (surface areas and maximum depth) and Secchi depth for the 30 virtual cisco lakes was subjective, the selected values are representative

of the 620 Minnesota cisco lake database. Figure 1.3 gives the cumulative distributions of lake surface area, geometry ratio and Secchi depth for all 620 cisco lakes in the Minnesota DNR database, as well as for the 30 virtual cisco lakes. Table 1.3 gives cumulative distributions (% less than) and classifications of lake surface area, geometry ration, and Secchi depth for the 30 virtual lakes in comparison to all 620 cisco lakes in the MN DNR database. The 30 virtual cisco lakes are all stratified lakes based on geometry ratio, they cover small to large surface areas and include eutrophic to oligotrophic lakes (Table 1.3). It can be seen that the 30 virtual lakes match the actual 620 lakes well.

Figure 1.2 shows the distribution of the 30 virtual cisco lakes on the plot of SD versus GR as well as the distributions of the 21 cisco study lakes used for model calibration and the 620 cisco lakes in the Minnesota DNR database. The 30 virtual cisco lakes cover the domain of the 620 real cisco lakes more completely than the 21 cisco study lakes in Fig. 1.2. That is the reason why virtual lakes were selected and used in the study. Besides, Secchi depths used to plot the 21 cisco study lakes are the summer average values for the years when temperature and DO profiles were measured, whereas the Secchi depths in the MN DNR database may be different.

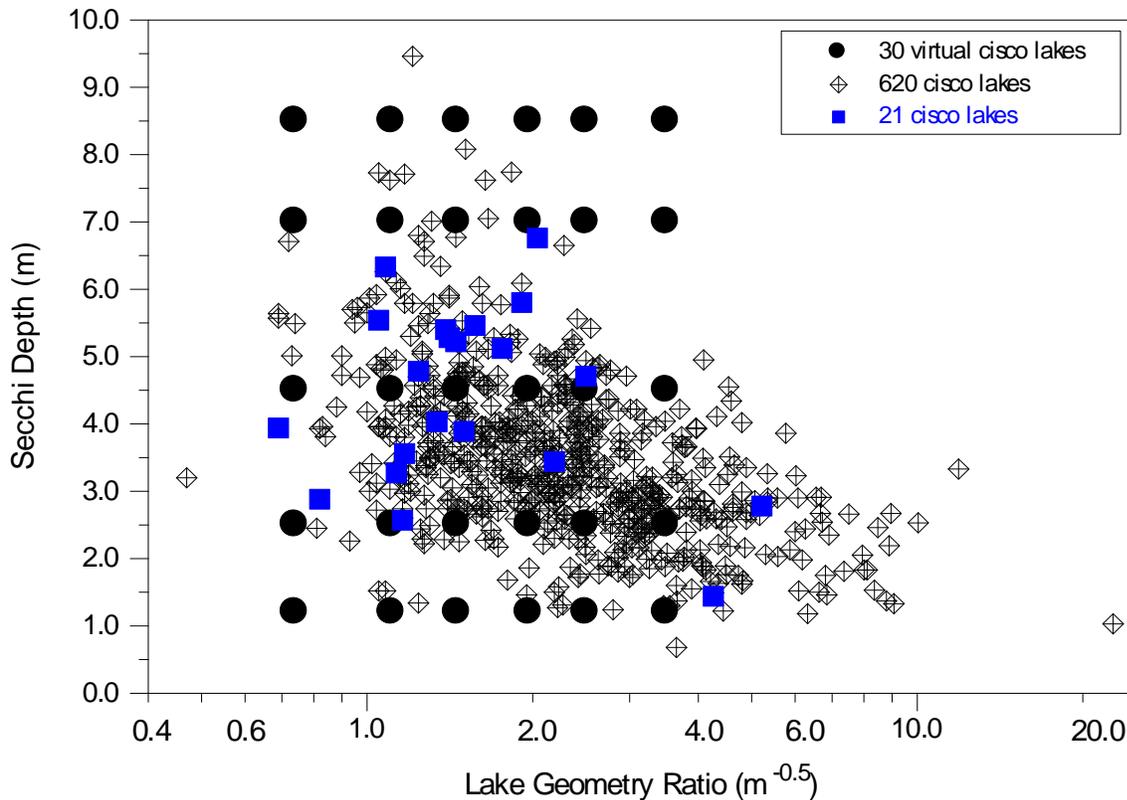


Figure 1.2 Distribution of 30 virtual cisco lakes, 21 cisco study lakes, and 620 cisco lakes in Minnesota on a plot of Secchi depth versus lake geometry ratio ($GR = A_s^{0.25}/H_{max}$).

Table 1.2 Morphometric characteristics and names of the 30 virtual cisco lakes used in the MINLAKE2010 model simulations.

Max. Depth	Surface Area	Secchi Depth SD (m)					Geometry Ratio
		1.2	2.5	4.5	7.0	8.5	
H _{max} = 24 m (Deep)	A _S (km ²)						A _S ^{0.25} /H _{max}
	0.1	LakeC01	LakeC02	LakeC03	LakeC04	LakeC05	0.74
	0.5	LakeC06	LakeC07	LakeC08	LakeC09	LakeC10	1.11
	1.5	LakeC11	LakeC12	LakeC13	LakeC14	LakeC15	1.46
	5.0	LakeC16	LakeC17	LakeC18	LakeC19	LakeC20	1.97
	13.0	LakeC21	LakeC22	LakeC23	LakeC24	LakeC25	2.50
	50.0	LakeC26	LakeC27	LakeC28	LakeC29	LakeC30	3.50

Table 1.3 Distributions and classifications of surface area, geometry ratio (GR) and Secchi depth (SD) of the 30 virtual cisco lakes.

Area (km ²)	% less than ¹	Classification	GR (m ^{-0.5})	% less than ¹	Classification	SD (m)	% less than ¹	Trophic status
0.1	1.0%	Small	0.74	1.0%	Stratified	1.2	0.6%	E
0.5	14.6%	Small*	1.11	7.1%	Stratified	2.5	19.0%	M
1.5	48.0%	Medium	1.46	21.1%	Stratified	4.5	81.5%	O
5.0	77.8%	Medium*	1.97	41.8%	Stratified	7.0	98.5%	O
13.0	92.0%	Large	2.50	62.0%	Stratified	8.5	99.8%	O
50.0	98.0%	Large	3.50	81.0%	Stratified	-	-	-

* - These are on the border of the previous 27 regional lake classification, E: Eutrophic lake, M: Mesotrophic lake, and O: Oligotrophic lake. ¹ in comparison to all 620 cisco lakes in the MN DNR database.

1.3 Cisco refuge lake identification

The goal of this study was to identify potential refuge lakes for cisco survival under future climate scenarios. The TDO3 approach was selected to identify viable cisco habitat in refuge lakes for future climate scenarios. Several different TDO3 parameters were explored for the purpose of refuge lake selection. As discussed in Chapter 3, lake geometry ratio (GR) and Secchi depth (SD) are two important parameters influencing thermal and DO conditions, and hence cisco habitat in a lake. Contours of different TDO3 parameters were drawn on plots with GR and SD as X- and Y-axis for both past climate and future climate conditions in order to identify refuge lakes. It was determined (Figure 1.2) that the 21 cisco study lakes used for model calibration did not cover the entire field of SD and GR values sufficiently well to make reliable contour plots. The 30 virtual cisco lakes discussed above covered the full range of GR

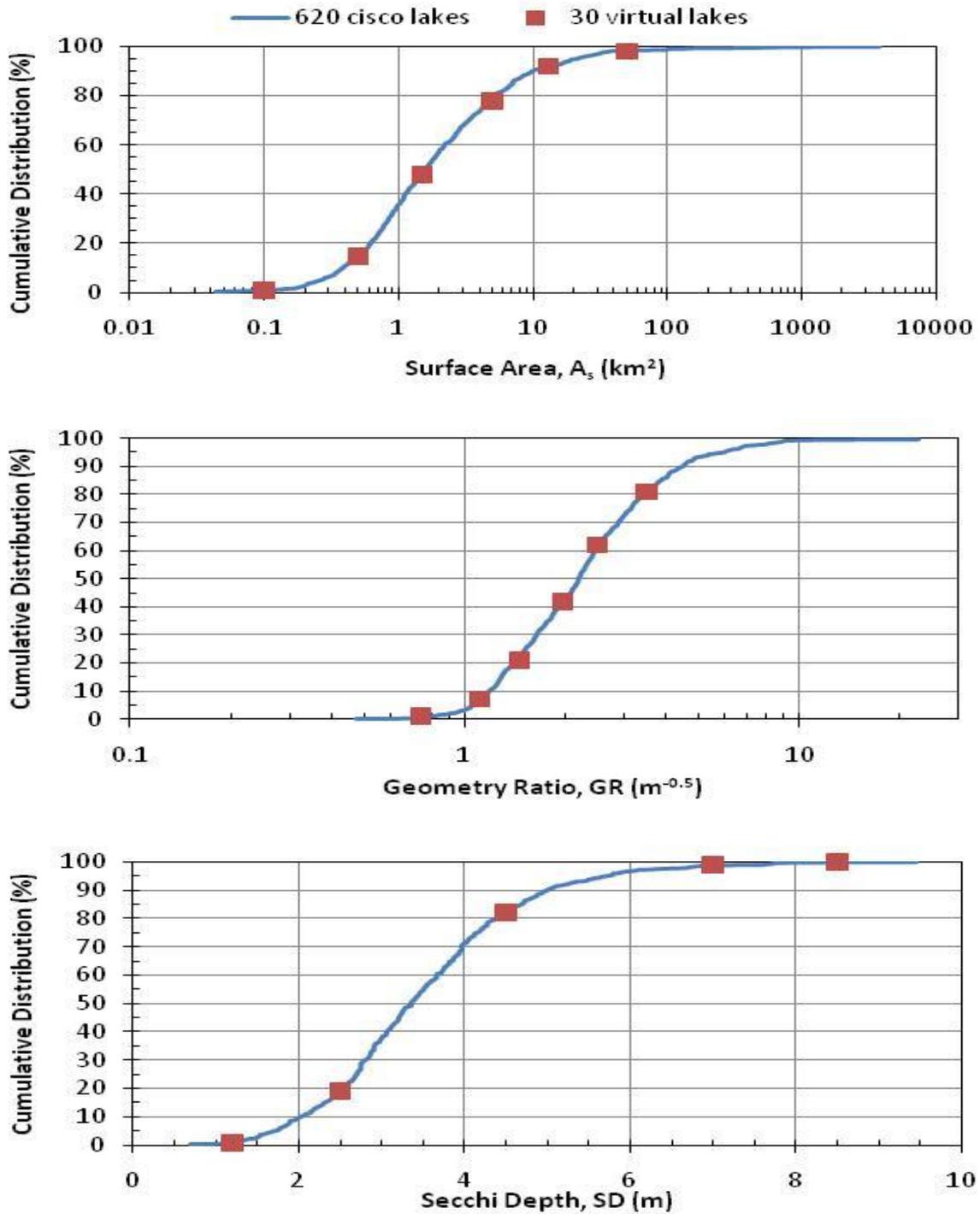


Figure 1.3 Cumulative distributions of lake surface area, geometry ratio, and Secchi depth for all 620 cisco lakes in the Minnesota DNR database and the 30 virtual cisco lakes.

and SD values more completely, and were therefore added. Simulated TDO3 values for the 30 virtual cisco lakes were used to develop the final contour plots of TDO3 to indentify refuge lakes.

A lower TDO3 value indicates better living conditions for cisco in a lake. Relative to lethal temperatures for cisco, a lower TDO3 suggests a more suitable thermal and DO environment for cisco to survive and grow. Therefore, lakes with the lowest TDO3 values are potential refuge lakes. Contour plots of TDO3 give valuable information on the limiting values of GR and SD for cisco refuge lakes. Cisco lakes which fall within the limiting values of GR and SD are identified in the MN DNR cisco lake database and proposed as future cisco refuge lakes.

The next five chapters of this third and final project report, provide the following information:

Chapter 2 gives information on future climate scenarios that were used to run the calibrated year-round water quality model in order to make water quality and fish habitat projections.

Chapter 3 defines 12 TDO3 parameters calculated from simulated daily temperature and DO profiles. It presents time-series of TDO3 parameters in selected lakes and ranges of TDO3 parameter values in selected lakes.

Chapter 4 presents contour plots of selected TDO3 parameters that were interpolated from data points simulated for 21 cisco study lakes and 30 virtual cisco lakes.

Chapter 5 presents results for the selection of cisco refuge lakes in Minnesota using different TDO3 parameters and different climate scenarios. It includes a frequency analysis of lake characteristic parameters for selected refuge lakes.

Chapter 6 gives a summary and conclusions of the study and includes recommendations for future investigations.

Chapter 2 Future Climate Scenarios

In this study we are not only to identify whether a Minnesota lake can support cisco habitat under past (observed historical) climate conditions, but also to project whether a lake can support cisco habitat under future climate scenarios, i.e. after climate warming. To make the projection, we have available the model output from a number of General Circulation Models (GCMs) of the earth's atmosphere. These GCM models simulate time series of climate parameters that can be used to create future climate scenarios. As input to the MINLAKE2010 model, the GCM future climate scenarios facilitate the projection of future lake water quality conditions from which future cisco habitat is derived. In previous fish habitat projections for the contiguous United States (Stefan et al. 2001), GCM 2.0 model output from the Canadian Climate Centre for Climate Modeling and Analysis (CCCma) was used. For the present study, we used the output of two new GCMs (CCCma CGCM 3.1, and MIROC 3.2), and output from the earlier model (CCCma GCM 2.0) used in our previous studies (Stefan et al. 2001). In this chapter these GCM models are described briefly, and the assembly and utilization of the GCM output data are discussed.

2.1 General circulation models

A General Circulation Model (GCM) is a mathematical simulation model of the general circulation of a planetary atmosphere or ocean on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat). The fluid dynamic and thermodynamic equations used are the basis for complex computer programs called GCMs and commonly used for simulating the atmosphere or oceans of the Earth. Atmospheric and Oceanic GCMs (AGCMs and OGCMs) are key components of global climate models along with sea-ice and land-surface components. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change.

In the early stage of GCM research, atmospheric and oceanic GCMs were separate. AGCMs typically contain a land-surface model and impose sea surface temperatures. They may include atmospheric chemistry. AGCMs consist of a dynamical core that integrates the equations of fluid motion, typically for surface pressure, horizontal components of velocity in layers, and temperature and water vapor in layers. There is generally a radiation code, split into solar/short wave and terrestrial/infra-red/long wave. Parameterizations are used to include the effects of various processes. All modern AGCMs include parameterizations for convection, land surface processes, albedo, hydrology, and cloud cover.

OGCMs model the ocean (with fluxes from the atmosphere imposed) and may or may not contain a sea ice model. The standard resolution of HadOM3 (Hadley Oceanic Model 3) is 1.25 degrees in latitude and longitude, with 20 vertical levels, leading to over 2,000,000 variables.

In recent GCM research, atmospheric and oceanic models are combined and called Coupled Atmosphere-Ocean GCMs (AOGCMs) or more simply Coupled GCMs (CGCMs).

These models have removed the need to specify fluxes across the ocean surface, and are the basis for sophisticated model predictions of future climate. CGCMs represent the pinnacle of complexity in climate modeling and incorporate as many processes as possible. They are the only tools that can provide detailed regional predictions of future climate change. However, they are still under development. The simpler models are generally susceptible to simple analysis and their results are generally easy to understand. AOGCMs, by contrast, are often nearly as hard to analyze as the real climate system.

2.2 Selection of the GCMs used in the study

Recent GCM model outputs that can be used to develop future climate scenarios are available on the website (<http://www.ipcc-data.org/>) of the Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC). The DDC is overseen by the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA). The identification, selection, and application of baseline and scenario data are crucial steps in projections of the potential impact of climate change. The IPCC TGICA defined a set of criteria that were applied to identify a small number of GCM experiments whose results could be deposited at the IPCC DDC website and can be used for climate change impact studies. IPCC selected models that fulfill the following criteria:

- the models should be full 3D coupled ocean-atmospheric GCMs,
- the models should be documented in the peer reviewed literature,
- the models should have performed a multi-century control run (for stability reasons) and
- the models should have participated in CMIP2 (Second Coupled Model Intercomparison Project).

In addition, preferably

- the models have been used to perform a 2 x CO₂ mixed layer run,
- the models have participated in AMIP (Atmospheric Model Intercomparison Project),
- the models have a resolution of at least T40, R30 or 3° latitude x 3° longitude
- the models consider explicit greenhouse gases (e.g. CO₂, CH₄, etc.)

For this cisco lake habitat study, we selected two GCMs which meet the standards of IPCC; they are the CGCM 3.1 and MIROC 3.2. We have also used GCM 2.0 that was applied in our previous studies (Stefan et al. 2001). These three GCMs are discussed in the next section.

2.3 Description of the GCMs used in the study

Three GCMs were used in this study. Two, i.e. GCM 2.0 and CGCM 3.1 are from the Canadian Climate Centre for Climate Modeling and Analysis (CCCma). The third is The Model for Interdisciplinary Research on Climate, MIROC 3.2, which was developed at the Center for Climate System Research (CCSR), University of Tokyo and associates. Background information on the future climate scenarios specified by the three selected CGCMs is given below.

2.3.1 CCCma Models – GCM 2.0 and CGCM 3.1

The Canadian Centre for Climate Modeling and Analysis has developed a number of climate models. They are used to study climate change and variability, and to understand the various processes that govern the climate system. They are also used to make quantitative projections of future long-term climate change (given various greenhouse gas and aerosol forcing scenarios), and increasingly to make initialized climate predictions on time scales ranging from seasons to decades. The first generation atmospheric general circulation model (AGCM1) was developed in the early 1980s. The first coupled global climate model (CGCM1) was developed in the early 2000s. After the coupled global climate models, called CGCMs, had come on the scene, previous atmospheric general circulation models were first called GCMs, and now AGCMs.

- **GCM 2.0**

The second generation atmospheric GCM 2.0 (Boer et al. 1992; McFarlane et al. 1992), includes higher spatial resolution $3.75^\circ \times 3.75^\circ$ than previous models and full diurnal and annual cycles. This model provides the increments or ratios for monthly climatic parameter values representative of a doubling of atmospheric CO_2 ($2 \times \text{CO}_2$). This model was developed in the early 90s. The output of GCM 2.0 was used by the authors in previous studies to examine fish habitat in small lakes in the contiguous United States. Hence, the output of this model was available for the present study. Although GCM 2.0 it is not one of the current models developed by CCCma, the availability of its model output data led us to use the GCM 2.0 for some model runs in the present study. It has one grid center point within Minnesota and eight grid points surrounding Minnesota (Fig. 2.1).

- **CGCM 3.1**

The newest version of the Coupled Global Climate Models (CGCMs) from the Canadian Centre for Climate Modeling and Analysis (CCCma) is CGCM 3.1 (Kim et al. 2002; Kim et al. 2003). This third generation model makes use of the ocean component from the earlier Second Generation Coupled Global Climate Model, but applies a substantially updated atmospheric component - the third Generation Atmospheric General Circulation Model (AGCM). CGCM 3.1 was run at two different resolutions. The T47 version has a surface grid whose spatial resolution is roughly 3.75 degrees latitude and longitude, and 31 levels in the vertical. The T63 version has a surface grid whose spatial resolution is roughly 2.8 degrees latitude and longitude and 31 levels in the vertical. Because not all weather parameters for the T63 version are yet available, the T47 version had to be used for this study. It has one grid center point in Minnesota and eight grid points in surrounding states

and provinces (Fig. 2.2). The distribution of grid center points for CGCM 3.1 looks almost the same as for GCM 2.0 (Fig. 2.1) but the CGCM 3.1 grid center points do have slightly different coordinates.

2.3.2 MIROC 3.2 model

The Model for Interdisciplinary Research on Climate, MIROC3.2 (Hasumi and Emori 2004), was developed by the Center for Climate System Research (CCSR), University of Tokyo; the National Institute for Environmental Studies (NIES); and the Frontier Research Center for Global Change (FRCGC) - Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Two sets of output from the MIROC 3.2 model are available: high resolution and medium resolution. For this study, output with high spatial resolution has been used; it has a surface grid whose spatial resolution is roughly 1.12 degrees latitude and longitude. Among the three GCMs selected for this study MIROC 3.2 has the smallest spatial resolution. It has seventeen grid center points in Minnesota and many more grid points in surrounding states and provinces (Fig. 2.3).

2.4 Atmospheric CO₂ scenarios for the GCMs

The Intergovernmental Panel on Climate Change (IPCC) published a set of future climate scenarios in 2000 for use in the Third Assessment Report (IPCC 2001) on global climate warming. This publication is known as the **Special Report on Emissions Scenarios (SRES)**. Because the future world may take different routes regarding social, cultural and financial development, the SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. There are four major scenario families (A1, A2, B1, and B2) and a number of sub-scenarios which result in a total of 40 different scenarios. Some of these are reproduced in Figure 2.3. The major scenario families are described as follows:

- **A1 scenario family:** a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- **A2 scenario family:** a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other scenarios.
- **B1 scenario family:** a convergent world with the same global population as in the A1 scenario but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
- **B2 scenario family:** a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

In Table 2.1, atmospheric CO₂ concentrations projected for 2100 under the different emission scenarios are listed. In the future climate scenario A1B the projected atmospheric CO₂

concentration in 2070 – 2099, would be double of what it was in the base period (1990). The global average CO₂ concentration in 1990 was 375 ppm. Because previous studies related to the present study were also using a doubling of CO₂, the A1B scenario provides some continuity. Hence, the output of GCMs using the A1B scenario was selected for this study.

Table 2.1 Atmospheric CO₂ concentrations in 2100 for different climate scenarios

Scenarios	CO ₂ concentration (ppm)
A1B	705
A2	842
B1	538
B2	618

2.4.1 Temperature and sea level rise for each SRES scenario family

There are six families of SRES scenarios in the IPCC’s Fourth Assessment Report (Solomon et al. 2007). This Fourth Assessment Report gives projected temperature and sea level rises (excluding future rapid dynamical changes in ice flow) for each scenario family as reproduced in Table 2.2

Table 2.2 Temperature rise and sea level change in different scenarios from IPCC’s Fourth Assessment Report (IPCC 2007).

Scenarios	Best estimated temperature rise	Likely range of temperature rise	Sea level rise (cm or inches)	
			cm	inches
B1	3.2 °F (1.8 °C)	2.0 -5.2 °F	18 - 38 cm	7 - 15 inches
A1T	4.3 °F (2.4 °C)	2.5 - 6.8 °F	20 - 45 cm	8 - 18 inches
B2	4.3 °F (2.4 °C)	2.5 - 6.8 °F	20 - 43 cm	8 - 17 inches
A1B	5.0 °F (2.8 °C)	3.1 - 7.9 °F	21 - 48 cm	8 - 19 inches
A2	6.1 °F (3.4 °C)	3.6 - 9.7 °F	23 - 51 cm	9 - 20 inches
A1F1	7.2 °F (4.0 °C)	4.3 - 11.5 °F	26 - 59 cm	10 - 23 inches

Note : Temperature rise is the difference from the period 1980-1999.

2.5 Generation of future climate scenario data for the MINLAKE2010 water quality and fish habitat model simulations

The GCMs generate global weather data (air temperature, dew point temperature, solar radiation, precipitation and wind speed) at all grid points for current and future years, e.g., for 2010-2039, 2040-2069, and 2070-2099. GCM outputs are not generally of a sufficient resolution or reliability to be applied directly to represent the present-day climate. Instead, the **climate change** simulated by GCMs is usually applied to baseline observational weather data, such as time series of historic daily weather data. A scenario of future climate is obtained by adjusting the baseline observations by the difference (or ratio) between period-averaged results from GCM experiments (usually 10 or 30 year periods are used) and the corresponding averages for the GCM control simulation. In recent transient experiments developed for the IPCC's Fourth Assessment Report (IPCC 2007) a simulated baseline period (e.g. 1961-1990) is used in place of the control-run. The differences or ratios known as a "change field" are produced and reported for all grid center points at monthly interval. Table 2.3 lists which types of the change fields are available for the three GCMs selected for the present study. The change field data for the period 2070 - 2099, 30 year averages that are compatible with the IPCC's Third Assessment Report (IPCC 2001), were downloaded from the IPCC website for use in the present study.

Data available from the Data Distribution Center of IPCC: As discussed in section 3.2 output data from the GCMs which meet a strict standard are eligible to be stored on the IPCC server. IPCC designed a Data Distribution Center (DDC) (<http://www.ipcc-data.org>) primarily for climate change researchers, but also of interest to educators, governmental and non-governmental organizations, and the general public. For the current study, output of the CGCM 3.1 and the MIROC 3.2 models was retrieved from the website of the DDC. The data files are stored as 'tar' files. Each tar file contains three sets of NetCDF files:

- 20x: Twenty year averages, +20-39, +46-85, +80-99, +180-199 (used in Chapter 10 of IPCC (2007), Fourth Assessment Report)
- 30a: Thirty year averages, +01-30, +31-60, +61-90 (used by observational climatologists)
- 30b: Thirty year averages, +10-39, +40-69, +70-99 (for compatibility with the IPCC (2001), Third Assessment Report)

For the specific scenarios and models used in the present study, data files for the 20x and 30b options are available to download. We used data files from option 30b, because that was more related to previous studies. For 30b there were 3 files that could be downloaded for each weather parameter. We used only data files for 2070 -2099 (+70-99).

Location of Grid Points: The GCM output files do not provide future daily weather data for any specific weather stations, but for grid center points on the globe. Figures 2.1 to 2.3 show the location of the weather stations used and the grid center points in and near Minnesota. When the MINLAKE2010 model is run for a specific weather station, the model identifies the grid center point that is closest to that weather station, based on distance using longitude and latitude as coordinates. Table 2.4 shows the nearest grid center points of the three GCM models for different weather stations used in this study. Tables 2.5 and 2.6 list monthly changes of air

temperature (°C) and solar radiation (Langley/day) projected by CGCM 3.1 and MIROC 3.2 for the three principal weather stations used in this study. They are the Class I weather stations of the NWS in International Falls Duluth and St. Cloud, MN. Projected average annual changes of air temperature ranged from 4.00 to 4.24°C; projected monthly changes of air temperature had relatively larger variations when projected from CGCM 3.1 rather than from MIROC 3.2. For example, the monthly changes of air temperature at International Falls were projected to be from 2.89 to 6.89°C by CGCM 3.1 and from 3.53 to 5.15°C by MIROC 3.2. The highest change of air temperature was projected by CGCM 3.1 to be 8.09°C in February at Duluth.

The monthly ‘change field’ data at the nearest grid point were applied to the daily weather data of the respective weather station for the simulation period (e.g., 1961 to 2008 or 1991 to 2008). The resulting projected daily weather parameter values of the selected climate scenario are used as input to the MIN LAKE2010 model simulation. Figure 2.4 gives plots of the average and the standard deviation for air temperature, dew point temperature, wind speed, and solar radiation at Duluth for past climate (1961-2008) and projected future climate conditions.

Table 2.3 Type of ‘change field’ data provided by the three selected GCM models.

Weather Parameter	GCM 2.0	CGCM 3.1	MIROC 3.2
	Difference or Ratio	Difference or Ratio	Difference or Ratio
Air Temperature	Difference	Difference	Difference
Dew Point Temperature	Difference	Difference	Difference
Wind Speed	Ratio	Difference	Difference
Solar Radiation	Ratio	Difference	Difference
Total Cloud Cover	Ratio	-	-
Precipitation	Ratio	Difference	Difference
Snowfall	Difference	Difference	Difference

Table 2.4 Location (longitude and latitude) of weather stations used in the study and the nearest grid center points of the three GCM models for these stations.

Weather Station			GCM 2.0		CGCM 3.1		MIROC 3.2	
Longitude	Latitude	Location	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
96.800W	46.900N	Fargo, ND	97.50W	46.39	277.5 ¹	46.36	276.75	47.65
92.183W	46.833N	Duluth, MN	93.75W	46.39	273.8	46.36	272.25	47.65
93.383W	48.567N	International Falls, MN	93.75W	50.10	273.8	50.07	273.38	48.78
93.217W	44.883N	Minneapolis, MN	93.75W	46.39	273.8	46.36	273.38	45.41
94.067W	45.550N	Saint Cloud, MN	93.75W	46.39	273.8	46.36	274.5	46.53
94.130W	46.400N	Brainerd, MN	93.75W	46.39	273.8	46.36	274.5	46.53
94.930W	47.005N	Bemidji, MN	93.75W	46.39	273.8	46.36	274.5	47.65
93.510W	47.201N	Grand Rapids, MN	93.75W	46.39	273.8	46.36	273.38	47.65

¹ For CGCM 3.1 and MIROC 3.2 longitudes are expressed in degrees (from 0° to 360°) from the International Date Line clockwise (absolute form), hence $277.5 = 277.5 - 180 = 97.5^{\circ}\text{W}$.

Table 2.5 Monthly changes of air temperature (°C) and solar radiation (Langley/day) projected by CGCM 3.1 for the three principal weather stations used in this study.

Station	International Falls		Duluth		St. Cloud	
Parameters	Air temperature ¹	Solar radiation ²	Air temperature	Solar radiation	Air temperature	Solar radiation
Jan	6.89	-5.69	4.84	-7.49	4.84	-7.49
Feb	5.07	-9.51	8.09	-38.21	8.09	-38.21
Mar	3.90	1.83	6.25	-55.05	6.25	-55.05
Apr	4.31	-18.77	3.60	-25.99	3.60	-25.99
May	4.12	-29.39	3.47	-19.96	3.47	-19.96
Jun	4.59	9.63	3.28	2.28	3.28	2.28
Jul	3.80	14.43	3.25	14.78	3.25	14.78
Aug	3.30	7.63	3.32	3.66	3.32	3.66
Sep	3.49	10.69	3.34	0.34	3.34	0.34
Oct	3.19	3.94	3.39	-1.18	3.39	-1.18
Nov	2.89	-1.82	3.06	-2.16	3.06	-2.16
Dec	4.14	-4.86	2.91	-1.32	2.91	-1.32
Average	4.14	-1.82	4.07	-10.86	4.07	-10.86

¹ Conversion: 1.0 °C = 1.8 °F ; ² 1.0 Langley/day = 4.84×10⁻⁵ Watts/cm²

Table 2.6 Monthly changes of air temperature (°C) and solar radiation (Langley/day) projected by MIROC 3.2 for the three principal weather stations used in this study.

Station	International Falls		Duluth		St. Cloud	
Parameters	Air temperature	Solar radiation	Air temperature	Solar radiation	Air temperature	Solar radiation
Jan	5.15	-20.34	4.67	-15.92	4.35	-4.60
Feb	4.70	-25.36	4.67	-23.42	4.17	-9.13
Mar	4.64	-24.84	4.53	-15.75	4.08	0.35
Apr	4.52	-3.32	3.89	0.78	3.88	9.80
May	4.37	-4.43	4.21	-15.22	4.33	2.45
Jun	3.62	-3.82	3.59	-3.92	3.67	0.36
Jul	3.53	-5.38	3.68	10.36	3.67	17.08
Aug	3.75	-0.49	3.82	0.52	3.92	3.64
Sep	3.80	16.57	3.81	19.27	3.87	24.14
Oct	4.46	-2.76	4.29	3.03	4.30	9.87
Nov	4.10	-4.22	3.89	3.03	3.87	5.79
Dec	4.18	-12.80	3.99	-9.24	3.92	-3.16
Average	4.24	-7.60	4.09	-3.87	4.00	4.71

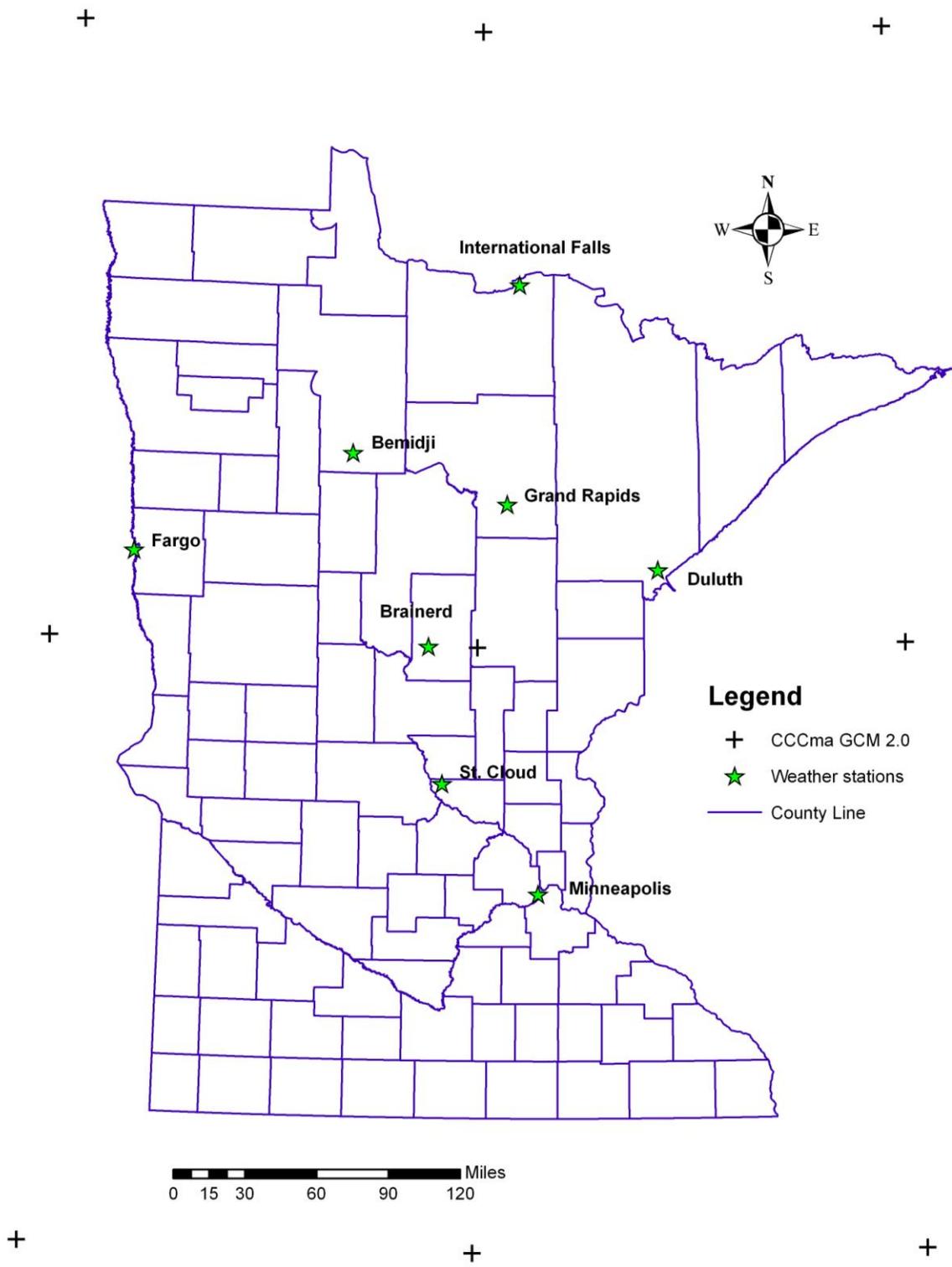


Figure 2.1 Grid center points (+) of CCCma GCM 2.0 and weather stations.

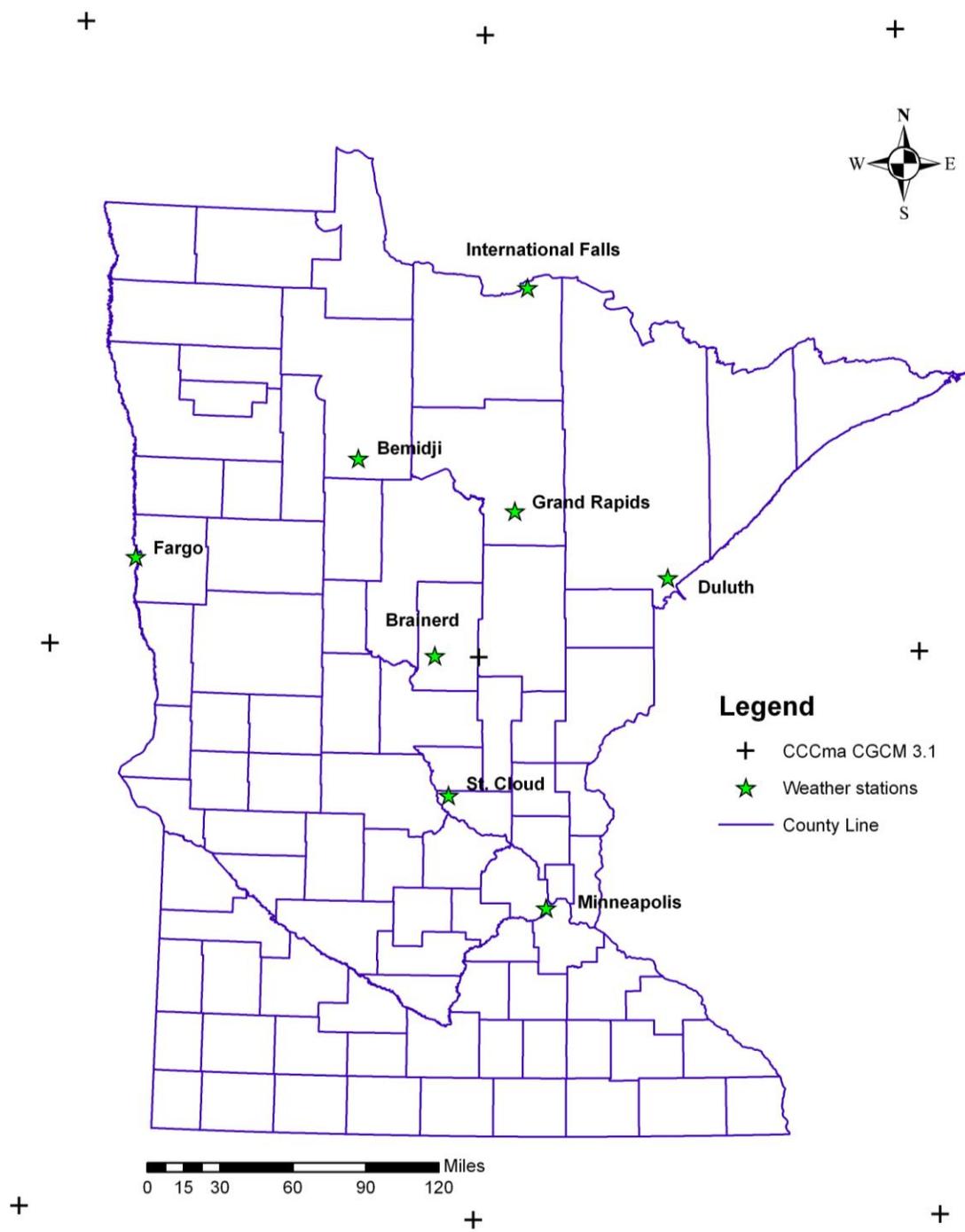


Figure 2.2 Grid center points (+) of CCCma CGCM 3.1 and weather stations

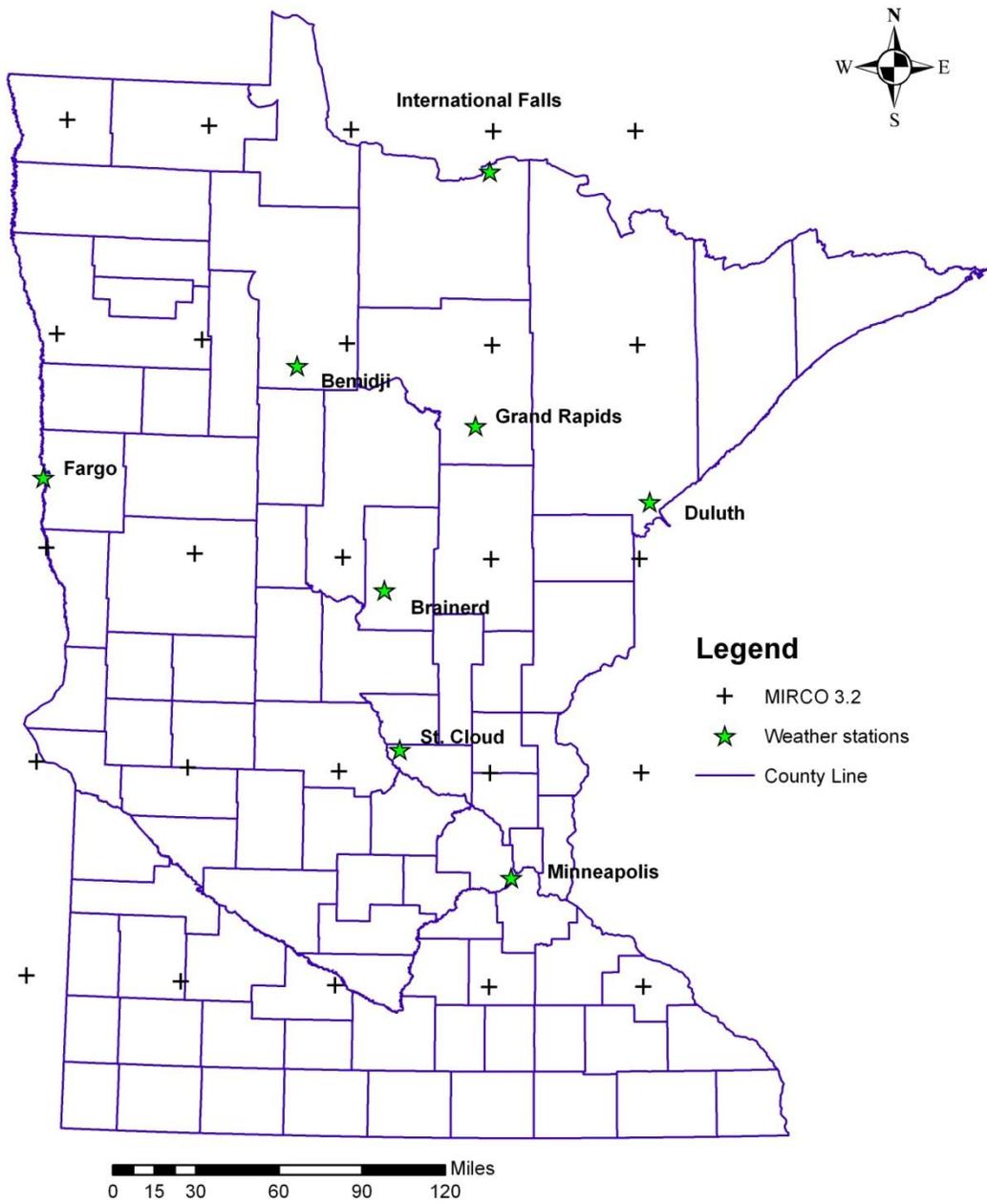


Figure 2.3 Grid center points (+) of MIROC 3.2 and weather stations.

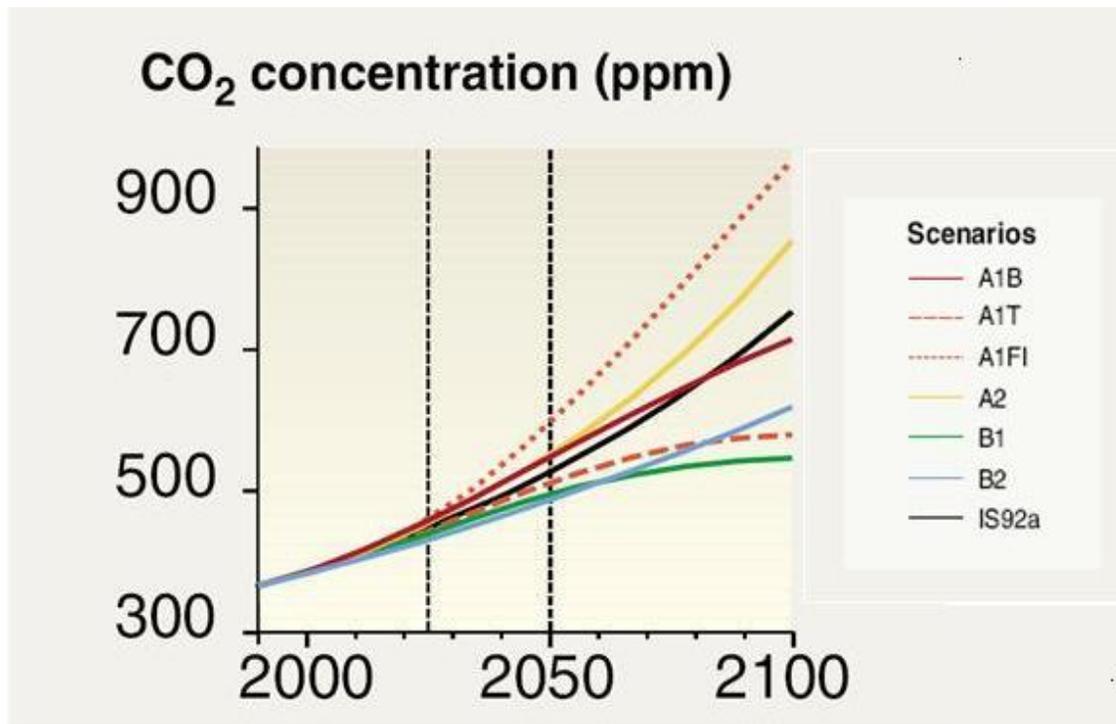


Figure 2.4 Change of atmospheric CO₂ concentration with time for different climate change scenarios (IPCC, Third Assessment Report, 2001).

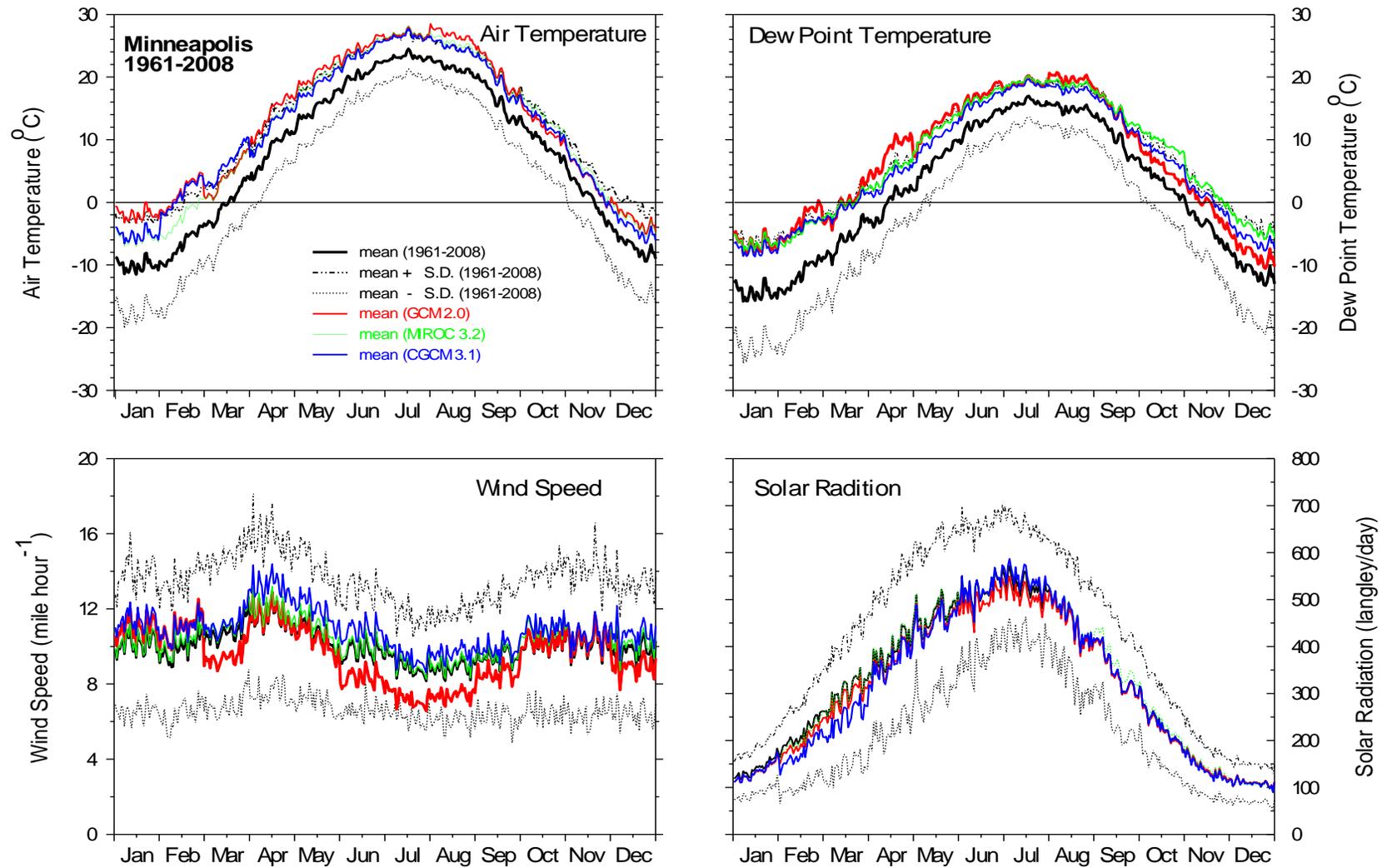


Figure 2.5 Averages and standard deviations (S.D.) for air temperature, dew point temperature, wind speed, and solar radiation at Duluth for past climate conditions and future climate scenarios.

Chapter 3 Oxythermal Habitat Parameters for Cisco

3.1 Oxythermal fish habitat parameter - TDO3

The oxythermal habitat variable, commonly used in coldwater fish niche modeling (Ryan and Marshall 1994; Dillon et al. 2003), defines an upper boundary for temperature and a lower boundary for dissolved oxygen concentration. Previous oxythermal habitat models determine the water volume or layer thickness in a stratified lake between an upper temperature bound and a lower dissolved oxygen bound that represent either optimal thermal habitat (Dillon et al. 2003) or non-lethal/useable habitat (Ryan and Marshall 1994, Stefan et al. 2001). Jacobson et al. (2010) combined the two bounds and proposed a single variable to quantify oxythermal habitat across several coldwater fish species (lake trout, cisco, lake whitefish, and burbot) that have different requirements for cold, oxygenated water. The single generalized oxythermal habitat variable is defined as the water temperature at 3 mg/L of dissolved oxygen (DO), and is called, TDO3. The TDO3 can be determined by interpolating the temperature of water at the DO concentration of 3 mg/L from measured vertical temperature and DO profiles. Non-monotonic profiles generate low oxygen concentrations with more than one TDO3 value, and the coldest TDO3 is used.

As an alternative to the use of measured lake temperature and DO profiles, Jacobson et al. (2010) developed a generalized model to predict TDO3 as a function of lake productivity, climate, and relative depth (lake geometry ratio, $A_s^{0.25}/H_{\max}$). Summer total phosphorus concentration was the variable used to represent lake productivity of each lake (Jacobson et al. 2010).

In this study, total phosphorus concentration was not one of the model parameters to characterize any of the 21 cisco study lakes or 30 virtual lakes; instead Secchi depth (SD), a measure of lake transparency, was used to represent trophic state in addition to radiation attenuation in a Minnesota lake. The trophic state expresses primary productivity and DO production (photosynthesis of plants) in a lake, and ranges from oligotrophy (nutrient-poor, biologically unproductive) to eutrophy (nutrient-rich, productive).

In this study, temperature and DO profiles in lakes are simulated by the MINLAKE2010 model. The model uses climate data as model input, and can therefore simulate future climate conditions for which no measurements exist. Chlorophyll-a concentration that represents biomass or phytoplankton in the MINLAKE2010 model for each cisco lake was calculated from the relationship between chlorophyll-a and Secchi depth used in the Carlson trophic index (Carlson 1977). Therefore, lake geometry ratio (GR) and Secchi depth (SD) are two representative parameters to characterize each of the 620 cisco lakes in the database, and were used to identify refuge cisco lakes at different geographic locations in Minnesota. That was why contour plots of TDO3 parameters presented in Chapter 4 used lake geometry ratio and Secchi depth as the x- and y-axes.

In summer, DO concentrations and water temperatures in lakes usually decrease monotonically with depth below the thermocline (metalimnetic oxygen maxima are an exception). It is unlikely that suitable oxythermal habitat occurs below a depth at which DO is limiting for coldwater fish. Above that depth, habitat will only exist if water temperatures are suitable for coldwater species. Therefore, the water temperature at the depth where DO starts to become limiting is an indicator of the coldest available, oxythermal habitat. Although identifying one value of DO that is physiologically limiting for all coldwater taxa is impossible, selecting a limiting DO concentration that represents an undesirable level for all species, is useful for a developing a generalized oxythermal habitat variable. Selection of 3 mg/L as the limiting oxygen concentration was somewhat arbitrary because proximate, alternative benchmark concentrations of 2, 4, and 5 mg/L were highly correlated. However, 3 mg/L is an oxygen concentration that is probably lethal or nearly so for many coldwater species (Frey 1955, USEPA. 1986, Evans 2007) and therefore represents a desirable benchmark for a presence/absence niche model. Low values of TDO3 indicate excellent oxythermal habitat for coldwater fish, i.e., fish have a wide range of temperatures available in the hypolimnion with sufficient oxygen concentrations. High values of TDO3 indicate poor oxythermal habitat for coldwater fish, with little or no cold water with sufficient oxygen. Very high values of TDO3 indicate hypolimnia that are anoxic or are found in unstratified lakes. The oxythermal requirements of different species of coldwater fish can be compared by the maximum tolerated values of the single variable TDO3. Cisco were present in lakes with a broad range of maximum TDO3 values during a summer time benchmark period, with borders of 4.0 and 16.9 °C (Jacobson et al. 2010).

Figure 3.1 illustrates the procedure how TDO3 can be extracted from temperature and DO profiles in two lakes. Rose Lake had good coldwater oxythermal habitat with $T_{DO3} = 10.6$ °C on August 3, 2006; and Little Pine Lake had very poor coldwater oxythermal habitat with $T_{DO3} = 23.9$ °C on July 25, 2006. Rose Lake (latitude 46.675° and longitude -95.740°) has surface area of 481 ha, maximum depth of 42 m, and total Phosphorus concentration of 17.0 µg/L (on August 3, 2006). Little Pine Lake (latitude 46.634° and longitude -95.557°) has surface area of 797 ha, maximum depth of 19 m, and total phosphorus concentration of 29.8 µg/L (on 25 July 2006).

In this study, a fish habitat computer program was designed to calculate TDO3, i.e., to search and determine the water depth where $DO = 3$ mg/L on the simulated daily DO profiles, and then to determine the simulated water temperature at that depth. Examples of time series of daily TDO3 values in four selected lakes are given in Figures 3.2 and 3.3. For each lake, time series plots of daily TDO3 values for two selected simulated years are shown. The two selected years had the highest or lowest annual maximum daily TDO3 in the simulation period. For example, $TDO3_{AM}$ in South Twin Lake was 20.7 and 26.9°C in 1993 and 2006, respectively (Fig. 3.3).

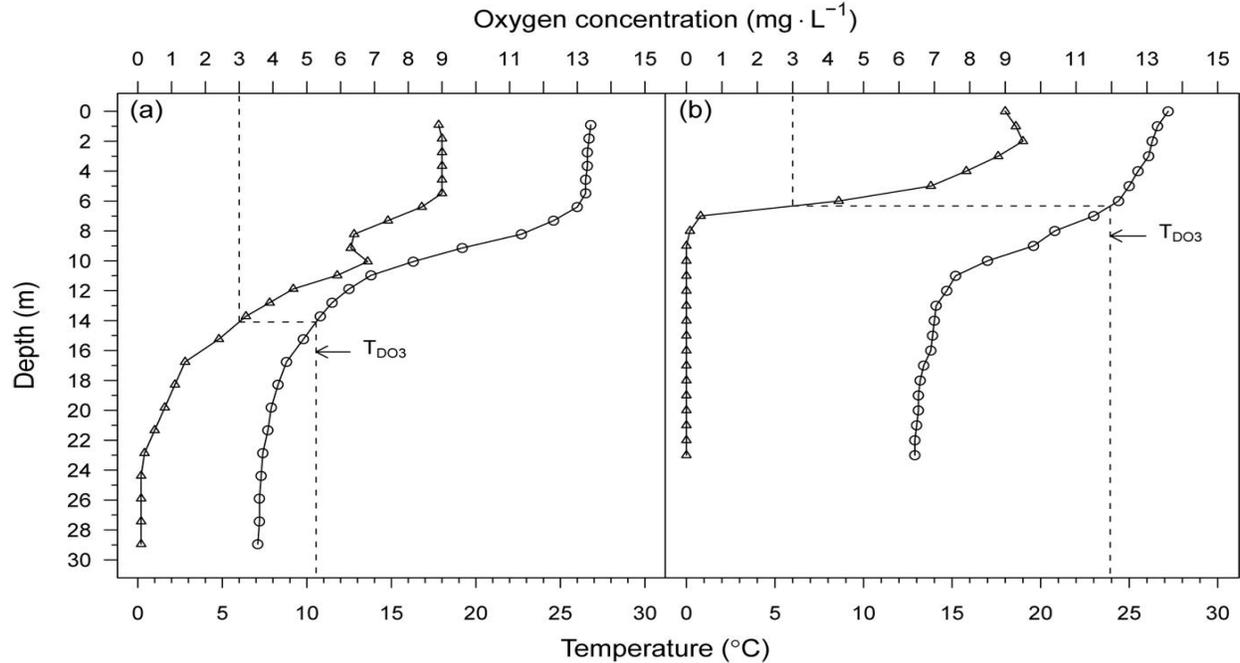


Figure 3.1 Examples of TDO3 (temperature at 3 mg/L DO) determination from temperature (circles) and dissolved oxygen (triangles) profiles in (a) Rose Lake and (b) Little Pine Lake (from Jacobson et al. 2010).

Time series of daily TDO3 values were obtained for each study lake and each simulation year during the simulation period, e.g., 1962 to 2008 or 1992 to 2008, depending on weather station used. The temperature and DO profiles simulated for the first-year (1961 or 1991) were not used to extract TDO3 values in order to avoid possible effects of assumed initial conditions on simulations. When the DO concentration was less than 3.0 mg/L along the entire profile (e.g. in Carrie Lake during winter of 1987, Figure 3.2), TDO3 was set at 0°C (temperature at the ice-water interface) because the program searches for DO = 3.0 mg/L along the DO profile from lake bottom to surface. From the time series of daily TDO3 values for each simulation year and over the total simulation period (1962 to 2008 or 1992 to 2008), different TDO3 values can be extracted as single day values, monthly averages, multi-year averages, etc. Twelve options are defined in Table 3.1, and can be calculated for each lake. These alternatives are further explained and discussed below.

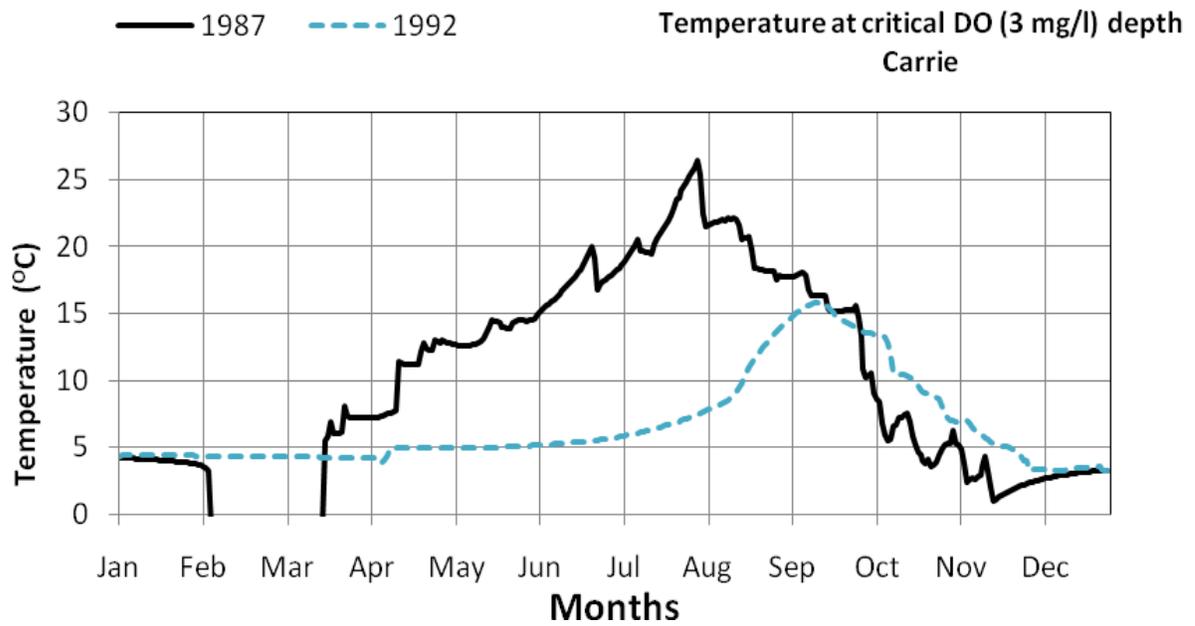
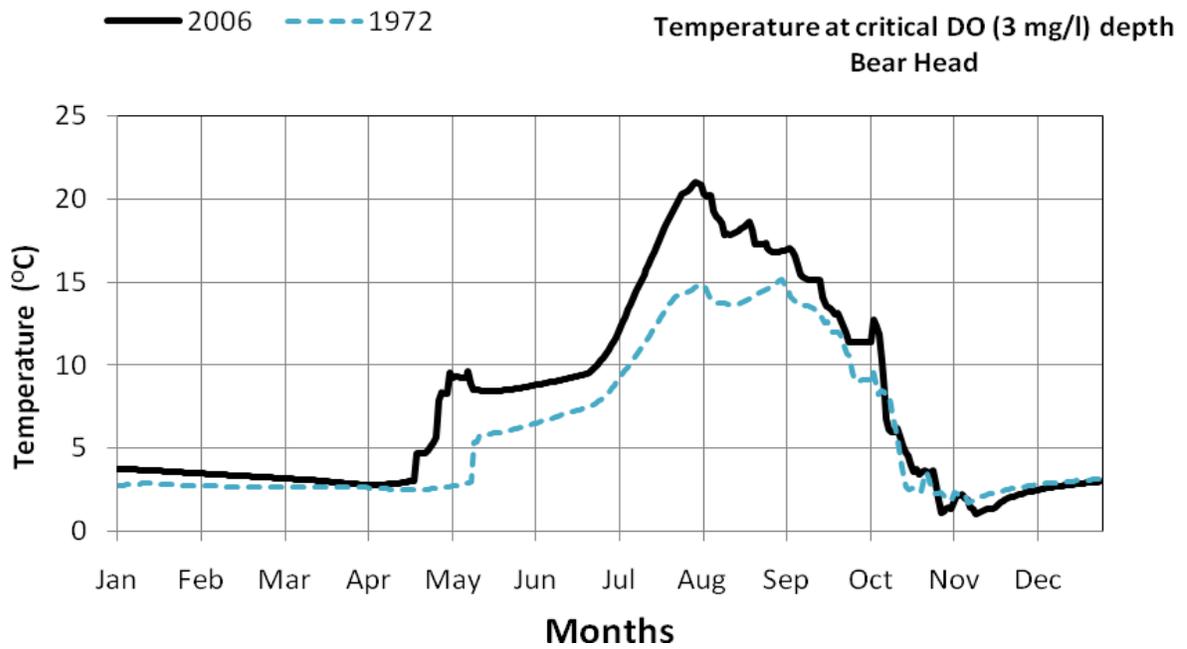


Figure 3.2 Time series of simulated daily TDO3 for Bear Head Lake and Carrie Lake (non-cisco lakes). The two selected years have the highest or lowest annual maximum TDO3 in the simulation period.

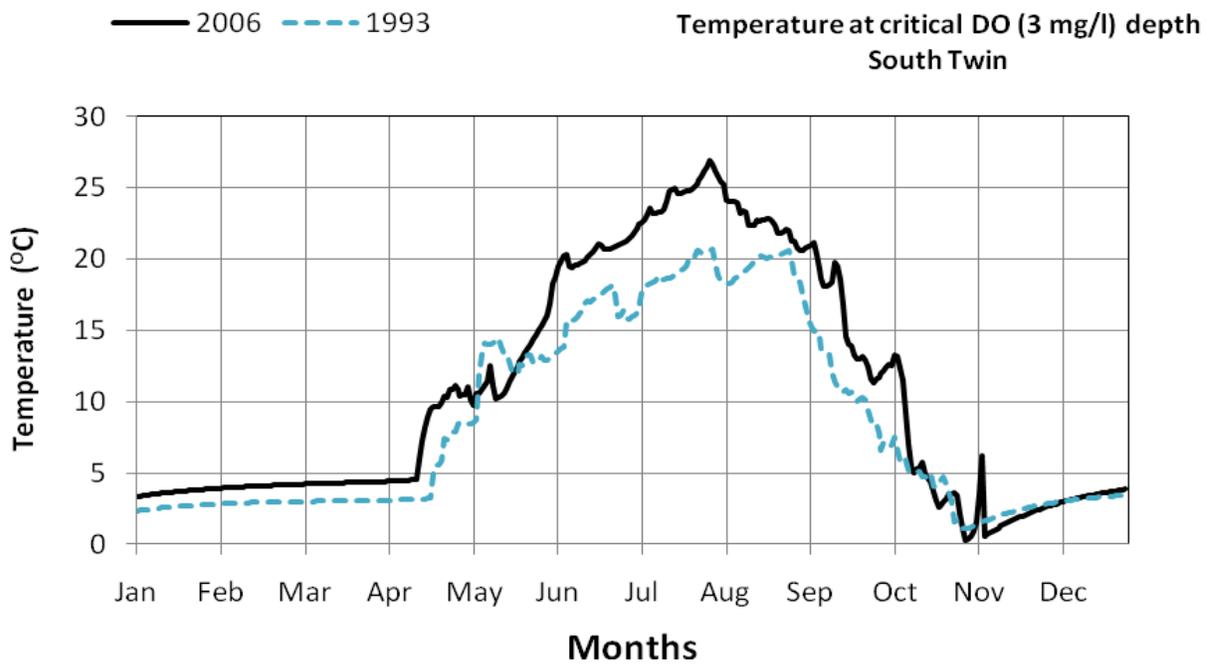
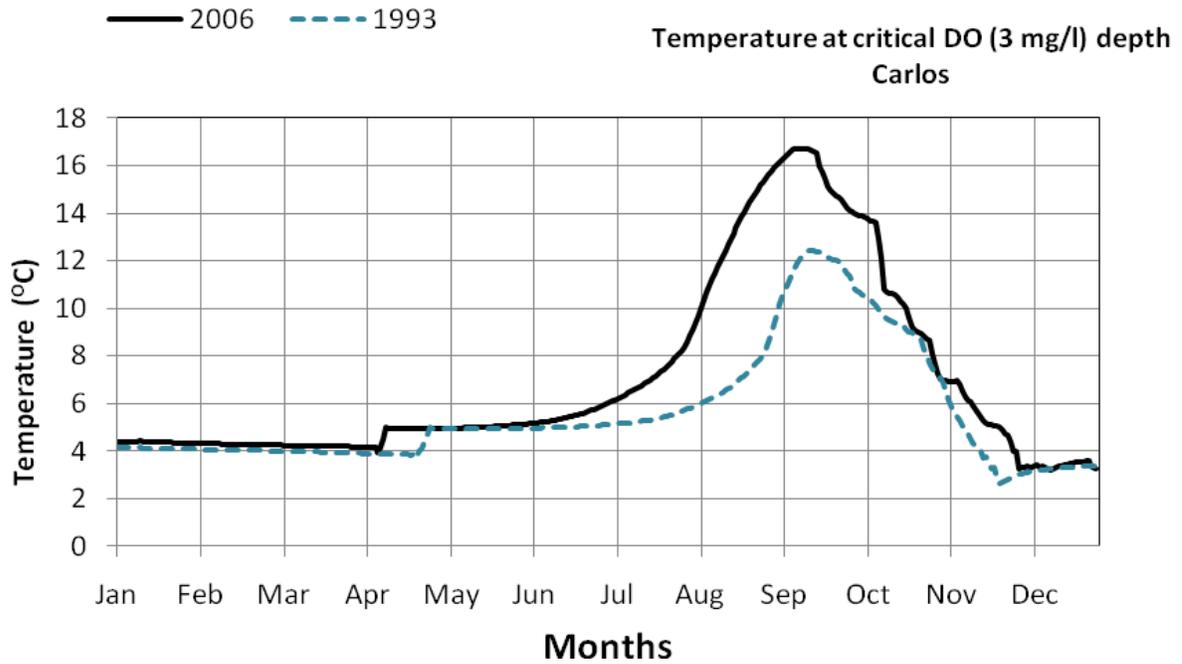


Figure 3.3 Time series of simulated daily TDO3 for Lake Carlos and South Twin Lake (cisco lakes). The two selected years (2006 and 1993) have the highest or lowest annual maximum TDO3 in the simulation period.

Table 3.1 Definitions of twelve different TDO3 parameters that can be extracted from simulated daily temperature and DO profiles.

Parameter		Definition or Description
1. TDO3 _{AM}	TDO3 _A	Maximum daily TDO3 value for each simulated year = annual maximum daily TDO3 (47 values for 1962-2008 simulation period). The subscript “AM” stands for “annual maximum”.
2. MaxTDO3 _{AM}	TDO3 _B	Maximum of annual maximum daily TDO3 values in the simulation period (one value for 1962-2008).
3. AvgTDO3 _{AM}	TDO3 _C	Average of annual maximum daily TDO3 values in the simulation period (one value for 1962-2008).
4. ATDO3 _{FB}	TDO3 _D	Mean daily TDO3 value over the fixed 31-day benchmark period (DOY 209 to DOY 239) for each simulated year (47 values for 1962-2008). The subscript “FB” stands for “fixed benchmark”, and the first letter “A” stands for “average” or mean over the benchmark period.
5. MaxATDO3 _{FB}	TDO3 _E	Maximum of mean daily TDO3 values over the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
6. AvgATDO3 _{FB}	TDO3 _F	Average of mean daily TDO3 values over the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
7. MTDO3 _{FB}	TDO3 _G	Maximum daily TDO3 value within the fixed 31-day benchmark period (DOY 209 to DOY 239) for each simulated year (47 values for 1962-2008). The first letter “M” before TDO3 stands for “maximum daily” within the fixed benchmark period
8. MaxMTDO3 _{FB}	TDO3 _H	Maximum of maximum daily TDO3 values within the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
9. AvgMTDO3 _{FB}	TDO3 _I	Average of maximum daily TDO3 values within the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
10. ATDO3 _{VB}	TDO3 _J	Highest mean daily TDO3 value over variable (sliding) 31-day benchmark periods for each simulated year. The subscript “VB” stands for “variable (sliding) benchmark”. Only the highest mean value in any of the sliding benchmark periods of a year is retained (47 values in 1962-2008).
11. MaxATDO3 _{VB}	TDO3 _K	Maximum of highest mean daily TDO3 values over variable (sliding) 31-day benchmark periods in each simulated year over the simulation period (one value for 1962-2008).
12. AvgATDO3 _{VB}	TDO3 _L	Average of highest mean daily TDO3 values over variable (sliding) 31-day benchmark periods in each simulated year over the simulation period (one value for 1962-2008).

3.2 Annual maximum daily TDO3

The maximum daily TDO3 value for each simulated year is labeled $TDO3_{AM}$; the subscript “AM” stands for “annual maximum”. There are 47 values of $TDO3_{AM}$ if the simulation period is from 1962 to 2008 for a study lake. From these 47 values of $TDO3_{AM}$, two more characteristic TDO3 values can be calculated: $MaxTDO3_{AM}$ and $AvgTDO3_{AM}$ (Table 3.1). $MaxTDO3_{AM}$ is the highest of the 47 annual maximum daily TDO3 values in the simulation period, and there is only one value for the entire simulation period 1962-2008. $AvgTDO3_{AM}$ is the average of the 47 annual maximum daily TDO3 values in the simulation period 1962-2008. The examples of time series of daily TDO3 values in Figures 3.2 and 3.3 are for the years with the highest or lowest annual maximum daily TDO3 in the simulation period. For example, $TDO3_{AM}$ in South Twin Lake was 26.9 °C and 20.7 in 2006 and 1993, respectively (Fig. 3.3).

Table 3.2 gives the ranges of $TDO3_{AM}$ values, and the days of occurrence of $TDO3_{AM}$ in 15 study lakes. For example, water temperature and dissolved oxygen profiles in Lake Carlos were simulated from 1961 to 2008 and $TDO3_{AM}$ values were found in 47 years (1962 to 2008). Table 3.2 shows that $TDO3_{AM}$ values in Lake Carlos ranged from 12.43 °C (lowest) to 16.72 °C (highest) and occurred between DOY (day of year or calendar day) 251 (Sep 07) and 275 (Oct 1). Table 3.2 also lists the averages, standard deviations, and ranges (highest and lowest or earliest and latest) annual $TDO3_{AM}$ values and the day of occurrence of annual $TDO3_{AM}$ in the 15 study lakes. The highest $TDO3_{AM}$ values listed in Table 3.2 are the $MaxTDO3_{AM}$ values in the simulation period. The highest and lowest $TDO3_{AM}$ values and the earliest and latest days of occurrence in the 15 study lakes are presented graphically in Figures 3.4 and 3.5. Figure 3.6 gives time series plots of annual maximum daily TDO3 in the simulation periods (1961 to 2008 or 1991 to 2008) of the 15 study lakes; cisco lakes are shown by bold lines. The red line for each lake in Figure 3.6 gives $AvgTDO3_{AM}$, i.e., the average of annual maximum daily TDO3 values in the simulation period (1961 to 2008 or 1991 to 2008). Values presented in Table 3.2 and Figures 3.2 to 3.6 were calculated from daily temperature and DO profiles simulated using weather stations that are closest to each lake. Table 3.3 lists $AvgTDO3_{AM}$ values (column 4) for 21 cisco study lakes, which were calculated from daily temperature and DO profiles simulated using International Falls as the same and sole weather station. Two cisco lakes, White Iron and South Twin, have relative large lake geometry ratio ($GR > 4.0$) and their $AvgTDO3_{AM}$ values are much larger than for the other 19 cisco lakes that have geometry ratios $GR < 3.0$. The reason is that $GR > 4.0$ characterizes polymictic lakes, whereas $GR < 2.0$ is characteristic of seasonally stratified dimictic lakes.

3.3 Average daily TDO3 over a fixed benchmark period

From observed temperature and DO profiles, Jacobson et al. (2010) identified two 31-day summer benchmark periods when the annual maximum daily TDO3 typically occurs in stratified

and unstratified Minnesota lakes. The benchmark period is the period of greatest oxythermal stress for coldwater fish, i.e., it is the period with the highest values of TDO3. For stratified lakes ($GR < 2.0$), the 31-day benchmark period extends from DOY 209 to DOY 239, which is from July 28 to August 27. For unstratified lakes ($GR > 4$), the 31-day benchmark period is from DOY 194 to DOY 224, which is from July 13 to August 12. The difference between stratified and unstratified lakes is about two weeks; unfavorable fish habitat conditions occur earlier in unstratified (polymictic) lakes.

Because most of the cisco lakes in Minnesota are deep stratified lakes, potential refuge lakes will most likely be stratified lakes; a fixed benchmark period from DOY 209 to 239 was therefore used to define the remaining six TDO3 values in Table 3.1. $ATDO3_{FB}$ is the average or mean daily TDO3 value over the fixed 31-day benchmark period (DOY 209 to 239) for each simulated year. The subscript “FB” stands for “fixed benchmark”, and the first letter “A” stands for “average” or mean over the fixed benchmark period. There are 47 values of $ATDO3_{FB}$ if the simulation period is from 1962 to 2008 for a study lake. From these 47 values of $ATDO3_{FB}$, two more characteristic TDO3 values can be calculated: $MaxATDO3_{FB}$ and $AvgATDO3_{FB}$ (Table 3.1).

Figure 3.7 shows time-series plots of average daily TDO3 values over the fixed benchmark period 1962 to 2008 for two cisco lakes: Mukooda Lake (top) with lake geometry ratio $GR = 1.76$ and mean summer Secchi depth $SD = 5.12$ m, and Little Trout Lake (bottom) with $GR = 1.76$ and $SD = 5.12$ m. TDO3 values were calculated from daily temperature and DO profiles simulated under past climate conditions (1962-2008) at the weather station in International Falls. $ATDO3_{FB}$ in Mukooda Lake ranged from 5.68 to 9.75°C with standard deviation of 0.78°C over the 47-year period. The maximum value of $ATDO3_{FB}$ in the simulation period, i.e., $MaxATDO3_{FB}$, occurred in 1965 and 1964, and was 9.75°C and 6.93°C in Mukooda and Little Trout Lake, respectively. Little Trout Lake had better oxythermal habitat conditions for cisco indicated by $ATDO3_{FB}$ values ranging from 4.53 to 6.93°C with standard deviation of 0.44°C. The average value in the simulation period $AvgATDO3_{FB}$ was 7.04°C and 5.42°C in Mukooda and Little Trout Lake, respectively. $AvgATDO3_{FB}$ and $MaxATDO3_{FB}$ values (lines 5 and 6 in Table 3.1) for the 21 cisco study lakes are summarized in Table 3.3. Lakes in Table 3.3 are arranged by lake geometry ratio, from lowest to highest.

Table 3.2 Statistical summary of TDO_{3AM} and calendar day of occurrence of TDO_{3AM} in the simulation period (1962-2008 or 1992-2008).

Name of lake	TDO _{3AM} in the simulation period (°C)				Day of occurrence of TDO _{3AM} in the simulation period				
	Highest TDO _{3AM}	Lowest TDO _{3AM}	Average TDO _{3AM}	Standard Deviation	Earliest Day	Latest Day	Variation ²	Average day	Standard Deviation
Cisco lakes									
Carlos	16.72	12.43	14.51	0.95	251	275	24	264	6
Cedar	17.77	12.14	15.15	1.39	238	274	36	257	7
Elk ¹	18.45	13.95	16.32	1.24	222	258	36	240	11
Kabekona ¹	14.21	10.94	12.64	1.10	258	277	19	268	5
South Twin ¹	26.89	20.66	23.78	1.64	175	250	75	209	19
Ten Mile ¹	11.52	9.02	10.46	0.74	266	299	33	281	10
Trout	6.81	5.81	6.38	0.26	283	313	30	299	7
White Iron	24.64	19.03	21.51	1.15	201	252	51	222	12
Non-cisco lakes									
Bear Head	20.99	15.13	18.15	1.27	207	253	46	227	11
Carrie	26.36	18.82	22.99	1.59	188	253	65	216	16
Elephant	25.26	19.62	22.56	1.44	179	248	69	213	15
Hill ¹	27.65	10.35	23.26	4.77	202	290	88	230	24
Madison	27.70	20.28	24.16	1.45	176	254	78	210	17
S. Center	25.92	18.44	21.91	1.63	192	251	59	213	15
St Olaf	26.75	19.65	22.99	1.46	177	243	66	211	16

¹ The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008.

² “Variation” is the difference between the latest and the earliest day of occurrence of TDO_{3AM} in the simulation period.

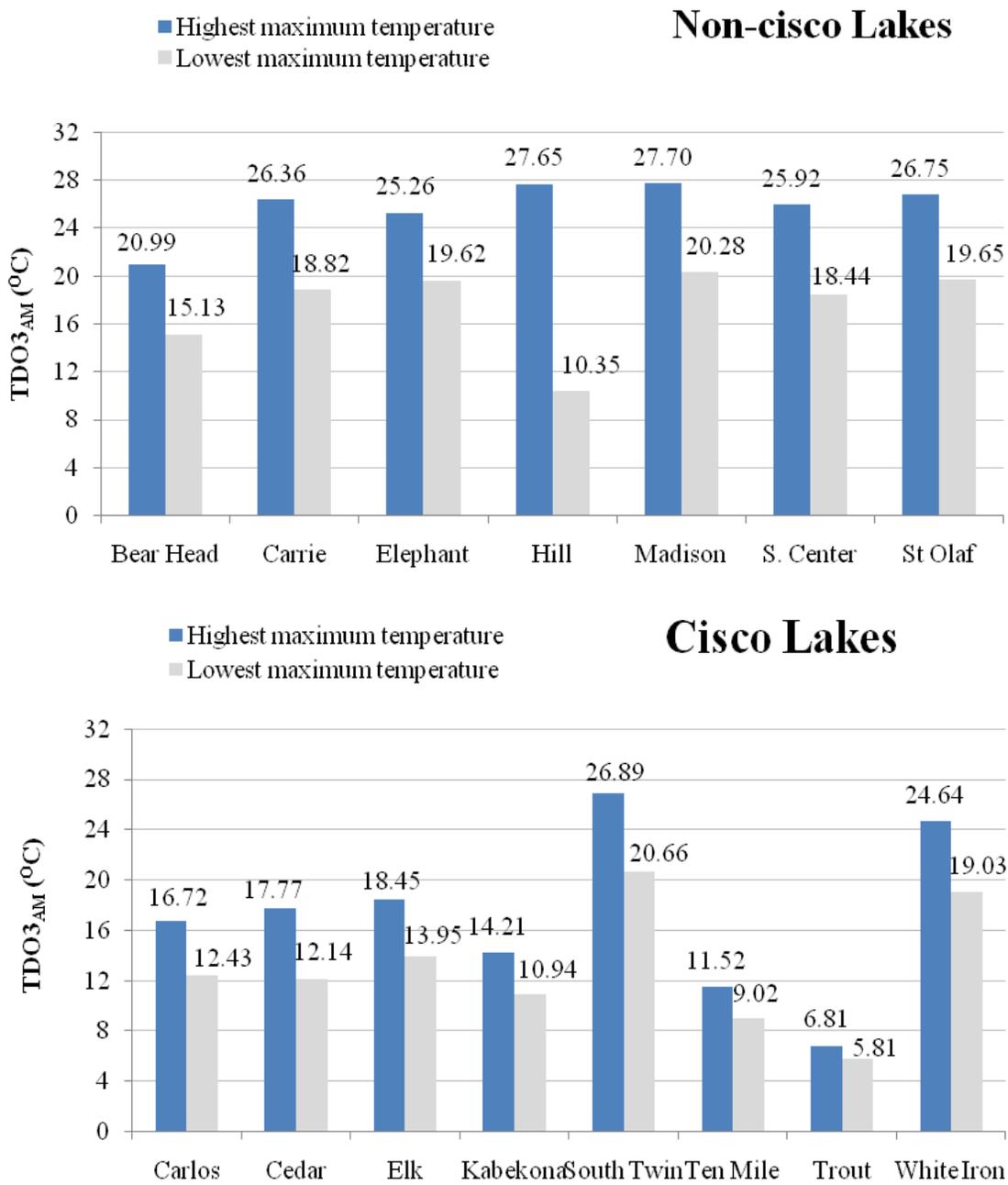


Figure 3.4 Ranges of TDO_{3AM} during the simulation period (1962-2008 or 1992-2008) in cisco lakes and non-cisco lakes.

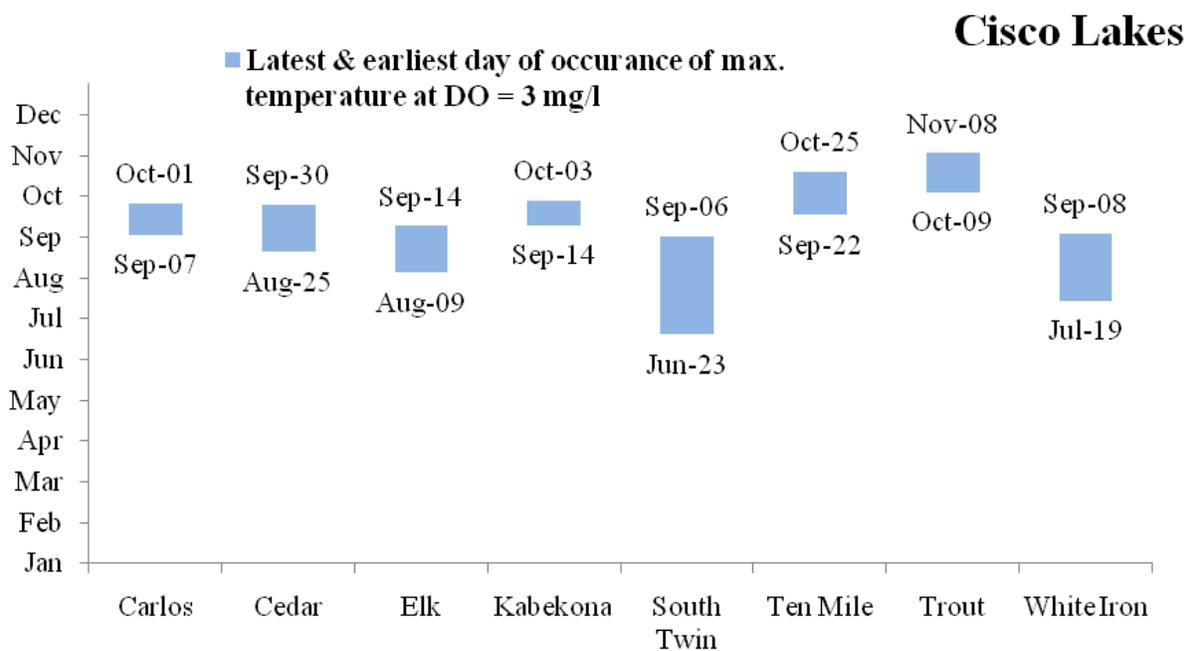
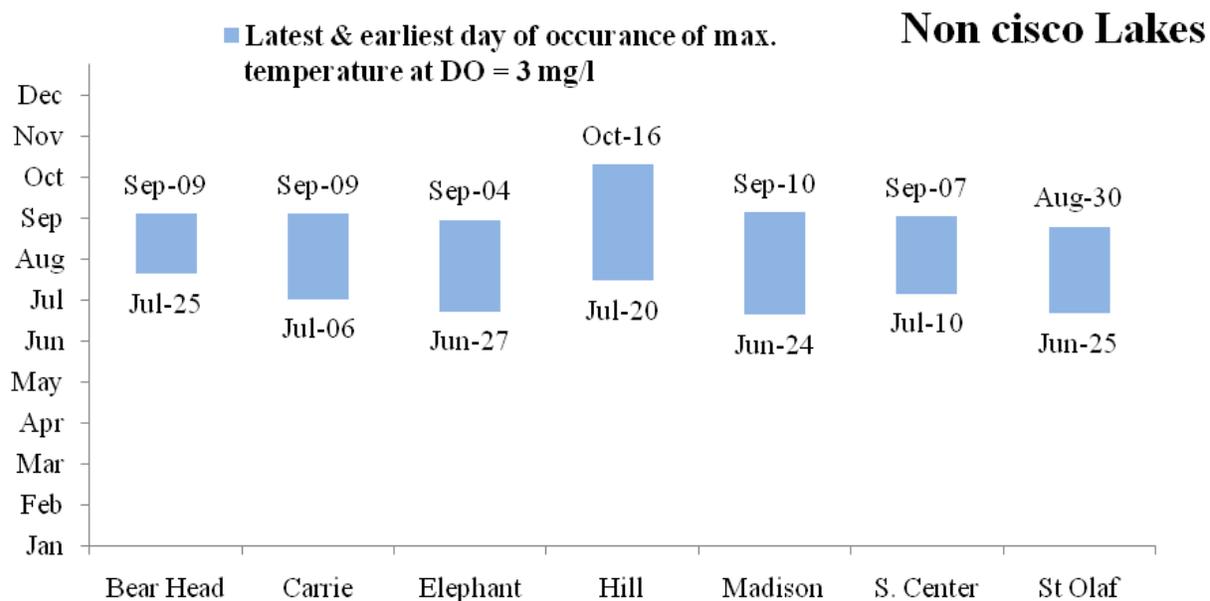


Figure 3.5 Ranges of days of occurrence of TDO_{3AM} during the simulation period (1962-2008 or 1992-2008) in cisco lakes and non-cisco lakes.

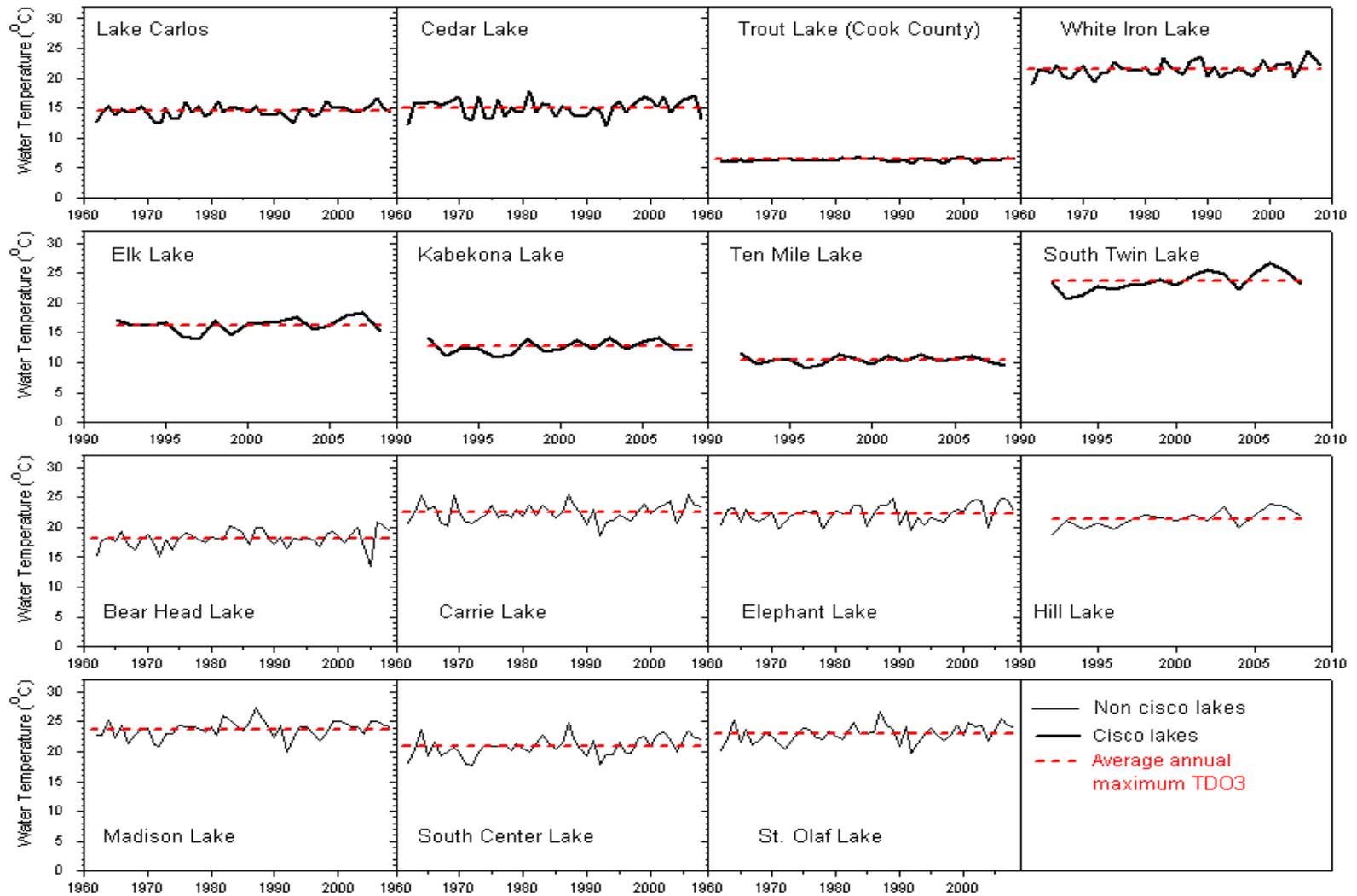


Figure 3.6 Time series of annual maximum TDO3_{AM} in 8 cisco and 7 non-cisco lakes under past climate conditions.

Table 3.3 Values of GR, SD, and three TDO3 parameters ($^{\circ}\text{C}$) (**AveTDO3_{AM}**, **AveATDO3_{FB}**, and **MaxATDO3_{FB}**, Table 3.1, lines 4, 5, and 6) for **21 cisco lakes** under past climate conditions from 1962 to 2008. **International Falls weather** data were used for the simulations.

Lake Name	Geometry ratio (GR, $\text{m}^{-0.5}$)	Secchi depth (SD, m)	Annual maximum AveTDO3 _{AM}	Benchmark mean AveATDO3 _{FB}	Benchmark maximum MaxATDO3 _{FB}
Six	0.69	3.94	9.12	6.62	7.42
Grindstone	0.82	2.88	5.22	4.52	4.55
Ten Mile	1.05	5.92	9.78	8.01	8.54
Little Trout	1.08	6.33	5.72	5.42	5.49
Carlos	1.13	3.40	11.78	6.37	7.47
Elk	1.16	2.50	14.55	12.69	14.11
Cedar	1.17	3.40	12.52	9.24	10.78
Big Trout	1.24	4.78	8.00	5.94	6.30
Kabekona	1.34	3.70	11.55	7.67	9.04
Trout (Cook)	1.39	5.40	10.20	6.51	7.36
Snowbank	1.41	5.28	8.09	6.44	6.74
Little Sand	1.45	5.22	7.65	6.06	6.38
Siseebakwet	1.50	3.89	14.14	10.30	12.30
Greenwood	1.57	5.46	8.09	6.47	6.81
Mukooda	1.76	5.12	9.41	7.04	7.51
Burntside	1.91	5.80	7.41	6.30	6.52
Blue	2.04	6.76	14.93	11.88	13.64
Fish Hook	2.19	3.44	15.06	12.26	14.33
Trout (St. Louis)	2.50	4.71	11.23	8.91	9.51
White Iron	4.26	1.50	21.95	20.47	21.71
South Twin	5.22	2.90	22.95	20.31	22.23

3.4 Annual maximum daily TDO3 value within the fixed benchmark period

MTDO3_{FB} is the maximum daily TDO3 value within the fixed 31-day benchmark period (DOY 209 to 239) for each simulated year. The letter “M” stands for “maximum daily” within the fixed benchmark period, indicated by subscript FB. There are 47 values of MTDO3_{FB} if the simulation period is from 1962 to 2008 for a study lake. From these 47 values of MTDO3_{FB}, two more characteristic TDO3 parameters can be calculated: MaxMTDO3_{FB} and AvgMTDO3_{FB} (lines 8 and 9 in Table 3.1). Figure 3.7 shows time-series plots of maximum daily TDO3 values over the fixed benchmark period from 1962 to 2008 (using International Falls weather data) for Mukooda Lake (top) and Little Trout Lake (bottom). MTDO3_{FB} in Mukooda Lake ranged from 6.08 to 10.42°C with a standard deviation of 0.87°C. The maximum value of MTDO3_{FB} in the simulation period, i.e., MaxMTDO3_{FB}, was 10.42°C and 6.95°C in Mukooda and Little Trout Lake, respectively. The average value in the simulation period AvgMTDO3_{FB} was 7.51°C and 5.49°C in Mukooda and Little Trout Lake, respectively. The average difference between MTDO3_{FB} (maximum daily TDO3) and ATDO3_{FB} (average daily TDO3) in Mukooda Lake was 0.46°C (range from 0.28 to 1.06°C from 1962 to 2008); in Little Trout Lake it was only 0.084°C (range from 0.02 to 0.13°C from 1962 to 2008). Figure 3.7 shows that the year by year variations of MTDO3_{FB} and ATDO3_{FB} due to weather variations within the simulation period are much larger than the differences between the MTDO3_{FB} and ATDO3_{FB}.

3.5 Average daily TDO3 over a sliding benchmark period

The period of greatest oxythermal stress for coldwater fish depends on the type of lake (strongly stratified versus weakly stratified, as related to lake geometry ratio GR). One may ask whether the benchmark period could shift under future climate scenarios. To answer this question, the concept of a sliding benchmark period evolved in discussions among research team members. The sliding benchmark period can still be 31 days long, the same as the fixed benchmark period used before and proposed by Jacobson et al. (2010). In a simulation period from May 1 to October 31 there would be 184 31-day sliding benchmark periods.

Each sliding benchmark period must contain the day when the annual maximum daily TDO3 occurs in that year. Over each sliding benchmark period, the average daily TDO3 can be calculated, and only the highest of these values in any of the sliding benchmark periods of a year is retained. This value is called ATDO3_{VB}. The subscript “VB” stands for “variable (sliding) benchmark” period. There are 47 values of ATDO3_{VB} for a study lake if the simulation period is from 1962 to 2008. From these 47 values of ATDO3_{VB}, two more characteristic TDO3 parameters can be calculated: MaxATDO3_{VB} and AvgATDO3_{VB} (lines 11 and 12 in Table 3.1).

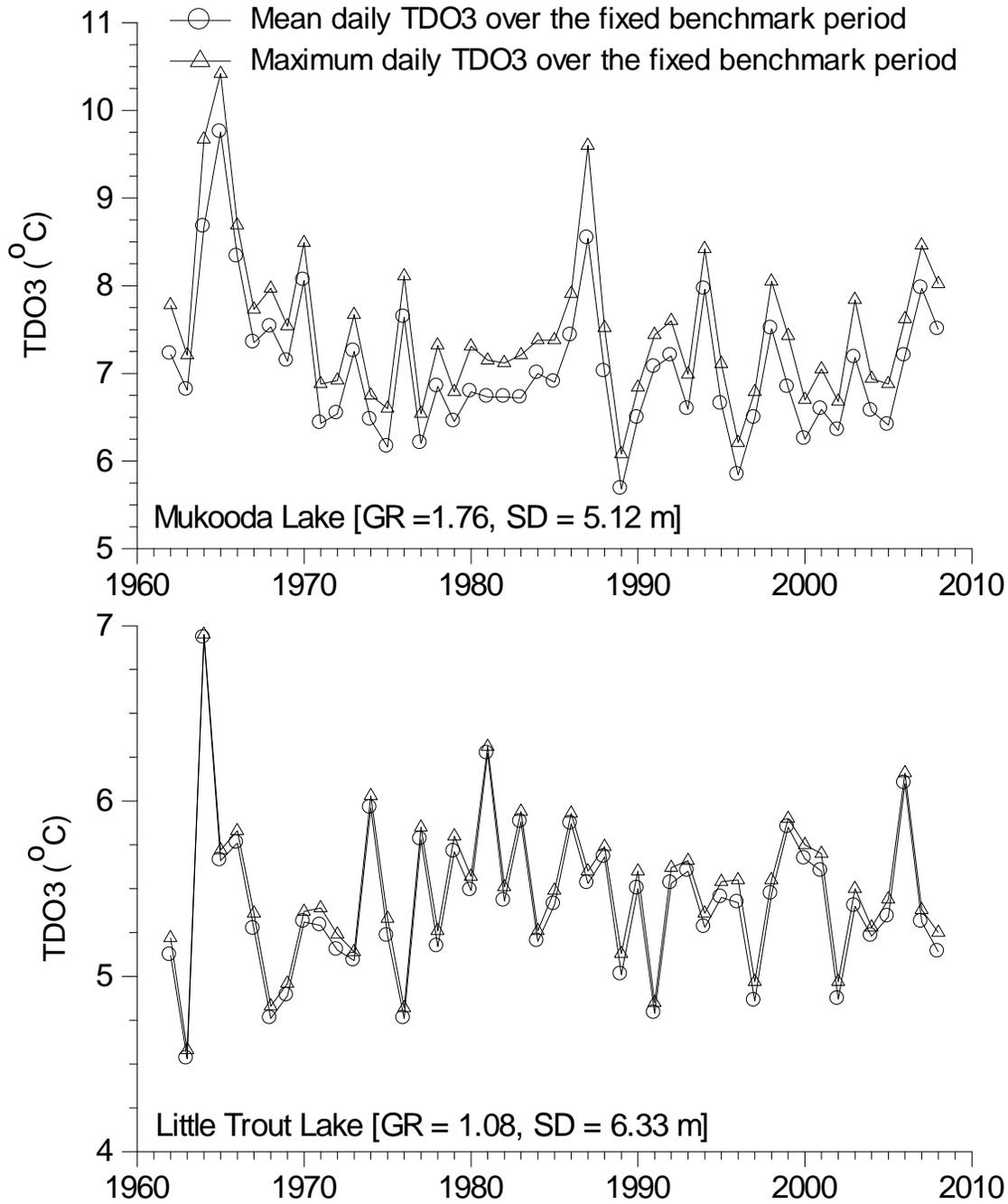


Figure 3.7 Time series plot of average (mean) and maximum daily TDO3 values for the **fixed benchmark period** (DOY 209 to 239) from 1962 to 2008 for Mukooda (top) and Little Trout Lake (bottom). **International Falls weather** data were used for the simulations.

We also determined the beginning dates of the variable (sliding) 31-day benchmark periods that had given the highest $ATDO3_{VB}$ value, i.e., the average (mean) daily TDO3 value that was the highest of all sliding benchmark periods in each simulated year (line 10 in Table 3.1). The fish habitat computer program was updated for that purpose. Annual time series and average values of the beginning dates over the simulation period (e.g., 47 years from 1962 to 2008) were calculated for each of the 30 virtual lakes. Figure 3.8 shows time series of the benchmark period beginning dates for past climate (1962 to 2008) and the CGCM 3.1 future climate scenario. For these examples, LakeC06 and LakeC08 (Table 1.2), and Duluth weather data were used in the model simulations.

The beginning dates of the variable benchmark periods that had given the highest $ATDO3_{VB}$ values ranged from DOY 192 to 226 for LakeC06 and from DOY 241 to 271 for LakeC08 under past climate condition. Average beginning dates were DOY 210 for LakeC06 and DOY 253 for LakeC08 under past climate conditions (1962 to 2008). These two virtual lakes have the same lake geometry ($GR = 1.11$) but different Secchi depth, LakeC06 is a eutrophic lake with $SD = 1.2$ m and LakeC08 is an oligotrophic lake with $SD = 4.5$ m (Table 1.2 and Fig. 3.8). Figure 3.8 illustrates that the beginning date of greatest oxythermal stress for coldwater fish in different types of lakes can be quite different. It is noteworthy that there is not much difference between future and past climate scenarios; the average beginning date of the highest $ATDO3_{VB}$ benchmark period is projected to be DOY 205 for LakeC06 and DOY 251 for LakeC08 under the CGCM 3.1 future climate scenario, only 5 and 2 days, respectively, different from past climate conditions.

Figures 3.9, 3.10, and 3.11 show the average beginning dates of greatest oxythermal stress under past climate conditions (1962 to 2008), and the CGCM 3.1 and MIROC 3.2 future climate scenarios for Duluth, International Falls, and St. Cloud weather data, respectively. The beginning dates are given as contours on a plot of Secchi depth (SD) vs. geometry ratio (GR); the contours were derived by interpolation from simulated data points for the 30 virtual lakes (Table 1.2). A listing of average beginning dates of the variable benchmark periods for the 30 virtual lakes is given in Appendix B (Tables B.1 to B.3). Statistical summaries of average beginning dates of variable benchmark periods in the 47-year simulation period are given in Table 3.4 for the three principal weather stations and the three climate scenarios. Average beginning dates of variable benchmark periods for $ATDO3_{VB}$ ranged from DOY 200 (July 19) to DOY 288 (October 15). Later dates occur in lakes with lower geometry ratio and higher Secchi depth, i.e. stratified oligotrophic lakes produce oxythermal stress for cisco later in the season than other lakes. The difference between the latest and earliest beginning date of the greatest oxythermal stress period for cisco in Minnesota lakes was 59 to 89 days, i.e. 2 to 3 months. Simulations of 30 virtual lakes with input data from three weather stations gave these results (Table 3.4). Therefore, it seems advisable to calculate mean daily TDO3 values using variable (sliding) benchmark periods in order to identify periods of greatest oxythermal stress. In this study, the

value of AvgATDO3_{VB} in Table 3.1, may therefore be the most useful to identify refuge lakes for cisco. A comparison with other options will be given in Chapter 5.

Differences of average beginning dates of variable benchmark periods for highest mean daily TDO3 between future climate scenarios and past climate are given in Table 3.5. Maximum differences ranged from -11 to 19 days (Table 3.5), and mean differences from -1 to 3 days. Under a future climate scenario, the beginning date of the variable benchmark period occurs later if the difference is positive, and earlier if the difference is negative. The differences in beginning dates of oxythermal stress on cisco between future and past climate are much smaller (nearly negligible) compared to the differences among different lake types (Figs. 3.9 to 3.11), and from year to year (Fig. 3.8).

Table 3.4 Statistics of the beginning date (DOY = day of year or calendar date) of the variable (sliding) benchmark period for highest mean daily TDO3 (ATDO3_{VB}, line 10 in Table 3.1) under **past climate conditions (1962-2008) and two future climate scenarios** using weather data from **three principal weather stations**.

Station	International Falls			Duluth			St. Cloud		
	Past	CGCM	MIROC	Past	CGCM	MIROC	Past	CGCM	MIROC
Maximum	265	278	284	269	279	282	276	288	288
Minimum	206	200	204	207	204	204	202	199	200
Mean	237	237	240	236	236	238	238	236	238
Standard Deviation	19	25	26	20	25	27	24	28	29

Table 3.5 Statistics of the differences between beginning dates of **variable (sliding) benchmark periods** given in Table 3.4. Numbers are in days.

Weather station	CGCM 3.1 – Past			MIROC 3.2 – Past		
	International Falls	Duluth	St. Cloud	International Falls	Duluth	St. Cloud
Maximum	13	13	12	19	16	14
Minimum	-11	-9	-10	-8	-8	-8
Mean	0	-1	-1	3	1	1
Standard Deviation	8	7	7	8	8	7

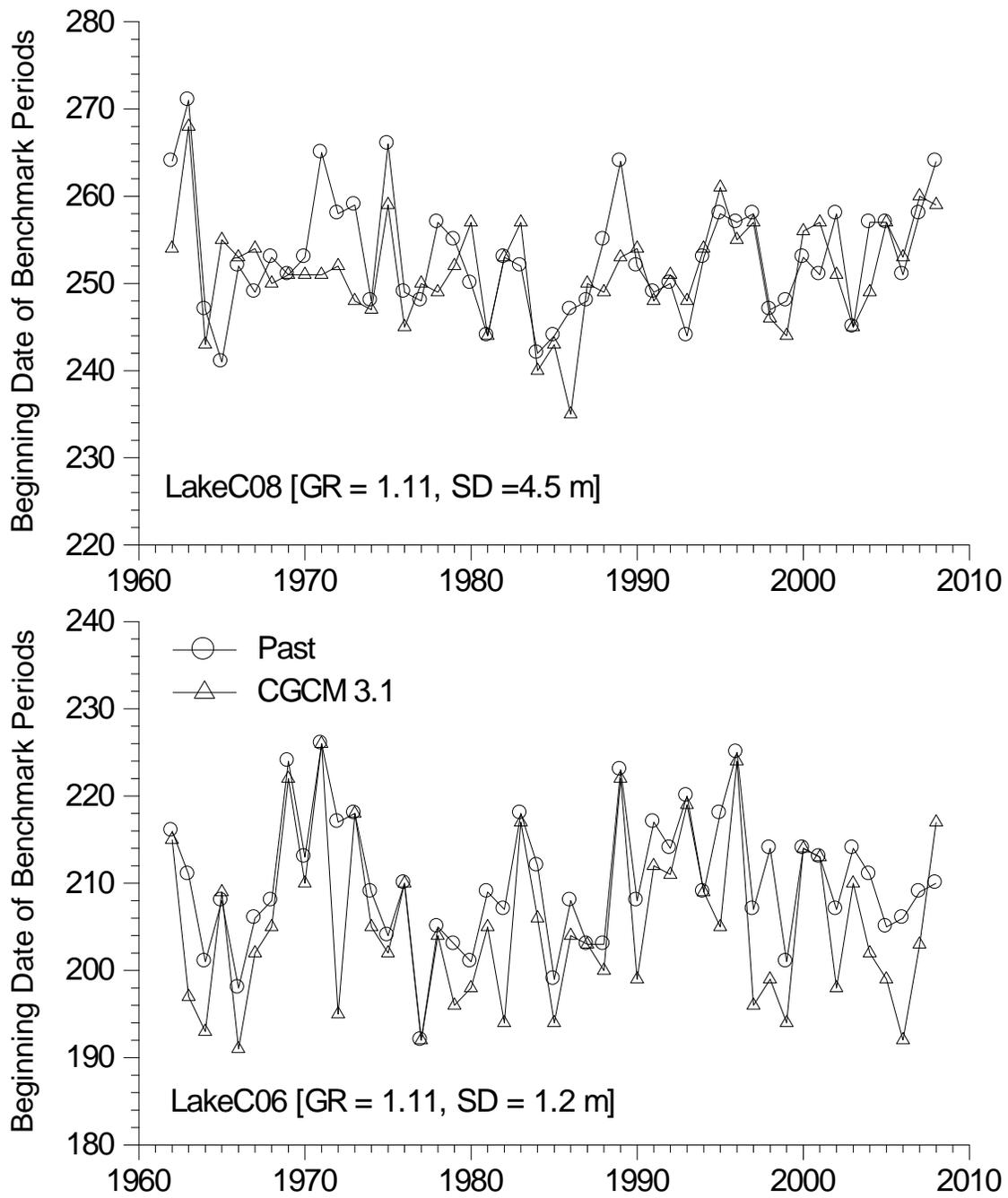


Figure 3.8 Time series plot of the beginning date of the variable benchmark periods for **past climate (1962-2008)** and the **CGCM 3.1 future climate scenario** for virtual LakeC06 and LakeC08. **Duluth weather** data were used for the model simulations.

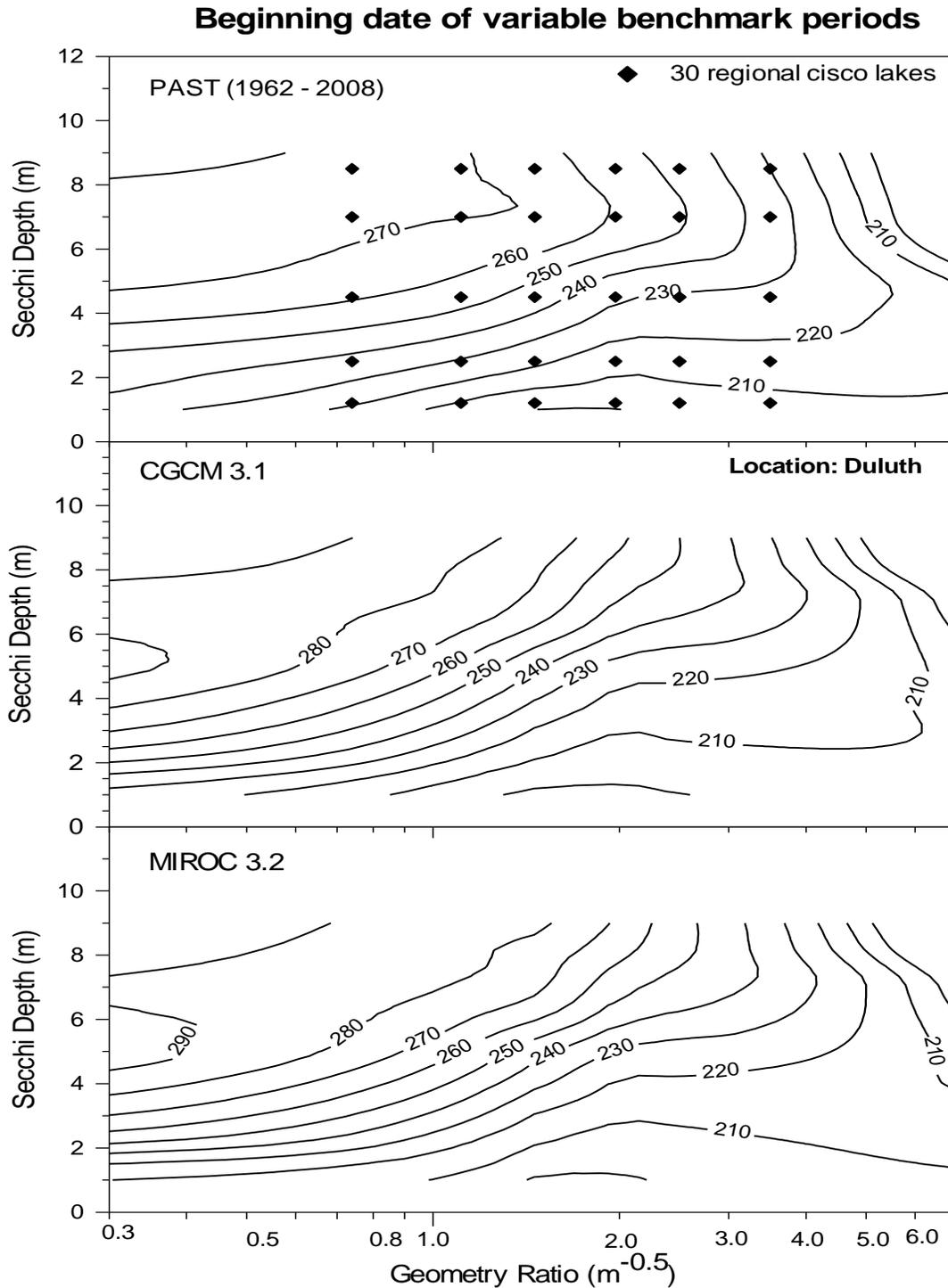


Figure 3.9 Contour plots giving the average beginning date of the variable benchmark periods under **past climate (1962-2008)**, **CGCM 3.1** and **MIROC 3.2** future climate scenarios. **Duluth** weather data were used for the model simulations. Contours were derived by interpolation from simulated data points for **30 virtual lakes**.

Beginning date of variable benchmark periods

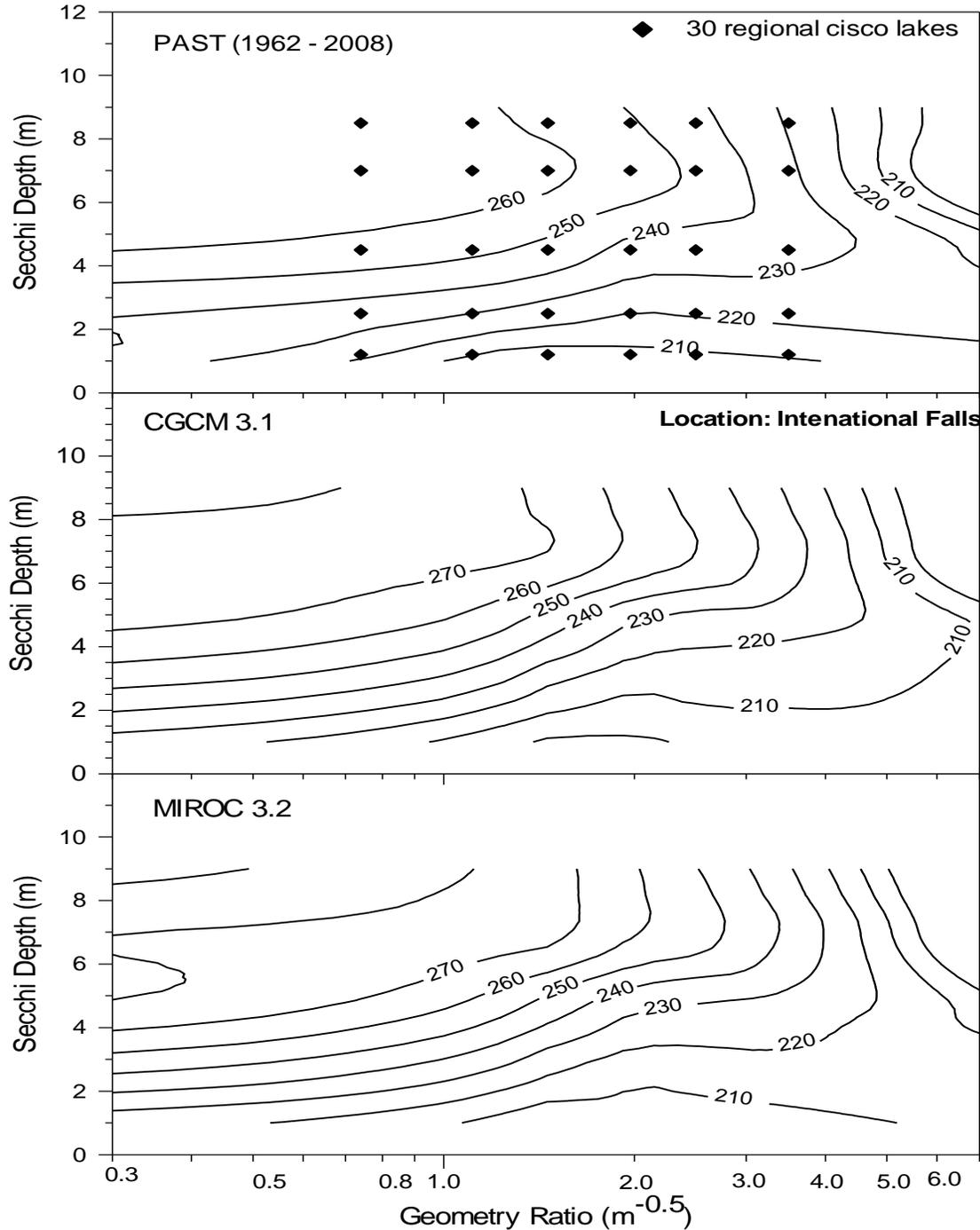


Figure 3.10 Contour plots giving the average beginning date of the variable benchmark periods under **past climate (1962-2008)**, **CGCM 3.1** and **MIROC 3.2 future climate scenarios**. **International Falls weather data** were used for the model simulation. Contours were derived by interpolation from simulated data points for **30 virtual lakes**.

Beginning date of variable benchmark periods

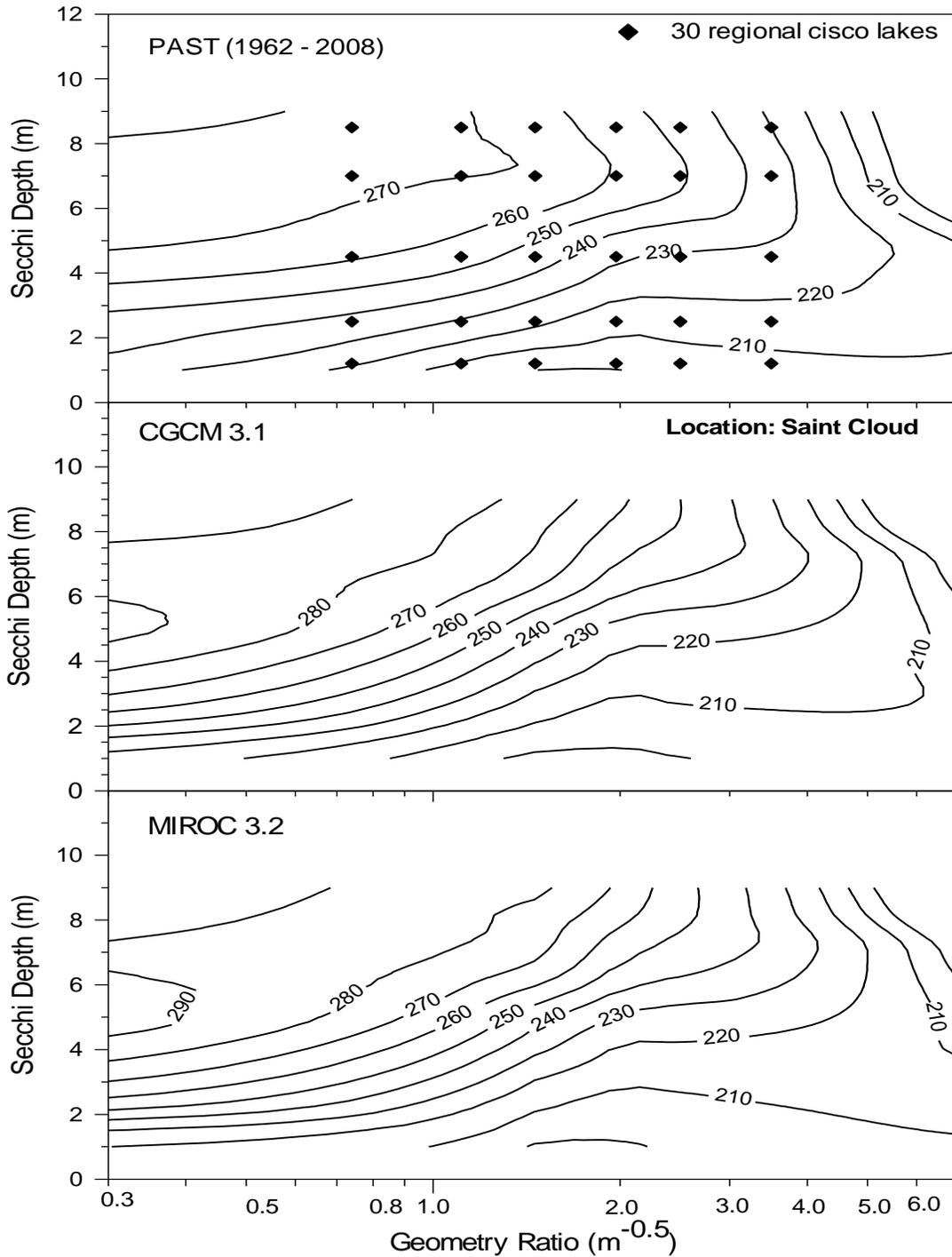


Figure 3.11 Contour plots giving the average beginning date of the variable benchmark periods under **past climate (1962-2008)**, **CGCM 3.1** and **MIROC 3.2** future climate scenarios. **St. Cloud** weather data were used for the model simulation. Contours were derived by interpolation from simulated data points for **30 virtual lakes**.

3.6 TDO3 values under future climate scenarios

MINLAKE2010 was run to simulate water temperature and DO profiles under two future climate scenarios: CGCM 3.1 and MIROC 3.2. Annual maximum daily TDO3 ($TDO3_{AM}$) values for the first set of 15 study lakes were calculated using projected temperature and DO profiles in lakes under the future climate scenario CGCM 3.1. Results are plotted in Figure 3.12. A comparison between Figure 3.4 and Figure 3.12 shows that all 15 study lakes have higher $TDO3_{AM}$ values under a future warmer climate scenario.

The three cisco lakes with the lowest projected $TDO3_{AM}$ values under the future CGCM 3.1 climate scenario were Kabekona, Ten Mile and Trout Lake. These three lakes have a low geometry ratio ($GR = 1.34, 1.05$ and $1.39 \text{ m}^{-0.5}$, respectively), and a high Secchi depth ($SD = 5.92 \text{ m}$ for Ten Mile and $SD = 5.4 \text{ m}$ for Trout Lake). These are strongly stratified and very transparent lakes in summer. On the other hand, two cisco lakes (South Twin and White Iron Lake) have relatively high $TDO3_{AM}$ values for both past (Fig. 3.4) and future climate (Fig. 3.12) conditions. Both lakes are weakly stratified (or polymictic) lakes ($GR = 5.22$ and $4.26 \text{ m}^{-0.5}$, respectively). These observations show that TDO3 values are closely related to GR and SD values of individual lakes. This will be illustrated and analyzed further in Chapter 4.

Table 3.6 gives sample results of average TDO3 values for a 47-year simulation period for the 21 cisco study lakes in the expanded sample set. The future climate scenario CGCM 3.1, and International Falls weather data were used for the model simulations. Lakes in Table 3.6 are sorted by lake geometry ratio from lowest to highest. The values given in Table 3.6 are for $AveTDO3_{AM}$, $AveATDO3_{FB}$, and $MaxATDO3_{FB}$ as defined in Table 3.1. Values of these same TDO3 parameters for simulated past climate conditions (1962 to 2008) were given in Table 3.3 and can be compared with those in Table 3.6.

Table 3.6 Values of GR, SD and three TDO3 parameters (°C) (**AveTDO3_{AM}**, **AveATDO3_{FB}**, and **MaxATDO3_{FB}**, Table 3.1, lines 4, 5, and 6) in the simulation period for **21 cisco study lakes** under the **CGCM 3.1 future climate scenario**. **International Falls weather data** were used.

Lake Name	Geometry ratio (GR, m ^{-0.5})	Secchi depth (SD, m)	Annual maximum AveTDO3 _{AM}	Benchmark mean AveATDO3 _{FB}	Benchmark maximum MaxATDO3 _{FB}
Six	0.69	3.94	10.89	7.45	8.39
Grindstone	0.82	2.88	5.63	4.79	4.85
Ten Mile	1.05	5.92	11.59	8.80	9.34
Little Trout	1.08	6.33	6.30	5.73	5.82
Carlos	1.13	3.40	15.31	8.11	10.57
Elk	1.16	2.50	18.46	16.91	18.2
Cedar	1.17	3.40	16.43	12.44	14.52
Big Trout	1.24	4.78	10.23	6.98	7.54
Kabekona	1.34	3.70	14.61	9.94	12.02
Trout (Cook)	1.39	5.40	12.95	7.50	8.83
Snowbank	1.41	5.28	10.05	7.31	7.74
Little Sand	1.45	5.22	10.07	6.85	7.55
Siseebakwet	1.50	3.89	17.64	13.85	16.38
Greenwood	1.57	5.46	11.33	7.48	8.47
Mukooda	1.76	5.12	12.01	8.43	9.33
Burntside	1.91	5.80	8.29	6.89	7.08
Blue	2.04	6.76	18.66	14.79	17.38
Fish Hook	2.19	3.44	18.54	16.35	18.11
Trout (St. Louis)	2.50	4.71	14.95	10.77	13.17
White Iron	4.26	1.50	25.32	23.46	24.93
South Twin	5.22	2.9	26.15	23.2	25.31

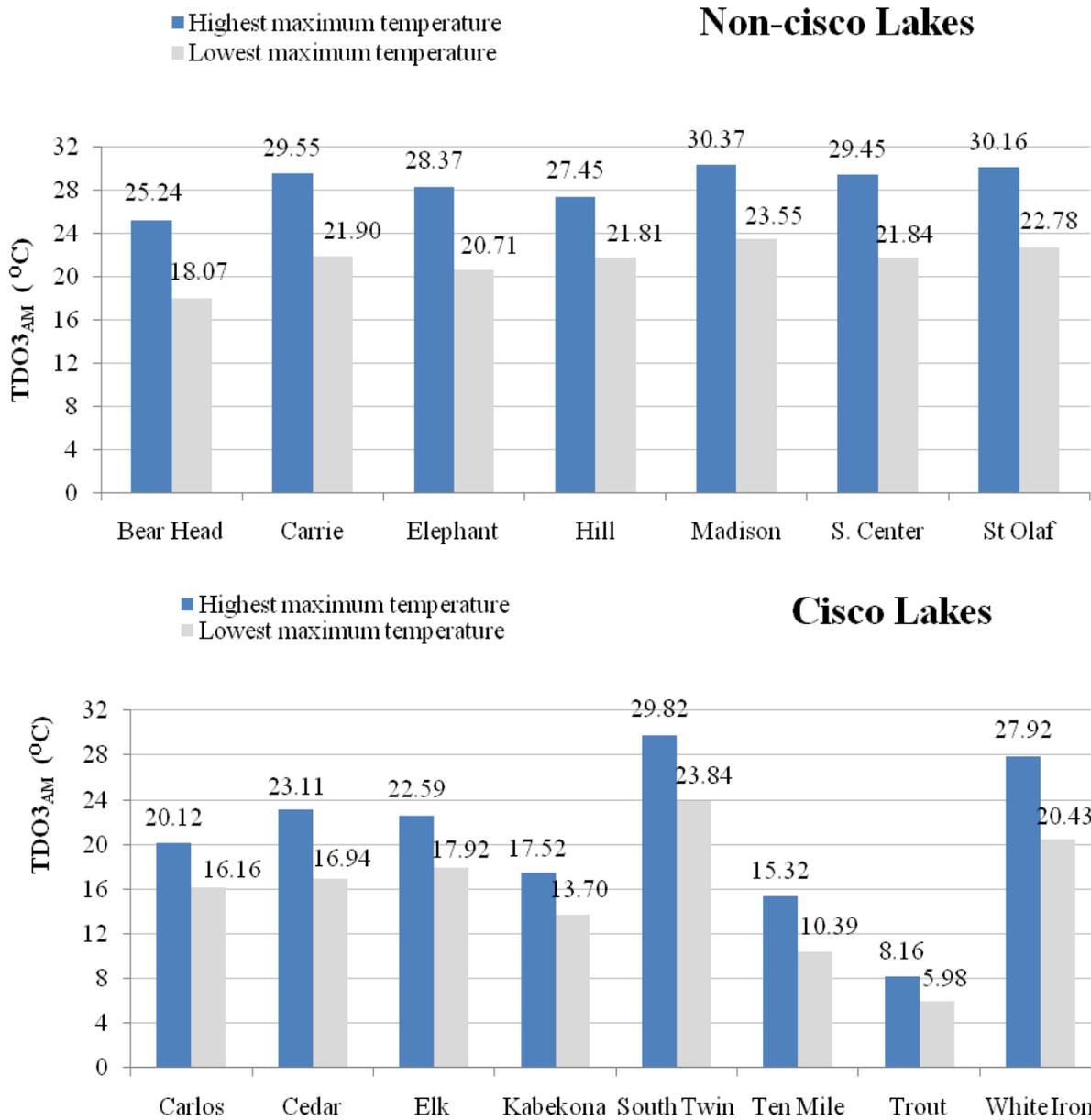


Figure 3.12 Ranges of TDO_{3AM} (annual maximum temperature where DO is 3.0 mg/L) under the CCC GCM 3.1 future climate scenario (A1B scenario) in cisco and non-cisco lakes.

Chapter 4 Simulation Results for TDO3 Parameter Values in Minnesota Cisco Lakes under Past and Future Climate Scenarios

Oxythermal habitat parameters TDO3 defined in Table 3.1 were calculated from simulated daily temperature and DO profiles for the 21 cisco study lakes (Table 1.1) and 30 virtual cisco lakes (Table 1.2) under past and future climate conditions. Daily water temperature and DO profiles were simulated using the MINLAKE2010 model. In this chapter the simulated and computed results for selected TDO3 parameters are presented as tabulated results and in contour plots as a function of two principal lake characteristic parameters, i.e., lake geometry ratio (GR) (Gorham and Boyce 1989) as a measure of the strength of stratification, and Secchi depth (SD) as a measure of transparency and lake trophic status. The choice of these two parameters will be justified in the next paragraphs. The results given in this chapter provide the basis for the selection of cisco refuge lakes presented in Chapter 5.

As an alternative to the use of measured lake temperature and DO profiles, Jacobson et al. (2010) developed a generalized model to predict TDO3 as a function of lake productivity, climate, and relative depth (lake geometry ratio, $GR = A_s^{0.25}/H_{max}$). Summer total phosphorus concentration was the variable to represent lake productivity of each lake (Jacobson et al. 2010).

In this study, total phosphorus concentration was not a model parameter, and is not used to characterize any of the 21 cisco study lakes or 30 virtual lakes. Instead, Secchi depth (SD), a measure of lake transparency, was used to represent trophic state as well as radiation attenuation in a Minnesota lake. The trophic state expresses primary productivity and is directly related to DO production by photosynthesis in a lake. Trophic state ranges from oligotrophy (nutrient-poor, biologically unproductive) to eutrophy (nutrient-rich, productive).

In this study, daily water temperature and DO profiles in lakes were simulated by the MINLAKE2010 model under past climate conditions and two future climate scenarios. The model uses climate data as model input, and can therefore simulate future climate scenarios for which no measurements exist. Chlorophyll-a concentration that represents biomass or phytoplankton in the MINLAKE2010 model for each cisco lake was calculated from the relationship between chlorophyll-a and Secchi depth used in the Carlson trophic index (Carlson 1977). Typical (generic) seasonal growth patterns derived from extensive field observations in temperate lakes (Marshall and Peters 1989) were imposed in the model. Secchi depth (SD) and lake geometry ratio (GR) are representative parameters to characterize each of the 620 cisco lakes in the database. Contour plots of TDO3 parameters presented in this chapter used lake geometry ratio and Secchi depth as x- and y- axes.

4.1. Contour plots of TDO3 characteristic parameters in 21 cisco study lakes

During a research project meeting in February 2010, three TDO3 characteristic parameters, $AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$ (Table 3.1, line 3, line 6 and line 9, respectively), were identified as useful TDO3 parameters to identify and select refuge lakes that have the potential to sustain cisco habitat after climate warming in Minnesota. Because summer water temperature and DO stratification in a lake are very much related to geometry ratio (GR) and Secchi depth (SD) of a lake (Stefan et al. 1996), contour plots of $AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$ were created for the 21 cisco study lakes using GR and SD as independent variables.

Calibrations of the MINLAKE2010 model for each of the 21 cisco study lakes had been conducted with climate data from a weather station closest to each lake as model input as described in Project Report 2 of this study (Fang et al. 2010). Although Class I weather stations in Minnesota had continuous daily weather data from 1961 to 2008, daily data for Class II weather stations were limited to the period from 1991 to 2008. A common simulation period from 1991 to 2008 was therefore used to calculate numerical values of the above three TDO3 characteristic parameters for use in the contour plots.

Table 4.1 gives geometry ratio, mean summer Secchi depth, and $AvgTDO3_{AM}$ for the 21 cisco study lakes, determined by using the weather station closest to each lake and the same simulation period (1991 to 2008). Figure 4.1 shows contour plots of $AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$ that were obtained by interpolating computed values at the data points shown as filled circles in Fig. 4.1. TDO3 parameter values reported in Figure 4.1 were calculated using simulated daily temperature and DO profiles using weather data from the weather station closest to each individual lake.

To facilitate the comparison of TDO3 parameter values, contour plots should be developed by using weather data over the same simulation period and from the same weather station for all study lakes. Figure 4.2 presents contour plots of $AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$ using the same weather data (from Duluth) for all 21 cisco study lakes for the same simulation period from 1962 to 2008.

The distribution of the 21 cisco study lakes (dots) on the plot of lake geometry ratio (GR) vs. Secchi depth (SD) is shown in the top frame of Figs. 4.1 and 4.2. One can see that the 21 cisco study lakes are not distributed uniformly on the contour plot as previously discussed in Chapter 1. In areas of the plot where simulated TDO3 parameter values are missing extrapolations can result in misleading contour patterns. This is the case in Figs. 4.1 and 4.2 where Secchi depth becomes larger, and most of the contour lines bend towards smaller geometry ratios (to the left), although no data points exist to support this behavior. TDO3 parameter values for lakes with higher Secchi depths (more oligotrophic lakes) are missing from

the plot. The extrapolated higher TDO3 parameter values in the more oligotrophic lakes erroneously indicate unfavorable habitat conditions for cisco. This is incorrect, because it contradicts field observations: we have already documented that cisco prefer to live in deep oligotrophic lakes. Additional data points are needed for areas not covered by actual study lakes on the plot. These data points can be provided by simulations of virtual cisco lakes that fill in the gaps on the contour plots of TDO3 parameters using geometry ratio (GR) and Secchi depth (SD) as x- and y-axes.

Thirty virtual cisco lakes were introduced as discussed in Section 1.2. They are more or less uniformly distributed on the plot of lake geometry ratio versus Secchi depth (Figure 1.2). Even though the selection of lake geometry (surface areas and maximum depths) and SD for the 30 virtual cisco lakes was arbitrary, the selected values are in general representative of the 620 cisco lake database as indicated in Table 1.3 and Figure 1.3. Therefore, daily water temperature and DO profiles were simulated using MINLAKE2010 under past climate conditions and two future climate scenarios not only in the 21 cisco study lakes but also in the 30 virtual cisco lakes. Characteristic TDO3 parameters defined in Table 3.1 were calculated from these profiles and plotted as point values in a coordinate system of SD versus GR. By interpolation of simulated data points of characteristic TDO3 parameter values from the 21 study cisco lakes and the 30 virtual cisco lakes combined, or only using the 30 virtual cisco lakes, contour plots for selected TDO3 parameters were developed for past and future climate conditions.

In the model simulations of the 21 cisco study lakes, calibrated model parameters were used to enhance the performance of the MINLAKE2010 model. Six model parameters were used for model calibration as described in Project Report 2 (Fang et al. 2010). An analysis of each calibration parameter was performed, and generalized model parameters were proposed and tested. For example, the proposed BOD values are 1.50, 0.75, and 0.50 mg/L for eutrophic, mesotrophic, and oligotrophic lakes, respectively. EMCOE(2) is the multiplier for sedimentary oxygen demand (SOD) below the mixed layer and was found to depend on both maximum depth and trophic status (Fang et al. 2010). Proposed SOD values below the mixed layer after applying EMCOE(2) were 1.50, 1.25, and 1.00 g O₂ m⁻² day⁻¹ for deep ($H_{\max} \geq 24$ m) eutrophic, mesotrophic, and oligotrophic lakes, respectively. Although there is no lake with a Secchi depth greater than 7.0 m in the 21 cisco study lakes we have some knowledge of model parameter values for virtual cisco lakes having large Secchi depths. For these highly oligotrophic lakes with large SD values, photosynthesis is not limited by light but by low phytoplankton populations expressed by low chlorophyll-concentrations in the model. In these lakes photosynthesis occurs at a low rate throughout the euphotic zone, and there is little production of organic matter in the epilimnion that settles into the hypolimnion and to the lake bottom (Cole 1983). Therefore, sediment oxygen demand below the mixed layer is low, and the multiplier for SOD below the mixed layer needs to be reduced. For virtual cisco lakes with SD = 7.0 m and 8.5, the proposed SOD values below the mixed layer after applying EMCOE(2) were 0.40, and

0.20 g O₂ m⁻² day⁻¹, respectively. These generalized model parameters were used in the model simulations of the virtual cisco lakes for past and future climate scenarios.

Table 4.1 Values for GR, SD, and the average of annual maximum daily TDO3 (**AvgTDO3_{AM}**, Table 3.1, line 3) for the **simulation period (1962 to 2008)** determined with **weather data input from a station closest to each of the 21 cisco study lakes**.

Lake Name	Geometry Ratio (m^{-0.5})	Secchi depth (m)	AvgTDO3_{AM} (°C)
Big Trout	1.24	4.78	8.75
Blue	2.04	6.76	15.49
Burntside	1.91	5.80	7.92
Cedar	1.17	3.40	13.70
Carlos	1.13	3.40	11.64
Elk	1.16	2.50	15.43
Fishhook	2.19	3.44	15.20
Greenwood	1.57	5.46	8.91
Grindstone	0.82	2.88	5.44
Kabekona	1.34	3.70	11.95
Little Sand	1.45	5.22	8.67
Little Trout	1.08	6.33	6.08
Mukooda	1.76	5.12	10.26
Siseebakwet	1.50	3.89	13.62
Six	0.69	3.94	9.00
Snowbank	1.41	5.28	8.49
South Twin	5.22	2.90	22.26
Ten Mile	1.05	5.92	10.12
Trout (Cook)	1.39	5.40	9.87
Trout (St. Louis)	2.50	4.71	11.49
White Iron	4.26	1.50	21.51

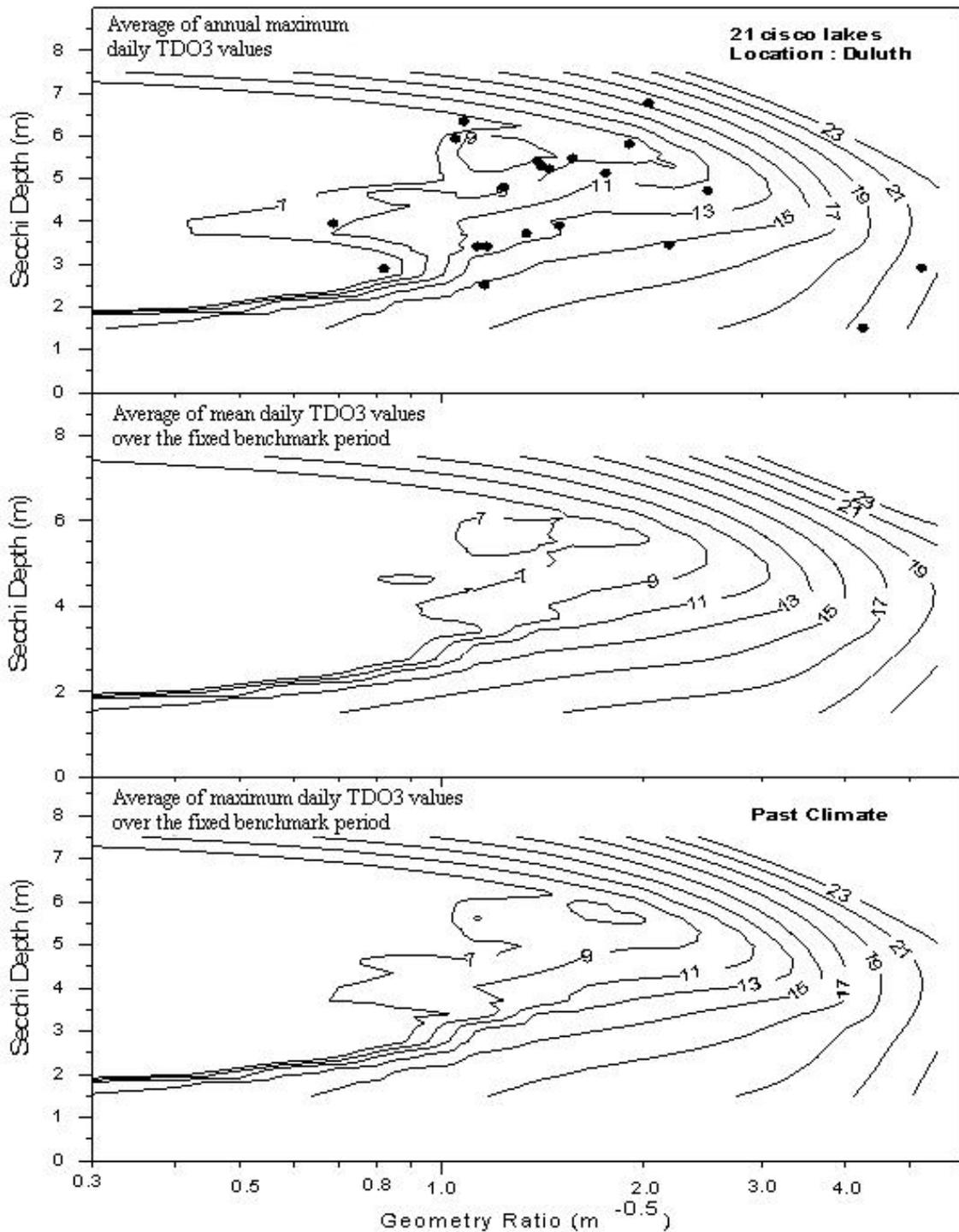


Figure 4.2 Contour plots of $\text{AvgTDO3}_{\text{AM}}$ (top panel, Table 3.1, line 3), $\text{AvgATDO3}_{\text{FB}}$ (middle panel, Table 3.1, line 6), and $\text{AvgMTDO3}_{\text{FB}}$ (bottom panel, Table 3.1, line 9). Simulations are for the period **from 1962 to 2008** using **Duluth weather data**. Contours were derived by interpolation of simulated data points for **21 cisco lakes**.

4.2 Contour plots of selected TDO3 parameters for past (1962 to 2008) climate conditions

Averages of annual maximum daily TDO3 values ($AvgTDO3_{AM}$), mean and maximum daily TDO3 values over the fixed benchmark period ($AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$) in the 47-year simulation period under past climate (1962 to 2008) and the CGCM 3.1 future climate scenario are summarized in Table 4.2 for the 21 cisco study lakes and in Table 4.3 for the 30 virtual cisco lakes. The fixed benchmark period for stratified lakes is from DOY 209 to DOY 239. Results presented in Tables 4.2 and 4.3 are also plotted in Figure 4.3, and were calculated from daily temperature and DO profiles simulated using International Falls weather data. Results simulated with Duluth and St. Cloud weather data as model input are given in Appendix C (Tables C.1 to C.11).

Figure 4.3 shows contour plots of averages of annual maximum daily TDO3 values ($AvgTDO3_{AM}$), mean and maximum daily TDO3 values over the fixed benchmark period ($AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$) in the 47-year simulation period under past climate conditions (1962 – 2008) using International Falls weather data. Contours in Fig. 4.3 were derived by interpolation from simulated data points for 21 cisco lakes and 30 virtual cisco lakes. Similar contours in Figure 4.4 were derived by interpolation from simulated data points for the 30 virtual cisco lakes only. When combined results of these TDO3 parameter values for the 21 cisco study lakes and the 30 virtual cisco lakes were used in Figure 4.3 to develop contour plots, some contour islands appeared, because the 21 cisco study lakes are not distributed uniformly on the plot of Secchi depth versus geometry ratio. Figure 4.3 does show, however, that the contours derived from the 21 cisco study lakes using calibrated model parameters are largely consistent with contours derived from the 30 virtual cisco lakes using generalized model parameters. Contour plots in Figure 4.4 derived by interpolation from simulated data points for the 30 virtual cisco lakes only, show a clearer pattern of changes of TDO3 parameters as a function of lake geometry ratio and Secchi depth than the contour plots in Figure 4.3. Similar contour plots of TDO3 parameters derived from simulated data points using Duluth and St. Cloud weather data are presented in Appendix C (Figures C.1 to C.4).

Figures 4.3 and 4.4 provide additional insights. The pattern of the contour lines indicates that the dependence of $AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$ on lake geometry ratio GR and Secchi depth SD shifts, when lake stratification shifts from dimictic (seasonal) to polymictic. The transition occurs at GR values ≈ 2 to 3.

The TDO3 parameters strongly depend on lake geometry ratio GR and weakly on Secchi depth SD when the GR is on the order of 3 or larger (weakly stratified, polymictic lakes). Above $GR > 3$ the values of all three TDO3 parameters ($AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and

AvgMTDO3_{FB}) rise when GR increases. Virtual lakes LakeC26 to LakeC30 have lake geometry ratios of 3.5 and averages of annual maximum daily TDO3 values (AvgTDO3_{AM}) from 16.3 to 18.0 °C under past climate conditions using International Falls weather data (Table 4.3 and Fig. 4.4).

On the other hand, in lakes with $GR < 2$ (seasonally stratified, dimictic lakes) the TDO3 parameters depend significantly on SD, provided that SD is low (less transparent, mesotrophic or eutrophic lakes). Virtual lakes LakeC01 to LakeC05 have a lake geometry ratio of 0.74 and are strongly stratified lakes; their averages of AvgTDO3_{AM} ranged from 7.9 to 15.6 °C (Table 4.3). Figure 4.4 shows that TDO3 parameter values in lakes with low geometry ratio (LakeC01 to LakeC05) depend more strongly on Secchi depth or lake trophic status than TDO3 parameter values in lakes with high lake geometry ratio (LakeC25 to LakeC30).

Table 4.2 Values of GR, SD, and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period ($AvgTDO3_{AM}$, $AvgATDO3_{FB}$ and $AvgMTDO3_{FB}$, Table 3.1, lines 3, 6 and 9, respectively) . Past **climate conditions (1962-2008)** and the **CGCM 3.1 climate scenario**, and **International Falls weather** data have been used in the simulations of the **21 cisco study lakes**.

Lake Name	Geometry ratio ($m^{-0.5}$)	Secchi depth (m)	Past climate (1962 – 2008)			Future CGCM 3.1 climate scenario		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	9.12	6.62	7.42	10.89	7.45	8.39
Grindstone	0.82	2.88	5.22	4.52	4.55	5.63	4.79	4.85
Ten Mile	1.05	5.92	9.78	8.01	8.54	11.59	8.80	9.34
Little Trout	1.08	6.33	5.72	5.42	5.49	6.30	5.73	5.82
Carlos	1.13	3.40	11.78	6.37	7.47	15.31	8.11	10.57
Elk	1.16	2.50	14.55	12.69	14.11	18.46	16.91	18.20
Cedar	1.17	3.40	12.52	9.24	10.78	16.43	12.44	14.52
Big Trout	1.24	4.78	8.00	5.94	6.30	10.23	6.98	7.54
Kabekona	1.34	3.70	11.55	7.67	9.04	14.61	9.94	12.02
Trout (Cook)	1.39	5.40	10.20	6.51	7.36	12.95	7.50	8.83
Snowbank	1.41	5.28	8.09	6.44	6.74	10.05	7.31	7.74
Little Sand	1.45	5.22	7.65	6.06	6.38	10.07	6.85	7.55
Siseebakwet	1.50	3.89	14.14	10.30	12.30	17.64	13.85	16.38
Greenwood	1.57	5.46	8.09	6.47	6.81	11.33	7.48	8.47
Mukooda	1.76	5.12	9.41	7.04	7.51	12.01	8.43	9.33
Burntside	1.91	5.80	7.41	6.30	6.52	8.29	6.89	7.08
Blue	2.04	6.76	14.93	11.88	13.64	18.66	14.79	17.38
Fish Hook	2.19	3.44	15.06	12.26	14.33	18.54	16.35	18.11
Trout (St. Louis)	2.50	4.71	11.23	8.91	9.51	14.95	10.77	13.17
White Iron	4.26	1.50	21.95	20.47	21.71	25.32	23.46	24.93
South Twin	5.22	2.90	22.95	20.31	22.23	26.15	23.20	25.31

Note: Annual maximum is average of annual maximum daily TDO3 values in the simulation period, and is $AvgTDO3_{AM}$ defined in Table 3.1. Benchmark mean is average of mean daily TDO3 values over the fixed benchmark period, and is $AvgATDO3_{FB}$ defined in Table 3.1. Benchmark maximum is average of maximum daily TDO3 values over the fixed benchmark period, and is $MaxATDO3_{FB}$ defined in Table 3.1

Table 4.3 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively). Past **climate conditions (1962-2008)** and the **CGCM 3.1 climate scenario**, and **International Falls weather** data have been used in the simulation of the **30 virtual cisco lakes**.

Lake Name	GR (m ^{-0.5})	SD (m)	Past climate (1962-2008)			Future CGCM 3.1 climate scenario		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	15.60	14.33	15.44	18.05	17.07	17.93
LakeC02	0.74	2.50	12.51	9.66	11.31	15.13	10.76	13.08
LakeC03	0.74	4.50	9.10	6.50	7.12	10.53	7.05	7.77
LakeC04	0.74	7.00	8.01	6.29	6.58	8.92	6.58	6.93
LakeC05	0.74	8.50	7.92	6.35	7.10	8.65	6.98	7.37
LakeC06	1.11	1.25	16.72	15.12	16.64	20.87	19.24	20.79
LakeC07	1.11	2.50	13.30	10.62	12.55	16.90	13.60	16.07
LakeC08	1.11	4.50	9.73	6.50	7.32	12.20	7.57	8.75
LakeC09	1.11	7.00	7.99	6.41	6.68	9.16	6.83	7.12
LakeC10	1.11	8.50	8.29	7.40	7.68	8.91	7.90	8.16
LakeC11	1.46	1.25	16.97	15.40	16.88	21.68	19.25	21.35
LakeC12	1.46	2.50	14.37	12.02	13.88	18.73	16.98	18.47
LakeC13	1.46	4.50	11.03	7.35	8.63	14.73	9.71	12.06
LakeC14	1.46	7.00	8.46	7.16	7.43	10.05	7.84	8.12
LakeC15	1.46	8.50	9.36	8.12	8.48	10.34	8.95	9.30
LakeC16	1.97	1.25	17.22	15.87	17.13	21.71	19.73	21.41
LakeC17	1.97	2.50	15.24	13.67	15.00	20.04	18.69	19.96
LakeC18	1.97	4.50	13.06	9.53	11.56	17.73	14.56	17.06
LakeC19	1.97	7.00	10.52	8.84	9.27	12.82	9.93	10.48
LakeC20	1.97	8.50	11.64	9.81	10.35	13.08	11.00	11.56
LakeC21	2.50	1.25	17.16	16.02	17.08	21.52	19.91	21.28
LakeC22	2.50	2.50	15.35	13.91	15.14	19.87	18.67	19.78
LakeC23	2.50	4.50	14.03	11.04	13.01	18.54	16.25	18.15
LakeC24	2.50	7.00	12.98	10.82	11.48	15.28	12.38	13.20
LakeC25	2.50	8.50	14.16	11.89	12.69	16.13	13.55	14.38
LakeC26	3.50	1.25	17.97	16.96	17.88	21.98	20.65	21.82
LakeC27	3.50	2.50	16.63	15.37	16.40	20.61	19.59	20.52
LakeC28	3.50	4.50	16.30	14.05	15.65	20.04	18.57	19.80
LakeC29	3.50	7.00	17.07	14.71	15.93	19.47	16.87	18.14
LakeC30	3.50	8.50	18.02	15.84	17.16	20.55	18.13	19.49

Note: Annual maximum is average of annual maximum daily TDO3 values in the simulation period, and is AvgTDO3_{AM} defined in Table 3.1. Benchmark mean is average of mean daily TDO3 values over the fixed benchmark period, and is AvgATDO3_{FB} defined in Table 3.1. Benchmark maximum is average of maximum daily TDO3 values over the fixed benchmark period, and is MaxATDO3_{FB} defined in Table 3.1

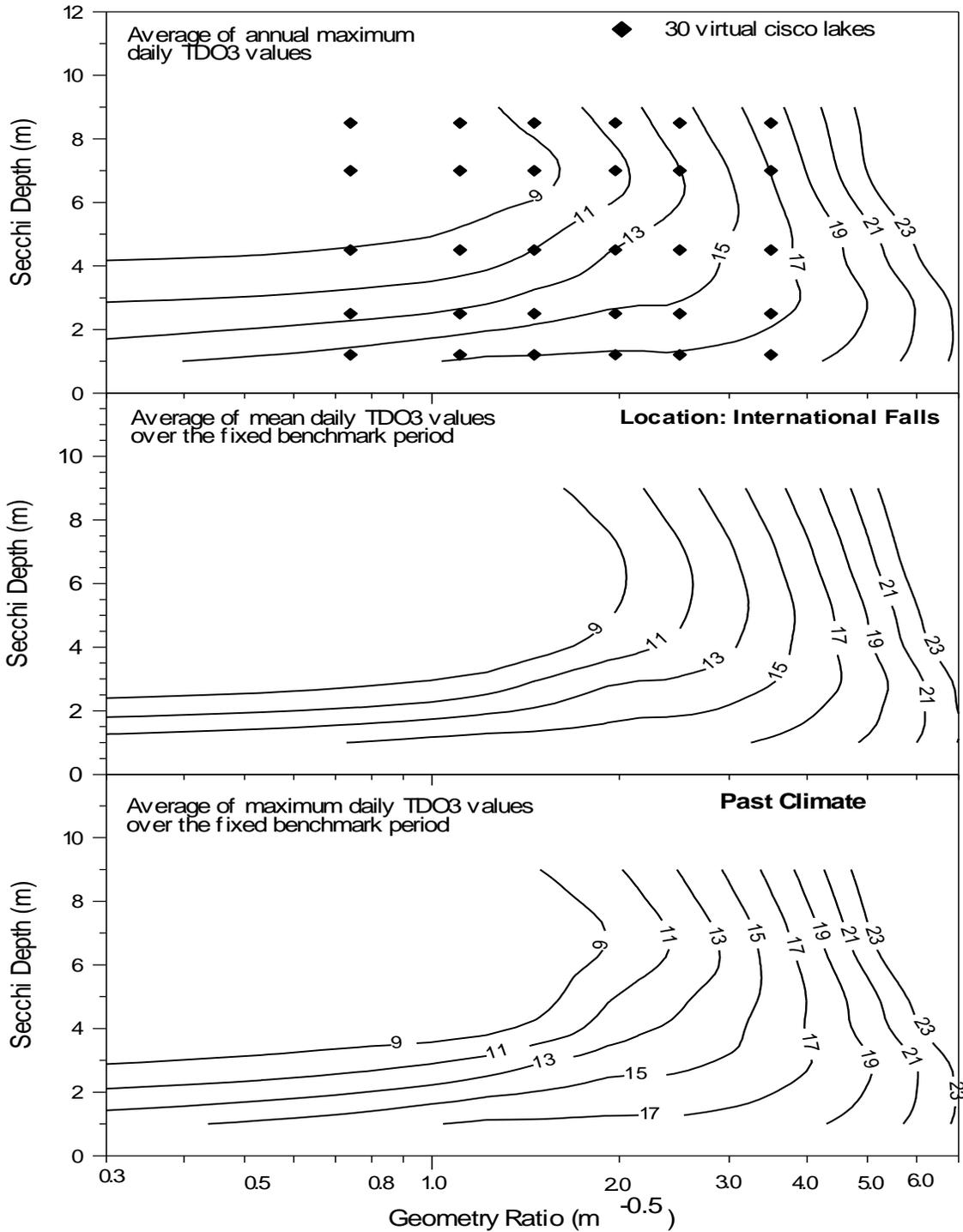


Figure 4.4 Contour plots of $\text{AvgTDO3}_{\text{AM}}$ (Table 3.1, line 3), and $\text{AvgATDO3}_{\text{FB}}$, and $\text{AvgMTDO3}_{\text{FB}}$ (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **International Falls weather** data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

4.3 Contour plots of selected TDO3 parameters for future climate scenarios

Output from two recent GCM models (CGCM 3.1 and MIROC 3.2) was used to generate two future climate scenarios. Daily water temperature and DO profiles were simulated by using the CGCM 3.1 and MIROC 3.2 climate scenarios as input to the MINLAKE2010 simulations of 21 cisco study lakes and 30 virtual cisco lakes. Figures 4.5, 4.6, and 4.7 show results in the form of contour plots for averages of annual maximum daily TDO3 values ($AvgTDO3_{AM}$), mean and maximum daily TDO3 values over the benchmark period ($AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$) for the future 47-year simulation period. These contour plots were derived by applying the MIROC 3.2 climate change scenario to the International Falls, Duluth, and St. Cloud weather data, respectively; lines were obtained by interpolation from simulated data points for 30 virtual cisco lakes only. Similar contour plots were derived by interpolation from simulated data points for 21 cisco lakes and 30 virtual cisco lakes under the CGCM 3.1 climate change scenario at all three weather stations; these plots are given in Appendix C (Figures C.5 to C.13). A comparison of Figure 4.3 with 4.5 reveals that under future climate conditions TDO3 parameter values rise by around 2.0 to 3.0 °C. The contour plots in Figures 4.5 to 4.7 are useful to select refuge lakes for cisco in consideration of future climate warming.

Tables 4.4, 4.5, and 4.6 list statistical differences for the three TDO3 parameters ($AvgTDO3_{AM}$, $AvgATDO3_{FB}$, and $AvgMTDO3_{FB}$) between the CGCM 3.1 future climate scenario and past (1962-2008) climate conditions. The differences of $AvgTDO3_{AM}$ for the 21 cisco lakes ranged from 0.41 to 3.91 °C with a mean of 2.67 °C and a standard deviation of 1.09°C when International Falls weather data were used (Table 4.4). A similar magnitude of increases was projected for the 30 virtual cisco lakes and at other weather stations (Tables 4.5 and 4.6). The maximum and minimum increases of the three TDO3 parameters from past climate to the CGCM 3.1 future scenario were projected to be from 3.91 to 6.51 °C, and from 0.00 to 0.78°C, respectively.

Almost the same values were projected for 21 cisco lakes and 30 virtual cisco lakes for increases from past climate (1962 to 2008) to the MIROC 3.2 future scenario and at all three weather stations (Tables 4.7, 4.8, and 4.9). The maximum and minimum increases of the three TDO3 parameters were projected to be from 4.07 to 6.40°C, and from 0.14 to 0.81°C, respectively.

The mean increases of all three TDO3 parameters from past climate to the CGCM 3.1 or the MIROC 3.2 future scenarios for 21 cisco lakes and 30 virtual cisco lakes were projected to be from 1.84 to 3.47°C and from 1.84 to 3.56°C, respectively. All these increases were slightly larger when St. Cloud weather data were used instead of International Falls weather data (Tables 4.6 and 4.9).

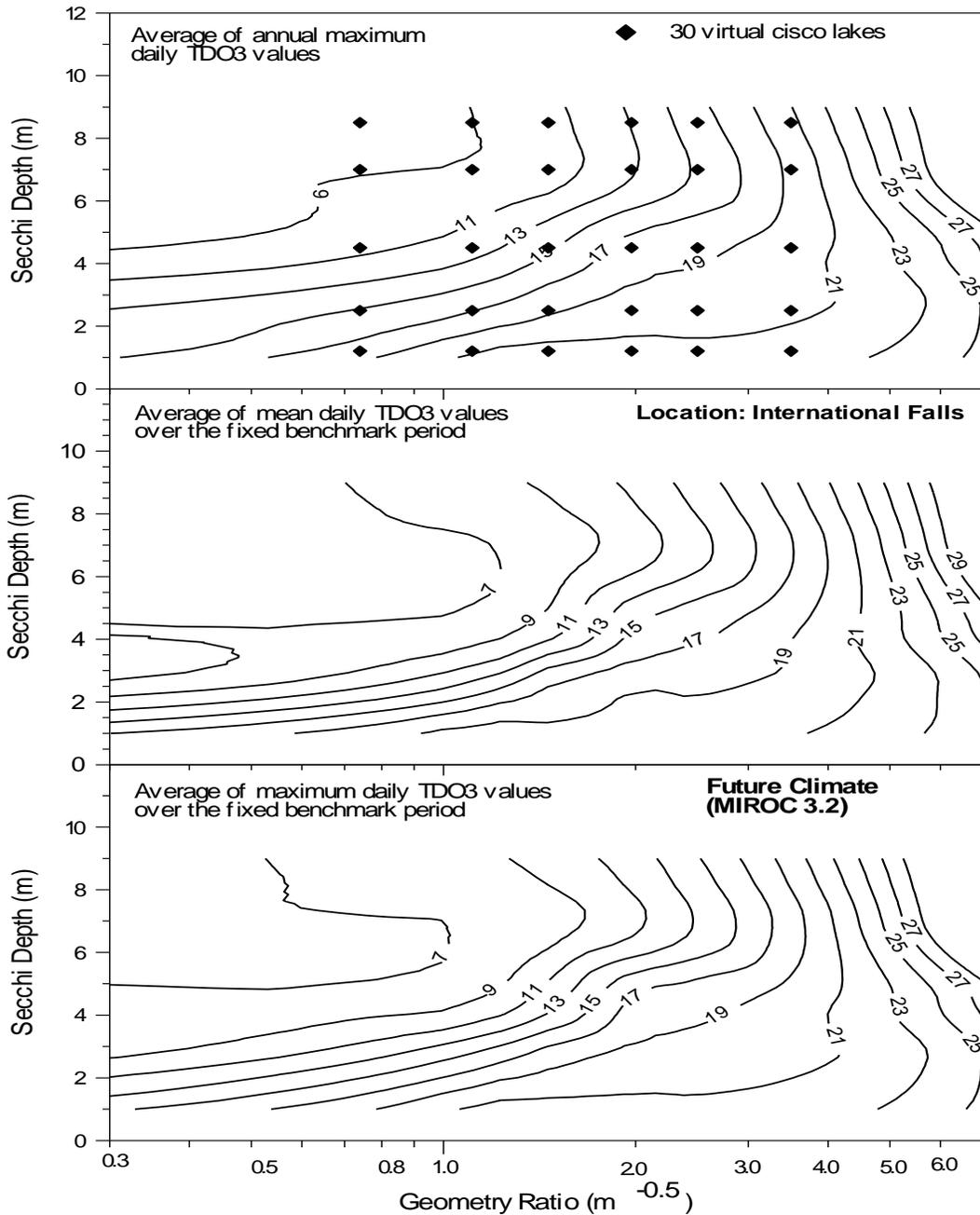


Figure 4.5 Contour plots of $\text{AvgTDO3}_{\text{AM}}$ (Table 3.1, line 3), and $\text{AvgATDO3}_{\text{FB}}$ and $\text{AvgMTDO3}_{\text{FB}}$ (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated for the **MIROC 3.2 future climate scenario** using **International Falls weather** data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

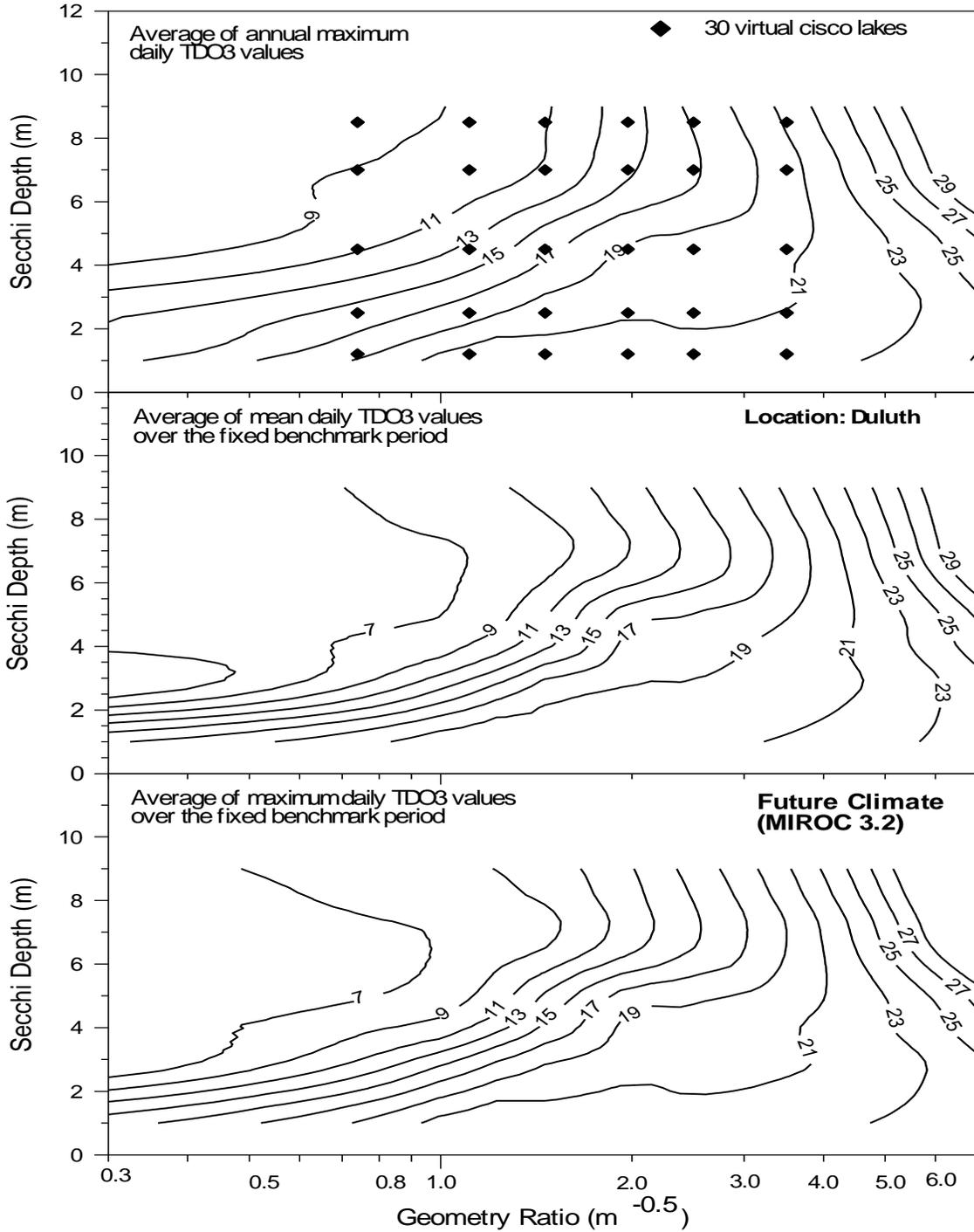


Figure 4.6 Contour plots of $AvgTDO3_{AM}$ (Table 3.1, line 3), and $AvgATDO3_{FB}$ and $AvgMTDO3_{FB}$ (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **Duluth weather** data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

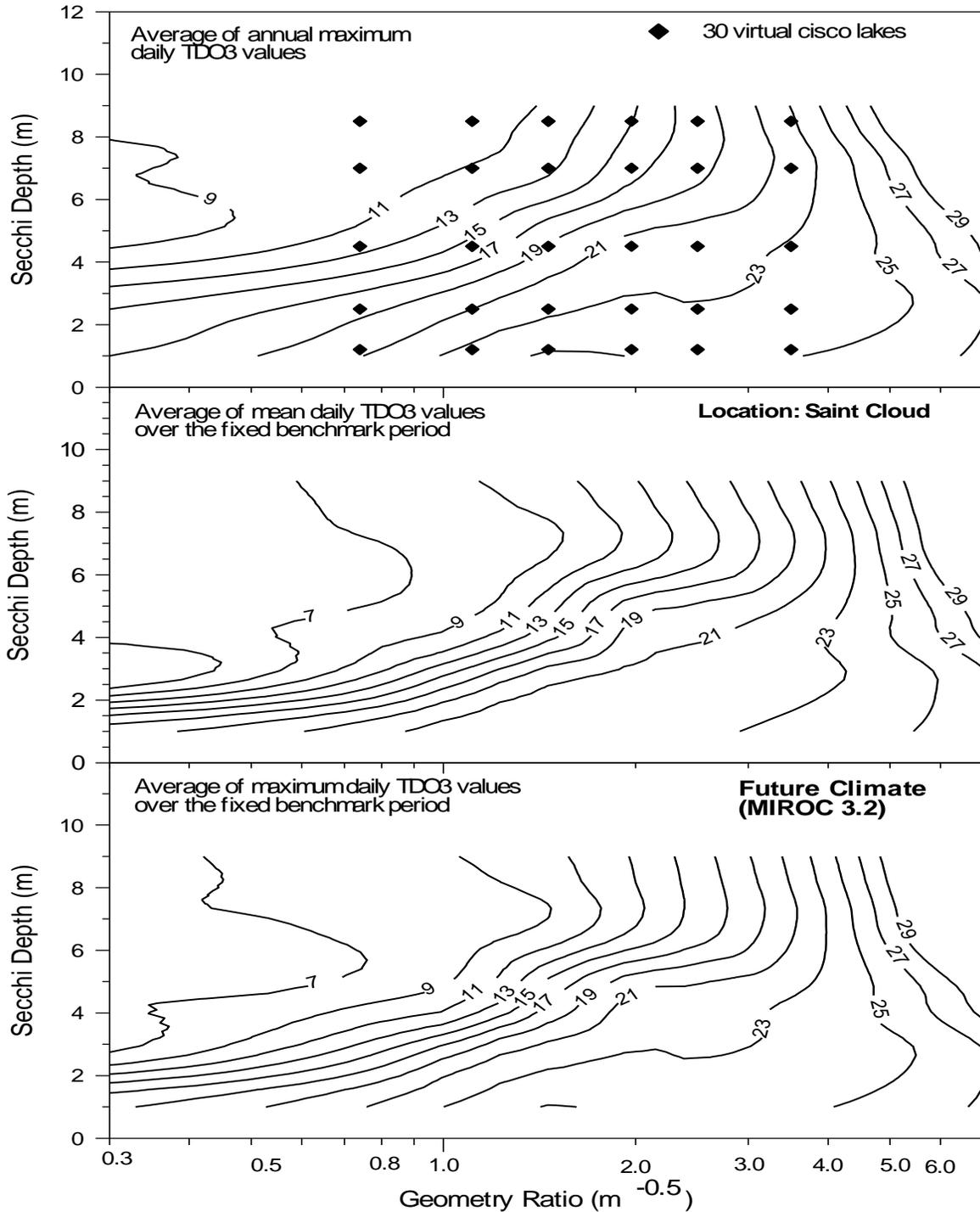


Figure 4.7 Contour plots of $AvgTDO3_{AM}$ (Table 3.1, line 3), and $AvgATDO3_{FB}$ and $AvgMTDO3_{FB}$ (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **St. Cloud weather data**. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

Table 4.4 Statistical differences for three TDO3 parameters (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively) between the **future CGCM 3.1 climate scenario and past climate conditions (1962 to 2008)** at the **International Falls** weather station.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	3.91	4.22	4.09	4.80	5.21	5.50
Minimum	0.41	0.27	0.30	0.62	0.29	0.27
Mean	2.67	1.84	2.23	2.92	2.57	2.70
Standard Deviation	1.09	1.27	1.37	1.40	1.70	1.72

Table 4.5 Statistical differences for three TDO3 parameters (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively) between the **future CGCM 3.1 climate scenario and past climate conditions (1962 to 2008)** at the **Duluth** weather station.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	4.81	5.34	5.18	4.80	5.58	5.42
Minimum	0.78	0.55	0.60	0.49	0.13	0.15
Mean	3.45	2.72	3.11	3.11	2.82	2.91
Standard Deviation	1.17	1.49	1.50	1.26	1.63	1.56

Table 4.6 Statistical differences for three TDO3 parameters (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively) between the **future CGCM 3.1 climate scenario and past climate conditions (1962 to 2008)** at the **St. Cloud** weather station.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	5.14	5.13	6.13	5.41	6.51	6.18
Minimum	0.77	0.39	0.44	0.44	0.00	0.01
Mean	3.47	2.79	3.26	3.16	2.75	2.89
Standard Deviation	1.12	1.52	1.74	1.40	1.79	1.74

Table 4.7 Statistical differences for three TDO3 parameters (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively) between the **future MIROC 3.2 climate scenario and past climate conditions (1962 to 2008)** at the **International Falls weather station**.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	4.26	4.19	4.07	4.80	5.21	5.50
Minimum	0.69	0.14	0.17	0.62	0.29	0.27
Mean	2.92	1.84	2.28	2.92	2.57	2.70
Standard Deviation	1.11	1.32	1.47	1.40	1.70	1.72

Table 4.8 Statistical differences for three TDO3 parameters (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively) between the **future MIROC 3.2 climate scenario and past climate conditions (1962 to 2008)** at the **Duluth weather station**.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	4.77	4.77	4.83	4.99	5.53	5.29
Minimum	0.46	0.23	0.26	0.82	0.28	0.32
Mean	3.24	2.24	2.66	3.32	2.83	2.97
Standard Deviation	1.24	1.54	1.57	1.35	1.75	1.71

Table 4.9 Statistical differences for three TDO3 parameters (**AvgTDO3_{AM}**, **AvgATDO3_{FB}** and **AvgMTDO3_{FB}**, Table 3.1, lines 3, 6 and 9, respectively) between the **future MIROC 3.2 climate scenario and past climate conditions (1962 to 2008)** at the **St. Cloud weather station**.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	5.27	5.20	6.11	5.63	6.40	6.04
Minimum	0.81	0.27	0.28	1.02	0.34	0.40
Mean	3.56	2.55	3.10	3.55	2.93	3.12
Standard Deviation	1.13	1.52	1.79	1.37	1.81	1.80

4.4 Contour plots of TDO3 parameters using variable benchmark periods

The benchmark period is the period of greatest oxythermal stress for coldwater fish. It is defined as the 31-day period with the highest value of TDO3 (Jacobson et al. 2010). In addition to using a fixed benchmark period (from DOY 209 to DOY 239) introduced by Jacobson et al. (2010), variable (sliding) benchmark periods were explored to compute TDO3 parameters. The sliding 31-day benchmark period retained in this study must contain the day when the annual maximum daily TDO3 ($TDO3_{AM}$ in Table 3.1) occurs in that year. Over each sliding benchmark period the mean daily TDO3 was calculated, and only the highest mean value in any of the sliding benchmark periods of a year ($ATDO3_{VB}$ in Table 3.1) was retained. Averages of the beginning dates of sliding benchmark periods for $ATDO3_{VB}$ ranged from DOY 210 (July 29) to DOY 280 (October 7) for 30 virtual lakes and past climate conditions (1962 to 2008) (Figs 3.9 to 3.11). Because of this wide variation of beginning dates, it is necessary and recommended to calculate mean daily TDO3 values using variable (sliding) benchmark periods for each lake in order to identify the greatest oxythermal stress for coldwater fish.

Figure 4.8 shows contour plots of averages of highest mean daily TDO3 over variable benchmark periods ($AvgATDO3_{VB}$ in Table 3.1) under past climate conditions (1962 to 2008), and the CGCM 3.1 and MIROC 3.2 future climate scenarios. Contours were derived by interpolation from simulated data points for the 30 virtual cisco lakes (dots in top frame of Figure 4.8), and simulated $AvgATDO3_{VB}$ values given in Appendix B (Tables B.1 to B.3). Duluth weather data was used for the model simulations in Fig. 4.8, and similar contour plots derived from model simulations using International Falls and St. Cloud weather data are given in Figure 4.9 and 4.10, respectively. Statistics for $AvgATDO3_{VB}$ values under past climate and future scenarios at all three weather stations (International Falls, Duluth, and St. Cloud) are given in Table 4.10. The $AvgATDO3_{VB}$ values ranged from 7.28 to 19.91°C under past climate conditions and from 8.02 to 23.28°C under two future climate scenarios at three weather stations for 30 virtual cisco lakes (Table 4.10). Statistical differences of $AvgATDO3_{VB}$ values between future climate scenarios and past climate (1962-2008) are given in Table 4.11 for the three principal weather stations. The projected increases of $AvgATDO3_{VB}$ values from past climate to future scenarios ranged from 0.30 to 5.11°C (Table 4.11), and average increases were projected to be from 2.79 to 3.40°C. Because of these increases, it is important to use TDO3 parameter values projected for future climate scenarios to select cisco refuge lakes in Minnesota.

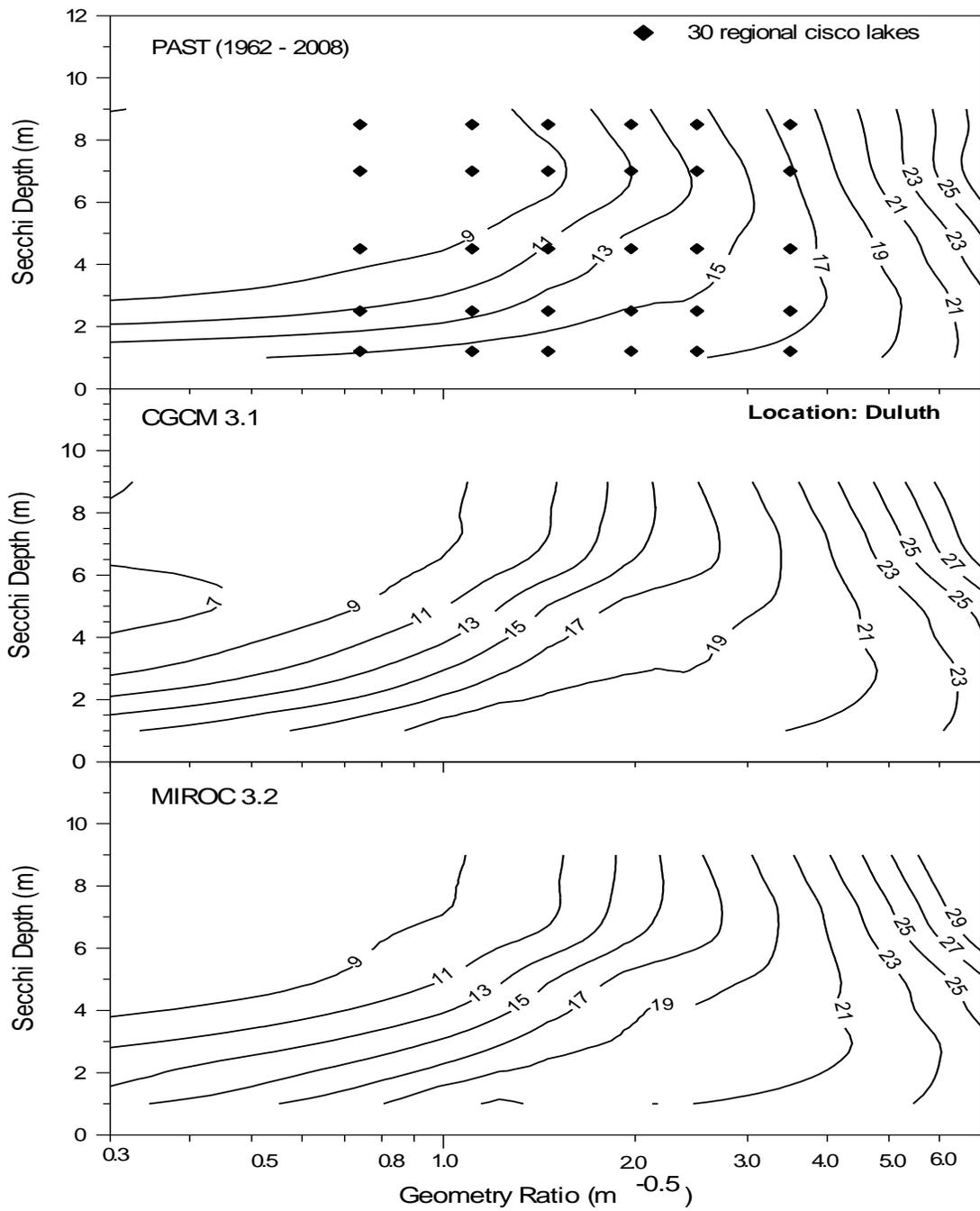


Figure 4.8 Contour plots of averages of highest mean daily TDO3 over variable benchmark periods ($ATDO3_{VB}$, Table 3.1, line 10) under **past climate (1962-2008)**, and **CGCM 3.1 and MIROC 3.2 future climate scenarios**. **Duluth weather** data were used for the model simulations. Contours were derived by interpolation from simulated points for **30 virtual lakes**.

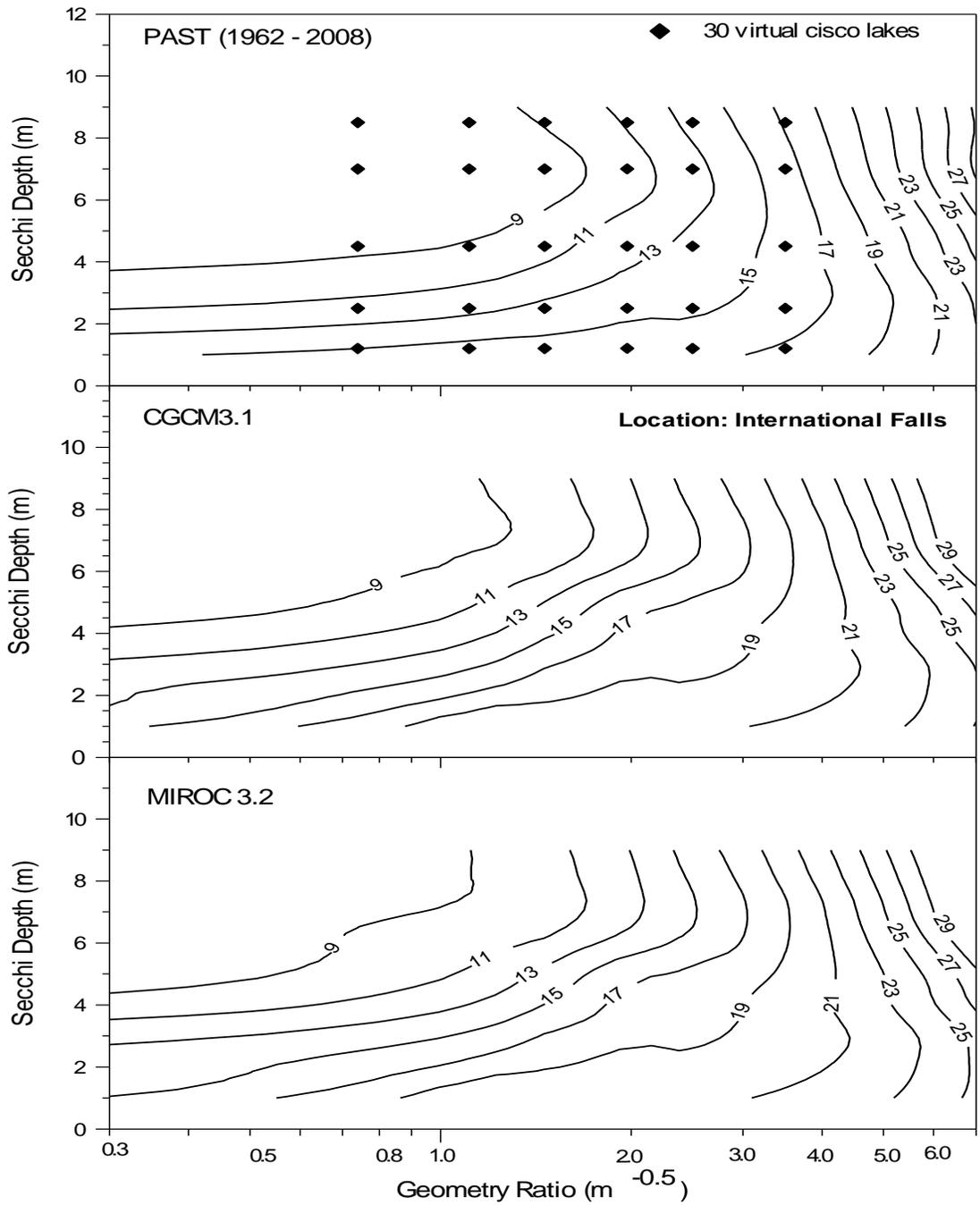


Figure 4.9 Contour plots of averages of highest mean daily TDO3 over variable benchmark periods ($ATDO3_{VB}$, Table 3.1, line 10) under **past climate (1962-2008)**, and **CGCM 3.1 and MIROC 3.2 future climate scenarios**. **International Falls** weather data were used for the model simulations. Contours were derived by interpolation from simulated points for **30 virtual lakes**.

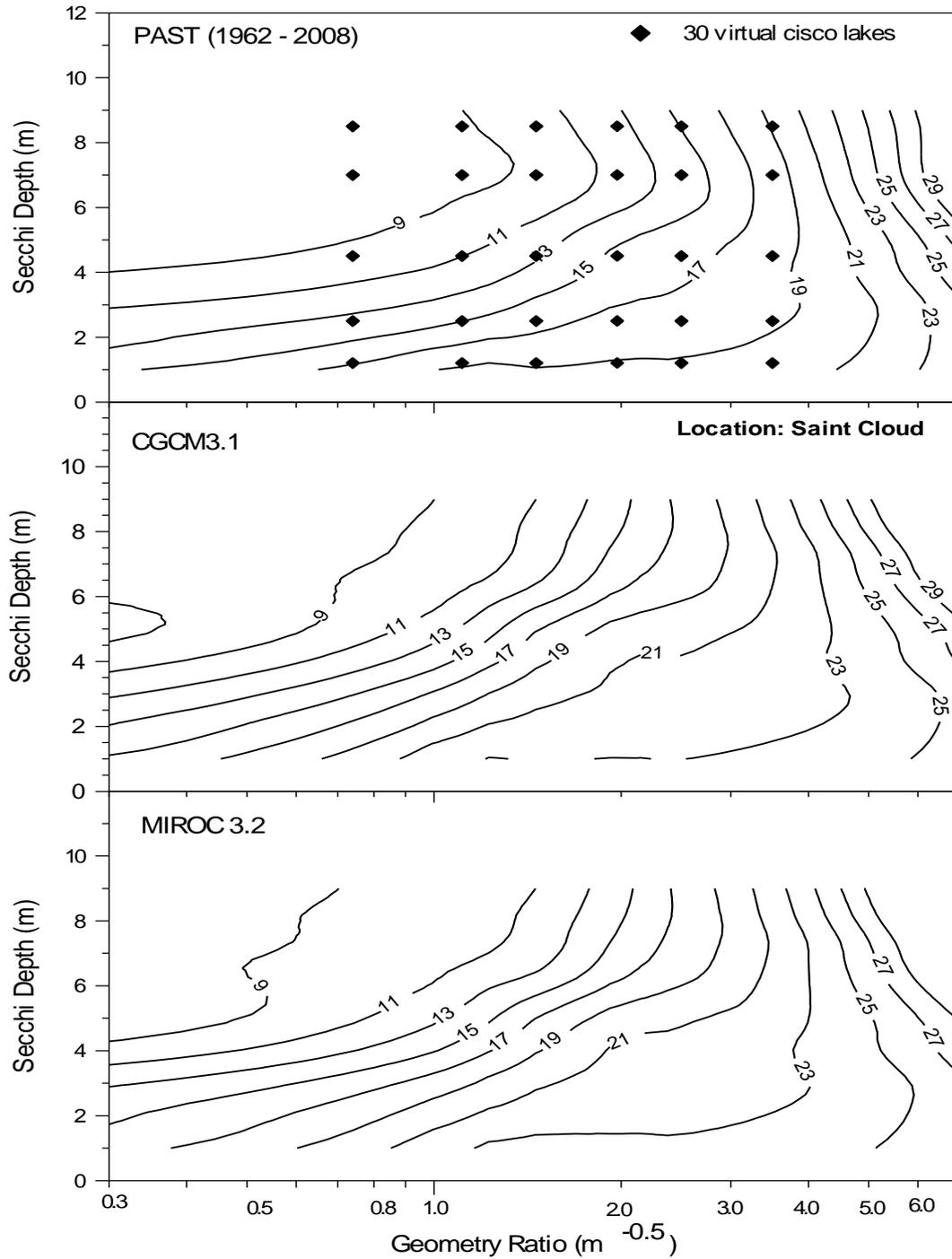


Figure 4.10 Contour plots of averages of highest mean daily TDO3 over variable benchmark periods ($ATDO3_{VB}$, Table 3.1, line 10) under **past climate (1962-2008)**, and **CGCM 3.1 and MIROC 3.2 future climate scenarios**. **St. Cloud weather** data were used for the model simulations. Contours were derived by interpolation from simulated points for **30 virtual lakes**.

Table 4.10 Statistics of AvgATDO3_{VB} (Table 3.1, line 12) under **past climate conditions (1962-2008) and future climate scenarios** at three weather stations.

Statistical parameter	International Falls			Duluth			St. Cloud		
	Past	CGCM	MIROC	Past	CGCM	MIROC	Past	CGCM	MIROC
Maximum	17.23	21.06	21.12	17.66	20.86	21.34	19.91	23.28	23.70
Minimum	7.64	8.33	8.46	7.48	8.02	8.35	8.24	8.54	9.14
Mean	12.59	15.38	15.62	12.96	15.98	16.18	14.63	17.66	18.03
Standard Deviation	3.25	4.34	4.26	3.39	4.25	4.38	3.96	4.90	4.89

Table 4.11 Statistical differences of AvgATDO3_{VB} (Table 3.1, line 12) **between future climate scenarios and past climate conditions (1962-2008)** at three weather stations.

Statistical parameter	CGCM 3.1 minus past			MIROC 3.2 minus past		
	International Falls	Duluth	St. Cloud	International Falls	Duluth	St. Cloud
Maximum	4.54	5.11	5.01	4.79	5.11	5.27
Minimum	0.61	0.42	0.30	0.78	0.75	0.90
Mean	2.79	3.02	3.02	3.03	3.22	3.40
Standard Deviation	1.33	1.22	1.33	1.30	1.32	1.31

Chapter 5 Selection of Cisco Refuge Lakes

This is the final chapter of the project report. It is about the identification, selection and ranking of cisco habitat in potential refuge lakes under future (warmer) climate scenarios in Minnesota. The selection was based on the oxythermal parameter TDO3, which is a temperature that measures survival stress on adult cisco: the lower the TDO3, the lower the stress.

Time series of daily TDO3 values had to be calculated from simulated daily profiles of water temperature and DO in each lake. The simulations were made for two future climate scenarios, CGCM 3.1 and MIROC 3.2. From these time series one or several TDO3 characteristic parameters had to be obtained and used to identify and select refuge lakes from approximately 620 cisco lakes (Table D.1) in Minnesota. Table 3.1 identifies twelve different options for the calculation of TDO3 characteristic parameters, ranging from a single annual daily maximum value to an average over a fixed or variable benchmark period of 31 days length. An acceptable frequency of occurrence of a critical TDO3 value had to be selected.

The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to 2008 were used. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes in Minnesota.

One associated weather station had to be selected for the simulation of each lake, but data from only three Class I NWS weather stations were useful and available. Three options (methods) were used to associate each lake with one of the three weather stations: (1) association by shortest distance, (2) association by latitude, (3) association of one single weather station with all lakes simulated. Refuge lakes were determined using each of the three options.

Two upper TDO3 boundaries for cisco refuge lakes were selected, and the pool of 620 Minnesota cisco lakes was divided into three tiers accordingly: Lakes in Tier 1 have the most suitable cisco habitat, those in Tier 2 have suitable habitat, and those in Tier 3 are marginal or non-cisco lakes. This decision was based on Jacobson et al. (2010).

5.1 Criteria for refuge lake selection

5.1.1 Choice of TDO3 parameter

In Table 3.1 twelve TDO3 characteristic parameters were defined. Each can be calculated from simulated daily water temperature and DO profiles over the multi-year simulation period. Although simulations are continuous, and give daily profiles of water temperature and DO in a lake year-round, only the summer results (May 1 to October 31) were used to determine TDO3

values. Simulations could be made for the 21 actual cisco study lakes for which the MINLAKE2010 model had been calibrated, or for the 30 virtual cisco lakes modeled with generalized calibration parameters as described in Project Report 2 (Fang et al. 2010). As an example, Table 5.1 gives values and ranges of the twelve TDO3 characteristic parameters defined in Table 3.1 calculated for two virtual cisco lakes (LakeC06 and LakeC08) using Duluth weather data under past climate conditions (1992 to 2008) and under the CGCM 3.1 climate scenario.

Table 5.1 Values and ranges (in °C) of twelve TDO3 parameters (defined in Table 3.1) extracted from simulated daily temperature and DO profiles in two virtual cisco lakes (LakeC06 and LakeC08) using **Duluth weather** data under **past climate conditions (1992-2008)** and the **CGCM 3.1 climate scenario**.

TDO3 Parameter		LakeC06 (Past)	LakeC06 (CGCM 3.1)	LakeC08 (Past)	LakeC08 (CGCM 3.1)
TDO3_{AM}	TDO3 _A	12.71–20.43	18.26–23.70	7.75–12.98	10.23–17.94
MaxTDO3_{AM}	TDO3 _B	20.43	23.70	12.98	17.94
AvgTDO3_{AM}	TDO3 _C	17.16	21.58	9.93	13.52
ATDO3_{FB}	TDO3 _D	11.71–19.21	16.97–22.98	5.09–8.68	6.34–12.02
MaxATDO3_{FB}	TDO3 _E	19.21	22.98	8.68	12.02
AvgATDO3_{FB}	TDO3 _F	15.26	19.42	6.54	8.46
MTDO3_{FB}	TDO3 _G	12.38–20.01	18.26–23.70	5.48–10.03	7.40–14.36
MaxMTDO3_{FB}	TDO3 _H	20.01	23.7	10.03	14.36
AvgMTDO3_{FB}	TDO3 _I	17.03	21.49	7.40	9.95
ATDO3_{VB}	TDO3 _J	11.80–19.86	17.08–23.16	7.28–12.10	9.62–16.47
MaxATDO3_{VB}	TDO3 _K	19.86	23.16	12.10	16.47
AvgMTDO3_{VB}	TDO3 _L	15.59	20.00	9.32	12.65

Which TDO3 characteristic parameter(s) should be used to identify and select refuge lakes from the 620 cisco lakes in Minnesota?

Calculation of the four TDO3 parameters TDO3_{AM}, ATDO3_{FB}, MTDO3_{FB}, and ATDO3_{VB}, for each simulated year in the 47-year simulation period, is not a good option because there would be four times 47 values in the simulation period for each lake. The values of these TDO3 parameters would vary due to weather variations in the 47-year simulation period. Annual maximum daily TDO3 values (TDO3_{AM}) and maximum daily TDO3 values (MTDO3_{FB}) over the fixed benchmark period (DOY 209 to DOY 239) are the highest TDO3 values that occur on a particular day or in the fixed benchmark period of a particular simulated year.

Another four maximum TDO3 parameter values calculated over the 47-year simulation period, i.e., MaxTDO3_{AM}, MaxATDO3_{FB}, MaxMTDO3_{FB}, MaxATDO3_{VB}, are not good options either, because they are the highest values that occur in a particularly warm years for each lake.

For example, in LakeC06 (Table 5.1) and under past climate conditions $\text{MaxTDO3}_{\text{AM}}$ was 20.43°C and occurred on August 7, 1983; the range of TDO3_{AM} values in the 47-year simulation period was from 12.71 to 20.43°C .

Average TDO3 parameter values in the 47-year simulation period, i.e., $\text{AvgTDO3}_{\text{AM}}$, $\text{AvgATDO3}_{\text{FB}}$, $\text{AvgMTDO3}_{\text{FB}}$, $\text{AvgATDO3}_{\text{VB}}$, are better choices than maximum TDO3 parameter values, and good candidates of TDO3 characteristic parameters to be used to identify and select cisco refuge lakes. Contour plots of four average TDO3 parameters ($\text{AvgTDO3}_{\text{AM}}$, $\text{AvgATDO3}_{\text{FB}}$, $\text{AvgMTDO3}_{\text{FB}}$, and $\text{AvgMTDO3}_{\text{VB}}$) using lake geometry ratio and Secchi depth as independent variables were presented and discussed in Chapter 4.

Jacobson et al. (2010) studied coldwater fish oxythermal habitat in Minnesota lakes, and introduced and calculated TDO3, temperature at 3 mg/L of dissolved oxygen, from measured temperature and DO profiles. The oxythermal habitat variable was calculated by Jacobson et al. (2010) as a mean TDO3 value (not a daily maximum) over the greatest oxythermal stress period or benchmark period. Using the findings of the study by Jacobson et al. (2010), $\text{AvgATDO3}_{\text{FB}}$ and $\text{AvgATDO3}_{\text{VB}}$ were chosen as TDO3 parameters for the selection of cisco refuge lakes.

As discussed in Chapter 3 summer benchmark periods with the greatest oxythermal stress shift greatly from one lake type to another, and also with climate warming. Therefore, the first choice for the TDO3 parameter to be used to identify and select cisco refuge lakes was $\text{AvgATDO3}_{\text{VB}}$ (or TDO3_{L} , Table 3.1, line 12). The research team members decided that the second choice was $\text{AvgATDO3}_{\text{FB}}$ (or TDO3_{F} , Table 3.1, line 6)). $\text{AvgATDO3}_{\text{VB}}$ is the average of the highest mean daily TDO3 values over a variable (sliding) 31-day benchmark period in each simulated year over the 47-year simulation period. There is one $\text{AvgATDO3}_{\text{VB}}$ value for each lake in the 1962-2008 simulation period. Similarly there is only one $\text{AvgATDO3}_{\text{FB}}$ value, and it is the average of the mean daily TDO3 values over the fixed 31-day benchmark period (DOY 209 to DOY 239) in each simulated year over the 47-year simulation period. So the only difference between $\text{AvgTDO3}_{\text{FB}}$ and $\text{AvgTDO3}_{\text{VB}}$ is that one is from values in the same fixed benchmarked period of every year, whereas the other is from values in a benchmark period that shifts from year to year.

The multi-year average values, $\text{AvgATDO3}_{\text{FB}}$ and $\text{AvgATDO3}_{\text{VB}}$ calculated over 47-year periods, were the final choices. They are defined in Table 3.1, lines 6 and 12. Each of these two TDO3 parameters is calculated over the length of a 31-day benchmark period; one uses a fixed benchmark period from DOY 209 to DOY 239 (July 28 to August 27); the other uses a variable (sliding) benchmark period.

5.1.2 Choice of limiting TDO3 values: Sub-division of 620 cisco lakes into Tiers

The oxythermal parameter TDO3 measures environmental conditions and stress in a lake. To determine which lake is an acceptable refuge lake for cisco, especially under future climate scenarios, an upper limit for TDO3 had to be specified. Jacobson et al. (2010) used species response curves, developed from values of TDO3 measured in the period of greatest oxythermal stress in late summer (maxT_{DO3}), to illustrate oxythermal habitat differences in four coldwater taxa common in Minnesota. Lake Trout were present in lakes with the lowest values of maxT_{DO3} and were represented by central species response borders of maxT_{DO3} from 4.0 to 5.1°C

(Jacobson et al. 2010). Cisco were present in lakes with a broad range of $\max T_{\text{DO}_3}$, with central species response borders of $\max T_{\text{DO}_3}$ from 4.0 to 16.9°C (Jacobson et al. 2010). Species response curves of lake whitefish and burbot were between lake trout and cisco, with central borders of 4.0 to 11.1°C for lake whitefish and 4.0 to 8.8°C for burbot (Jacobson et al. 2010). Through discussion among the researcher team members, it was decided that cisco refuge lakes should be selected and identified in two categories (Table 5.2): Tier 1 refuge lakes and Tier 2 refuge lakes. Tier 1 refuge lakes have TDO3 less than or equal to 11°C, and Tier 2 refuge lakes have TDO3 less than or equal to 17°C but greater than 11°C. Lakes having TDO3 greater than 17°C are classified as non-refuge lakes. The limit of 17°C corresponds to the upper cisco central response border of TDO3, and the limit of 11°C closely corresponds to the upper of the lake whitefish central response borders of TDO3. Therefore, Tier 1 refuge lakes identified for cisco in this study are also useful to the management of lake whitefish in Minnesota. Tier 1 cisco refuge lakes allow for a wider margin of error and are therefore a safer choice than Tier 2 cisco refuge lakes.

The TDO3 parameters and their values used to identify and classify Minnesota’s cisco lakes into three tiers are summarized in Table 5.2.

Table 5.2 Categories of refuge lakes and criteria for classification.

Lake Classes	Criteria
Tier 1 refuge lakes	$\text{AvgATDO3}_{\text{FB}}$ or $\text{AvgATDO3}_{\text{VB}} \leq 11.0^\circ\text{C}$
Tier 2 refuge lakes	$11.0^\circ\text{C} < \text{AvgATDO3}_{\text{FB}}$ or $\text{AvgATDO3}_{\text{VB}} \leq 17.0^\circ\text{C}$
Non-refuge lakes	$\text{AvgATDO3}_{\text{FB}}$ or $\text{AvgATDO3}_{\text{VB}} > 17.0^\circ\text{C}$

5.1.3 Choice of weather stations

It is noteworthy that cisco lakes in Minnesota are primarily found in two ecoregions: North Central Hardwood Forests and Northern Lakes and Forests (Fig. 5.1). In this study, effects of climate on cisco were considered in model simulations using daily weather data at eight weather stations (Table 2.3). Weather stations at International Falls, Duluth, St. Cloud, and Minneapolis in Minnesota and Fargo in North Dakota are the Class I NWS stations. We were able to retrieve daily data from 1961 to 2008 from the Class I stations. Weather stations at Bemidji, Brainerd, and Grand Rapids in Minnesota are Class II NWS stations. They have daily data available for the period from 1991 to 2008.

Weather data from Minneapolis were used only to calibrate the MINLAKE2010 model for two non-cisco lakes in southern Minnesota. Similarly, Class II weather stations were used only to calibrate the MINLAKE2010 model for cisco and non-cisco lakes in central and north central Minnesota.

For identifying cisco refuge lakes in Minnesota, the three (principal) Class I weather stations located at International Falls, Duluth, and St. Cloud (Fig. 5.1) were used to cover all

cisco lakes. These three Class I NWS station had long-term (48 years) high quality weather data for the model simulations of daily temperature and DO profiles in cisco lakes.

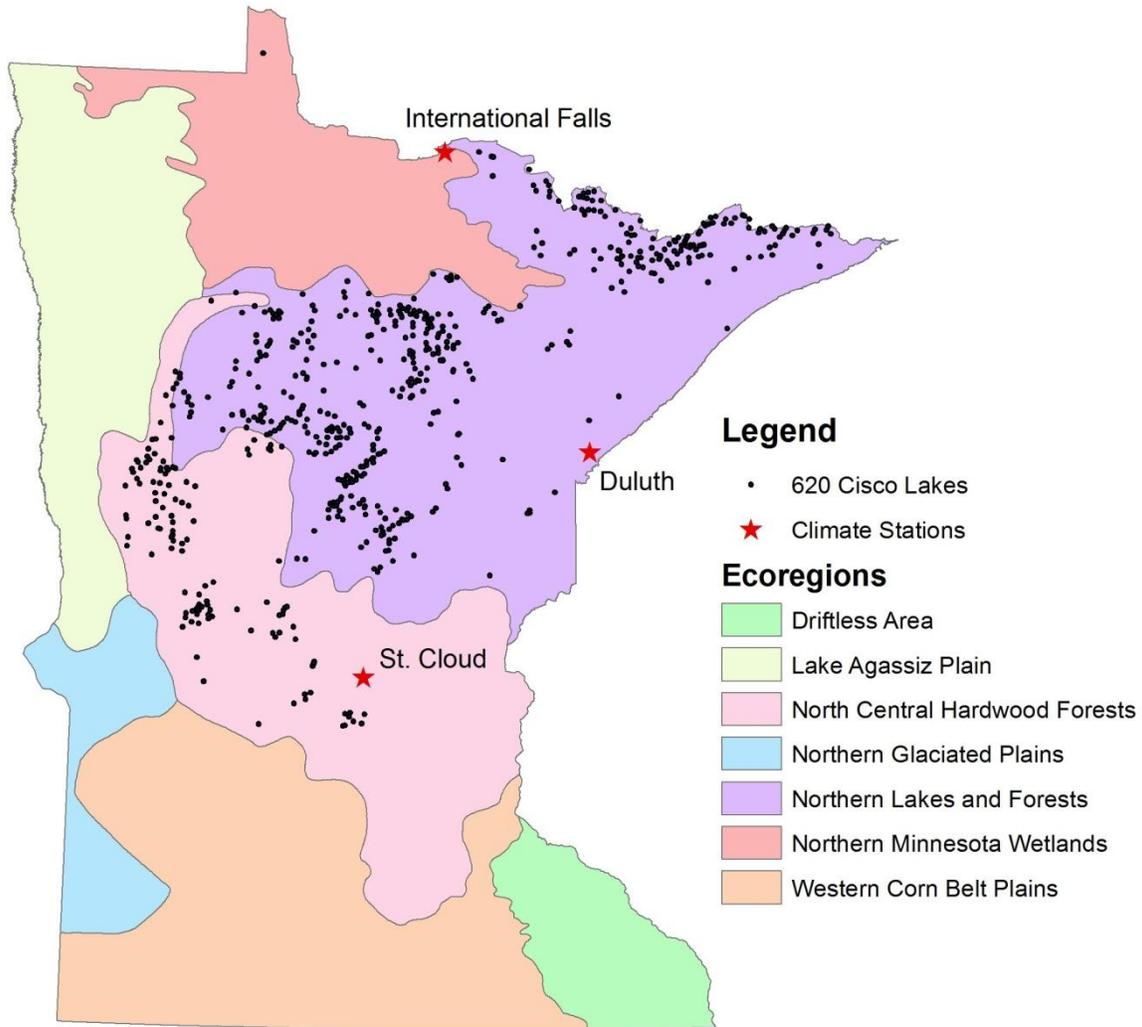


Figure 5.1 Distributions of 620 cisco lakes in the ecoregions of Minnesota. Three Class I weather stations used to identify cisco refuge lakes are also shown.

5.1.4 Choice of simulation period

The length of the multi-year simulation period depended on the availability of weather data as MINLAKE2010 model input. The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to

2008 were used. The three principal weather stations used were in International Falls, Duluth and St. Cloud, Minnesota. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles and associated AvgATDO3_{FB} and AvgATDO3_{VB} for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes.

5.1.5 Choice of weather station pairing with lakes

Each lake had to be simulated with daily weather data as model input. Three Class I weather stations (International Falls, Duluth, and St. Cloud) had been selected, but which station to use for each lake was unclear. Three options were explored for the pairing of lakes and principal weather stations, and simulation results were obtained for each option. The options are: (1) association by shortest distance, (2) association by latitude, (3) association of one single weather station with all lakes simulated. Refuge lakes were determined using each of the three options. Actually, the option (3) contains three options: associating all lakes with one of the three principal weather stations, International Falls, Duluth, and St. Cloud, respectively. Therefore, five options to associate each cisco lake to a weather station were used and explored in the cisco habitat simulations.

5.2 Selection of refuge lakes paired with a single principal weather station - for past climate and two future climate scenarios

Contour lines of 11°C and 17°C in the contour plots of AvgATDO3_{FB} and AvgTDO3_{VB} were used to identify cisco refuge lakes in the database of 620 Minnesota cisco lakes (Table D.1 in Appendix D). These contour lines were derived by interpolation from simulated points for the 30 virtual lakes. The final selection of cisco refuge lakes was based on TDO3 parameters projected under the two future climate scenarios. Selections of cisco refuge lakes were also performed for past climate conditions (1962 - 2008) because the results are useful to understand the impact of climate warming on cisco refuge lakes in Minnesota.

Figure 5.2 shows the distribution of the 620 cisco lakes on a plot of Secchi depth versus lake geometry ratio. Based on Figure 5.2 there are 94 Tier 1 refuge lakes (green circles with cross), 429 Tier 2 refuge lakes (blue rhombuses with cross), and 97 non-refuge lakes (filled black rhombuses) out of 620 cisco lakes in Minnesota. Contour lines based on the parameter AvgATDO3_{VB} (or TDO3_L defined in Table 3.1, line 12), were used to identify refuge lakes, and AvgATDO3_{VB} values for constructing contour lines (green and blue dashed lines) were simulated under past climate conditions (1962 – 2008) using Duluth weather data. The two contour lines are from Fig. 4.8 (top).

Figure 5.3 shows the distribution of selected refuge lakes and non-refuge cisco lakes based on contour lines of the other selected parameter AvgATDO3_{FB} (TDO3_F, defined in Table

3.1, line 6). Values of $AvgATDO3_{FB}$ for constructing contour lines in Fig. 5.3 were simulated under the CGCM 3.1 future climate scenario using Duluth weather data. The two contour lines are from Fig. C.4 (Appendix C). Based on Figure 5.3 it is projected that there are 79 Tier 1 refuge lakes, 134 Tier 2 refuge lakes, and 407 non-refuge lakes out of 620 cisco lakes in Minnesota.

The difference in the number of Tier 1 plus Tier 2 cisco refuge lakes between Figs. 5.2 and 5.3 is substantial, 523 versus 213. The dramatic drop reflects the simulated or projected effect of climate change, because the data in both figures were obtained by identical simulations, except that the weather data used for Fig. 5.2 were historical data from 1962 to 2008, and those used for Fig 3.2 were historical data incremented by the predictions of the CGCM 3.1 future climate scenario model.

Figure 5.4 shows distribution of refuge and non-refuge cisco lakes using contour lines of $AvgATDO3_{VB}$ for variable (sliding) benchmark periods instead of a fixed benchmark period as shown in Fig. 5.3. The simulations were again made for the CGCM 3.1 future climate scenario using Duluth weather data. Using the contour lines of $AvgATDO3_{VB}$, it is projected from Fig. 5.4 to have 25 Tier 1 refuge lakes, 54 less than identified using contour lines of $AvgATDO3_{FB}$ from Fig. 5.3 for the fixed benchmark period under the same climate scenario (CGCM 3.1). Because $AvgATDO3_{VB}$ (over the sliding benchmark periods) is always greater than $AvgATDO3_{FB}$ (over the fixed benchmark period), the variable benchmark method always projects a smaller number of refuge lakes. For example, in Table 5.1, $AvgATDO3_{VB} = 12.65^{\circ}C$ and $AvgATDO3_{FB} = 8.46^{\circ}C$ for LakeC08.

Figure 5.5 shows the distribution of refuge and non-refuge cisco lakes identified by using again contour lines of $AvgATDO3_{VB}$ ($TDO3_L$) = $11^{\circ}C$ and $17^{\circ}C$ (for Tier 1 and Tier 2, respectively), however, the MIROC 3.2 future climate scenario and Duluth weather data were used in the simulations. The number of Tier 1 plus Tier 2 refuge lakes identified under the MIROC 3.2 and CGCM 3.1 future climate scenarios is almost the same (154 in Fig. 5.4 versus 155 in Fig. 5.5). Table D.1 in Appendix D lists all 620 cisco lakes by MN DNR DOW number and lake name and four lake characteristic parameters (surface area, maximum depth, lake geometry ratio, and Secchi depth). Refuge lake types identified in Fig. 5.5 for each of 620 cisco lakes are listed in the last column of Table D.1. Refugee lakes are identified by 1, 2, and 3 in Table D.1; the numbers stand for Tier 1 refuge lake, Tier 2 refuge lake, and Tier 3 or non-refuge lake. Refuge lakes were selected using contour lines of averages of mean daily TDO3 for **fixed and variable** benchmark periods ($AvgATDO3_{FB}$, $AvgATDO3_{VB}$, Table 3.1, lines 6 and 12) for the MIROC 3.2 future climate scenario using Duluth weather data for all 620 cisco lakes. Lakes in Table D.1 are sorted by refuge lake type selected using fixed benchmark period and then by lake name.

The geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on the results in Figure 5.5 is shown in Figure 5.6 (green circles for Tier 1 refuge lakes, pink pentagons for Tier 2 refuge lakes, and black rhombuses for non-refuge lakes).

Tables 5.3 and 5.4 summarize the numbers of Tier 1 and Tier 2 refuge lakes and non-refuge lakes out of 620 cisco lakes in Minnesota using contour lines of $AvgATDO3_{VB}$ (variable benchmark periods) and $AvgATDO3_{FB}$ (fixed benchmark period) as boundary limits between tiers. Results in Tables 5.3 and 5.4 are for past climate and two future climate scenarios. All 620 cisco lakes were simulated with weather data from three weather stations (International Falls, Duluth and St. Cloud). The numbers of refuge lakes in Tables 5.3 and 5.4, were simulated by applying three different sets of weather data to all 620 cisco lakes, even though some of the cisco lakes are far away from a particular weather station. This is not the final selection of refuge cisco lakes in Minnesota but the results provide insight into the impact of weather station location and climate scenarios. For example, under the MIROC 3.2 future climate scenario, when weather data at International Fall, Duluth, and St. Cloud are used, Minnesota is projected to have 199, 155, and 86 refuge lakes (Tier 1 plus Tier 2), respectively. By comparison there were 534, 523, and 340 refuge lakes, respectively, under past climate conditions (Table 5.3). Climate warming is projected to decrease by 335, 368, and 254 the number of refuge lakes, respectively, when weather data from International Fall, Duluth, and St. Cloud are used to determine the contour lines for $AvgATDO3_{VB}$ for variable benchmark periods.

More refuge lakes (Tier 1 plus Tier 2) were found using $AvgATDO3_{FB}$ (Table 5.4) than using $AvgATDO3_{VB}$ (Table 5.3) under the same climate conditions because $AvgATDO3_{FB}$ can only be equal to or less than $AvgATDO3_{VB}$. Under the MIROC 3.2 future climate scenario, when weather data at International Fall, Duluth, and St. Cloud were used, Minnesota was projected to have 298, 218, and 163 refuge lakes (Tier 1 plus Tier 2) out of 620 cisco lakes, respectively, when contour lines of $AvgATDO3_{FB}$ for the fixed benchmark period (DOY 209 to DOY 239) were used (Table 5.4). The number of refuge lakes increased from 63 to 99 lakes when the fixed benchmark period ($AvgATDO3_{FB}$ or $TDO3_F$ in Table 3.1) was used instead of the variable benchmark period ($AvgATDO3_{VB}$ or $TDO3_L$ in Table 3.1). Table D.1 in Appendix D also shows that 61 lakes were identified as Tier 1 refuge lakes using the fixed benchmark period but were identified as Tier 2 refuge lakes using the variable benchmark periods, and 63 lakes were identified as Tier 2 refuge lakes using the fixed benchmark period but were identified as Tier 3 or non-refuge lakes using the variable benchmark periods.

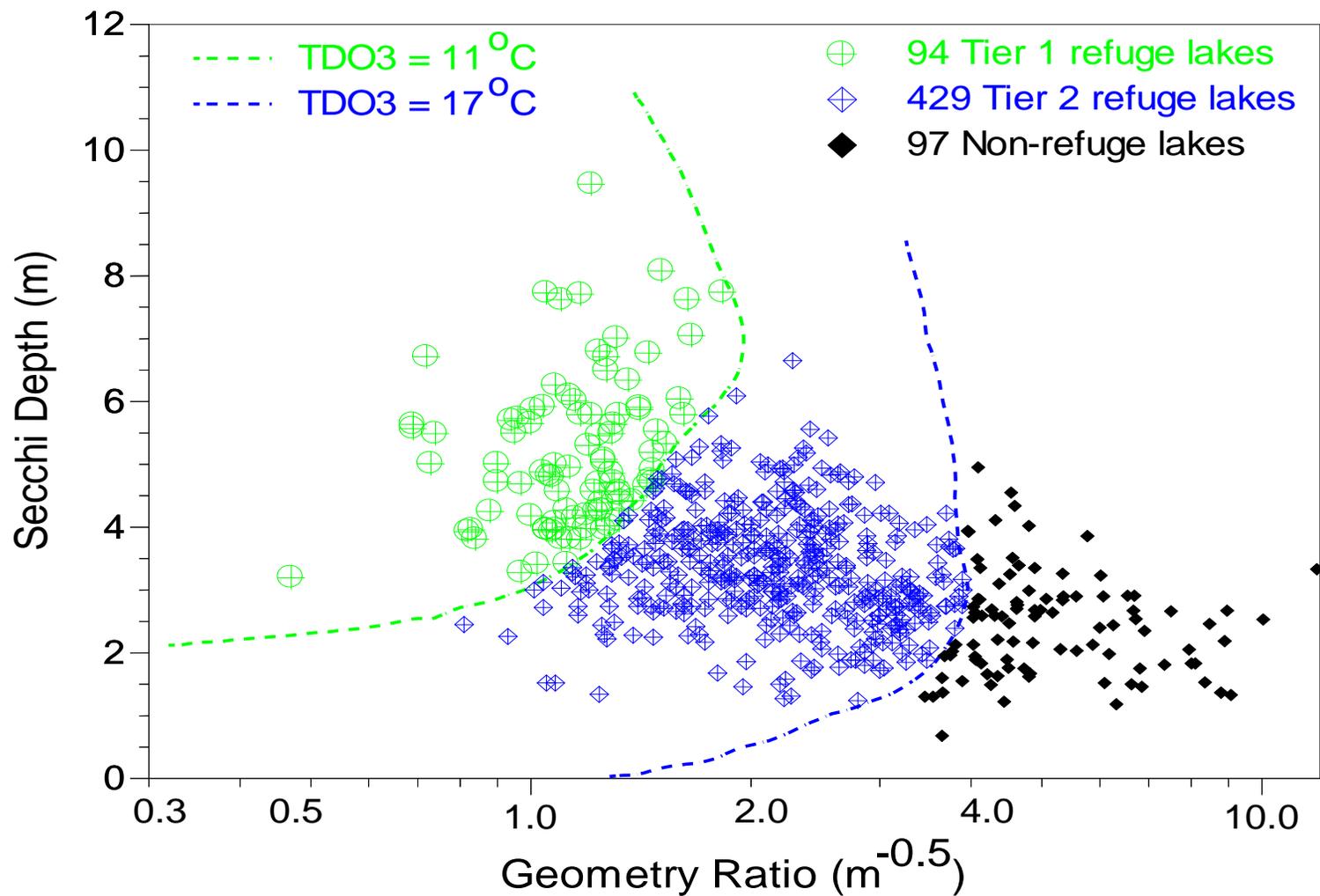


Figure 5.2 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}})$ and were derived for **variable benchmark periods** simulated for **past climate conditions (1962-2008)** using **Duluth weather data**.

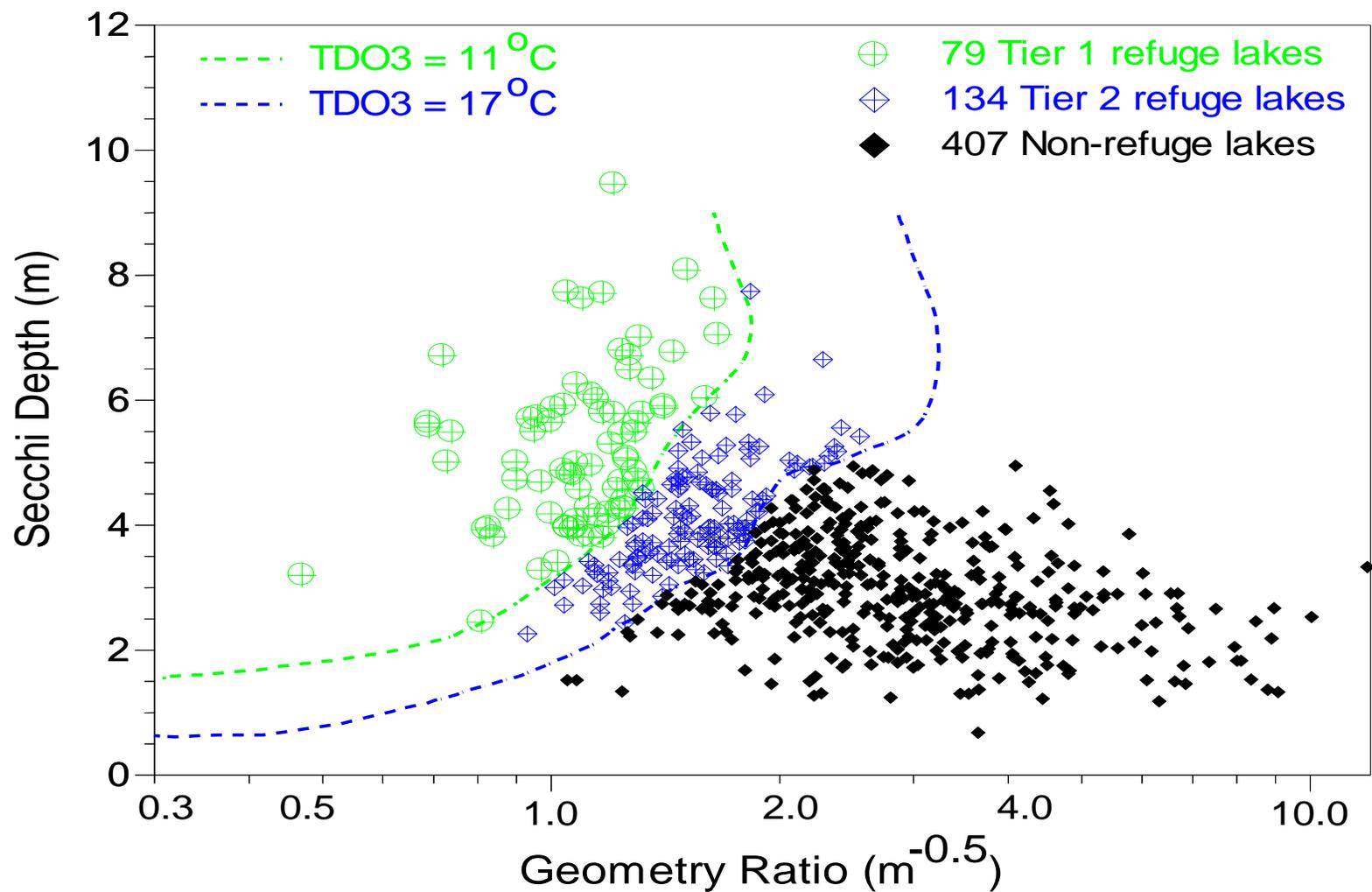


Figure 5.3 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for $\text{AvgATDO3}_{\text{FB}}$ (TDO3_{F}) and were derived for the **fixed benchmark period** (DOY 209 to DOY 239) simulated for the **CGCM 3.1 future climate scenario** using **Duluth weather data**.

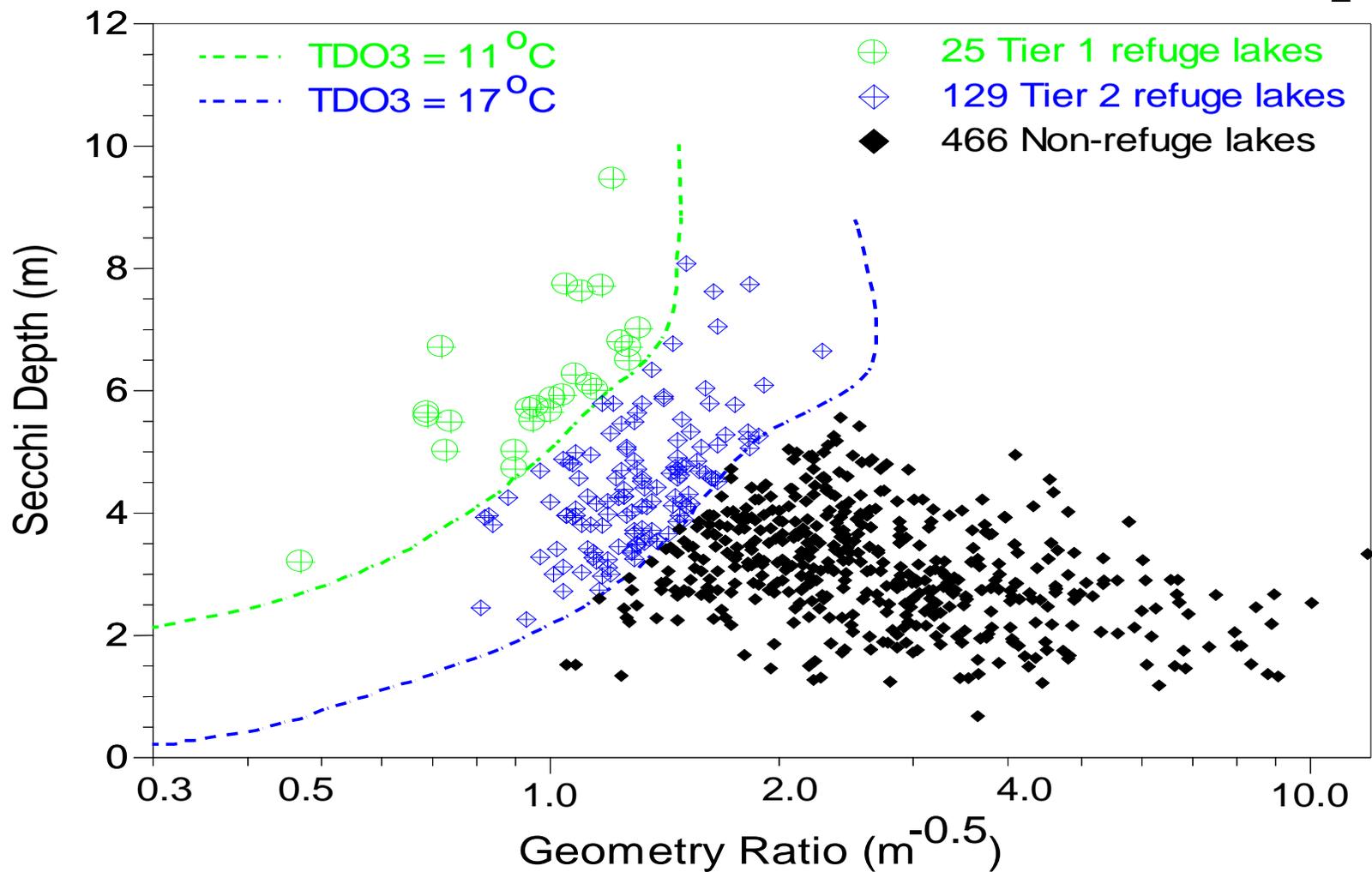


Figure 5.4 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for $\text{AvgATDO3}_{\text{VB}}$ (TDO3_{L}) and were derived for **variable benchmark periods** simulated for the **CGCM 3.1 future climate scenario** using **Duluth weather data**.

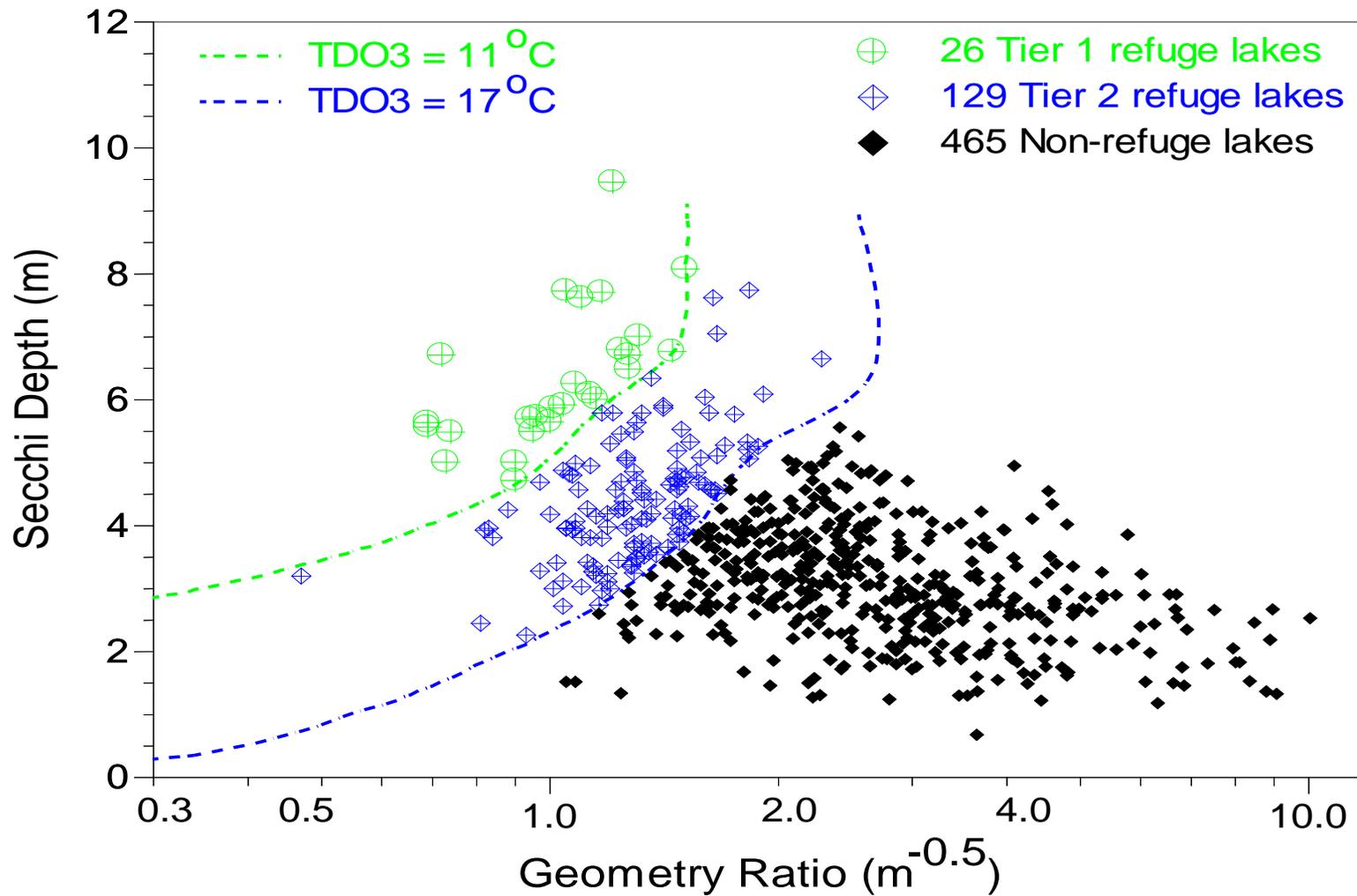


Figure 5.5 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for AvgATDO3_{VB} (TDO3_L) and were derived for variable benchmark periods were simulated for the MIROC 3.2 future climate scenario using Duluth weather data.

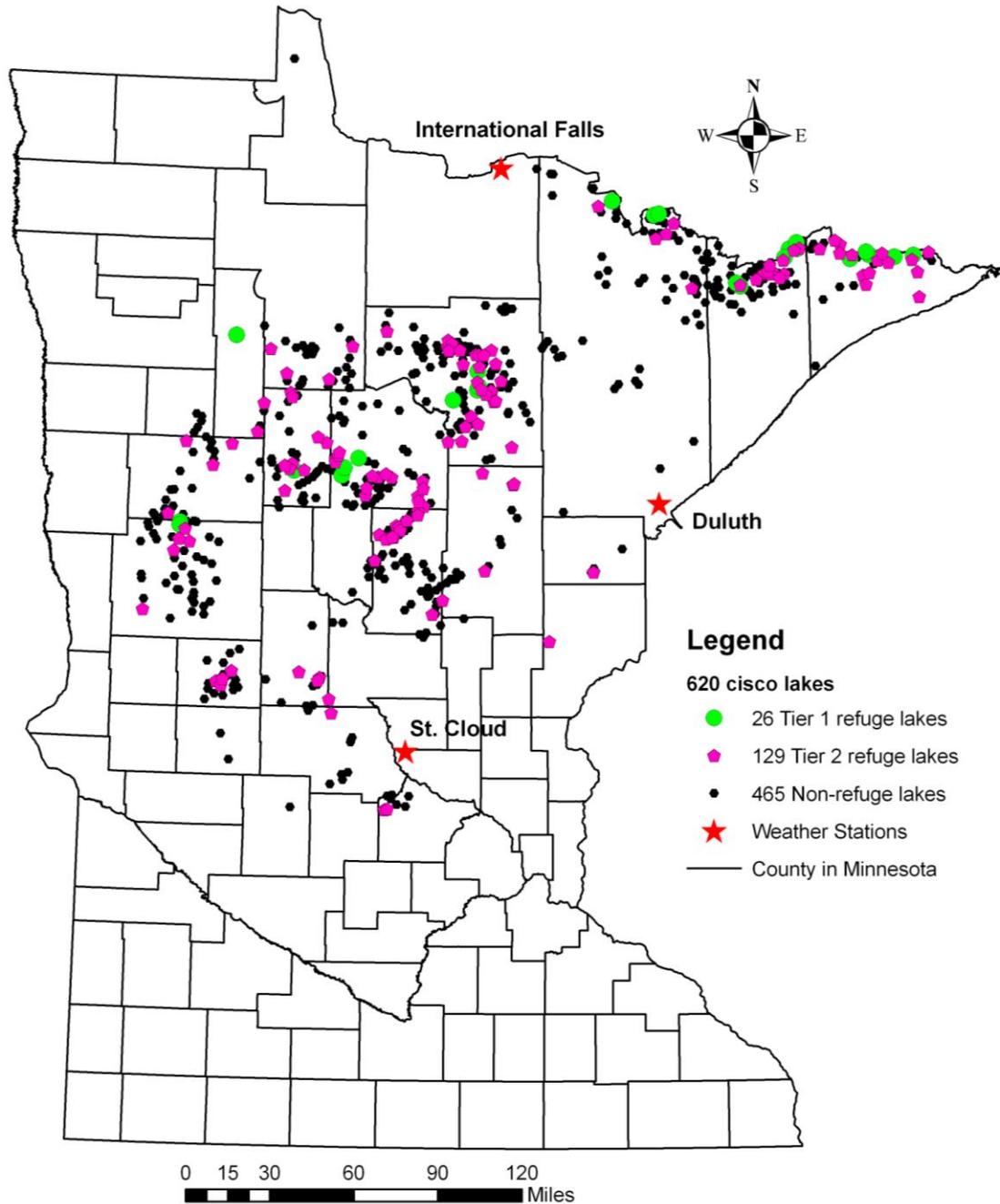


Figure 5.6 Geographic distribution of Tier 1 and Tier 2 refuge lakes and non-refuge cisco lakes simulated with the **MIROC 3.2 future climate scenario**. The boundary limits for selection of refuge lakes were contour lines of $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 17^{\circ}\text{C}$ and 11°C , respectively. Variable benchmark periods and **Duluth weather** data were used in the simulations.

Table 5.3 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from 620 cisco lakes in Minnesota using $\text{AvgATDO3}_{\text{VB}} = 11^{\circ}\text{C}$ and 17°C as boundary limits for Tier 1 and Tier 2, respectively, for variable benchmark periods defined in Table 3.1, line 12). A single weather station was used to simulate all 620 cisco lakes.

One weather station for all 620 lakes	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
International Falls	Past	117	417	534	86	620
	CGCM 3.1	44	174	218	402	620
	MIROC 3.2	31	168	199	421	620
Duluth	Past	94	429	523	97	620
	CGCM 3.1	25	129	154	466	620
	MIROC 3.2	26	129	155	465	620
St. Cloud	Past	50	290	340	280	620
	CGCM 3.1	17	70	87	533	620
	MIROC 3.2	9	77	86	534	620

Table 5.4 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from 620 cisco lakes in Minnesota using $\text{AvgATDO3}_{\text{FB}} = 11^{\circ}\text{C}$ and 17°C as boundary limits for Tier 1 and Tier 2, respectively, for the fixed benchmark period (defined in Table 3.1, line 6). A single weather station was used to simulate all 620 cisco lakes.

One weather station for all 620 lakes	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
International Falls	Past	247	305	552	68	620
	CGCM 3.1	118	181	299	321	620
	MIROC 3.2	117	181	298	322	620
Duluth	Past	182	361	543	77	620
	CGCM 3.1	79	134	213	407	620
	MIROC 3.2	87	131	218	402	620
St. Cloud	Past	144	258	402	218	620
	CGCM 3.1	65	97	162	458	620
	MIROC 3.2	68	95	163	457	620

5.3 Selection of refuge lakes paired with one of three principal weather stations by shortest distance

Each of the 620 cisco lakes in Minnesota shown on Figure 5.1 is closer to one weather station than another. It therefore makes sense to group cisco lakes by distance to the principal weather stations used for the selection of refuge lakes. The simplest method to associate cisco lakes with the principal weather stations is based on distance between weather station and lake. Figure 5.7 shows the distribution of the 620 cisco lakes as well as the three principal weather stations used for the selection of refuge lakes. There are 169, 189, and 262 cisco lakes associated with International Falls, Duluth, and St. Cloud weather station, respectively.

The selection process for refuge lakes used in the previous section was repeated for cisco lakes grouped by weather station. We used again contour lines of $\text{AvgATDO3}_{\text{VB}}$ (TDO3_{L}) for variable benchmark periods and $\text{AvgATDO3}_{\text{FB}}$ (TDO3_{F}) for the fixed benchmark period as boundary limits for Tier 1 and Tier 2, and we simulated past climate condition (1962 to 2008) and two future climate scenarios. The TDO3 contour lines of 11°C and 17°C used to identify refuge lakes were derived by interpolation from simulated points for the 30 virtual lakes. Results are summarized in Table 5.5 (using TDO3_{L}) and 5.6 (using TDO3_{F}). Figures 5.8, 5.9, and 5.10 show distributions of Tier 1 and Tier 2 refuge lakes and non-refuge lakes for cisco lakes near International Falls, Duluth, and St. Cloud, respectively. The selection of refuge lakes on Figs. 5.8, 5.9, and 5.10 was again based on contour lines of $\text{AvgTDO3}_{\text{VB}}$ (TDO3_{L}) for variable benchmark periods simulated under the MIROC 3.2 future climate scenario. Tables 5.5 and 5.6 also include information on the total number of selected refuge lakes associated with each of the three weather stations.

Under the MIROC 3.2 future climate scenario, Minnesota was projected to have 41, 70, and 26 refuge lakes (Tier 1 plus Tier 2) out of 169, 189, and 262 cisco lakes associated with International Fall, Duluth, and St. Cloud weather station, respectively, when contour lines of $\text{AvgATDO3}_{\text{VB}}$ are used for the selection. Minnesota was projected to have 137 and 207 refuge lakes (Tier 1 plus Tier 2) out of 620 cisco lakes under the MIROC 3.2 future climate scenario when contour lines of $\text{AvgATDO3}_{\text{VB}}$ (Table 5.3) and $\text{AvgATDO3}_{\text{FB}}$ (Table 5.6) were used, respectively. Climate warming under the MIROC 3.2 future climate scenario is projected to decrease by 312 the number of refuge lakes from past climate conditions when contour lines of $\text{AvgATDO3}_{\text{VB}}$ are used (Table 5.5).

The geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on results in Figures 5.8, 5.9 and 5.10 is shown in Figure 5.11. Minnesota is projected to have 22 Tier 1 refuge lakes, 115 Tier 2 refuge lakes, and 483 non-refuge lakes out of the 620 cisco lakes in Minnesota under the MIROC 3.2 future climate scenario when contour lines of $\text{AvgATDO3}_{\text{VB}}$ are used (Fig. 5.11) and refuge lakes are associated by weather stations. These results are not much different from results presented in Fig. 5.6 when the selection of refuge lakes was performed using Duluth weather data for all lakes.

Figure 5.12 shows the geographic distribution and number of Tier 1 and Tier 2 refuge lakes and non-refuge cisco lakes associated with each of the three weather stations for the MIROC 3.2 future climate scenario.

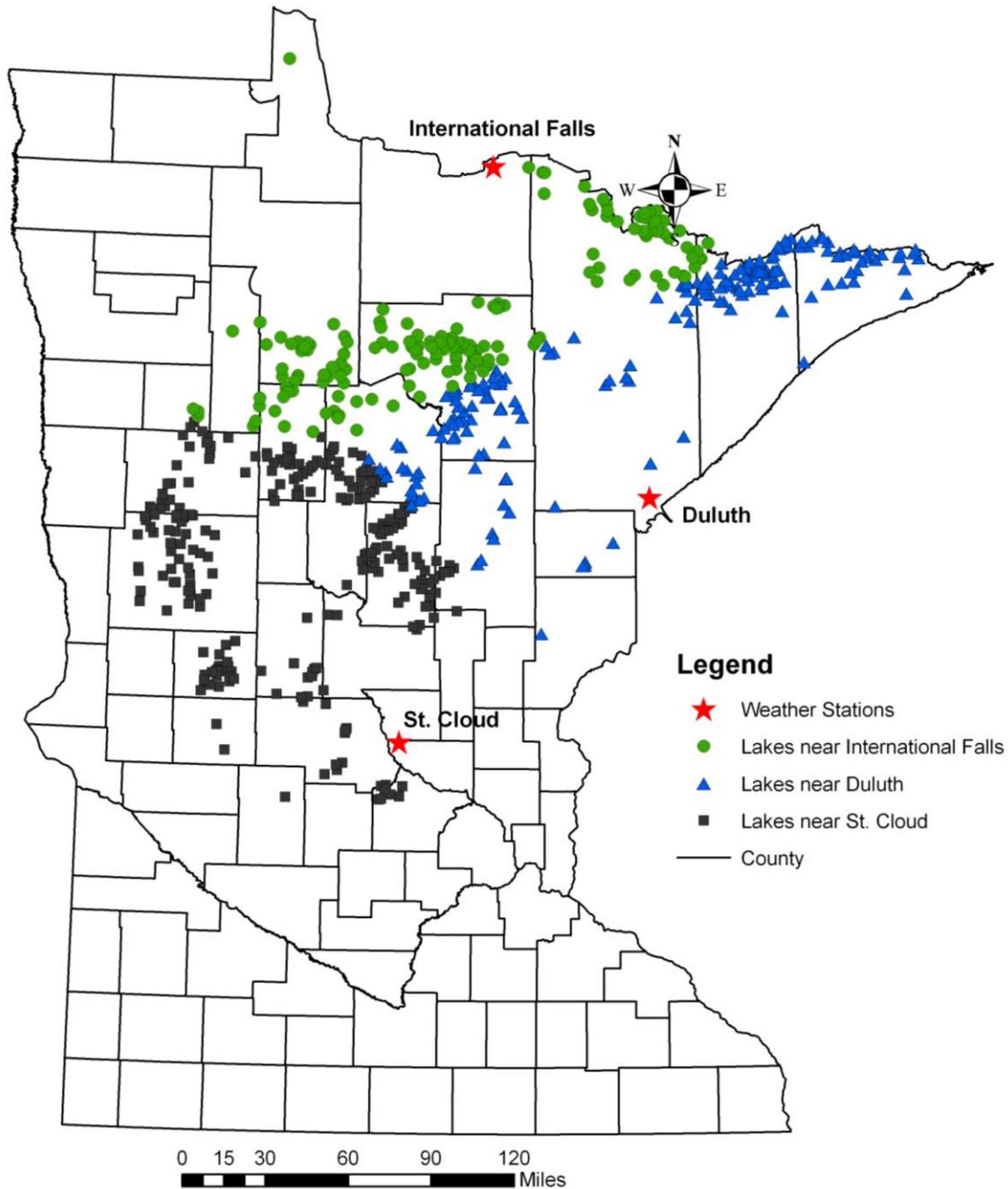


Figure 5.7 Geographic distribution of 620 cisco lakes paired with weather stations based on the shortest distance between weather station and lake location.

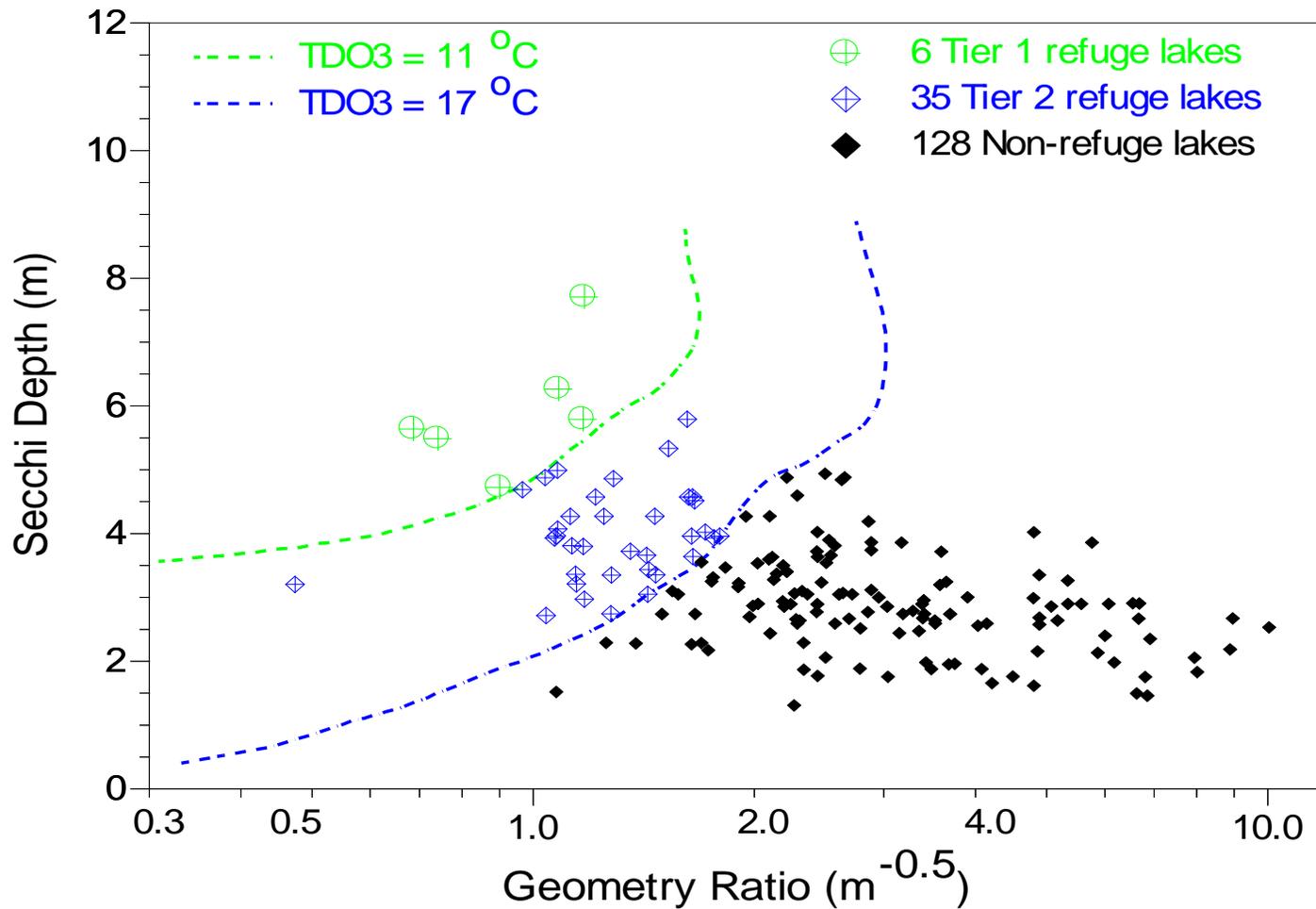


Figure 5.8 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **169** cisco lakes associated with the **International Falls weather station**. The boundary limits for selection of refuge lakes were contour lines of $AvgATDO3_{VB}$ ($TDO3_L$) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **International Falls weather data**.

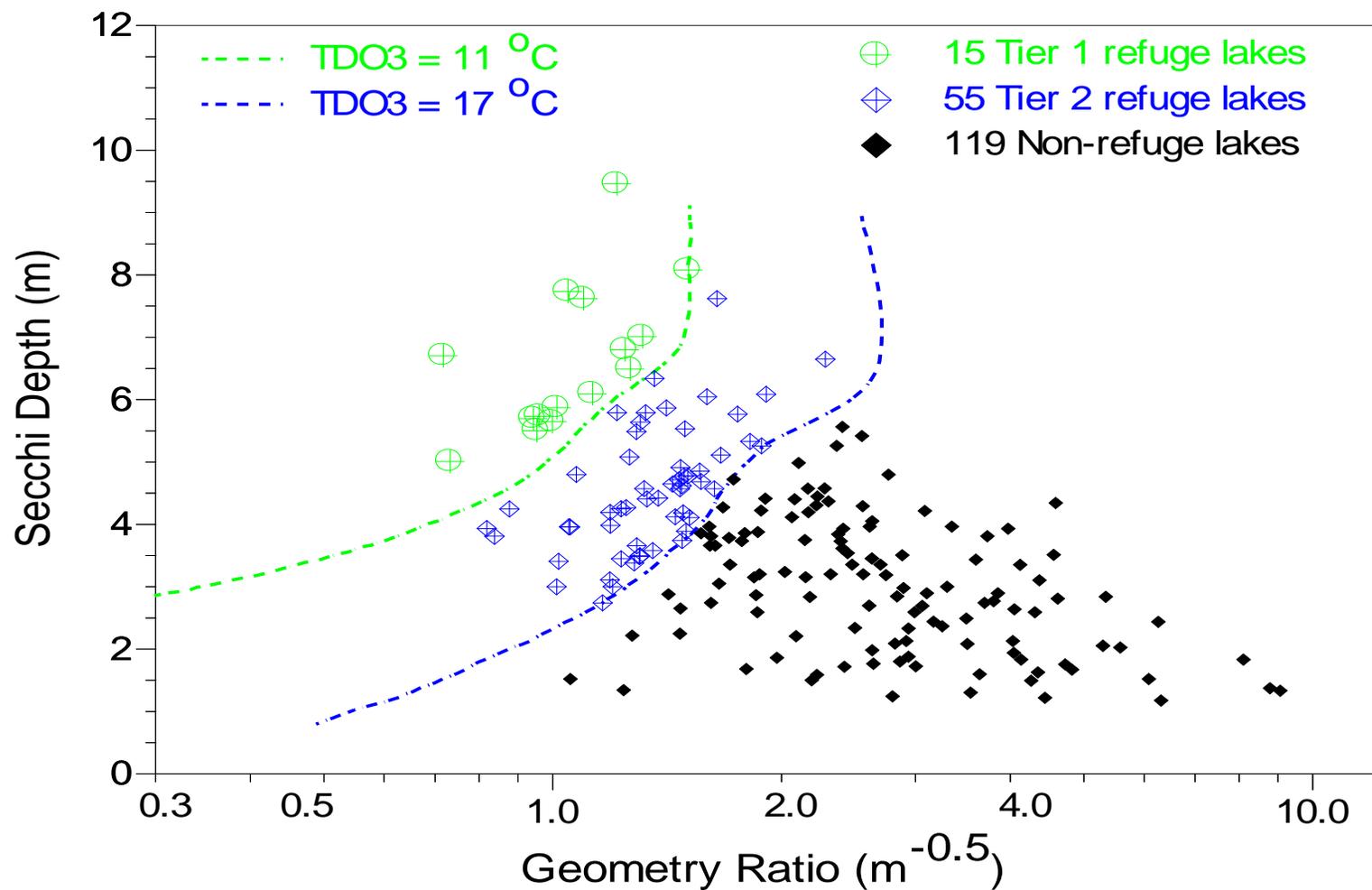


Figure 5.9 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **189** cisco lakes associated with the **Duluth weather station**. The boundary limits for selection of refuge lakes were contour lines of $\text{AvgATDO3}_{\text{VB}}$ (TDO3_L) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

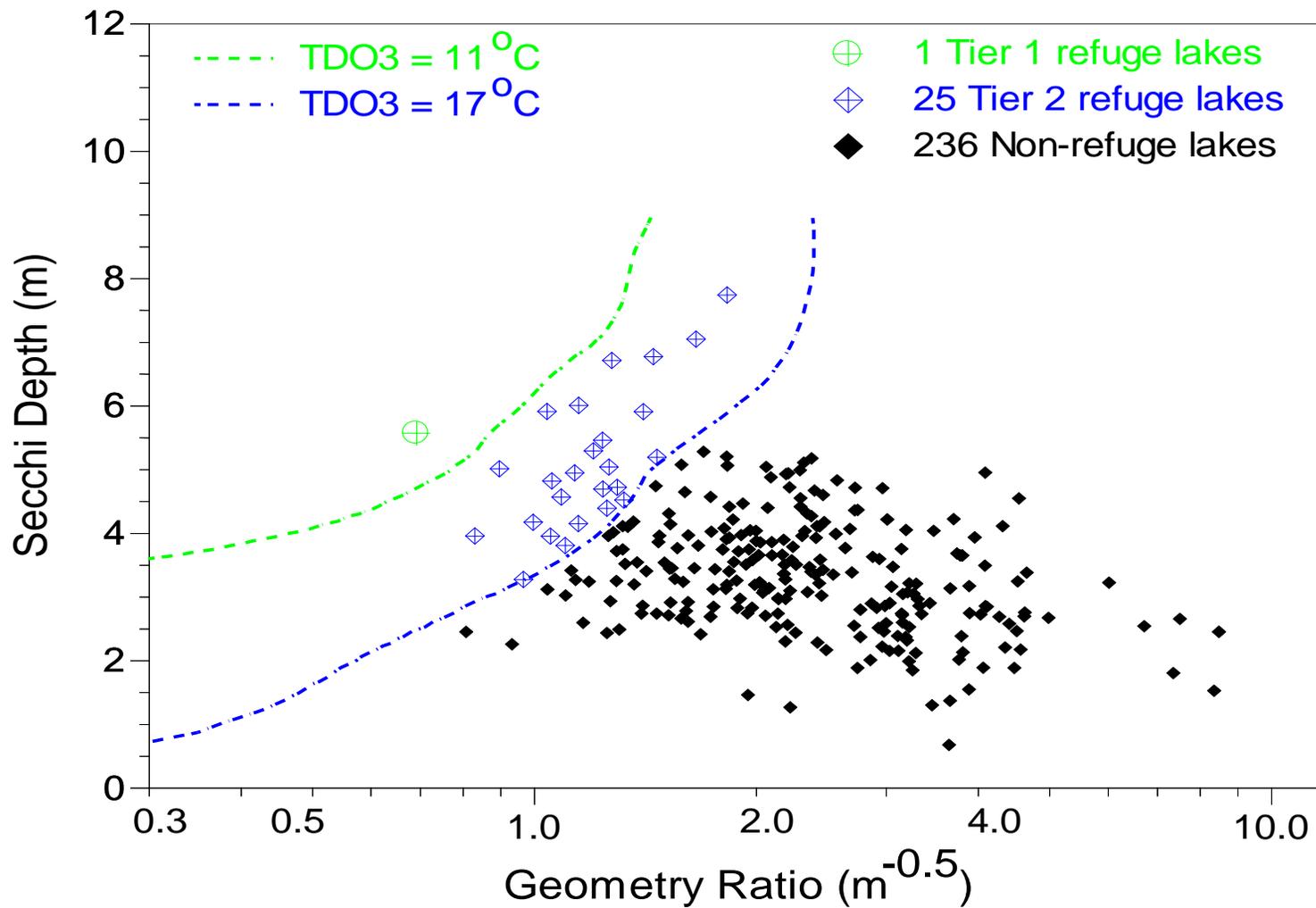


Figure 5.10 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **262** cisco lakes associated with the **St. Cloud weather station**. The boundary limits for selection of refuge lakes were contour lines of $AvgATDO3_{VB}$ ($TDO3_L$) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **St. Cloud weather data**.

Table 5.5 Number of Tier 1 and Tier 2 refuge lakes and non-refuge lakes selected from **cisco lakes paired by shortest distance to one of the three principal weather stations** using $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 11^{\circ}\text{C}$ and 17°C as boundary limits for Tier 1 and Tier 2, respectively, for variable benchmark periods (defined in Table 3.1, line 12). Three principal weather stations are used separately to simulate their paired cisco lakes.

Closest weather station	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
International Falls	Past	23	112	135	34	169
	CGCM 3.1	9	36	45	124	169
	MIROC 3.2	6	35	41	128	169
Duluth	Past	42	120	162	27	189
	CGCM 3.1	14	55	69	120	189
	MIROC 3.2	15	55	70	119	189
St. Cloud	Past	15	137	152	110	262
	CGCM 3.1	2	25	27	235	262
	MIROC 3.2	1	25	26	236	262
All three stations	Past	80	369	449	171	620
	CGCM 3.1	25	116	141	479	620
	MIROC 3.2	22	115	137	483	620

Table 5.6 Number of Tier 1 and Tier 2 refuge lakes and non-refuge lakes selected from **cisco lakes associated by distance to one of the three principal weather stations** using $\text{AvgATDO3}_{\text{FB}} (\text{TDO3}_{\text{F}}) = 11^{\circ}\text{C}$ and 17°C as boundary limits for Tier 1 and Tier 2, respectively, for the fixed benchmark period (defined in Table 3.1, line 6). Three principal weather stations are used separately to simulate their associated cisco lakes.

Closest weather station	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
International Falls	Past	49	88	137	31	169
	CGCM 3.1	23	39	62	106	169
	MIROC 3.2	23	39	62	106	169
Duluth	Past	78	91	169	20	189
	CGCM 3.1	36	51	87	102	189
	MIROC 3.2	39	50	89	100	189
St. Cloud	Past	49	128	177	85	262
	CGCM 3.1	19	37	56	206	262
	MIROC 3.2	22	34	56	206	262
All three stations	Past	176	307	483	137	620
	CGCM 3.1	78	127	205	415	620
	MIROC 3.2	84	123	207	413	620

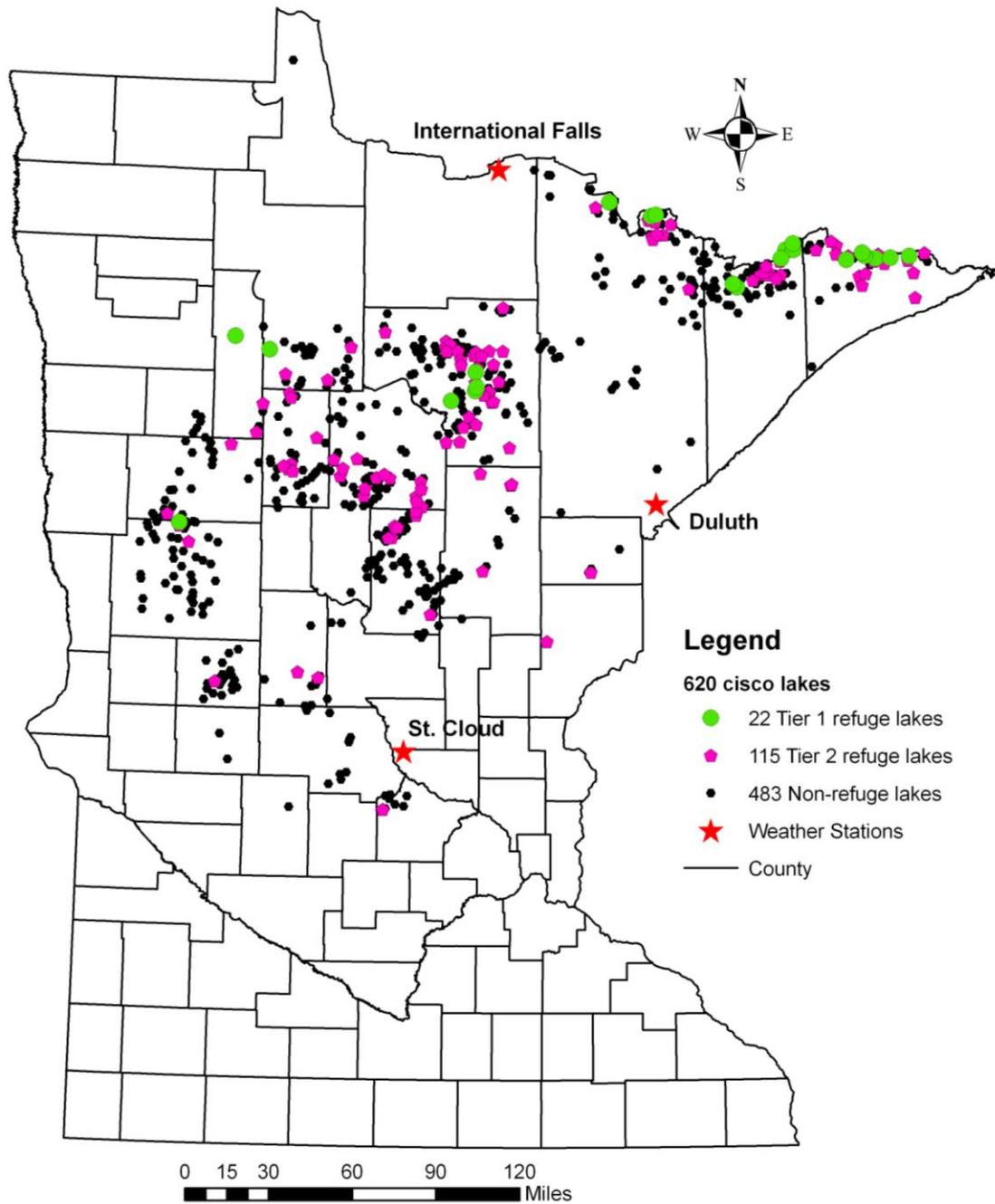


Figure 5.11 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and non-refuge cisco lakes simulated with the **MIROC 3.2 future climate scenario**. The boundary limits for selection of refuge lakes were contour lines of $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 17^{\circ}\text{C}$ and 11°C , for Tier 1 and Tier 2, respectively. Variable benchmark periods and weather data from the three associated weather stations (**International Falls, Duluth, and St. Cloud**) were used in the simulations.

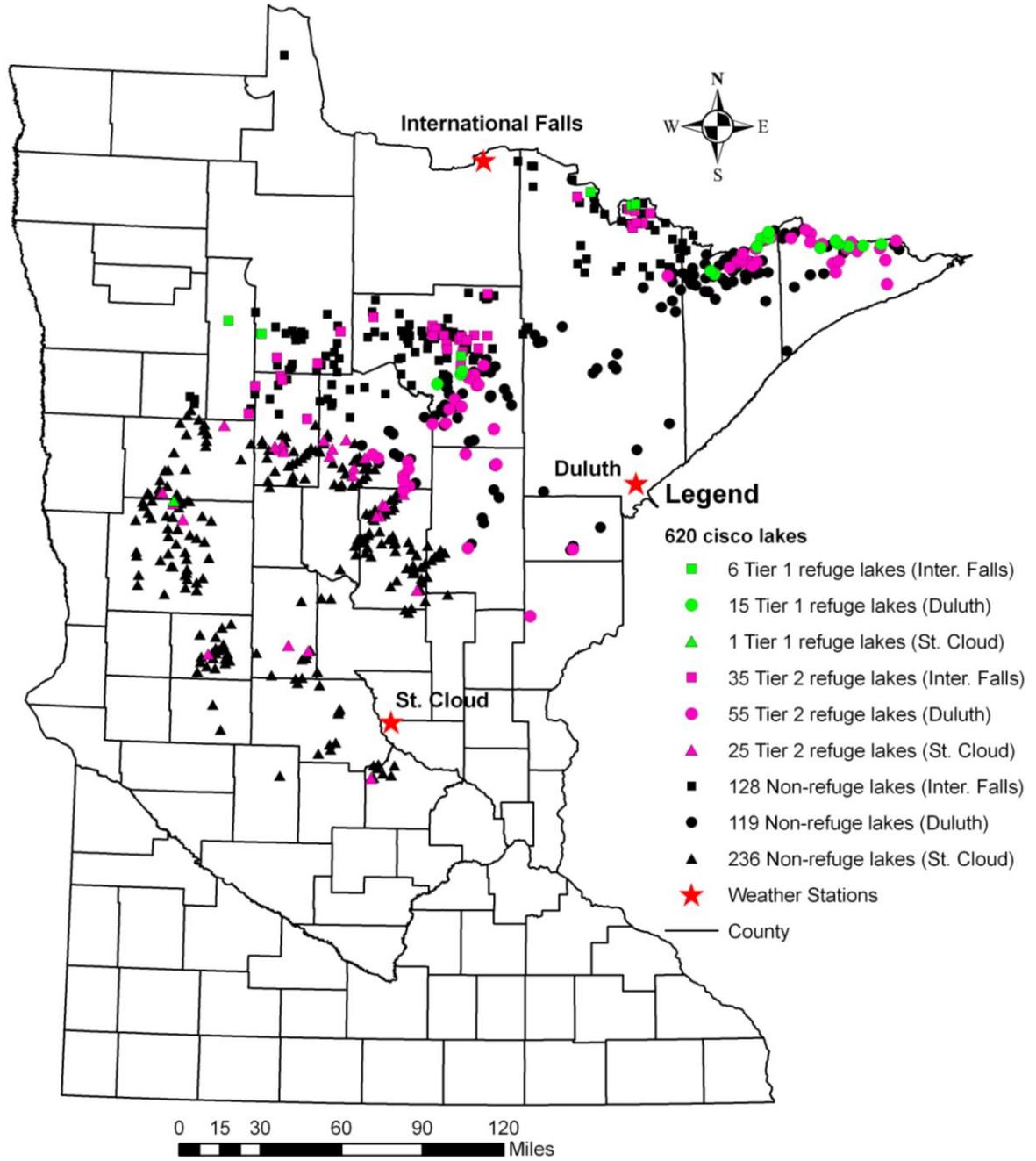


Figure 5.12 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and non-refuge cisco lakes simulated under the same conditions as lakes in Figure 5.11. The pairing of each lake with a specific weather station is shown more clearly than in Figure 5.11.

5.4 Selection of refuge lakes paired by latitude with one of three principal weather stations

Using distance from the lake to a weather station, as the criterion to associate a cisco lake with a weather station may not be the best approach. There is a strong climate gradient with latitude in Minnesota, and a weaker one with longitude. There is also a strong climate divide running east-west through about the middle of Minnesota. In earlier studies Minnesota was divided into a northern region and a southern region for this very reason (Hondzo and Stefan 1993). Therefore, two constant latitudes were proposed as boundary limits to associate cisco lakes with weather stations (Figure 5.13). The latitudes proposed as dividing lines are 46.10°N and 47.65°N. 46.10°N runs through central Minnesota (Figure 5.13). There are 55 cisco lakes below 46.10°N through central Minnesota that were assigned to the St. Cloud weather station. There are 166 lakes above the dividing line of 47.65°N through northern Minnesota that were assigned to the International Falls weather station. There are 399 lakes between the dividing lines of 47.65°N and 46.10°N latitudes that were assigned to the Duluth weather station. In Figure 5.13 and in the following discussion, the three groups of cisco lakes are named “northern cisco lakes” assigned to International Falls, “mid-latitude cisco lakes” assigned to Duluth, and “southern cisco lakes” assigned to St. Cloud.

The refuge lake selection process was repeated for cisco lakes grouped by latitude with weather stations. Contour lines of $\text{AvgATDO3}_{\text{VB}}$ (TDO3_{L}) = 11°C and 17°C were again used for variable benchmark periods and $\text{AvgATDO3}_{\text{FB}}$ (TDO3_{F}) = 11°C and 17°C for the fixed benchmark period as boundary limits for Tier 1 and Tier 2 refuge lakes, and again simulations were made for past climate conditions (1962 – 2008) and for two future climate scenarios. The TDO3 contour lines of 11°C and 17°C used to identify refuge lakes were derived by interpolation from simulated points for the 30 virtual lakes.

The results are summarized in Table 5.7 (using TDO3_{L}) and 5.8 (using TDO3_{F}). Figures 5.14, 5.15, and 5.16 show distributions of Tier 1 and Tier 2 refuge lakes and non-refuge lakes for the 166 northern, 399 mid-latitude, and 55 southern cisco lakes, respectively. The selections of refuge lakes for Figs. 5.14, 5.15, and 5.16 were again based on contour lines of $\text{AvgATDO3}_{\text{VB}}$ (TDO3_{L}) for variable benchmark periods simulated under the MIROC 3.2 future climate scenario, which has finer spatial resolution (Fig. 2.3) than the CGCM 3.1 scenario (Fig. 2.2).

Under the MIROC 3.2 future climate scenario, it was projected that 62, 94, and 4 lakes out of 166 northern, 399 mid-latitude, and 55 southern cisco lakes, respectively, would be Tier 1 plus Tier 2 refuge lakes, when contour lines of $\text{AvgATDO3}_{\text{VB}}$ for variable benchmark periods were used (Table 5.7 and Figs. 5.14 to 5.16). It was projected to have 160 and 229 refuge lakes (Tier 1 plus Tier 2) out of 620 cisco lakes under the MIROC 3.2 future climate scenario when contour lines of $\text{AvgATDO3}_{\text{VB}}$ (Table 5.7) and $\text{AvgATDO3}_{\text{FB}}$ (Table 5.8) were used, respectively. Climate warming under the MIROC 3.2 future climate scenario is projected to decrease by 346 the number of refuge lakes from past climate conditions when contour lines of $\text{AvgATDO3}_{\text{VB}}$ were used (Table 5.7).

The geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on results in Figures 5.14, 5.15 and 5.16 is shown in Figure 5.17. A division of the 620 Minnesota

cisco lakes into 29 Tier 1 refuge lakes, 131 Tier 2 refuge lakes, and 460 non-refuge cisco lakes was projected for the MIROC 3.2 future climate scenario when contour lines of AvgATDO3_{VB} were used as boundary limits (Fig. 5.17) and refuge lakes were selected separately from three cisco lakes groups divided by latitude. Overall, the results are not much different from the results presented in Fig. 5.6 for all 620 cisco lakes and Fig. 5.11 for the three lake groups obtained by using minimum distance.

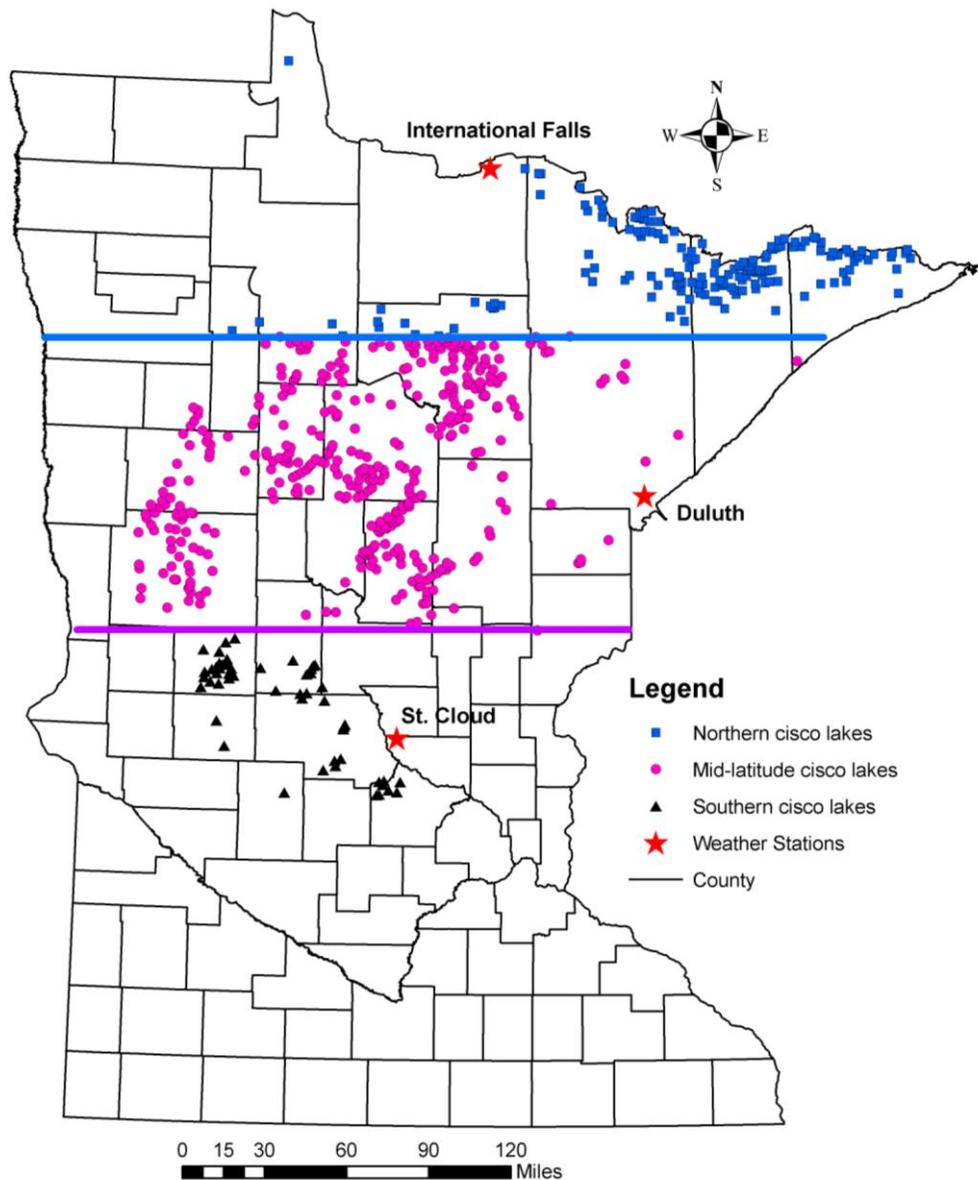


Figure 5.13 Geographic distribution of 620 cisco lakes in Minnesota relative to latitudes 46.10°N and 47.65°N. The two latitudes divide the 620 cisco lakes into 166 northern cisco lakes, 399 mid-latitude cisco lakes, and 55 southern cisco lakes.

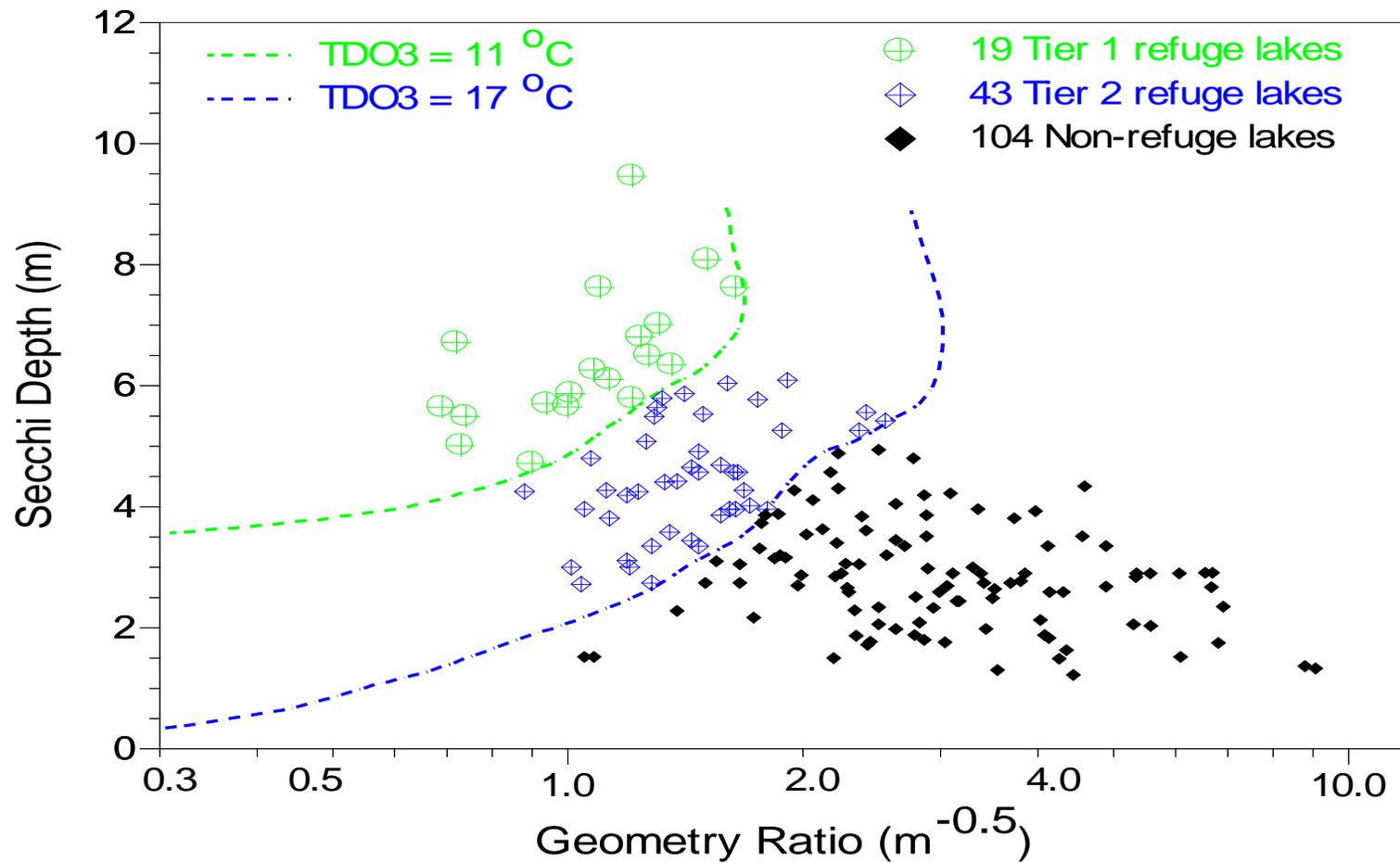


Figure 5.14 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **166 northern cisco lakes**. The boundary limits for selection of refuge lakes were contour lines of $AvgATDO3_{VB}$ ($TDO3_L$) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **International Falls weather data**.

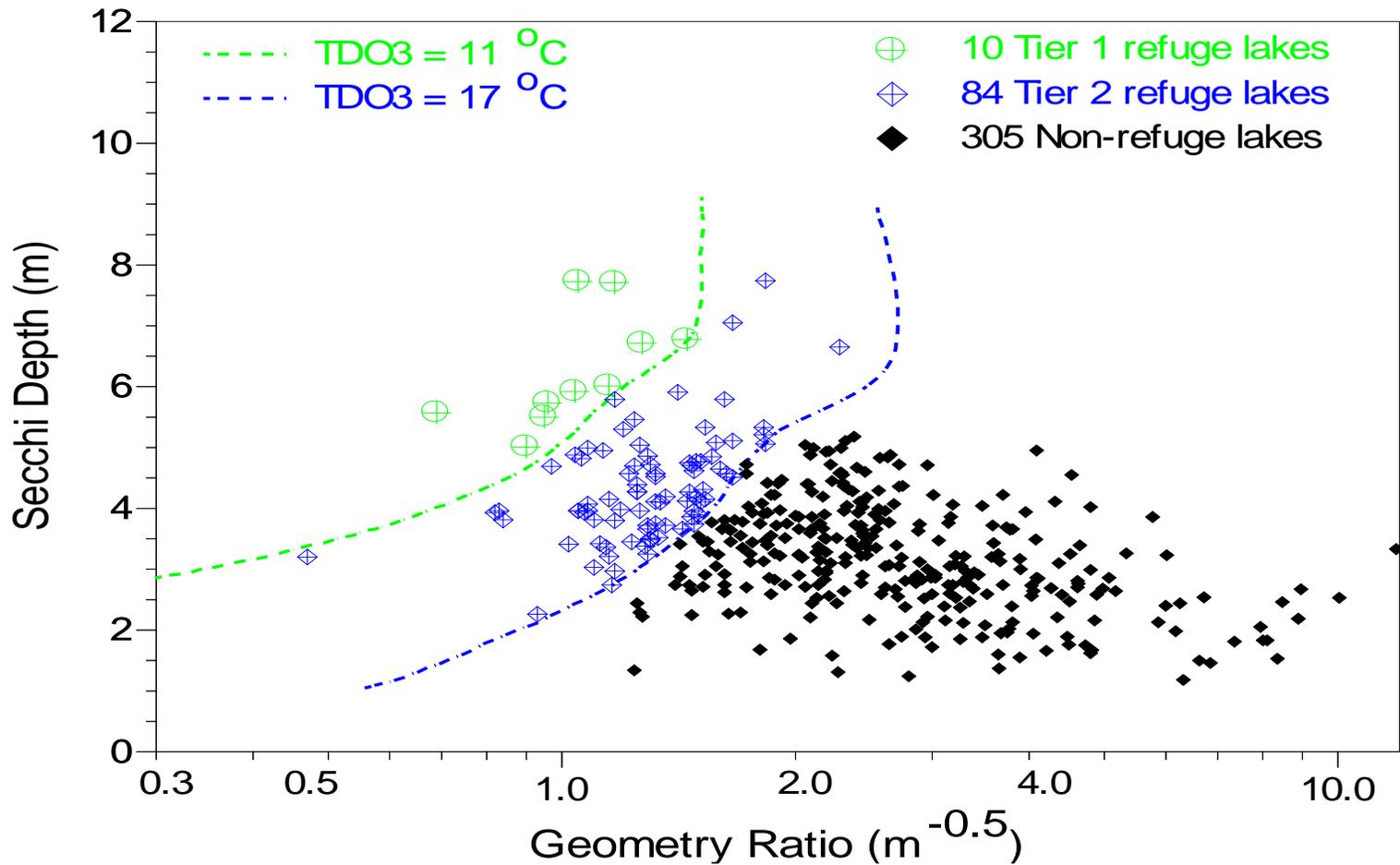


Figure 5.15 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **399 mid-latitude cisco lakes**. The boundary limits for selection of refuge lakes were contour lines of **AvgTDO3_{VB} (TDO3_L)** for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather** data.

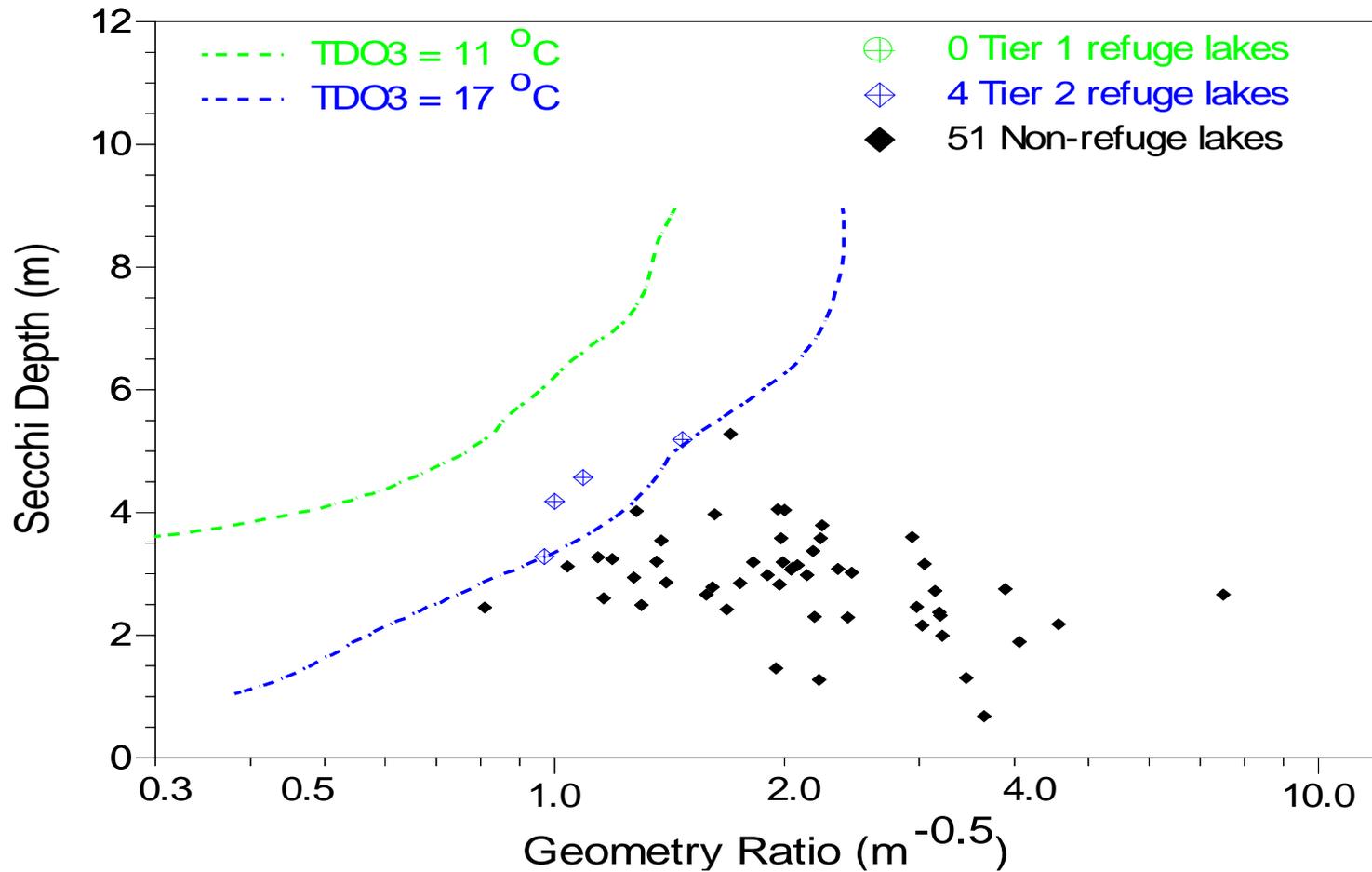


Figure 5.16 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **55 southern cisco lakes**. The boundary limits for selection of refuge lakes were contour lines of $AvgTDO3_{VB}$ ($TDO3_L$) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **St. Cloud weather** data.

Table 5.7 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from **cisco lakes grouped by latitude** using $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 11^{\circ}\text{C}$ and 17°C as boundary limits for Tier 1 and Tier 2, respectively, for variable benchmark periods (defined in Table 3.1, line 12). Three principal weather stations each assigned to a different range of latitudes are used to simulate all 620 lakes.

Weather station by latitude	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
Northern (International Falls)	Past	41	96	137	29	166
	CGCM 3.1	24	43	67	99	166
	MIROC 3.2	19	43	62	104	166
Mid-latitude (Duluth)	Past	52	285	337	62	399
	CGCM 3.1	10	83	93	306	399
	MIROC 3.2	10	84	94	305	399
Southern (St. Cloud)	Past	1	31	32	23	55
	CGCM 3.1	0	4	4	51	55
	MIROC 3.2	0	4	4	51	55
All three latitudes	Past	94	412	506	114	620
	CGCM 3.1	34	130	164	456	620
	MIROC 3.2	29	131	160	460	620

Table 5.8 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from **cisco lakes grouped by latitude** using $\text{AvgATDO3}_{\text{FB}} (\text{TDO3}_{\text{F}}) = 11^{\circ}\text{C}$ and 17°C as boundary limits for Tier 1 and Tier 2, respectively, for the fixed benchmark period (defined in Table 3.1, line 6). Three principal weather stations each assigned to a different range of latitudes are used to simulate all 620 lakes.

Weather station by latitude	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
Northern (International Falls)	Past	72	71	143	23	166
	CGCM 3.1	42	40	82	84	166
	MIROC 3.2	42	40	82	84	166
Mid-latitude (Duluth)	Past	109	243	352	47	399
	CGCM 3.1	43	90	133	266	399
	MIROC 3.2	47	88	135	264	399
Southern (St. Cloud)	Past	9	29	38	17	55
	CGCM 3.1	2	10	12	43	55
	MIROC 3.2	2	10	12	43	55
All three latitudes	Past	190	343	533	86	620
	CGCM 3.1	87	140	227	392	620
	MIROC 3.2	91	138	229	390	620

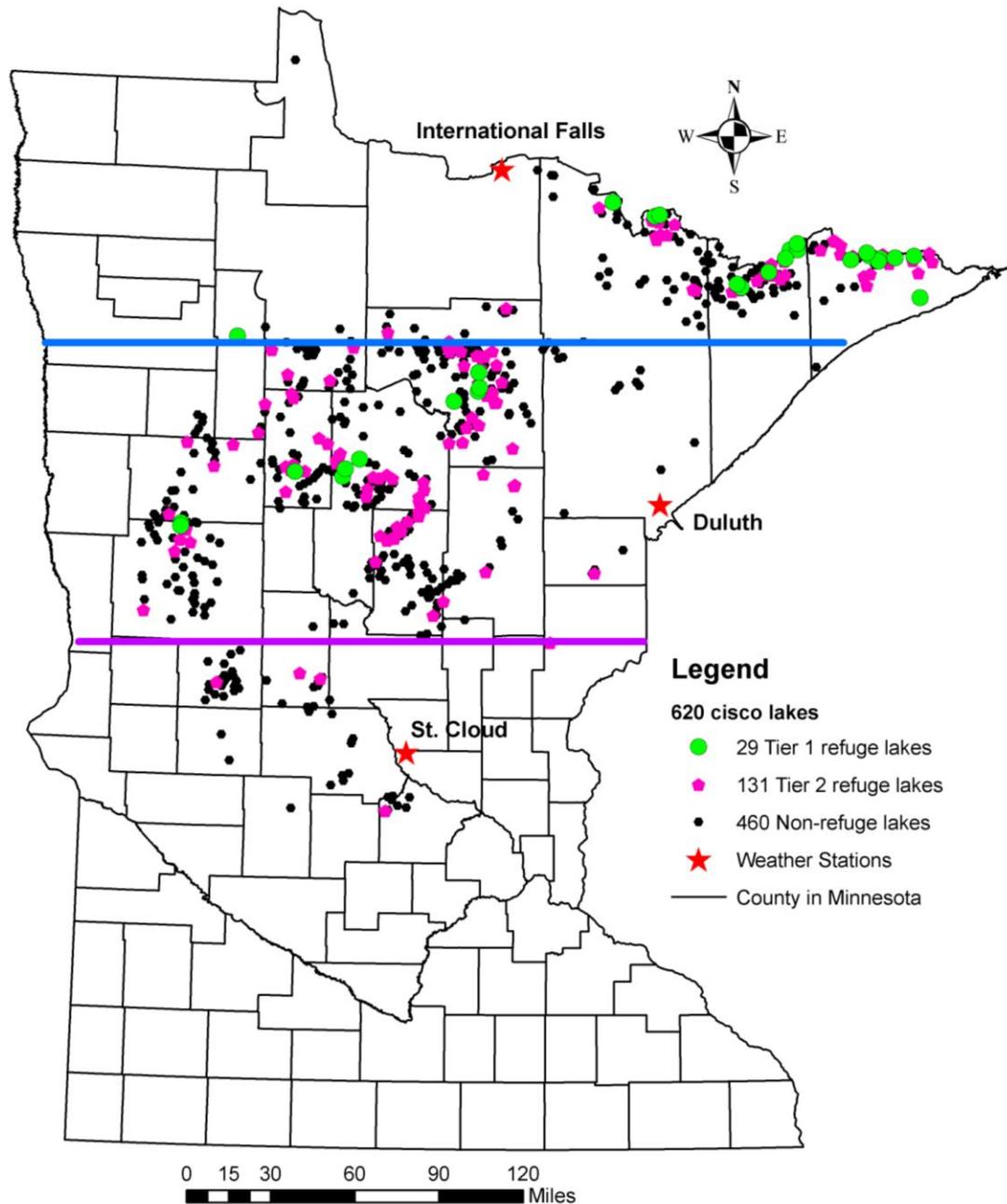


Figure 5.17 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and non-refuge cisco lakes simulated with the **MIROC 3.2 future climate scenario**. Lakes are grouped by latitude into 166 northern, 399 mid-latitude, and 55 southern cisco lakes. The boundary limits for selection of refuge lakes were contour lines of $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 17^{\circ}\text{C}$ and 11°C , for Tier 1 and Tier 2, respectively. Variable benchmark periods were used, and principal weather stations (**International Falls**, **Duluth**, and **St. Cloud**) were associated by latitude with each lake group.

5.5 Characteristics of cisco refuge lakes in Minnesota: Statistics of geometry ratios, Secchi depths, maximum depths, and surface areas

Bathymetric and other limnological characteristics of 620 Minnesota cisco lakes (Table D.1) had been analyzed and compared with the same characteristics in another and larger Minnesota lake database (Schupp, MNDNR) consisting of 3002 lakes (Fang et al. 2009). It was found that, on average, cisco lakes in Minnesota are deeper, more transparent and less trophic than other lakes. They are preferentially located in north central and northeastern Minnesota (Figure 5.1). To explore the characteristics of the selected cisco **refuge** lakes, we analyzed the statistical distributions of lake surface area A_s , maximum depth H_{\max} , geometry ratio GR (= $A_s^{0.25}/H_{\max}$) and mean Secchi depth SD of the selected refuge lakes. Tables 5.9 to 5.11 list the statistics of these lake parameters for Tier 1 and Tier 2 refuge lakes, and for comparison for non-refuge lakes as well. These lakes had been classified based on simulated values of $\text{AvgATDO3}_{\text{VB}}$ (TDO3_{L}) under the MIROC 3.2 future climate scenario and by pairing lakes and weather stations by shortest distance (Table 5.10) or by latitude (Table 5.11).

Table 5.12 summarizes the statistics of the four lake parameters for refuge lakes only (Tier 1 plus Tier 2). For the simulations, lakes had been paired with weather stations by latitude or by shortest distance. The statistical results for the four lake characteristics were hardly affected by the distinction, although the number of refuge lakes was different (160 versus 137). For the 160 refuge lakes, the mean Secchi depths were from 2.26 to 9.46 m, lake geometry ratios from 0.47 to 2.55 $\text{m}^{-0.5}$, and maximum depths from 13.1 to 64.9 m. The first, second (median), and third quartile values of bathymetric parameters and Secchi depths are reported in Tables 5.9 to 5.12. For example, from quartile values, we know that 75%, 50% and 25% of the 160 refuge cisco lakes (Table 5.12) have Secchi depths greater than 4.0, 4.6, and 5.5 m, respectively, and that 50% of these lakes have maximum depths greater than 25.6 m, and geometry ratios less than 1.29 $\text{m}^{-0.5}$. On the other hand, of the 460 non-refuge lakes in Table 5.11, 50% have maximum depths less than 14.32 m, geometry ratios greater than 2.54 $\text{m}^{-0.5}$, and mean Secchi depths less than 3.0 m (Table 5.11).

Figures 5.18, 5.19, 5.20, and 5.21 give graphical representations of the cumulative distributions of, summer mean Secchi depth SD, lake geometry ratio GR, lake maximum depth H_{\max} , and lake surface area A_s , respectively, for all cisco refuge lakes (Tier 1 plus Tier 2) under a future climate scenario, as well as for all 620 cisco lakes (Table D.1). Refuge lakes for the cumulative distribution curves were identified by three choices: using Duluth weather data for all lakes or by pairing cisco lakes with weather stations by latitude or by distance as discussed in the previous sections. As can be clearly seen, the choice did not matter, because the three cumulative distributions for the cisco **refuge** lakes under the MIROC 3.2 future climate scenario in Figures 5.18 to 5.21 are very similar, but are substantially different from distributions of SD, GR, and H_{\max} for all 620 cisco lakes. Refuge lakes selected under the MIROC 3.2 climate scenario have Secchi depths greater than ≈ 2.5 m (Fig. 5.18), lake geometry ratio less than ≈ 2.5 $\text{m}^{-0.5}$ (Fig. 5.19), and maximum depths greater than ≈ 15 m (Fig. 5.20). The cumulative distributions of surface areas of cisco refuge lakes and all 620 lakes are not significantly different. Refuge lakes selected for the MIROC 3.2 climate scenario have surface area up to 28.9 km^2 , and only 3.2% or 20 cisco

lakes out of 620 cisco lakes in the MN DNR database have a surface area greater than 28.9 km². These 20 large surface area lakes are identified as non-refuge lakes.

We have identified major and significant differences between cisco refuge lakes and non-refuge lakes. Refuge lakes are highly transparent and deep lakes. Their size (surface area) is somewhat, but not much smaller than that of the non-refuge lakes. The twenty largest current cisco lakes are not projected to be refuge lakes. Overall it appears that the cisco refuge lakes are a very special group among Minnesota lakes in general.

It can be concluded that the cisco refuge lakes (Tier 1 and Tier 2) identified in this report have bathymetric and transparency characteristics that are different from the ensemble of 620 cisco lakes in Minnesota. In the first project report of this study (Fang et al. 2009) it was shown that the 620 cisco lakes in Minnesota are substantially different from the bulk of Minnesota's lakes. In this third project report of the study it has been shown that refuge lakes are even more exceptional.

Table 5.9 Statistics of characteristics of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3_{VB}** (TDO3_L in Table 3.1, line 12). Simulations used **Duluth weather data for all 620 cisco lakes**.

Statistical Parameter	26 Tier 1 Refuge Lakes				129 Tier 2 Refuge Lakes				465 Non-refuge lakes			
	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)
Maximum	21.27	63.40	1.51	9.46	28.90	64.92	2.28	7.74	3847.77	56.08	22.70	5.56
Minimum	0.19	22.25	0.69	4.72	0.04	13.11	0.47	2.26	0.05	3.05	1.05	0.68
Average	3.55	36.98	1.05	6.36	2.60	27.12	1.32	4.40	17.84	15.66	3.04	3.08
Standard deviation	5.39	11.73	0.23	1.09	4.01	9.70	0.26	0.98	186.02	7.74	1.78	0.90
3rd Quartile	3.84	42.29	1.20	6.79	3.11	32.61	1.48	4.91	4.80	19.51	3.51	3.72
Median	1.40	35.97	1.05	6.06	0.97	25.30	1.29	4.27	1.79	14.32	2.51	3.05
1st Quartile	0.82	27.43	0.91	5.64	0.51	19.81	1.14	3.75	0.80	10.36	2.02	2.52

Table 5.10 Statistics of characteristics of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3_{VB}** (TDO3_L in Table 3.1, line 12). Simulations for **cisco lakes grouped by paired by shortest distance from the International Falls, Duluth, and St. Cloud weather stations.**

	23 Tier 1 Refuge Lakes				115 Tier 2 Refuge Lakes				484 Non-refuge lakes			
Statistical Parameter	A_s (km²)	H_{max} (m)	GR (m^{-0.5})	SD (m)	A_s (km²)	H_{max} (m)	GR (m^{-0.5})	SD (m)	A_s (km²)	H_{max} (m)	GR (m^{-0.5})	SD (m)
Maximum	21.27	61.57	1.51	9.46	28.90	64.92	2.28	7.74	3847.77	56.08	22.70	5.56
Minimum	0.19	22.25	0.69	4.72	0.04	13.11	0.47	2.72	0.05	3.05	0.81	0.68
Average	3.16	36.93	1.03	6.39	2.62	26.85	1.32	4.52	17.90	16.07	3.03	3.11
Standard deviation	4.74	10.88	0.22	1.15	4.37	10.27	0.27	1.03	186.02	8.30	1.79	0.91
3rd Quartile	3.84	42.29	1.17	6.96	2.49	32.31	1.48	5.03	4.91	19.81	3.51	3.75
Median	1.40	36.57	1.03	5.98	0.96	24.99	1.29	4.41	1.91	14.32	2.51	3.05
1st Quartile	0.76	27.81	0.91	5.64	0.52	19.36	1.14	3.81	0.83	10.36	2.02	2.53

Table 5.11 Statistics of characteristics of Tier 1 and Tier 2 cisco refuge lakes, and non-refuge lakes under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3_{VB}** (TDO3_L in Table 3.1, line 12). Simulations for **cisco lakes grouped by latitude** (166 northern, 399 mid-latitude, and 55 southern cisco lakes).

Statistical Parameter	29 Tier 1 Refuge Lakes				131 Tier 2 Refuge Lakes				460 Non-refuge lakes			
	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)
Maximum	21.27	63.40	1.64	9.46	28.90	64.92	2.55	7.74	3847.77	56.08	22.70	5.28
Minimum	0.19	17.98	0.69	4.72	0.04	13.11	0.47	2.26	0.05	3.05	0.81	0.68
Average	3.28	35.49	1.08	6.38	2.48	26.21	1.36	4.37	18.05	15.83	3.04	3.06
Standard deviation	5.16	12.00	0.25	1.06	3.93	9.78	0.31	0.91	187.02	8.03	1.79	0.88
3rd Quartile	2.89	41.15	1.24	6.80	2.82	32.00	1.51	4.87	4.92	19.81	3.52	3.66
Median	1.13	35.05	1.08	6.10	0.97	24.69	1.32	4.27	1.86	14.32	2.54	3.00
1st Quartile	0.81	26.21	0.94	5.65	0.51	18.60	1.17	3.81	0.80	10.36	2.02	2.49

Table 5.12 Statistics of characteristics of cisco **refuge lakes** (combined Tier 1 plus Tier 2) under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3_{VB}** (TDO3_L in Table 3.1, line 12) simulated for **cisco lakes grouped by latitude or shortest distance**.

Statistical Parameter	160 Refuge Lakes (lakes grouped by latitude)				137 Refuge Lakes (lakes grouped by shortest distance)			
	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)
Maximum	28.90	64.92	2.55	9.46	28.90	64.92	2.28	9.46
Minimum	0.04	13.11	0.47	2.26	0.04	13.11	0.47	2.72
Average	2.63	27.89	1.31	4.74	2.70	28.47	1.28	4.82
Standard deviation	4.18	10.79	0.32	1.21	4.42	10.98	0.28	1.26
3rd Quartile	2.87	34.14	1.48	5.49	2.89	34.44	1.47	5.64
Median	1.01	25.60	1.29	4.57	0.98	25.60	1.26	4.62
1st Quartile	0.59	19.74	1.10	3.95	0.59	21.03	1.08	3.96

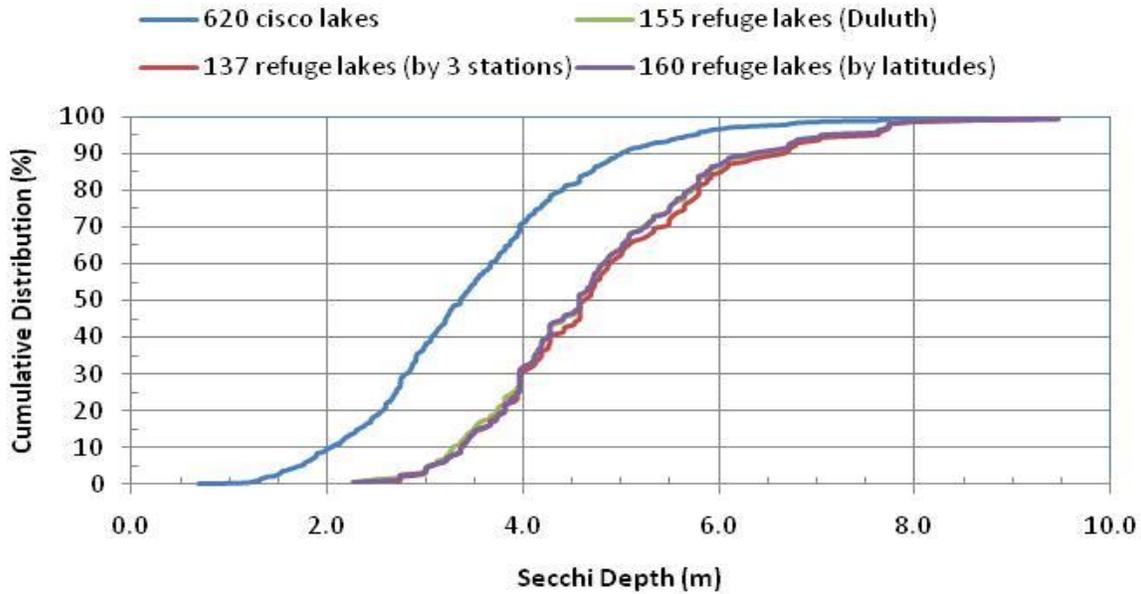


Figure 5.18 Cumulative distributions of **mean Secchi depth** for 620 cisco lakes and refuge lakes simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

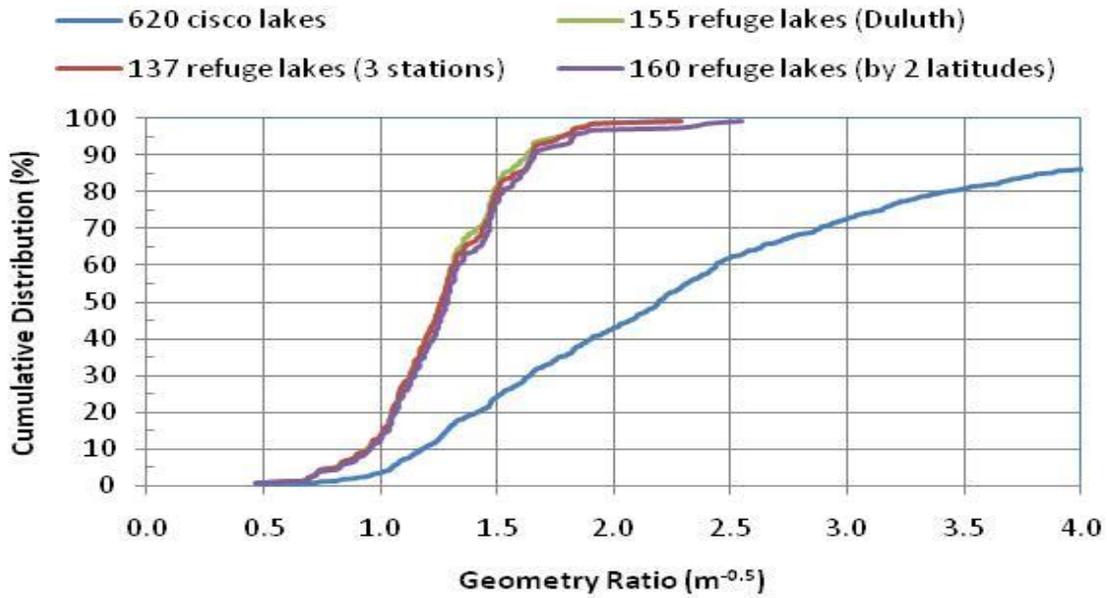


Figure 5.19 Cumulative distributions of **lake geometry ratio** for 620 cisco lakes and refuge lakes simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

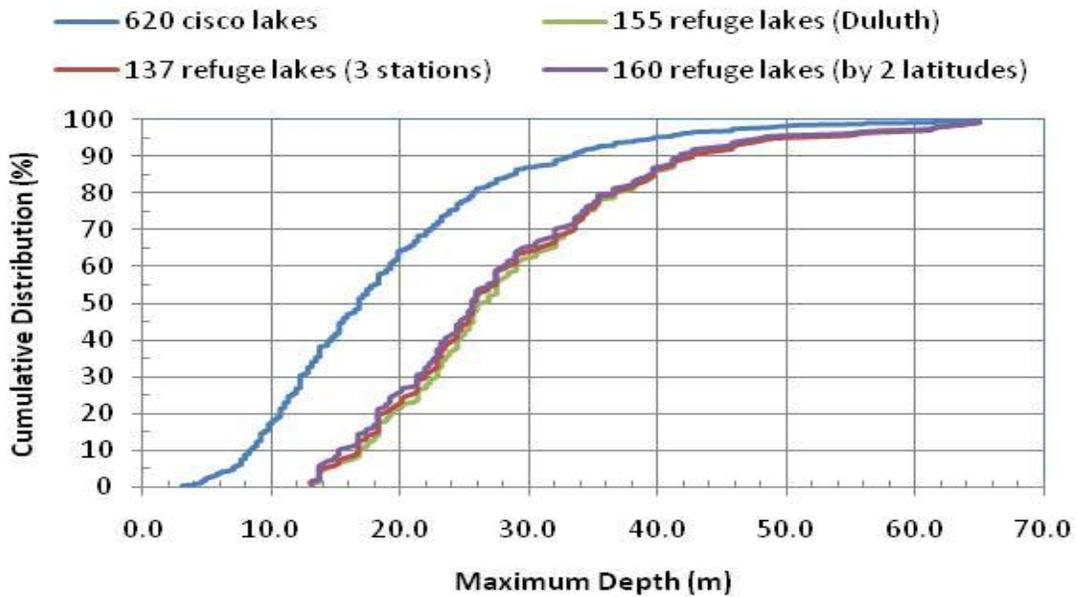


Figure 5.20 Cumulative distributions of **lake maximum depth** for 620 cisco lakes and refuge lakes simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

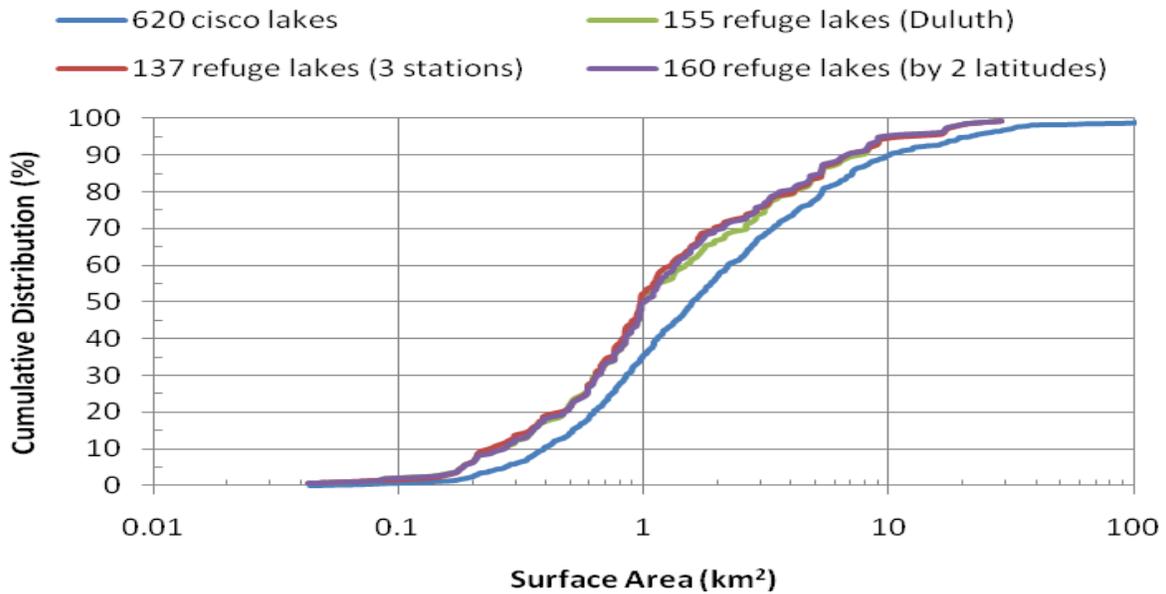


Figure 5.21 Cumulative distributions of **lake surface area** for 620 cisco lakes and refuge lakes selected simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

5.6 Validation (hindcasting) of cisco lake numbers for past climate

We cannot validate the number of refuge lakes predicted for future climate scenarios, but we can compare the number of refuge lakes **projected (hindcast)** for past climate conditions to 620, the number of **known** cisco lakes in Minnesota. Ten different projections of refuge lakes for past climate from 1962 to 2008 were made, and individual results are listed in Tables 5.3 to 5.8. The ten projections were made with variable and fixed benchmark periods, and by five different pairings of lakes with the principal weather stations, as described earlier. The five pairings were (1) International Falls for all 620 lakes, (2) Duluth for all 620 lakes, and (3) St. Cloud for all 620 lakes, (4) shortest distance to a weather station, and (5) most similar latitude with a weather station. To make the comparison easier, results from Tables 5.3 to 5.8 have been summarized in Table 5.13.

Tier 1 and Tier 2 refuge lakes identified for cisco under historical climate conditions (1961-2008) may be called viable cisco lakes where cisco is capable of living, developing, or spawning under favorable conditions. Cisco can still persist in lakes with TDO3 values greater than 17 °C but at a reduced probability of occurrence (Jacobson et al. 2010).

Table 5.13 Number (percentage of 620) of cisco refuge lakes projected (hindcast) for past (1962-2008) climate conditions.

Lake and weather station pairing	Variable Benchmark	Fixed Benchmark
International Falls weather for all 620 lakes	534 (86%)	552 (89%)
Duluth weather for all 620 lakes	523 (84%)	543 (77%)
St. Cloud weather for all 620 lakes	340 (55%)	402 (65%)
Shortest distance from lake to weather station	449 (72%)	483 (78%)
Similar latitude of lake and weather station	506 (82%)	533 (86%)
Average	470 (76%)	503 (81%)

The analysis and modeling procedure applied in this study was able to identify (hindcast) from 340 to 552 cisco lakes (55% to 89%) or on average 487 cisco lakes (78%) out of the 620 cisco lakes in the Minnesota data base as viable cisco (refuge) lakes. This means that on average the methodology underpredicted the viability of lakes as cisco refuge lakes. There were no overpredictions of viability. This may be interpreted as conservative in the context of this study. We used a long simulation period from 1962 to 2008 to make the projections and the results reflect averages for this period, as does the number 620 of documented cisco lakes. We did not account for trends in recent Minnesota climate.

Adult cisco mortality (see Fig. 1.1) was reported in 18 lakes in Minnesota during the unusually warm summer of 2006 (Jacobson et al. 2008). Water temperature and dissolved oxygen profiles in 22 cisco lakes, including 17 of the 18 lakes in which cisco mortality was reported, and 5 reference lakes without cisco mortality, were measured and analyzed by Jacobson et al. (2008). The data were used to determine the lethal oxythermal niche boundary. With the exception of two lakes (Lake Bemidji and Long Lake), all 21 cisco study lakes used by Jacobson et al. (2008) are in the MN DNR cisco lake database.

Lake names and DOW numbers of Jacobson et al.'s (2008) 21 study lakes are listed in Table 5.14 with an indication whether cisco mortality occurred in 2006 or not. Table 5.14 also lists the number of times that these 21 study lakes were identified as Tier 1 or Tier 1 plus Tier 2 refuge lakes by the five different methods discussed earlier in this report. AvgATDO3_{VB} (Table 3.1, line 12) contour lines for variable benchmark periods were used to rank the 21 study lakes as refuge lakes. A comparison of the model predictions with actual observations gave the following results: Of the 16 study lakes with adult cisco mortality in 2006, none was identified as a Tier 1 refuge lakes by any of the five methods (red "0" in Table 5.14), and three (Cotton Lake, Little Turtle Lake, and Mille Lacs Lake) were not identified as either Tier 1 or Tier 2 refuge lakes by

any of the five methods (Table 5.14). All five reference lakes that did not experience adult cisco mortality in 2006, were identified as either Tier 1 or Tier 2 refuge lakes by all of the five methods (bold “5” Table 5.14). These are remarkable agreements between model predictions of refuge lakes and observed adult cisco mortality events in 2006.

Table 5.14 Number of times that each of the 21 study lakes (Jacobson et al. 2008) is identified as Tier 1 or Tier 1 plus Tier 2 refuge lake under **past climate conditions (1962 to 2008)** by the five pairing methods presented above. **AvgATDO3_{VB}** (Table 3.1, line 12) was used for the identification of refuge lakes.

DOW Number	Lake Name	Cisco mortality in 2006	Number of times as Tier 1 refuge lake	Number of times as Tier 1 plus Tier 2 refuge lake
04003800	Andrusia	Yes	0	4
21005700	Carlos	Yes	0	5
03028600	Cotton	Yes	0	0
29007200	8th Crow Wing	Yes	0	1
11030500	Gull	Yes	0	3
15001600	Itasca	Yes	0	2
11020300	Leech	Yes	0	4
18026600	Little Pine (Cass)	Yes	0	3
56014200	Little Pine (Ottetail)	Yes	0	3
31077900	Little Turtle	Yes	0	0
48000200	Mille Lacs	Yes	0	0
11041100	Pine Mountain	Yes	0	3
29009100	7th Crow Wing	Yes	0	3
56038500	Star	Yes	0	5
03001000	Straight	Yes	0	3
11020100	Woman	Yes	0	1
18031500	Big Trout	No	3	5
29007500	Kabekona	No	0	5
56036000	Rose	No	3	5
56035800	Scalp	No	5	5
11041300	Ten Mile	No	5	5

However, some disagreement between the prediction (of the refuge lakes) and the observed cisco mortality does exist. For example, 13 of the 16 study lakes with adult cisco mortality in 2006 were identified as Tier 2 refuge lakes by one to five methods. One reference lake (Lake Kabekona) was not identified as a Tier 1 refuge lake by any of five methods, although it had no mortality. One cause for the discrepancies may be that long-term (47 year) averages of highest mean daily TDO3 values (AvgATDO3_{VB} for variable benchmark periods) were used to

make the refuge lake predictions, while the observed mortality events were for one specific year and an unknown recurrence interval. If TDO3 parameters that are averages of 47 years are too conservative predictors, shorter averaging periods and recurrence intervals that pair fish growth cycles with weather cycles can be considered. The agreement between projections and observations may become even better.

5.7 Summary of cisco refuge lake projections for future climate scenarios

5.7.1 Number of Tier 1, Tier 2, and total refuge lakes

Tables 5.3 to 5.8 give the number of refuge lakes projected by 10 different methods (using TDO3s for fixed or variable benchmark periods and different pairings of lakes with weather stations). The numbers for Tier 1, Tier 2, and the total number of projected refuge lakes (Tier 1 plus Tier 2) are summarized in Table 5.15. The TDO3 contour lines of 11°C and 17°C used to identify refuge lakes were derived by interpolation from simulated points for the 30 virtual lakes.

Table 5.15 Projected number of Tier 1, Tier 2, and total cisco refuge lakes under two future climate scenarios (CGCM 3.1 and MIROC 3.2).

Weather station and lake pairing	Climate scenario	Variable benchmark			Fixed benchmark		
		Tier 1	Tier 2	Total	Tier 1	Tier 2	Total
International Falls for all 620 lakes	CGCM 3.1	44	174	218	118	181	299
	MIROC 3.2	31	168	199	117	181	298
Duluth for all 620 lakes	CGCM 3.1	25	129	154	79	134	213
	MIROC 3.2	26	129	155	87	131	218
St. Cloud for all 620 lakes	CGCM 3.1	17	70	87	65	97	162
	MIROC 3.2	9	77	86	68	95	163
Shortest distance	CGCM 3.1	25	116	141	78	127	205
	MIROC 3.2	22	115	137	84	123	207
Similar latitude	CGCM 3.1	34	130	164	87	140	227
	MIROC 3.2	29	131	160	91	138	229
Average	Number	26	124	150	88	134	222
	(% of 620)	4%	20%	24%	14%	22%	36%

The numbers obtained by the variable benchmark and the fixed benchmark method are significantly different for Tier 1 and total refuge lakes, but the two climate scenarios (CGCM 3.1 and MIROC 3.2) gave mostly similar results. Tier 1 cisco refuge lakes obtained for a very

stringent water temperature constraint ($\leq 11.0^{\circ}\text{C}$, Table 5.2) numbered only 4% to 14% of the total 620 cisco lakes in the Minnesota database. Tier 2 cisco refuge lakes for the water temperature range from 11.0°C to 17.0°C comprised from 20 to 22% of the 620 cisco lakes. In total, projected cisco refuge lakes comprise from 24% to 36% of all current 620 cisco lakes (Table 5.15). Consequently 76% to 64% of all current 620 cisco lakes are projected to lose cisco habitat under the two future climate scenarios investigated, if the stringent water temperature constraint of 17.0°C is used as a criterion (lethal temperature for coldwater fish used in previous studies was as high as 23.4°C).

5.7.2 Names and locations of Tier 1 and Tier 2 cisco refuge lakes

The number of Tier 1 and Tier 2 cisco refuge lakes determined for the future climate scenario MIROC 3.2 varies depending on the chosen lake and weather station pairing (Table 5.15). Although the numbers are different, many lakes are the same. Therefore, refuge lakes were listed by name and geographic coordinates in Table 5.16 for Tier 1 and in Appendix E for Tier 1 plus Tier 2. They were first ordered by the number of times that they were found by the five different methods (listed in the first column of Table 5.14) using the fixed benchmark period and the MIROC 3.2 future climate scenario and were then listed by lake name in alphabetical order. The number of times that they were identified as Tier 1 refuge lakes by the five methods is also listed in Table 5.16 when the fixed benchmark and the variable benchmark were used with the future climate scenarios MIROC 3.2 and CGCM 3.1.

Lakes that were identified most often are on top of the list. For example, when the fixed benchmark period and the MIROC 3.2 future climate scenario were used to identify Tier 1 refuge lakes, a total of 68, 12, 4, 14, and 19 cisco lakes were identified as Tier 1 refuge lakes by 5 methods, 4 methods, 3 methods, 2 methods, and 1 method, respectively (Fig. 5.22). In total, 117 Tier 1 cisco refuge lakes, with the geographic distribution shown in Fig. 5.22, were identified at least by one method. Similar information for all refuge lakes (Tier 1 plus Tier 2) is given in Table E.1 in Appendix E. In total, 298 cisco lakes were identified as either Tier 1 or Tier 2 refuge lakes at least by one method, and 163 cisco lakes were identified as either Tier 1 or Tier 2 refuge lakes by all five methods that associate a cisco lake to weather station (Table 5.14). These two lists (Table 5.16 and Table E.1 in Appendix E) give recommended cisco refuge lakes independent of method used for their determination. The Tier 1 cisco refuge lakes from Table 5.16 are plotted on a map of Minnesota in Figure 5.22 and the Tier 1 plus Tier 2 refuge lakes from figure E.1 are plotted in Figure 5.23. The number of times that they were identified as refuge lakes is given in the legend.

Table 5.16 Names and geographic locations of Tier 1 cisco refuge lakes in Minnesota and number of times identified as Tier 1 cisco refuge lakes by five different methods.

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
31034900	Antler	466207.0	5275090.0	5	5	0	0
38050200	Ashigan	624749.0	5320500.0	5	5	2	2
03008500	Bad Medicine	317655.0	5221710.0	5	5	1	1
18003000	Barbour	432303.0	5123450.0	5	3	0	0
11027700	Big Deep	394595.0	5196110.0	5	5	0	0
29018500	Big Sand	350361.0	5207040.0	5	5	0	1
31079300	Big Too Much	440872.0	5277200.0	5	5	0	0
18031500	Big Trout	411532.0	5174230.0	5	5	0	0
18021100	Blue	423977.0	5180350.0	5	1	0	0
31039500	Bluewater	458235.0	5252040.0	5	5	4	5
04029700	Buzzle	339646.0	5276030.0	5	5	2	2
77012000	Charlotte	355635.0	5090450.0	5	5	0	0
31074900	Chase	444194.0	5246180.0	5	5	5	5
38016600	Cherry	641319.0	5333210.0	5	5	4	5
16013900	Clearwater	697251.0	5328720.0	5	5	5	5
31054000	Clubhouse	457155.0	5272470.0	5	5	0	2
15009000	Deep	320013.0	5283860.0	5	5	4	4
11023700	Deep Portage	393944.0	5191690.0	5	5	0	0
16023200	Duncan	688691.0	5328360.0	5	5	4	5
11046600	Fifth	376618.0	5212610.0	5	5	0	1
04021700	Grant	348931.0	5261900.0	5	5	0	0
58012300	Grindstone	499427.0	5107650.0	5	5	0	0
69048700	Gun	559422.0	5352420.0	5	5	5	5
16035600	Gunflint	672943.0	5329800.0	5	5	0	0
31045200	Gunn	459357.0	5265500.0	5	5	0	0
31091100	Hamrey	406242.0	5285940.0	5	5	0	0
38020600	Hanson	642735.0	5333610.0	5	5	0	2
18026900	Island Loon	413256.0	5173460.0	5	3	0	0
11040000	Jack	390145.0	5213090.0	5	5	3	3
18036100	Kimball	408024.0	5167390.0	5	5	0	0
38022900	Little Knife	636926.0	5333150.0	5	5	5	5
56032800	Little McDonald	292892.0	5165460.0	5	5	0	1
29015000	Little Sand	353063.0	5205920.0	5	5	3	1
31039400	Little Trout	458897.0	5254040.0	5	5	4	5
69068200	Little Trout	535431.0	5360490.0	5	5	4	5
16044800	Loon	671907.0	5327530.0	5	5	5	5
29018000	Lower Bottle	352030.0	5210180.0	5	5	0	1
31023900	Lower Hanson	466217.0	5250430.0	5	5	0	0
16046300	Magnetic	665952.0	5330660.0	5	5	0	2
03037100	Meadow	280699.0	5181750.0	5	5	0	0

Table 5.16 (cont'd.)

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
77002200	Mons	367464.0	5087210.0	5	5	0	0
16004300	Moose	716878.0	5331470.0	5	5	0	2
16023400	Moss	687734.0	5326820.0	5	5	2	2
29023700	Newman	351221.0	5250800.0	5	5	0	2
16033100	North	681002.0	5331430.0	5	5	4	2
38064000	Ojibway	608799.0	5311710.0	5	5	4	5
38021100	Ottertrack	641140.0	5336920.0	5	5	4	4
11047600	Portage	381932.0	5207450.0	5	5	3	3
31042200	Ruby	458339.0	5262900.0	5	5	5	5
56035800	Scalp	287474.0	5174890.0	5	5	3	3
38071400	Section Twelve	608813.0	5312520.0	5	5	0	0
56036900	Six	287670.0	5176620.0	5	5	5	5
38052900	Snowbank	617945.0	5315770.0	5	5	0	2
16024400	South	682582.0	5329800.0	5	5	5	5
38038800	Spoon	633501.0	5326830.0	5	5	0	0
18035900	Star	410022.0	5167710.0	5	5	0	1
69036900	Takucmich	562210.0	5353350.0	5	5	5	5
01010900	Taylor	460999.0	5204520.0	5	5	0	0
11041300	Ten Mile	380379.0	5203110.0	5	5	3	5
38072400	Tofte	606653.0	5313510.0	5	5	4	4
38017200	Topaz	639601.0	5332420.0	5	5	0	0
16004900	Trout	711435.0	5305720.0	5	5	2	2
31041000	Trout	458192.0	5256660.0	5	5	0	2
31072500	Turtle	448327.0	5275130.0	5	5	0	0
16008600	West Pike	708128.0	5329680.0	5	5	4	4
16035400	Winchell	679256.0	5318140.0	5	5	0	2
01004600	Ball Bluff	478651.0	5197700.0	4	4	0	0
16014700	Flour	693783.0	5325350.0	4	2	0	0
38037200	Fraser	634053.0	5318890.0	4	2	0	0
16031900	Gaskin	682846.0	5319510.0	4	2	0	0
16058000	Granite	666146.0	5335850.0	4	4	0	0
31077800	Little Too Much	441738.0	5274880.0	4	4	0	0
01008900	Long	462404.0	5148280.0	4	4	0	0
31078100	Long	441433.0	5280740.0	4	4	0	0
31021900	O'Reilly	467570.0	5245500.0	4	4	0	0
16004100	Pine	707341.0	5327100.0	4	4	0	0
31021800	Shamrock	468692.0	5245840.0	4	4	0	0
29023900	Spearhead	352132.0	5248390.0	4	4	0	0
11046900	Anway	376737.0	5211040.0	3	1	0	0
29004800	Benedict	371657.0	5221980.0	3	1	0	0

Table 5.16 (cont'd.)

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
29018400	Blue	347677.0	5209100.0	3	1	0	0
11086600	Tamarack	401048.0	5202160.0	3	3	0	0
31027800	Barwise	468711.0	5267270.0	2	2	0	0
69011800	Burntside	581302.0	5310720.0	2	2	0	0
15001000	Elk	331973.0	5228580.0	2	2	0	0
16061700	Gneiss	662965.0	5338100.0	2	2	0	0
16007700	Greenwood	710490.0	5320110.0	2	2	0	0
31046600	Horseshoe	461830.0	5272270.0	2	2	0	0
21010600	Latoka	310959.0	5082980.0	2	1	0	0
21010800	Mina	307985.0	5085170.0	2	2	0	0
16023000	Rose	690083.0	5330660.0	2	2	0	0
16062900	Sea Gull	654464.0	5333260.0	2	2	0	0
04008500	Swenson	373092.0	5258540.0	2	2	0	0
38035100	Thomas	631603.0	5316590.0	2	2	0	0
16026700	Vernon	680957.0	5312910.0	2	2	0	0
86027900	West Lake Sylvia	404790.0	5011290.0	2	1	0	0
77002400	Bass	366498.0	5085360.0	1	1	0	0
21005700	Carlos	316947.0	5091130.0	1	1	0	0
18029800	East Fox	417710.0	5177450.0	1	1	0	0
18039600	Edna	399225.0	5154230.0	1	1	0	0
11017400	Girl	405649.0	5204090.0	1	1	0	0
31037300	Hale	458520.0	5232670.0	1	1	0	0
01005700	Little Ball Bluff	479174.0	5198320.0	1	1	0	0
31057500	Little Bass	454599.0	5237110.0	1	1	0	0
09003500	Little Hanging Horn	524719.0	5147700.0	1	1	0	0
31039900	Little Wabana	462902.0	5249760.0	1	1	0	0
31057100	Loon	451222.0	5231220.0	1	1	0	0
18037800	Lower Hay	401812.0	5169230.0	1	1	0	0
11028200	Mann	397848.0	5203010.0	1	1	0	0
56082900	Pebble	265969.0	5126590.0	1	1	0	0
56036000	Rose	290565.0	5172740.0	1	1	0	0
18031100	Rush-Hen	413972.0	5171730.0	1	1	0	0
31008400	Shallow	477729.0	5219260.0	1	1	0	0
29011700	Spider	358726.0	5206440.0	1	1	0	0
31039200	Wabana	460476.0	5252590.0	1	1	0	0

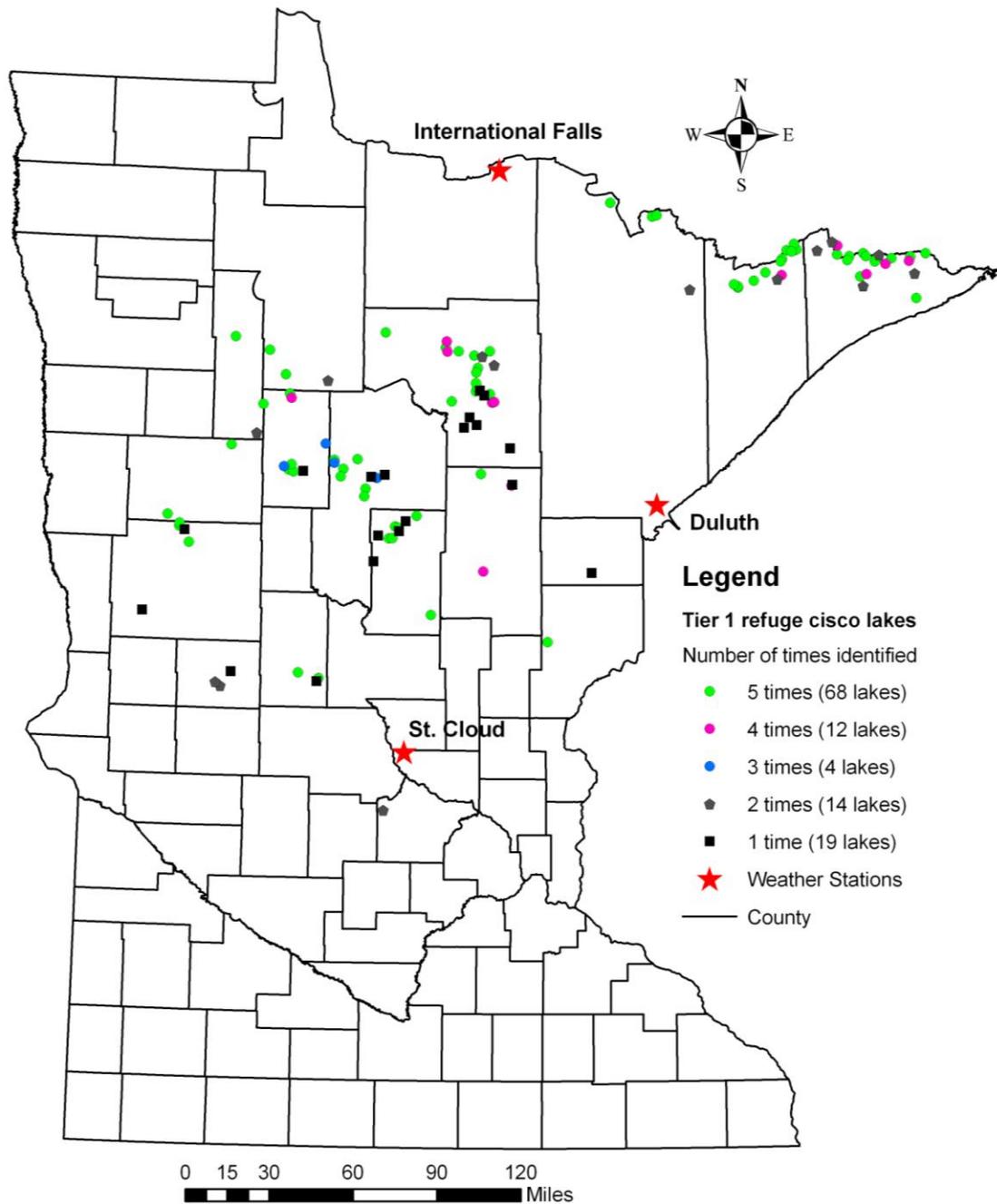


Figure 5.22 Geographic distribution of **Tier 1 cisco refuge lakes** for the **MIROC 3.2 future climate scenario** using $AvgATDO3_{FB}$ (Table 3.1 line 6) in the fixed benchmark period and **five options for the pairing of a lake with a weather station**. The number of times that a lake was identified as Tier 1 refuge lake is indicated in the legend.

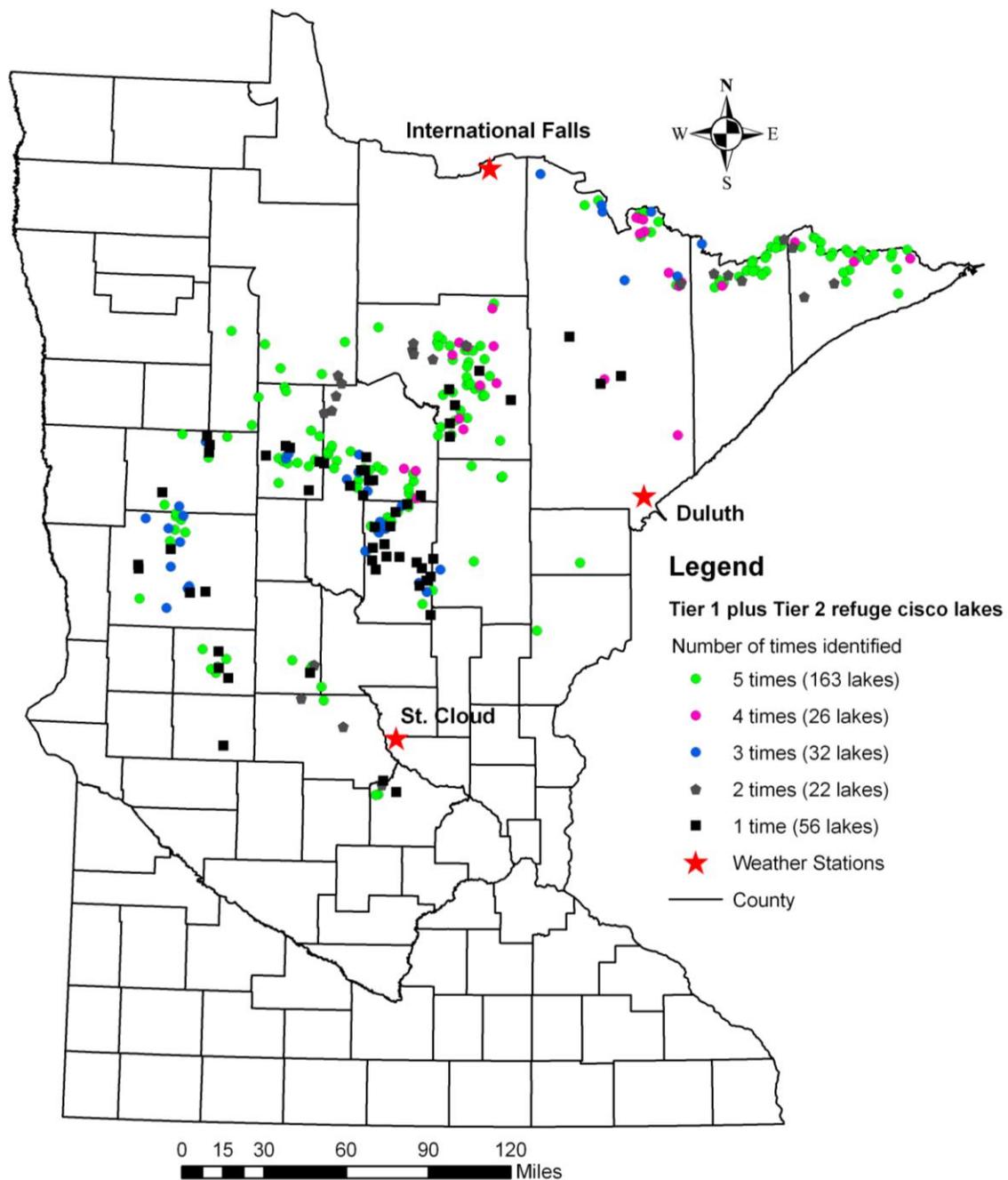


Figure 5.23 Geographic distribution of **Tier 1 plus Tier 2** cisco refuge lakes for the **MIROC 3.2 future climate scenario** using **AvgATDO3_{FB}** (Table 3.1 line 6) in the fixed benchmark period and **five options for the pairing of a lake with a weather station**. The number of times that a lake was identified as a Tier 1 or a Tier 2 refuge lake is indicated in the legend.

5.7.3 Cisco lakes within 2°C bands of TDO3 contour lines (isotherms)

Another approach to the selection of refuge lakes is to rank all cisco lakes according to where a cisco lake is located between TDO3 contour lines. For the selection of Tier 1 and Tier 2 refuge lakes, and Tier 3 or non-refuge lakes, we used only two TDO3 contour lines or isotherms (11°C and 17°C). To refine the ranking of the 620 cisco lakes in Minnesota we divided them into narrower bands between contour lines. Increments of 2°C between TDO3 contour lines from 5°C to 23°C were first selected. Cisco lakes in Minnesota were therefore grouped into the following ten TDO3 intervals: 5 – 7°C, 7 – 9°C, 9 – 11°C, 11 – 13°C, 13 – 15°C, 15 – 17°C, 17 – 19°C, 19 – 21°C, 21 – 23°C, and > 23°C. Nine TDO3 contour lines (from 5 to 25 °C in 2°C increments) and 620 cisco lakes were plotted in the previously used coordinate system of Secchi depth (SD) versus lake geometry ratio (GR) (Figs. 5.24 and 5.25). The TDO3 contour lines from 5°C to 23°C used to group cisco lakes were derived by interpolation from simulated points for the 30 virtual lakes.

Figure 5.24 and 5.25 show the distribution of all 620 cisco lakes between contour lines of **AvgATDO3_{FB}** and **AvgATDO3_{VB}** (Table 3.1, lines 6 and 12) for fixed and variable benchmark periods, respectively, simulated using Duluth weather data and the MIROC 3.2 future climate scenario. There are some contour lines of TDO3 with values greater than 23°C in Figs. 5.24 and 5.25, but we did not rank cisco lakes for TDO3 > 23°C. The geographic distribution of all 620 cisco lakes grouped between contour lines of **AvgATDO3_{FB}** (Table 3.1, line 6) in Fig. 5.24 is shown in Fig. 5.26. TDO3 intervals and the number of cisco lakes in each interval (2°C increment) are shown in the legend.

Table 5.17 Number of cisco lakes between 2°C TDO3 contour lines simulated using Duluth weather data for the MIROC 3.2 future climate scenario for fixed and variable benchmark periods (**AvgATDO3_{FB}**, **AvgATDO3_{VB}**, Table 3.1, lines 6 and 12).

Fixed Benchmark Period		Variable Benchmark Periods	
TDO3 values	Number of lakes	TDO3 values	Number of lakes
5 - 7°C	15	N/A	
7 – 9°C	42	< 9°C	3
9 – 11°C	30	9 – 11°C	23
11 – 13°C	39	11 – 13°C	27
13 – 15°C	41	13 – 15°C	35
15 – 17°C	51	15 – 17°C	67
17 – 19°C	162	17 – 19°C	123
19 – 21°C	169	19 – 21°C	261
21 – 23°C	43	21 – 23°C	52
>23°C	28	>23°C	29

Table 5.17 gives the number of cisco lakes that are found in each of the ten TDO3 intervals (2°C increment). The results of TDO3 are from the same simulations used in Figs. 5.24 and 5.25. As many as 169 and 261 cisco lakes (or 27% and 42% of the 620 cisco lakes) fall within the interval 19–21°C when fixed and variable benchmark periods were used to calculate TDO3 values, respectively. If number of lakes between 2°C contour lines is regrouped as two contour lines (11°C and 17°C) for identifying Tier 1 to 3 refuge lakes, results presented in Table 5.17 are consistent with results presented in Tables 5.3 and 5.4 for Duluth weather station.

Names and geographic locations of all 620 cisco lakes in Minnesota grouped by 2°C TDO3 contour lines are listed in Appendix F. Lakes in Table F.1 are sorted from lowest to highest TDO3 interval first and then sorted by lake name alphabetically for lakes within the same contour interval. Table F.1 can be very useful cisco lake management program to develop a strategy conservation and protection efforts on different cisco lakes.

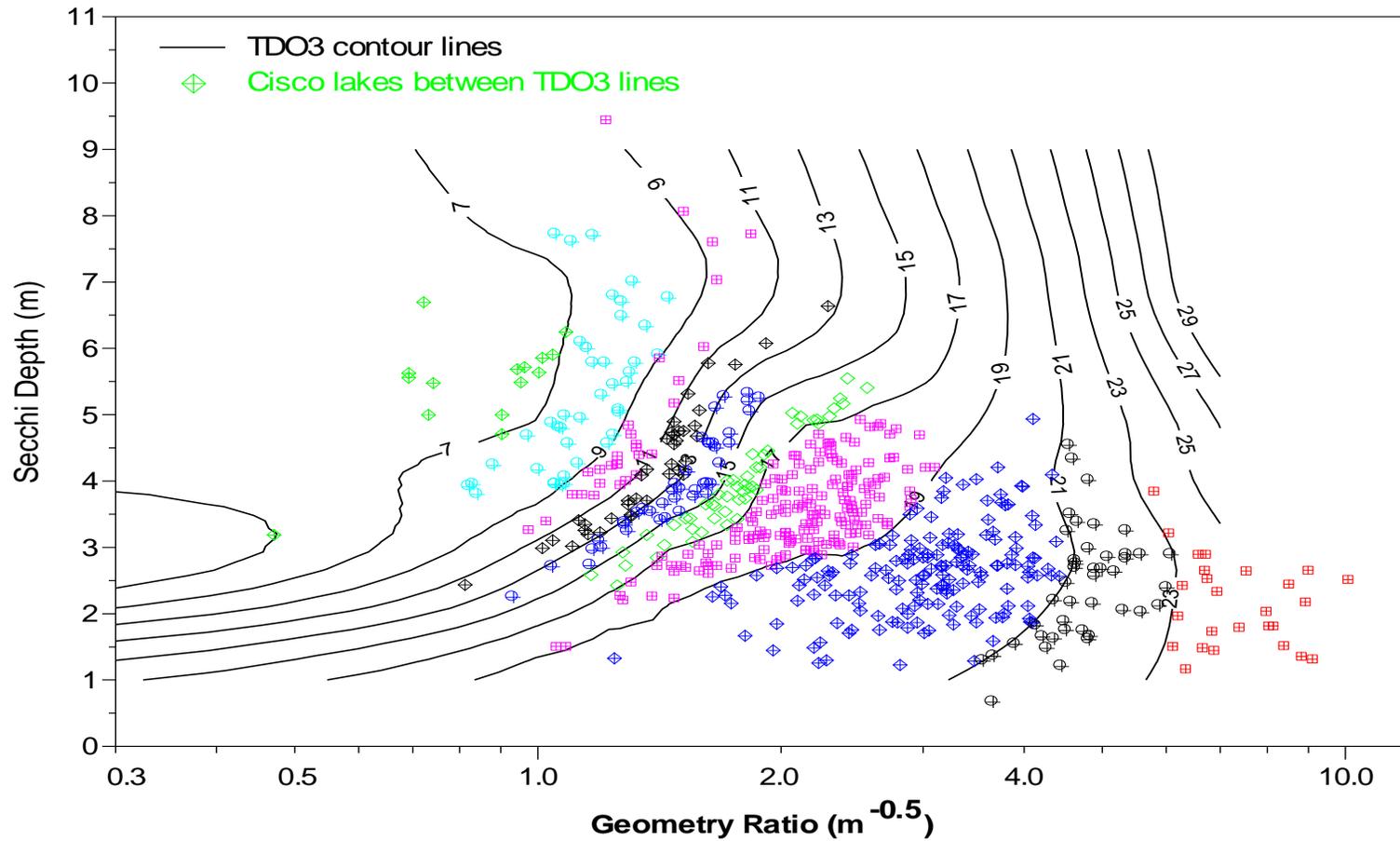


Figure 5.24 Distribution of 620 cisco lakes between 2°C contour lines of AvgATDO3_{FB} (Table 3.1, line 6) for **fixed benchmark period** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

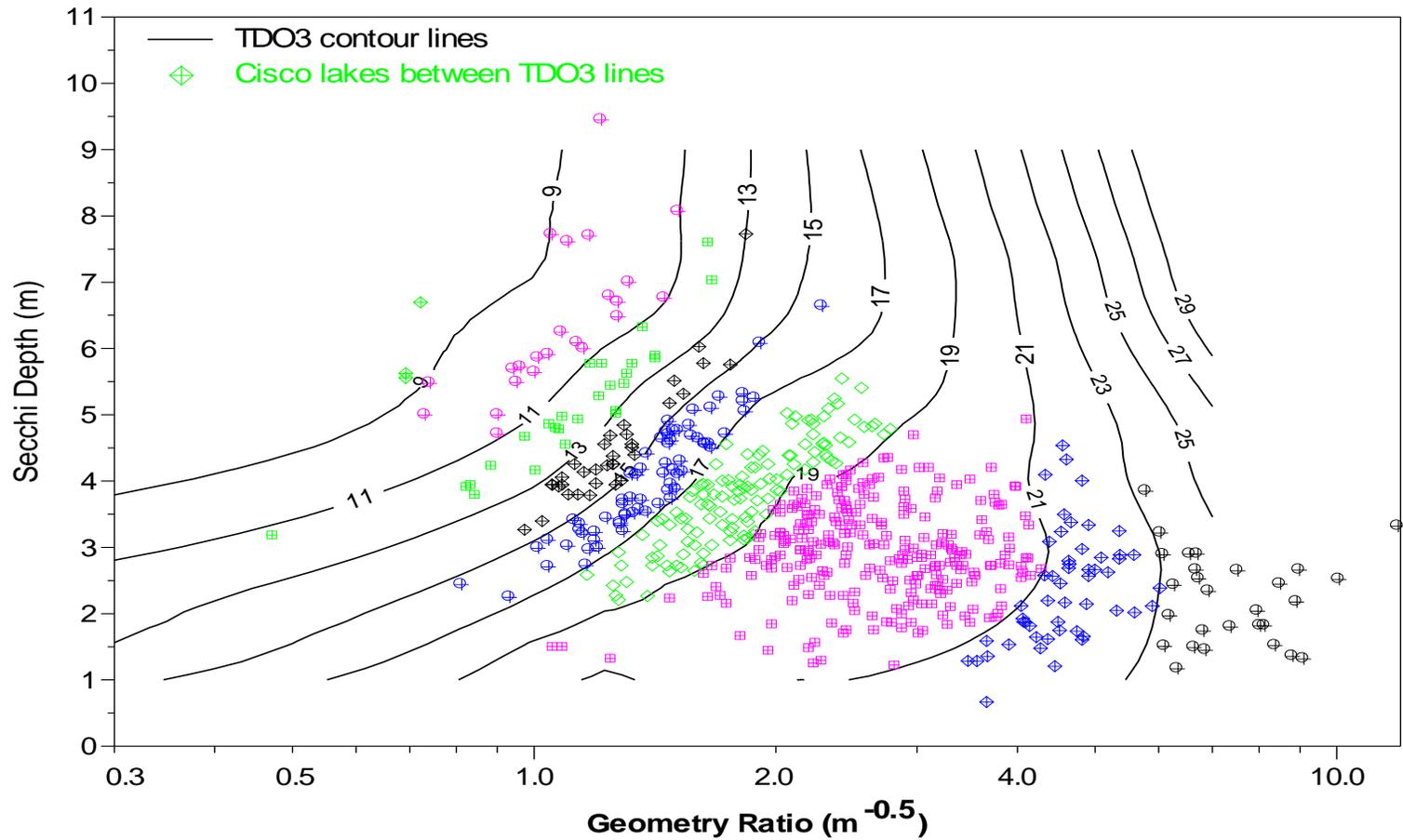


Figure 5.25 Distribution of 620 cisco lakes between 2°C contour lines of $\text{AvgATDO3}_{\text{VB}}$ (Table 3.1, line 12) for **variable benchmark periods** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

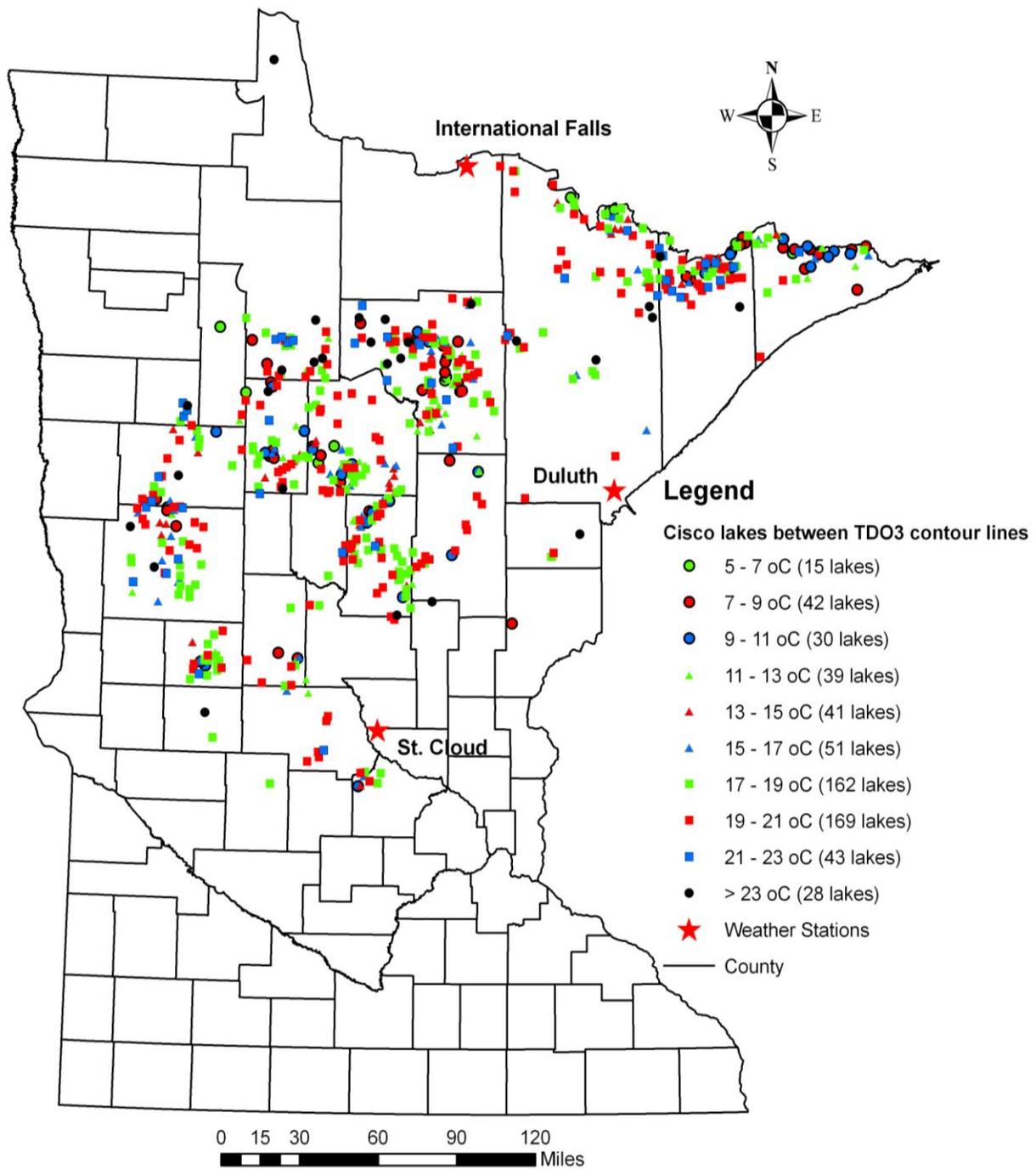


Figure 5.26 Geographical distribution of 620 cisco lakes with different $\text{AvgATDO3}_{\text{FB}}$ (Table 3.1, line 6) values in a fixed benchmark period. Results are for the **MIROC 3.2 future climate scenario** using **Duluth weather data**. Bands of 2°C TDO3 increment values and numbers of cisco lakes that fall within a band are given in the legend.

5.7.4 Cisco lakes within 1°C bands of TDO3 contour lines (isotherms)

To further refine the ranking of the 620 cisco lakes in Minnesota we divided them into further narrower bands between contour lines. Increments of 1°C between TDO3 contour lines from 5°C to 24°C were selected. Cisco lakes in Minnesota were therefore grouped into the following 25 TDO3 intervals: 5 – 6°C, 6 – 7°C, ..., 23 – 24°C and > 24 °C (Table 5.18). For 1°C increment of TDO3 values, e.g., 5 – 6°C, lakes were grouped for TDO3 > 5°C but ≤ 6°C. Twenty-five TDO3 contour lines (from 5 to 24 °C in 1°C increments) and 620 cisco lakes were plotted in the previously used coordinate system of Secchi depth (SD) versus lake geometry ratio (GR) (Figs. 5.27 and 5.28). The TDO3 contour lines from 5°C to 24°C used to group cisco lakes were derived by interpolation from simulated points for the 30 virtual lakes.

Figure 5.27 and 5.28 show the distribution of all 620 cisco lakes between 1°C contour lines of **AvgATDO3_{FB}** and **AvgATDO3_{VB}** (Table 3.1, lines 6 and 12) for fixed and variable benchmark periods, respectively, simulated using Duluth weather data and the MIROC 3.2 future climate scenario. There are some contour lines of TDO3 with values greater than 24°C that are not shown in Figs. 5.27 and 5.28, but we did not rank cisco lakes for TDO3 > 24°C because the lethal temperature for coldwater fish species was 23.4°C (Stefan et al. 2001). The results of TDO3 in Figs. 5.27 and 5.28 are from the same simulations used in Figs. 5.24 and 5.25 but are plotted for 1°C increment.

Table 5.18 gives the number of cisco lakes that are found in each of the 25 TDO3 intervals (1°C increment). As many as 107 and 90 cisco lakes (or 17% and 15% of the 620 cisco lakes) fall within the interval 18 – 19°C when fixed and variable benchmark periods were used to calculate TDO3 values, respectively. Results presented in Table 5.18 are consistent with results presented in Tables 5.3, Table 5.4 (for Duluth weather station) and 5.17 if number of lakes between 1°C contour lines is regrouped as two contour lines (11°C and 17°C) for identifying Tier 1 to 3 refuge lakes or 2°C bands for ranking cisco lakes.

Table 5.18 Number of cisco lakes between 1°C TDO3 contour lines simulated using Duluth weather data for the MIROC 3.2 future climate scenario for fixed and variable benchmark periods (AvgATDO3_{FB}, AvgATDO3_{VB}, Table 3.1, lines 6 and 12).

Fixed Benchmark Period		Variable Benchmark Periods	
TDO3 values	Number of lakes	TDO3 values	Number of lakes
5 - 6 °C	1	5 - 6 °C	0
6 - 7 °C	13	6 - 7 °C	0
7 - 8 °C	23	7 - 8 °C	0
8 - 9 °C	17	8 - 9 °C	3
9 - 10 °C	18	9 - 10 °C	10
10 - 11 °C	18	10 - 11 °C	14
11 - 12 °C	18	11 - 12 °C	15
12 - 13 °C	23	12 - 13 °C	11
13 - 14 °C	20	13 - 14 °C	18
14 - 15 °C	18	14 - 15 °C	19
15 - 16 °C	16	15 - 16 °C	31
16 - 17 °C	36	16 - 17 °C	35
17 - 18 °C	54	17 - 18 °C	36
18 - 19 °C	107	18 - 19 °C	90
19 - 20 °C	107	19 - 20 °C	164
20 - 21 °C	64	20 - 21 °C	93
21 - 22 °C	32	21 - 22 °C	43
22 - 23 °C	7	22 - 23 °C	9
23 - 24 °C	12	23 - 24 °C	12
> 24 °C	15	> 24 °C	16

Names and geographic locations of all 620 cisco lakes in Minnesota grouped by 1°C TDO3 contour lines are listed in Appendix G. Lakes in Table G.1 are sorted from lowest to highest TDO3 interval first and then sorted by lake name alphabetically for lakes within the same contour interval. Table G.1 can be very useful cisco lake management program to develop a strategy conservation and protection efforts on different cisco lakes.

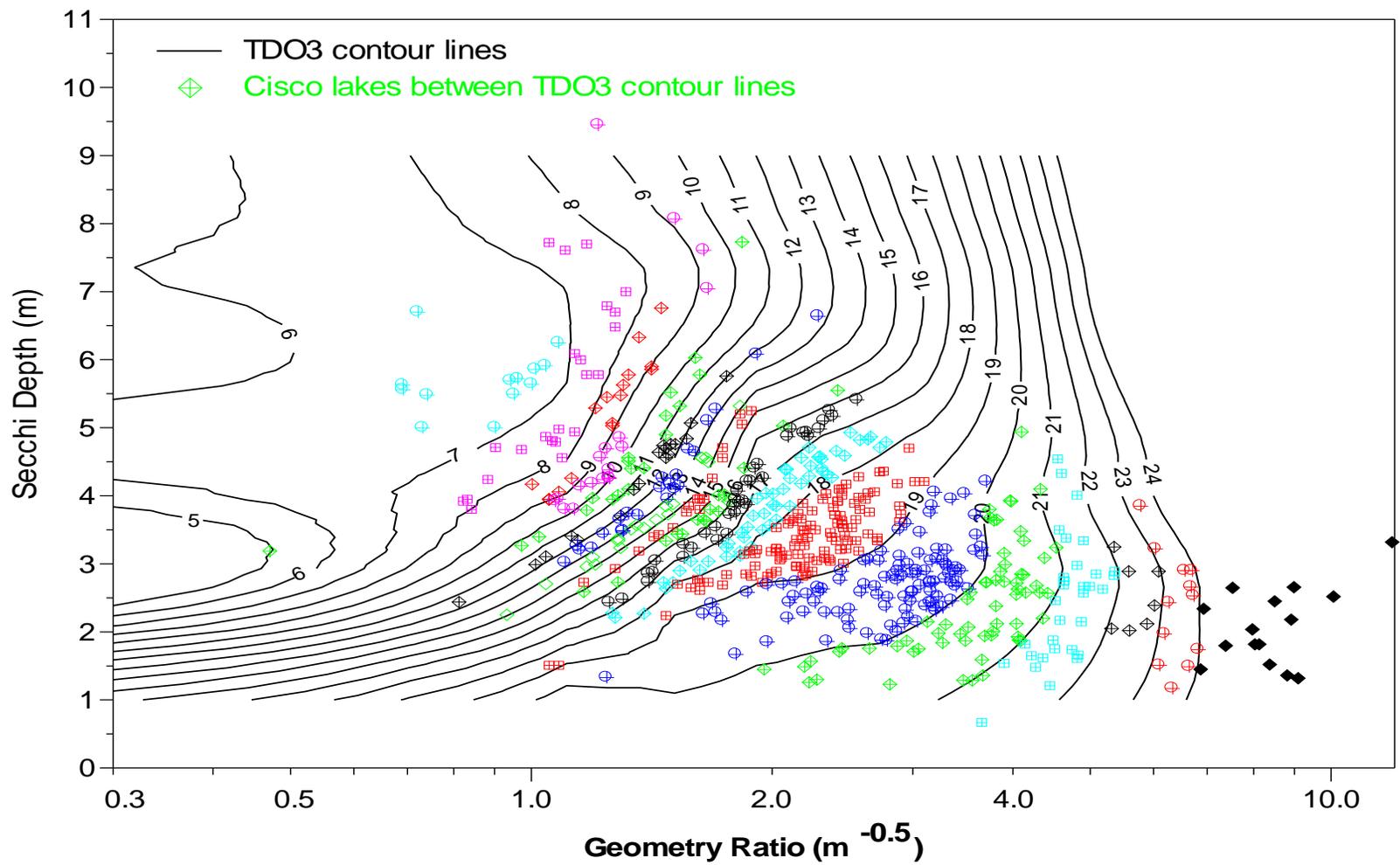


Figure 5.27 Distribution of 620 cisco lakes between 1°C contour lines of AvgATDO3_{FB} (Table 3.1, line 6) for **fixed benchmark period** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

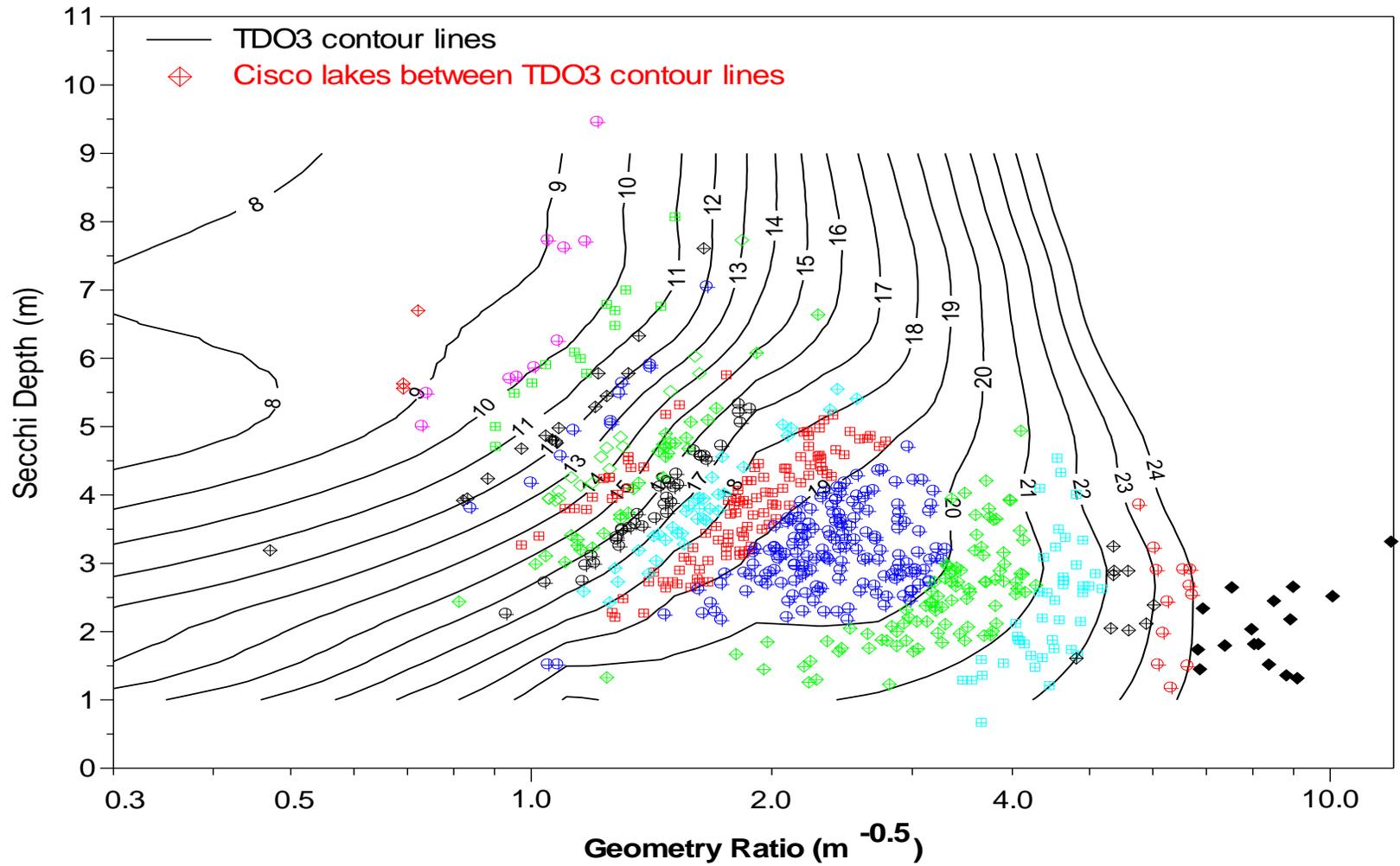


Figure 5.28 Distribution of 620 cisco lakes between 1°C contour lines of $\text{AvgATDO3}_{\text{VB}}$ (Table 3.1, line 12) for **variable benchmark periods** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

Chapter 6 Summary and Conclusion

6.1 Summary

This is the third and final project report of the project “Identification of potential coldwater refuge lakes important for sustaining cisco habitat under climate warming scenarios in Minnesota” for the Minnesota Department of Natural Resources. Cisco (tullibee, lake herring), is a valuable coldwater fish in Minnesota lakes.

The first project report (Fang et al. 2009) gave an overview of the characteristics of cisco lakes in Minnesota. The second project report (Fang et al. 2010) described the development of the water quality model MINLAKE2010 and results of water temperature and dissolved oxygen (DO) model simulations for selected Minnesota (cisco) lakes. This third report gives the numbers and names of Minnesota lakes in which cisco habitat is most likely to continue to exist under global warming scenarios. The current cisco lakes are ranked by an oxythermal parameter (TDO3) that measures stress on adult cisco. This third report describes the methodology and results of computer model simulations of cisco habitat in Minnesota lakes. The results are projections of potential cisco ‘refuge lakes’ under projected warmer climate scenarios in Minnesota.

This report has six chapters. Chapter 1 introduces the concepts and general methodology used to evaluate cisco habitat in lakes. It also introduces 21 actual cisco study lakes and 30 virtual cisco lakes in Minnesota. Both were used in the model simulations of water quality and cisco habitat.

Chapter 2 is about future climate scenarios. The chapter introduces General Circulation Models (GCMs) of the earth’s atmosphere, and how the results of these models are used to quantify the many available future climate scenarios. Options for the selection of climate scenarios are presented, and the selection of the GCM 2.0, CGCM 3.1 and the MIROC 3.2 future climate scenarios for this projected is discussed. In the end, the chapter explains how climate input data are generated for the MINLAKE2010 simulation model that was used to simulate daily water temperature and DO profiles in a lake.

Chapter 3 gives a general discussion of the oxythermal habitat descriptors or parameters that can be used to characterize fish habitat in a lake. Adult cisco habitat is severely limited by critical water temperature and dissolved oxygen (DO) conditions in different strata of a cisco lake. The oxythermal variable TDO3 (Jacobson et al. 2010) that is used in this study to separate viable from non-viable cisco habitat is introduced. TDO3 relates to the survival stress of adult cisco; the lower the TDO3, the lower the stress is to cisco. TDO3 is a water temperature that occurs where DO = 3 mg/L (Jacobson et al. 2010).

Methods to determine time series of daily TDO3 values from simulated daily temperature and DO profiles are discussed. Because fish are unlikely to respond to daily TDO3 values alone, biologically meaningful ‘TDO3 parameters’ must be extracted from the daily TDO3 time series.

These ‘TDO3 parameters’ can be averages or extreme values of daily TDO3 values over monthly and multi-year timescales. This is a central issue of this study, because the ‘TDO3 parameters’ relate daily water quality characteristics in a lake to long-term fish responses.

Twelve options for TDO3 parameters were identified (Table 3.1), although there are more. They range from single-day values to multi-year averages, and from extreme values to average values. They were defined in Table 3.1 and calculated from simulated daily temperature and DO profiles. Two TDO3 parameters (AvgATDO3_{FB} and AvgATDO3_{VB}) were selected to characterize cisco habitat in this study following the analysis of field data by Jacobson et al (2010). The selected TDO3 parameters are averages of daily TDO3 over 31-day benchmark periods. Annual maxima of these benchmark averages and multi-year averages over the entire simulation period of 47 years were also considered as options. Benchmark periods were either between fixed calendar days (DOY 209 to DOY 239, i.e. July 28 to August 27, 31 days) or sliding 31-day periods from which the highest TDO3 parameter values were selected.

At the end of Chapter 3 time-series of the selected TDO3 parameters in selected lakes and ranges of TDO3 parameter values in selected lakes are analyzed to project if a lake can be a cisco refuge lake. The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to 2008 were used. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes in Chapter 5.

Chapter 4 presents the results of numerous simulations of selected TDO3 parameters in tabular or graphical form. The graphs are in a format that was used very successfully in previous studies: TDO3-values are presented as isolines on a coordinate system of lake geometry ratio GR vs. Secchi depth SD. GR and SD appear to be sufficient to represent essential features of different lake types, GR characterizes the potential for stratification and mixing dynamics, and SD characterizes transparency, but also trophic state as a surrogate, at least in most Minnesota lakes. Lake turbidity from suspended inorganic sediment is relatively rare in Minnesota, and total phosphorus or chlorophyll *a* in most Minnesota lakes are well correlated with SD. Monthly variations in these parameters follow well-established generic patterns in Minnesota lakes. Numerical values of TDO3 given in tables and graphs of Chapter 4 were generated by MINLAKE2010 with daily weather data input representative of past climate and the above mentioned three future climate scenarios.

Cisco habitat simulations were first made for continuous, year-round weather time series from 1962 to 2008 (47 years) at the daily time scale. Simulations were then extended to projected future climate scenarios. A year-round water quality model MINLAKE 2010, that had previously been calibrated against 7384 pairs of temperature and DO data points measured in 28 cisco study lakes between 1979 and 2008 with overall standard errors of 1.47 °C for water temperature, and 1.5 mg/L for DO, was used in all cisco habitat simulations. Year-round water temperatures and DO concentrations in Minnesota cisco lakes ranged from 0 to 26 °C and 0 to 16 mg/L, respectively.

In Chapter 5 of this report the key and final results are presented. Refuge lakes for cisco are selected (identified). Each simulated lake had to be paired with a weather station, but useful

data were available only from three Class I NWS weather stations. Three options (methods) were used to pair each lake with one of the three weather stations: (1) using one single weather station for all lakes, (2) assigning a lake according to the shortest distance to a weather station, and (3) by pairing lakes and weather stations according to latitude. Refuge lakes were determined using all three options.

For refuge lake selection, the pool of 620 Minnesota cisco lakes was divided into three tiers. Tier 1 for a $TDO3 \leq 11^{\circ}\text{C}$, Tier 2 for the range $11^{\circ}\text{C} < TDO3 \leq 17^{\circ}\text{C}$, and Tier 3 for $TDO3 > 17^{\circ}\text{C}$. Tier 1 and Tier 2 were identified as cisco refuge lakes, Tier 3 as non-refuge lakes for cisco. This decision was based on Jacobson et al. (2010). Tier 1 has the most suitable coldwater fish habitat, Tier 2 has suitable coldwater fish habitat, and Tier 3 is considered unsuitable for coldwater fish. These ranges are defined by fairly stringent limiting TDO3 temperatures. Tier 1 and Tier 2 refuge lakes identified may be called viable cisco lakes where cisco is capable of living, developing, or spawning under favorable conditions. Cisco can still persist in lakes with TDO3 values greater than 17°C but at a reduced probability of occurrence (Jacobson et al. 2010). The TDO3s used for the refuge lake selection were simulated for the future climate scenarios CGCM 3.1 and MIROC 3.2. The $\text{AvgATDO3}_{\text{FB}}$ and $\text{AvgATDO3}_{\text{VB}}$ values, defined in Table 3.1, lines 6 and 12, were the actual ‘TDO3 parameters’ applied to select the refuge lakes.

Results are presented in tables or in graphical form. Graphs use isolines of selected TDO3 parameter values in a diagram of Secchi depth (as an indicator of lake trophic state) vs. lake geometry ratio (as an indicator of lake stratification and mixing dynamics), as described in Chapter 4. These contour plots of selected TDO3 values were interpolated from data points for the 30 virtual cisco lakes for both past climate conditions and two future climate scenarios. Cisco refuge lakes in Minnesota were identified for the two future climate scenarios CGCM 3.1 and MIROC 3.2 as Tier 1 or Tier 2 refuge lakes as defined above.

The number of lakes that qualify as cisco refuge lakes depends, of course, on the assumptions and choices made in the method of selection and the climate scenarios. Projections made for past climate conditions (1962 to 2008) identified on average 487 lakes or 78% of 620 cisco lakes investigated as viable (Table 5.13). This hindcasting is considered to be a good validation of the methodology used for refuge lake selection. It is also indication of a conservative approach for the projection of cisco refuge lakes under future climate warming scenarios, because no overpredictions were made by any of the methods used.

Another model validation was made by comparing the names of the 16 lakes that experienced cisco mortality in the exceptionally warm summer of 2006 to the names of identified cisco refuge lakes (Table 5.14). None of the 16 lakes had been identified as a Tier 1 refuge lake, but 10 had been identified as Tier 2 refuge lakes by more than 2 methods. Five other cisco lakes that had no documented cisco kill in 2006 had all been identified as Tier 1 cisco refuge lakes. The comparison is not very rigorous, because the projections were made with 47-year averages of TDO3s, whereas the recurrence interval of the single year cisco kill event occurred in is unknown.

6.2 Conclusion

The conclusion of this study is that under fairly stringent selection criteria ($\text{DO} > 3 \text{ mg/L}$ and $\text{TDO3} \leq 17^\circ\text{C}$) at least one fourth to one third of the lakes that currently have cisco populations, are projected to maintain cisco habitat under projected future climate scenarios (Table 5.15). Many such ‘refuge’ lakes are located in northeastern and central Minnesota (Figures 5.22 and 5.23).

Tier 1 plus Tier 2 refuge lakes selected e.g. under the future climate scenario MIROC 3.2 have Secchi depths greater than $\approx 2.5 \text{ m}$ (Fig. 5.18), lake geometry ratio less than $\approx 2.5 \text{ m}^{-0.5}$ (Fig. 5.19), maximum depths greater than $\approx 15 \text{ m}$ (Figure 5.20), and surface areas less than $\approx 30 \text{ km}^2$ (Figure 5.21).

The number of refuge lakes determined, e.g., for the future climate scenarios MIROC 3.2, varies depending on the selection method used (Tables 5.3 to 5.13). Tier 1 refuge lakes are listed by name in Table 5.16 and are grouped in five batches according to the number of methods by which they were identified. Lakes on top of Table 5.16 are presumed to be the best candidates for cisco refuge lakes. The lakes on the list have been plotted on a map of Minnesota in Figure 5.22.

Instead of dividing the 620 cisco lakes into three tiers, individual cisco lakes can be ordered (ranked) by the number of times that they were identified as Tier 1 plus Tier 2 refuge lakes by the five options to pair a lake with a weather station (Appendix E) and their respective TDO3 values. Therefore, 620 cisco lakes in Minnesota were assembled in narrow (2°C and 1°C) bands of TDO3 values (Figures 5.24, 5.25, 5.27, and 5.28). Names and locations of lakes in each band are given in Appendix F (2°C band) and Appendix G (1°C band). Lakes on top of the list (Tables F.1 and G.1) are again presumed to be the best candidates for cisco refuge lakes because they are for the lowest TDO3 values, and low TDO3 values are presumed to reflect the least stress on adult cisco. The number of lakes in each band of TDO3 values is given in Tables 5.17 and 5.18.

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