Section 4

HYDROMETEOROLOGY: CLIMATE AND HYDROLOGY OF THE GREAT LAKES

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4.1 Introduction

4.1.1 Description and Scope

The climate of the Great Lakes Region is determined by the general westerly atmospheric circulation, the latitude, and the local modifying influence of the lakes. Due to the lake effect, the regional climate alternates between continental and semi-marine. The semi-marine climate is more consistent contiguous to the lakes, but with favorable meterological conditions, it may penetrate deeply inland. The Great Lakes climate and hydrology are closely related. Variations in mean lake levels, and consequently lake outflows, are controlled by the imbalance between precipitation and evaporation.

The Great Lakes drainage basin is discussed in other appendixes and a brief summary of the climatic and hydrologic elements of the drainage basin is given in Section 1 of this appendix. The major storm tracks affecting the Great Lakes Region are indicated in Figure 4–13. Distributions of mean annual values for air temperature, precipitation, runoff, and water losses over the land areas of the Basin, showing latitudinal and lake-effect variations, are indicated in Figures 4–15, 17, 19, and 20, respectively. The average monthly means, highs, and lows of overland air temperature for the individual lake basins and for the total Great Lakes Basin are shown in Figure 4–16.

4.1.2 Lake Effect

With a total water volume of 22,813 km^3 (5,473 cu. mi.) stored in the lakes, varying from 484 km^3 in Lake Erie to 12,234 km^3 in Lake Superior, the Great Lakes have a tremendous heat storage capacity. Through air-water interaction, the lakes influence the climate over them and over adjacent land areas. Because of the lake effect, air temperatures are moderated, winds and humidities are increased, and precipitation patterns are modified. Although these phenomena have been recognized for decades, it is only in recent years that intensive programs have been undertaken to determine the more exact nature and magnitudes of these processes.

The Great Lakes moderate temperatures of the overlying air masses and surrounding land areas by acting as heat sinks or sources. The process of heat exchange between the lakes and atmosphere is both seasonal and diurnal. During spring and summer, the lakes are generally colder than air above and have a cooling effect on the atmosphere. During fall and winter, the lakes are generally warmer than the atmosphere and serve as a heat source. However, during the winter months, the ice cover reduces the lake effect.

A daily pattern of heat exchange is superimposed upon the seasonal pattern. This daily pattern is produced by land-water temperature differences. Because lakes are more efficient than land areas in storing heat, lake temperatures have a tendency to remain stable, while land temperatures undergo daily variations that are more in line with the air temperatures. When the land is warmer than water, the relatively warmer air over adjacent land areas tends to rise and is replaced by colder, heavier air from the lakes. When the land is colder, the process is reversed. This

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process of heat exchange produces light winds, which are known as lake breezes. The offshore and onshore lake breezes are illustrated in Figure 4–14. The direction of lake breezes is governed by the land-water temperature differences and is independent of the general atmospheric circulation. However, lake breezes occur only during relatively calm weather and affect a limited air mass along the shoreline, rarely extending more than several kilometers (2–3 miles) inland. The moderation of temperatures by the lakes affects regional agriculture by reducing frost hazards in the early spring and in the fall, thus lengthening the growing season, especially in coastal areas. Examples of this effect are the cherry orchards of the Door Peninsula in Wisconsin and the Grand Traverse Bay area in Michigan, and the vineyards of the western Lake Erie islands in Ohio.

Because lake breezes have a limited range and require special conditions, the lake effect on winds is minor. A much more important effect is the considerable increase in geostrophic wind speed over the lakes. This increase is caused by reduced frictional resistance to air movement over the relatively smooth water surface, and by the difference in atmospheric stability created by air-water temperature differences. Recent studies indicate that the increase in overwater wind speed varies from approximately 15 percent in midsummer to as much as 100 percent in late fall and early winter. The average annual increase is approximately 60 percent.

The Great Lakes also cause an increase in overwater humidity by releasing large quantities of moisture through evaporation. On an annual basis the humidity over the lakes averages 10 percent to 15 percent higher than that over the land. Seasonal changes in humidity over the lake compared to that over land vary from a decrease of approximately 10 percent due to overwater condensation in the late spring, to an increase of approximately 10 percent in the summer, 15 percent in the fall, and 30 percent in the winter.

The Great Lakes also influence the distribution of cloud cover and precipitation. Modification of precipitation patterns due to lake effect is caused by the changes in atmospheric stability in combination with prevailing wind direction and topographic effects. During summer, the air undergoes overland warming before passing over the lakes. The warm air over relatively cold water results in the development of stable atmospheric conditions, which discourage formation of air-mass showers and thunderstorms. During winter, the conditions are reversed, and the cold, inland air passing over relatively warm water becomes less stable and picks up moisture, which encourages snow flurries. As the winter air masses move over the lakes, the moisture that accumulates in the air produces heavy snowfalls on the lee sides of the lakes, due to orographic effects of the land mass. The fact is well documented that heavy snowbelt areas result from the lake effect. These areas include Houghton on Lake Superior, Owen Sound on Lake Huron, Buffalo on Lake Erie, and Oswego on Lake Ontario.

4.1.3 Measurement Networks

Basic meteorological data in the Great Lakes Basin are available from regular observation networks operated by the National Weather Service and the Canadian Meteorological Service. The networks consist of a limited number of first order stations that provide hourly observations for air temperature, precipitation (total and snow), wind speed and direction, humidity, and duration of sunshine and cloud cover. More numerous cooperative stations provide daily observations for air temperature and/or precipitation. Certain more specialized stations collect additional data on solar radiation, radiosonde information, weather radar, and pan evaporation. Other regularly observed data useful in Great Lakes climatology include water temperatures recorded by municipalities at their water intake structures and by Federal agencies at selected lake perimeter locations.

In addition to the regular networks, more sophisticated data are collected periodically or seasonally for research on lake climatology. These include special precipitation networks, established and operated on lake islands and adjacent shorelines; synoptic surveys conducted by research vessels that take observations for the whole range of hydrometeorologic parameters; lake towers that give measurements with vertical profiles for selected parameters for air-water interaction studies; aerial surveys by conventional aircraft for ice reconnaissance and water surface temperatures, using infrared and airborne radiation thermometer techniques; and weather satellites that provide useful information for the investigation of cloud and ice cover on the lakes.

Hydrologic data on the Great Lakes Basin are compiled and published by several agencies. Records of tributary streamflow to the lakes are available from the U.S. Geological Survey and the Canada Centre for Inland Waters, Department of the Environment, Canada. The extent of gaged area increased substantially in the late 1930s, giving coverage to approximately 50 percent of the Basin. At present approximately 64 percent of the Basin is gaged; gaged areas for Lakes Superior, Michigan, Huron, Erie, and Ontario basins represent approximately 53, 71, 66, 67, and 63 percent of their respective basins. In addition to surface water data, these agencies and the Geological Survey of Canada publish observation well records providing information on ground-water conditions. However, the network of observation wells useful in determining ground-water flow to the lakes is extremely limited.

The Great Lakes levels and outflows are available from the Lake Survey Center. Lake levels are determined from a network of water level gages maintained by the Lake Survey in the United States and the Fisheries and Marine Service, Department of the Environment, in Canada. Flows in the connecting channels are determined by the Lake Survey from appropriate water level gage ratings based on periodic current meter flow measurements.

4.2 Radiation

4.2.1 Total Radiation Spectrum

Total radiation received at the surface of the earth consists of shortwave radiation coming directly from the sun or scattered downward, and longwave radiation, emitted from the atmosphere. Portions of the incoming radiation in both short and long wavelengths are reflected and additional longwave radiation is emitted to the atmosphere. The main radiation exchange processes taking place within the terrestrial system (space-atmosphere-earth) are illustrated in Figure 4–93, presenting annual radiation balance, which is based largely on information provided by London.[503] The net effect of shortwave radiation is the solar heating of the earth, while longwave radiation results in cooling.

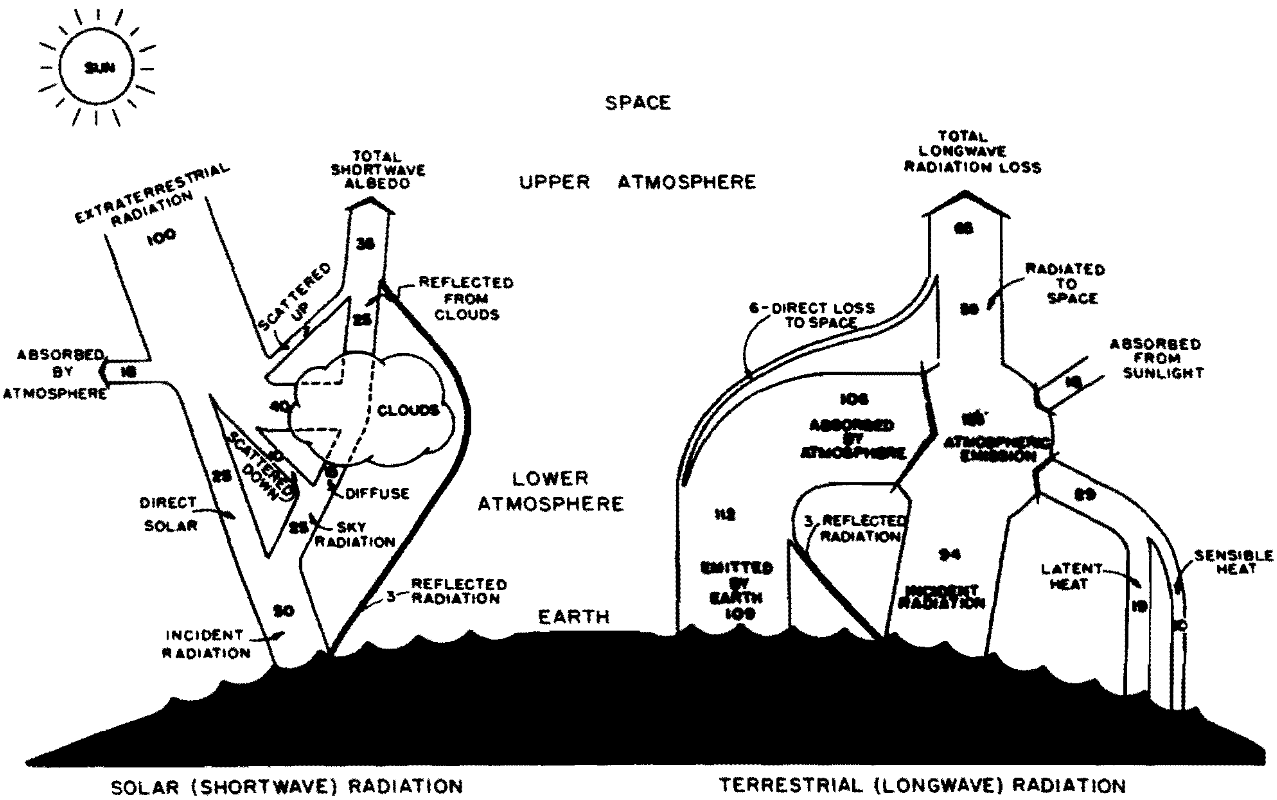

FIGURE 4–93 Annual Atmospheric Heat Budget. Shows percentage distribution of radiation components for northern hemisphere.

After London, 1957

There is some duplication of names used for the same radiation components. Shortwave or global radiation is generally referred to as solar radiation and both names are used interchangeably in this report. Insolation is incident or incoming solar radiation. Similarly, terrestrial radiation is used synonymously with longwave radiation, while longwave radiation from the atmosphere is called atmospheric radiation.

A regular network for measuring shortwave radiation has been established but only few of these are in the Great Lakes Region. A regular network for total radiation measurements (shortwave and longwave) has not been established, since there are only a limited number of radiometers in operation at various research installations. Available information indicates that the average monthly all-wave incident radiation in the Great Lakes Region varies from a winter low of approximately 400 langleys per day (ly/day) in December to a summer high of approximately 1400 ly/day in June or July.

4.2.2 Solar Radiation

Solar radiation is reduced by the atmosphere before reaching the earth's surface. Attenuation of the extraterrestrial solar radiation is caused by scattering, reflection, and absorption by gas molecules, water vapor, clouds, and suspended dust particles (Figure 4–93). As a result of the attenuation, the incoming shortwave radiation on a horizontal surface arrives partly as direct solar radiation and partly as sky radiation (scattered downward by atmosphere and diffused through the clouds). Sky radiation is a high percentage of the total incident radiation during low declination of the sun and on overcast days.

Part of the incoming solar radiation is reflected from the receiving surface (clouds and earth) back to the atmosphere, the amount of reflection depending on the surface albedo or the ratio of reflected to incident radiation. Albedo values for a water surface depend on the solar altitude (angle of the sun above the horizon), cloud cover, and the roughness of the water surface, but for many practical purposes these factors can be assumed to be constant for daily or longer periods. During the Lake Hefner study, Anderson[16] developed empirical curves, which interpret water surface albedo as a function of sun altitude for various cloud cover conditions. Based on results of that study, Kohler and Parmele[464] recommended an average daily albedo for water surface of 6 percent. The relatively low albedo for open water conditions increases drastically with ice and snow cover. Bolsenga[76] gives albedo values for various types of ice common on the Great Lakes. These values range from 10 percent for clear ice to 46 percent for snow ice, both free of snow cover, The presence of partial or complete snow cover on the ice can significantly increase these values.

There is a limited network of regular stations that measure incident solar radiation in the Great Lakes Region. The average monthly values from these stations are shown in Figure 4–94. Periods of record for the stations vary from 10 to 50 years. Based on records from the radiation network, the average monthly incoming solar radiation in the Great Lakes Basin varies from a low of approximately 100 ly/day in December (winter solstice) to a high of approximately 550 ly/day in June and/or July (near the summer solstice), with an average annual value of about 320 ly/day. The average monthly extremes for reflected solar radiation from the lakes represent from 6 to 33 ly/day (6 percent water surface albedo).

Beginning in the last decade, direct overwater measurements of solar radiation were included in the synoptic surveys of the Great Lakes conducted by several research organizations. These measurements are generally limited to the navigation season (April-December), are not continuous, and are somewhat biased towards fair weather conditions, but nevertheless they represent actual conditions over the lakes and provide a basis for comparison of the overwater and overland radiation. Richards and Loewen[653] conducted a preliminary study of this type, which shows that incident solar radiation over the lakes is greater than that recorded on adjacent land stations during summer and smaller during winter months. This confirms the physical concepts of the lake effect. Their study is limited to four years of data during the April-December periods and shows that overwater radiation at the beginning and end of the period amounts to 90 percent of the overland radiation. The overwater radiation increases gradually during spring and summer to an average high of approximately 140 percent of the overland radiation in the late summer, then it decreases rapidly in the fall.

Other recent studies of solar radiation on the Great Lakes include determination of the radiation balance for Lake Ontario (Bruce and Rodgers[108] and Rodgers and Anderson[675]). Determination of the total atmospheric water

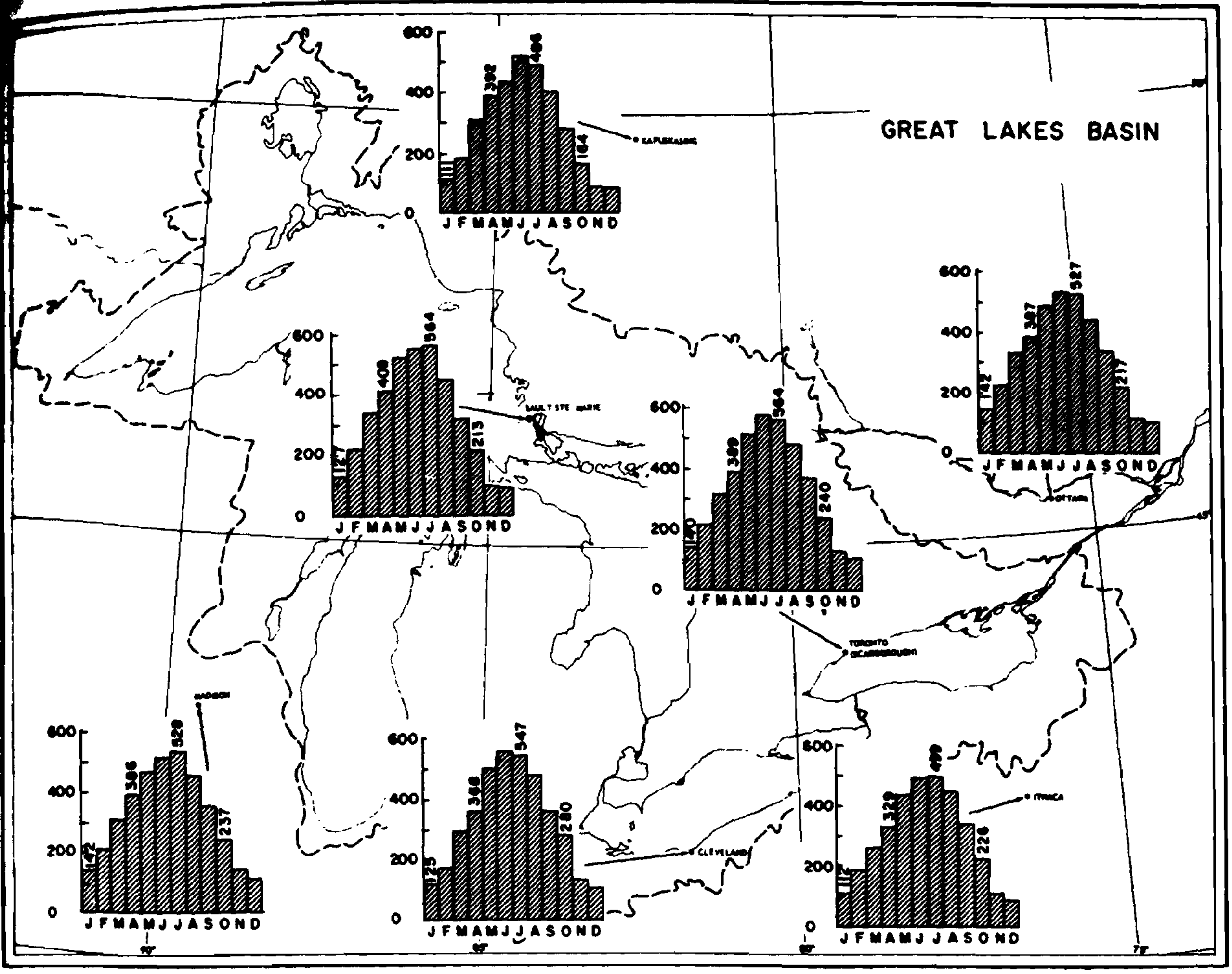

FIGURE 4–94 Average Daily Solar Radiation (Langleys) in the Great Lakes Basin

From Phillips, 1969

vapor over the Great Lakes Basin and derivation of a relationship between atmospheric water vapor and surface dew point (Bolsenga[74,77]) could contribute to parameterization of the solar radiation term. This might compensate for the lack of recording stations in the lakes.

4.2.3 Terrestrial Radiation

Terrestrial radiation over a body of water (or over land) consists of the incident atmospheric radiation, reflected atmospheric radiation, radiation emitted by the water body, and energy released through the processes of evaporation, condensation, and precipitation (latent heat), and turbulent heat transfer (sensible heat). The net result of the incident, reflected, and emitted radiation components is the net back radiation, a longwave radiation loss to the atmosphere (Figure 4–83). The net back radiation is primarily a function of the temperature of the water surface, which controls emitted radiation, and the water vapor content of the air, which controls atmospheric radiation. Other factors that affect the net back radiation include the emissivity of water (relative power of a surface to emit heat by radiation), which reduces emitted radiation below that of black body (an ideal surface that emits maximum radiation); the reflectivity of water, which controls reflected atmospheric radiation; and the concentration of carbon dioxide and ozone in the atmosphere, which are minor contributors to the atmospheric radiation. The reflectivity of a water surface for atmospheric radiation is 3 percent (Anderson[16]), only about half as much as for the solar radiation.

The earth and the atmosphere can absorb and emit more than 100 percent of radiation, exceeding the original input from the sun. This is possible because of the so-called greenhouse effect of the atmosphere. By blocking terrestrial radiation (very small direct loss to space), the atmosphere forces the earth surface temperature to rise above the value that would occur in the absence of the atmosphere, which in turn produces upward vertical transfer of both latent and sensible heat.

Terrestrial radiation may be determined indirectly from the total (all-wave) and solar (shortwave) radiation measurements, but all-wave measurements are too sparse for this purpose. Atmospheric radiation may also be computed utilizing various radiation indices (temperature, percent of sunshine or cloud cover, vapor pressure). Anderson and Baker[15] present a method of computing incident terrestrial radiation under all atmospheric conditions from observations of surface air temperature, vapor pressure, and incident solar radiation. Emitted radiation is determined from water surface temperatures. Based on available information, estimates of terrestrial radiation for the Great Lakes are as follows: monthly incident atmospheric radiation varies from a winter low of approximately 300 ly/day in December to a summer high of approximately 800 ly/day in June or July; reflected atmospheric radiation for these months represents 9 to 24 ly/day (3 percent reflectivity); monthly emitted radiation from the lakes varies from a low of approximately 400 ly/day during winter to a high of 900 ly/day during summer; monthly net back radiation (longwave radiation loss) is roughly 100 ly/day throughout the year (Figure 4–100).

4.3 Winds

4.3.1 Lake Perimeter Winds

Winds are a critical factor of lake climate because they provide energy for lake waves, constitute a principal force for driving lake currents and shifting of ice cover, and through air movement provide means for the regulation of thermal budget over the lakes and adjacent land areas by heat dissipation and transfer. In the Great Lakes Region the global atmospheric circulation with prevailing westerly winds is of particular importance on the lower lakes where it coincides with the longitudinal axes of the lakes, exposing the full lengths of the lakes to the winds and the lee shores to the maximum lake effect.

Because of the lake effect on adjacent land areas, wind data from stations located around the perimeter of the lakes are of particular interest to the Great Lakes. Since more representative data were not available, these data have often been used in past studies as overwater winds, frequently without adjustment for anemometer height or the increase in wind speed over the lakes. Average monthly perimeter wind speeds for the Great Lakes are given in Table 4–7. The average annual perimeter wind speed generally increases from north to south, from approximately 4.5 m/s (10 mph) to 5.0 m/s (11 mph). Average monthly wind speeds increase from the summer low of 3.5 m/s to 4.0 m/s (8–9 mph) to the winter high of 4.5 m/s to 5.5 m/s (10–12 mph).

A summary of wind direction for selected stations around the lakes and the St. Lawrence River is presented in Figure 4–12. The wind roses in this figure show wind direction frequencies for the months of February, May, August, and November, indicative of the four seasonal periods.

Actual wind conditions on the lakes and further inland vary somewhat from those indicated by shore stations, which are affected to a varying degree by the lakes and lake-land interaction. The perimeter weather stations are located at some distance inland, and may generally be unaffected by lake breezes, but the stations located on the lee sides of the lakes are certainly affected by the lakes during winds from the prevailing wind directions.

The long east-west axis of Lake Superior is divided by the Keweenaw Peninsula, which separates the lake into two basins where winds are frequently of opposite direction. On the western end of the lake (Duluth) the winds are predominantly from the west and northwest during cold months and from the east and northeast during the warm months. On the eastern end of the lake (Sault Ste. Marie) there are predominantly easterly winds in the cold months and westerly winds during warm months. In the middle section of the lake (Marquette) predominant winds are from the northern and southern quadrants. The mean monthly wind speed at these stations varies from 3 m/s (7 mph) in the summer to 6 m/s (14 mph) in the winter (for average perimeter wind speeds for the whole lake see Table 4–7). The maximum recorded wind velocity was 41

TABLE 4-7 Average Perimeter Wind Speeds for the Great Lakes (m/s)

Period	Lake				
	Superior	Michigan	Huron	Erie	Ontario
January	4.6	5.4	4.8	5.5	5.0
February	4.5	5.3	4.4	5.5	5.0
March	4.6	5.5	4.6	5.5	5.0
April	4.8	5.5	4.6	5.4	4.8
May	4.6	5.0	4.2	4.7	4.3
June	4.0	4.3	3.7	4.2	3.9
July	3.8	3.8	3.6	3.8	3.8
August	3.8	3.8	3.5	3.8	3.6
September	4.1	4.3	4.0	4.1	3.8
October	4.4	4.9	4.3	4.4	4.0
November	4.6	5.4	4.8	5.2	4.6
December	4.5	5.3	4.8	5.3	4.8
Annual	4.4	4.9	4.3	4.8	4.4

Values are based on mean data published in 1969 for the following stations:
Superior: Sault Ste. Marie, Marquette, Duluth, and Thunder Bay.
Michigan: Milwaukee, Muskegon, and Green Bay.
Huron: Alpena, Gore Bay, and Wiarton.
Erie: Toledo, Cleveland, Buffalo, and London.
Ontario: Rochester, Syracuse, Trenton, and Toronto.

m/s (91 mph) from the south at Marquette in May, 1934.

Around Lake Michigan the predominant wind direction is from the western quadrant, perpendicular to the long axis of the lake. Because of the north-south lake orientation, the highest seas generally coincide with strong northerly and southerly winds. Prevailing winds from these directions are reported at some locations, in contrast to the general predominant westerly direction. The variation in prevailing winds is evident in northern Lake Michigan where winds in Traverse City come from the south during fall, while Green Bay, on the opposite (western) shore, is assailed by westerly winds. Around the southern portion of the lake prevailing winds in the spring at Milwaukee are from the north, while at Chicago they are from the southwest. The mean monthly wind speed at these stations varies from 3m/s to 6 m/s (7–14 mph), which is similar to Lake Superior, but the annual wind speed around Lake Michigan is higher. The highest wind velocity recorded on all the Great Lakes, 49 m/s (109 mph) from the southwest, occurred at Green Bay in May 1950.

Winds on Lake Huron may be equally effective on the sea state from all directions due to the lake configuration. There is considerable variation in wind direction around the lake, but in general, prevailing winds are from the western quadrant. In some locations prevailing winds shift seasonally to the south during fall (Wiarton, Ontario), and a large percentage of winds along the western shore come from the eastern quadrant during warmer months, as indicated at Alpena and Bay City (Saginaw River Light) in Michigan. The range of mean monthly wind speed at these stations varies from the summer low of 4 m/s (8 mph) to the winter high of 6 m/s (13 mph). The highest velocity recorded was 27 m/s (61 mph) from the southwest at Alpena in November 1940.

The highest monthly wind speeds around the Great Lakes occur on Lake Erie, which also has the largest range between the monthly values of wind speed. The mean monthly wind speed at stations located around the lake varies from 4 m/s to 8 m/s (8–18 mph). These winds are predominantly from the western quadrant with a prevailing direction from the southwest, which coincides roughly with the long axis of the lake. This fact, along with the relative shallowness of the lake, makes Lake Erie highly susceptible to large-scale water level motions, especially at the eastern and western extremes of the lake. Because of the prevailing wind direction, lake effect on the lee shores is quite pronounced and the monthly wind speeds at Buffalo are normally somewhat higher than at other stations around the lake. Prevailing winds at some locations are from the eastern quadrant, and in the middle section of the lake (Cleveland), prevailing winds during warmer months shift to the north and south directions. The maximum velocity recorded was 41 m/s (91 mph) from the southwest at Buffalo in January 1950.

The predominant wind direction around Lake Ontario is similar to that of Lake Erie, with prevailing winds during most months from the southwest (Rochester, Trenton), which approaches the direction of the long axis of the lake. During winter months the predominant wind direction shifts to the west. On the northwestern end of the lake (Toronto) winds frequently prevail from the west, and at times from the north. The mean monthly wind speed at these stations varies from 3 m/s to 6 m/s (7–13 mph). The highest wind velocity recorded was 33 m/s (73 mph) from the west at Rochester in January 1950. The prevailing winds along the St. Lawrence River are parallel to the river, primarily from the southwest and secondarily from the northeast.

4.3.2 Overwater Winds

Overwater winds differ from overland

winds, both daily and seasonally, because of differences in air stability conditions and frictional resistance. Daily variation is caused mainly by diurnal heating and cooling, which are more pronounced over land areas than over water and result in larger daily wind variations over land than over water. Seasonal variation is caused by the winter heating and summer cooling effects of the lakes. The lakes offer less resistance to wind movement, resulting in considerably higher overwater wind speeds regardless of the season.

The highest wind speeds (one-minute wind gusts) on the Great Lakes, reported from anemometer-equipped vessels since 1940, are listed for each lake as follows: Lake Superior, 42 m/s (93 mph) from the northwest in June 1950; Lake Michigan, 30 m/s (67 mph) from the west-southwest in November 1955; Lake Huron, 49 m/s (109 mph) from the west-northwest in August 1965; Lake Erie, 38 m/s (85 mph) from the north-northwest in June 1963; Lake Ontario, 26 m/s (57 mph) from the west-northwest in November 1964. These velocities were observed during the navigation season and are based largely on observations taken four times daily during synoptic hours (0100, 0700, 1300, and 1900 hours, EST). Higher wind speeds may have occurred during winter months and at times other than synoptic hours. Most of the shipboard wind directions listed by the National Weather Service verify the predominantly westerly wind direction indicated by the perimeter stations.

The first intensive effort to determine overwater winds utilized various ships-of-opportunity programs, which were conducted periodically and consisted initially of commercial vessels making wind observations four times daily. The data collection program has now been expanded to off-shore towers, buoys, research vessels, and research stations located on small islands in the Great Lakes. Because of practical limitations imposed on measurement of wind data for prolonged periods of time over the lakes, the primary aim of wind measurement programs was to determine the relationship between overland and overwater winds. Several studies of this type have been conducted, relating shore data with observations from ships and islands located on the Great Lakes (Hunt,[397,398] Lemire,[492] Bruce and Rodgers,[108] and Richards et al.[649]).

The ratios of wind speed over water to wind speed over land vary diurnally and seasonally, and are a function mainly of the stability of the air. For unstable atmospheric conditions, with water temperature much higher than air, lake-land wind ratios are about two, and for stable atmospheric conditions, with air much warmer than water, wind speed ratio values are near one; for the adiabatic or neutral stability conditions values are intermediate. Hunt's investigation was conducted mainly for Lake Erie during navigation season (April–November), with results grouped into the spring and fall periods. Bruce and Rodgers[108] prepared a similar study for Lake Ontario. Their investigation was extended by Lemire[492] who included data from some of the other Great Lakes and derived monthly wind speed ratios for the spring, summer, and fall months (March–October). Richards[648] extended these ratios for the winter months using partial results determined by Lemire and extrapolation based on the air-water temperature difference, along with limited wind observations on Lake Ontario. The variation of wind speed ratios determined in these studies is shown in Table 4–8. Monthly ratios vary from 1.2 to 2.1, with low values during summer and high during winter, and an overall annual average of about 1.7.

The effects of overwater fetch (length of open water) on lake winds, besides atmospheric stability, were studied by Richards et al.,[649] who utilized wind data collected during synoptic surveys on Lakes Erie and Ontario. Their analysis included five stability ranges (from very unstable to very stable), four wind speed classes (3 m/s to 8 m/s), and five fetch ranges (10 km to 65 km). They found that the lake-land wind ratio increases with the atmospheric instability, but the increase is most pronounced in light winds. Under very unstable atmospheric conditions (large negative air temperature-water temperature difference, $T_A - T_W$) the wind ratio increases gradually from 1.4 for strong winds to 3.0 for light winds, with a 2.2 value for all winds. Under very stable atmospheric conditions (large positive $T_A - T_W$ difference) the wind ratio increases gradually from 0.8 for strong winds to 1.4 for light winds, with a value of 0.9 for all winds. Thus, under very stable conditions the lakes may reduce the wind speed, especially in strong winds. The effect of overwater fetch was not as pronounced and somewhat erratic. Under unstable atmospheric conditions the wind speed ratio increases with the overwater fetch, but only for lengths smaller than 50 km (25 nautical miles). Under stable atmospheric conditions the relationship between wind ratios and overwater fetch was highly erratic. Summarized results of this study are listed together with other wind studies in Table 4–8.

TABLE 4–8 Lake-Land Wind Speed Ratios for the Great Lakes

Hunt (1958)		Lamire (1961)		Richards, Dragert, McIntyre (1966)	
Period	Ratio	Period	Ratio	Stability Range T_A-T_W (°C)	Ratio
		January	1.96[1]		
		February	1.94[1]		
		March	1.88		
		April	1.81		
Spring	1.35	May	1.71	≤-12.6	2.24
		June	1.31	-12.5 to - 4.1	1.88
		July	1.16	- 4.0 to 4.0	1.44
		August	1.39	4.1 to 12.5	1.06
Fall	1.82	September	1.78	≥ 12.6	0.92
		October	1.99		
		November	2.09[1]		
		December	1.98[1]		
Navigation Season	1.58		1.63		
Annual			1.75		1.51

[1]Values for winter months were extended by Richards (1964) through extrapolation.

4.4 Air Temperature

4.4.1 Lake Perimeter Temperature

Temperature is one of the principal indicators of climate and exerts a large influence on other climatic elements, such as precipitation and evaporation. The vast water expanses of the Great Lakes moderate air temperature over the lakes, which in turn has a moderating effect on adjacent land areas. An indication of the lake effect on shoreline temperatures is given in Figure 4–95 prepared by Pond,[622] which compares mean hourly air temperatures for March, June, and September at Douglas Point, located on the eastern shores of Lake Huron, to those at Paisley climatological station, some 20 km (12 miles) inland. During late winter (March), the lakeshore station is consistently warmer by 2°C to 4°C (3–7°F) than the inland station. This effect changes gradually during spring to the summer effect, providing daytime cooling of the lakeshore station by as much as 4°C (7°F) and nighttime warming by 2°C (3°F) in June. In the early fall the effect reverses again and the lakeshore station is consistently warmer throughout the day.

Because of the lake effect and lack of direct overwater measurements for any longer period of time, various investigators used data from perimeter stations to estimate air temperature over the lakes. The average monthly and annual air temperatures for the individual lakes, based on perimeter data for the 1931–69 period, are listed in Table 4–9. Average annual temperatures vary from 4°C (39°F) on Lake Superior to 9°C (48°F) on Lake Erie, with intermediate values on other lakes. Average monthly temperature extremes also occur on Lakes Superior and Erie, and vary from monthly lows of approximately −11°C and −4°C (13 and 26°F) in January to monthly highs of about 18°C and 22°C (65 and 71°F) in July, on the two lakes, respectively.

The air temperature decreases as latitude increases, being lowest for Lake Superior and highest for Lake Erie. Disregarding minor local variations, the average annual temperature on Lake Superior varies from 1°C (34°F) along the extreme northern shore to 5°C (41°F) along the southern shoreline (see Figure 4–15). Distribution of average annual temperature on Lake Michigan varies from approximately 6°C (43°F) in the north to 10°C (50°F) in the south. On Lake Huron, the average annual temperature increases southward from 5°C to

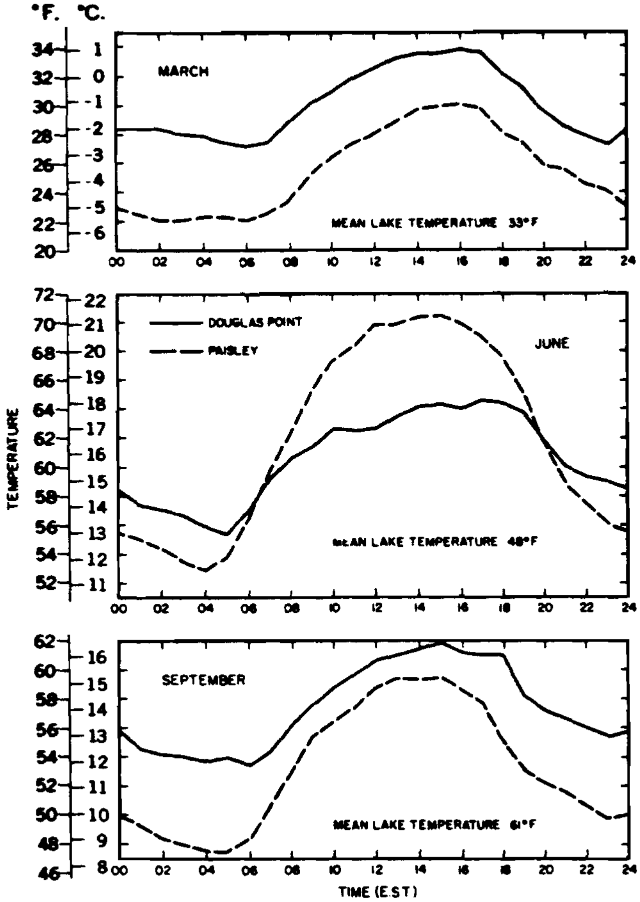

FIGURE 4–95 Mean Hourly Temperatures for Douglas Point and Paisley, Lake Huron, for the Months of March, June, and September, 1962
From Pond, 1964

8°C (41 to 47°F). The annual temperature on Lake Erie increases from a low of 8°C (47°F) along the northeastern shore to a high of 11°C (52°F) along the southwestern shoreline. On Lake Ontario, the annual air temperature increases from 7°C to 9°C (45 to 48°F) between the northern and southern shores.

It should be noted that the air temperatures discussed above are based on lake perimeter stations and may be different from those representing mid-lake conditions. Some difference in these temperatures is introduced by the land effect, which takes place not only at shore stations but also in the shallow coastal waters. Furthermore, most first order perimeter stations used to derive temperature estimates are located some distance inland, where the land effect is more pronounced. Nevertheless, because of data limitations, air temperatures from the perimeter stations around the lakes are generally used as representative values for the average conditions on the lakes (Hunt,[395] Powers et al.,[624] Snyder,[751] Rodgers and Anderson,[675] Derecki,[214] and Richards[648]).

4.4.2 Overwater Temperature

The difference between air temperature over lake and land areas in the Great Lakes Basin has been studied by several investigators. In describing the climate of South Bass Island in western Lake Erie, Verber[848] compared island records (Put-in-Bay) with perimeter and inland stations and concluded that the mean mid-summer temperature (July) decreases gradually from Put-in-Bay to perimeter stations (Sandusky and Toledo) and to inland stations (Tiffin and Bucyrus) located within 80 km (50 miles) south of the lake. He attributes the higher overlake temperatures to the increased solar radiation due to less precipitation and cloud cover over the lake. During mid-winter (January) the reverse is true, because the portion of Lake Erie around the island region is shallow and normally freezes over and is largely ice covered, thus reducing the lake effect. Although Put-in-Bay has the highest mean July temperature and the lowest mean January temperature of the five stations, its average monthly range during the year is the smallest, because thermal stability over the lake acts as a damper against sudden heating or cooling. The aver-

TABLE 4–9 Average Perimeter Air Temperature for the Great Lakes, 1931–1969 (Degrees Centigrade)

Period	Lake: Superior	Michigan	Huron	Erie	Ontario
January	-11.2	- 6.4	- 7.4	- 3.8	- 5.2
February	-10.4	- 5.6	- 8.0	- 3.7	- 5.2
March	- 4.7	- 0.4	- 3.5	0.9	- 0.1
April	3.1	6.8	4.1	7.4	6.8
May	9.2	12.7	10.2	13.6	13.1
June	14.6	18.4	15.8	19.2	18.7
July	18.1	21.3	18.9	21.8	21.4
August	17.4	20.4	18.7	20.9	20.3
September	13.0	16.4	14.2	17.2	16.4
October	7.2	10.3	8.7	11.1	10.2
November	- 0.7	2.8	2.0	4.3	3.8
December	- 7.7	- 3.6	- 4.2	- 1.7	- 2.8
Annual	4.0	7.8	5.8	8.9	8.1

Values are based on data for the following stations:
Superior: Sault Ste. Marie, Marquette, Duluth, and Thunder Bay.
Michigan: Milwaukee, Muskegon, and Green Bay.
Huron: Alpena, Gore Bay, and Wiarton.
Erie: Toledo, Cleveland, Buffalo, and London.
Ontario: Rochester, Syracuse, Trenton, and Toronto.

age monthly maximum-minimum temperature range increases gradually inland from approximately 8°C (14°F) at Put-in-Bay to approximately 12°C (22°F) at Bucyrus, and the frost-free season decreases gradually inland from more than 200 days to approximately 150 days. Also, the hottest days in July show higher temperatures on mainland stations than at Put-in-Bay. During the winter an ice cover around the island region, usually forming in January and lasting through February, acts as an insulator between the warm water and cold air, producing enough change in the normal temperature pattern to make February colder than January. On exceptional occasions when the lake is free of ice during these two months, temperature was approximately 3°C (5°F) higher.

Summer temperature conditions for western Lake Erie may be assumed to be indicative of temperature modification by the other Great Lakes, although mid-lake modification is undoubtedly more pronounced since the island itself produces some effect. Winter conditions, on the other hand, may not be comparable because other lakes have much greater depths and different ice-cover conditions. In a comparison of summer data for Fort William and Caribou Island (175 miles away) made in connection with a synoptic survey of Lake Superior, Anderson and Rodgers[14] show that air temperature on the island is much more stable than and differs considerably from that at Fort William, on the perimeter of the lake. They state that measurements from the island are extremely valuable since they represent an entirely maritime situation, which is caused by modification of low level air masses by the lake. However, there are only a few island stations measuring air temperatures on the lakes and most are operated only during the navigation season.

Measurement of air temperature on lake towers or buoys, and synoptic surveys by vessels initiated in the late 1950s, provide more reliable data by eliminating possible island effects. Based on synoptic survey data collected by the research vessel *Porte Dauphine* on Lake Ontario, Bruce and Rodgers[108] observed that air temperatures at 3 m (10 ft) above the water surface are much closer to water surface temperatures than to land temperatures at the lake perimeter (mean of temperatures at Toronto and Rochester). Rodgers and Anderson,[675] utilizing these data in the energy budget study of Lake Ontario, made similar observations and showed that air temperature over water in June is about 6°C (10°F) higher than water surface temperature, while air temperature at Toronto displays a different pattern and is on the average approximately 17°C (30°F) higher than water temperature. These figures are based on only three days of data from a single cruise, and their magnitudes may not be valid for longer periods. Rodgers and Anderson[675] state that there are insufficient data to provide a reliable conversion of land station temperatures to the overwater air temperatures. At present, with approximately a decade of data available, this difficulty has been overcome but the conversion factors have not been developed. There are no published reports presenting overwater temperatures on the lakes, other than data reports for the individual surveys.

4.5 Water Temperature

4.5.1 Water Surface Temperature

The oldest sources of water surface temperature data in the Great Lakes are the records obtained at various marine structures, such as docks, breakwaters, and lighthouses. These stations were later replaced by the somewhat more sophisticated sites offered by the intake structures of the water treatment plants located around the lakes. Water temperature at the intake stations is obtained in the coastal waters, a few hundred to a few thousand meters off shore, and at depths of 3 to 15 meters (10 to 50 feet) below the surface. These data obviously do not represent the temperature at the surface and require adjustments for open lake conditions. Initially, open lake measurements were made by commercial vessels along their navigation routes, and more recently by research vessels engaged in synoptic surveys of the lakes. The latest development in measuring surface water temperatures involves the use of airborne infrared thermometers. The use of airborne radiation thermometers permits fast and regular observations of surface temperatures over large areas. Information on surface temperatures is also provided by satellite imagery, but in the present state of art this information cannot be used for quantitative temperature determination.

Among the earlier studies of the water surface temperatures in the Great Lakes were those by Freeman[271] and by Horton and Grunsky.[376] In both studies water temperature records from daily observations at various harbor locations for the 1874–86 period

TABLE 4-10 Comparison of Great Lakes Water Surface Temperature (Degrees Centigrade)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Lake Superior													
Lake Survey (1944) 1904-43[1]	0	0	0	1	3	4	8	12	11	8	5	1	4
Millar (1952) 1935-39	-	-	-	-	2	4	7	13	12	9	6	-	-
Richards & Irbe (1969) 1959-68	2	0	0	1	2	4	7	12	12	9	6	4	4
Lake Michigan													
Lake Survey (1944) 1904-43[1]	0	0	1	4	7	12	17	18	16	11	7	2	8
Millar (1952) 1935-41	-	-	-	-	5	11	16	21	18	12	8	-	-
Lake Huron													
Lake Survey (1944) 1904-43[1]	0	0	1	3	6	12	18	19	17	12	7	2	8
Millar (1952) 1935-41	-	-	-	-	4	9	18	20	16	12	7	-	-
Richards & Irbe (1969) 1959-68	3	2	1	1	4	8	15	18	16	12	8	6	8
Lake Erie													
Lake Survey (1944) 1904-43[1]	0	0	3	6	9	18	22	22	21	14	7	1	10
Millar (1952) 1937-41	-	-	-	-	10	17	21	23	19	15	9	-	-
Richards & Irbe (1969) 1950-68	1	1	1	3	9	17	21	22	19	15	9	4	10
Lake Ontario													
Lake Survey (1944) 1904-43[1]	0	0	2	5	9	14	18	19	17	13	7	1	9
Millar (1952) 1936-46	3	2	2	3	6	12	19	21	18	13	7	4	9
Richards & Irbe (1969) 1950-68	3	2	2	3	6	12	19	21	18	13	7	4	9

[1]Period shown for Lake Survey study indicates extreme limits and not actual length of data.

were used as basic data. Monthly temperatures for the individual lakes were derived by applying correction factors for time of observations and some adjustment for open lake conditions.

The U.S. Lake Survey[825] compiled monthly water surface temperatures for each lake from temperature data collected at various locations by the field parties from 1904 through 1943. Derived values differ somewhat from those given by Freeman and are considerably different from Horton and Grunsky's values.

Probably the best known and most often used Great Lakes water surface temperatures are those determined by Millar.[543] Millar's study is based on the data obtained from continuous recordings of water temperature taken by thermographs installed on the condenser intakes of steamships. Data collection covers the 1935–46 period for Lake Ontario and the 1935–41 period for all other lakes. Millar developed temperature distributions on each lake by months and derived average monthly values for each lake. Due to restricted navigation, winter temperatures for lakes other than Ontario were either not available or gave insufficient coverage to derive reliable monthly means. Many investigators in recent years have used Millar's temperatures, most frequently to adjust surface temperatures derived for various periods from the water intakes or other sources. Studies of this type include Hunt,[395] Snyder,[751] Rodgers and Anderson,[675] and Richards and Rodgers.[654]

Determinations of Great Lakes water surface temperatures, limited to a single lake, were made by several investigators. Church[142,143,144] analyzed water temperatures for Lake Michigan, based on bathythermograph observations obtained during 1941–44 period. He showed that irregularities in the water temperature distribution are the result of strong winds and upwelling, both of which act to lower the water temperature at the surface. Another presentation of Lake Michigan temperatures for the summer months is given by Ayers et al.[29] Their values are based on synoptic surveys conducted in 1955. Ayers et al.[28] also determined water temperatures for Lake Huron from a similar survey conducted on that lake in 1954. The last two studies are summarized by Ayers.[25] Monthly water temperatures on Lake Erie are given by Powers et al.[624] who present a comparison of long-term water intake records to offshore cruise data.

The most recent determination of water surface temperatures was made by Richards and Irbe.[651] Their study covers the 1950–68 period for Lakes Erie and Ontario, and the 1959–68 period for Lakes Huron and Superior. Monthly temperatures determined for each year on the individual lakes were based on available information from airborne radiation thermometer surveys, ship observations, water intake stations, and subjective adjustments of mean lake temperatures based on mean air temperatures from shoreline stations. The subjective adjustments of mean water temperatures were used primarily during winter months for lakes lacking sufficient temperature measurements.

A comparison of the Great Lakes mean water surface temperatures (Table 4-10) shows that surface temperatures vary with latitude and depth of the lakes. The average annual surface temperatures vary from 4°C (40°F) for Lake Superior, the northernmost and deepest lake, to 10°C (50°F) for Lake Erie, the southernmost and shallowest lake. Average annual surface temperatures on the other lakes, with intermediate latitudes and depths, amount to 8°C (46°F) for Lakes Michigan and Huron and 9°C (48°F) for Lake Ontario. The average monthly surface temperatures vary from the winter lows of 0°C (32°F) on Lake Superior and 2°C (36°F) on Lake Ontario to the summer highs of 13°C (55°F) on Lake Superior and 23°C (73°F) on Lake Erie.

4.5.2 Temperature at Depth

Many of the studies mentioned in the preceding discussion on water surface temperature also deal with the vertical temperature distribution in the Great Lakes. Church[142,143] showed that the annual temperature of Lake Michigan undergoes four basic seasonal cycles with distinct characteristics, namely, the spring warming, summer stationary, autumn cooling, and winter stationary. Because of different latitudes and depths, the timing and duration in the lakes of these cycles are not synchronous, but all lakes display these four basic seasonal periods. Occurrence of the periods is governed by the lake temperature-water density relationship.

The seasonal changes of thermal structure in large deep lakes of mid-latitudes, such as the Great Lakes, are shown graphically in Figure 4-96, and discussed in Section 6. As the warming season progresses, the top layers of water absorb heat from the atmosphere, becoming progressively warmer, and through conduction of heat downward and mixing induced by winds, the warm layer becomes deeper. The warm upper water (epilimnion) is separated from the cold deeper water (hypolimnion) by the thermocline. The epilimnion is less dense and literally floats on top of the hypolimnion. In the early stages of development, the thermocline is rather weak and is easily broken down by wind action, which readily mixes the thin surface layer of heated water with colder water below, thus producing further development and deepening of the thermocline. As the thermocline approaches its maximum depth, the mixing becomes progressively less. The final deepening occurs during summer storms with relatively little activity during calmer periods.

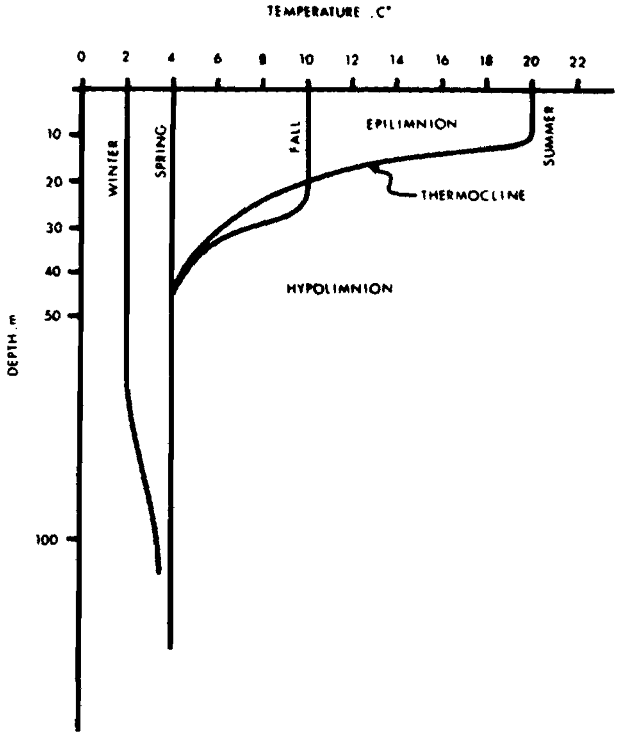

FIGURE 4-96 Seasonal Changes in the Thermal Structure of a Large, Deep Lake of Midlatitudes

The summer stationary period is characterized by nearly stationary lake surface temperatures in their maximum range. At the beginning of this period the thermocline descends to its maximum depth, where it remains relatively stable. The establishment of a strong thermocline at constant depth indicates that there is only a negligible transfer of heat by conduction, either above or below the thermocline. Anderson and Rodgers[14] showed that the maximum depth of the thermocline during this period of peak heat content is about 15 m (50 ft) in all the Great Lakes, in spite of marked difference in their transparency, configuration, size, orientation, and latitude.

Lake cooling begins in the fall, with substantial net loss of heat resulting from the interaction of cooling and heating processes, such as radiation, evaporation, conduction, precipitation, and condensation. In the fully developed cooling period of late fall, with water surface temperature substantially above that of maximum density, cooling of the homogeneous surface layer proceeds rapidly, since only this layer is affected due to stability of the thermocline. At the same time, with the increased frequency of storms in this season the upper layer becomes deeper as well. As the cooling continues, temperature of the upper layer approaches that of maximum density, the thermocline becomes less stable, and the wind-stirring may be complete from top to bottom with the destruction of the thermocline. Church[142] indicates this critical temperature of the homogeneous surface layer to be 6°C (43°F) or slightly above. In the advanced stages of cooling, depth exerts an important control on temperatures in the lakes. With the loss of the thermocline the entire column of water becomes isothermal and further cooling at the surface proceeds slowly because the entire water column loses heat.

During the winter stationary period the lake waters are again at less than maximum density, but in this case the surface is colder than 4°C. In coastal areas and lakes with shallower depths temperatures are generally isothermal vertically. In deep waters an inverse stratification develops, with colder epilimnion and slightly warmer hypolimnion. This stratification is not as pronounced as during the summer, because the downward mixing process is aided by strong winds and convection produced by daytime heating during winter. Water temperature in the entire column or the deep upper layer, whichever the case, approaches freezing point on the lakes with extensive ice cover, and stays at about 2°C (36°F) on the lakes which are largely free of ice. Because great depths are affected, water temperature changes during this period are naturally slow. Thus, Lake Erie with its shallow depths freezes sooner and more often than Lake Superior, which because of its great depths is capable of sustaining tremendous heat losses. By the same token, ice breakup on Lake Erie is much faster.

Since each lake consists of a whole range of depths, which generally increase from shallow coastal waters to a maximum depth in mid-lake, each lake contains water masses with distinct thermal structures characteristic of their depth, particularly during warming and cooling periods. In the beginning stages of the spring warming period the shallow waters along the shore warm up much faster than mid-lake areas, producing large horizontal temperature gradients near the boundary between the warm and cold surface temperatures. The coastal waters are well above 4°C at the surface and vertically stratified, while those in mid-lake are less than 4°C and uniform in temperature from top to bottom in depths as great as 180 m (600 ft) (Church[142] and Rodgers[672]). The most extensive investigation of this phenomenon, named the thermal bar, was made on Lake Ontario by Rodgers.[673] As the warming season progresses the thermal bar zone moves lakeward from the shores and eventually disappears. During the fall cooling period the process is repeated, with the cold temperatures moving offshore towards the center of the lake.

In the above discussion of seasonal temperature changes within a column of water, no consideration was given to any movement of water into or out of the column due to the normal lake currents. Actually, water temperatures and currents in a lake are closely related. Any lake is subject to water movement resulting from the inflow-outflow balance and the general water circulation induced by winds and geostrophic forces. Thus, once established, a thermocline seldom stays still, but fluctuates in a wave-like motion (Section 6). Rodgers[672] states that the thermocline moves up and down through a distance of 10 to 20 m (30 to 60 ft), with wavelengths of tens of kilometers. He also states that these internal waves are seldom evident to the casual observer and their detection requires continuous observation of temperatures at one or more locations within the lake.

Periodically, strong winds blowing steadily from one direction may tilt the thermocline, deepening the epilimnion on the downwind shore and reducing its depth on the upwind shore. Prolonged strong winds pile up warm surface water and produce sinking on the downwind shore, while at the same time they remove warm surface water and produce corresponding upwelling of cold water from deeper layers on the upwind shore. Upwelling occurs frequently on the northwest shoreline of Lake Ontario and the west shores of Lake Michigan. Tilting of the thermocline can be observed from the water temperature records of municipal water intakes located on the opposite shores of the lake.

4.5.3 Air-Water Temperature Relationship

The difference between air and water surface temperatures is the primary indicator of the atmospheric stability over the lakes. When the air is warmer than the water sur-

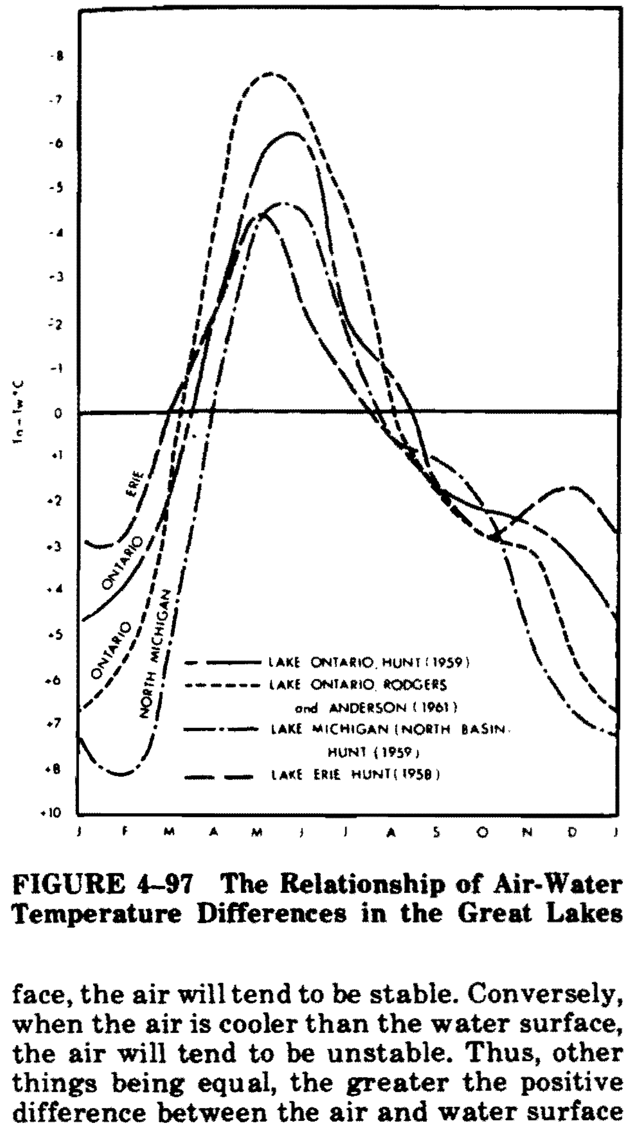

FIGURE 4–97 The Relationship of Air-Water Temperature Differences in the Great Lakes

face, the air will tend to be stable. Conversely, when the air is cooler than the water surface, the air will tend to be unstable. Thus, other things being equal, the greater the positive difference between the air and water surface temperatures, the more stable the atmosphere and smaller the opportunity for the occurrence of overwater precipitation, high winds, and evaporation. On the other hand, the greater the negative difference between the air and water surface temperatures, the more unstable the atmosphere and greater the opportunity for the occurrence of the above climatic processes.

Atmospheric stability over the Great Lakes varies appreciably during the year. The air is normally warmer than the water surface during spring and colder for a somewhat longer period in fall (Figure 4–97). Because of the shortcomings in data used for air-water temperature differences, their magnitude may not be representative of the actual mid-lake conditions, and considerable variation in the magnitude shown at times for the same lake seems to indicate this deficiency. For Lake Ontario, Hunt[396] used mean values from three perimeter stations (Toronto, Oswego, and Trenton) for the 1937–56 period to obtain average air temperature over the lake. Water surface temperatures for this lake were obtained by adjusting values given by Freeman,[271] U.S. Lake Survey,[825] and Millar.[543] In the same study, for the northern Lake Michigan air temperature, Hunt used St. James and Beaver Island data from 1911 to 1956; water surface temperatures were obtained from records in the vicinity of Beaver Island from unstated sources. In a study on Lake Erie, Hunt[398] used the water surface temperatures given by Freeman, U.S. Lake Survey, and Millar, and the normal air temperatures from four perimeter stations (Detroit, Cleveland, Erie, and Toledo). In a second study for Lake Ontario, Rodgers and Anderson[675] used Millar's water surface temperatures and normal air temperatures from Toronto and Rochester.

In all cases except Lake Michigan, air temperature over the lakes was determined from perimeter stations and may be considerably different than at mid-lake, as pointed out by Rodgers and Anderson in their study. Because land area is more sensitive to both heating and cooling, these air temperatures obtained at perimeter stations would tend to intensify the extreme conditions, being higher than at mid-lake during summer and lower during winter periods. Air temperature data for Lake Michigan represent conditions over an island and may be more representative. The water surface temperatures, except those by Millar, were also determined mostly from perimeter stations and would tend to have the same deficiencies, but probably not to the same degree. Thus, the air-water relationships shown probably over-accentuate the magnitudes between these temperatures.

The monthly values of air-water temperature difference indicate that there are four periods of prevailing atmospheric conditions over the Great Lakes. Duration and timing of these periods vary for different lakes, depending primarily on latitude. Generally, the air is normally warmer than water during spring months of April, May, and June (also July in northern areas), and the atmospheric conditions are stable. During mid-summer months of July and August the air and water temperatures are approximately the same, thus indifferent or adiabatic (occurring without loss or gain of heat) equilibrium conditions exist in the atmosphere. From early fall to mid-winter months (September through February) the air is normally colder than water and the atmosphere is unstable. However, during winter months the presence of ice and snow cover has a significant modifying effect on the air-water temperature relationship. Finally, during late winter in March (also April in northern areas) the air and water temperatures are again about the same, and the adiabatic equilibrium conditions prevail. The adiabatic equilibrium conditions occur during relatively short, transitory periods and variation in the atmospheric conditions during these two periods may be considerable. In contrast, the spring stable conditions and the fall unstable conditions present long, well-established periods.

4.6 Humidity

4.6.1 Lake Perimeter Humidity

The influence of the lakes produces higher and more stable humidity in the Great Lakes area than at similar latitudes in the mid-continent. Since warmer atmosphere is capable of holding more water vapor, the amount of water vapor present in the atmosphere varies constantly with temperature and availability of moisture. However, this discussion is concerned with the relative humidity or the ratio between the actual vapor pressure and the saturation vapor pressure at the same temperature. Since all lakes provide large quantities of moisture through evaporation, the upper Great Lakes with lower temperatures and corresponding lower dew points attain somewhat higher values of relative humidity. Prevailing winds and lake breezes are important factors in raising or lowering humidity values on land areas adjacent to the lakes.

Humidity measurements on lake perimeters are provided by the first order meteorological stations located around the lakes. Humidity values at these stations are generally published for the four daily synoptic hours (1:00 and 7:00, a.m. and p.m.), but hourly values are also available. Data from these stations are the sole source of continuous humidity records for extended periods of time. Because of the lake effect on adjacent land areas, various investigators have utilized these data to obtain estimates of humidity over the lakes by averaging records from several perimeter stations. Some of the more recent studies also employed correction factors to adjust these estimates to overlake conditions. The correction factors were derived from infrequent overwater measurements, similar to those used for winds, and are discussed later.

TABLE 4–11 Average Perimeter Humidity for the Great Lakes (Percent)

	Lake				
Period	Superior	Michigan	Huron	Erie	Ontario
January	77	76	81	77	78
February	76	73	79	77	77
March	74	73	76	74	74
April	69	69	73	70	69
May	68	66	70	69	68
June	72	69	74	70	70
July	74	71	74	71	68
August	76	74	77	74	72
September	79	76	78	75	74
October	76	73	79	75	74
November	78	76	83	78	78
December	79	78	83	79	78
Annual	75	73	77	74	73

Values are based on mean data published in 1969 for the following stations:
Superior: Sault Ste. Marie, Marquette, Duluth, and Thunder Bay.
Michigan: Milwaukee, Muskegon, and Green Bay.
Huron: Alpena, Gore Bay, and Wiarton.
Erie: Toledo, Cleveland, Buffalo, and London.
Ontario: Rochester, Syracuse, Trenton, and Toronto.

An estimate of the average monthly and annual humidity values for the individual Great Lakes, based on data from perimeter stations, is given in Table 4–11. The perimeter humidity for all lakes increases from a low of approximately 70 percent in the spring to a high of approximately 80 percent during the late fall. Average annual humidity varies from 73 percent for Lake Michigan to 78 percent for Lake Huron, with intermediate values for other lakes.

Examination of records for the individual stations around the lakes indicates a daily variation and a general northward increase in humidity. Based on four observations a day, highest humidity normally occurs late at night and during early morning hours (1:00 and 7:00 a.m. readings), while lowest humidity occurs in the early afternoon (1:00 p.m. reading). At most stations average annual relative humidity values for the night and morning readings range between 75 and 85 percent, with the maximum values occurring during summer. The afternoon readings range between 60 and 70 percent, and are lowest in the spring and summer. At most locations average daily range in humidity is from 5 to 10 percent during winter and from 15 to 20 percent during summer.

4.6.2 Overwater Humidity

The humidity records from perimeter stations contain both lake and land effects and

TABLE 4-12 Lake-Land Humidity Ratios for the Great Lakes

Period	Richards & Fortin (1962) 1959-1961	Jackson (1963) 1959-1962
January	1.33	1.25
February	1.30	1.24
March	1.21	1.22
April	1.14	1.04
May	.86	.89
June	.94	.94
July	1.09	1.10
August	1.09	1.10
September	1.11	1.09
October	1.15	1.14
November	1.15	1.13
December	1.31	1.28
Annual	1.14	1.12

are not necessarily representative of the extensive water areas included in the Great Lakes. The major controlling factor of humidity is the air temperature, and temperatures over lake and land areas differ. Overwater humidity data are obtained either from direct overwater measurements, which are available only on an intermittent basis, or from empirical relationships derived from those measurements. Such relationships combine many of the differences between overwater and overland conditions into a single correction factor, a lake-land humidity ratio (Richards and Fortin,[650] Jackson[420]). The monthly humidity ratios derived in these studies are shown in Table 4-12. They indicate that on an annual basis overwater humidity is some 10 to 15 percent higher than overland humidity at perimeter stations. During spring, overwater humidity is approximately 10 percent lower than perimeter humidity, but during the rest of the year overwater humidity is higher, with a maximum difference of approximately 30 percent in the winter.

The average daily variation of the humidity ratios presented in the studies shows high humidity ratios during the night and low ratios during daytime hours. The nighttime maximum occurs generally between 1:00 and 4:00 a.m. and the daytime minimum occurs around noon. Richards and Fortin, based on four daily observations, indicate lowest humidity ratios at 1:00 p.m., while Jackson, using eight daily observations, shows the lowest ratio at 10:00 a.m. Inspection of their diurnal variation curves shows that the difference in time is related to the number of daily observations, and indicates that four observations a day are not sufficient to obtain the daily humidity distribution.

TABLE 4-13 Average Perimeter Precipitation for the Great Lakes, 1937-1969 (cm)

Period	Lake: Superior	Michigan	Huron	Erie	Ontario
January	5.5	4.8	6.7	6.5	6.8
February	4.1	3.9	5.3	5.7	6.4
March	4.4	5.0	5.3	6.9	6.5
April	6.0	7.3	6.5	8.5	7.2
May	7.6	7.6	7.0	8.2	7.5
June	9.0	8.6	7.2	8.3	6.3
July	7.2	7.5	6.7	7.7	7.2
August	8.7	7.7	7.5	8.1	7.4
September	8.6	8.4	8.2	7.1	7.0
October	6.4	6.2	6.9	6.8	6.9
November	6.8	6.3	7.7	7.4	7.5
December	5.5	4.8	7.3	6.5	7.0
Annual	79.8	78.1	82.3	87.7	83.7

Note: Based on data assembled by the Lake Survey Center, NOAA.

4.7 Precipitation

4.7.1 Lake Perimeter Precipitation

Precipitation includes all forms of moisture deposited on the earth surface from the atmosphere. The principal forms of precipitation include rain, hail, sleet, and snow, all of which are readily measurable. Of particular interest in the Great Lakes Basin is the precipitation measured at lake perimeters. Investigations of precipitation distribution indicate that perimeter stations show marked variation from precipitation further inland, and since direct overwater measurements are generally not available, it is assumed that perimeter observations are sufficiently representative of overwater conditions (e.g., Freeman[271]).

Estimates for the average monthly and annual precipitation on individual lakes during the 1937-69 period are shown in Table 4-13. The annual precipitation varies from 78 cm (30.8 inches) for Lake Michigan to 88 cm (34.5 inches) for Lake Erie, with an overall average for all the lakes of 81 cm (32.0 inches). Annual precipitation increases from north to south and from west to east. The southward increase in precipitation is climatic, since warmer atmosphere is capable of sustaining more moisture, while the eastward increase is caused by the lake effect, since additional moisture is supplied to the atmosphere by the lakes as

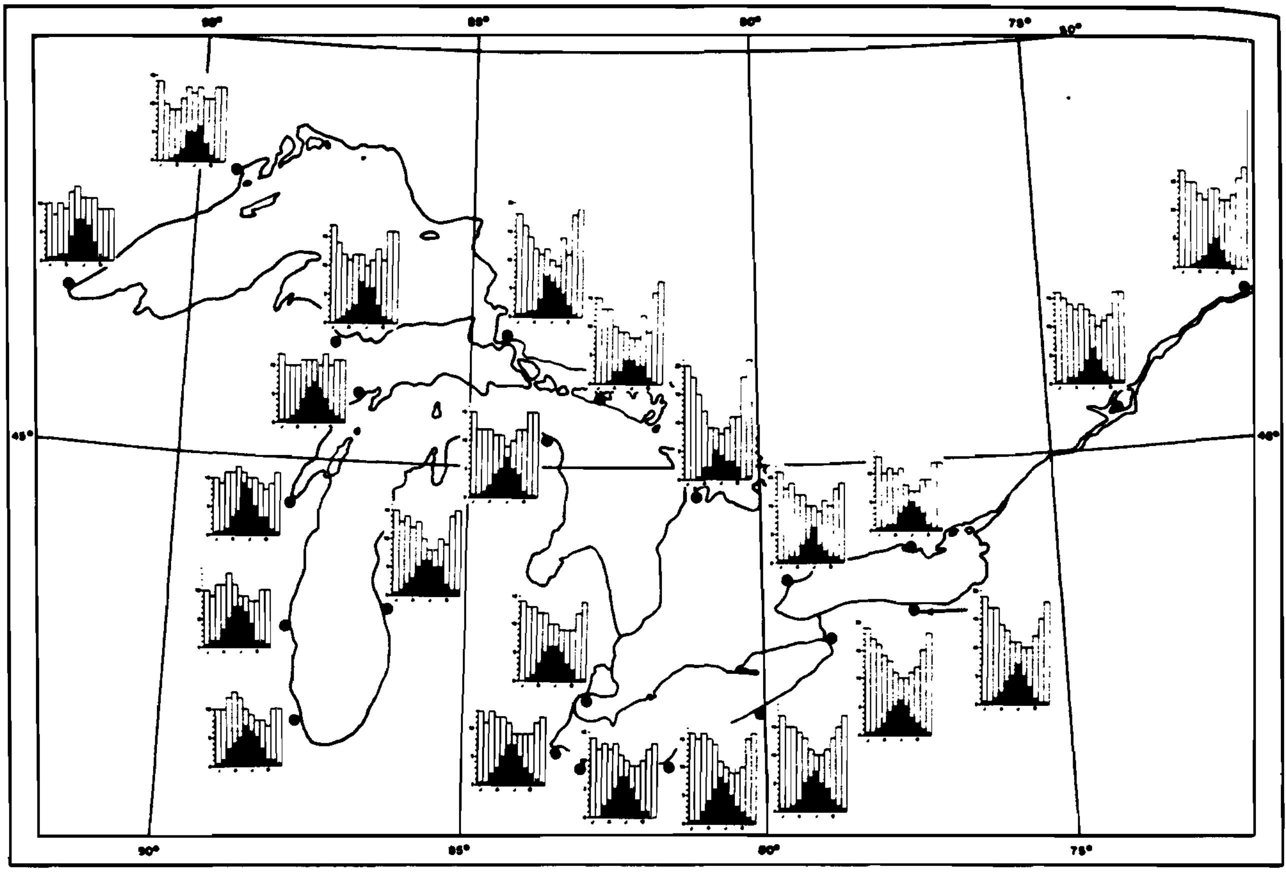

FIGURE 4–98 Mean Monthly Number of Days with Measurable Precipitation (open bars) and Thunderstorms (shaded) in the Great Lakes Basin

From U.S. Weather Bureau, 1959

they are exposed to the prevailing westerly winds.

The seasonal precipitation pattern shows well-distributed and abundant precipitation throughout the year, although a larger portion of the annual supply falls during the summer months, a characteristic of continental climates. The relatively high summer rainfall is especially pronounced on the western and northern lakes. The average monthly precipitation increases from a winter low of 4 cm to 5 cm (1.6 to 2.0 inches) in the upper lakes and 6 cm to 7 cm (2.4 to 2.8 inches) on the lower lakes to a summer high of 8 cm to 9 cm (3.1 to 3.5 inches) on all lakes.

The mean number of days per month with measurable precipitation at perimeter stations increases from the windward to the lee sides of the lakes, and also increases generally from summer to winter months. Exceptions to this seasonal distribution occur along the western and northern shores of Lakes Michigan and Superior. The number of days with measurable precipitation and thunderstorms at perimeter stations is shown in Figure 4–98. Highest thunderstorm frequencies occur along the western shore of Lake Michigan and the southern shore of Lake Erie.

During the winter months precipitation in the Great Lakes Basin is largely in the form of snow. In the northern areas it generally consists of snowfall exclusively, with permanent snow cover throughout the winter. In the southern areas precipitation alternates between snowfall and rainfall, with intermittent snow cover on the ground.

4.7.2 Overwater Precipitation

Observations have indicated that large bodies of water, such as the Great Lakes, modify the atmosphere above them, including precipitation patterns. One theory explaining the reduction of overwater precipitation in the summer is that the water cools the air above it.

ever, precipitation measurements on the islands fail to confirm this in all cases. Horton and Grunsky[376] and Verber[848] suggested that reduced overwater precipitation in the summer may be due to less thunderstorm activity. This results from the cooling effect of the lakes, which produces a more stable atmosphere over the water than over surrounding land areas. Byers and Braham[117] made a similar observation about Lake Michigan and added that in the winter the warming effect of the lakes encourages greater precipitation on the lee shore than on the windward shore. Pearson,[599] from a study of precipitation observations by radar, found that the formation of air-mass showers over Lake Michigan in the summer was inhibited.

The elements affecting overwater precipitation in the winter are less definite. It is apparent that the warming effect of the lakes encourages snow flurries, but whether the precipitation is less, equal to, or more than that falling on the adjacent shorelines is a matter of controversy. Light precipitation belts on windward sides and heavy precipitation belts on the lee sides of the lakes are well established, but the quantities recorded at these locations do not necessarily yield representative overwater precipitation. The observed heavy snowfall on the lee shores of the lakes might be confined to the lake perimeters and would then represent an accumulation of precipitation resulting from the lake-land interaction. The elevation of the air mass as it moves from the water to the land surface, coupled with the air movement from the warm water to the cold land during winter, combine to cause more precipitation on the lee shores. This may apply to the islands as well. Winter measurements are also less accurate because snow is more sensitive to wind, increasing the effects of exposure, so the gages do not adequately measure winter precipitation. Freezing of the lakes complicates the process further.

Recognizing the shortcomings of perimeter observations for estimating overwater precipitation, several investigators derived relationships of overwater to perimeter precipitation, utilizing data from islands to represent overwater conditions. However, island data may not be reliable for this purpose, and results of the studies are often contradictory.

Based on records from Beaver Island in the Lake Michigan and North Bass Island in Lake Erie, Horton and Grunsky[376] concluded that precipitation on the lakes was lower than at perimeter stations. They calculated seasonal lake-land precipitation ratios, which indicate that precipitation on Lakes Superior, Michigan, and Huron (Beaver Island) averages 93 percent of that measured at shore stations during winter months, and 94 percent during summer months. For Lakes Erie (North Bass Island) and St. Clair their overwater precipitation amounts to 84 percent of perimeter precipitation for winter and 85 percent for summer months. However, Day[205] suggests that the differences in island and shore precipitation are due to wind reduction of precipitation gage catch at the more exposed island sites, rather than any real deficit in precipitation on the lakes.

To study overwater precipitation a storage-type precipitation network was established in 1952 on a number of islands in northern Lake Michigan by the U.S. Lake Survey and the U.S. Weather Bureau. Based on twice-a-year precipitation records from this network and monthly records from Beaver Island and adjacent shore stations, Hunt[395] concluded that annual overwater precipitation on Lakes Michigan and Ontario averages 79 percent of that measured at perimeter stations, with monthly values varying from 60 percent in August to 91 percent in November. Hunt assumed precipitation at the smallest, exposed island to be true overwater precipitation. Kohler[461] questioned that assumption and indicated that the relative catch of the island gages is highly correlated with windiness, and that virtually all the differences in precipitation catches could be explained by relative windiness at the gage sites. In another precipitation study of the northern Lake Michigan island network, Kresge, Blust, and Ropes[476] agreed with Kohler and used the higher measured amounts at both island and land gages as true overwater and shore precipitation and corrected the other gage records for gage exposure. The annual overwater precipitation was about the same (102 percent) as precipitation from shore stations. Seasonally, overwater precipitation ranged from 3 to 10 percent less than perimeter precipitation in the summer, depending on the offshore and onshore winds, respectively; and 9 percent more in the winter.

In a Lake Michigan precipitation study based on records from the Four-Mile Crib in the southern tip of the lake and land gages in the Chicago area, Changnon[137] determined a lake-land precipitation relationship similar to that derived by Hunt. Changnon's lake-land precipitation ratios show monthly variations ranging from 78 percent in October to 95 per-

TABLE 4–14 Lake-Land Precipitation Ratios for Lake Michigan and Lake Erie

	Lake Michigan				Lake Erie
Period	Hunt (1959a) 25 years 1911-56	Changnon (1961) 11 years 1945-56	Kresge, Et al. (1963) 30 years 1906-62	Upchurch[1] (1970) 6 years 1963-68	Derecki (1964) 13 years 1920-46
January	.88	.95	1.13	1.39	.95
February	.85	.86	1.13	2.26	.89
March	.81	.84	1.07	1.05	1.03
April	.78	.81	1.01	.89	1.04
May	.75	.87	.96	.83	1.07
June	.73	.79	.93	.49	.92
July	.69	.82	.90	.70	1.04
August	.60	.87	.91	.64	1.03
September	.74	.83	.98	1.10	.95
October	.89	.78	1.05	.96	.89
November	.91	.79	1.10	1.62	1.02
December	.89	.89	1.13	1.32	1.03
Winter (Nov-Apr)	.85	.86	1.09	1.42	.99
Summer (May-Oct)	.73	.83	.96	.79	.98
Annual	.79	.84	1.02	1.10	.99

[1]Upchurch ratios are based on inland stations located 160 km west of the lake (this appendix).

cent in January, with an annual average of 84 percent.

The lake-land precipitation ratios calculated for Lake Erie (Derecki[214]) show considerable monthly variations, without a definite seasonal trend. Overwater precipitation was based on records from Pelee, South Bass (Put-in-Bay), and Catawba Islands, and land precipitation on records from surrounding perimeter stations. The resultant annual ratio was 99 percent with monthly ratios that varied from 89 percent in February and October to 107 percent in May.

In 1963 the U.S. Lake Survey, in cooperation with the U.S. Weather Bureau, modified their existing precipitation network in northern Lake Michigan by replacing the storage-type gages, which were read twice a year, with precipitation recorders producing hourly readings. Similar gage networks were established in western Lake Erie in 1964 and eastern Lake Ontario in 1969. Using recorded data from Lake Michigan islands and land stations located some 160 km (100 miles) west of the lake (Figure 4–18), Upchurch[808] derived lake-land ratios which vary from 49 percent in June to 226 percent in February, with an annual average of 110 percent.

The monthly precipitation ratios derived in the above studies are tabulated in Table 4–14. Monthly ratios given by Hunt[395] and by Kresge et al.[476] represent values from smoothed annual graphs, while those of others are arithmetic averages for the number of years used in their derivations. The Upchurch data are not comparable directly with other data in the table, because Upchurch used remote inland gages while all others used lake perimeter gages. The inland stations, however, indicate more correctly the lake effects on precipitation distribution throughout the year.

4.7.3 Weather Radar

Present methods of measuring precipitation have many shortcomings, such as use of point measurements to represent an area, variations in gage catch, accuracy, effects of windiness and exposure on the catch, and access or installation difficulties in remote areas on large bodies of water. A potentially powerful tool for eliminating some of these problems and obtaining more truly representative precipitation data may be the use of weather radar. Weather radar is applicable to both land and water areas, but it is of particular interest for large lakes because of gage installation and access difficulties.

The use of weather radar for obtaining quantitative precipitation data requires climatological analysis of photographed precipitation echo patterns. The process involves use of a grid overlay on radar photographs, counting echo occurrences, and correlating with measured precipitation. Current use of radar precipitation observations, although promising, is not advanced sufficiently to provide usable, quantitative data. Poor performance is attributed mainly to weak radar equipment, which displays a decrease of echo occurrences per volume of rainfall outward from the radar location, thus limiting the effective range (Bruce and Rodgers[108]). More powerful radar equipment is required. Further developments in radar technology in combination with high-speed computers may provide an ideal answer to the overwater precipitation measurement problem.

4.8 Evaporation

4.8.1 Determination of Evaporation

Evaporation from the lakes is the loss of water from the lake surface to the atmosphere in the form of water vapor. Considering lake and land areas of the Great Lakes Basin, two-thirds of the water supplied by precipitation is lost by evaporation. Evaporation losses from the water surface of the lakes, where the supply of moisture is continuous, are substantially higher than from the land and amount to approximately three-quarters of the overwater precipitation. Thus, it is readily apparent that evaporation has a great effect on the availability of water and on the heat budget of the lakes, since evaporation is basically a cooling process.

There is no direct method to measure evaporation from large water bodies. Since the actual evaporation losses are dependent directly on meteorological factors, it is possible to develop methods that use hydrologic and meteorologic data and permit determination of evaporation losses from the lakes with acceptable accuracy. These methods include water budget, mass transfer, energy budget, evaporation-pan observations, atmospheric humidity budget, and momentum transfer. The first four of these methods have been used to compute evaporation from the Great Lakes.

The water budget method consists of solving the water budget or mass-balance equation, described at the end of this section, for the unknown evaporation component. All other major components of the water budget necessary to compute evaporation from the Great Lakes are either measured directly or can be estimated from related measurements. This is the only direct method of computing evaporation estimates and has been used in various studies to provide control for other methods, which require determination of empirical constants. Evaporation, as determined by the water budget method, is a residual of several large factors and includes the errors of these factors, which may affect the computed evaporation values considerably. Care must be exercised to reduce these errors to a minimum by using all available data and considering the effects of the lakes on some of them, such as on overwater precipitation.

The mass transfer method of computing evaporation is a modified application of Dalton's law, where evaporation is considered to be a function of the wind speed and the difference between the vapor pressure of saturated air at the water surface and the vapor pressure of the air above. A summary of the theoretical development of the mass transfer method and a review of the equations developed by various investigators is given by Anderson et al.[17] The more promising of these equations were tested by Marciano and Harbeck.[512] The problem in applying this method to the Great Lakes is that climatological data for any appreciable period of time are almost exclusively restricted to the perimeter land stations, which may be and often are not representative of open-lake conditions. Variations in air stability that affect both wind and vapor pressure are essentially diurnal in character over land and seasonal over water. The required adjustments for perimeter data, or lake-land ratios for wind and humidity have been made in recent years and are being improved as more overwater data are collected. Thus, the mass transfer method of computing evaporation from the Great Lakes holds great promise for the future. Its primary advantage is the elimination of the main objections of the water budget method, namely, uncertainties with respect to ground water and dependence of computed evaporation on large factors, such as inflow and outflow from the lakes.

The energy budget method requires determination of the energy exchange between a body of water and the atmosphere, which includes such factors as the net solar and atmospheric radiation, conduction of sensible heat to the atmosphere, energy utilized by evaporation, net advective energy, and energy storage within the body of water, disregarding some minor heat sources or sinks (chemical, biological, exchange with bottom sediments). The water loss is determined from the related energy or heat loss by evaporation. Detailed discussion of various terms comprising the energy budget and its practical application is presented by Anderson.[16] However, in the Great Lakes this method has been used infrequently because of the difficulty in obtaining data on energy components.

A convenient and inexpensive method of obtaining evaporation estimates, although frequently questioned on theoretical grounds, is that of evaporation-pan observations, which utilize observed water losses from evaporation pans and experimentally determined pan-to-lake relationships. The ratios of pan evaporation to lake evaporation, or pan coefficients, vary depending on pan characteristics. An extensive investigation of the relationships between pan and lake evaporation was reported by Kohler et al.[462]

4.8.2 Evaporation from Lakes

To compute evaporation from the Great Lakes various investigators have used one or more of the four methods described above. The water budget and mass transfer methods were used most frequently. There are only two known studies which utilize the energy budget approach. The evaporation-pan observation method has also been used infrequently. Results obtained by various investigators often differ considerably, especially for shorter, monthly periods. Some of this variation is natural, reflecting variability of evaporation between the various periods of record involved, but some of it, especially in extreme cases, is due to computation procedures and inaccuracies of basic data. More recent determinations use better basic data and should be more accurate.

Among the earliest methods used to determine evaporation from the Great Lakes is that of evaporation-pan observations. Henry[341] concluded that the ratio of evaporation from floating pans to land pans was approximately 0.5 and used this ratio to estimate lake evaporation. Hickman[355] described experiments in which water temperature in the pan was maintained at the lake surface water temperature, and the pan-lake ratio or pan coefficient was assumed to be 1.0. The latest estimates of evaporation from the lakes by this method (U.S. Weather Bureau[828]) give pan coefficients ranging from approximately 0.75 in the southern areas of the Basin to 0.80 in the northern areas. The above studies give annual evaporation estimates, without breakdown into seasonal or monthly amounts.

The water budget is one of the traditional methods of determining lake evaporation (Russell,[692] Freeman,[271] Pettis,[605] Hunt,[395] Brunk,[111] and Derecki [213,214]). In some studies (Hunt, Derecki) precipitation from perimeter stations was adjusted by lake-land ratios to represent overwater conditions. Others used unadjusted perimeter precipitation. Later studies showed that Hunt's reduction was probably too extreme, resulting in somewhat lower evaporation than indicated by most of the other recent studies for Lake Ontario. Because Lakes Michigan-Huron have a common outlet (St. Clair River), water budget determinations for these lakes can be made only for both lakes as a single unit.

Probably the first mass transfer determination of Great Lakes evaporation is that given by Freeman[271] who used a relatively simple formula similar to those used in all subsequent Great Lakes mass transfer studies. Other evaporation studies, mostly of Lake Ontario, which employed mass transfer methods are those by Horton and Grunsky,[376] Hunt,[395] Kohler,[461] Snyder,[751] Bruce and Rodgers,[108] Richards,[648] Richards and Rodgers,[654] and Richards and Irbe.[651] Richards[648] modified the mass transfer equation by introducing monthly wind and humidity ratios for adjusting data obtained from land stations. In previous studies wind data from perimeter stations were being adjusted to overwater winds based on seasonal periods. Because of data limitations, most studies mentioned above employed inconsistent periods of record to determine various factors of the mass transfer equation. In some of them, the average evaporation values are based on only a few years of record, which is much too short to establish reliable long-term trends. The first mass transfer determination of evaporation with consistent periods of record for all factors was made for Lake Ontario by Richards and Rodgers.[654] This study was extended to include other lakes bordering on Canada by Richards and Irbe.[651]

Evaporation studies by the energy budget method conducted on the Great Lakes are limited to Lake Ontario (Bruce and Rodgers,[108] and Rodgers and Anderson[675]). The results of these studies are practically identical. The authors concede that their estimates are high due to inaccuracies of data used, and they discuss the possible errors. Continuing research on interaction between the atmosphere and lake surface should enable more direct evaluation of the energy exchange factors, reduce their dependence on empirical relationships, and improve the accuracy of evaporation estimates determined by the energy budget method.

Evaporation from the Great Lakes varies with latitude and depth. The warmer, lower latitudes provide greater evaporation opportunity, and the lake depths govern heat storage capacity. The influence of lake depths is mainly seasonal. Deeper lakes warm and cool more slowly, retarding the seasonal low and high evaporation losses. The depths of the Great Lakes coincide with latitude; Lake Superior is deepest (410 m) and Lake Erie is the shallowest (65 m), while the centrally located lakes have approximately similar intermediate depths (230 to 280 m). Thus, evaporation from the lakes increases from north to south, being lowest for Lake Superior and highest for Lake Erie. The centrally located lakes, Michigan, Huron, and Ontario, have intermediate evaporation rates.

The average evaporation values for individual lakes, obtained in some of the better known or more recent studies mentioned in the preceding paragraphs, are listed in Table 4–15. The table also shows the methods used, the source, and the periods of record, although, for methods other than water budget and the last

TABLE 4–15 Comparison of Great Lakes Evaporation (Centimeters)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
LAKE SUPERIOR													
WATER BUDGET													
Freeman (1926) 1921-25	8.9	7.9	6.6	5.8	0.3	0.3	1.5	-0.3	3.3	5.3	7.9	9.7	57.2
Derecki (1965) 1939-59	8.9	6.6	5.8	-0.8	-1.0	-1.0	-0.5	2.8	5.8	6.9	9.7	9.7	52.8
MASS TRANSFER													
Freeman (1926) 1900-24	9.1	8.4	6.9	2.5	0.0	0.0	0.0	3.0	4.3	7.1	6.9	8.1	56.4
Snyder (1960) 1921-50	7.6	6.4	4.8	1.8	-1.8	-5.8	-7.4	-0.5	5.6	6.4	6.9	8.4	32.3
Richards & Irbe (1969) 1959-68	11.7	9.1	5.8	1.5	1.0	-3.6	-8.1	-4.1	3.3	6.4	10.4	12.2	45.7
LAKE MICHIGAN													
MASS TRANSFER													
Freeman (1926) 1900-24	7.6	7.1	4.1	2.3	1.5	1.8	7.9	9.9	9.1	8.6	6.6	6.6	73.2
Snyder (1960) 1921-50	7.6	6.6	4.1	1.0	-2.3	-3.0	3.0	7.9	9.9	8.6	6.9	7.6	57.9
LAKES MICHIGAN-HURON													
WATER BUDGET													
Freeman (1926) 1915-24	8.4	2.8	4.3	3.6	-0.3	-0.3	0.5	4.8	9.7	10.4	10.2	10.7	64.8
LAKE HURON													
MASS TRANSFER													
Freeman (1926) 1900-24	7.9	7.9	5.1	2.0	2.0	2.5	7.9	10.2	9.1	7.1	6.1	7.1	74.9
Snyder (1960) 1921-50	7.9	6.9	4.3	1.3	-1.5	-2.8	3.3	8.3	9.9	8.1	6.9	8.4	61.2
Richards & Irbe (1969) 1959-68	11.9	8.9	4.6	-0.8	0.0	-2.0	0.5	5.1	8.6	11.4	11.7	11.7	71.6
LAKE ERIE													
WATER BUDGET													
Freeman (1926) 1951-24	4.6	2.8	12.7	-3.8	0.0	0.8	4.8	11.4	13.7	15.0	12.2	9.1	83.3
Derecki (1964) 1937-59	5.3	1.5	1.5	0.0	1.0	2.8	9.4	13.7	16.0	13.7	12.2	7.1	84.3
MASS TRANSFER													
Freeman (1926) 1900-24	6.4	6.6	2.8	3.6	1.9	7.4	17.0	18.3	16.0	13.5	7.1	6.1	106.4
Snyder (1960) 1921-50	6.6	5.1	2.5	1.3	2.0	4.6	9.4	12.2	12.7	10.9	9.7	8.9	85.9
Richards & Irbe (1969) 1950-68	5.6	4.1	1.3	-3.0	5.8	7.6	7.1	11.2	14.2	15.7	13.7	7.6	90.9
LAKE ONTARIO													
WATER BUDGET													
Hunt (1959a) 1934-53	6.1	3.0	1.8	1.0	0.5	-0.5	2.8	7.9	9.7	11.4	10.4	9.7	63.8
Morton & Rosenberg (1959) 1934-52	8.1	5.8	2.0	2.0	1.3	0.5	4.6	10.2	10.7	11.7	11.4	11.2	79.5
MASS TRANSFER													
Freeman (1926) 1900-24	6.6	6.6	4.1	2.5	0.8	2.8	9.4	13.0	11.7	10.9	6.1	6.1	80.5
Hunt (1959a) 1937-52	7.1	5.6	5.6	2.0	0.0	0.3	4.8	6.4	9.7	8.1	7.1	6.1	62.7
Snyder (1960) 1921-50	7.9	6.9	4.3	1.5	-1.5	0.3	5.8	10.2	10.7	9.4	6.6	7.6	69.6
Richards & Irbe (1969) 1950-68	9.7	7.4	4.3	-1.8	1.0	0.3	4.8	8.1	10.9	9.1	8.9	8.9	71.6
ENERGY BUDGET													
Rogers & Anderson (1961) 1958-60	12.4	8.9	5.1	0.5	-1.8	0.0	11.7	8.9	10.2	9.4	10.9	10.7	86.9

NOTE: Energy budget and mass transfer studies (except Richards & Irbe, 1969) used variable periods of record for various factors involved.

mass transfer study (Richards and Irbe,[651]) these periods are only approximations. Results of most studies show reasonable agreement between different computations.

The average long-term seasonal variation of evaporation from the Great Lakes is shown in Figure 4–99, presented as smoothed graphs based on studies indicated in Table 4–15. Lakes Michigan and Huron are included in a single graph, because of common water budget computations and limited determinations by other methods. The available information indicates that the evaporation from these lakes is similar and compares with that of Lake Ontario. In view of the latitude and depth distributions of these three lakes, this similarity appears to be quite reasonable.

The long-term average annual evaporation from the Great Lakes amounts approximately to 65 cm (25 cm (25 in.) The following are estimates of annual evaporation for the individual lakes: Superior, 55 cm (21 in.); Michigan-Huron, 65 cm (26 in.); Erie, 85 cm (33 in.); and Ontario, 70 cm (28 in.). These estimates were based on several studies and should be considered as indicators of the long-term average value. During individual years annual evaporation may vary considerably from the long-term values listed above.

Seasonally the low evaporation normally occurs in the spring, when the water temperature is close to or even below the dew point temperature of the air. These low evaporation rates vary from slight evaporation to condensation. With rising water temperatures evaporation increases until it reaches the high

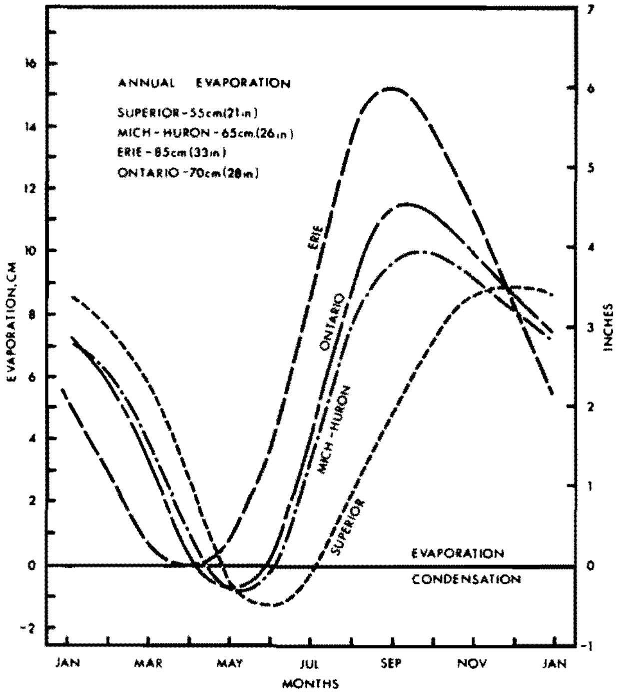

FIGURE 4-99 Evaporation from the Great Lakes. The smoothed lines are based on several studies from 1926-1969.

evaporation season, which for most lakes is in the fall, when the water temperature is considerably above the dew point temperature of the air. Because of its great depth and tremendous heat storage capacity, highest evaporation from Lake Superior occurs in the late fall and early winter period. The long-term average values of the highest monthly evaporation vary from approximately 9 cm (3.5 in.) for Lake Superior to 15 cm (6.0 in.) for Lake Erie. These high evaporation rates, coupled with low air temperatures, cause rapid dissipation of heat from the water surface. With the sharply falling water temperatures, evaporation begins to decrease.

4.9 Runoff from Drainage Basin

4.9.1 Surface Runoff

Water enters the lakes from the drainage basin mainly through the tributary streams. When rainfall exceeds the infiltration capacity of the soil the excess water reaches the tributary streams either as direct surface runoff or as interflow. Interflow is defined as that water which percolates through the soil above the phreatic or permanently saturated ground-water zone. Although interflow reaches the streams with more delay than direct surface runoff, the two are difficult to distinguish, and together are referred to as surface runoff. The infiltration capacity of soils varies widely depending upon precipitation factors such as intensity, duration, and type of precipitation, and soil factors such as antecedent soil moisture, type of soil, shape and slope of the basin, and vegetation. During winter months, the ground is usually frozen, and interflow is reduced to the periods of ground thaws, but surface runoff still occurs during intermittent snowmelts. Basin hydrology is considered in Appendix 2, *Surface Water Hydrology*.

Water which infiltrates into the soil is transmitted downward to the ground-water table and becomes a part of the ground-water reservoir. Ground-water flow is discussed later in this section.

The storage of water on the drainage basin in whatever form, be it ground water, channel storage, or snowpack, is a fundamental hydrologic factor of runoff delay. Natural regulation by upland lakes and artificial regulation by man-made reservoirs and control structures are also common in the basins of all the Great Lakes. Lake regulation delays, prolongs, and diminishes the peak runoff by storing water during periods of high runoff.

Runoff is measured at gaging stations on many of the tributary streams and together with measured flows in connecting rivers is the most accurate data in the hydrologic cycle. Unlike measurements of other components, which sample only points within an area, gaged runoff effectively integrates the entire area about the point of measurement. However, runoff data contain some uncertainties, but these are considered to be random. Errors may be introduced in the measurement of runoff, particularly during winter months due to ice effects, and by extrapolating the gaged runoff to the nearby ungaged areas to obtain coverage for the entire drainage basin.

Routine computations of the total average surface runoff to the lakes are not made by any agency associated with the Great Lakes, but runoff estimates have been made in the course of hydrologic studies. The values of runoff presented in this report were obtained by direct areal extrapolation of the available gaged streamflow records to the nearby ungaged areas, and summation of the total runoff amounts from individual basins of the tributary streams within each lake basin, which in turn were combined to obtain total runoff from

TABLE 4–16 Runoff-Precipitation Ratios, 1937–1969

Period	Lake Superior	Michigan	Huron	Erie	Ontario
January	.49	.47	.43	.55	.55
February	.50	.66	.48	.68	.55
March	.61	.62	.75	.86	.95
April	1.01	.61	.93	.63	1.13
May	.85	.42	.67	.35	.60
June	.46	.26	.37	.19	.34
July	.36	.24	.27	.12	.20
August	.26	.18	.18	.08	.15
September	.28	.18	.16	.08	.16
October	.40	.28	.28	.13	.25
November	.44	.32	.33	.20	.34
December	.52	.44	.43	.40	.48
Annual	.52	.39	.44	.35	.48

TABLE 4–17 Average Runoff into the Great Lakes, 1937–1969

Period	Runoff in cm depth on lake surface: Superior[1]	Michigan	Huron	Erie[2]	Ontario
January	3.4	4.3	5.5	8.2	13.2
February	2.9	5.1	5.2	8.9	12.5
March	3.8	6.4	8.4	14.1	22.8
April	8.6	9.2	12.7	12.8	30.3
May	9.8	7.2	10.2	7.2	17.7
June	6.5	5.2	6.1	4.2	9.2
July	4.5	3.9	4.2	2.4	5.7
August	3.6	3.1	3.0	1.5	4.4
September	3.6	3.2	3.0	1.3	4.6
October	3.7	3.7	4.1	2.0	6.5
November	4.2	4.1	5.3	3.3	9.8
December	3.7	4.2	6.0	5.9	12.8
Annual	58.3	59.6	73.7	71.8	149.5

[1] Includes diversions into Lake Superior (about 5cm/yr - 140 m^3/s). See DIVERSIONS.
[2] Excluding drainage area of Lake St. Clair.

the entire drainage area of the Great Lakes. Similar methods were employed in previous studies (Freeman,[271] Horton and Grunsky,[376] Pettis,[605] Hunt[395]). Results obtained by various investigators generally differ somewhat because of different periods of record and varying coverage of the gaged tributary area, which increases steadily. Peak runoff to all the lakes usually occurs in the early spring as a result of melting snow augmented by rainfall and lack of growing vegetation. The low point usually occurs in the late summer.

To facilitate comparison with other components of the hydrologic cycle, such as precipitation or evaporation, runoff values are frequently given in units of depth over respective areas, and this practice is retained in this report. Runoff distribution on the drainage basin is shown in Figure 4–19. Comparison of runoff with the corresponding overland precipitation for both monthly and annual periods, expressed as runoff-precipitation ratios, is shown in Table 4–16. These ratios indicate that average annual runoff during the period from 1937 to 1969 represents from 35 to 49 percent of the overland precipitation, while average monthly runoffs vary from a high of 113 percent in the spring to a low of 8 percent during the summer. The substantial differences in the retention of precipitation on the basins of the individual lakes are due primarily to higher evapotranspiration losses in the south, but other factors such as infiltration capacity of soils, forest cover, land cultivation, and urbanization, also affect the relationship between runoff and precipitation. Although precipitation on Lake Erie is among the highest and is comparable with that of Lake Ontario, runoff into Lake Erie is low because of the high water losses by evapotranspiration. Similarly, the Lake Superior basin, with the lowest precipitation, has a high runoff because of the reduced water losses in the north. High runoff in the spring accounts for 30 to 40 percent of the annual amount.

The importance of surface runoff to the hydrology of the Great Lakes depends not only on the absolute magnitude of flow but also on the relative magnitude of runoff with respect to surface area of each lake. Runoff represents one-third to one-half of the overland precipitation and is almost equal to overwater precipitation on all the lakes except Ontario, where runoff is almost twice as high. The average runoff values for monthly and annual periods, expressed in centimeter depth on the lake surface, are listed in Table 4–17. Average annual runoff during the 33-year period (1937–69) varied from 58 cm (23 in.) for Lake Superior to 150 cm (59 in.) for Lake Ontario, 60 cm for Lake Michigan, 74 cm for Lake Huron and 72 cm for Lake Erie. The annual value for Lake Superior includes approximately 5 cm (2 in.) from the Ogoki and Long Lake Diversions, which are channeled and measured in the tributary streams, while Lake Erie runoff excludes streamflow tributary to Lake St. Clair, since it is measured in the Detroit River and thus becomes part of the inflow to that lake. The average monthly runoff varied from a high of 30 cm (12 in.) during April on Lake Ontario to a low of 1.3 cm (0.5 in.) during September on Lake Erie.

4.9.2 Underground Flow

Underground flow from ground water

reaches the lakes by percolation, either directly through the lake bottom or through tributary streams. Since most streams in the Great Lakes Basin derive their base flow from ground water, the underground flow reaching the lakes through tributary streams is measured and considered with the surface runoff. Thus, direct contribution from ground water to the lakes is of primary interest to the lake hydrology. Depending on the geohydrologic characteristics of the system and the water levels in lakes, the underground flow could be either into or out of the lakes.

There is very little information on the underground flow in the Great Lakes Basin, particularly on direct ground-water supplies, and knowledge in this field should be expanded. The evaluation of direct underground flow requires ground-water profiles, which can be derived from a network of observation wells located around the lakes. There is only a handful of wells located within 15 km (10 mi.) of the lakes, and wells located further inland may be poor indicators of ground-water flow. In addition to lake perimeters, special attention should also be concentrated on any areas where, because of geologic structure, ground-water divides may be significantly different from topographic divides.

There are many geological studies of ground-water conditions for specific areas of the Basin. However, these studies cover relatively small areas (one section of a lake basin) and are not related directly to the underground flow into or out of the lakes. They are approached from the geological point of view and consider areal geology, water use, economics of water development, and the usual ground-water data obtained from observation wells, pumping tests, and chemical analysis. Thus, they reveal only limited information, which is not readily adaptable to large areas encompassing one or more lake basins. Large area hydrologic studies dealing with ground water are more important for the underground flow aspect. Because of the varying geologic and climatic conditions over such large areas, estimation of the underground flow into any one lake is very difficult, and ground-water data are not sufficient to determine this flow by direct methods.

In most hydrologic studies underground flow was considered negligible and assumed to be zero (Freeman,[271] Horton and Grunsky,[376] Hunt,[395] Morton and Rosenberg,[561] Derecki[214]). Horton and Grunsky state that there is a marginal belt around the perimeters of Lakes Michigan and Huron, from which water reaches the lakes mainly through ground water and not through surface streams. They also state that there are numerous instances of watershed leakage from one drainage basin to another and probably from the higher-lying drainage basins directly into the lakes. Based on these considerations, they concluded that the summer runoff to the lakes estimated from measured streamflow may be less than the actual runoff by an amount exceeding 13 cm (5 in.) on the lakes, but in their study they assumed the underground flow to be zero. Hunt acknowledges a possibility of a considerable underground flow between Lakes Erie and Ontario, due to the very large potential head between them. He investigated this matter and concluded that there is no appreciable ground-water flow into Lake Ontario, and that what flow might exist is probably steady throughout the year.

In some hydrologic studies underground flow was estimated by various forms of water budget computations. Russell[692] estimated monthly amounts of water entering the lakes from underground sources, which resulted in the annual values 65 cm (25 in.) on Lake Superior, 83 cm (33 in.) on Lakes Michigan-Huron, 51 cm (20 in.) on Lake Erie, and 130 cm (51 in.) on Lake Ontario. However, Russell did not distinguish between ground-water flow into streams and ground-water flow directly into lakes, so values listed above include base flow of streams. Pettis[605] estimated direct underground flow into the upper lakes as 42 cm (16 in.) to Lake Superior and 58 cm (23 in.) to Lakes Michigan-Huron. Pettis also states that a considerable part of a large underground water body in the northern part of the State of Ohio has a definite motion towards Lake Erie.

In contrast to the high underground flow claimed by the above investigators, Bergstrom and Hanson[62] computed inflow to Lakes Michigan-Huron from the ground-water sources to be approximately 0.5 cm (0.2 in.). They suggest that the actual discharge along the shore could be several times that given above, but the amount would still be relatively small, and probably less than the error inherent in extrapolation of runoff, lake evaporation, and precipitation. Snyder[751] indicates that there are underground outflows from Lake Superior and Lakes Michigan-Huron that amount to approximately 22 cm (9 in.) and 5 cm (2 in.) on these lakes, respectively. He also suggests that there are underground inflows to Lakes Erie and Ontario of approximately 19 cm (8 in.) and 8 cm (3 in.), respectively. Snyder bases his indicated groundwater flow on the differences in evaporation estimates computed by mass transfer and water budget methods.

Widely divergent opinions on the amount and direction of underground flow to the Great Lakes leave the subject in a state of controversy. For example, Pettis[605] claims the underground inflow to Lake Superior is 42 cm on lake surface per year and Snyder[751] indicates an outflow from the same lake of approximately 22 cm. It is apparent from the cautious wording and the conflicts that exist in the preceding studies that the estimates are little more than conjectures.

4.10 Lake Inflow and Outflow

4.10.1 Inflow

The inflow to any of the Great Lakes is the quantity of water supplied by the lake above, modified by the local inflow to the connecting river. Local inflow is usually less than one-half percent of the total flow and generally is disregarded in computing lake outflows and the corresponding inflows to the lakes below. However, the Lake Huron outflow and Lake Erie inflow normally differ by approximately 2 percent and occasionally the difference is much higher. Therefore, flow at the head of St. Clair River is used to determine outflow from Lakes Michigan-Huron, while the flow of the Detroit River is used to obtain inflow to Lake Erie. The importance of inflow to the lakes increases progressively in descending order through the lakes. The smaller lower lakes are affected by these flows to a much greater extent than the upper lakes. Inflow to Lakes Michigan-Huron is of the same order of magnitude as the overwater precipitation, but in Lakes Erie and Ontario, it is an order of magnitude greater. During the period of hydrologic study, 1937–69, the average annual inflow was equivalent to 60 cm (24 in.) for Lakes Michigan-Huron, 640 cm (250 in.) for Lake Erie, and 927 cm (365 in.) for Lake Ontario. The variation in the annual inflow during this time had a range of approximately 40 cm (15 in.) for Lakes Michigan-Huron, and approximately 240 cm (95 in.) for Lakes Erie and Ontario. Thus, in the lower lakes the variation in the annual inflow is three times greater than the average annual overwater precipitation. Because of the magnitude and fluctuation of the inflows to the lower lakes, accuracy of inflow is extremely important in studies of the hydrologic cycle.

4.10.2 Outflow

The outflow of each of the Great Lakes is the quantity of water flowing from a given lake through its natural outflow river and through man-made outlets. As a factor in the hydrologic cycle of the lakes the outflow of any lake, including that through man-made diversions, represents the water yield of the entire basin above the point of outflow measurement.

The outflow from Lake Superior through the St. Marys River has been artificially controlled since 1922 by a gated dam structure, which allows diversions for the generation of power. Release of water through the control structure and for the generation of power is made in accordance with a regulation plan, designed to maintain the level of Lake Superior within specified limits.

The outflow from Lakes Michigan-Huron through the St. Clair and Detroit Rivers, which together with Lake St. Clair constitute the natural outlet of these lakes, is controlled largely by the level of Lake Huron at the head of the St. Clair River and the level of Lake Erie at the mouth of the Detroit River. No man-made control of this flow exists, except for the fixed remedial control provided by the dikes constructed in the lower Detroit River to compensate for the effects of deepening the navigation channels in that river. These compensating controls do not regulate lake levels. However, they are designed to provide the same net discharge capacity in the rivers as existed before the improvements, so that the levels upstream are maintained. The navigation improvements in the St. Clair River, including some works recently completed, cause a lowering of the levels of Lakes Michigan-Huron, and remedial works are being evaluated. In the winter period ice normally slightly reduces the open water flow of the St. Clair and Detroit Rivers.

The outflow from Lake Erie through the Niagara River is controlled largely by the level of Lake Erie at the head of the river and the level of the Chippawa-Grass Island Pool above Niagara Falls. If the diversions of water from the Chippawa-Grass Island Pool for the generation of power are not compensated for, they can lower the levels of Lake Erie. However, a submerged weir was constructed during the period 1942–47 at the downstream end

TABLE 4-18 Average Flows in Connecting Rivers of the Great Lakes, 1937-1969 (m^3/s)

Period	St. Marys	St. Clair	Detroit	Niagara	St. Lawrence
January	1,980	4,420	4,620	5,240	6,230
February	1,980	4,250	4,420	5,240	6,230
March	1,940	4,810	4,960	5,320	6,400
April	2,020	5,130	5,270	5,640	6,830
May	2,180	5,240	5,350	5,920	7,020
June	2,310	5,350	5,410	5,950	7,190
July	2,450	5,410	5,490	5,830	7,140
August	2,570	5,440	5,490	5,720	7,000
September	2,550	5,380	5,440	5,580	6,770
October	2,510	5,320	5,380	5,470	6,570
November	2,430	5,270	5,300	5,470	6,460
December	2,110	5,130	5,240	5,470	6,460
Annual	2,250	5,100	5,200	5,570	6,690

of the pool, as the initial phase of the remedial works designed in part to counteract this effect. Presently, a gated control structure extending partially into the river from the Canadian shore provides compensation for the power diversion, which was increased by the 1950 treaty between the United States and Canada. This second control structure is located downstream and runs parallel to the weir.

The outflow from Lake Ontario through the St. Lawrence River since 1958 has been largely controlled by the release of water through the Iroquois Dam near Iroquois, Ontario. Beginning in April 1960 the release of water has been made in accordance with a regulation plan, which provides for weekly flow changes throughout the year. Thus, Lake Ontario levels are fully regulated and are independent of any channel changes or diversions. Prior to the construction of the Iroquois Dam in 1958, the Galop Rapids, a short distance downstream from Ogdensburg, New York, constituted a natural weir, the flow over which was controlled substantially by the level of Lake Ontario.

The average monthly and annual flows of the outflow rivers for the 1937-69 period are listed in Table 4-18. Prior to 1957 the flows of the St. Clair River were based on published records of combined St. Clair-Detroit River flows, since the flows in both rivers were considered to be essentially equal. During the period of study, annual flow from the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence Rivers averaged 2,250 m^3/s, 5,100 m^3/s, 5,210 m^3/s, 5,580 m^3/s, and 6,680 m^3/s (79, 180, 184, 197, and 236 thousand cfs), respectively. Low flows occur in the winter and high flows in the summer, with a progressive delay of the summer highs in the upstream rivers. The range in the average monthly flows was approximately 700 m^3/s (25,000 cfs) for the St. Marys and Niagara Rivers, and 1,300 m^3/s (45,000 cfs) for the other rivers. The difference between the high and low annual flows during the 33-year period varied from approximately 1,400 m^3/s (50,000 cfs) on the St. Marys River to 2,000 m^3/s (70,000 cfs) on the Detroit River. The relatively large variations in flow of the St. Clair and Detroit Rivers, in comparison with other rivers, are due primarily to ice retardation of winter flows.

The importance of outflow to lake hydrology increases progressively with downstream lakes. The average annual outflows (river flows and diversions), expressed in units depth on the lake surface, represent 86 cm (34 in.) on Lake Superior, 139 cm (55 in.) on Lakes Michigan-Huron, 706 cm (278 in.) on Lake Erie and 1,077 cm (424 in.) on Lake Ontario. Variation in the annual outflow during the period of study had a range of approximately 50 cm (20 in.) for Lakes Superior and Michigan-Huron, 190 cm (75 in.) for Lake Erie, and 300 cm (120 in.) for Lake Ontario.

Numerous studies of the connecting river flows have been made. These studies have analyzed the effects on flow equations of regimen changes, formation of ice, weed retardation, and water temperatures. Detailed discussion of outflows is given in Appendix 11, *Levels and Flows*. Flow equations and the means of revising them when channel changes occur, and turbine ratings used to compute flows through power structures are generally well established. As a result, data on the flows in the connecting rivers of the Great Lakes are considered to have a greater accuracy than for any other hydrologic factor, except the change in lake storage.

4.10.3 Diversions

Water diversions in the Great Lakes Basin may be broadly divided into two types: outside diversions, which take water into or out of the system; and inside diversions, which retain water entirely within the system. Diversions of water into the Basin have the effect of raising water levels of the lake into which the diverted water is discharged and the levels of the lakes downstream through which the diverted water must pass on its way to the sea. Diversions of water from the Basin have the converse effect on the levels of the lakes at and downstream from the point of diversion. Diversions from one point to another within the

Basin may have no effect on the lake levels if within the same lake basin; or, if not compensated for, diversions may lower the levels of the lake upstream and temporarily raise the levels downstream. The temporary rise in levels downstream is due to increased discharge rates while the levels of the lake above drop to adjust to the larger outlet capacity due to the diversion. The rate of adjustment in lake levels decreases exponentially with time, and the period of adjustment depends on the size of the lake involved and the capacity of its outlet. For example, Lakes Michigan-Huron reach 90 percent adjustment in approximately seven years and Lake Erie in less than one year (Bajorunas[35a]).

There are five major diversions in the Great Lakes Basin (Figure 4–1): the Ogoki and Long Lake Projects divert water into Lake Superior; the Chicago Sanitary and Ship Canal diverts water out of Lake Michigan; and the Welland Canal and the New York State Barge Canal divert water from Lake Erie and Niagara River into Lake Ontario. All other diversions presently in existence on the St. Marys, Niagara, and St. Lawrence Rivers divert water from one point to another within the same river and with remedial structures have no effect on lake water supplies and lake levels.

The Ogoki and Long Lake Projects divert water into Lake Superior from the Albany River drainage basin in the Hudson Bay watershed. The Ogoki diversion diverts water from the Ogoki River into the Nipigon River. The Long Lake diversion diverts water from Long Lake at the head of the Kenogami River to the Aguasabon River. These diversions have increased the supply of water to Lake Superior by an average rate of approximately 142 m^3/s (5,000 cfs), which is equivalent to approximately 5 cm (2 in.) on the lake surface per year.

The Chicago Sanitary and Ship Canal, along with the Calumet Sag Canal, a branch which connects with Lake Michigan south of Chicago, diverts water from Lake Michigan through the Des Plaines and Illinois Rivers to the Mississippi River. This diversion, commonly referred to as the Chicago diversion. represents the amount of water diverted from Lake Michigan for navigation purposes and for domestic use by the City of Chicago. The total diversion from the lake at Chicago amounts to 88 m^3/s (3,100 cfs), which represents an annual amount of water exceeding 2 cm (about 1 in.) on the surface of Lakes Michigan-Huron. The net effect of all three outside diversions, the inputs to Lake Superior and the output from Lake Michigan, is to increase the supplies to Lake Michigan-Huron and the downstream lakes by approximately 54 m^3/s (1,900 cfs).

The diversion of water through the Welland Canal, from Lake Erie at Port Colborne to Lake Ontario at Port Weller, includes water used in the DeCew Falls power plant, which amounts to most of this diversion, plus diversions for navigation purposes. The total Welland Canal diversion amounts to approximately 198 m^3/s (7,000 cfs), which is equivalent to approximately 25 cm (10 in.) on the Lake Erie surface per year.

The New York State Barge Canal withdraws water from the Niagara River at Tonawanda, New York, for navigation purposes, but the water diverted into the canal is returned to Lake Ontario at Oswego, New York. The Barge Canal diverts approximately 31 m^3/s (1,100 cfs) during the navigation season. Since 1956 there has been no diversion during winter months.

The average monthly and annual flows during the period of study, 1937–69, for the major diversions described above are listed in Table 4–19. Annual values listed in the table are somewhat different from the normal values presented in the discussion because of periodic variations from the normal.

4.11 Lake Level Fluctuations

4.11.1 Lake Levels

The elevations of the water surface of the Great Lakes are tied to the mean sea level at Father Point, Quebec, on the Gulf of St. Lawrence. This plane of reference, established especially for the Great Lakes in 1955, is called the International Great Lakes Datum. The average monthly and annual lake levels for the 33-year period, 1937–69, are given in Table 4–20. These levels are based on mean lake level tabulations published by the Lake Survey, and represent records from master gages, each lake having a single master gage located at a strategic point. Approximate water surface elevations of the lakes are 183 m (601 ft.) for Lake Superior; 176 m (578 ft.) for Lakes Michigan-Huron; 174 m (570 ft.) for Lake Erie; and 75 m (245 ft.) for Lake Ontario.

Of primary interest in lake hydrology are the variations of lake levels caused by the changing volume of water in the lakes. These

TABLE 4–19 Major Diversions in the Great Lakes Basin, 1937–1969 (Cubic Meters per Second)

Period	Ogoki Project into L. Superior 1943-69[1]	Long Lake Project into L. Superior 1939-69[2]	Chicago Diversion out of L. Michigan 1937-69[3]	Welland Canal from L. Erie to L. Ontario 1937-69[4]	N. Y. State Barge Canal from Niagara R. to L. Ontario 1937-69[5]
January	94	35	90	160	9
February	75	35	88	162	9
March	65	29	85	162	4
April	67	28	95	170	22
May	148	54	99	177	31
June	216	65	107	178	31
July	152	48	110	172	31
August	121	39	114	181	31
September	111	34	105	180	31
October	105	33	91	182	31
November	120	36	85	181	31
December	111	35	98	170	16
Annual Average	115	39	97	173	23

[1] Period of record starts in July 1943. Since 1945 total amount of Ogoki and Long Lake diversions has averaged 142 m^3/s (5,000 cfs).
[2] Period of record starts in July 1939.
[3] Since 1938 total diversion (navigation plus domestic pumpage) has averaged 88 m^3/s (3,100 cfs). However, higher flows were authorized on two occasions by the U. S. Supreme Court.
[4] Since 1950 total diversion (navigation and hydropower) has averaged 198 m^3/s (7,000 cfs).
[5] Since 1929 during navigation season this diversion has amounted to 31 m^3/s (1,100 cfs). Since 1956 there has been no diversion during winter months.

volumetric changes are generally referred to as lake level fluctuations and apply to the entire lake. They involve time periods of sufficient duration to allow absorption of any local short-period variations, so that entire water surface can be assumed to be level. The local short-period variations, classified as water level disturbances, do not involve volumetric changes but displacement of water level caused primarily by winds and variations in barometric pressure. Water level disturbances are discussed in Section 6, while detailed discussion of lake levels is given in Appendix 11, *Levels and Flows*.

The water level fluctuations represent storage or depletion of water in the lakes. Seasonal fluctuations undergo a relatively regular cycle; high levels usually occur in the summer and low in the winter.

TABLE 4–20 Average Levels of the Great Lakes, IGLD (1955), 1937–1969 (Meters)

Period	Superior at Marquette	Michigan-Huron at Harbor Beach	Erie at Cleveland	Ontario at Oswego
January	183.00	176.01	173.66	74.40
February	182.93	176.01	173.68	74.42
March	182.89	176.02	173.76	74.50
April	182.92	176.09	173.92	74.71
May	183.04	176.19	174.03	74.85
June	183.13	172.26	174.07	74.92
July	183.20	176.32	174.06	74.88
August	183.23	176.30	174.00	74.77
September	183.23	176.25	173.90	74.64
October	183.20	176.19	173.79	74.51
November	183.15	176.13	173.70	74.44
December	183.08	176.08	173.68	74.42
Annual	183.08	176.15	173.85	74.62

4.11.2 Change in Storage

The change in storage on the lakes for any

TABLE 4–21 Average Change in Storage on the Great Lakes, 1937–1969 (Centimeters)

Period	Superior[1]	Michigan-Huron[2]	Erie[3]	Ontario[4]
January	-6.7	-2.1	0.6	0.9
February	-5.2	0.0	2.4	3.4
March	-2.1	4.0	14.0	15.2
April	9.1	11.3	15.5	21.3
May	11.3	8.2	6.4	11.0
June	8.8	6.7	1.8	0.3
July	4.0	0.9	-4.3	-7.6
August	1.8	-3.4	-8.5	-12.8
September	-1.8	-5.8	-10.7	-13.4
October	-4.9	-6.7	-9.4	-10.7
November	-5.8	-4.6	-4.9	-4.3
December	-8.5	-5.8	0.0	-1.8
Annual	0.0	2.7	2.9	1.5

Note: Change in storage determined from 10-day means (5 at end and 5 at beginning of following month) by averaging records from the following gages:

[1] Thunder Bay, Duluth, Michipicoten, Marquette, and Pt. Iroquois.
[2] Milwaukee, Ludington, Mackinaw City, Harbor Beach, Thessalon, and Goderich.
[3] Cleveland and Port Stanley.
[4] Oswego, Kingston, Cobourg, Toronto, Port Weller, and Rochester.

given period is determined from the change in lake levels. Mean lake levels for several days are used for the determination of beginning-of-period levels. This minimizes the effect of external forces such as winds or barometric pressure. The mean level of a lake at any given time is determined by averaging recorded levels of several gages, situated at points around the lakes in a pattern selected to provide good approximation of the whole lake level.

In recent years, the gage patterns used for determination of lake storage have been coordinated by the Lake Survey and Canadian agencies to provide consistent values in both countries. These gage patterns consist of five gages for Lake Superior, six gages for Lakes Michigan-Huron and Ontario, and two gages for Lake Erie. Each determination is based on ten days of recorded levels (five at the end of one month and five at the beginning of the next month). This determination period is rather long for the beginning-of-month levels. In other determinations four (two plus two) or two (one plus one) days were normally used. The most recent determination is based on two days of recorded levels (one at end and one at beginning of month), employing more gages weighted by the Thiesson polygon method to reduce possible effects of short-term water level disturbances (Quinn,[635a] Quinn and Todd[635b]).

The coordinated average change in storage for monthly and annual periods on each lake during the 1937–69 period is shown in Table 4–21. Since the change in lake storage is primarily a seasonal phenomenon, the long-term annual values should be small due to balancing of rising and falling lake levels, as indicated in the table. The average seasonal change in storage varies with latitude. The lower lakes have rising lake levels during winter and spring, and falling lake levels during summer and fall. This distribution is delayed by approximately one month on Lakes Michigan-Huron and by a full season (3 months) on Lake Superior. The highest average monthly rise was approximately 11 cm on Lakes Superior and Michigan-Huron, 16 cm on Lake Erie, and 21 cm on Lake Ontario; the highest average monthly decline was approximately 8 cm for Lake Superior, 7 cm for Lakes Michigan-Huron, 11 cm for Lake Erie, and 13 cm for Lake Ontario. During individual years the variation in annual and monthly change in lake storage may be considerable. In extreme cases this range may exceed several times the highest average monthly change in storage on each lake.

The change in storage discussed above includes volumetric changes, which are affected by water density variations. A mass of water expands or contracts as it is heated or cooled. The amount of expansion or contraction depends on the change in temperature and depth to which this change becomes effective (thermocline depth). Investigations of the thermal expansion of water in the Great Lakes indicate that thermal expansion is insignificant and may be disregarded (Hunt,[395] Derecki[214]).

4.12 Heat Budget

The interaction of the various climatic and hydrologic elements results in heating and cooling processes within the lakes. Some processes take place at the lake surface and are transmitted through the water body while others produce heat changes by mixing of the water masses. Meteorological factors such as radiation, air temperature, precipitation, and evaporation affect surface temperature, while winds contribute to the deepening of the surface layer. Hydrologic factors such as runoff, inflow, and outflow cause temperature changes by horizontal movement of water mass.

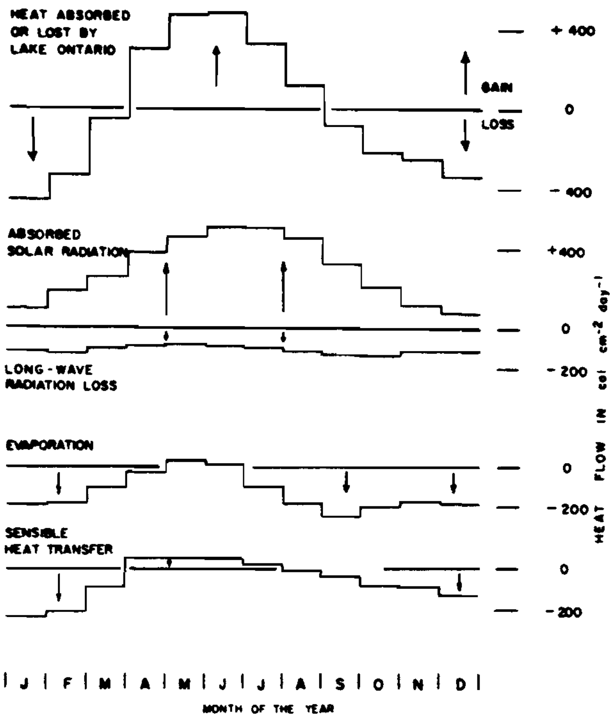

FIGURE 4–100 The Heat Budget of Lake Ontario

From Rodgers, 1969

The heating and cooling processes are summarized in the heat budget of the lakes, which represents the amount of energy gained or lost by the lakes during various temperature changes. There are five basic energy or heat processes affecting the Great Lakes. The four major processes include energy produced by radiation, sensible heat transfer to or from the atmosphere, heat loss by evaporation, and energy storage within the lake. A fifth process of net advected energy may be important locally, especially at the mouths of the inflow rivers and near the effluents of sewage disposal or cooling water from power plants. However, this process has very little effect on the total heat content of the lakes because such inflows with substantial difference in temperatures are relatively small. The energy exchange may be expressed by the equation:

$$O_s + Q_v = Q_b + Q_h + Q_e + Q_t$$

where Q_s = net solar radiation (incident minus reflected)

Q_v = net advected energy (heat due to water input minus output and snow melt)

Q_b = net terrestrial radiation (emitted minus atmospheric)

Q_h = conduction of sensible heat to or from the atmosphere

Q_e = energy utilized by evaporation

Q_t = energy storage within the body of water.

The heat budget for Lake Ontario, the only lake for which such determination has been made (Rodgers and Anderson,[675] Bruce and Rodgers,[108] and Rodgers[672]), is presented in Figure 4–100. The largest energy change is produced by the absorption and loss of heat by the lake water mass; the lake gains heat during spring and summer months and loses heat in the fall and winter. The radiation processes produce both gain and loss of heat; the lake absorbs heat from solar radiation and loses heat through the longwave radiation exchange between water surface and atmosphere. Evaporation cools the water surface and produces heat loss, except during spring when slight condensation produces small heat gain. The transfer of sensible heat to the atmosphere results from the air-water temperature differences; the lake surface is cooler than air and gains heat in the spring and summer, and the process is reversed in the fall and winter. The net effect of all these processes is to produce heat gain during the spring-summer period and heat loss during fall and winter months.

The heat budgets for the other lakes would follow generally similar patterns, although the amounts of energy contained in various processes would differ depending on the hydrometeorological conditions on each lake. The accuracy of heat budget presented for Lake Ontario may be sufficient to indicate general trends for various energy processes, but evaporation studies show that accuracy should be improved for successful application to the solution of practical problems. This was one of the objectives of the International Field Year for the Great Lakes, an intensive field observation program conducted on Lake Ontario in 1972.

4.13 Water Budget

4.13.1 Water Budget Computations

The water budget of the Great Lakes is an accounting of all incoming and outgoing water, such as inflow and outflow by the rivers, supply from and storage in the ground, overwater precipitation, evaporation, and varia-

TABLE 4–22 Average Water Budget, 1937–1969 (Centimeters)

Lake	Water Supply			Water Loss		Storage	Balance Needed
	P	R	I	O	E	ΔS	B
Superior	80	58	0	86	55	0	-3
Michigan-Huron	80	67	60	139	65	3	0
Erie	88	72	640	706	85	3	6
Ontario	84	150	927	1,077	70	2	12

$P + R + I - O - E - \Delta S = \pm B$

P = precipitation on the lake surface
R = runoff from drainage area (surface and underground)
I = inflow from the upstream lakes
O = outflow to the lake below
E = evaporation from the lake surface
ΔS = change in storage of water in the lake
B = balance needed

NOTE: Diversions are included in runoff, inflow, or outflow, where applicable.
Evaporation values are the long-term estimates, not necessarily applicable to this 33-year period.

tion of water storage in the lakes. These water budget factors are interrelated in the hydrologic cycle, which is composed of a perpetual sequence of events governing the depletion and replenishment of water in the Basin. The Great Lakes water budget may be expressed by the equation:

$$P + R + I = O + E \pm \Delta S$$

where P = precipitation on the lake surface
R = runoff from drainage area (surface and underground)
I = inflow from the upstream lakes
O = outflow to the lake below
E = evaporation from the lake surface
ΔS = change in storage of water in the lake (plus if storage increases, minus if decreases)

In practical applications the water budget equation may be modified by eliminating all factors that are negligible or not applicable to individual lakes (e.g., inflow for Lake Superior). Factors other than those listed may also be included. For example, runoff and ground water may be treated separately, and diversions may be included as a separate factor.

The average annual water budget for the 1937–69 period is shown in Table 4–22, which contains groupings of water supply, water losses, lake storage, and algebraic accumulation of these factors for each lake. The differences needed for balancing of the major factors represent a combination of any possible ground-water flow and cumulative errors in estimating other factors. For most lakes these differences are quite small for the average annual values, and are well within the limits of error. The largest difference, for Lake Ontario, is approximately equal to 15 percent of precipitation or evaporation, 8 percent of runoff, or 1 percent of inflow or outflow. For shorter monthly periods and for individual years, the percent differences should increase significantly, because the effect of compensating reduction of random errors would be smaller.

Further studies pertaining to the water budget of the Great Lakes should be directed towards elimination of existing gaps in present knowledge, improvement of data collection networks, comparability of measurement accuracies for various factors, development and implementation of new measurement methods, and closer coordination of these efforts in both countries.

4.13.2 Importance of Water Budget

Lake levels and outflows of the Great Lakes effectively integrate all other components of the water budget and are of primary interest to lake users. However, growth of the population and economy of the area has resulted in an increase in and diversification of demands for lake water, and the competition for its use is increasing rapidly. Use of the lakes for navigation, water power, municipal and industrial water supplies, sanitation, irrigation, fish and wildlife, recreation, and other riparian interests frequently results in conflicting demands, some of which are detrimental to water quality. To provide optimum utilization and preservation of the lakes, a thorough understanding of the entire hydrologic cycle of the system is necessary.

The importance of the water budget to lake water resources has been recognized in many studies and investigations (e.g., Freeman,[371] Horton and Grunsky,[376] U.S. Congress-Senate[817,821]). Knowledge of the magnitudes and variations of the individual water budget components is needed for the improvement of forecasts of lake levels and outflows, for the refinement of lake regulation plans, and for determination of the effects of diversions into and out of the system. Because of the vastness of the Great Lakes, changes in lake levels take place rather slowly and advanced information on the expected stages is of great interest to navigation, hydropower, and for shore protection. For Lakes Superior and Ontario, the only lakes presently regulated, accurate forecasts are even more important to permit planning for the most beneficial operation of the regulating structures.