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Vernal thermal fronts in large lakes: A case study from Lake Michigan

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Introduction

Many temperate large lakes of the world undergo a transition in the spring from fully mixed winter conditions to thermally stratified summer conditions (RODGERS 1966, TIKHOMIROV 1963). That transition often includes the formation of a well defined front characterized by a nearly vertical, shore-parallel 4 °C isotherm (SAYLOR et al. 1981). This front, which is maintained by a convergent secondary circulation and accompanied by geostrophic currents, induces a significant redistribution of heat and other properties in the coastal waters (BENNETT 1971, ROUSAR 1973). Many vernal thermal fronts are characterized by large chemical and biological gradients (SCAVIA & BENNETT 1980).

The current state of knowledge of vernal thermal fronts in large lakes is largely based on theoretical studies that are relatively unconfirmed by field observations. Given this state of knowledge, our study group elected to begin a multidisciplinary, multiyear study of vernal thermal fronts in southeastern Lake Michigan. The point of departure for this study was the theoretical framework of water circulation in the vicinity of vernal fronts developed by HUANG (1969, 1972) and MORTIMER (1974, 1988). The purpose of this paper is to provide an overview of the results from five field seasons of study (1988 to 1992) of the Lake Michigan vernal thermal front.

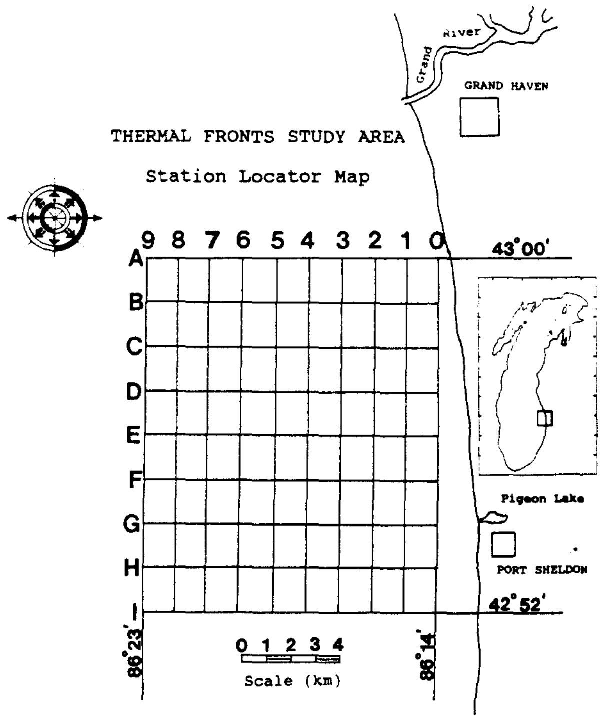

Fig. 1. Thermal front sampling grid in southeastern Lake Michigan.

Experimental design and methods

An important feature of the Lake Michigan vernal thermal front is its predictable developmental sequence. This element of predictability allowed the formation of an experimental design that had a high probability of observing different phases of frontal development. That experimental design shifted somewhat among years, but was basically as follows: one to three day field trips were conducted at one to two week intervals during the spring transition period, normally from early April until late May of each year. A grid of 90 stations comprised a sampling area in southeastern Lake Michigan (Fig. 1). This experimental design resulted in a minimum of three to a maximum of nine field trips in any one season.

During the early development stages of the vernal thermal front, sampling began along the eastern edge of the sampling grid, less than one km from shore. As the spring transition period progressed and the thermal front moved offshore, the sampling grid was expanded offshore to include stations up to 25 km from shore.

Sampling was conducted in one of four general modes: ship-based measurements using a CTD; collection of water and biological samples using Niskin bottles and plankton nets; deployment of moored or tethered instruments in the sampling grid; and satellite-based remote sensing measurements. A Sea Bird CTD (model SBE-9-01) was used to measure temperature, conductivity, pH, underwater light transmission, and in vivo fluorescence with depth. Water samples were collected for in vitro determinations of chlorophyll, nitrate-nitrogen, silica, total and soluble phosphorus, chloride, organic carbon, and bacterial abundance. Moored current meters were used to measure current speed and velocity. These instruments included two bottom mounted, upward-looking RD (model RD-SC0600) acoustic doppler

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current profilers (ADCP) and two strings of Marsh McBirney (model 515M) moored current meters. Both the ADCPs and strings of meters had sensors to monitor water temperature in conjunction with measuring current speeds.

In addition to the sampling scheme described above, special measurements of surface currents and/or primary productivity were made on two occasions in 1988 and three occasions in 1992. Surface currents were assessed by radar tracked drifters attached to underwater drogues. Primary productivity was estimated via the ^{14}C uptake method where samples were incubated in situ with the objective to determine P vs. I curves for samples collected immediately inshore and offshore of the thermal front.

Results and discussion

The vernal thermal front typically began as a shore-parallel feature in late March or early April in southeastern Lake Michigan. Warming of nearshore waters began when buoyant plumes from rivers flowed into cold Lake Michigan waters. Geostrophic flow redistributed those warmed waters along the shore inducing a small ring of 4 °C water along the edge of the lake. This ring of warmed water expanded as additional runoff and solar insolation heated the lake surface. Between 1988 and 1992 the thermal front migrated offshore at a rate of 0.5 to 1.0 km/day dependent upon several factors which varied from year to year. Key factors appeared to be the amount of runoff, the degree of heating, advective heat transport, and the amount of wind stress. In some cases wind stress appeared to force the front back toward shore, while winds from the east accelerated the offshore movement of the front. Others have reported that wind stress also can cause the leading edge of the front to change from a relatively straight shore parallel feature to one with numerous curves and swirls (Csanady 1978).

Moored current strings and ADCP instruments revealed the relatively uniform surface to bottom current flows in the vicinity of the thermal front. Flows were typically 5–15 cm/s during non-storm conditions and in opposite directions on either side of the front. As predicted earlier (Huang 1969, 1972, Mortimer 1988), a shear existed across the front with water inshore of the front having moved northward and offshore southward along the southeastern coast of Lake Michigan. During major wind stress events, the ADCPs showed that currents tended to increase in velocity and water moved in the same direction on both sides of the front. Upon reduction of the wind stress, currents resumed the pattern described above.

In 1988, measurement of near surface currents by drogues showed a modest degree of convergence at the thermal front. This convergence is consistent with a downwelling rate of 0.11 to 0.24 mm/s or 9.5 to 20.7 m/day respectively in April, 1988. The inferred downwelling rate was sufficient to move a "parcel" of water from the surface to the bottom at the thermal front in two to six days. Similar findings were observed in 1992 using surface drifters.

The transition from the thermal front regime to thermally stratified conditions was surprisingly abrupt occurring in a period of only two or three days. The current regime as measured by the ADCPs showed a change from uniform surface to bottom flow to two layered flow. This change appeared to be a manifestation of the transition from vernal frontal conditions to the inertial mode typically found during thermal stratification.

The physical regime associated with the vernal thermal front typically produces substantial biological and chemical gradients (Scavia & Bennett 1980) with the largest horizontal gradients found across the front (Rossmann 1986). In southeastern Lake Michigan we observed that chemical and biological gradients were usually sharpest inshore of the front due to the dilution of enriched coastal water with oligotrophic offshore water (Table 1). In general, the position of the front determined the offshore extent to which the enriched coastal water was mixed. This pattern was best expressed in the chloride data where elevated concentrations usually were restricted to inshore of the front and their offshore extent varied as a function of the frontal position. An exception to this pattern occurred on April 28 when strong onshore winds pushed low chloride offshore water towards the coast. On this date the position of the 4 °C front had receded a kilometer inshore from the previous week. In contrast to the chloride distribution, horizontal gradients for two biologically limiting nutrients, phosphate and silica, were very small (Table 1). Biological utilization may have exerted sufficient force on the concentration patterns of these two nutrients and to some degree uncoupled the relationship to the physical processes associated with the front.

The distribution of chlorophyll across the front was also examined to assess how biological structure may be coupled to the governing physical processes. In general the highest chlorophyll levels were always found inshore of the front where nutrient levels were higher and the water column thermally stratified. However, as observed on sev-

Table 1. Surface concentrations (0–20 m) of Chloride, Nitrate-N, Silica, Total phosphorus, and Chlorophyll in relation to the vernal thermal front in southeast Lake Michigan (all results from 1992).

Position Relative to Front	Distance Offshore (km)	Chloride ($mg \cdot l^{-1}$)	Nitrate ($mg \cdot l^{-1}$)	Silica ($mg \cdot l^{-1}$)	Total-P ($\mu g \cdot l^{-1}$)	Chlorophyll ($\mu g \cdot l^{-1}$)
			April 13			
Inshore	1.2	12.5	0.42	1.8	13.0	4.6
At Front	2.6	12.6	0.45	1.8	18.0	4.4
Offshore	12.4	10.4	0.42	1.6	15.0	2.4
			April 21			
Inshore	4.0	11.9	0.40	1.5	9.9	4.3
At Front	6.8	11.2	0.39	1.4	9.4	3.0
Offshore	8.2	10.5	0.35	1.4	9.2	3.1
			April 28			
Inshore	4.0	10.9	0.36	1.5	9.4	2.9
At Front	5.4	10.4	0.34	1.5	8.9	3.0
Offshore	13.8	10.3	0.34	1.4	8.1	2.7
			May 07			
Inshore	4.0	13.4	0.48	1.6	15.1	7.1
At Front	11.0	11.3	0.34	1.3	9.7	4.4
Offshore	13.8	10.9	0.32	1.2	9.4	2.5

eral dates in 1992 (April 13 and May 7, Table 1) and in the previous 1991 field season, the position of the front did appear to regulate the timing and position of elevated chlorophyll levels. The critical forcing function regulating these abundances appeared to be the onset of thermal stratification which occurred very quickly after the front passed. With the onset of stratification, presumably phytoplankton were no longer mixed down below a critical light level. Furthermore, immediately adjacent to the front, chlorophyll distributions were found to be nearly uniform with depth. This observation supports the hypothesis of a convergence/downwelling circulation pattern driving the system. The preliminary conclusion from the observations of the distribution of these dissolved and suspended materials is that materials injected into the nearshore by runoff are carried out to the front by surface convergence and then moved down into the water column along the surface of the front.

Measurements of primary productivity in 1992 showed that phytoplankton populations in the immediate vicinity of the front were highly productive. Assimilation coefficients (mg C fixed/mg Chlor *a*/hr) ranged from a high of 7.79 in late April to a low of 0.33 in mid May. High productivity was observed from samples collected between 2 and 5 m from both just inshore and offshore of the front. Highest production was not necessarily associated with the highest levels of dissolved nutrients, but was observed in the immediate vicinity of the front. At another Great Lakes front, rapid algal growth consumed much of the available nutrient pool immediately inshore of the front to produce a similar pattern (MOLL et al. 1980).

Conclusions

The spring transition period in southeastern Lake Michigan was characterized by a distinct frontal zone bounded offshore by a nearly vertical 4 °C isotherm. The current regime observed during 1991 and 1992 showed a pattern that is consistent with the scheme suggested by MORTIMER (1988). Those currents resulted in a shear across the front and a moderate degree of surface convergence. Inshore of the front, the water column was in the early stages of vertical thermal stratification while offshore the water column remained fully mixed. This current regime, combined with nutrient, organic carbon and chloride inputs from spring runoff, resulted in a distinct pattern that can best be characterized by high gradients of most critical elements across the front. However, those patterns were modulated by wind stress and/or nutrient uptake associated with primary productivity. Chloride concentrations were almost always higher inshore of the front. The vernal thermal front was always accompanied by high concentrations of chlorophyll found just inshore of the front. As the front migrated toward the center of Lake Michigan, the band of high chlorophyll concentrations migrated along with the front. High chlorophyll concentrations were also observed along the frontal zone from the top to the bottom of the water column.

While these general patterns were observed over the course of five field seasons, interannual variation was substantial. That variation, which is only approximately understood, has significant implications for overall function of large lake ecosystems. The preliminary conclusion from this study is that the spring transition period includes key sequences of events that may influence system status for the rest of the spring and much of the summer. More study of vernal thermal fronts in large lakes of the world would greatly help to decipher the importance of this transition period.

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