Thermal Structure of Lakes Varying in Size and Water Clarity

Asit Mazumder; William D. Taylor

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Abstract—The epilimnion depth of lakes is related both to lake size, which affects wind-induced mixing, and to water clarity, which affects the depth over which solar radiation heats the water. Here we attempt to isolate the relative importance of these two variables by examining lakes that have changed in water clarity with time (between years), by examining nearby lakes of comparable size, and by partitioning a large number of lakes into subsets with a restricted range in size or Secchi depth. Overall, results indicate that both lake size and water clarity are important determinants of epilimnion depth, but the absolute effect (indicated by slope) of Secchi depth is approximately constant in small (<12.5 km^2) as well as large lakes and the Laurentian Great Lakes, while its relative importance (indicated by r^2) appears to be restricted to the small lakes.

Thermal structure affects virtually all biological, chemical, and physical processes in lakes, including primary and secondary production, nutrient regeneration, oxygen depletion, and water movement (e.g. Schindler 1971; Cornett and Rigler 1980; Quay et al. 1980; Gliwicz 1980; Mazumder et al. 1990*a*). It is determined by extrinsic features of the lake, such as inflows and weather, through their effect on the input of heat and physical mixing. It is also determined by intrinsic factors: basin morphometry and water clarity. Water clarity is particularly interesting from a biological viewpoint, because in most lakes water clarity is largely determined by the number and kinds of planktonic organisms. Hence, plankton communities have the potential to affect their microclimate (Mazumder 1990) as do terrestrial plant communities (Lowry 1969).

Many of the empirical studies dealing with thermal structure of lakes consider mainly the influences of morphometric characteristics such as surface area, mean depth, and volume (Gorham 1964; Schindler 1971; Geller 1992), degree of exposure or shelteredness of lakes (Hutchinson 1957), and fetch—the longest axis of a lake uninterrupted from wind (Shuter et al. 1983; Patalas 1984; Hanna 1990). These studies, therefore, suggest that wind-induced transport of heat to deeper strata determines the depths of the epilimnion and thermocline and retention of heat by the water column (Hutchinson 1957; Wetzel 1975). The influence of water clarity and associated direct solar absorption on the thermal structure has been assumed less important. However, many mechanistic models simulate the thermal structure of lakes and oceans from underwater light penetration and windspeed (e.g. Spigel and Imberger 1980; Imberger and Patterson 1981; Simpson and Dickey 1981), and these models are often very sensitive to the way optical attenuance is modeled (Lewis et al. 1983). Krauss and Turner (1967) observed that the effects of radiation are likely to be important even for models of the oceans.

Although it has always been recognized that water clarity is important in influencing the heating of the water column and associated

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thermal structure of lakes (Birge 1916; Birge and Juday 1929; Hutchinson 1957), the patterns of interaction between water clarity and thermal structure have not been well investigated empirically for a large number of lakes with wide variations in size. To explain the heating of the hypolimnion, Ricker (1937) and Bachmann and Goldman (1965) suggested that direct absorption of radiant energy could be important. Yan (1983) found that increased water clarity following acidification of Lohi Lake was associated with increased epilimnetic thickness, thermocline depth, and hypolimnetic heating rate. Mazumder et al. (1990*b*) found that treatments that affected the biomass and size distribution of algae, and, therefore, water clarity, could affect thermal structure in 8-m-diameter lake enclosures. They also reported empirical evidence that water clarity was related to thermal structure among lakes of small surface area (<10 km^2) where wind-induced mixing in regulating thermal structure was assumed to be less important.

The objective of this paper is to examine the influence of water clarity on the thermal structure among a large number of lakes varying 7 orders of magnitude in surface area. Specifically, we test the hypothesis that the importance of water clarity in determining epilimnion depth diminishes with increasing surface area of lakes. The complicating factor is that water clarity and lake size may covary among lakes, making it difficult to isolate the importance of these two factors in determining epilimnion depth. We use two approaches to deal with this difficulty. First, we examine the relationship between water clarity and epilimnion depth in several lakes that have changed dramatically in clarity between years. Hence, morphometry of the basin is constant. These data are supplemented with two other sets of data we believe are comparable; one is from several small kettle lakes that are near each other but differ greatly in water clarity, while the other is from the Laurentian Great Lakes. In these latter data sets, we believe that the lakes are sufficiently similar in size (within the same order of magnitude) and close enough together that they can be compared in the same way as the lakes showing interannual variation in water clarity. Our second approach is to look at a large number of lakes, partitioning the lakes into subsets of size or of Secchi depth in order to minimize the range in one variable at a time and then testing the influence of the other variable on epilimnion depth.

First, we analyzed the relationship between Secchi depth and epilimnion depth in three small lakes of similar surface area. Tory Lake (0.02 km^2, 9-m max depth, Secchi depth 0.2–1 m), Lake St. George (west basin, 0.04 km^2, 15-m max depth, Secchi depth 1.2–2.5 m), and Haynes Lake (0.03 km^2, 16-m max depth, Secchi depth 3.5–6.5 m) are small, kettle lakes situated within 5 km of each other, 50 km north of Toronto, Ontario. Second, we analyzed the within-lake interannual variation of Secchi depth and epilimnion depth in four lakes. Unpublished data were available for Round Lake, Minnesota (0.03 km^2), in which Secchi depth tripled following the manipulation of fish communities (Shapiro and Wright 1984). Three years of data on the temperature profile and Secchi depth were available from Lake Washington (87 km^2): for 1967 when the lake was eutrophic (mean Secchi depth of 1.2 m and mean Chl *a* of 14.5 μg liter^{-1}) and for 1977 and 1978, when nutrient loading was low, the abundance of large *Daphnia* was high, mean Chl *a* was <3 μg liter^{-1}, and mean Secchi depth was 7.5 m (Edmondson and Lehman 1981; Edmondson and Litt 1982). Published and unpublished data were also available for Lohi Lake (0.41 km^2; Yan 1983) and Mountaintop Lake (0.04 km^2; Yan and Lafrance 1984; unpubl. data). Lohi Lake provided 7 yr of data on the influence of Secchi depth (following neutralization in 1974–1976 and then acidification from 1977 to 1979) on epilimnion depth. Mountaintop Lake provided 3 yr of data (1976–1978) on the influence of reduced Secchi depth following whole-lake fertilization in fall 1976. Temperature profiles and Secchi depth for August for the Laurentian Great Lakes were provided by H. Dobson. The seven data points for the Great Lakes included one measurement during August from each of Lakes Superior, Michigan, Huron, Erie (eastern and central basins), and Ontario (2 yr).

Finally, we analyzed a large data set: the original OMNR Lake Inventory Data Set had ~10,000 lakes. From these, we selected lakes based on the following criteria: they were not highly colored (<code 3 in the data set); they stratified in summer (lakes >20-m max depth

Table 1. Morphometric and physical characteristics (averages) of lakes used in the analysis. Lakes are classified into size classes with 5-fold increments in surface area (km^2), except for the Great Lakes where they were grouped into one class (>10,000 km^2). Numbers in parentheses are ranges. Data on lake shape were not available, but the data on the perimeters of islands and the percentage of lakes having at least one island per lake may indicate complex basin structure.

	Size classes of lakes					
	<0.5	>0.5–2.5	>2.5–12.5	>12.5–62.5	>62.5–312.5	>10,000
Number	371	578	339	124	23	7
Location	48°64′N, 83°87′W	49°01′N, 89°00′W	49°47′N, 90°61′W	49°68′N, 90°90′W	50°31′N, 90°57′W	42°16′N, 83°25′W
Elevation (m)	325.4 (145–549)	375.2 (130–496)	377.1 (115–503)	368.6 (105–488)	354.8 (195–457)	157.2 (75–183)
Mean area (km^2)	0.33	1.25	5.49	25.39	126.46	41,487.7
Mean fetch (km)	0.57 (0.14–0.70)	1.09 (0.71–1.58)	2.27 (1.6–3.3)	4.92 (3.5–7.9)	10.85 (7.9–18.6)	195.77 (138–287)
Secchi depth (m)	4.5 (0.3–15.6)	4.5 (0.7–19.8)	4.5 (1.1–15.6)	4.2 (1.4–9.3)	4.0 (2.5–6.8)	6.0 (3.0–9.0)
Epilimnion depth (m)	3.7 (0.7–7.7)	4.3 (0.8–12.4)	5.4 (1.7–12.1)	6.3 (1.9–12.8)	7.5 (4.6–13.2)	15.3 (12.0–20.0)
Island perimeter (km)	2.3	9.3	9.6	17.5	22.6	
Lakes with islands (%)	62	26	19.5	18.2	16.3	

and showing distinct hypolimnia); and their temperature profiles were measured between 15 July and 15 August. Also included were data gleaned from the literature and presented by Mazumder et al. (1990*b*). Altogether, data from 1,442 lakes were used (Table 1).

Sterner (1990) used the OMNR data set to test the influence of lake morphometry on mean irradiance in the surface layer. Because he used different criteria (max depth ranging 0.3–213 m compared to >20 m in this paper; temperature profiles for all dates in summer compared to the profiles at the time of maximum heat content in this paper) to select his lakes and selected ~1,100 from the 10,000, the overlap between his and our lakes is probably small.

Temperature was measured at every meter depth except for Lake Washington, the Great Lakes, and several very deep lakes in the OMNR data set where the depth intervals varied from 2 to 5 m or more. Epilimnion (E_d), metalimnion, and hypolimnion depths were calculated from the temperature profiles following Wetzel (1975). Epilimnion depth is the surface layer of the water column in which change in temperature is <1°C per meter. We chose to use epilimnion depth instead of thermocline depth to indicate the depth of mixing because we found it easier to estimate; for deep lakes where the sampling interval was coarse, it was difficult to determine the actual plane of maximum thermal gradient.

Least-squares regression analysis was used to examine the relationship between E_d and the independent variables of interest: Secchi depth (S_d) and fetch (F). Fetch was estimated as the square root of surface area (A) (Arai 1981; Patalas 1984; Gorham and Boyce 1989). As the fetch was calculated from surface area, it is possible that the calculated fetch will overestimate the actual length of the lake basin exposed to wind because the presence of islands and complex basin structures can modify the exposure of surface water to wind. Although we did not have the data on lake shape, lakes of glacial origin (as is the case for most lakes in Ontario) appear to exhibit complex basin structures (pers. obs.). However, we had data on the perimeter of islands for the lakes used in this study (Table 1). We also calculated the percentage of lakes having at least one island. The presence of islands may suggest complex basin structure.

Multiple regressions were used to determine the improvement of predictability of E_d by both S_d and F. Partial correlation coefficients and partial probabilities of multiple regression were used to determine the significance of S_d and F effects on E_d. As mentioned before, the covariance of F with S_d may complicate the interpretation of F-E_d, S_d-E_d, and F + S_d-E_d relationships produced by regression analyses. We took two independent approaches to isolate the influence of S_d and F on E_d. First, we performed ANCOVA for the effects of F on E_d

with S_d as a covariate and the effects of S_d on E_d with F as a covariate. Second, we analyzed F-E_d relationships for lakes with a narrow range of S_d (<4, 4–8, and >8 m), and S_d-E_d relationships for lakes with a narrow range of surface area (<0.5, >0.5–2.5, >2.5–12.5, >12.5–62.5, >62.5–312.5, >10,000 km^2). Except for the smallest (<0.5 km^2) and the largest (>10,000 km^2) size classes (the <0.5-km^2 size class included lakes ranging from 0.02 to 0.5 km^2, and the >10,000 km^2 size class included the Great Lakes ranging from 13,000 to 82,000 km^2), the size classes included lakes with 5-fold increment in surface area. The F-E_d relationship within each S_d class served two purposes: to examine whether F explained more variance in E_d when S_d effect on E_d was reduced and whether high clarity lakes (S_d > 8 m) exhibited significantly deeper E_d than low clarity lakes (S_d < 4 m) and to examine whether this difference was consistent along the size gradient of lakes (different *y*-intercepts with similar slopes).

Table 2. Seasonal averages (April–August or September) of climatological data from the weather stations nearest to the lakes. Data for Sudbury Airport are from Yan (1983).

Lakes	Air temp. (°C)	Windspeed (km h^{-1})	Full sunshine (h $month^{-1}$)
Round Lake (source—NOAA, St. Paul Airport, Minnesota)			
1980	18.6	14.6	312
1981	16.8	16.1	297
1982	17.5	16.5	303
Lake Washington (source—NOAA, Seattle-Tacoma Airport, Washington)			
1967	15.8	10.3	303
1977	16.1	12.3	260
1978	15.6	10.7	221
Lohi Lake and Mountaintop Lake (source—Sudbury Airport, Ontario)			
1973		17.7	199
1974		17.9	190
1975		20.2	243
1976		18.9	232
1977		18.7	223
1978		18.0	226
1979		15.5	215

Results indicated that within lakes and lake groups of comparable size, increasing Secchi depth was associated with deeper epilimnion (slope > 0; P < 0.0001) (Fig. 1). This pattern was observed in small lakes (<0.05 km^2) as well as in the Great Lakes. In addition, the *y*-intercept of the S_d-E_d relationship for the Great Lakes was 5 times greater than that exhibited by the small lakes. Lake Washington, three orders of magnitude smaller in surface area than the Great Lakes and three orders of magnitude larger than the small lakes, has an epilimnion depth half as shallow as the Great Lakes and twice as deep as the small lakes. A deeper epilimnion depth in the larger lakes was consistent with the hypothesis we proposed to test, as well as with other studies (Patalas 1984; Gorham and Boyce 1989; Hanna 1990). In addition, a significant deepening of E_d with increasing water clarity at constant lake size was consistent with our hypothesis as well as other empirical (Mazumder et al. 1990*b*) and simulation models (Spigel and Imberger 1980; Imberger and Patterson 1981; Simpson and Dickey 1981). Therefore, both the lake size and water clarity seemed to be important in influencing E_d in small and large lakes. The observed interannual variation in epilimnion depth may not have been due to variable meteorological conditions (Table 2). However, our observation that the slope of the S_d-E_d relationships for the small lakes was not significantly different from that for Lake Washington or the Great Lakes was not consistent with our hypothesis that the effects of water clarity in deepening epilimnion depth diminishes with increasing lake size. We expected that a constant increase in S_d would be associated with a smaller increase in epilimnion depth in larger lakes where physical mixing is assumed to be more important in determining epilimnion depth than water clarity. As these observed patterns of greater *y*-intercepts, but with more or less constant slopes among lakes of increasing surface area were based on data sets covering narrow ranges of Secchi depth and small sample sizes (Fig. 1), we tested these patterns with a larger data set (discussed below).

Among 1,442 lakes covering a 7-orders-of-magnitude variation in surface area and a two-orders-of-magnitude variation in Secchi depth (Table 1), E_d was positively related with F and S_d (Table 3). Individually, each of these two independent variables explained an approximately equal amount of variance in E_d (22 and 26%). Among the lakes used here, lake size (surface area) and S_d were not strongly related [$S_d = (4.91 \pm 0.06) - (0.15 \pm 0.15)(\log_{10}F)$, $r^2 = 0.001$, $P = 0.312$, $F = 1.02$, $n = 1{,}442$; slope not significantly different from zero], although

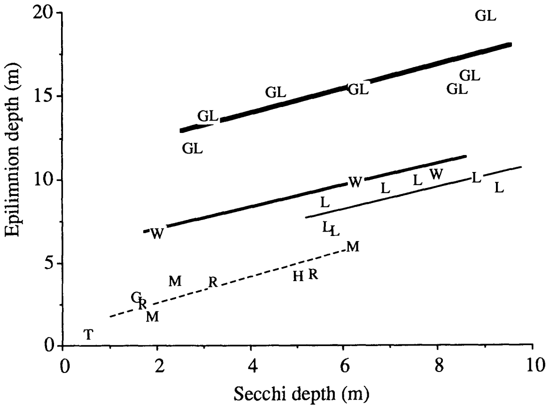

Fig. 1. Water-clarity effect on E_d at constant lake size, illustrated by within-lake and between-year variation in S_d and E_d of lakes of varying surface area. To demonstrate the influence of lake size on E_d, we superimposed data for the Great Lakes [GL; 13,000–89,000 km^2; $E_d = (11.12 \pm 1.57) + (0.72 \pm 0.72)S_d$, $r^2 = 0.64$, $n = 7$, $F = 8.9$, $P = 0.030$] ($n = 7$). W—Lake Washington [87 km^2; $E_d = (5.91 \pm 0.66) + (0.61 \pm 0.11)S_d$, $r^2 = 0.97$, $n = 3$, $F = 29.3$, $P = 0.116$]; L—Lohi Lake [0.4 km^2; $E_d = (4.69 \pm 1.49) + (0.62 \pm 0.21)S_d$, $r^2 = 0.63$, $n = 7$, $F = 8.7$, $P = 0.032$]; M—Mountaintop Lake (0.04 km^2); R—Round Lake (0.03 km^2); G—Lake St. George (0.04 km^2); H—Haynes Lake (0.03 km^2); T—Tory Lake (0.02 km^2). Dotted line is least-square regression fit [$E_d = (1.54 \pm 0.56) + (0.64 \pm 0.16)S_d$, $r^2 = 0.69$, $n = 9$, $F = 15.7$, $P = 0.005$] for lakes <0.04 km^2.

there is an expectation that water clarity increases with lake size. In addition, except for the Great Lakes, mean S_d was not significantly deeper in the larger lakes (Table 1; $P > 0.05$, ANOVA). Accordingly, a multiple regression model using both the independent variables produced a coefficient of determination of 0.48 (Table 4)—approximately equal to the sum of the coefficients for the two independent variables individually (Table 3). The partial probabilities for both independent variables were significant. The interaction term between S_d and F was not significant.

For each subset of lakes with respect to surface area, the strength of the relationship between S_d and E_d weakened with increasing lake size (Table 3); the coefficient of determination was greatest for lakes <0.5 km^2, declines to <0.1 for lakes >12.5 km^2, and shows no significant relationship for lakes >62.5–312.5 km^2. Errors associated with the *y*-intercepts and slopes of the equations predicting epilimnion depth from Secchi depth were also wider for larger lakes. The good relationship for the Great Lakes might be because the two variables (S_d and F) are correlated. It might also reflect that the lakes are nearby, of simple morphology, and larger than a critical size. Although the mean slope of the S_d-E_d relationship did not change systematically with lake size, the error associated with the mean slope increased and approached a nonsignificant slope for lakes >62.5–312.5 km^2. The weaker S_d-E_d relationships for larger lakes (>12.5–62.5 and >62.5–312.5 km^2) were possibly due to the narrow ranges of S_d exhibited by these two size classes (Table 1; Fig. 2). The S_d-E_d relationships for the first three size classes of lakes

Table 3. Results of least-squares regressions predicting epilimnion depth (E_d) from Secchi depth (S_d) and fetch (F) for all lakes together and for each size class of lakes separately.

Variable	Intercept	Slope	*N*	r^2	*F*	*P*
S_d (independent variable)						
All lakes	3.24±0.19	0.35±0.02	1,442	0.22	244.7	0.0000
<0.5 km^2	1.62±0.11	0.37±0.02	371	0.44	210.4	0.0000
0.5–2.5 km^2	2.56±0.13	0.42±0.03	578	0.34	294.4	0.0000
2.5–12.5 km^2	3.81±0.22	0.39±0.04	339	0.21	87.6	0.0000
12.5–62.5 km^2	5.14±0.58	0.35±0.12	124	0.06	8.2	0.0050
62.5–312.5 km^2	5.94±1.85	0.49±0.43	23	0.05	1.3	0.2689
>10,000 km^2	11.11±1.57	0.72±0.24	7	0.64	8.9	0.0304
$\log_{10}$ F (independent variable)						
All lakes	4.69±0.05	2.69±0.12	1,442	0.26	471.1	0.0000
<0.5 km^2	4.03±0.13	0.71±0.23	371	0.01	6.1	0.0470
0.5–2.5 km^2	4.60±0.07	1.87±0.65	578	0.01	8.4	0.0037
2.5–12.5 km^2	4.52±0.35	3.42±0.97	339	0.04	12.5	0.0005
12.5–62.5 km^2	3.57±1.31	4.63±1.91	124	0.05	5.9	0.0169
62.5–312.5 km^2	−1.12±5.02	8.87±4.89	23	0.14	8.9	0.0838
>10,000 km^2	−18.73±10.55	15.05±4.63	7	0.68	8.9	0.0227

Table 4. Results of multiple regressions and ANCOVA showing the significance of Secchi depth (S^d) and fetch (F) effects on epilimnion depth (E_d) ($n = 1,442$). F data are $\log_{10}$ transformed to spread out the low end of the range. For F effect on E_d, six levels of F (same as Table 1) were used. For S_d effect on E_d, three levels of S_d (<4, 4–8, >8 m) were used; *r* (partial) represents partial correlation coefficient.

	Multiple regression showing the relationship of E_d with F and S_d					
Variables	Coefficients	SE	*P* (2-tail)	*r* (partial)	r^2 (overall)	*F* (overall)
Constant	2.88	0.099	<0.0001		0.48	376.5
S_d	0.37	0.018	<0.0001	0.48		
$\log_{10}$ F	2.34	0.259	<0.0001	0.52		
$S_d \times F$	0.09	0.052	0.055			

	SS	df	MS	*F*	*P*
	F effect on E_d (F levels = 6; $r^2 = 0.48$)				
$\log_{10}$ F	13.6	5	2.3	124.2	<0.0001
S_d (covariate)	11.0	1	11.0	604.3	<0.0001
Error	26.4	1,436	0.018		
	S_d effect on E_d (S_d levels = 3; $r^2 = 0.47$)				
S_d	6.83	2	2.27	121.9	<0.0001
$\log_{10}$ F (covariate)	11.80	1	11.77	630.9	<0.0001
Error	25.08	1,439	0.019		

appeared to be less influenced by the confounding effects of F on E_d because F explained only 1–4% of the variance in E_d while S_d explained 21–44% of the variance. Therefore, we concluded that the relative importance (indicated by r^2) of S_d as a determinant of E_d weakens gradually with increasing lake size, at least within the domain of the data set used in this study.

However, it is possible that weaker S_d-E_d relationships among larger lakes are due to smaller sample sizes and to changes in lake shape with increasing lake size. Although we did not have data indicating lake shape directly, the lower frequency of islands in larger lakes may indicate that basin structure is less complex (irregular) among larger lakes (Table 1). The parallel S_d-E_d relationships for lakes with increasing surface area suggests that the absolute effect of water clarity on epilimnion depth is similar (indicated by similar slopes) in small (<12.5 km^2) and large lakes (>12.5–312.5 km^2). The *y*-intercept increased monotonically from 1.6 m for lakes <0.5 km^2 to 5.9 m for lakes >62–312.5 km^2 to 11.1 m for the Great Lakes (Fig. 2 and Table 4). The pattern of an elevated series of approximately parallel S_d-E_d linear fits within individual lakes or among a set of lakes with roughly equal surface area (Fig. 1) is shown by each size class of lakes in the large data set (Fig. 2).

When the lakes were partitioned into limited ranges of S_d, the ability of F to predict E_d improved significantly (Fig. 3). While F explained 26% of the variance in E_d for all the lakes (Table 3), it explained up to 19% more variance when used to predict E_d in a narrow range of S_d. We analyzed F-E_d relationships within each of the three S_d classes with and without the data points for the Great Lakes. We wanted to test whether 2–3 data points for the Great Lakes which are scattered more

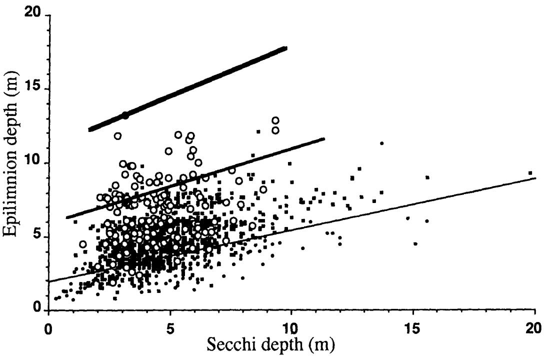

Fig. 2. Relationship between S_d and E_d. Lakes <12.5 km^2—●, ■; lakes >12.5–312.5 km^2—○. The bottom linear fit is for lakes <0.5 km^2 and the middle linear fit is for lakes >62.5–312.5 km^2. The linear fit for the Great Lakes (same as in Fig. 1) has been superimposed for comparison. Only three linear fits are presented to illustrate the similarities of patterns produced by similar-sized lakes in Fig. 1. Linear fits for all the size classes are listed in Table 3.

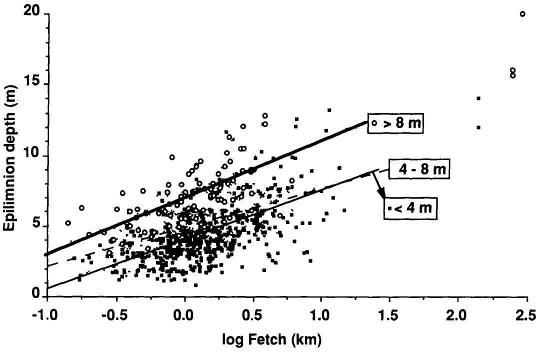

Fig. 3. Relationship between $\log_{10}$F and E_d among lakes covering narrow ranges of S_d. Lakes with $S_d < 4$ m—$E_d = (3.94 \pm 0.07) + (2.92 \pm 0.18)\log_{10}F$, $r^2 = 0.36$, $F = 266$, $n = 484$, $P < 0.0001$; lakes with S_d 4–8 m—$E_d = (4.89 \pm 0.05) + (2.58 \pm 0.12)\log_{10}F$, $r^2 = 0.30$, $F = 339$, $n = 784$, $P < 0.0001$; lakes with $S_d > 8$ m—$E_d = (6.71 \pm 0.16) + (3.76 \pm 0.46)\log_{10}F$, $r^2 = 0.41$, $F = 66$, $n = 97$, $P < 0.0001$. Fetch has been $\log_{10}$ transformed to spread the low range values. The Great Lakes are not included in the linear fits (explained in text).

than an order of magnitude beyond the rest of the lakes in each S_d class could modify regression fits. Including the Great Lakes, the slope for the lakes with $S_d > 8$ m was larger [$E_d = (6.72 \pm 0.16) + (4.12 \pm 0.29)\log_{10}F$; $r^2 = 0.66$; $F = 190$; $n = 100$] than that for the lakes with $S_d < 4$ m [$E_d = (3.94 \pm 0.07) + (2.97 \pm 0.18)\log_{10}F$; $r^2 = 0.37$, $F = 289$; $n = 486$], and for the lakes with S_d 4–8 m [$E_d = (4.89 \pm 0.05) + (2.77 \pm 0.14)\log_{10}F$; $r^2 = 0.32$; $F = 376$; $n = 786$].

If we exclude the Great Lakes (equations in Fig. 3), slopes for the lakes with $S_d < 4$ m and $S_d > 8$ m were not significantly different from each other ($P > 0.05$). However, the slope for the lakes with S_d 4–8 m was smaller than either group ($P < 0.005$) (Fig. 3). The y-intercepts of F-E_d relationships for all three S_d classes did not change following the exclusion of the Great Lakes, however (Fig. 3). On average, the lakes with $S_d > 8$ m exhibited a 2.8 m deeper epilimnion depth than the lakes with $S_d < 4$ m (Fig. 3), and this difference was approximately consistent along the size gradient of lakes ranging 0.02–312 km^2. Although there was some overlap of E_d between the two groups of lakes ($S_d < 4$ m and > 8 m), <5% of the lakes with $S_d > 8$ m were below the mean predicted E_d of lakes with $S_d < 4$ m, and <5% of the lakes with $S_d < 4$ m were above that for lakes with $S_d > 8$ m. The reason for a shallower slope for the lakes with S_d 4–8 m than for the two other groups is not clear. It may be because among lakes with S_d 4–8, the S_d values were as deep as or deeper than E_d in the small lakes and they were as deep as or shallower than E_d in large lakes. If S_d is deeper than E_d, the impact of direct solar heating on the thermal structure may be greater than when S_d is $\leq E_d$.

In conclusion, the thermal structure of lakes, as indicated by epilimnion depth, is influenced by both lake size and water clarity. We expected that the importance of water clarity in determining E_d would be restricted primarily to small lakes. However, the analyses of E_d within lakes and among a large number of lakes indicate that the absolute effect of water clarity (indicated by the slopes) is approximately constant in small as well as large lakes, although its relative importance (indicated by r^2) is less in large lakes. Weaker S_d-E_d relationships for larger lakes (>12.5–312.5 km^2) may also be due to the smaller sample sizes represented by these size classes (Tables 1 and 3). We observed that the relationship between fetch and epilimnion depth was weaker, especially for the smaller lakes, than we expected. It may be because fetch is a weak indicator of lake size when the shapes of the lake basins are highly irregular, as is the case for the OMNR data set (Sterner 1990). Although we could not test the effect of lake shape on F as a predictor of E_d, it is possible that larger lakes are more circular or uniform in shape than smaller lakes. However, the data on the percentage of lakes having islands show that fewer large lakes have islands (18.8%) than the smaller lakes (35%), and therefore, the exposure of lakes to wind may be less interrupted in larger lakes. Therefore, fetch calculated from surface area may be a better approximation of actual fetch in larger lakes than smaller lakes, and consequently F becomes a stronger predictor of E_d in larger lakes.

Empirical assessment of the importance of two independent variables is difficult when they are not independent of each other. However, we are encouraged by two aspects of these results. First, interannual variation within lakes, which is independent of lake size, is consistent with the results of comparisons among lakes. Second, the correlation between these two independent variables (S_d and F) was very weak in our data set. Sterner (1990) reached a similar conclusion in his analysis of a different subset of the OMNR data.

This analysis has focused on epilimnion depth. However, the results also imply that the other aspects of thermal structure, such as total heat content, temperature of the epilimnion and hypolimnion, and thermal gradient of the metalimnion, will also change with water clarity. Changes in water clarity are common objectives or consequences of human interactions with lakes. Predictions concerning the effects of changes in water clarity should include those resulting from changes in thermal structure.

Asit Mazumder

Sciences Biologiques
Université de Montréal
Montréal, Québec H3C 3J7

William D. Taylor

Department of Biology
University of Waterloo
Waterloo, Ontario N2L 3G1

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Development of a new method for direct measurement of pCO_2 in natural waters

Abstract—A new direct measurement method for pCO_2 in water samples is presented. The technique is based on the fact that the dissolved CO_2 in a water sample is able to diffuse through the wall of a thin silicon rubber tubing, whereas the dissolved ions remain. The CO_2 passing through the wall is equilibrated with the deionized water flowing inside the tubing, and its electric conductivity is measured by a conductivity flow cell afterward.

Laboratory experiments on 255 CO_2 standard samples with pCO_2 varying from 300 to 30,000 ppmv show a mean CO_2 exchange ratio R across the silicon rubber membrane of 0.95, with SD = ±0.04. For pCO_2 in the 40–300 ppmv range (40 CO_2-standard samples), a mean exchange ratio $R = 0.93 \pm 0.09$ has been determined. The detection limit of this method is 0.6 μM (~18 ppmv at 25°C).

CO_2 is of considerable interest because it plays a major role in aquatic carbonate systems, water biology, and the global carbon cycle. Up to the present, pCO_2 has been measured mainly by infrared absorption spectroscopy, gas chromatography, and pH-titration methods (Takahashi et al. 1970). However, each of these methods has limitations. Infrared absorption and gas chromatography usually require high professional operating skill and suit, in principle, the measurement of gas samples only. To determine the pCO_2 of a water sample, the equilibrium of CO_2 exchange between water and the gas phase must be established, and the equilibrated gas sample must be dried before measurement (water vapor would influence the results). These procedures are expensive and time consuming. pH titration is a convenient technique for determining carbonate (HCO_3^-, CO_3^{2-}), alkalinity, and acidity in water samples. The pCO_2 of a water sample is easily calculated from the equilibrium constant, the pH value, and HCO_3^- concentration. The accuracy of the pH measurement usually is satisfactory only if a very precise pH detector is used. The purpose of this study was to develop a simple, flexible, and economical technique and to design a device that allows direct pCO_2 measurement of a water sample; this can be done by measuring the electric conductivity. The procedure is superior to methods published previously.

CO_2 gas is very soluble in water and under low partial pressure and concentrations it obeys Henry's law:

$$CO_{2(g)} + H_2O \rightleftharpoons CO_{2(aq)} \qquad (1a)$$

$$[CO_{2(aq)}]/[CO_{2(g)}] = K_{CO_2}. \qquad (1b)$$

$[CO_{2(g)}]$ is the CO_2 concentration in the gas phase ($=pCO_2$), $[CO_{2(aq)}]$ is the dissolved CO_2 concentration in water, and K_{CO_2} is Henry's constant.

The dissolved CO_2 is hydrated slowly, relaxation time ~22 s, yielding carbonic acid (Wetzel 1975):

$$CO_{2(aq)} + H_2O \rightleftharpoons H_2CO_3$$

$$\text{(dominant if pH} < 8); \qquad (2)$$

$$CO_{2(aq)} + OH^- \rightleftharpoons HCO_3^-$$

$$\text{(dominant if pH} > 10). \qquad (3)$$

H_2CO_3 is a weak acid that dissociates to

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