5. WATER ECOLOGY

study conducted by

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The Laurentian Great Lakes of North America collectively represent the largest body of surface freshwater in the world, both in terms of area (245,240 km^2) and volume (25,310 km^3). The lakes represent 20% of the Earth's surface freshwater and 95% of the surface freshwater resources of the United States. They are unique in ecological character, as well as size. They occupy a diversity of ecological settings, from small wetlands nestled in scattered bays to vast ocean-like expanses of deep, open water. The temperatures to which the organisms of the lake are exposed range from the freezing point of water at 32°F (0°C), to upwards of 86°F (30°C) in protected, nearshore areas. Offshore surface dwellers may experience temperatures between 36 and 77°F (2 and 25°C), while inhabitants of deep basins may only experience an annual change between 36 and 39°F (2 and 4°C). Plants and animals inhabiting the lakes range from wetland species to open water plankton and pelagic fishes of sport and commercial significance.

A climatic warming with higher water temperatures could result in a change in the species composition of the lakes with cooler water species giving way to warm water species [5-1]. Loss of cold, deep-water habitat and stresses caused by low oxygen could contribute to degrading the health of the food web, the fishery it supports and the balance of the entire ecosystem (Figure 5.1).

The fish in the Great Lakes are high on the food chain, so they rely on simpler forms of aquatic life for nourishment, such as algae and invertebrate animals. Algal growth (e.g., primary productivity) in the Great Lakes depends on water temperature, sunlight, mixing, and nutrients such as nitrogen and phosphorus. In winter, the lakes are mixed from top to bottom at temperatures at or below 39°F (4°C) (Figure 5.2a). The mixed water comes in contact with the bottom sediments and the phosphorus and other nutrients contained therein. The low winter sun angle and the short day length reduce the amount of sunlight reaching the lakes and limit photosynthesis and the rate of primary production. The few algal cells that are in the water are mixed to depths greater than that to which the sunlight can reach, so little primary production occurs under these conditions. As spring approaches (Figure 5.2b), sunlight increases and can penetrate to greater depths. When light of

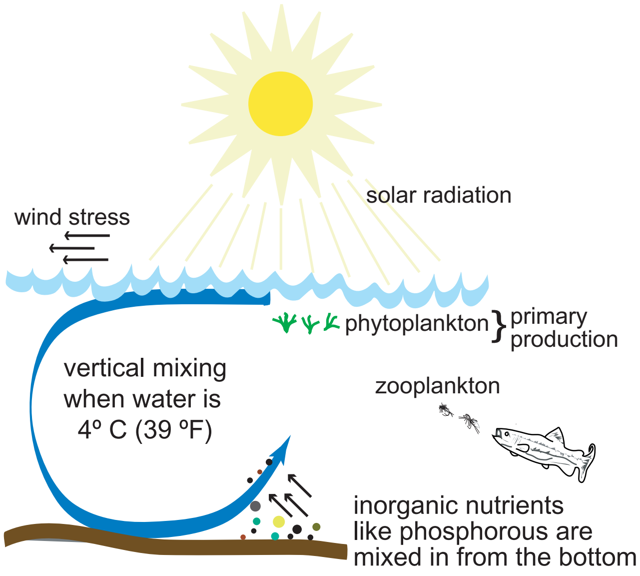

Figure 5.1: Stylized food web of the Great Lakes during autumn to spring mixing period, showing the interaction of climate forcing functions (wind and sunlight) with the chemistry and biology of the ecosystem.

high enough intensity penetrates to a critical depth below the surface, more carbon is fixed by photosynthesis than is consumed by respiration and the algae begin to grow rapidly in what is termed the spring bloom. As long as the water column remains mixed to the bottom so phosphorus may be released from the sediments, and mixed upward into the lighted depths, production will increase the biomass of the primary producers [5-2, 5-3]. As soon as the surface waters warm above 39°F (4°C) thermal stratification sets up and inhibits further mixing to the bottom. At this point, the bloom ceases due to lack of phosphorus, even though light intensities are approaching the annual maximum (Figure 5.2c). In the fall the surface mixed layer deepens and nutrients are again mixed back to the surface. However, now light intensity is on the wane as winter approaches, and only a slight pulse of production occurs (Figure 5.2d).

Current Stresses

Over the years there have been several stresses with which algae, and hence the entire food web including fish and humans, have had to cope. Some of these stresses are biotic, including species invasions by predators, competitors, or pathogens; variations in recruitment success and human intervention by exploitation, such as sport and commercial fishing. Other stresses are abiotic and include excess additions of one nutrients (e.g., phosphorus and nitrogen) as well as potentially toxic compounds (PCB's, mercury, etc.). Fluctuations in water clarity; and variations in cloud cover, wind, temperature, evaporation and lake depth are also potentially important stresses. Climate change acts as a master force on these latter physical stresses that set the stage upon which the biota must act.

Climate change acts as a master force on each of the stresses. Although the mechanisms by which climate acts on the stresses are complex, there is enough understanding that some linkages can be expressed in quantitative terms. One way to contend with the complexity of biological responses is to evaluate composite biological properties, like biomass or productivity. These composite properties have produced good agreement between prediction and measurement in many applications in environmental science, and so they are good candidates for study under climate change scenarios. Plankton biomass and productivity were, therefore, selected as the biological properties to be examined in this study with respect to the effects of potential future climate change.

Previous Assessments

Previous studies have used output from 2 X CO_2 climate change scenarios to drive temperature, mixing, and nutrient models [5-4, 5-5, 5-6, and 5-7]. General results include increased water temperatures, longer time of warm surface stratification, shallower depth of warming, and more extensive depletion of oxygen from deep waters. Oxygen is typically reduced in bottom waters that are isolated from atmospheric oxygen by thermal stratification. Under these conditions, the respiratory activities of plants, animals and, bacteria consume oxygen that cannot be immediately replaced from above until mixing resumes in the autumn. McCormick [5-6] estimated that under extreme warming conditions, Lake Michigan would not mix thoroughly

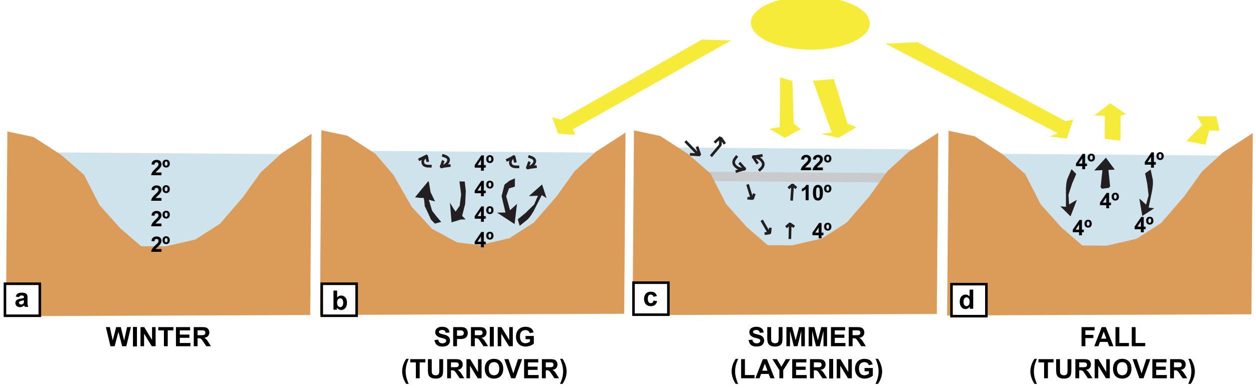

Figure 5.2: Stylized seasonal thermal and mixing cycle in the offshore, non-ice covered areas of the Great Lakes.

during the winter, and that a deep zone could be permanently isolated and become depleted of oxygen.

Other studies have addressed the potential implications for thermal habitats of Great Lakes fish. Magnuson et al. [5-7] studied the potential implications for thermal habitats of Great Lakes fish. They concluded that the size of the habitat favorable for cold-, cool- and warmwater fish would increase in Lake Michigan, but habitats suitable only for cool-and warmwater fish would increase in Lake Erie. Fish yields, estimated from empirical models relating thermal habitat to sustained yields remained about the same for Lake Trout and Whitefish, but increased for Walleye.

Hill and Magnuson [5-8] examined growth of Lake Trout, Yellow Perch, and Largemouth Bass (cold, cool, and warmwater fish respectively) at three nearshore sites in Lake Erie, Lake Michigan, and Lake Superior. Their findings indicate that growth of yearling fish would increase with climate warming if prey consumption also increased, but would decrease if prey consumption remained constant. They noted that changes in growth would be most pronounced in spring and fall due to the projected lengthening of the period of thermal stratification, during which time habitats of differing temperatures are available for fishes that can move to an area with appropriate temperatures for optimal growth.

Estimates of primary production and zooplankton abundance were developed for a 2 X CO_2 climate scenario by Magnuson et al [5-7] based on the work of Regier et al [5-9]. Hill and Magnuson [5-8] report that the ratios of the 2 X CO_2 to 1 X CO_2 scenarios ranged from 1.6 to 2.7 for phytoplankton production, from 1.3 to 2.3 for zooplankton biomass, and from 1.4 to 2.2 for fishery yields. They further note that the actual rates of primary and secondary production in the Great Lakes due to climate warming will depend on a myriad of food web interactions. They state that, "The dynamics of Great Lakes food webs subjected to climate warming must be considered in detail to answer the question of whether increases in primary and secondary production will be sufficient to meet the increased predatory demands of fishes." They concluded that food web dynamics and possible oxygen depletion would, "greatly influence the direction and magnitude of changes in fish growth as the climate warms." Hill and Magnuson [5-8] also cite the appendix of a 1989 EPA report in which primary production, zooplankton, and fish yields are projected to increase with climate warming. Nonetheless, they expressed reservations about whether the potential increases would be realized, owing to complexities of food web processes.

Abiotic Stresses vs. Biotic Stresses

Abiotic Stresses

- variations in solar irradiance caused by day length and cloud cover, because sunlight is necessary for plant growth
- supply rates of essential nutrient elements (e.g., phosphate), because nutrients act as fertilizer for plant growth and for establishment of food webs
- concentrations of potentially toxic compounds (mercury, PCBs, etc.)
- variations in water temperature, because temperature affects the rates of all metabolic processes
- variations in mixing depth, water circulation, and oxygen supply, because oxygen is needed by all higher life forms
- variations in water transparency, because the penetration of light is needed for plant growth, and because visibility affects predator-prey interactions

Biotic Stresses

- species invasions by predators, competitors, or pathogens
- variations in recruitment success and abun dance of predators and competitors
- human intervention by exploitation, such as sport and commercial fisheries
- human intervention by artificial stocking of fish at rates or of non-native species that alter the native species and native food webs
- human intervention by alteration of environmental conditions

There have been few if any specific assessments of the impact of climate change on the primary productivity of the Great Lakes. Assessments have been published for open water and coastal marine waters [5-10, 5-11, 5-12], and studies on the Great Lakes have reported the influence of seasonal and interannual variability in the stressors discussed above [5-2, 5-15], but no integrated assessment exists. The present study attempts to assess the influence of potential climate change on the primary producers at the base of the Great Lakes food web that must be present in great enough abundance to support prey species and any projected increase of fishery yield.

Current Assessment

Existing records of phytoplankton, water quality, temperature, primary productivity, and weather, were used to interpret output from two General Circulation Models (GCMs) and to determine the potential impacts of climate change on primary productivity of free-floating phytoplankton that occupy the open waters of the Great Lakes. Evaluation of the GCM output showed: (1) Both (i.e. CGCM1 and HadCM2) models lead to predicted increases in the temperature of mixed layers and lake bottom water in all five lakes by as much as 5°C (9°F) during the next century; (2) For each scenario year (2030, 2050, or 2090) the CGCM1 model leads to higher predicted maximum and mean temperatures in the mixed layers, and higher mean temperatures at the bottom of all five lakes, with respect to predictions for the same years using the HadCM2 model; (3) Both models lead to prediction of longer periods of thermal stratification in all 5 lakes; (4) Both models lead to prediction of deeper daily mixing depths during peak thermal stratification than at the present time. The CMCG1 model output generally suggests deeper mixing depths than does the HadCM2 model.

The biological implications of the physical changes predicted by the climate models suggest that: (1) For Lake Erie, no substantial differences in maximum algal biomass would be expected; (2) For Lake Ontario, where peak algal biomass is governed by optical depth rather than by the duration of nutrient limitation, both climate models lead to prediction of modest decreases in peak algal biomass during summer; (3) For Lakes

Scenario	Cloud Cover	Primary Productn.	% BASE MEAN	Stratification Start	Stratification End	Duration
BASE	Mean	122	100	June 13	Oct. 26	135 Days
	Max	117	92			
	Min	132	108			
CGCM1 2030	Mean	107	87	May 13	Nov. 07	177 Days
	Max	98	81			
	Min	115	94			
CGCM1 2050	Mean	105	86	May 01	Nov. 07	190 Days
	Max	97	79			
	Min	113	92			
CGCM1 2090	Mean	100	82	April 05	Nov. 20	225 Days
	Max	93	76			
	Min	107	88			
HADCM2 2030	Mean	115	94	May 31	Nov. 03	155 Days
	Max	106	87			
	Min	124	102			
HADCM2 2050	Mean	114	94	May 28	Nov. 06	161 Days
	Max	106	86			
	Min	123	101			
HADCM2 2090	Mean	108	88	May 05	Nov. 10	189 Days
	Max	100	81			
	Min	116	95			

Table 5.1: Primary production (g C m^{-2} $year^{-1}$) for Lake Michigan for selected model scenarios and current (BASE) conditions. Three sets of cloudiness conditions (Mean, Max, and Min) are shown.

Huron, Michigan, and Superior, the duration of nutrient limitation of algal growth is predicted to increase sharply and thereby reduce primary production.

Looking at Lake Michigan in more detail (Table 5.1), the anticipated changes in the physical characteristics of the lake may impact primary production in two ways, both of which are related to incoming solar radiation. First, altered light intensity, due to an increase or decrease in cloud cover, directly influences rates of photosynthesis. Second, changes in incoming solar radiation change the surface warming and the thermal structure of the lake by extending or retarding the onset and ending dates of stratification. Both GCMs suggest a warming of the lake and longer periods of stratification starting earlier in the spring and extending later into the fall. The "base scenario," was determined from recent conditions in the lake that represent the coolest conditions and the shortest periods of thermal stratification. Under the base scenario, the mean date for the onset of thermal stratification occurs on or about June 13 and extends for 135 days through October 26. Using the calculation of Fee [5-14], the mean annual primary production under these conditions is about 122.1 g C m^{-2} yr^{-1}. (Table 5-1 and Figure 5.3). These numbers agree well with published values for Lake Michigan [5-13, 5-15].

Calculations of primary production were also run with base biological input parameters, but with projected extreme maximum and minimum percentage cloud cover from the climate models, and the extremes of thermal stratification duration derived in this study. Those values are shown in Figure 5.3 and in Table 5.1 as well. Under the predicted extreme conditions for the year 2090, stratification would be present from April 5

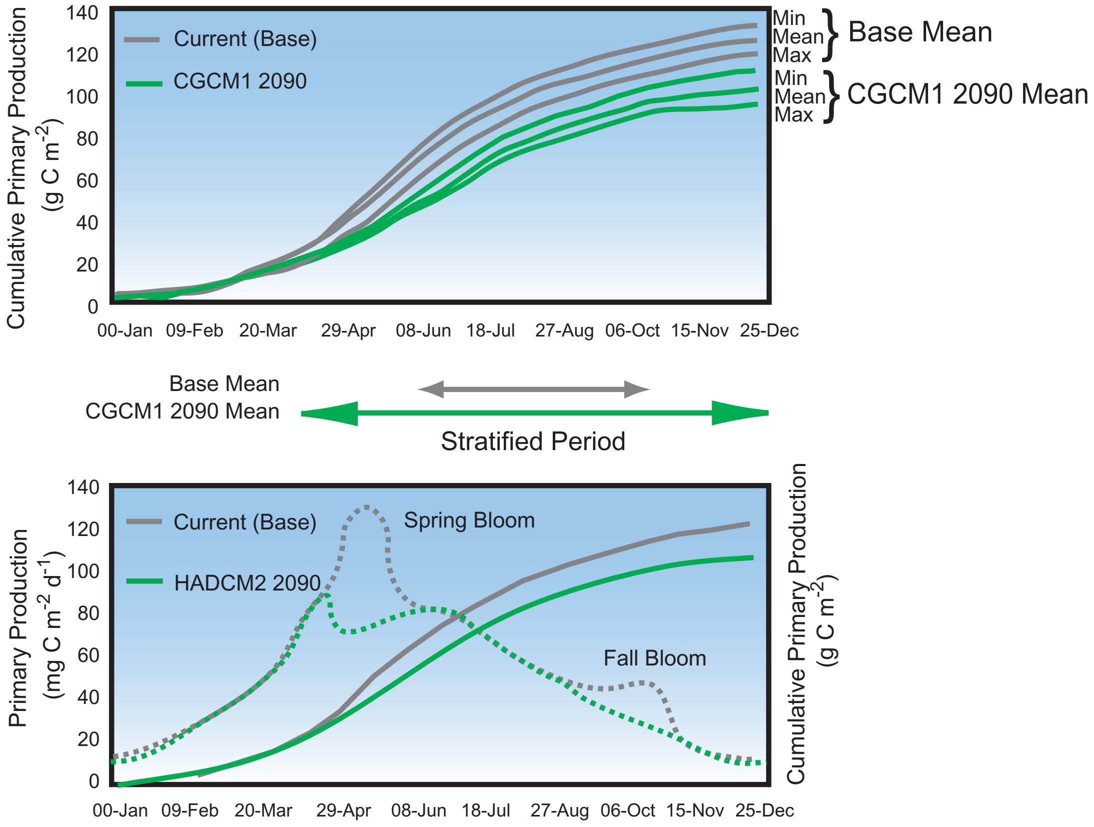

Figure 5.3: Upper: annual primary production for Lake Michigan. Cumulative primary production using current (BASE) conditions and CGCM1 2090 scenario for mean, maximum, and minimum cloud cover, and hence, inversely, mean, minimum and maximum sunlight impinging on the lakes. Lower: Daily (dashed lines) and cumulative primary production (solid lines) using current (BASE) conditions and HadCM2 2090 scenario for mean cloud cover conditions.

to November 20, or 225 days. Estimated mean annual primary production under these conditions was 100.4 g C m^{-2} yr^{-1}. Maximum and minimum light conditions produce the expected increase and decrease in production, respectively, while the extension of the period of stratification into the spring growth period tended to truncate the spring bloom and lower the overall annual production by approximately 20% in 2090.

The results of this research suggest that primary production in Lake Michigan will decline as the climate warms. This decline will occur principally as a result of increased duration of thermal stratification that will limit the availability of nutrients in the lighted zone of the lake. When these results are coupled with the projections of Hill and Magnuson [5-8], they suggest if the food web is diminished, then fishery production will also decline. The magnitude of this decline will require more detailed study of the intermediate links in the food web to better understand the complexities of the system. Compounding these predictions are unknowns, such as changes in tributary runoff and nutrient inputs, and the invasion or introduction of new exotic species that could completely change the structure of the food web as we know it today. Such changes have been well documented in the past with the invasion of the alewife, sea lamprey, gobies, zebra mussels, *Bythotrephes* and the stocking of exotic salmon. The effects of climate change alone on the biological productivity of the Great Lakes would appear to be the easiest to predict in the face of unknown invaders and to changes related to politically-driven fishery management decisions.

Coping Strategies

Responses and strategies must be divided into two categories according to whether they apply to the general public or to the scientific community that is involved in the measurements, understanding, and prediction.

The public will likely find that the Lakes are accessible for sport fishing and recreation for longer periods each year than at present. However, the targets of sport fishers will gradually change as the lakes warm and species more tolerant of such conditions move into the lakes.

The Great Lakes are not corn fields to which one can add more or less fertilizer and water, develop heat-tolerant varieties to plant, or keep predators at bay with pesticides in order to maintain a desired state of production in the face of climate change. The lakes are part of a very complex ecosystem that has been altered by the presence of humans. Nutrients and toxic chemicals have been added to the system. Exotic species have been introduced intentionally, or accidentally via ships and canals constructed to support commerce throughout the region. The best response to cope with the projected effects of climate change may be to continue efforts to rebuild stocks of native species that have survived in the lakes through centuries of postglacial change, and to minimize any future degradation of the system by human activities. Attempts to maintain shipping channels and harbors through the regulation of water flows and dredging should strive to minimize impacts on critical habitat required for spawning of native species and the nurturing of young. The projected decline in primary production may require the adjustment of stocking strategies for the sport fishery and appropriate public education programs to explain such changes in light of uncontrolled, external factors brought about by climate change.

Information & Research Needs

The scientific community finds itself with an opportunity to develop and test theory about the Great Lakes ecosystems. The response by this community must be to develop refined, increasingly quantitative and specific predictions that can be tested. It is fair to say that most of the models that are being applied to climate change assessment have significant shortcomings that remain to be discovered and fixed. Shortcomings and erroneous assumptions will come to light only if model predictions are framed in a form that permits them to be proved wrong. Hence, the scientific community must respond to climate change with a strategy that provides predictions on short time horizons, and with an observational program that can detect the strengths and weaknesses of the predictions.

Research will be required to integrate the results of individual projects conducted under the climate assessment program. Critical to our understanding of the food web in the lakes will be knowledge of future atmospheric precipitation inputs to the lakes and their drainage basin. Information on runoff from the basin and the load of nutrients and sediments carried to the lakes will be needed to adjust production calculations if significant changes in such variables are projected. Projected changes in wind patterns that may alter lake mixing conditions will also be important to have in refining our knowledge of variables forcing the physical state of the lakes. More research will also be needed to better understand the links in the food web between the primary producers and the top, economically important fish in the system.

By assembling the elements needed for this study it became obvious that additional lines of inquiry are required for a comprehensive climate change assessment, including:

- Oxygen dynamics should be incorporated in future models to assess the magnitudes of likely change in that critical chemical property.
- Improved information is needed about the magnitudes and seasonal variation of photosynthetic parameters among lakes. Basic information is needed about rates of respiration in these lakes and variation of the rates with temperature.
- A review is needed to identify the maximum levels of algal biomass sustainable by nutrients in the five Great Lakes.
- Future versions of the mixed layer model should incorporate actual lake morphometry, heat advection by river discharge, and ice dynamics predicted by the NOAA lake evaporation model in order to assess their effect on model predictions.
- Cloud cover changes should be evaluated with respect to the sunlight actually reaching the lake surface.
- Further review is needed to characterize the variation in net intrinsic growth rates of Great Lakes algae and zooplankton with water temperature.
- Future climate predictions should be developed in a probabilistic context by using known interannual variance in meteorologic variables to develop a family of extreme events that would strengthen the validity of longer-term climate-coupled projections.