MONITORING MIDLAKE WATER TEMPERATURE IN SOUTHERN LAKE MICHIGAN FOR CLIMATE CHANGE STUDIES

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Abstract. Recent studies of potential climatic change on Great Lakes fisheries (e.g. Meisner , 1987; Magnuson , 1990; Regier *et al.*, 1990) and our general ignorance of the natural variability of the basic physical properties of the Great Lakes (McCormick, 1990) have demonstrated the need for a long-term observation program which is representative of the lake-wide environment. In April 1990 a site was established in Lake Michigan to continuously monitor the offshore thermal structure and vertical velocity profile. The site is located near the center of the lake's southern basin in 160 m of water. Temperature is measured at 16 depths (winter) to 28 depths (summer), and the horizontal velocity components are measured at 5 levels which allows us to characterize the offshore environment with high temporal resolution. The goals of this effort are to provide basic physical measurements to better describe the flow of energy through the lake ecosystem and to provide a basis against which future change can be better gauged.

1. Introduction

A rapidly growing body of literature exists on climatic change and the possible impacts of human activity upon future climates. Controversies exist over the timing, magnitude, and even the possible direction of future change which reflects on our limited knowledge and understanding of climate. Attempts to simulate potential climatic impacts on regional scales, such as the Great Lakes, are no more certain than those calculations done on global scales.

In the Great Lakes concerns are centered around physical and ecological changes that may occur in the lakes as a result of climate change. Various studies by Assel (1991), Croley (1990), and Magnuson *et al.* (1990) have suggested that the Great Lakes are sensitive responders to climate change. Under future climate change scenarios (Smith, 1991) surface water temperatures in Lake Michigan may increase 3–4 °C and large alterations in the temperature structure and cycle may be felt throughout the water column (McCormick, 1990). These potential changes to the lake's thermal structure result from an annual increase in the net surface heat flux of 6 Wm^{-2} from estimated current conditions. Although this is a large increase in the net annual heat flux, it is small compared to daily (yearly range of $\pm$ 1,000 Wm^{-2}) and monthly (yearly range of $\pm$ 250 Wm^{-2}) values suggesting that not only may large changes in the climate occur from small yet persistent changes in the net

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heat flux, but that these changes may also be difficult to detect from conventional meteorological data.

Knowledge of the thermal structure and its dynamics is fundamental to understanding the Great Lakes ecosystems. For example, changes in the temperature field can change the volume of the optimal thermal habitats of fish species and result in permanent changes in the fish community and in fish production (Hill and Magnuson, 1990). Further, increased thermal stratification can cause reduced vertical mixing and lead to the formation of anoxic bottom waters and seriously degrade water quality (Blumberg and DiToro, 1990). Permanent changes in the thermal behavior of the Great Lakes can also create new habitats and increase the probability of successful colonization by invading exotic species (Mandrak, 1989; Johnson and Evans, 1990), and the unknown ecosystem impacts that they would pose.

The previously mentioned studies, our limited understanding of natural variability, and concern over future climate have demonstrated the need to better understand the thermal behavior of the Great Lakes. One strategy employed by NOAA's Great Lakes Environmental Research Laboratory to meet this goal has been to establish a permanent program to continuously monitor the offshore thermal structure of Lake Michigan.

There are three reasons for monitoring the offshore thermal structure. First, because of the small signal-to-noise ratio associated with climate change issues we wanted to select a measurement program that would be efficient and allow the greatest opportunity for observing regional change. The large thermal capacity of water compared to air results in the lake behaving as a natural low-pass filter of atmospheric thermal forcing and thus improves the signal/noise ratio. Second, although nearshore measurements of water temperature have been made over time at various locations in the Great Lakes, severe limitations exist on inferences that can be made from such data. This results from data being collected at shallow depths, in regions of high hydrodynamic variability and poor spatial correlation in the flow field. This poor correlation results from the complex interaction between the nearshore and offshore environments. The selection of our study site (Figure 1) in 160 m of water is more representative of the entire lake than any shore site (mean lake depth 85 m). Finally, the rapid increase in climate related research has helped in emphasizing the need for a better understanding of the basic physics and biology of the Great Lakes. In general there are very limited data (i.e. Church, 1945; Ayers, 1965; Lesht and Brandner, 1992) available which adequately describe the heating and cooling cycle of the Great Lakes and its interannual variability. Our monitoring program described here will serve as a basis for bridging the gap in our ability to understand the long-term behavior of the offshore lake environment.

Approach and Data Examples

In April 1990, a site was established in the southern basin of Lake Michigan to measure the vertical thermal structure and the velocity profile. The monitoring site

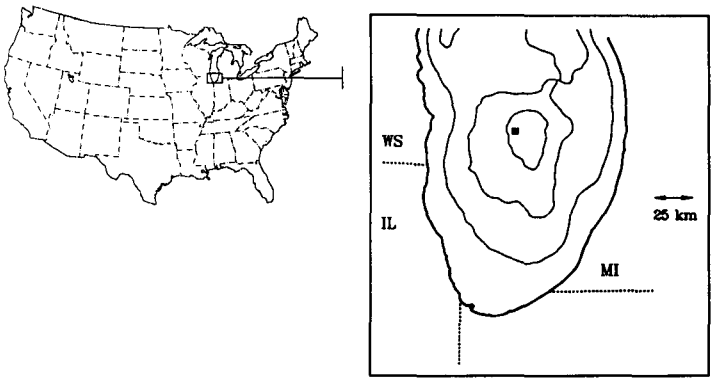

Fig. 1. Monitoring site location (solid square) in southern Lake Michigan. The 50, 100, and 150 m bathymetry is shown.

consists of three different moorings and a meteorological buoy. The first mooring contains five vector averaging current meters (VACMs) at 15, 25, 60, 120 and 157 m below the surface. Current velocities and temperature are measured and recorded every 15 minutes. The mooring is subsurface and thus free from any potential damage due to ice or shipping. A second subsurface mooring contains an 80 m-long thermistor chain moored to cover depths from approximately 20–100 m. Eleven thermistors record temperature every 3 h and are located at the following depths: 23, 28, 33, 38, 43, 53, 63, 73, 83, 93, and 103 m. The third mooring is a surface deployed 20 m-long thermistor chain with sensors at 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, and 21 m below the surface. The surface mooring records temperatures every hour and is deployed from approximately May to November.

To increase the potential usefulness of the temperature data, the moorings are located near a meteorological buoy maintained and operated by NOAA's National Data Buoy Center. The meteorological buoy is deployed during the ice free months and collects conventional meteorological data including wave spectral information and surface water temperature on an hourly basis. Therefore, the total number of sensors measuring the thermal structure range from a minimum of 16 in winter to a maximum of 28 during summer. All thermistors are accurate to ± 0.1 °C with negligible annual drift yet are annually compared against CTD data to insure data quality. The large number of thermistors and their stretched grid spacing allows us to characterize the thermal behavior of the water column with high temporal resolution.

Figure 2 depicts the thermal structure of Lake Michigan from 7 June 1990 through 18 April 1991. For clarity sake only daily averaged data were used to generate the contours. By early June the surface waters begin to stratify. Surface heating continues to strengthen stratification, but the maximum temperature gradients are not seen until sometime after surface cooling starts. The strongest gradients in these data are seen during late August through most of September. After

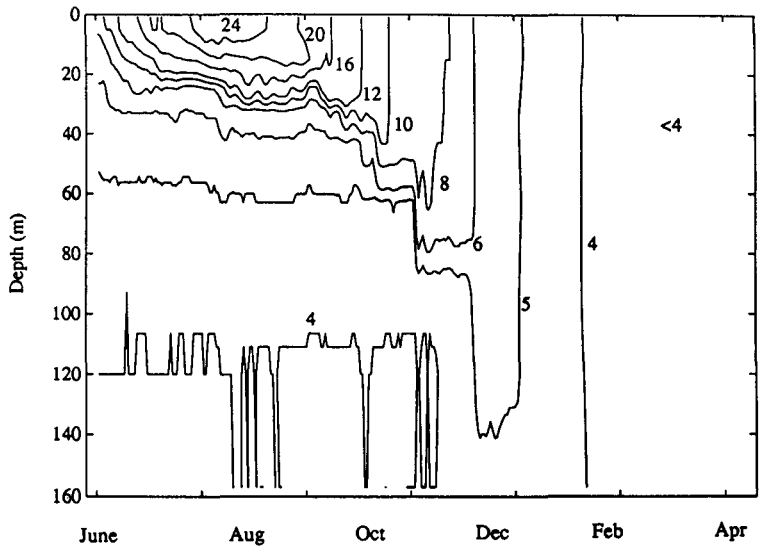

Fig. 2. Temperature contours for the offshore waters of Lake Michigan from 7 June 1990 through 18 April 1991. Contours were generated from daily averaged data.

this time period, surface cooling controls the rate of weakening of the summer stratification and the deepening of the surface mixed layer. Progressive mixed layer deepening continues until late December when near isothermal conditions exist throughout the water column. With subsequent winter cooling near isothermal profiles continue until the temperature of maximum density (~4 °C) is reached at which point further surface cooling stratifies the water column. Only under rare circumstances will the entire lake surface freeze over (Assel and Quinn, 1979). The water column continues to lose heat until sometime in late March to early April when the total heat content reaches its minimum. Following this minimum the offshore waters slowly heat up until mid May to late June when summer stratification begins and rapid heating of the surface waters can take place.

Current Meter Data

The basic objective common to studies of ecosystems is to describe the flow of energy through the system. The temperature field reflects the balance between mechanical and thermal energy in the lake environment. Thermal energy inputs and its vertical distribution can be estimated from surface meteorology and *in situ* temperature observation. The mechanical energy input too may be estimated from surface meteorology but its distribution in the water column is not as easily determined. The vertical distribution of mechanical energy reveals itself through the flow field and is important because it determines the rate at which energy, particles, and dissolved substances are transferred in the water column. Thus, the nature of the

horizontal flow structure and how it changes with depth, i.e. velocity profile, governs transport and mixing.

One of the goals of our program is to develop models useful for long-term simulations. To successfully model the one-dimensional thermal structure at a single location places assumptions on the nature of mixing, i.e. all mixing is surface driven and the energy available for mixing is proportional to *local* surface forcing. This requires that significant changes in the vertical temperature structure are not caused by the horizontal transport into the region of water masses at different temperatures but rather by vertical mixing of the water column. If a local balance between surface forcing and mixing does exist then the mixing energy can be estimated through modelling or inferred from observation of the velocity profile. For example, Pollard *et al.* (1973) and Thompson (1976) were among the first to demonstrate the importance of shear instabilities at the base of the mixed layer as an important mechanism controlling surface mixing. During the stratified season the shear velocity may be estimated in offshore regions from simple models (Thompson, 1976), or it may be prescribed from data based estimates. McCormick and Meadows (1988) have successfully used the former approach in Great Lakes applications, however, there is no substitute for observation particularly during episodes that are difficult to accurately model such as the spring transition to stratification when the offshore dynamics are fully three-dimensional. Therefore, measurements of the velocity profile allow us to better estimate the vertical transfer of mass and energy, to estimate the mixing energy during the winter months when overwater meteorological observations are unavailable for forming model based estimates, to explore and test new ideas on vertical mixing, and to form a more comprehensive understanding of long-term variability.

To provide the needed velocity data, five VACMs are collocated with the thermistor moorings. VACMs are proven oceanographic instruments and data examples are displayed in Figure 3 for July 1990 and January 1991. As stratification strengthens for the month of July, less and less energy is seen at depth. During this time, for a given wind stress, the surface currents are strongly enhanced because the wind energy input into the water column is more effectively trapped in the surface waters. Under these conditions strong velocity shears are often evident. Most of the kinetic energy is contained near the 17 h inertial period and is evident in the 15 m current data. These inertial period oscillations result from surface forcing and the earth's rotation.

An example of the winter VACM data is seen for January 1991 in Figure 3. The absence of any significant stratification allows the entire water column to be stirred as suggested by the strong signal similarity seen in the data at all depths. Also present in the data is a strong topographically controlled circulation first identified in the southern basin of Lake Michigan by Saylor *et al.* (1980) which is a remarkable feature in the raw data. The velocity vector is seen to rotate counterclockwise with an apparent period of 5 days consistent with Saylor *et al.*'s (1980) earlier findings. These data not only provide a means for direct estimation of the

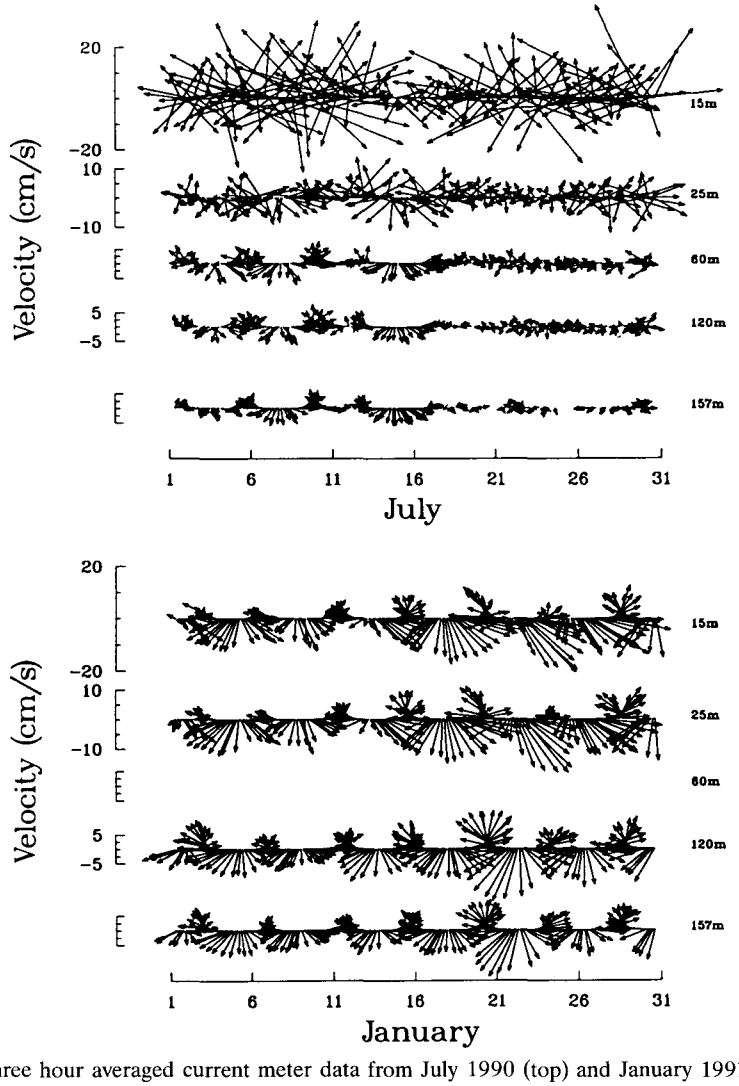

Fig. 3. Three hour averaged current meter data from July 1990 (top) and January 1991 (bottom). The 60 m deep current meter failed in January.

velocity profile, but they are also useful as a verification tool for circulation modeling.

In summary, concern over regional climate change has helped to focus attention on how observationally ignorant we are of the most basic physical properties of the Great Lakes. Furthermore, because temperature is an ecological resource (Magnuson *et al.*, 1979) a complete understanding of the ecosystem is not possible without knowledge of the thermal regime. Therefore, a modest monitoring program has been started in the offshore region of Lake Michigan to provide data critical to understanding natural variability over long time scales and to better describe the flow of energy through the ecosystem.

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