ART. VI.—*On the Solution of Ice formed on Inland Waters*; by
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FROM the first settlement of this country, the people residing near some of our inland waters have observed that the great fields of ice, which covered these waters during the winter, have broken up at the approach of spring and disappeared so suddenly, as to excite the astonishment of all who beheld it. At the meeting of the American Association for the Advancement of Science, held at Springfield, Mass., General Totten stated that he had known the ice to disappear from the whole surface of Lake Champlain in a single night, when the ice was many inches in thickness, though it had previously lost much of its solidity.¹

In the year 1859, for the purpose of investigating this subject, I commenced a series of observations on the waters and ice of a little lake about one mile long by half a mile broad and twenty-

² The following paragraph was extensively circulated in the public papers a few years ago. Some expressed doubts respecting the accuracy of the figures, but no explanation, so far as I observed, was offered. As Adelaide is situated near the coast (lat. 35° S.), the wind spoken of was doubtless from the *interior*, and that circumstance in connection with what has been here set forth, would fully explain the high heat described.

Australian Heat.—The Sumpter (S. C.) Watchman publishes the following extract from a private letter, dated Adelaide, Feb. 18, 1858:—"I can assure you we have nearly been roasted alive: we have had ten days and nights of the hottest weather remembered for several years past. The heat at noon in the shade was 136° to 146°, according to situation, and during the night, it was never less than 94° to 106° in-doors. The hot wind never ceased blowing, and the innumerable deaths from *coup de soleil* have been appalling in the extreme."

¹ See General Totten's article in this Journal, [2], xxviii, 359.

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five feet deep, situated in latitude a little less than $42\frac{1}{2}^{\circ}$ N., on the borders of New Haven and Middlesex counties, in the state of Connecticut. On the north and east the lake is sheltered by trap hills rising abruptly to the height of two or three hundred feet, and on the south and west there are long rolling hills of no great elevation, so that the south and southwest winds alone sweep unimpeded over its surface. The surface drained by the lake is small, probably not exceeding twice its own surface—there are some small springs and little streams flowing into it, but probably none of them are sixty rods in length. These circumstances render the lake entirely exempt from those influences which are exerted by large flowing streams, and which also lead to an annual change of level of 16 or 18 inches. The lake has an outlet through which a small stream flows except in some of the driest seasons.

Sept. 3, 1859, I found the temperature of the water at the surface of the lake 71° F. Nov. 2d it was 48° F. Dec. 31st, 1859, I visited the lake again and learned that it had been covered with ice since Dec. 5th. I found the ice at the time of this visit pretty uniformly 7 inches thick. I selected two stations, one 5 or 6 rods from the shore, the other near the centre of the lake and observed the temperature at different depths as shown in the following table.

Temperature of water 5 or 6 rods from shore.			Station near centre of the lake	
Dec. 31, 1859. } Ice 7 in. thick. }	Depth below surface.	Temperature.	Below the surface.	Temperature.
Mean temperature of the waters of the lake $35^{\circ}.1$ as determined from the most reliable experiments.	Under the ice.	33° F.	Under the ice.	33° F.
	6 feet.	34°	6 feet.	33°
	12 "	34°	12 "	34°
	22 "	38°	18 "	$37\frac{1}{2}^{\circ}$
			25 "	$39\frac{1}{2}^{\circ}$
Jan. 23, 1860, ice 10 } or 11 in. thick. }	Under the ice.	34°	Under the ice.	$34\frac{1}{2}^{\circ}$
Mean temperature of the lake from the most reliable of these experiments, $38^{\circ}.7$ giving a rise since Dec. 31st of $3^{\circ}.6$.	3 feet.	38°	3 feet.	37°
	6 "	39°	6 "	$38\frac{1}{2}^{\circ}$
	12 "	40°	12 "	$39\frac{1}{2}^{\circ}$
	18 "	40°	18 "	40°
	23 " bottom	42°	24 "	$41\frac{1}{2}^{\circ}$
			25 " bottom	$43\frac{1}{2}^{\circ}$
Feb. 15, 1860, ice 14 } or 15 in. thick. }	Under the ice.	$33\frac{1}{2}^{\circ}$	Under the ice.	33°
Mean temperature of the water at both stations $39^{\circ}.4$. Rise in temperature for the last 23 days $0^{\circ}.7$.	3 feet.	41°	6 feet.	40°
	12 "	41°	12 "	$40\frac{1}{2}^{\circ}$
	18 "	$41\frac{1}{2}^{\circ}$	18 "	$41\frac{1}{2}^{\circ}$
	23 "	42°	24 "	42°

The mean temperature of the atmosphere from Dec. 31st, 1859, to Jan. 23d, 1860, was $26^{\circ}.3$. The fall of water for the same

time was 2·17 inches, which included the water obtained by melting snow, which fell to the depth of 10 inches.

The mean temperature of the atmosphere from Jan. 23 to Feb. 15 was $26^{\circ}\cdot4$. The fall of water for this period was 1·36 inches, including six inches of snow. The observations of Feb. 23d were made with great difficulty, as the temperature of the atmosphere was only 18° F., and the water on the thermometer when brought to the surface was quickly converted into ice so that it was difficult to keep it clear.

March 6th, 1860, I found that the lake had been open at the borders for three or four days. One-fourth to one-third of the lake was now free from ice, and the remainder of the ice was rapidly disappearing: one-fourth or one-third of the ice which I found on the lake disappeared during two hours while I remained in sight of the lake. With the aid of a boat I found the temperature of the lake, in the middle of the open water, to be 42° from the surface to the bottom. Near the edge of the remaining field of ice the temperature was 41° from the surface to the bottom. Close to the edge of the ice the temperature varied from 34° to 38° . The mean temperature of the lake at this time may be considered about $41^{\circ}\cdot5$ F.

July 11th, 1860, I found the temperature of the lake at the surface $73^{\circ}\cdot5$. Aug. 18th, 1860, the temperature of the surface of shallow water near the shore was 77° ; near the centre of the lake the surface water was 75° ; at a depth of 15 feet, 74° ; at the bottom (24 feet), 73° .

Sept. 15th, 1860 (at $5\frac{1}{2}$ P. M.), surface water 67° to 68° with no perceptible difference from the surface to the bottom.

Oct. 27th, 1860. Clear and warm all day—no wind. Observations were made at 4 P. M. Temperature of the surface of the lake $54^{\circ}\cdot5$; 6 ft. below the surface 53° ; at 12 ft., 53° ; at 18 ft., $52^{\circ}\cdot5$; at 24 ft., $52^{\circ}\cdot5$.

Dec. 6th, 1860. There was no ice on the lake and the temperature was $42^{\circ}\cdot5$ from the surface to the bottom.

Dec. 17th, 1860. The lake was covered with ice 6 in. thick. Temperature of the surface under the ice, 34° .

At a depth of 6 ft. $35\frac{1}{4}^{\circ}$,	at 12 ft. $35\frac{1}{4}^{\circ}$.
“ “ 18 “ $35\frac{2}{3}^{\circ}$,	“ 24 ft. (bottom) $36\frac{2}{3}^{\circ}$.

The mean of the whole is $35^{\circ}\cdot4$; but it is probable that the observation at the surface was affected by the agitation of the water in cutting the ice;—if we put the temperature of the surface at $32\frac{1}{2}^{\circ}$ the mean will be $35^{\circ}\cdot1$. The temperature of the air at 2 P. M. was 35° .

Jan. 5th, 1861, the ice was 10 inches thick. Temperature of the water immediately under the ice $32\frac{1}{2}^{\circ}$.

At a depth of 3 ft.	36°,	at 6 ft.	37°.
" " 9 ft.	37½°,	" 12 ft.	38°.
" " 15 ft.	38°,	" 18 ft.	38°.
" " 21 ft.	39°,	" 24½ ft. (bottom)	40°.

Mean temperature of the lake 37°·33. The mean temperature of the air since Dec. 17th, 26°·78. Amount of water fallen, 4·24 inches, of which there were 1½ inches of melted snow. Rise of mean temperature of the lake in 19 days, 2°·23, although the mean temperature of the air had been nearly eleven degrees lower than the temperature to which the lake attained.

Jan. 23d, 1861, found the ice on the lake 16 or 17 inches thick. Temperature of water at the surface under the ice 31°·5.

At a depth of 3 ft.	35°·5,	at 6 ft.	38°·33.
" " 9 ft.	38°·5,	" 12 ft.	38°·5.
" " 15 ft.	38°·5,	" 18 ft.	38°·67.
" " 21 ft.	39°·5,	" 24 ft.	40°·5.
" " 25 ft.	40°·5,		

Mean temperature of the lake 37°·95.² Mean temperature of the air since Jan. 5th, 22°·88. Amount of water fallen during the interval, 2·19 inches, including the water from 11 inches of snow. Rise in the mean temperature of the lake, 1°·7.

Feb. 1st, 1861. Thickness of the ice not noted. Temperature at the surface of the water under the ice 33°.

At a depth of 3 ft.	34°·5,	at 6 ft.	38°·5.
" " 9 ft.	39°,	" 12 ft.	38°·75.
" " 15 ft.	39°,	" 18 ft.	39°·25.
" " 21 ft.	40°,	" 24 ft.	40°·25.

Mean temperature of the lake 38°. Mean temperature of the atmosphere since Jan. 23, 22°·9. Rise in mean temperature of the lake in 9 days, 0°·62. Water fallen, 1·29 inches, part of which was from 8 inches of snow melted.

Feb. 27, 1861. Ice 9 inches thick. Temperature of surface water 35°.

At a depth of 3 ft.	40°·5,	at 6 ft.	41°.
" " 9 ft.	41°·5,	" 12 ft.	41°·66.
" " 15 ft.	41°·66,	" 18 ft.	41°·66.
" " 21 ft.	41°·66,	" 24 ft.	41°·75.
" " 27 ft.	41°·75.		

Mean temperature of the lake 40°·8. Rise in temperature of the lake since Feb. 1st, 2°·8. Water fallen, 2·9 inches—no snow. Mean temperature of the air for the same period, 31°·48, but for the last half of the period the mean temperature was 35°

² The temperature of the open air at this time was 15°, which probably diminishes the observed temperature at the surface. If we call the surface temperature 32° the mean will be 38°.

or 36°. After the last observations, I did not visit the lake for a long period, but I believe the ice disappeared early in March. Such a result might have been anticipated as the temperature of the air had already risen several degrees above the freezing point and the water beneath the ice (which was nowhere broken) contained heat sufficient to dissolve one and three-fourths times as much ice as then covered its surface.

In considering the causes of the phenomena here recorded, it becomes important to take into consideration the temperature of the earth's surface in this latitude, and the variations of temperature for a short distance below the surface. The mean temperature of the earth at all depths short of one hundred feet is very little higher than the mean temperature of the atmosphere. But while the successive seasons impart their varying temperatures to the surface, these temperatures are so slow in finding their way to the depths below, that it is nearly January before the temperature of July has reached to its greatest depth, and hence at that point the seasons are reversed. At these greater depths, the differences between the seasons is exceedingly small, diminishing as the depth increases nearly in a geometrical ratio, so that while the mean daily temperature of the atmosphere varies 40° or 45° between winter and summer, at the depth of 25 feet the variation of temperature is only two degrees, and at 50 feet only one-fifth of a degree.

I have ascertained that the water in the lake, where my observations have been taken, attained, during the warm season, a temperature throughout its depth above the mean temperature of the air for the season, although I have not examined the water at different depths with sufficient frequency to decide whether it is constantly so during the warm season. This temperature, as might be expected, in its progress falls behind the season, but I have not observed precisely how much.

Having ascertained these facts it necessarily follows that the earthy basin in which the lake rests is heated up, during the warm season, to as high a temperature as the same extent of uncovered earth. At the approach of the cold season, the waters will not only part with the heat acquired during the summer, but the earth below the lake will have as much heat to part with as any other equal surface of land.

Open water, exposed to the wind, parts with its heat not only by radiation and conduction, but by transportation or convection, that is, the water which is chilled at the surface sinks while the warmer water rises, until the surface reaches its maximum density, 39°·2 F. (=4° C.). When the surface becomes covered with ice the process of cooling proceeds much less rapidly. But when the ice has covered the surface of the lake, and all agitation of its waters has ceased, the earthy bed still continues to impart its re-

dundant heat to the superincumbent waters. My observations show that the basin of the lake is in much the same relation with the heat of summer that it would be if there were no water in it—that is, it receives about the same mean temperature; but in winter the case is widely different. The bottom of the lake is never cooled below 39° , and even this temperature is considerably lower than would be reached at an equal depth (25 feet) in the solid earth, where, if the authorities are correct, the temperature should not fall below 46° for our latitude. The lake in winter has assimilated itself to the solid earth in that it has attained its maximum density and its surface is converted into solid ice; both the ice and the water in this condition are so slow conductors of heat that very little can escape into the atmosphere. Under these circumstances, the tendency to the equilibrium of heat in the earth will raise the temperature at the depth of 25 feet (the bottom of the lake) to its usual amount at that depth from the earth's surface, and that too quite independent of any accumulation of summer heat. Thus we find another source of heat below the lake, which we may expect to augment the temperature of the waters under the ice. It thus happens that the bottom of the lake attains the mean temperature of the atmosphere in the warm season, and that it always is maintained at a temperature 20° above the mean of the coldest months.

Water attains its maximum density at $39^{\circ} \cdot 2$ F., from which point it is said to expand by a change of temperature in either direction; yet my observations appear to show that water in large masses may be heated up to 42° without disturbing its equilibrium. I have often found the temperature of 42° at the bottom of the lake (25 feet) when the surface was 33° , and 39° was found only 6 feet below the surface. A mass of water with its maximum density at a distance from its surface of only one-fourth part of its depth would doubtless have its equilibrium very easily disturbed by any agitation, as of the wind, and thus bring the warmer water of the bottom into contact with the ice at its surface. I do not claim that all the ice is dissolved in this manner, I only propose to show that, when the solution has commenced, natural laws bring into action an amount of reserved heat sufficient to finish the solution in a very short time.

When, on the approach of winter, the process of cooling commences it proceeds much more rapidly in the waters of the lake than in the earthy bed on which it rests;—the heat escaping from the water by radiation, evaporation, conduction and convection, the colder water at the surface sinking and the warmer rising, until the water of the lake attains its greatest density, after which the surface water expands as it cools and soon freezes, producing a covering of ice which protects the water from agitation by the winds. The process of heating from below then

commences, and, according to my observations in the winter of 1859 and 1860, this process proceeds more rapidly for the first few weeks than afterwards. From Dec. 31st, 1859 to Jan. 23d, 1860, the mean temperature of the lake rose $3^{\circ}6$, and in the next 23 days only $0^{\circ}7$. During both these intervals, the mean temperature of the atmosphere was about 26° , from which it appears that the increase of temperature was not due to the atmosphere. The rise of temperature could not have been produced to any notable degree by the sun's rays, for the ice was opaque with air bubbles, and it was also soon covered with snow; this was especially true in the latter part of the winter, when the heat again increased more rapidly, and was always found to be greatest in the mud at the bottom of the lake. During the 20 days ending March 6th, 1860, the mean temperature of the lake rose $2^{\circ}1$, but the mean temperature of the air was $35^{\circ}25$, and 2.5 inches of rain had fallen, a part of it from the southeast, and quite warm; a large amount of heat had also been expended in the solution of ice, so that we have no data for estimating accurately the supply and expenditure of heat during this period. From Dec. 31st, 1859, to Jan. 23, 1860, the temperature of the lake rose $3^{\circ}6$ (from $35^{\circ}1$ to $38^{\circ}7$), and as the mean temperature of the air was only $26^{\circ}3$, we may be sure that the accession of heat took place entirely from below.

Taking the mean depth of the lake at 22 feet, or 264 inches, a rise of $3^{\circ}6$ would be equivalent to a rise of one degree through a depth of $3.6 \times 264 = 950.4$ inches; and since the latent heat of water is 142° , this amount of heat would melt a layer of ice $950.4 \div 142 = 6.69$ inches thick over the entire surface of the lake.

The observations made during the winter of 1860 and 1861 show similar results. In the first interval of 19 days, the mean temperature of the lake rose $2^{\circ}23$, while the mean temperature of the atmosphere was $26^{\circ}78$. During the second interval (18 days), the mean temperature of the lake rose $0^{\circ}7$, while the mean temperature of the atmosphere was $22^{\circ}88$. During the third interval (9 days), the temperature of the lake rose $0^{\circ}62$, with an atmospheric temperature of $22^{\circ}9$. During the fourth interval (26 days), the temperature of the lake rose $2^{\circ}8$, with the mean temperature of the atmosphere $31^{\circ}48$; but during the latter half of this period the mean atmospheric temperature was 35° to 36° ; no snow, but 2.9 inches of rain fell; it was warm for the season. Since with an atmospheric temperature of $31^{\circ}48$ there could have been little or no loss of heat, and during the latter part of the period there should have been some gain from above, it was to be expected that more heat would accumulate, including that from below, than during other periods. In the first interval of observations the accumulation of heat was as rapid

as in the last, although the temperature of the atmosphere was much lower,—so low, indeed, as to cause a constant loss of heat from the waters of the lake even by bad conductors. The water was at no point found as high as 42° , not even at the bottom, although it was as high as last year.³

The observations made during the summer and autumn of 1860 show that the water at the bottom of the lake (at a depth of 25 feet,) attains a temperature above the mean of any month in the year in this latitude. How much of this heat is imparted to the earth, or to what depth it penetrates, I have had no means of observing. The rapidity with which the water receives heat, after the surface is covered with ice, is as conspicuous this season as it was the last. From Dec. 17th, 1860, to Jan. 5, 1861, (19 days), the temperature of the lake rose $2^{\circ}23$. From Jan. 5th to the 23d, (18 days), the temperature of the lake rose only $0^{\circ}7$, with a difference of only two degrees in the mean temperature of the atmosphere. From Jan. 23d to Feb. 1, (8 days), there was no perceptible change, but from Feb. 1st to the 27th the temperature of the water rose $2^{\circ}8$; the temperature of the atmosphere had in the mean time risen too high to allow any loss of heat in that direction, and even sufficiently high to supply heat.

On the approach of spring, when the rains and the increasing heat of the atmosphere have thinned the ice and opened some holes so that the winds may agitate the waters, this great store of heat accumulated in the lower strata of waters, which now have their unstable equilibrium disturbed, begins to be applied to the ice, which under such circumstances could not be expected to resist solution more than a few hours.

It should be remembered that the mean temperature of the earth at a depth of twenty feet is sufficient to supply a large amount of heat to the bottom of the lake in winter, independent of any accumulation during the warm season.

Similar observations were continued in the winter of 1861-'62, with results so exactly coincident with the preceding, that their presentation could be of no other value than to confirm the conclusions which have here been given.

³ The thermometer used in the winter of 1860 and '61 gives temperatures a fraction of a degree lower than the thermometer used the previous year. The observations for the summer and autumn of 1860 and winter of 1861 were made with a self-registering thermometer constructed by James Green of New York.