Research Notes

EXPERIMENTS ON ATMOSPHERIC EVAPORATION UNTIL THE END OF THE EIGHTEENTH CENTURY

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The importance of the loss of water due to evaporation was first recognized during the Hellenic period.[1] For example, the historian Herodotus of Halicarnassus (484–425 B.C.), who considered all knowledge to be within his jurisdiction and pursued with great enthusiasm his inquiries into a host of different things, was fascinated by the River Ister (Danube), which remained at the same level during summer as well as winter. The reason, explained Herodotus, was not very difficult to find. The Ister flowed at its "natural height" during winter as there was scarcely any rainfall in that period—only snow. The extra water brought to the river during summer, due to both melting of snow and rainfall, was counterbalanced by the greater power of attraction of the sun, and, consequently, the flow in the Ister remained at the same level as in winter.[2] It should, however, be pointed out that his phraseology that the sun *attracts* or *draws* the water was probably a metaphorical term "intended to denote some more general and abstract conception than that of the visible operation which the word primarily signifies. This abstract notion of 'drawing' is, in the historian, as we see, very vague and loose; it might, with equal propriety, be explained to mean what we now understand by mechanical or by chemical attraction, or pressure, or evaporation."[3] Later, the Roman architect Vitruvius was worried about the loss of water due to evaporation and suggested that the aqueducts should be arched over[4] to practice water conservation. These ancient

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[1] Asit K. Biswas, "Hydrology during the Hellenic Civilization," *Bulletin International Association of Scientific Hydrology*, XII, No. 1 (March 1967), 5–14.

[2] Herodotus, *The Histories*, trans. A. de Selincourt (Baltimore, 1959), p. 268.

[3] W. Whewell, *History of Inductive Science* (London, 1857), I, 26–27.

[4] Vitruvius, *Architecture in 10 Books*, trans. J. Gwilt (London, 1826), p. 252; Asit K. Biswas, "Hydrology during the Roman Civilization," *Water and Sewage Works*,

speculations were based perhaps on observation but not on experimentation.

The first experiment on evaporation that we know of was carried out by Hippocrates (460–400 B.C.?), the father of medicine, and it was primarily to show that some quantity of water (which according to him was the thinnest and lightest of elements) was lost due to the process. A measured quantity of water was poured into a vessel and was exposed to the open air in winter until it was frozen. The following day it was brought into a "warm situation" until the ice melted—whereupon it was measured and found to be much less than the original quantity. Some hundred years earlier, Anaximenes had enunciated his concept on the effect of reduction of temperature on density, that is, the hotter the thinner, the colder the denser.[5] Had he tried a simple experiment like Hippocrates, he would have thought twice before propounding such a general and universal concept. Water when heated does become vapor and expands—but what happens when it is frozen? Does it contract into a smaller volume, as anticipated by his theory? Had he kept a jar of water outside on a wintry night, he would have seen that instead of contracting it expanded and could have possibly split the jar. Thus the simple experiment of Hippocrates was a major development and undoubtedly was a step forward in the direction of evolving experimental methods of scientific investigations.

Hippocrates' experiment on evaporation did not involve precise measurement, and credit for the first quantitative measurement must go to the versatile English astronomer Edmond Halley (1656–1742). Primarily considered a pioneer in astronomy, geophysics, and mathematics, Halley's interests covered such diverse fields as history, archeology, navigation, and, last but not least, civil engineering. He wrote poems in Latin, translated books from Arabic and Greek, and also was the founder of population and actuarial statistics, and co-founder of experimental hydrology along with Pierre Perrault (1608–1680) and Edmé Mariotte (1620–1684).

Halley's experiments on evaporation were conducted at Gresham College in London, which was also the early meeting place of the Fellows of the Royal Society. The results of his investigation were reported in a series of four papers published in the *Philosophical Transactions of the Royal Society* in 1687, 1691, 1694, and 1715.

Halley's explanation of the process of evaporation was that if an "atom of water" was heated so that it expanded to become a bubble ten

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CXIV, No. 9, Part 1 (September 1967), 344–47; CXIV, No. 10, Part 2 (October 1967), 373–76; CXIV, No. 10, Part 3 (November 1967), 422–25.

[5] F. M. Cornford, "Was the Ionian Philosophy Scientific?" *Journal of Hellenic Studies*, LXII (1942), 1–7.

times its original diameter, it would become lighter than air and would consequently rise upward. With the increment of heat, more and more particles of water were separated and emitted with a greater velocity, as could be seen in the case of the boiling cauldrons. The sun heats up the air during the day and also raises "more plentiful vapours from the water." Warm air is capable of holding more aqueous vapor, and hence during the night when it becomes gradually cooler, some of the vapor is discharged as dew. The process was somewhat analogous to the fact that warm water can contain more salt than cold water; but as the temperature of the solution comes down, some of the dissolved salt is precipitated.[6]

In a further paper[7] presented to the Royal Society, Halley demonstrated that enough evaporation takes place from the oceans to more than replenish all springs and rivers. In order to determine the amount of water evaporating from the oceans, he took a pan of water, 4 inches deep and 7.9 inches in diameter. A thermometer was placed in the water which was heated to that of the air "in our hottest summer." At the end of two hours, it was found that 233 grains of water had evaporated. The unit of weight used by the astronomer was pound troy, which is at present obsolete. The relationship between pound troy and pound avoirdupois is as follows: 1 ounce troy = 480 grains = 1.09714 ounces avoirdupois; 12 ounces = 1 pound troy = 0.82286 pound avoirdupois.

Thus the depth of water evaporating from the pan in two hours was:

$$\frac{233 \times 76}{1726} \times \frac{1}{49} = \frac{1}{53} \text{ inch} .$$

He assumed that 1 cubic foot of water weighs 76 pounds troy and credited Edward Bernard of Oxford for its determination. The depth of evaporation from the pan, for simplifying subsequent calculations, was taken as 1/120 inch per hour. He considered that the evaporation took place in summer for twelve hours per day, because "dews return in the night, as much if not more vapours than are then emitted." Halley calculated that if the Mediterranean Sea was assumed to be 40 degrees (1 degree = 69 miles) long and 4 degrees broad, the total amount of water lost from the sea by evaporation per summer day would be 5,280 million

[6] E. Halley, "An Account of the Circulation of Watry Vapours of the Sea, and of the Cause of Springs," *Philosophical Transactions of the Royal Society*, XVI, No. 192 (January/February 1691), 468–73.

[7] E. Halley, "An Estimate of the Quantity of Vapour Raised Out of the Sea by the Warmth of the Sun," *Philosophical Transactions of the Royal Society*, XVI, No. 189 (September/October 1687), 366–70 (this was later published in *Miscellanea Curiosa*, ed. W. Derham (London, 1726), I, 1–12); Asit K. Biswas, "Beginning of Quantitative Hydrology," *Journal of the Hydraulics Division of the American Society of Civil Engineers*, XCIV, No. HY5 (September 1968), 1299–1316.

tons. He went on to say that the figure arrived at was very conservative, because even though evaporation depends to a great extent on wind, its effect was completely neglected in his calculations.

Halley next calculated the amount of water the Mediterranean received from the nine major rivers—the Iberus, the Rhone, the Tiber, the Po, the Danube, the Neister, the Borysthenes, the Tanais, and the Nile. If the River Thames had a cross-sectional area of 900 feet $\times$ 9 feet and a mean velocity of 2 miles per hour, the total flow per day would be 20,300,000 tons. Assuming each of the above nine rivers had a discharge equal to ten times that of the Thames, total fresh water received by the Mediterranean per day would be $20.3 \times 10 \times 9 = 1{,}827$ million tons. Since it is slightly more than one-third the total loss of water, it was proved that enough water evaporated from the ocean to supply all the streams and rivers.

In a third paper,[8] Halley reported the results of an investigation carried out at Gresham College by a Mr. Hunt "with great care and accuracy," under his direction in 1693. The evaporation from a screened and sheltered water surface—having a surface area of 8 square inches—was noted every day for the year 1693. Also recorded were temperature (outside?), pressure, and general precipitation conditions (snow, rain, or frost); and all observations were taken at 8 A.M. The total annual evaporation turned out to be 64 cubic inches, or 8 inches of water per square inch of the area. He compared it with Pierre Perrault's[9] recording of 19 inches of annual rainfall in Paris and Richard Townley's[10] 40 inches at the foot of the hills in Lancashire, but evidently water evaporated was too little to account for the total annual precipitation. His explanation, for the residual evaporation required to balance the rainfall, was that the direct effects of the sun and the wind had been excluded in his experiment. He concluded that the wind effect would have increased the evaporation at least three times, and the sun perhaps might have doubled it.

The experiment also indicated that the evaporation during the months of May, June, July, and August are approximately equal, and are about three times the monthly evaporation occurring during November, December, January, and February, and twice as much as March, April, Sep-

[8] E. Halley, "An Account of the Evaporation of Water," *Philosophical Transactions of the Royal Society*, XVIII, No. 212, 183–90.

[9] P. Perrault, *De l'Origine des fontaines* (Paris, 1674); translated by A. La Rocque as *Origin of Fountains* (New York, 1967).

[10] R. Townley, "A letter from Richard Townley, of Townley in Lancashire, Esq., Containing Observations on the Quantity of Rain Falling Monthly for Several Years Successively," *Philosophical Transactions of the Royal Society*, XVIII, No. 208 (February 1694), 52.

tember, and October. Regrettably Halley does not state anything about the container of water from which evaporation took place. Probably it was a "pan of water"—like the one used for his previous evaporation experiment, and was filled to the top every morning at 8 o'clock.

The final paper[11] of Halley's series appeared much later, in 1715, and is of considerable interest to all historians of science and technology. Halley considered four closed-in (i.e., having no exit) seas and lakes—the Caspian Sea, the Dead Sea, the Lake of Mexico, and Lake Titicaca in Peru. He reasoned that since the lakes and seas considered have no exits but receive water continuously through various rivers, the levels will rise "until such time as their surfaces are sufficiently extended so as to exhale in vapour that water that is poured in by the rivers." He suggested that as the rivers are continually carrying dissolved salt to the ocean, and the loss through evaporation is only of fresh water, the salinity of the sea must be steadily increasing. Halley concluded that from the degree of salinity it would be possible to estimate the age of the earth.

After Halley, the first noteworthy measurements of evaporation were taken by D. Dobson in Liverpool, Lancashire, who recorded the rainfall, evaporation, and temperature for four consecutive years, from 1772 to 1775 (Table 1). Dobson used a site overlooking Liverpool, 75 feet above sea level, on rising ground having free exposure to sun, wind, and rain, and measurements were taken in the middle of a grass plot. He used "two well-varnished tin vessels; one of which was to serve the purpose of raingauge; the other to be employed as my evaporating vessel. The evaporating vessel was cylindrical, twelve inches in diameter and six inches deep. The raingauge consisted of a funnel twelve inches likewise in diameter, the lower end of which was received into the mouth of a large stone-bottle; and to prevent any evaporation from the bottle, the pipe of the funnel was stopped with grooved cork."[12]

Water level in the evaporation measurement vessel was kept 2 inches below the crest. Depending on rainfall or evaporation, water was either taken out or added so that the level in the vessel was kept constant. Knowing the rainfall and the amount of water added or removed, he

11 E. Halley, "A Short Account of the Cause of the Saltness of the Ocean," *Philosophical Transactions of the Royal Society*, XXIX, No. 344 (June/August 1715), 296–300.

12 D. Dobson, "Observations on the Annual Evaporation at Liverpool in Lancashire; and on Evaporation Considered as a Test of the Dryness of the Atmosphere," *Philosophical Transactions of the Royal Society*, LXVII (1777), 244–59; Asit K. Biswas, "Development of Rain Gages," *Journal of the Irrigation and Drainage Division of the American Society of Civil Engineers*, XCIII, No. IR3 (September 1967), 99–124.

could calculate the monthly evaporation. The temperature was measured by a thermometer attached to a shaded wall at 2 P.M. every day. The main defects of such a method were: the difficulty of restoring the water level in the tank exactly back to the original one, the precise measurement of water added or removed or water lost by splashing, and the possibility of loss of water due to overflowing.

TABLE 1

METEOROLOGICAL OBSERVATIONS OF DOBSON AT LIVERPOOL

MONTH	1772			1773			1774			1775		
	Temp. (° F)	Evapor. (in.)	Rain. (in.)	Temp. (° F)	Evapor. (in.)	Rain. (in.)	Temp. (° F)	Evapor. (in.)	Rain. (in.)	Temp. (° F)	Evapor. (in.)	Rain. (in.)
January	38.0	1.28	3.26	44.0	1.85	3.15	37.0	1.38	4.43	44.5	1.51	3.21
February	39.0	1.25	2.35	42.5	1.13	2.37	45.3	1.67	2.42	49.0	3.02	4.62
March	44.0	2.35	1.62	50.0	2.76	0.65	49.6	2.87	1.38	48.5	2.57	2.45
April	48.0	2.53	1.85	54.0	2.89	2.47	54.5	4.56	2.23	57.5	3.21	1.01
May	57.0	4.25	3.42	57.0	3.79	4.56	59.5	4.31	1.65	61.0	5.02	0.85
June	67.0	4.62	3.12	64.5	2.66	1.42	63.0	3.52	3.26	70.5	6.86	2.12
July	70.0	5.53	1.59	67.0	4.92	1.32	66.6	4.97	2.68	68.5	5.03	5.31
August	68.0	5.35	3.65	70.0	5.75	2.21	67.0	4.52	2.36	66.5	4.42	4.26
September	62.0	2.32	6.05	60.0	3.35	6.55	61.3	4.02	5.52	65.0	3.05	4.00
October	60.0	3.18	3.42	55.0	2.79	4.57	57.0	1.95	1.68	54.5	2.12	7.01
November	50.0	2.15	4.85	47.5	1.15	6.69	46.3	1.12	2.69	45.0	1.63	3.03
December	44.0	1.13	2.21	41.5	1.55	4.32	41.6	1.75	1.63	48.0	1.52	3.35
Total or mean	54.0	35.95	37.39	54.5	34.59	40.18	54.0	36.64	31.93	54.0	39.96	40.22

SOURCE.—D. Dobson, "Observations on the Annual Evaporation at Liverpool in Lancashire; and on Evaporation Considered as a Test of the Dryness of the Atmosphere," *Philosophical Transactions of the Royal Society*, LXVII (1777), 244–59.

J. C. Rodda[13] has estimated (Table 2) the evaporation of the same period from Dobson's data, using the equation:

$$E = 0.17T - 7.18 ,$$

where

E = monthly pan-evaporation in inches,

and

T = monthly mean maximum temperature in ° F.

Even allowing for the fact that no factors were included in the equation to compensate for the climatic differences between Wallingford (Rodda) and Liverpool (Dobson), and to account for other controls of evaporation, the values obtained by Dobson were rather high. This is

[13] J. C. Rodda, "Eighteenth Century Evaporation Experiments," *Weather*, XVIII, No. 9 (September 1963), 266.

also substantiated by the fact that Penman's[14] estimate of annual average evaporation at Southport (near Liverpool) was 26 inches (Table 2).

John Dalton (1766–1844) later used Dobson's method to determine evaporation at Kendal for eighty-two days in March, April, May, and June, and found it to be 5.414 inches. During this period, the maximum evaporation recorded in a day was little above 0.2 inches. Dalton stated that a certain Dr. Hale, from a few experiments conducted, concluded that 6.66 inches of water evaporated annually from "green ground and

TABLE 2

ESTIMATED EVAPORATION IN INCHES

Month	At Liverpool (by Rodda)				At Stockport (by Penman) (Average)
	1772	1773	1774	1775	
January	0.0	0.3	0.0	0.4	0.2
February	0.0	0.0	0.5	1.0	0.7
March	0.3	1.3	1.2	1.0	1.5
April	1.0	2.0	2.1	2.6	2.7
May	2.5	2.5	2.9	3.2	3.9
June	4.2	3.8	3.5	4.8	4.3
July	4.7	4.2	4.2	4.5	4.2
August	4.6	4.7	4.2	4.2	3.6
September	3.4	3.0	3.3	3.9	2.2
October	3.0	2.2	2.5	2.1	1.1
November	1.3	0.9	0.7	0.5	0.1
December	0.3	0.0	0.0	1.0	0.1
Total	25.3	24.9	25.1	29.2	24.6

SOURCE.—J. C. Rodda, "Eighteenth Century Evaporation Experiments," *Weather*, XVIII, No. 9 (September, 1963), 266; and H. L. Penman, "Evaporation over the British Isles," *Quarterly Journal of the Royal Meteorological Society*, LXXV (1950), 372–82.

moist earth," which according to him "must be far below truth." The Bishop of Llandaff found that "in a dry season there evaporated from a grass plot that had been mowed close about 1600 gallons in an acre per day which amounts to 0.07 of an inch in depth; and that after rain the evaporation was considerably more."[15]

With the help of his friend Thomas Hoyle, Jr., Dalton determined the evaporation at an unspecified site near Manchester from the autumn of 1795. A cylindrical vessel of tinned iron—10 inches in diameter and 3

[14] H. L. Penman, "Evaporation over the British Isles," *Quarterly Journal of the Royal Meteorological Society*, LXXV (1950), 372–82.

[15] J. Dalton, "Experiments and Observations to Determine Whether the Quantity of Rain and Dew is Equal to the Quantity of Water Carried off by the Rivers and Raised by Evaporation; with an Enquiry into the Origin of Springs," *Memoirs* (Literary and Philosophical Society of Manchester) (Manchester, 1802), V, Part 2, 346–72; Asit K. Biswas, *History of Hydrology* (Amsterdam, in press).

feet deep—was used. Two pipes were connected to the vessel—one at the bottom and the other an inch below the top. The vessel was filled for a few inches with gravel and sand and the rest with good fresh soil. "It was then put into a hole in the ground and the space around filled up with earth, except on one side, for the convenience of putting bottles to the two pipes; then water was added to sodden the earth, and as much of it as would was suffered to run through without notice, by which the earth might be considered as saturated with water."[16] Initially, the soil

TABLE 3

DALTON AND HOYLE'S MEASUREMENT OF EVAPORATION NEAR MANCHESTER

Month	Flow of Water through Pipes (Inches)			Mean Flow (Inches)	Mean Rainfall (Inches)	Mean Evapor. (Inches)
	1796	1797	1798			
January....	1.897	0.680	1.774	1.450	2.458	1.008
February...	1.778	0.918	1.122	1.273	1.801	0.528
March.....	0.431	0.070	0.355	0.279	0.902	0.623
April......	0.220	0.295	0.180	0.232	1.717	1.485
May.......	2.027	2.443	0.010	1.493	4.177	2.684
June.......	0.171	0.726	....	0.299	2.483	2.184
July.......	0.153	0.025	....	0.059	4.154	4.095
August.....	....	....	0.504	0.168	3.554	3.386
September..	....	0.976	....	0.325	3.279	2.954
October....	....	0.680	....	0.227	2.899	2.672
November..	....	1.044	1.594	0.879	2.934	2.055
December..	0.200	3.077	1.878	1.718	3.202	1.484
Total....	6.877	10.934	7.379	8.402	33.560	25.158
Rainfall....	30.629	38.791	31.259	....	....	....
Evaporation	23.725	27.857	23.862	....	....	....

SOURCE.—J. Dalton, "Experiments and Observations . . . ," *Memoirs* (Literary and Philosophical Society of Manchester), (Manchester, 1802), V, Part 2, 346–72.

was kept about the level of the upper pipe for some weeks, but later it was below the pipe so as to preclude any water flowing down the pipe. Moreover, soil at the top was bare during the first year but was covered with grass for the subsequent two years. A regular record was kept of the quantity of rain water which ran off from the surface of the earth through the upper pipe and also the quantity that percolated through the sample to the bottom pipe. Rainfall during the corresponding time was measured by a cylindrical vessel having the same dimensions as the one used for evaporation measurements. Dalton assumed that: Evapora-

[16] *Ibid.*

tion = Rainfall — quantity of water in the two bottles. (Tables 3 and 4 show the results of Dalton and Hoyle's experiments.)

From the experiment Dalton concluded that: (1) the annual evaporation under the circumstances stated was 25 inches, (2) quantity of evaporation increases with the rain but not proportionally, and (3) there is no difference between evaporation from bare earth and vegetating grass.

In a subsequent paper,[17] Dalton gave the results of his observations of evaporation from the water surface of a cylindrical vessel 10 inches in diameter during the period 1799–1801. In 1802, he also put forward a generalized theory of vapor pressure[18] which provided an excellent basis to estimate the rate of evaporation from water surfaces. The theory is based on the observation that under given conditions evapora-

TABLE 4

DALTON AND HOYLE'S OBSERVATIONS OF FLOW RECORDS* DURING 1796

Date	Flow (Inches)	
	Top Pipe	Bottom Pipe
January:		
25	0.190	0.280
30	0.080	0.114
February:		
2	0.100	0.254
8	0.196	0.140
May:		
1	0.163	0.000
10	0.060	0.400
12	0.312	0.175
15	0.190	0.200
June:		
3	0.120	0.040
Total	1.411	1.603

* During the time when the vessel was filled up with earth above the level of the top pipe.

SOURCE.—J. Dalton, "Experiments and Observations . . . ," *Memoirs* (Literary and Philosophical Society of Manchester) (Manchester, 1802), V, Part 2, 346–72.

[17] J. Dalton, "Meteorological Observations," *Memoirs* (Literary and Philosophical Society of Manchester) (Manchester, 1802), V, Part 2, 666–74.

[18] J. Dalton, "Experimental Essays on the Constitution of Mixed Gases; on the Force of Steam or Vapour from Water and Other Liquids in Different Temperatures, Both in a Torricellian Vacuum and in Air, on Evaporation; and on the Expansion of Gases by Heat," *Memoirs* (Literary and Philosophical Society of Manchester) (Manchester, 1802), V, Part 2, 536–602.

tions is proportional to the deficit in vapor pressure. Expressed mathematically, it takes the following form:

$$E = C(e_w - e_a)\,,$$

where

E = rate of evaporation in inches per day,

C = a coefficient (depending on various uncounted factors),

e_w = maximum vapor pressure (in mercury),

e_a = actual vapor pressure (in mercury).

The method is still extensively used today with slight modifications to take into account effects due to wind and/or temperature.

Finally, mention should be made of the beginning of experimental research in the field of monolayers, which at present are being seriously studied for evaporation suppression. So far as I could find out, the first experiment on the spreading of oil on water surfaces was conducted by Benjamin Franklin (1706–90) in 1765 in a large pond at Clapham Common in England. In a letter to one William Brownrigg he pointed out that if a drop of oil was placed on a horizontal mirror or a highly polished table, the drop remained in its place, whereas "when put on water, it spreads instantly, becoming so thin as to produce prismatic colours, for a considerable space, and beyond them so much thinner as to be invisible, except in its effect of smoothing the waves at a much greater distance."[19] Franklin's main interest seemed to have been the use of oil as a method for wave damping, and from the experiments he concluded that the minimum thickness of the film should be about 25Å. Some 150 years later (1917), the distinguished scientist Irving Langmuir proved conclusively that the layers are one molecule thick and was awarded the Nobel Prize in 1932 for his research on monomolecular films. Later, in 1953, the Australian physical chemist William Mansfield suggested the use of monolayers to suppress evaporation and thus affect water conservation.[20]

[19] J. G. Crowther, *Famous American Men of Science* (London, 1937), pp. 101–5; Nathan M. Goodman, *The Ingenious Dr. Franklin* (Philadelphia, 1956), pp. 188–97.

[20] W. W. Mansfield, "Effect of Surface Films on Evaporation of Water," *Nature*, CLXXII (December 12, 1953), 1101.