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A simple model for predicting the date of spring stratification in temperate and subtropical lakes

Abstract—The date of onset of spring stratification in northern hemisphere lakes is predictable from mean annual air temperature. The prediction is further improved by also considering lake surface area (surrogate of wind exposure) and by the ratio (R) of lake surface area to mean depth, with R reflecting aspects of lake morphometry and heat storage capacity. Mean annual air temperature and R together explain 68% of the variance in the date of onset of stratification in a combined 70-lake data set from North America, Europe, and Asia. Nearly identical fractions were explained when the lakes were separated into dimictic and warm monomictic data sets. The remaining unexplained variation is probably largely attributable to interyear variation in weather, but also to unexamined differences in regional wind strength, local protection from winds, lake shape, and lake turbidity, as well as differences in the intervals at which temperature profiles were taken.

The stratification of lakes and its onset has preoccupied limnologists since the late 19th century, which reflects not only an interest in being able to categorize lake types by their stratification regimes, but also stems from a recognition of the importance of temperature and season in determining the structure and productivity of aquatic communities. The onset of spring stratification marks a major change in the light climate for phytoplankton in lakes that are sufficiently deep to stratify. Stratification allows a spring bloom to develop in many lakes (Reynolds 1984; Marshall and Peters 1989). The date of stratification has, furthermore, a major bearing on the length of the stratification period and thus on the probability of an anoxic hypolimnion developing in eutrophic lakes.

Nürnberg (1988) recently developed simple empirical models that allow estimation of the date by which north temperate lakes can be expected to have completed their autumnal destratification. The goal of the present study is to produce a complementary model able to predict the spring date by which temperate and subtropical northern hemisphere lakes can be expected to stratify.

Lakes in cold regions lose a portion of the annual heat income to melting of ice (Welch et al. 1987). Because this heat is not available to warm water, cold lakes stratify later than they otherwise would. For this reason, we examined the utility of mean annual air temperature in predicting the onset of stratification. When not available directly, the mean annual air temperature was estimated from published climatic maps (Wernstedt 1972). Temperature was used rather than latitude because the latter does not account for temperature differences associated with altitude and longitude (Kalff 1991). Large lakes can be expected to stratify later than small ones in the same region because of greater wind exposure. We therefore explored the importance of lake surface area in determining date of stratification. We also reasoned that the volume of water to be heated should affect the date of stratification; deep lakes should stratify later than shallow ones of the same surface area (Gorham 1964). Lastly, we examined the utility of the ratio of surface area to mean depth (R), which includes both a volumetric and a morphometric component. R proved to be superior to mean depth as a predictor of stratification. To examine whether there were major systematic differences between dimictic and warm monomictic lakes in the timing of their stratification, we also separated the lakes according to whether they developed an ice-cover.

Data on 70 north-temperate lakes were assembled from six sources (Janus and Vollenweider 1981; Davis et al 1978; Seyb and Randolph 1977; Milway 1970; ILEC/UNEP 1988, 1989). The data set includes 34 lakes from North America, 22 from Europe, and 14 from Asia, with the majority of the latter from Japan. With water temperature profiles determined at intervals, the date of stratification

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Table 1. Means, standard deviations (in parentheses), and ranges of several variables for the three data sets. Temp.—mean annual air temperature; A_0—surface area; z—mean depth; R—ratio of surface area to mean depth.

Variables	All lakes	Dimictic	Monomictic
Temp. (°C)	7.9(4.0) −1.0–20.6	6.2(2.5) −1.0–10.5	11.3(4.4) 5.78–20.6
A_0 (km²)	1,501(7,841) 0.11–58,016	833(4,589) 0.11–31,500	2,867(12,078) 1.2–58,016
z (m)	40(98) 3.6–740	30(108) 3.6–740	59(71) 6.2–177
log R	−0.0667 (1.00) −1.87–2.84	−0.176 (1.02) −1.87–1.94	0.151 (0.95) −1.13–2.84
Date	15 Feb–5 Jul	15 Mar–5 Jul	15 Feb–15 Jun
Day of the year	115(31)	127(19)	89(39)

was assumed to be the day of the year on which stratification was first reported. The degree of bias introduced by this method depends on the sampling interval. Univariate and bivariate regression analyses were performed with a statistical package (SAS Inst., Inc. 1985), with the ratio of lake area to depth logarithmically transformed to stabilize the variance.

The lakes ranged widely in area, depth, and morphometry, with the date on which stratification was first measured ranging between 15 February and 5 July (Table 1). Not surprisingly, the mean date by which the dimictic lakes, with their winter ice-cover, stratified was later than for the permanently ice-free, warm monomictic lakes.

The single best predictor of the date of stratification was mean annual air temperature which explained 60% of the variation observed for all lakes combined, but which plays a less important role for warm monomictic lakes (Table 2). The latter are characterized by higher average air and water temperatures and are proportionally more affected by differences in exposure to wind and lake morphometry. We were unable to determine whether the lesser importance of air temperature in warm monomictic lakes is primarily attributable to the smaller annual range in average water temperature encountered, thereby allowing the other variables to play a larger role, or to differences in the average wind exposure or volume of the two lake types (Table 2). The greater scatter of monomictic lakes around the overall line of best-fit linking air temperature and the date of onset of stratification is most evident at mean annual air temperatures of 6–10°C where monomictic and dimictic lakes overlap (Fig. 1).

Considerable additional variance in the lake model is explained by wind exposure (surface area) and in particular by the ratio (R) of surface area (wind exposure) and mean depth (water volume). Yet, an examination of the residuals (not presented) of our multivariate model (Table 2, Eq. 3) for all lakes combined shows

Table 2. Regression models predicting the onset of spring stratification (day—day of the year) as a function of mean annual air temperature (temp., °C) lake surface area (A_0, km²), and log of the ratio of surface area to mean depth (R).

Model	r^2	P
Combined lakes (n = 70)		
(Eq. 1) day = 162 − 6.05 temp.	$r^2 = 0.60$	$P < 0.001$
(Eq. 2) day = 159 − 5.38 temp. + $0.00089A_0$	$r^2 = 0.65$	$P < 0.0001$
(Eq. 3) day = 160 − 5.72 temp. + 8.46 log R	$r^2 = 0.68$	$P < 0.0001$
Dimictic lakes (n = 47)		
(Eq. 4) day = 164 − 6.03 temp.	$r^2 = 0.63$	$P < 0.0001$
(Eq. 5) day = 160 − 5.38 temp. + $0.0076A_0$	NS	
(Eq. 6) day = 160 − 5.14 temp. + 5.74 log R	$r^2 = 0.72$	$P < 0.0001$
Monomictic lakes (n = 23)		
(Eq. 7) log day = 2.1993 − 0.0251 temp.	$r^2 = 0.36$	$P < 0.01$
(Eq. 8) log day = 1.9684 − 0.0175 temp. + 0.0854 log A_0	$r^2 = 0.55$	$P < 0.001$
(Eq. 9) day = 123 − 3.429 temp. + 20.636 log R	$r^2 = 0.67$	$P < 0.0001$

that the major outliers identified with the univariate model (Fig. 1) remain outliers after surface area and the ratio of surface area to volume are considered. Therefore, environmental variables other than those considered must have an important bearing on the date of stratification. An examination of topographic maps reveals that those lakes that stratify much earlier than predicted (Fig. 1) are largely found in hill or mountain valleys and as a result probably have a much smaller wind stress on their surfaces than most lakes of similar size located in more exposed basins. Three lakes that stratify exceptionally early are the Lunzer Untersee (9) and Lake Zurich (12) in Europe and Lake Ikeda (8) in Japan—all lying in wind-protected mountain valleys characterized by an annual mean air temperature of 6–9°C.

At higher temperatures the extent of wind protection appears less important in determining onset of stratification. Thus, two Japanese reservoirs (17), located where the annual average air temperature is 14°C, require much less heating to develop the density differences needed to stratify early than much colder and apparently better wind-protected Lake Ikeda (8), with all these water bodies stratifying as early as 15 February. Among the late-stratifying lakes are Baikal (1), Michigan (6), Washington (14), and Shinji (16). The first two not only are very large, but their exposures to winds allows their enormous central water masses to be cooled much closer to 0°C than the average lake where the water mass upon freezing is close to 4°C. The combination of extreme winter cooling and large fetch means that an exceptionally large amount of heat input is needed subsequently to develop the needed resistance to mixing. The heat input required appears sufficient to explain a stratification date much later than predicted for most lakes in the data set.

That mean annual air temperature alone is an imperfect indicator of climatic conditions is particularly evident in the case of coastal Lake Washington which, in contrast to more continental lakes at similar mean annual air temperatures, is characterized by mild winters and cool summers. The temperature regime combined with high coastal winds results in a late stratification. Another outlier is large (80 km^2) but shallow (mean depth 6.4 m) Lake Shinji. Shallow lakes, such as Shinji are particularly affected by interyear differences in wind regime and solar radiation. Early attempts at stratification are easily reversed by only short periods of cool and(or) windy weather, making for late onset of stable stratification.

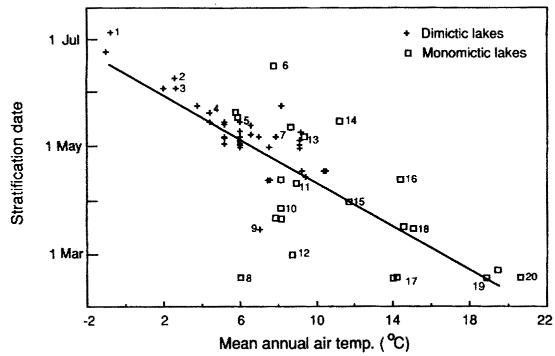

Fig. 1. Relationship between mean annual air temperature and date of onset of spring stratification for 70 temperate zone lakes. Some points represent more than one lake. Twenty lakes are identified, although not all are discussed. 1—Baikal, Russia; 2—Paijanne, Finland; 3—St-Jean, Canada; 4—Shagawa, U.S.; 5—Vanern, Sweden; 6—Michigan, U.S.; 7—Stechlin, Germany; 8—Ikeda, Japan; 9—Lunzer Untersee, Austria; 10—Lomond, U.K.; 11—Windermere, U.K.; 12—Zurich, Switzerland; 13—Mendota, U.S.; 14—Washington, U.S.; 15—Maggiore and Lugano, Italy; 16—Shinji, Japan; 17—Sagami and Okutama Res., Japan; 18—Biwa, Japan; 19—Kinneret, Israel; 20—Phewa, Nepal.

The influence of interyear differences in weather on the date of stratification is not restricted to shallow large lakes; it is also a principal impediment to the further improvement of all the models presented here. For example, the average date by which 14 smaller Ontario lakes stratified over a 5-yr period ranged between 21 April in 1980 and 13 May in 1978 (Fig. 2). Large interyear differences are not restricted to small lakes, as the onset of stable stratification in Lake Ontario varied widely between 14 May and 2 July over a 20-yr period (Rodgers 1987). As the present data (Fig. 1) were obtained for single years, an important fraction of the data scatter (Fig. 1) and the approximately 30% of the variance not explained by the best multivariate models (Eq. 3, 6, 7) must be attributable in part to unpredictable interyear differences in weather. In an equivalent analysis of year-to-year differences on the date of fall turnover, Nürnberg (1988) estimated that interyear differences in weather

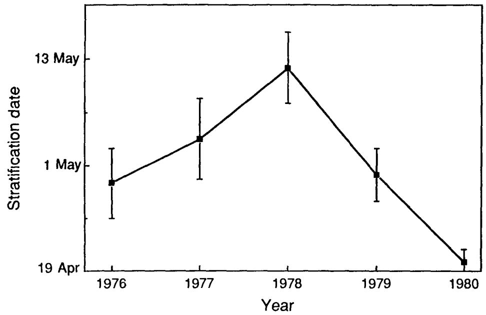

Fig. 2. Average date of onset of spring stratification (±1 SD) for 14 small Ontario lakes over a 5-yr period (1976–1980). (Data from Janus and Vollenweider 1981.)

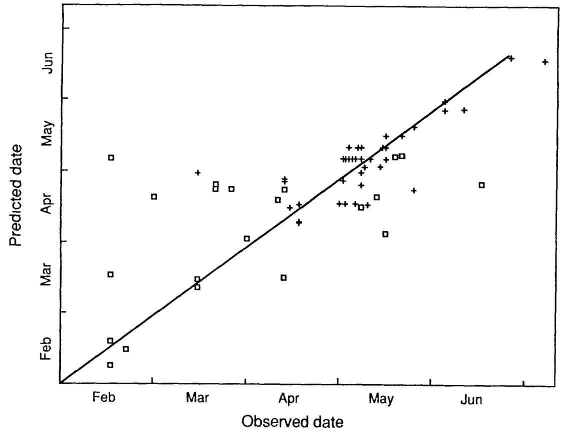

Fig. 3. Observed vs. predicted (Eq. 3) date of onset of spring stratification for the combined lakes. Symbols as Fig. 1. $y = 45.4 + 0.605x$; $r^2 = 0.60$.

accounted for 17% of the unexplained variation.

It is, however, most probable that some of the unexplained variation we found, beyond that attributable to interyear differences in weather, would have been explained if daily rather than weekly or biweekly temperature profiles had been available to determine the date of onset of stratification, if the spring or even the yearly averaged windspeed over each lake had been available, if lake shape as well as the position relative to prevailing winds had been known, and if comparative information on water turbidity had been available (Mazumder et al. 1990). With increasing turbidity or water color, the date of stratification will be advanced as more solar energy is absorbed in the surface layer (Bukaveckas and Driscoll 1991), raising the water temperature and associated water density differences needed to permit early stratification.

Although the models presented must be open to improvement upon consideration of the additional variables mentioned above, it is impressive that 67–72% of the variation in the time of onset of stratification of warm monomictic and dimictic lakes is explained by readily available mean annual air temperature and the ratio of lake area to mean depth. The proportion explained is very similar to the equivalent 67% explained by Nürnberg (1988) in predicting the fall turnover date from hypolimnetic temperature, adjusted latitude, and lake mean depth.

A plot of the individual stratification dates predicted from the best multivariate model vs. the observed dates of stratification showed the model to explain much more of the variation for the combined ($r^2 = 0.60$) data sets (Fig. 3) and for the dimictic data set ($r^2 = 0.62$, not shown) than for the warm monomictic lakes ($r^2 = 0.34$, not shown). Some of the warm monomictic lakes in protected valleys or having higher winter temperatures stratify much earlier than predicted by the best monomictic lake model.

The present models can be used to obtain a first estimate of the effect of climate change on the onset of lake stratification and are useful in estimating when the onset of the spring algal bloom is to be expected in those lakes that become well stratified. Lastly, the present models, together with those developed to estimate fall turnover (Nürnberg 1988), can be used to estimate the length of the average stratification period. When this period is then combined with estimates of hypolimnetic oxygen consumption rates (Cornett and Rigler 1984), the two sets of stratification models should be useful in predicting the probability of particular lakes developing anoxic hypolimnia in response to changes in climate or nutrient loading.

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A method to determine the contribution of bacteria to phosphate uptake by aerobic freshwater sediment

Abstract—An extraction method to determine the contribution of bacterial processes to phosphate uptake of aerobic freshwater sediment was tested on Fe hydroxyphosphate that was either synthesized or formed under in situ conditions and a pure culture of *Acinetobacter* 210A. A mild extraction with H_2SO_4 solubilized the entire Fe hydroxyphosphate fraction but did not extract bacterial phosphate.

Phosphate uptake of randomly sampled surface layers of the sediment of Lake Loosdrecht was considerable, ranging from 11 to 138 μmol g^{-1} on a dry weight basis. The contribution of bacterial processes ranged from 12 to 32%. Addition of an easily degradable substrate, such as acetate, to the sediment stimulated the uptake of phosphate and augmented the biologically bound phosphate fraction. The results indicated that growing bacteria play a considerable role in phosphate uptake by aerobic sediment.

Sediments of aquatic ecosystems play an important role in controlling the phosphorus content of the water. Over an annual cycle sediments act as a net sink for P due to sedimentation of particulate matter (Boström et al. 1982). After restoration measures leading to decreased phosphate concentrations in the water are applied, the sediment may act as a transient source of phosphate, thus retarding improvement of water quality. The flux of phosphate across the sediment–water interface depends on physical (temperature and resuspension), chemical (redox potential and pH),

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