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J. R. Sutton M.A. (Cantab.)

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RESULTS OF SOME EXPERIMENTS UPON THE RATE OF EVAPORATION.

By J. R. SUTTON, M.A. (Cantab.).

(Read November 27, 1901.)

Of the dozens of patterns of evaporators designed (and sometimes used) by different inventors, not one has hitherto been unreservedly accepted as a standard. Consequently, in the absence of any authoritative pronouncement, observers have used so-called gauges of all sorts of sizes and all sorts of mountings. Naturally the results differ as widely as the methods, some showing a rate of evaporation fully twice as great as others. Mr. Baldwin Latham, for example, showed that his fine evaporation gauge made of copper, 1 foot in diameter, containing 1 foot in depth of water, and floated by means of a hollow copper ring, placed 6 inches distant from the body of the gauge—to which it was attached by radial arms—on a tank 4 feet in diameter and 30 inches deep, gave an annual average evaporation of 19·95 inches; whereas a copper pan, 5 inches in diameter and 12 inches deep, standing in air, lost 38·19 inches.* In the Strathfield Turgiss experiments, again, the indicated evaporation for the six months April to September, 1870, varied between 20·64 inches from a large iron tank 6 feet square and 2 feet deep, sunk in the ground, to a trifle under 47 inches from a tin can 12 inches deep and 5 inches in diameter, standing upon the ground; some small pans under cover giving an annual average of about 14 inches at the same time.† “Dr. Brownrigg fixes the evaporation of some parts of England at

* Presidential Address to the Royal Meteorological Society. *Quarterly Journal Roy. Met. Soc.*, vol. xviii. p. 55.

† *British Rainfall*, 1889.

73·8 inches during the four summer months, May, June, July, and August, and the evaporation of the whole year at upwards of 140 inches." * This is probably the largest estimate for England ever seriously made.

Symons claimed that the different rates at which the water evaporated from different gauges "could not fail to convince any one that the key to the whole question was to be found in one item, the temperature of the water." Latham argued, however, that the greatest deviations arise as much, or more, from capillarity, "the water rising on the sides of the gauge and thus inordinately increasing the amount of evaporation. Consequently a small gauge, having a larger amount of side area, in proportion, than a large gauge, indicates a very much larger amount of evaporation. . . . In a 5-inch evaporating gauge this capillarity adds nearly 40 per cent. to the water area of the gauge, whereas in a gauge 1 foot in diameter the influence of capillarity is less than half that of a 5-inch gauge, whilst in a gauge 6 feet in diameter (or 6 feet square) the influence of capillarity is only one-sixth part of that of a 1-foot gauge." † The same authority showed, moreover, that if any given gauge were coated with some dressing, or pigment, which would lessen the capillary attraction between the walls of the gauge and its water, then the rate of evaporation would become notably decreased. For example, three 5-inch gauges, one plain copper, one enamelled white, and another enamelled black, but otherwise equal and similarly situated, standing in a tank of water up to the level of the evaporating surface, gave the following comparative annual average loss :—

	Inches.
Copper gauge	27·90
Black "	22·97
White "	21·74

while a copper gauge of the same dimensions, freely exposed in air, gave in the same period an average of 36·96 inches, and the 1-foot floating gauge 19·40 inches. Thus a given unprotected and unsheltered gauge lowered its indications by nearly 25 per cent. when relegated to the somewhat cooler and more humid (and presumably less windy) environment of the tank; whereas

* Dr. Dobson in some "Observations on the Annual Evaporation at Liverpool in Lancashire." *Phil. Trans.*, vol. lxvii.

† Many authors agree with Latham in making evaporation proportional to the surface area. But see Preston, who cites Stefan, making evaporation proportional to diameter. *Theory of Heat*.

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under given climatic conditions a restricted capillarity reduced the rate of evaporation by 22 per cent.

Without claiming that capillarity is responsible for all the increase of evaporation shown by an unpainted, as compared with a painted gauge, it seems likely that some of the high numbers indicated by the small gauges at Strathfield Turgiss were due, in great part, to this source of error.

At Camden Square, London, Symons tried three gauges:—

I. A cylinder (material not stated), 5 inches in diameter and $5\frac{1}{2}$ inches long, resting on the neck of a stone bottle, part of the body of which was sunk in the ground so that the rim of the evaporator was a foot above the surface of the ground. It is described as “an excellent arrangement for enabling the sun to heat the water as much as possible.”

II. A black japanned tin cylinder, 5 inches in diameter, 1 foot long, buried 9 inches in the earth. “The cheapest possible evaporator, partly protected against heating, but too small and unduly affected by the sides, which must be high to prevent out-splashing and overflow.”

III. A glass vessel, 5 inches in diameter and 9 inches deep, placed inside a tub of water—15 inches in diameter and also 9 inches deep—so that that inside the cylinder was always surrounded by water up to the same level. The rim of the tub was just above, and the surface of the water approximately flush with, the ground line. “A repetition of Major Phillips’s, insplashing and outsplashing nearly balance, but it breaks at the first frost.”

From July 22 to November 19, 1869, the results were:—

Gauge.	Water Evaporated.	Ratio Evaporated.
I.	15·75 inches	162
II.	13·57 ”	140
III.	9·72 ”	100

From July 22nd to August 12th the results were:—

Gauge.	Water Evaporated.	Ratio Evapo- rated.	Average Excess of Temperature above 65°.	Temperature Ratio.
I.	2·46 inches	178	15·7°	178
II.	3·13 ”	127	10·8	123
III.	4·37 ”	100	8·8	100

Of course the period is far too short from which to derive certain conclusions. And while some of the observed differences in the quantities were conceivably due to differences of temperature, it is not at all unlikely that a part were due to differences in capillarity, and a great part also to the wind. For it is clear enough that the surface of No. I. must have been more wind swept than II., and still more than III.

My own experiments upon the evaporation of water have not lacked variety, albeit not always complete or necessarily convincing. In none of them have I been able to detect the excessive perturbing influence that has been claimed for the temperature of the water. On the contrary, it seems to occupy a comparatively unimportant place in the list of acknowledged agencies.

Attention may be called here to some rather large numbers given by the Kimberley Waterworks Company from a "wrought-iron tank 4-feet cube sunk in the ground to within about an inch of the top, and kept nearly full of water." *

		Monthly Mean.
1891	86·68 inches.	January ..... 11·1 inches.
1892	104·39 "	February ..... 8·8 "
1893	101·32 "	March ..... 7·7 "
1894	91·26 "	April ..... 6·2 "
1895	101·84 "	May ..... 5·6 "
		June ..... 4·3 "
Mean..	97·10	July ..... 4·8 "
		August ..... 6·4 "
		September..... 8·3 "
		October ..... 10·8 "
		November ..... 11·0 "
		December ..... 12·1 "

The greatest evaporation numbers for any Kenilworth (Kimberley) gauge—which, as it happens, are considerably less than those for the Waterworks tank—are derived from the indications of a copper pan 8 inches in diameter and about 5 inches deep, kept nearly full of water. The outside of this gauge was protected from the sun's rays by a covering of water, sawdust, and wood. As originally received from the makers it had an inside coating of bath-enamel; but this got saturated and came off very soon. It always showed signs of having once been painted, however, and this may have reduced the capillarity effect. In July, 1897, the covering of the gauge was improved, but this necessitated raising the gauge some 20 inches higher than before. The change seems to have somewhat increased the evaporation, while it also seems to have decreased the range of

* R. H. Twigg, in the *Quarterly Journal of the Roy. Met. Soc.*, vol. xxii. p. 166.

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temperature of the water. The results of seven years' observations are—

		Monthly Mean.
1894	77·93 inches.	January ..... 10·42 inches.
1895	88·43 „	February ..... 9·33 „
1896	87·72 „	March ..... 7·22 „
1897	103·18 „	April ..... 4·80 „
1898	92·15 „	May ..... 3·80 „
1899	90·44 „	June ..... 3·10 „
1900	90·82 „	July ..... 3·58 „
		August ..... 5·59 „
Mean..	90·11 „	September ..... 8·18 „
		October ..... 10·59 „
		November ..... 11·73 „
		December ..... 11·77 „

I have not seen the Waterworks tank, but there is no doubt that it could not have attained a higher degree of temperature than the pan. The disagreement between the two is probably partially accounted for by the sheltered position of the pan; the wind being interfered with a great deal by the trees. For the years 1897–8 at Kenilworth a circular iron tank of about 130 gallons capacity, sunk in the ground, lost 81·75 inches and 68·92 inches respectively.

An analysis of some of the evaporation numbers derived from the different Kenilworth gauges during the year 1900, furnishes a number of details that are not without interest. A full account of the instruments and of the results has been published elsewhere,* so that it will only be necessary to repeat just such particulars as are essential for present purposes.

In addition to (1) the copper pan mentioned above there are :—
(2) An iron tub, enamelled white inside and out, 20 inches high † and 14 inches in diameter, standing with its rim about 2 feet above the ground, and sheltered by a single-louvred screen.

(3) A circular steel tank slightly less than 4 feet in diameter and 30 inches deep, standing in a cemented brick cistern of about 7 feet square and rather more than 3 feet deep. Thus the level of the rim of the tank is some 8 inches below the top of the cistern wall. The tank is kept nearly full of water, and the cistern also contains water up to about the same level. The indications are recorded by suitable machinery upon a rotating drum.

(4) A Piche evaporating tube of the usual pattern.

(5) Pickering “evaporimeters.”

* *Report of the Meteorological Commission for the year 1900; Cape Town, 1901.*

† Outside dimensions; the inside depth would be more than an inch less.

Of the last little need be said. They are troublesome to use as routine instruments, but they may be safely trusted to evaporate more water in a given time than any other evaporator in use.

Comparative monthly totals for the year 1900 are :—

	8-inch Copper Pan.	Screened Tub.	Tank.	Piche Tube.
	Inches.	Inches.	Inches.	Inches.
January	11·57	7·11	7·58	8·59
February	11·26	6·73	6·78	8·62
March	6·35	3·72	4·28	5·28
April	4·15	2·61	2·95	3·79
May	4·19	3·08	2·44	5·13
June	3·14	2·35	1·60	3·94
July	2·93	1·94	1·37	3·37
August	5·06	3·29	2·77	5·73
September	8·81	6·55	4·73	9·48
October	10·93	8·06	6·23	10·32
November	12·49	9·65	7·74	11·26
December	9·94	6·89	6·74	7·32
Year	90·82	61·98	55·21	82·83

The daily mean values are :—

	8-inch Copper Pan.	Screened Tub.	Tank.	Piche Tube.
	Inches.	Inches.	Inches.	Inches.
January	·373	·229	·244	·277
February	·402	·240	·242	·308
March	·205	·120	·138	·170
April	·138	·087	·098	·126
May	·135	·099	·079	·165
June	·105	·078	·053	·131
July	·095	·063	·044	·109
August	·153	·106	·089	·185
September	·294	·218	·158	·316
October	·353	·260	·201	·333
November	·416	·322	·258	·375
December	·321	·222	·217	·236
Year	·249	·170	·151	·227

Comparative daily extreme values chiefly, but not necessarily, occurring on the same day, are :—

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	8-inch Copper Pan.	Screened Tub.	Tank.	Piche Tube.
	Inches.	Inches.	Inches.	Inches.
January	·52	·35	·37	·43
February	·60	·38	·38	·46
March	·35	·24	·22	·29
April	·25	·16	·16	·20
May	·17	·15	·09	·21
June	·18	·11	·08	·22
July	·17	·12	·08	·22
August	·27	·24	·16	·31
September	·45	·37	·26	·49
October	·55	·41	·31	·51
November	·58	·46	·36	·51
December	·52	·42	·35	·38

For the purpose of showing how these different values have been influenced by the elements of climate, we give below in six columns (1) the mean temperature, humidity, and wind movement, of the successive months, derived from hourly observations, and (2) the mean temperature, humidity, and wind movement of the day, upon those days which saw the maximum amount of evaporation from the tank in each month :—

	MEAN VALUES.			EXTREME VALUES.		
	Air Temp.	Humidity.	Wind. Miles per day.	Air Temp.	Humidity.	Wind. Miles per day.
1900	°	%		°	%	
January	75	50	134	74	45	161
February	77	46	146	80	38	18
March	71	64	123	74	47	136
April	65	69	86	66	62	135
May	58	56	78	63	55	38
June	51	62	118	56	55	142
July	50	68	116	53	58	152
August	53	53	128	56	36	163
September	65	39	138	73	28	283
October	67	41	168	77	28	130
November	72	39	175	78	32	176
December	72	56	159	71	46	196

We notice that the air is much dryer than the mean in each instance of maximum evaporation, and the wind a good deal stronger in nearly every instance. But, singularly, the air, which under assigned conditions as to the total quantity of contained moisture,

would have a temperature curve vibrating in opposite phases to that of the humidity curve; and might therefore be antecedently expected to show high temperature numbers, shows no very great departure from the mean.

Such a fact is worth looking into somewhat more closely. So let us take in turn the highest mean temperature of the day during each month, the lowest mean humidity, and the greatest daily wind movement (each is obtained from hourly observations), and compare them separately with the respective evaporation on the same day from the different gauges. The results, in positive departures from the mean, are given below:—

	Temp. Excess.	8-inch Copper Pan.	Screened Tub.	Tank.	Piche Tube.
1900	°	Inches.	Inches.	Inches.	Inches.
January*	+ 5	+ .147	+ .121	+ .129	+ .033
January	+ 5	+ .127	+ .071	+ .083	+ .103
February	+ 6	+ .038	+ .030	— .018	+ .032
March	+ 4	+ .065	.000	+ .025	+ .060
April	+ 9	+ .112	+ .063	+ .053	+ .064
May	+ 5	+ .005	+ .001	+ .007	+ .005
June	+ 9	+ .035	+ .032	+ .012	+ .059
July	+ 9	+ .055	+ .047	+ .017	+ .091
August	+ 8	— .023	— .036	— .040	— .005
September	+ 11	+ .056	+ .072	— .001	+ .114
October	+ 11	+ .097	+ .070	+ .002	+ .107
November	+ 7	+ .164	+ .128	+ .064	+ .125
December	+ 6	+ .019	— .022	+ .013	— .026

	Humidity Excess.	8-inch Copper Pan.	Screened Tub.	Tank.	Piche Tube.
1900	%	Inches.	Inches.	Inches.	Inches.
January	— 20	+ .147	+ .071	+ .044	+ .153
February	— 17	+ .158	+ .140	+ .057	+ .152
March	— 21	+ .155	+ .090	+ .079	+ .120
April	— 15	+ .112	+ .063	+ .053	+ .074
May	— 9	+ .035	+ .021	— .002	+ .045
June	— 14	+ .045	+ .032	+ .016	+ .089
July	— 19	+ .065	+ .027	+ .012	+ .111
August	— 17	+ .117	+ .064	+ .069	+ .105
September	— 11	+ .156	+ .152	+ .097	+ .174
October	— 13	+ .157	+ .140	+ .111	+ .147
November	— 14	+ .074	+ .098	+ .083	+ .135
December	— 22	+ .179	+ .128	+ .102	+ .144

* There chanced to be two days in January each with the highest mean temperature of the day for the month.

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	Wind Excess.	8-inch Copper Pan.	Screened Tub.	Tank.	Piche Tube.
1900	M. per day.	Inches.	Inches.	Inches.	Inches.
January	+ 80	+ .067	+ .071	+ .017	+ .023
February	+ 113	— .102	+ .010	— .043	+ .012
March	+ 113	— .055	— .050	— .030	+ .020
April	+ 50	+ .022	— .013	— .005	+ .034
May	+ 95	— .005	— .019	— .008	+ .005
June	+ 71	+ .025	+ .002	+ .008	+ .059
July	+ 77	+ .065	+ .017	+ .027	+ .091
August	+ 198	+ .067	+ .044	+ .035	+ .105
September	+ 145	+ .156	+ .152	+ .097	+ .174
October	+ 229	— .023	+ .020	— .019	+ .067
November	+ 93	— .246	— .222	— .152	— .235
December	+ 89	+ .069	+ .078	+ .006	+ .024

That is, if we average the monthly numbers :—

1. When the mean temperature of the day rises 7°·3 above the monthly mean, the respective increases of evaporation are :—

	Inches.
8-inch Copper pan	+ .069
Screened Tub	+ .044
Tank	+ .027
Piche Tube	+ .059

2. When the mean humidity of the day falls below the mean of the month by 16 per cent. the respective increases of evaporation are :—

	Inches.
8-inch Copper pan	+ .117
Screened Tub	+ .086
Tank	+ .060
Piche Tube	+ .121

3. When the velocity of the wind for the day rises above the mean daily velocity for the month by 113 miles per day, the respective increases of evaporation are :—

	Inches.
8-inch Copper pan	+ .003
Screened Tub	+ .007
Tank	— .006
Piche Tube	+ .032

These conclusions are not altogether satisfactory. The second would seem rational enough ; but the numbers suggest that the first is merely a sort of undercurrent of the second. And a hasty inference from the third would be that the wind has no effect at all upon the rate of evaporation, which, of course, is not in agreement with what all reason and observation have assented to for many

years. As a matter of fact it happens that a very large proportion of our very windy days are also damper than usual: seven of the twelve of the days considered of maximum wind-velocity being also showery; and the humidity of one being as much as 37 per cent. above the mean of the month; the average excess very nearly 5 per cent.

It must not be forgotten that the above results are derived from the extreme cases. If we consider every day in the year 1900, for the tank only, we may arrange the results in the following way:—

1. First, assigned mean temperatures of the day; next, how many days there were of these; lastly, the average evaporation on these days:—

Temperature.	No. of Days.	Average Evaporation.
		Inches.
Under 50°	52	·057
50–55	25	·082
55–60	42	·098
60–65	56	·108
65–70	51	·156
70–75	78	·202
75–80	56	·268
80–85	5	·264

2. The same process for assigned percentages of saturation:—

Humidity.	No. of Days.	Average Evaporation.
		Inches.
Under 30 %	8	·296
30–40	75	·236
40–50	79	·185
50–60	88	·122
60–70	54	·101
70–80	42	·077
80–100	19	·057

3. The same process for assigned velocity of the wind:—

Wind.	No. of Days.	Average Evaporation.
		Inches.
Less than 100 m. per d.	126	·103
100–150 „	116	·160
More than 150 „	123	·191

Hence the rate of evaporation increases while the temperature rises, while the humidity ratio decreases, and while the wind increases in velocity. The temperature numbers make no very symmetrical curve, but the humidity numbers, within the observed limits, fall pretty evenly upon the parabola

$$(100 - H)^2 = 20,000 (E - e)$$

where E is the total amount of evaporation from the tank when the observed mean humidity of the day is H ; * e being the average evaporation when the mean humidity of the day is between 80 and 100 per cent. That is, since e is not very great, the depth of water evaporated will vary approximately as the square of the number representing the dryness of the air. Also the rate of evaporation and the velocity of the wind increase together, and in pretty much the same ratio. This last, however, is quite an accidental result, and owes its existence perhaps more to the fact that during the most humid months of the year—*i.e.*, April, May, and June—the wind is lightest, whereas the air is driest—in October, November, and December—when the strongest winds occur.

It would appear that the station is too sheltered to allow the wind to exert its maximum influence upon gauges on or near the ground. Indeed, if we consider all the observed daily amounts of evaporation occurring in a moderately dry air, say for mean daily humidity ratios lying between 30 and 40 per cent., during the year 1900, in all 75 occasions, we get 36 days with a wind-velocity below 140 miles per day,† and a concomitant average evaporation of .234 inch per day; and 39 days with a wind-velocity greater than 140 miles per day, and a concomitant average evaporation of .239 inch per day. There were, moreover, eleven of these occasions when the wind-velocity was less than 100 miles per day, and the average evaporation about one-fifth of an inch; and eleven other occasions when the wind-velocity was greater than 200 miles per day, and the average evaporation about one-quarter of an inch per day. Thus the Kenilworth experiments upon evaporation are not definite enough to reveal a wind factor anything like so influential as might have been anticipated, or at any rate to isolate it from amidst the variety of other contributing agencies.

Returning again to the question of the dryness of the air, we get the following average quantities of evaporation for assigned moisture conditions, from the pan, the tub, and the Piche gauge respectively:—

* Computed by the aid of the Greenwich factors.

† As recorded by a Robinson anemometer whose cups are 45 feet above the ground.

Humidity.	No. of Days.	8-inch Copper Pan.	Screened Tub.	Piche Tube.
		Inches.	Inches.	Inches.
Under 30 %	8	·515	·403	·49
30-40	75	·400	·291	·37
40-50	79	·303	·203	·27
50-60	88	·205	·134	·20
60-70	54	·160	·104	·14
70-80	42	·114	·069	·10
80-100	19	·053	·036	·05

The above formula applies to these results fairly well also, the numerical coefficient becoming respectively 10,500, 14,000, and 11,000 approximately. But the value of e is uncertain in the pan results because the evaporation from that source is greatly interfered with by rain when the air is very damp. It should be remarked also that while the humidity refers to the mean of hourly observations taken during the civil day, and the tank evaporation to civil day totals, the evaporation from the other gauges is measured at XX., and therefore the day begins four hours earlier for the latter than for the humidity.

In comparing the evaporation from the tank with the temperature of the air it has been tacitly assumed that the temperature of the water would follow that of the air pretty closely, and hence that for the one given we could roughly read the other. Now it was Symons's contention that a small gauge becoming heated to a very much greater degree by the sun's rays, thereby, for that chief reason, lost more than a large gauge. Hitherto I have not been able to make regular routine observations of the temperature of the water in my several gauges; but the following table giving some casual measurements during the winter and spring of 1901 has some points of interest. It contains (1) the hour of observation, (2) the temperature of the tank, (3) of the screened tub, (4) of a number of 5-inch copper pans, and (5) of the air:—

Hour.	Tank.	Screened Tub.	Copper Pans. Mean.	Air.
XXI.	55·4°	58·5°	—	—
XI.	57·2	51·4	60·9°	69·2°
XXIII.	51·8	53·9	48·5	50·0
XI.	55·5	46·2	54·2	57·0
XXIII.	55·0	58·4	54·8	53·0
XI.	60·6	55·6	64·4	70·3
XI.	65·4	64·8	74·8	82·0 (Strong Wind)
XI.	58·8	47·9	55·2	56·1
XI.	67·2	57·5	68·6	68·0
XXII.	70·8	68·6	—	65·4 (Cloudy)
XXIII.	69·0	66·5	—	60·0 (Do.)

With the exception of the last two rows all the observations were taken when the sky was clear. It will be seen that the tendency is for the tank to cool faster than the screened tub during the night, and to become warm much more quickly by day. We should expect then that the tank would lose more by day and less by night than the tub, and should not be blessed. The following are some comparative means and totals by night (XX.-VIII.) and by day (VIII.-XX.), during the year 1900.

	Night.	Day.
Air Temperature	56.7°	72.0°
Wind-Velocity, m. per h.	4.4	6.5
Humidity %	64.2	42.8
Tank Evaporation, inches	19.6	35.6
Screened Tub do do	21.1	40.9
Piche Tube do do	22.7	60.1
Tank Evaporation ratio	35.5	64.5
Screen Tub do do	34.1	65.9
Piche Tube do do	27.5	72.5

Thus, while the tank did lose a little less than the tub by night, it lost a great deal less by day, the ratios taking the relative positions they would take if temperature instead of accelerating actually retarded evaporation. The rapid evaporation from the Piche Tube during the day is remarkable, considering that it is suspended in the shade. No observations of its temperature are available, but in virtue of its slender stem this is not likely to depart greatly from that of the air. Various tests suggest, if they do not prove, that this instrument is the most susceptible of all to the strength of the wind.

So far as the experiments made during 1900 go, they seem to justify at the most the following conclusions: (1) The most potent agency regulating the rate of evaporation from the different gauges was the humidity of the air; (2) A wind factor is suggested; (3) The great perturbing influence attributed to the temperature of the water has not been exactly confirmed. The same experiments do not, therefore, furnish sufficiently precise data out of which a general evaporation formula, with accurate indices and coefficients, could be constructed.* The main difficulty lies in the fact that it is in general

* Even if it were sought, which is not my object. Professor Abbe quotes approvingly the formula proposed by D. FitzGerald:—

$$E = 0.0166 (V - v) (1 + \frac{1}{2}W),$$

in which V is the vapour pressure in inches at the temperature of the water, v the vapour pressure at the temperature of the dew-point, and W the velocity of the wind. (See *Meteorological Apparatus and Methods*, 1888, p. 377.)

not possible to vary either of the conditions without introducing variations into the others. As Tyndall truly remarked, "the essence of good experimenting consists in the exclusion of circumstances which would render the pure and simple questions which we intend to put to Nature, impure and composite ones;"* and for an illustration we have the case cited above of the rate of evaporation varying in its annual march with the velocity of the wind—the latter, as it will be remembered, also varying with the annual variation in the dryness of the air. No doubt the complexity of the meteorological law governing the rate of evaporation from a water surface must be accounted responsible for the illusory shape it has assumed in the hands of some theorists.

Occasional experimentalists have resorted to laboratory practice in order to surmount some of the inherent difficulties of the native problem. A typical instance may be quoted: "In my first experiments out of doors," says Mr. J. R. Mann, "I found that the amount of error in measuring the small variations of short periods prevented me obtaining any accurate idea of the fluctuations, in the amount of evaporation, that followed the constant and incessant alteration in the state of the atmosphere and the temperature of the water. I therefore looked to artificial means for obtaining a greater amount of evaporation under more fixed conditions; and having obtained some certain basis, I endeavoured therefrom to devise a rule by which the amount of evaporation going on under natural conditions might be arrived at. After many failures, I adopted an arrangement which I think gave satisfactory results. An ordinary evaporating vessel, about 8 inches in diameter and $1\frac{1}{4}$ inches deep, containing a measured quantity of water, was floated in a larger vessel of water; the large vessel was placed upon an ordinary gas stove, which gave the means of regulating the heat in the water contained in the evaporating vessel to a considerable nicety, and of retaining it for a length of time at one degree of temperature."† It is at the least to the credit of the gas stove that with a water temperature of 192° , an air temperature of 65° , and a humidity ratio

* *Heat a Mode of Motion.* Lecture xiii.

† *Proceedings of the Meteorological Society*, vol. v., 1871. Mann gives the following formula:—

$$(4666 E)^2 = G^2 T \left\{ 1 - \left(\frac{e}{e_1} \right)^{.25} \right\}$$

In which E is the depth evaporated in inches per hour, G the weight in grains of a cubic foot of vapour due to the temperature of the water, T the absolute temperature of the evaporating surface, e the elastic force of the vapour in the air in inches, and e_1 the elastic force of vapour due to the water temperature.

of 94%, it was able to "evaporate" more than three-quarters of an inch in depth per hour!

Nearly two centuries before, however, the immortal Halley had attempted in much the same way to acquire "one of the most necessary ingredients of a real and philosophical meteorology," namely a knowledge of the quantity of water passing into the atmosphere in the form of vapour. "I thought it might not be unacceptable," he said, "to attempt by experiment to determine the quantity of the evaporations of water, so far as they arise from heat; which, upon trial, succeeded as follows: We took a pan of water, about 4 inches deep and 7·9 inches diameter, in which was placed a thermometer, and by means of a pan of coals we brought the water to the same degree of heat which is observed to be that of the air in our hottest summers, the thermometer nicely showing it. This done we affixed the pan of water, with the thermometer in it, to one end of a beam of the scales, and exactly counterpoised it with weights in the other scale, and by the application or removal of the pan of coals we found it very easy to maintain the water in the same degree of heat precisely. Doing thus we found the weight of the water sensibly to decrease;" the final result being that at summer temperatures the loss by evaporation was "a skin of water" of a depth equal to 0·1 inch in twelve hours.*

But a fatal defect in all such laboratory methods is that they do not apply to any meteorological problem: their application is strictly limited to a determination of the number of units of heat it is necessary to *apply* to a given volume of water in order to evaporate a given portion of it, and so forth. Almost invariably the heat is communicated from beneath, and the whole body of water experimented upon must be, in consequence, at nearly the same temperature throughout. Hence each successive surface stratum will be driven off as vapour without appreciably cooling that next below. Under natural conditions of exposure, however, the changes of temperature are communicated from above, and there may be great differences of temperature at different depths of the body of water.†

* *Phil. Trans.*, xvi., 1687. "An estimate of the quantity of vapour raised out of the sea by the warmth of the sun; derived from an experiment shown before the Royal Society." I have ventured to translate the given fractions into decimals.

† This fact has been known for more than a century. See *inter alia*, "Of the Saltness and Temperature of the Sea," by Bishop Watson, in his charming *Chemical Essays*, 1781. "On Dr. Hales's Ventilators; also the Temperature and Saltness of the Sea." H. Ellis. *Phil. Trans.*, xlvii., 1751. *Our Earth and its Story*, i., 331. R. Brown, 1887. "Lakes." J. Y. Buchanan, *Ency. Brit.*, xiv. Ellis was captain of the ship *Earl of Halifax*, and is to be considered happy in having made it particularly wholesome and comfortable. His paper is interesting

De Saussure found the surface of some of the Swiss lakes more than 30° warmer, in summer, than the bottom. Symons mentions occasional differences of 10° to 15° between the surface and bottom of the Strathfield Turgiss tank in June and July—the warmer water being at the top of course. Therefore, in the daytime at any rate, the temperature of the surface has not only to assist in the process of evaporation, but it has also to assist in raising the temperature of the next lower stratum. So that it is not at all evident (has any one ever attempted to prove?) that a body of water heated from below will lose the same quantity by evaporation, so-called, as another equal body heated naturally from above, even though the surface temperatures be the same. There is another consideration: In heating the water from below, the heat of the stove, or of the sides of the vessel, will generate an upcast of warmer air whose humidity ratio will not be that of the air outside the laboratory, but something much less; consequently the readings of the dry and wet bulbs, meteorologically speaking, do not matter. These remarks refer more particularly to the experiments described in the few original papers on the subject it has been my good (or evil) fortune to have seen.

Halley has described the results of an experiment upon the rate of evaporation in which the water was allowed to evaporate without first being artificially heated. Unfortunately the results are scarcely more than a laboratory product, for the gauge was shielded from both sun and wind. His conclusions, nevertheless, were, as usual, pre-eminently sagacious: "I caused an experiment to be made," says the note, "of the quantity of vapour arising simply from the warmth of the water, without being exposed either to sun or wind, which has been performed with great care and accuracy by Mr. Hunt, operator to the Society: having added together the evaporations of the whole year, I find that from a surface, as near as could be measured, of 8 square inches there evaporated during the year 16,292 grains of water, which is 64 cube inches of water, and that divided by 8 inches, the area of the water surface, shows that the depth of water evaporated in one year amounts to 8 inches. But this is much too little to answer to the experiments of the French, who found that it rained

in these days of refrigerating machinery. He made several trials with a bucket sea-gauge in lat. $25^{\circ} 13' N.$, long. $25^{\circ} 12' W.$, letting it down to different depths from 360 to 5,346 feet. He discovered by means of a small thermometer of Fahrenheit, which went down with it, that the cold increased regularly, in proportion to the depths, to 3,900 feet, where the temperature was 53° or a little less; the temperature of the air and of the ocean-surface being 84° . It is remarked that the experiments, "which seemed at first but mere food for curiosity," afterwards proved very useful. By its means they supplied their cold bath, and cooled their wines and water at pleasure—"which was vastly agreeable in that burning climate."

19 inches of water in a year at Paris; or those of Mr. Townley, who by a long-continued series of observations has sufficiently proved that in Lancashire, at the foot of the hills, there falls about 40 inches of water in a year. Whence it is very obvious that the sun and the wind are much more the causes of evaporation than any internal heat or agitation of the water. The same observations also show an odd quality in the vapours of water, which is that of adhering to the surface that exhaled them, which they clothe, as it were, with a fleece of vaporous air, which once investing it the vapour rises afterwards in much less quantity: which was showed by the small quantity of water that was lost in 24 hours' time, when the air was very still from wind in proportion to what went off when there blew a strong gale, although the experiment was made, as I said, in a place as close from the wind as could well be contrived. For which reason I do not at all doubt that had the experiment been made where the wind had come freely it would have carried away at least three times as much as we found, without the assistance of the sun, which might perhaps have doubled it." *

A few years ago I contemplated a series of experiments upon the variations in the rate of evaporation from a given water surface, under natural conditions of exposure, where any one factor was to be caused to vary at will, while the others remained unaffected. But a satisfactory method of treating the humidity factor independently has not hitherto suggested itself; and the site of the station would have made an inquiry into the effect of the wind to a large extent futile. Wherefore the scheme eventually narrowed itself to a consideration only of the effect of the varying temperature of the water. After a fair share of false starts, and a reasonable number of unconvincing results, I managed in the winter of 1896 to devise the following plan of varying the water temperature without altering the other elements:—

The gauges were ordinary tin mugs of approximately $4\frac{1}{2}$ inches in diameter, enamelled a very light green (almost white) inside and out. They were placed on and between bricks just above the ground. They were covered by glass plates one-sixteenth of an

* "Account of the Evaporation of Water, as Experimented in Gresham College, &c." *Phil. Trans.*, xviii. Though only bearing indirectly upon the subject of the text, some of Halley's concluding remarks are worth quoting: "This fleece of vapour in still weather hanging on the surface of the water is the occasion of very strange appearances by the refraction of the said vapours differing from that of the common air. . . . And this may give a tolerable account of what I have heard of seeing the cattle at high water-time in the Isle of Dogs from Greenwich, when none are to be seen at low-water (which some have endeavoured to explain by supposing the Isle of Dogs to have been lifted by the tide coming under it)."

inch thick, of different colours, placed horizontally about one inch above the rims of the mugs, and large enough to prevent any sunlight reaching the water without having first passed through the glass. The sides of the mugs were also protected by bricks from the rays of the sun. The measures were taken with a graduated glass belonging to an 8-inch rain-gauge, the measures being multiplied by 3·55 to give the true loss in inches. The results were also verified by weighing. The temperatures of the waters were determined nearly every day at XVII. and sometimes at XIV. by means of a standard Kew-certified thermometer. The following were the results for the period July 20 to November 22, 1896—125 days:—

1. *July 20 to August 30, 1896.*

Colour.	Mean Temp. at XIV.	Mean Temp. at XVII.	Total Evap.
	°	°	Inches.
Red	72·8	65·4	6·01
Yellow	72·3	64·8	6·19
Green	69·6	64·1	5·59
Blue	70·8	64·3	6·17
Purple	72·2	64·8	6·27

2. *August 31 to November 7, 1896.*

Colour.	Mean Temp. at XVII.	Total Evap.
	°	Inches.
Red	77·7	20·21
Yellow	77·8	20·12
Green	77·0	18·76
Blue	77·8	19·97
Purple	77·6	20·38

3. *November 8 to 22, 1896.*

Colour.	Mean Temp. at XVII.	Total Evap.
	°	Inches.
Red	81·8	4·29
Yellow	81·6	4·22
Green	81·1	4·14
Blue	82·0	4·05
Purple	81·5	4·30

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4. July 20 to November 22, 1896.

Colour.	Mean Temp. at XVII.	Total Evap.
	"	Inches.
Red	72·3	30·52
Yellow	72·3	30·53
Green	71·5	28·49
Blue	72·1	30·19
Purple	72·2	30·95

During the same period the 8-inch copper pan open to the sky lost 30·69 inches.

Considering the roughness of the tools some considerable discrepancies in the sequence of the results could only be expected. Now at 5 p.m. air and water are cooling rapidly, so that the temperatures given for that hour are of limited usefulness in comparison with the total evaporation for the day. But in the first set we have some temperatures at 2 p.m., at which time air and water are both near their maximum. Now the net result of the first set is approximately a loss of about three-quarters of an inch in 41 days for an excess of temperature of about $2\frac{1}{2}^{\circ}$. Also if we take the temperature variation between the different colours to be about the same throughout the year, we get a loss of about $2\frac{1}{4}$ inches in 125 days for the same excess of temperature. Or, taking ratios, a mean loss of about $2\frac{1}{4}$ inches per annum for each excess of 1° of temperature. As between a copper 5-inch gauge standing in water, and therefore in a relatively humid atmosphere, and another fully exposed to the air, Latham's results give an increase of evaporation which may not differ greatly from 9 inches per annum for each excess of mean temperature of 2° ; or taking only the high temperatures of the middle of the day about 9 inches per annum for an excess of maximum temperature of about $5\frac{1}{2}^{\circ}$. Under all the circumstances this is not greatly different from the numbers derived from the use of coloured glass; although it must be admitted that the true temperature effect is not obvious from Latham's work.

During the progress of my experiment it was not expected that it should do more than furnish experience for a better future test. It seemed to be settled, at least, that it was possible to expose any number of gauges in an absolutely identical manner excepting that the one element of temperature could be easily varied at pleasure. Accordingly some better vessels were procured, and some thicker and better glass; and the subject re-examined under improved conditions, during the second half of 1897. In the following series of

observations, from July 5 to November 21, 1897, the gauges used were unpainted copper pans, 5 inches in diameter and 5 inches deep, with turned brass rims, by Messrs. Negretti and Zambra. They were fixed in a wooden frame and floated about 3 feet above the ground in a tank of 3 feet cube, so that the gauges dipped about $3\frac{1}{2}$ inches into the water with which the tank was kept nearly full. The plates of coloured glass covering them were 10 inches square and one-eighth of an inch thick. The five gauges were retained in the same relative position throughout, but the glass plates were permuted after each fortnightly determination of the loss. Water—rain-water—was added to the gauges as required during each fortnight, so as to keep the evaporating-level as near to the edge of the rim as safety would allow. There was a clear vertical space of about an inch between the gauge-rims and the glass plates, to allow the exhaled vapour to pass off. Temperatures were taken at intervals, as before, at XIV. and XVII., preferably on clear days.

The following tests of the absorptive properties of the glass plates will perhaps give the best idea of them :—

Col. 1 gives the colours.

Cols. 2 and 3 the relative absorptions of light, as determined by a wedge photometer, received from the sky in the vicinity of, and opposite to, the sun respectively.

Cols. 4 and 5, the temperatures shown by Board of Trade thermometers, the thermometers being about 1 inch underneath, and touching the glass underneath respectively.

Cols. 6 and 7, the colours transmitted, as determined by a direct-vision spectroscope, from the sun and from the sky.

Col.	LIGHT.		TEMPERATURE.		SPECTRA.	
	Near sun.	Opposite sun.	Under glass.	Touching glass.	Sun.	Sky.
P.	5.76	5.41	97.2	104.3	V', B', G', Y', R'	V', B', G', Y', R'
B.	5.72	5.09	98.9	109.3	B ² , G ² , Y ²	B ² , G ²
G.	5.58	4.50	96.3	111.0	V', B', G', Y', R ²	V ² , B ² , G', Y ² , R ²
Y.	5.69	4.82	98.4	108.4	V', B', G ² , Y', R ²	G', Y', R ²
R.	4.34	3.82	98.0	108.7	V ² , B ² , G ² , Y ² , R ²	Y ² , R'

All the above values are means derived from a number of observations. I was not lucky enough, however, to get calm days for the temperature observations, so that wind has probably somewhat vitiated the numbers. The temperature shown by a thermometer touching the red glass underneath has sometimes been higher and

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sometimes lower than that touching the yellow, the differences being considerable. One whole series gave the red invariably lower, the mean defect being 1.3° .

The evaporation results for the first ten weeks are (A) :—

Colour.	Mean Temperature at XVII.	Total Evaporation.
	°	Inches.
Purple	59.14	7.695
Blue	59.08	7.335
Green	59.00	7.115
Yellow	59.08	7.265
Red	59.06	7.690
Tank	58.32	—
Air	64.88	—

And for the second ten weeks (B) :—

Colour.	Mean Temperature at XIV.	Mean Temperature at XVII.	Mean Temperature XIV. and XVII.	Total Evaporation.
	°	°	°	Inches.
Purple	76.08	70.08	73.08	12.955
Blue	75.22	70.18	72.70	12.880
Green	74.08	69.72	71.90	12.480
Yellow	74.80	69.64	72.22	12.530
Red	75.54	69.82	72.68	12.885
Tank	71.52	69.56	70.54	—
Air	81.54	79.50	80.52	—

It is curious that in each of these ten-week periods the gauges stand in the same order with regard to the water evaporated, *i.e.*, beginning with that losing the least :—

Nos. II., IV., V., III., I.

The mean of the noted temperatures at XVII. is not, however, in the same order ; the first rising sequence being :—

Nos. III., I., II., V., IV.,

and the second :—

I., III., II., V., IV.

which is, notwithstanding, a remarkably similar pair. But both the evaporation and temperature arrays are doubtless accidental, although it is not unlikely that the former may be contributed to by some small differences in the sizes of the gauges, more particularly

below the brass rims ; for in spite of close attention the water level sometimes did sink below the rims.

In both (A) and (B) the depth of water evaporated occupies the same order relatively to the colours, albeit the ratios are not quite identical. The temperatures of (A) do not greatly differ, *inter se*, and seem to indicate that at XVII. they are falling to a nocturnal equality with that of the tank. In (B) we see that the greatest difference at XIV. is between the green and purple, and is exactly 2° . It is not likely that the mean difference would be much greater than this at any hour. We get, then, for a maximum increase of 2° of temperature an increase of evaporation in ten weeks of about half an inch, or, say, $2\frac{1}{2}$ to 3 inches per annum. This is in fair accordance with the previous result, considering the circumstances ; and it is also not antagonistic to Latham's, in which, however, it happened that the gauge which was coolest by day was also warmest by night. On the other hand the Camden Square results work out one to a rate of increase of nearly 13 inches per annum for an increase of 2° of temperature, the other to a rate of increase of nearly 24 inches for an increase of 5° .

A further test was attempted in which the gauges should stand in air instead of water, and the temperatures should be taken at XI. instead of later in the day. The gauges were placed on a board nearly 5 feet above the ground, and their sides were sheltered from the sun's rays. The glass plates were fixed a little higher—about two inches—above the gauge-rims for the sake of variety. These were kept in the same place, the gauges being permuted this time. The experiment lasted from July 14 to September 21, 1901—seventy days. There were earlier observations beginning early in May, but as a slight leak was developed in one of the gauges, it was thought best to begin again after making the necessary repairs. The results are:—

Colour.	Mean Temp. at XI.	Total Evap.
	$^{\circ}$	Inches.
Purple	62.8	10.08
Blue	61.9	9.78
Green.....	60.1	9.32
Yellow	61.8	9.73
Red	63.0	9.83
Air	67.2	—

The net result here, again, is an increase of evaporation of about $2\frac{1}{2}$ inches per annum for an excess of temperature of about 2° .

If we remember that in consequence of the absorption of heat by the green glass, the water-temperature will rise somewhat faster under the less absorptive colours, this result is practically a repetition of the former. Thus, in three different ways, in an excellent spot for receiving the maximum of insolation, and the greatest consequent heating of a gauge, we deduce an increased rate of evaporation due to overheating that looks ridiculously small by the side of some of the magnitudes advocated. It should be noted that observations of the temperatures at night, and very soon after sunrise, proved the temperatures of all the gauges to be equal, and almost uniformly that of the air. We may then enunciate this rule: *If the water-surfaces of a number of similar and similarly-situated evaporation gauges remain at a temperature in the shade the same for all, then if when fully exposed to the sun's rays, under the same elements of climate, they assume different maximum temperatures, the differences in the depth of water evaporated will be at the rate of $1\frac{1}{2}$ inches per annum for each excess of 1° of temperature (approximately).*

The care with which the tests were carried out, and the congruence of the different sets all go to warrant some present confidence in the accuracy of this rule within the limits of meteorological requirements. Some day I may be able to take the subject up again.