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Potential Changes in Thermal Structure and Cycle of Lake Michigan Due to Global Warming

MICHAEL J. MCCORMICK

National Oceanic and Atmospheric Administration
Great Lakes Environmental Research Laboratory
2205 Commonwealth Boulevard, Ann Arbor, Michigan 48105, USA

Abstract.—I used a one-dimensional numerical model to estimate the present and possible future temperature structures in Lake Michigan. The estimates were based on model output from simulations of the 1981–1984 offshore temperature field. Once the water temperature climatology was estimated, I examined three scenarios based on general circulation models in which atmospheric CO_2 was doubled. The models were those of the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU). In general, simulations based on these three scenarios suggested that winter and summer heat contents of the lake would be higher than at present; the summer increase would be less than that in winter. The higher winter heat content would cause an earlier onset of full thermal stratification, and the season of stratification would increase by up to two months. The earlier onset of stratification, coupled with little change in the wind stress pattern, would yield stronger stratification and less energy for large-scale vertical mixing. The GISS and GFDL scenarios suggest that the lake may not fully turn over in most winters, so a permanent thermocline may form in the deeper regions of Lake Michigan, below the shallow seasonal thermocline. Should future wind speeds be reduced from those I used here, sensitivity analyses suggest that the true effect on the annual thermal cycle and structure may be underestimated. Furthermore, given all of the uncertainties surrounding estimates of future climate, these results are best viewed as a sensitivity study, wherein the scales selected for the sensitivity tests are based upon the different general circulation model scenarios.

A growing concern over the potential effects of a possible change in the future climate continues to motivate research. The work reported here describes the simulated temperature field of Lake Michigan under both present and future climate scenarios, the latter based on three atmospheric general circulation models. These calculated temperature distributions can be used in fisheries recruitment studies. Given all of the uncertainties surrounding estimates of future climate, these results are best viewed as a sensitivity study wherein the scales selected for the sensitivity tests are based upon the different general-circulation model outputs. The remainder of this paper will focus on how the present (Base) and future water temperature scenarios were estimated and on their physical implications.

Background

Lake Michigan extends over 57,000 km^2; its maximum depth is 281 m and its mean depth is 85 m. Because of its large size, the dominant controlling physics of its environment is more similar to oceanic situations than to "small" lakes. Water temperature is one of the most fundamental physical properties and accurate knowledge of its distribution is often required to solve oceanographic and limnological problems. Before a future temperature structure and cycle can be estimated, the present water temperature climatology must be determined. Climatological water temperatures are the mean temperatures that result from averaging data over long time spans, typically 30 years. There are insufficient data describing temperature distributions in the Great Lakes to formulate water temperature climatologies from observation alone. For example, Feit and Goldenberg (1976) determined surface water temperature climatologies for Lakes Superior, Huron, Erie, and Ontario but the record lengths were short, ranging from only 4 to 10 years. Although records of municipal water intake temperatures of much longer duration exist for many Great Lakes locations, the nearshore locations of the intake structures makes them a poor source of data to be used in constructing meaningful water temperature climatologies. Other data sets from more favorable locations exist but their poor temporal coverage precludes their use as well.

To date, the most comprehensive data set of Lake Michigan temperatures in offshore waters was obtained by the National Data Buoy Center in the central southern basin (42.7°N, 87.1°W) of the lake from 1981 to 1984. The Buoy Center deployed a meteorological buoy with an attached thermistor string during the 1981–1984 shipping season only, and the thermistor string provided data on the top

50 m of the 150-m-deep water column. The buoy's data set was supplemented by hourly temperatures recorded from a nearby current meter mooring (2.4 km due south of the buoy's location) during 1982–1984. The current meter data provided information on the winter temperature structure and on the temperature behavior at depth. The combination of these two data sets did not fulfill all of the needs for generating a water temperature climatology. The only alternative was to estimate the present climatology by modeling the temperature field and to use these two data sets for model verification.

Methods

Mixed Layer Model

I used the one-dimensional Garwood (1977) model to estimate both the water temperature climatology of Lake Michigan and potential changes that may occur should the climate change. Intermodel comparisons by McCormick and Meadows (1988) and Martin (1985) demonstrated the success of this model in simulating the seasonal temperature cycles of inland seas and the open ocean, respectively. The version of Garwood's model I used here was described by McCormick and Meadows (1988). Briefly, the model is one-dimensional in the vertical and is based on the turbulence kinetic energy budget. In summer, the thermal structure at any given time generally depends on the dynamic balance between wind stress, which tends to destabilize and mix the water column, and a positive surface heat flux, which warms surface waters and tends to stabilize the water column and retard mixing. In winter, when the lake is cooling and surface heat flux is negative, wind-stress effects on mixing are supplemented by convective mixing that is generated from gravitational instabilities due to surface cooling. These and other important processes are expressed in the turbulence kinetic energy equation.

Two of the processes in the turbulence kinetic energy budget that also affect the vertical distribution of temperature are viscous dissipation and entrainment due to shear instabilities at the mixed layer base. The version of the Garwood model I used allows the mixed layer to deepen due to turbulent erosion and shear mechanisms. McCormick and Meadows (1988) added the shear instability source to the model and assumed that the major shear sources were pure inertial oscillations generated by the wind. Observations on the frequency distribution of kinetic energy in the Great Lakes support this interpretation (e.g., Saylor et al. 1980; Boyce and Chiocchio 1987). I estimated this contribution to the turbulence kinetic energy budget by estimating the shear strength from Thompson (1976).

If mixed layer deepening is to be described realistically for all possible forcing conditions, energy dissipation must be explicitly included in the turbulence kinetic energy budget. Garwood (1977) modeled dissipation on two scales. In the first dissipation process, energy is removed in proportion to the magnitude of the total turbulence kinetic energy; in the second, energy loss is proportional to both the turbulence kinetic energy and the depth of the mixed layer. This treatment of dissipation is advantageous to long-term simulation because it avoids the possible carry-over and buildup of potential energy over annual time scales. Thus, under well-behaved forcing conditions, cyclic solutions are possible.

Simulation of the winter temperature structure revealed the need to reevaluate the physics of the model. First, the cold winter temperatures of 1982 forced the modeled surface water temperatures to freezing conditions on several days. No facilities are included in the model to properly account for ice formation, buildup, and decay. Therefore, the surface temperature was artificially constrained to always be greater than or equal to zero. The modeled surface heat flux during these episodes was set equal to surface irradiance only and thus does not represent true surface heat flux. These episodes were infrequent and did not seriously bias the monthly averaged estimate of the surface heat flux. Second, Farmer and Carmack (1981) noted the important influence of the nonlinear pressure–temperature term on water density when temperatures are near the temperature of maximum density. The interaction between pressure and temperature has a strong influence on the depth of the mixed layer in deep lakes like Lake Michigan in winter. Hence, in contrast to most mixed layer modeling efforts, I retained the pressure–temperature term in the equation of state (Chen and Millero 1986) and used it for all density and stability calculations.

Water Temperature Data

During the ice-free months of 1981–1984, the National Data Buoy Center hung a thermistor string from their buoy. Nine thermistors were positioned about every 5 m within the top 50 m of the water column. Temperatures were recorded at hourly intervals but the data return and quality

were less than ideal. At no time were all thermistors operational; at various times as few as two thermistors and as many as seven were recording useful data. Furthermore, analyses of the low-frequency response of the data suggested that thermistor accuracy was no better than 0.5°C.

Additional water temperature data were obtained from a current meter mooring in the vicinity of the Buoy Center's buoy. The mooring was deployed from June 1982 to July 1984; there was a brief gap in data coverage to service the instruments in June 1983. Hourly temperature data from 1982–1983 were recorded at depths of 15, 50, 75, and 148 m. The 1983–1984 mooring had instruments at the 50-, 75-, and 148-m depths. In contrast to the Buoy Center's thermistors, the mooring instruments were accurate to less than 0.1°C and all sensors remained fully operational throughout the deployment.

Despite the limitations of these data, the survey years spanned much of the recent climatological variability in the seasonal onset of full thermal stratification. In Lake Ontario from 1965 to 1985, the earliest onset of full stratification occurred in 1983 and the latest in 1982 (Rogers 1987). The similarities between Lakes Ontario and Michigan in mean depth and general climate regime suggest that similar conclusions can be inferred for Lake Michigan.

Meteorological Data and Forcing

For my study, hourly meteorological data were assembled for a period spanning 30,359 h from 16 July 1981 through 31 December 1984. The meteorological data were obtained from the Buoy Center's buoy and from airport meteorological stations at Milwaukee, Wisconsin, and Muskegon, Michigan. The airport data were averaged and were used whenever buoy data were missing. Airport meteorological data were used for December 1981, January–March and October–December 1982, and January–March and December 1983 and 1984. Both the airport wind speeds and directions were adjusted for overwater conditions (Schwab 1983).

Hourly observations of wind speed and direction, air temperature, dew point temperature, and total cloud cover were used to force the model. Data on shortwave global radiation (0.29–4.0 μm) were unavailable and thus were estimated from an empirical model (Cotton 1979). The Buoy Center's buoy had no provisions for measuring the dew point temperature, essential for estimating latent heat flux, so all dew point data were taken from the shore-based airport data and were corrected for overwater conditions (Phillips and Irbe 1978). The remaining processes included in the local heat budget were sensible heat flux, latent heat flux, net longwave radiation, and shortwave global radiation. The sensible and latent heat fluxes were calculated by bulk aerodynamic formulas with atmospheric stability-dependent exchange coefficients. The stability dependence was based on the work of Businger et al. (1971) and the program documented in Schwab et al. (1981). The net longwave radiation was calculated after Wyrtki (1965) and the penetrating components of the solar irradiance were approximated after Ivanoff (1977). The extinction coefficients for the visible and infrared radiation bands were 0.21 m^{-1} and 2.85 m^{-1}, respectively. Once the meteorological data were assembled, the model testing and verification began.

The Garwood (1977) model was forced with hourly meteorological data and numerically integrated over 150 1-m-thick grid points in 1-h time steps. Initial conditions were estimated from the 16 July 1981 data and the model was integrated in time to the end of 1984.

McCormick and Meadows' (1988) simulation of Lake Erie temperatures with the Garwood (1977) model demonstrated optimal model constants that were identical to those found by Martin (1985) in his simulation of north Pacific Ocean data. The success of this model in such diverse environments instills confidence in the model description of the governing physics. Thus, all of the model simulations for the Base and future climate scenarios were made with the same model coefficients.

General Circulation Model Scenarios

Results from three general circulation models were used to force the one-dimensional Garwood (1977) model and were compared against the results from the Base simulation. The three simulations, corresponding to a climate with an effective doubling of atmospheric CO_2 concentration, were made with the following models: Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU). (See Mitchell [1989] for a general review.)

The data used to drive the Lake Michigan simulations were estimated from model output from the single-CO_2 (present CO_2 concentration) and doubled-CO_2 simulations. These data were formed into a (doubled CO_2/single CO_2) ratio and used to adjust the Base conditions as described below. The

TABLE 1.—Estimated changes in present meteorological conditions, based on monthly averaged input from the general circulation model scenarios.

Model[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Windspeed (m/s)[b]												
GISS	−0.4	−0.5	−1.7	−0.6	−0.8	−0.3	−0.1	0	0.1	1	1.1	−1.2
GFDL	−0.3	−1	0.3	−0.4	−1.6	−1.6	1.6	0.9	−0.7	−0.6	−0.1	−0.7
OSU	−0.5	−0.3	0.3	0.4	−0.2	−0.2	−0.6	0.2	−0.3	−0.4	−0.1	−0.1
Overwater air temperature (°C)[c]												
GISS	8	8	6	5	3	3	2	3	6	4	7	8
GFDL	7	7	6	5	4	8	9	5	6	6	7	8
OSU	6	4	3	3	3	3	3	3	2	3	3	3
Humidity ratio[d]												
GISS	1.82	1.49	1.64	1.4	1.3	1.28	1.07	1.28	1.39	1.23	1.54	1.5
GFDL	1.56	1.44	1.43	1.37	1.25	1.18	0.97	1.16	1.12	1.31	1.56	1.58
OSU	1.13	1.06	1.05	1.04	1.12	1.17	1.11	1.18	1.25	1.18	1.09	1.14
Shortwave solar radiation ratio[d]												
GISS	0.92	1.04	0.98	1.03	1	0.99	0.98	1.04	1.04	1.12	1.03	0.99
GFDL	2.05	1.15	1.15	0.93	1.05	1.05	1.02	1.01	1.01	1.01	1.07	1.74
OSU	1.05	1.04	1.07	1.09	1.03	0.99	1.01	0.98	1	1.02	1	1.01
Fractional cloud cover ratio[d]												
GISS	1.03	0.93	0.97	0.98	1.07	1.09	1.08	1	1.06	0.85	1	0.93
GFDL	1.13	1.18	0.92	1.09	0.90	0.83	0.95	0.82	0.90	1	1.09	0.92
OSU	0.76	0.83	0.74	0.61	0.68	0.94	0.85	1.17	0.83	0.81	0.90	0.91

[a] GISS = Goddard Institute for Space Studies; GFDL = Geophysical Fluid Dynamics Laboratory; OSU = Oregon State University.
[b] Doubled-CO_2 − single-CO_2 values; both doubled-CO_2 and single-CO_2 values were derived from general circulation model output.
[c] Doubled-CO_2 − present-condition values; present conditions are from the 1981–1984 Lake Michigan meteorological data set.
[d] Doubled-CO_2/single-CO_2 ratios.

single- and doubled-CO_2 simulations were run for a 30-year period that corresponded to 1951–1980. Monthly averages were formed for each meteorological variable, at each grid point, for each simulation (Table 1). A doubled CO_2/single CO_2 ratio for each variable was formed by dividing the monthly averaged quantity from the doubled-CO_2 simulation by the single-CO_2 value. The model output from the grid point closest to central southern Lake Michigan was used to represent the future climate inputs for the lake. Five variables were used from the general circulation model output: wind speed, air temperature, humidity, incident solar radiation at ground level, and fractional cloud cover. The hourly Base meteorological data from 1981 to 1984 (except the wind speed) were adjusted by multiplication with the applicable (doubled CO_2/single CO_2) ratios; these ratios were held constant over monthly intervals.

Wind speed adjustments were made differently. The available model estimates of monthly wind speed were made by vector-averaging rather than by scalar-averaging the model winds. The vector-averaged model winds for the single-CO_2 simulation were near zero for 2 months of the year, whereas the corresponding doubled-CO_2 model winds were not. The doubled-CO_2/single-CO_2 wind ratios for these two months were approximately 25. Thus, if these wind ratios were used, hurricane-force winds would have occurred for at least 2 months out of every simulation year. Therefore, to avoid potentially disastrous results and yet still salvage some of the information in the general circulation model winds, the difference between the monthly averaged doubled-CO_2 and single-CO_2 wind speeds were used in place of their ratio. These differences were then added to the Base winds. The resulting changes to the wind stress in the Base were small and more consistent with expectations from other studies (Cohen 1986).

Results

Simulation of Base Water Temperature Climatology

The root-mean-square (rms) error for all depths for the simulation of Base water temperature climatology was 2.8°C. Most of this error occurred during the spring transition period to full thermal stratification (Figure 1). During the spring period, the Garwood (1977) model that I used is either late or early in estimating the transition to summer stratification. The severe winter of 1982 produced the biggest discrepancies between simulated

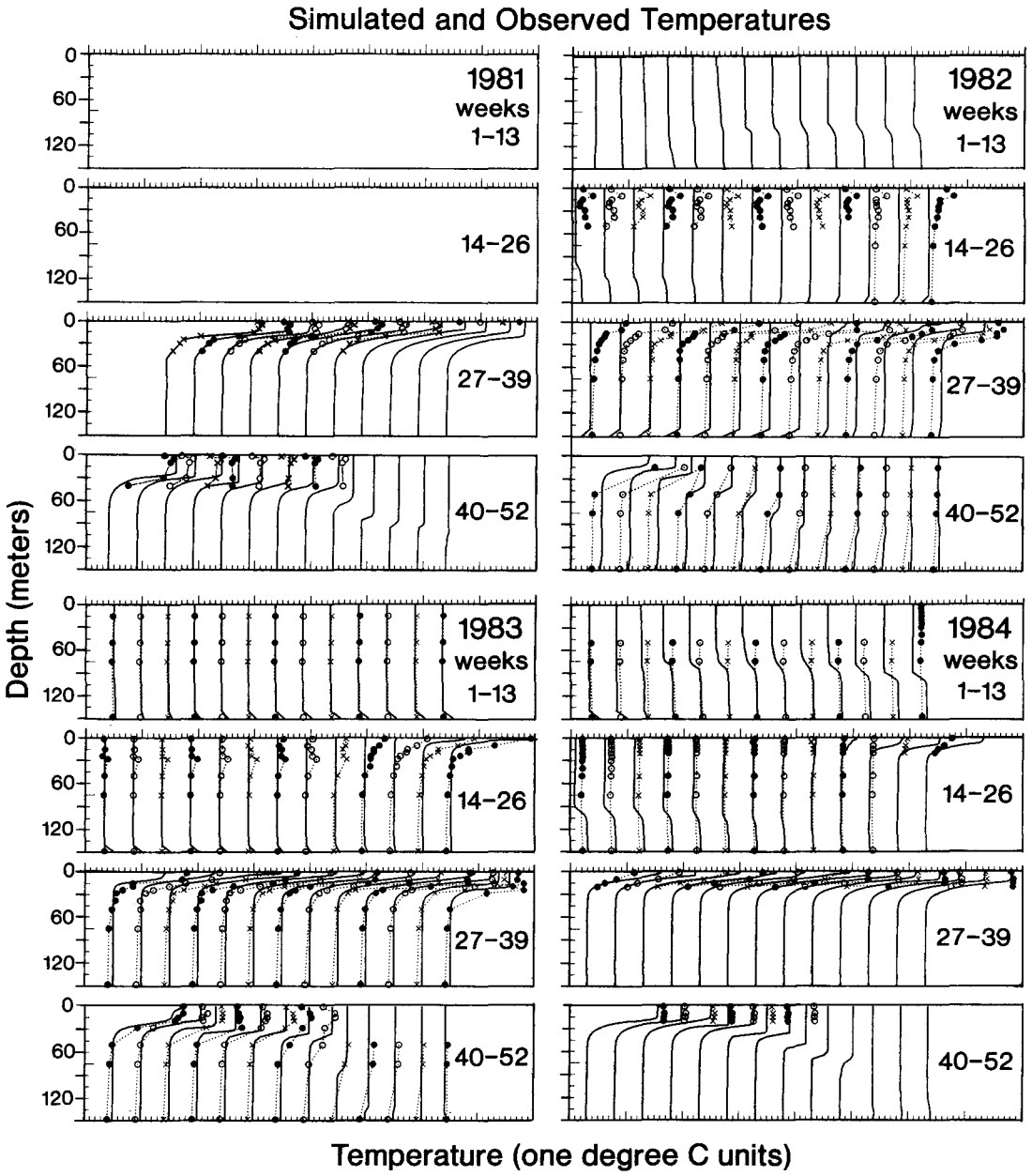

FIGURE 1.—Simulated temperature profiles of the Base (present-day) water temperature climatology of Lake Michigan shown at weekly intervals for 1981–1984. The profiles have been low-pass filtered and are shown against data. Each tick mark is 1°C and each profile is displaced to the right of the previous one by 5°C. Data symbols (●, O, and ×) are alternated weekly and are connected by a dotted line.

and observed temperatures: the model-estimated date of stratification occurred about 8 weeks later than the date suggested by data. After the milder winters of 1982–1983 and 1983–1984, model agreement with the actual timing of stratification was much improved over the severe winter of 1981–1982. The physical dynamics controlling the onset to offshore stratification is a three-dimensional process and the one-dimensional model used here cannot be expected to simulate these periods well. Ad hoc model refinements can be implemented to account for some of these three-dimen-

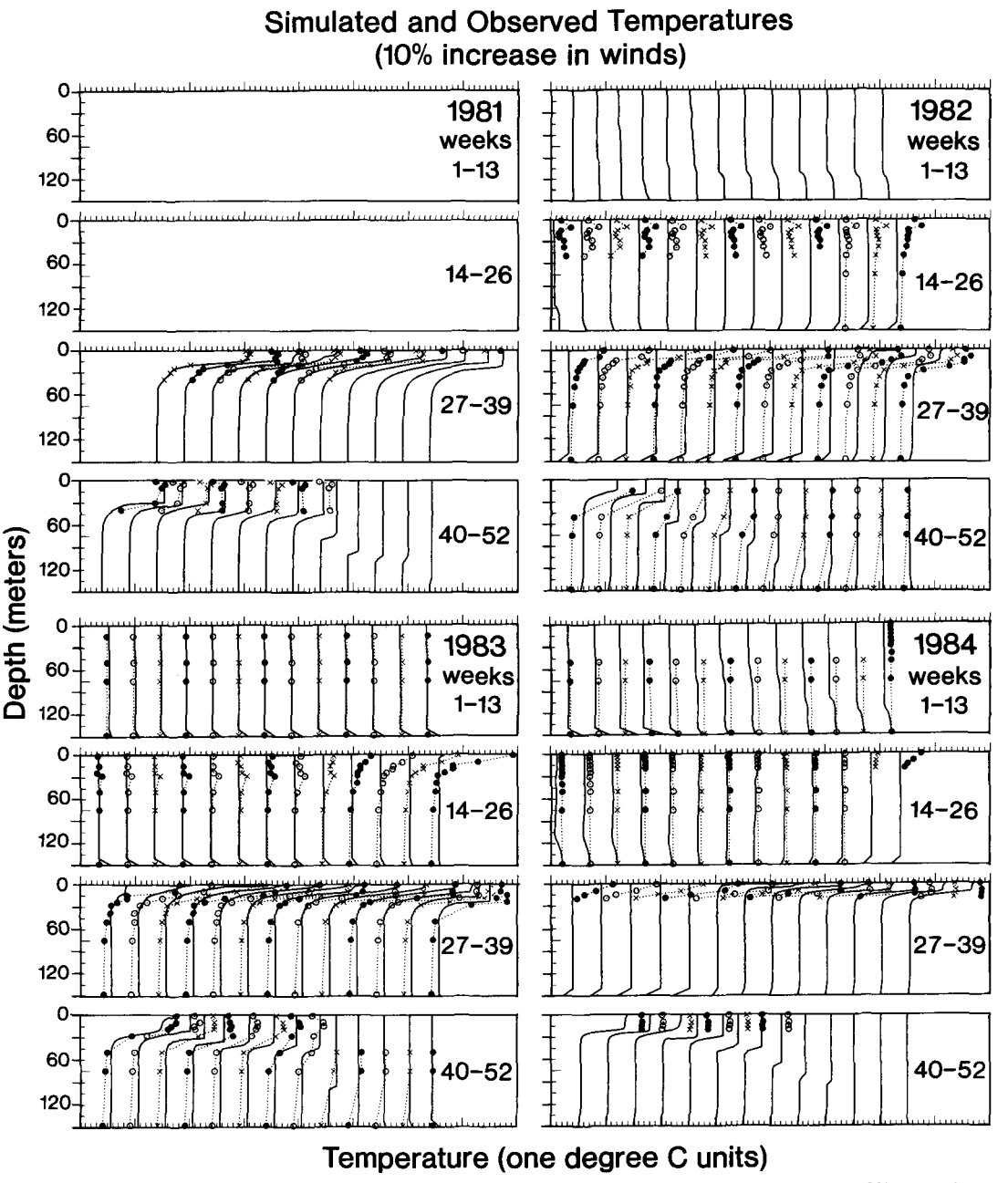

FIGURE 2.—Simulated temperature profiles of Lake Michigan with wind speeds increased by 10% over those used in the Base water temperature climatology simulation (Figure 1).

sional effects, such as offshore upwelling, but were abandoned because their effect on the thermal structure would be less important at the seasonal and annual time scales of interest here.

The plotted temperature profiles for the Base climatology (Figure 1) fail to show an isothermal water column, as one might otherwise expect, during time periods surrounding turnover. The lack of an isothermal water column does not mean the water column is stratified. Rather it is a reflection of the pressure effects on the temperature of maximum water density (Farmer and Carmack 1981).

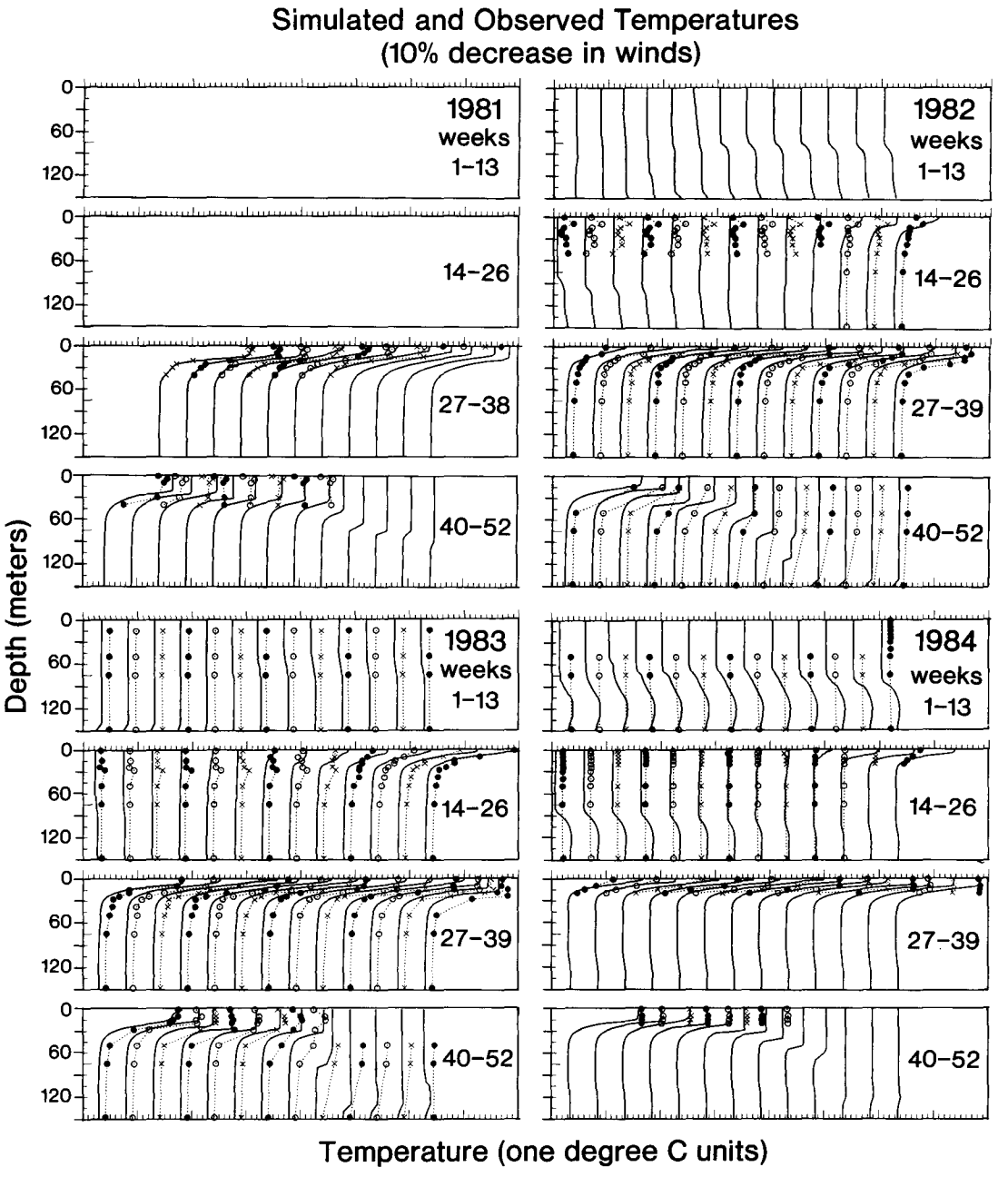

FIGURE 3.—Simulated temperature profiles of Lake Michigan with wind speeds decreased by 10% under those used in the Base water temperature climatology simulation (Figure 1).

For example, based on the equation of state (Chen and Millero 1986), the temperature of maximally dense water at depths of 0 and 150 m is 3.98, and 3.68°C, respectively. Thus, the entire water column can at times be neutrally buoyant and yet appear to be otherwise by showing temperature differences between surface and bottom waters. One effect of this pressure-sensitive term, therefore, is to modify the temperature profiles that one may see in winter; possible remnant effects may linger on later into the year for the deeper bottom waters.

Simulations in which wind speed was increased or decreased by 10% produced dramatic changes in the temperature structure (Figures 2 and 3). Greater wind speeds increased the overall rms error to 3.5°C, whereas lesser winds showed an rms error of 2.3°C. The increased wind speeds resulted in an increase in temperature at depth; reduced wind speeds induced the opposite effect. This strong sensitivity to wind speed suggests that some of the model error attributed to three-dimensional effects may be a result of poor estimates of the actual overwater meteorological data used to force the model. In general, despite problems with simulating the timing of stratification, the model performed well in simulating the seasonal and annual cycle of the offshore temperature structure.

Effects of Climate Change

The GISS, GFDL, OSU, and Base models generated closely similar surface heat fluxes for much of the year, particularly during late summer and early fall (Table 2). Of the four heat flux components, the net longwave and shortwave global radiation terms appeared to be the most consistent in their phase and magnitude from model to model. The remaining two processes—sensible heat flux and latent heat flux—showed less model-to-model agreement. The sensible heat flux loss was greatest in January for three of the models and greatest in December for OSU. The latent heat loss reached its maximum in January for Base, whereas it occurred markedly earlier in the other three models: October for GISS, September for GFDL, and November for OSU. When all the flux terms were summed, the resultant net heating rate suggested that the annual averaged net heat flux was within 5 W/m^2 of zero for all simulations. The maximum difference between the annual net heat flux under a general circulation model scenario and Base was 10 W/m^2. This emphasizes how the persistence of small changes in the net surface heat flux can lead to dramatic changes to the environment. Because of the uncertainties surrounding these estimates, they often lead to controversy.

In terms of the vertically averaged water temperature, the GISS and GFDL scenarios showed a consistently greater heat content than Base (Figure 4). The biggest differences occurred in winter, when the vertically averaged temperature was significantly higher than that of Base. In summer and

TABLE 2.—Monthly and annual averaged heat flux components from the Base[a] climatology and general circulation model simulations.

Model[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
						Sensible heat flux (W/m^2)							
Base	−234	−82	−49	8	19	13	5	6	−13	−20	−65	−165	−48
GISS	−95	−14	−6	−1	−20	−23	−10	−7	−3	−20	−2	−53	−22
GFDL	−124	−29	−4	2	−18	−17	15	1	−9	−7	−30	−51	−23
OSU	−81	−42	−21	10	−10	−26	−11	−4	−26	−21	−49	−110	−33
						Latent heat flux (W/m^2)							
Base	−143	−64	−61	−17	8	15	−22	−49	−89	−80	−101	−126	−61
GISS	−94	−62	−38	−32	−21	−25	−61	−85	−130	−145	−103	−103	−75
GFDL	−133	−56	−76	−32	−27	−57	−128	−133	−153	−119	−106	−111	−95
OSU	−129	−73	−83	−37	−26	−33	−63	−87	−115	−108	−132	−129	−85
						Net longwave radiation (W/m^2)							
Base	−82	−63	−60	−45	−33	−39	−28	−28	−50	−59	−64	−72	−49
GISS	−59	−50	−50	−49	−66	−69	−51	−39	−32	−60	−43	−55	−52
GFDL	−62	−47	−53	−44	−77	−76	−20	−33	−40	−47	−50	−55	−50
OSU	−72	−64	−66	−61	−73	−76	−58	−36	−59	−64	−64	−67	−63
						Shortwave global radiation (W/m^2)							
Base	61	89	138	188	216	257	252	221	173	115	73	53	153
GISS	51	101	137	196	204	240	234	225	169	147	71	56	153
GFDL	108	90	175	164	251	296	263	245	187	112	69	100	172
OSU	85	117	194	277	293	265	276	199	195	140	82	60	182
						Net surface heat flux (W/m^2)							
Base	−396	−116	−30	138	212	249	210	153	24	−41	−154	−307	−5
GISS	−197	−25	42	113	97	124	112	94	5	−78	−77	−156	4
GFDL	−212	−42	42	90	129	145	129	80	−15	−60	−116	−116	5
OSU	−197	−62	24	190	183	129	145	71	−5	−54	−163	−246	1

[a] Base (present-day) water temperature climatology is based on the one-dimensional Garwood (1977) model. Other models are defined in Table 1.

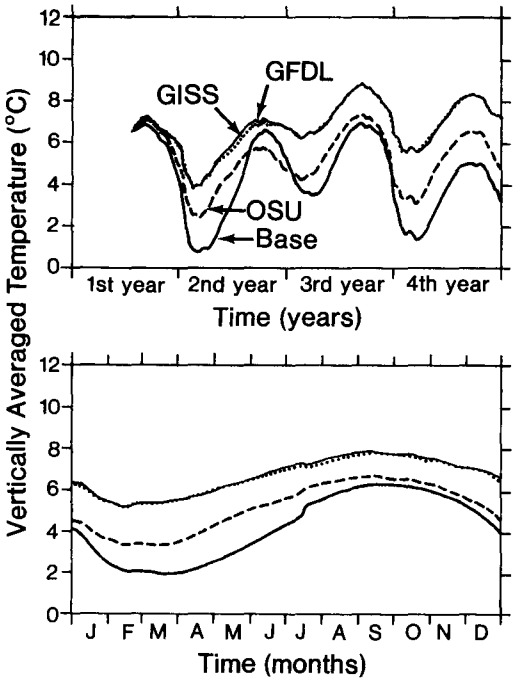

FIGURE 4.—Annual cycle (bottom) of Lake Michigan's heat content (low-pass filtered and expressed in the vertically averaged water temperature) as simulated under present (Base) and possible future conditions (GISS, GFDL, and OSU models). The full simulation (top) suggests that, under the OSU scenario, cold winters may cause a reduction in the lake's heat content in autumn.

early autumn, the heat content increase was less pronounced.

The OSU scenario departed from those of GISS and GFDL in that there was a slightly reduced heat content in the later part of the year compared with that calculated for the Base case (Figure 4, top). However, when averaged onto an annual cycle (Figure 4, bottom), the OSU heat content was always greater than that of the Base situation. The increased annual surface heat flux of OSU over Base conditions did not produce a higher lake heat content throughout the simulation. The strength of winter cooling, whether or not the water column overturns (i.e., whether or not surface waters reach 4°C or less), and the intensity of spring heating together determine whether the late fall heat content is higher or lower than at present. The OSU simulation showed both overturn in winter (Figure 5) and a higher winter heat content (Figure 4). However, the OSU winter temperature structure was closer to maximum density than Base, so the stronger-than-Base spring heating, under OSU, caused the lake to stratify earlier and more intensely and reduced the vertical heat transport at depth. The reduced heating at depth persisted throughout the stratification period. Consequently, OSU produced the largest volume of colder (than present) waters in late summer and autumn of the three general circulation models (Figure 6) and, when the large volume of colder bottom waters was averaged with the warm surface waters, the smallest change from present conditions in the lake's heat content.

Both the GISS and GFDL simulations of water temperature suggested the possibility of permanent stratification and the absence of a fall or spring overturn. Both of these scenarios showed warmer surface waters, higher heat content, a more pronounced thermocline, a reduction in bottom temperatures in autumn, and a longer season of stratification (Figures 4–6). Changes in the length of summer stratification may be inferred from the intervals between the first and last occurrences of 10°C temperatures at the lake surface (see highlighted isotherms in Figure 5). The summer stratification period may begin at least 1 month earlier in spring and end at least 2 weeks later in autumn than at present. This asymmetrical change in the duration of stratification reflects the nonlinear response of the temperature field to changes in the driving forces.

Discussion

There are times when the offshore temperature structure is best described with a three-dimensional model. For example, the spring transition to summer stratification is a three-dimensional phenomenon with large inshore–offshore temperature gradients as the nearshore environment heats up more rapidly than offshore regions. When conditions like this exist, the offshore vertical temperature structure is best described by inclusion of horizontal heat transport. It was not practical for this study to use a model wherein horizontal heat fluxes in Lake Michigan are simulated because a verified three-dimensional model suitable for Great Lakes applications does not exist. Moreover, for long-term simulations, a one-dimensional model may provide a more accurate description of the climatological water temperatures than a fully three-dimensional treatment (Blumberg and Mellor 1981).

Use of the word "predicted" has been consciously avoided throughout this paper because it conveys a degree of knowledge that does not exist. Our present state of knowledge is too uncertain to allow dependable quantification of climate change.

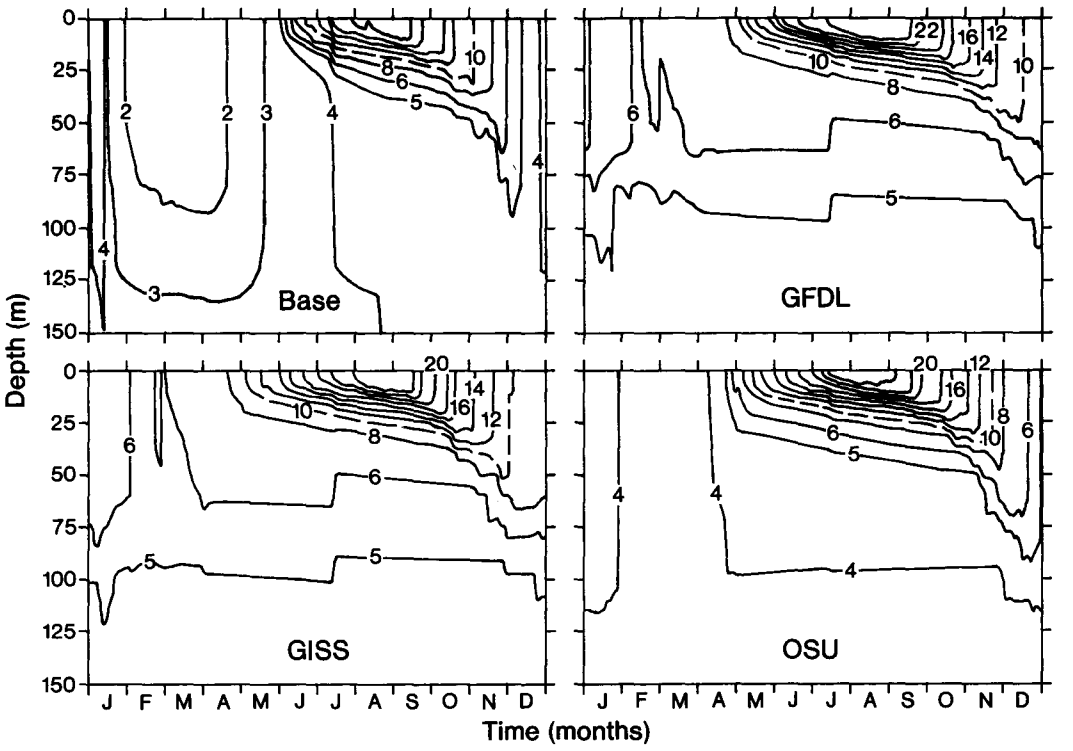

FIGURE 5.—Simulated temperature fields (low-pass filtered) under present (Base) and possible future conditions (determined by the global climate models, GISS, GFDL, and OSU). Contour interval is 1°C for temperatures below 6°C and 2°C for warmer temperatures; the 10°C isotherm is dashed.

For example, if the local surface meteorological data were our only clues for detecting climate change, it would be difficult to determine if climatic change were occurring. The surface heat flux can be expected to be in error by as much as 20–30 W/m^2 on monthly time scales (Wyrtki and Uhrich 1982), which is two to three times higher than the annual net increase in heating suggested by the general circulation model simulations (Table 2). Thus, it is only through examination of the temperature structure of the water column that the potential for discerning change begins to be realized. When the general circulation model simulations are related to the Base simulation, the model and data uncertainties are minimized such that greater confidence can be placed on the estimates of relative change. Therefore, the direction and not magnitude of change has been my focus here.

The primary factor controlling the direction of climatic change may be increased air temperatures (Tables 1 and 2). On a yearly averaged basis, of all the surface heat flux components, the sensible heat flux showed the greatest absolute change from the Base simulation, with the exception of shortwave global radiation for the OSU simulation. The large monthly increases in air temperature were up to 8°C (Table 1) and were responsible for the change in the sensible heat flux. The additional air temperature increase (relative to the general circulation model input) resulted from overwater modification of the land-based temperature, which was mandated in the Base climatology simulations to avoid excessively large surface heat losses. For consistency, the general circulation model inputs were treated in an identical fashion.

The net longwave radiation term showed the least variation or sensitivity between Base and any of the general circulation model scenarios. This is more of a consequence of the empirical formulation used to estimate the net longwave heat flux than it is a confident estimate of the true response. Indeed, a growing body of literature suggests that most empirical formulations of longwave radiation are not accurate enough for climatological applications (Fung et al. 1984; Frouin et al. 1988).

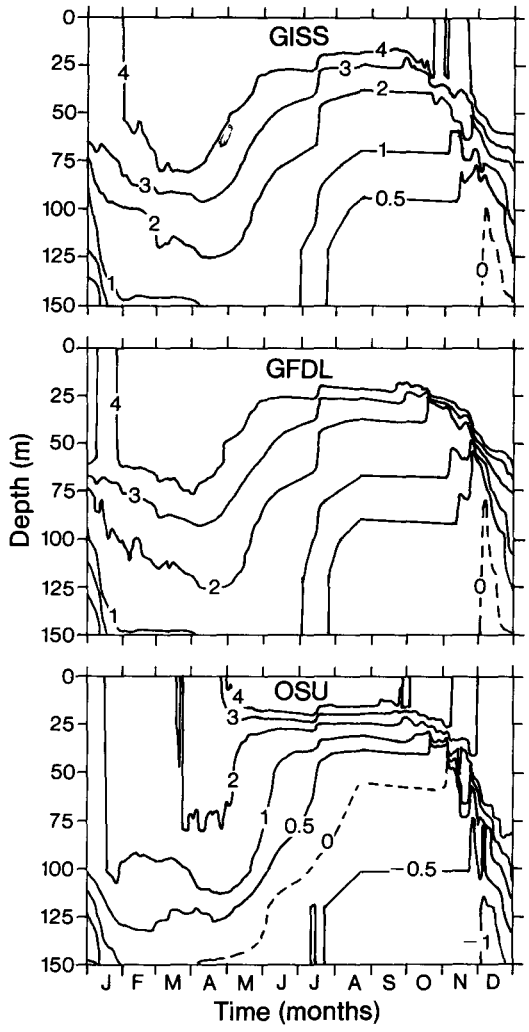

FIGURE 6.—Possible changes in the climatological temperature structure of Lake Michigan due to global warming. The dashed 0°C contour represents no net change in temperature between estimated present (Base) and possible future conditions (GISS, GFDL, OSU).

Wind Stress Uncertainty

Wind stress has been shown (Adamec and Elsberry 1984) to be the most sensitive term in controlling thermal structure of the water column. For example, a negative 10% bias in wind speed could cause a 20% improvement in the overall rms error of simulated water column temperatures. In these simulations, the wind played no greater role in the model calculations than in the Base simulation. This was supported by a comparison of the general circulation model simulations that used general circulation model winds and Base winds. Differences in the model results were insignificant. However, this by no means suggests that future wind fields are unimportant with respect to present conditions. All it does say is that the monthly vector-averaged wind speeds were unimportant, and inappropriate for assessing the role of possible future wind fields on the thermal structure.

An additional area of uncertainty derives from the use of monthly averaged data. McCormick and Meadows (1988) showed that over 90% of the energy associated with deepening of the mixed layer occurs at daily and higher frequencies. Thus, if an accurate estimate of the temperature distribution and an accurate assessment of mixing effects on water quality or other limnological problems are to be made, the spectral distribution of the wind stress must be well represented. The distribution of physical and chemical tracers is strongly influenced by the frequency and severity of storm events. Therefore, if the physical processes are to be described through process-oriented models, like here, the episodic nature of mixing requires high-frequency information on all the driving forces, particularly wind. Or equivalently, the ability to predict the temperature field accurately is determined by the quality of the wind data used to make the prediction.

In conclusion, this study is not a forecast of what may happen to Lake Michigan's temperature structure and cycle as much as it is a sensitivity study. In the study, the meteorological inputs used to force the mixed layer model have been adjusted on monthly time scales in accord with the output from scenarios based on three general circulation models (GISS, GFDL, and OSU). Potential changes to Lake Michigan suggested by these scenarios include the following. (1) Surface water temperatures would be higher throughout the year, and bottom temperatures would be colder in late summer and autumn. (2) The heat content of the water column would also be higher, increasing most in winter (although, after cold winters, the autumn heat content under OSU may be less than under present conditions). (3) The surface mixed layer and thermocline would be shallower in summer and the temperature gradients across the thermocline would be stronger. Thus, more energy would be required to effect large-scale vertical mixing. (4) The duration of the summer stratification period would be increased by up to 2 months, the biggest change occurring with the earlier springtime onset to full thermal stratification. (5) Under the GISS and GFDL scenarios, the lake may no longer turn over fully during most winters.

Thus, the deeper regions of Lake Michigan may experience a permanent thermocline, over which would occur a shallower seasonal thermocline (as for most of the world's oceans). If this occurs, and if these regions are polluted and deep enough for the presence of a permanent thermocline, the potential reduction in large-scale vertical mixing suggests a possible further degradation of water quality at these locales.

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