Lake hydrodynamics

Lakes are valuable natural resources for water supply, food, irrigation, transportation, recreation, and hydropower. They also provide a refuge for an enormous variety of flora and fauna. There are more than 110,000 lakes larger than 1 km^2 (0.39 mi^2) covering a total area of 2.3 × 10^6 km^2 (0.9 × 10^6 mi^2, 1.7% of the Earth terrestrial surface). Besides the many millions of smaller lakes (less than 1 km^2), approximately 800,000 artificial lakes and reservoirs have been constructed covering 0.5 × 10^6 km^2 (0.2 × 10^6 mi^2). Large cities not located along coasts are typically near freshwater lakes, and rely on these resources. As a result of near-lake development, pollutants and nutrients threaten the ecological integrity of lakes, since the former can poison or kill aquatic organisms and the latter stimulates excessive growth of algae and water plants.

Hydrodynamics is highly variable among lakes because of the many different geometries, surrounding topographies, hydrological and geochemical loadings, and meteorological exposures. Obvious differences are in the surface area, which ranges up to 82,100 km^2 (31,700 mi^2) for Lake Superior, the largest freshwater lake by area, and in depth, which ranges up to 1642 m (5378 ft) for Lake Baikal, whose 23,000 km^3 (5500 mi^3) makes it the largest freshwater lake by volume. Variability in heat fluxes through the lake surface, in addition to chemical and biological properties (such as concentrations of salt, dissolved gases, particles, and algae), also affect the stratification and water movement. The resulting internal hydrodynamics is important in understanding the lake's physical, chemical, and biological structure. The transport and distribution of dissolved and particulate substances have important management consequences for the wise use of lakes.

Density stratification. Crucial for the hydrodynamics as well as the ecosystem functioning is that almost all lakes, at least those deeper than a few meters, experience density stratification and destratification throughout the seasons. Most important for stratification is the temperature dependence of the water density, which reaches a maximum close to 4°C (39°F). During spring and summer, the surface

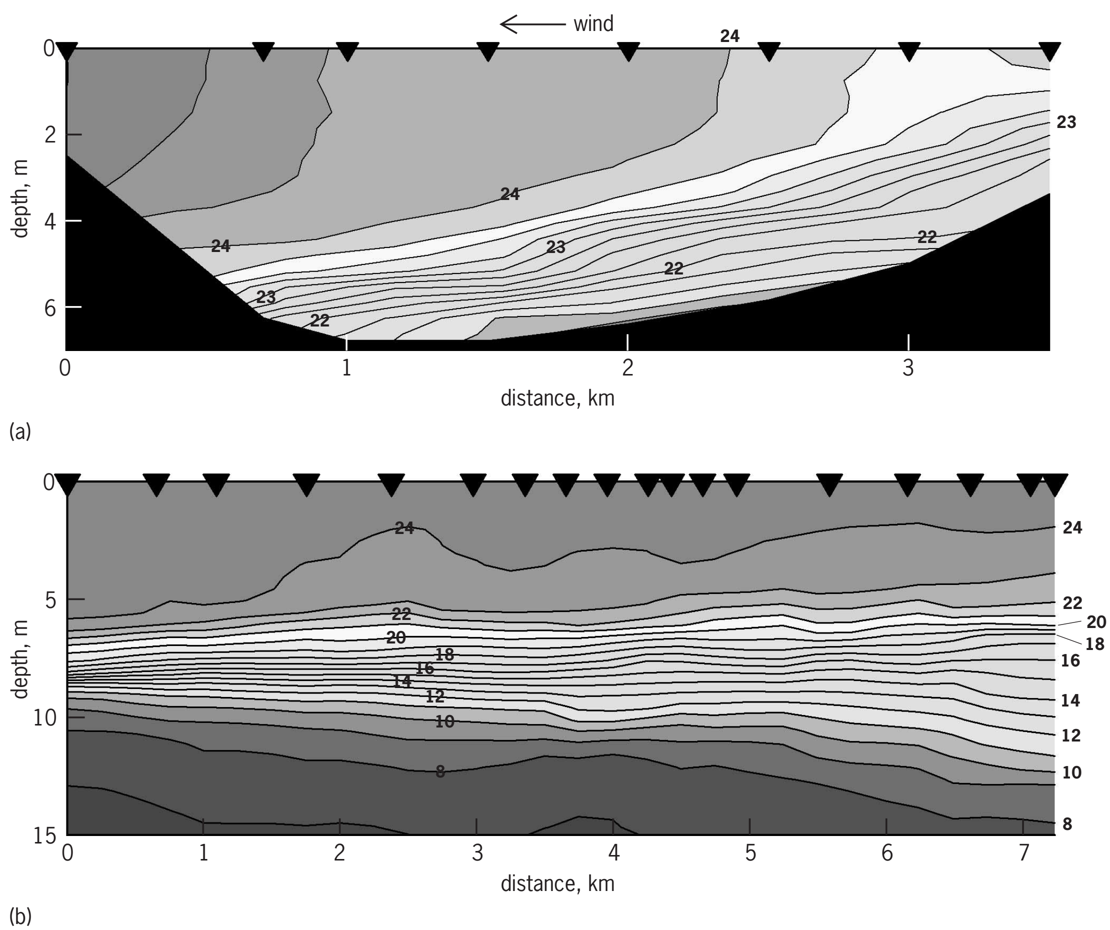

Fig. 1. Temperature contour plots for two lakes. Temperature profiles were obtained along the long axis of the lakes at various locations (inverted triangles on the top axis). Numbers on contour lines are temperatures in °C. °F = (°C × 1.8) − 32. 1 m = 3.3 ft. 1 km = 0.6 mi. (*a*) Plot for Müggelsee, Germany, on August 27, 1997, demonstrating temperature structure resulting from simple two-layer seiching (*from A. Lorke and A. Wüest, Turbulence and mixing regimes specific to lakes, in H. Baumert, J. Simpson, and J. Sündermann (eds.), Marine Turbulence: Theories, Observations and Models, Cambridge University Press, 2005*). (*b*) Plot for Lake Hallwil, Switzerland, on August 29, 2001, showing temperature structure resulting from three-layer seiching.

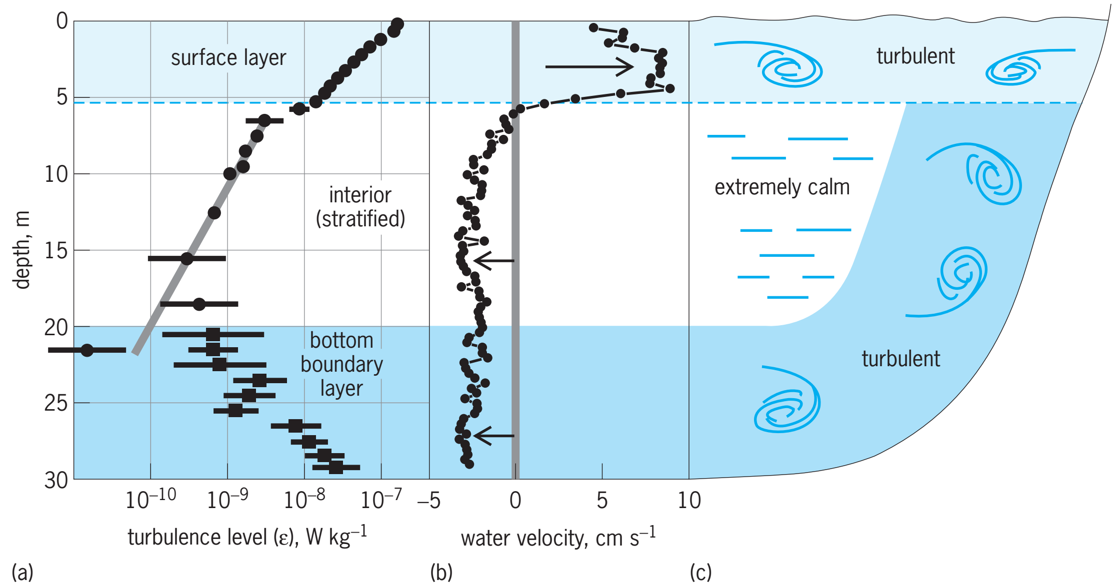

Fig. 2. Vertical profiles in lakes. (*a*) Turbulence profile in Lake Alpnach, Switzerland, demonstrating the high turbulence levels in the surface layer due to wind mixing and in the bottom boundary layer due to bottom (seiche) currents at the sediment-water interface. (*b*) Typical velocity profile for two-layer seiching. Measurements were obtained in Lake Hallwil, Switzerland, which has similar geometry and wind forcing. 1 cm s^{-1} = 0.4 in. s^{-1}. (*c*) Schematic of resulting turbulent zones in a lake enclosing the low-turbulence, quiescent zone in the interior.

water is heated and usually a quasi-two-layer structure develops, with warmer and lighter water on top of the cooler and heavier water underneath (**Fig. 1**). These two layers are usually separated by a zone of rapid temperature change, the thermocline, which forms anywhere from just below the surface to tens of meters deep. The temperature contour plot in Fig. 1*b* shows such a thermocline at a depth of about 5–10 m (15–30 ft), which is typical for a midlatitude lake during summer. This thermocline implies a large density change [since water at 25°C (77°F) is about 3 kg m^{-3} (0.2 lb ft^{-3}) lighter than water at 4°C (39°F)], which leads to strong stability of the water column. This stability effectively suppresses vertical mixing, and consequently the deep water can remain cold (sometimes near 4°C) for the entire summer.

The water density also depends on pressure (not relevant for shallow lakes and internal motions), salinity (salt content), and particle and gas concentrations in the water. This implies that strong vertical gradients of these properties can also contribute to the stability of the water column stratification. Temperature is usually the most important stratifying agent in roughly the top 50 m (150 ft) in small- and medium-sized lakes, whereas at greater depths it is often salinity. Salinity gradients result from the algal production-decomposition cycle, subaquatic sources, and river inflow. In cold alpine reservoirs, very fine suspended glacial particles can sometimes lead to density stratification, whereas in volcanic crater lakes the vertical gradient of the dissolved gases, particularly carbon dioxide (CO_2), contributes to stability.

In fall and winter—especially at night—the lake surface cools and the uppermost water becomes denser. Subsequently, small parcels of water form plumes sinking at a few millimeters per second. This small-scale convection mixes the entire surface layer, which slowly deepens until the entire lake volume is mixed. In some deep lakes, the convection during the cool season (or dry period in the tropics) may not last long enough for complete mixing and some deep regions stay stratified. If the stratification is due to chemical gradients, the lake may remain permanently stratified (for hundreds or thousands of years). Many small lakes with high algal productivity are permanently stratified, as well as several large freshwater (for example, Tanganyika and Malawi) and saltwater bodies (for example, the Caspian Sea and Lake Van).

Large-scale horizontal motions. During the stratification season, the vertical exchange is greatly reduced and the main motions are almost entirely horizontal, following the contours of equal density (Fig. 1). The two major drivers of horizontal motion are wind and density differences in horizontal directions. As water is 800 times denser than air and as momentum is transferred at the surface, the lake receives only about 3.5% of the wind energy from the atmosphere. Surface waves transport and dissipate a portion of this energy, whereas the remaining energy forms large-scale currents, with typical surface water speeds of about 1.5–3% of the wind velocity. For example, in **Fig. 2*b*** the water velocity is between 5 and 7.5 cm s^{-1} (2.3 in. s^{-1}) in the surface layer, but it can occasionally reach up to several tens of centimeters per second. In large lakes, surface currents cause a stratified water body to pivot with warm water piling up at the downwind end and deepwater surfacing at the upwind end. After

the wind ceases, the water displacement relaxes, and two-layer seiching motions occur; that is, the top and bottom layers oscillate in opposite directions (Fig. 2*b*), resulting in a vertical shifting of the temperature isotherms (Fig. 1*a*). While two-layer seiching is generally observed in most lakes, such as in the example shown in Fig. 2*b*, more complex three-layer seiching patterns can occasionally also be observed; that is, the top and deep layers oscillate in the same direction with the thermocline moving in the opposite direction in between (Fig. 1*b*). Seiching can continue for many days in small-to-medium sized lakes and for several months in very large lakes (for example, Tanganyika) until the energy dies out due to friction. The eigenperiod of the seiche (the time for a complete oscillation) is determined by the depth structure of the basin geometry and the strength of stratification. Seiching is the simplest form of many types of wind-forced waves occurring in stratified lakes. Other types include gravitational surface waves, high-frequency internal waves, as well as inertial, Poincaré, Kelvin, and Rossby waves.

Wind also results in another type of large-scale horizontal current pattern. These currents typically form cyclonic gyres and are often observed in larger lakes (for example, Lake Michigan) ranging in speed from 1 to 10 cm s^{-1} (0.4 to 4 in. s^{-1}; **Fig. 3**). Gyres form mainly as a result of the Coriolis effect and nonuniform wind forcing. The Coriolis effect is the observed deflection of the current direction due to the Earth's rotation, and is to the right (left) in the Northern (Southern) Hemisphere. Factors contributing to the formation of vortices include variable wind stress and stratification. Uniform wind can also result in gyres, but these are typically due to asymmetric lake topography. As a result, the surface water is transported to the shore whereas deeper water surfaces in the center of the gyre. If the gyre persists for long enough, it leads to a curved, convex thermocline, with a thinner top layer in the center and a thicker top layer along the shore, and to a vertical circulation cell, consisting of shoreward flow at the surface and toward the center of the lake in the upper thermocline.

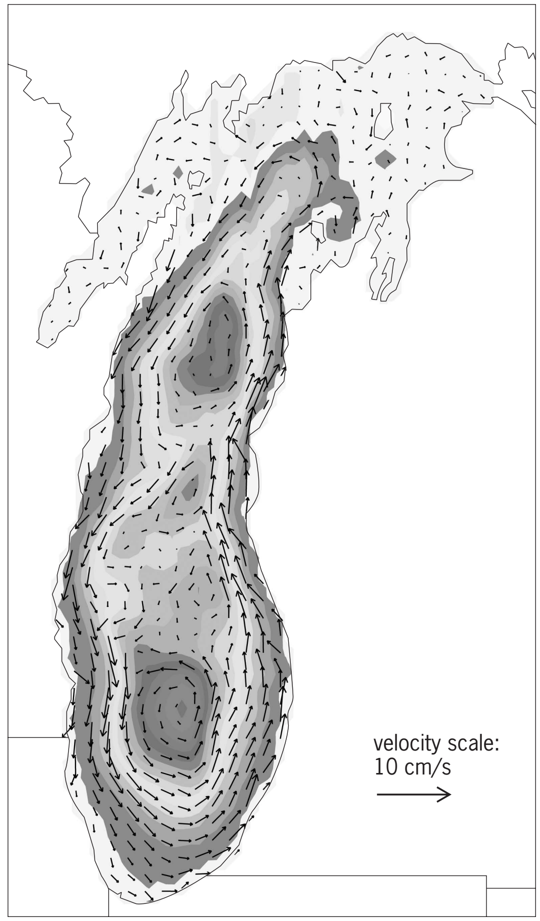

Fig. 3. Two counterclockwise gyres in Lake Michigan. The current speeds were averaged from November 2002 to April 2003. Lightly shaded areas indicate generally clockwise (anticyclonic) rotation, and more heavily shaded areas indicate counterclockwise (cyclonic) rotation. (*From D. J. Schwab and D. Beletsky, Relative effects of wind stress curl, topography, and stratification on large-scale circulation in Lake Michigan, J. Geophys. Res., 108(C2): 26–1 to 26–10, 2003. Copyright 2003 by American Geophysical Union. Reproduced/modified by permission of American Geophysical Union*)

Residual mixing of stratified water. During the warm season (rainy season in the tropics), at least some parts of the lake are usually stratified. However, wind-driven horizontal currents cause vertical shear, resulting in turbulence and vertical exchange within the water column. The direct effect of the wind generates turbulence in the surface layer (Fig. 2*a*). The mixing energy from the wind rapidly dies out with increasing depth, resulting in slow (even approaching molecular diffusion) vertical mixing in the lake interior (Fig. 2*a*). Seiching, other large-scale motions, and the breaking of internal waves also cause shear, particularly in the thermocline and above the sediment (Fig. 2*b*). Shear above the sediment increases turbulence, creating a well-mixed bottom boundary layer (Fig. 2*a*). The absence of the vertical density gradients in this bottom boundary layer allows much more rapid vertical transport near the sediment compared to the lake interior, where the vertical density gradients are orders of magnitude stronger.

Relevance. Many intriguing hydrodynamic processes govern how substances are transported and distributed in a lake. For example, excessive algal growth due to high nutrient input (agriculture and wastewater) can lead to the depletion of dissolved oxygen in the lake water through the settling of dead algae, which undergo bacterial decomposition, thereby consuming oxygen. As the only significant source of dissolved oxygen is from transfer at the lake surface, oxygen can become depleted in the deepwater, jeopardizing fish habitats. Anaerobic bacteria then take over the decay process, resulting in the production of undesirable substances, for example the greenhouse gas methane. Additionally, drinking water withdrawn from lakes should be cool and

relatively low in organic matter (algae) to avoid disinfection by-products as well as taste and odor problems. Mixing processes in a lake will therefore dictate the location where water is withdrawn and where nutrient-rich effluents should be discharged to avoid additional algal growth that conflicts with the water supply. Understanding naturally occurring mixing processes in lakes also aids in determining the ultimate fate of pollutants, and supports good management strategies and practice.

For background information *see* CORIOLIS ACCELERATION; LAKE; MEROMICTIC LAKE; SEICHE; WAVE MOTION IN LIQUIDS in the McGraw-Hill Encyclopedia of Science & Technology.

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Bibliography. J. Imberger, *Physical Processes in Lakes and Oceans*, Coastal and Estuarine Studies, no. 54, American Geophysical Union, Washington, DC, 1998; A. Lerman, D. M. Imboden, and J. R. Gat (eds.), *Physics and Chemistry of Lakes*, Springer, Berlin, 1995; P. E. O'Sullivan and C. S. Reynolds (eds.), *The Lake Handbook: Limnology and Limnetic Ecology*, Blackwell, 2004; D. J. Schwab and D. Beletsky, Relative effects of wind stress curl, topography, and stratification on large-scale circulation in Lake Michigan, *J. Geophys. Res.*, 108(C2):26-1 to 26-10, 2003; R. G. Wetzel, *Limnology*, 3d ed., Academic Press, 2001; A. Wüest and A. Lorke, Small-scale hydrodynamics in lakes, *Annu. Rev. Fluid Mech.*, 35:373–412, 2003.