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WET BULB TEMPERATURES - A COMPARISON BETWEEN READINGS FROM CLEAN AND DIRTY INSTRUMENTS

by

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Wet bulb temperatures - a comparison between readings from clean and dirty instruments

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Wet bulb temperatures - a comparison between readings

from clean and dirty instruments

1. Introduction

Proposals to mount instruments on tall masts, 1000 ft or more in height, to give more detailed information about the lower atmosphere provide for measurements of temperature and humidity at several levels. The measurements are to be made using electrical resistance thermometers mounted as wet and dry bulb pairs at each level in screens similar to the standard marine type, single louvered, Stevenson screen. Thus in order to reduce the amount of maintenance required, it is necessary to decide how long the muslin and wick can be left unchanged, without introducing into the readings unacceptable errors, due to atmospheric pollution of all sorts affecting the wet bulb system and inhibiting its depression.

Measurements made by Lawrence (1, 2), suggest a variation of atmospheric pollution with height, the level of maximum concentration being related to the height of pollution sources (e.g. chimneys) in the area. The measurements were made, not in the free atmosphere, but near the ground at sites up a steeply sloping hillside; the results, nevertheless, may be significant close to sources of pollution and in hilly districts where the level of maximum concentration may depend on the height of hills between the source and the site of the measuring instruments.

Lawrence also found a seasonal change in the vertical distribution of atmospheric pollution, the pollution in winter being approximately twice that measured in summer at heights up to about 1200 ft above msl, (about 700 ft above valley level).

Another result reported by Lawrence is the direct dependence of accumulated pollution on the run-of-wind. The flow of air through a screen, especially a single louvered screen, at heights up to several hundreds of feet above ground level is likely to be significantly different, in the mean, from the flow of air through a standard Stevenson screen housing instruments at four feet above the ground. Consequently the dirtying of a wet-bulb muslin and wick at a hundred or more feet above ground level may proceed much faster than at the ground.

It follows that the length of time a wet bulb muslin and wick may reasonably be left unchanged, depends on the height of the instrument above the ground and the effectiveness of the sheltering screen in regulating the flow of air past the thermometer bulb. Other important factors are the surrounding topography and pollution sources, season of the year, direction and speed of the mean wind, and also significant departures from the mean on particular occasions. Lawrence's measurements were made at Helmshore, in a hilly district away from the sea in Lancashire, at a rural site almost encircled by industrial areas of Lancashire and the West Riding of Yorkshire. His results, therefore, may not be valid in coastal regions, where, with winds off the sea, the pollution is different and the source is at the surface; nor may they be entirely valid in relatively flat inland areas. The required answer may be obtained ideally, only by testing at each observing level at each mast site, but significant information would be obtained from experiments on, say, the 120 ft mast at Cardington.

In the absence of data from masts, and because the method was simple and easy to organise, tests were arranged with instruments exposed at the standard height of four feet in Stevenson screens at ground level.

/Acceptable

Acceptable practice for ensuring a suitable standard of cleanliness, and hence of accuracy, of wet bulb thermometers exposed in Stevenson screens, is described in standard reference sources (3, 4). Most experimental work reported in the literature is concerned either with aspirated psychrometers, e.g. Best (5), or with other types of hygrometric instruments. Experiments to determine the rate and extent of the deterioration in efficiency of a wet bulb thermometer have been made by Sutcliffe (6), Garnett (7) and Durward (8), while other relevant experiments have been described by Whipple (9, 10) and in the Meteorological Magazine (11). The experiment described below extends such work to a number of varied locations, including rural, semi-rural and urban areas, coastal areas and ships at sea.

2. Nature of the experiment and stations participating

At each station a second wet bulb thermometer was suspended from the roof of the Stevenson screen, closely alongside the standard wet bulb instrument, which was maintained in the usual way and referred to as the clean wet bulb (C). Once the second wet bulb thermometer was mounted in the screen, the muslin and wick were left unchanged throughout the course of the experiment, the thermometer being referred to as the dirty wet bulb (D). In this context "dirty" includes the effect on the muslin and wick of all forms of atmospheric pollution or contamination and is used in the same sense as "dirty or contaminated" on page 163 of the Handbook of Meteorological Instruments Part I (3). The experiment commenced at Bracknell on 8th January, 1964 and was soon extended to Kew where readings began on 5th February. At Bracknell readings were recorded at 0900 GMT on five days each week; at Kew readings were recorded daily at 0900 GMT, and on most days, at 1200 and 1500 GMT as well.

After nearly eleven weeks at Bracknell and seven weeks at Kew, during which time only occasional differences of 0.1°C, and very occasional differences of 0.2° or 0.3°C were observed between the two wet bulb readings, it was decided that the results justified extending the experiment to include records from areas where the effects of industrial and urban pollution might be greater than at Kew, and also to examine the effects of proximity to the sea. With the co-operation of Met.O.6., Met.O.7., and Met.O.14., the stations listed below were selected to participate in the experiment, most of them commencing the comparison of readings early in April, 1964.

Participating Stations

Bracknell	(initial pilot experiment)
Kew	(initial urban area station)
Eskdalemuir	(clean air station)
Birmingham Airport	(urban/industrial area station)
London Weather Centre (LWC)	(" " " ")
Manchester Weather Centre (MWC)	(" " " ")
Acklington	(coastal or near coastal station)
Benbecula	(" " " ")
Leuchars	(" " " ")
Mount Batten	(" " " ")
Valley	(" " " ")
Wick	(" " " ")

/At

At this stage Met.O.1 were informed of the proposal to extend the experiment to the additional stations listed above and their co-operation was invited. As a result, arrangements were made for two of the Ocean Weather Ships to take part, returns being received from OWS Weather Surveyor and OWS Weather Monitor covering voyages made between May and October, 1964.

Participating stations were asked to make returns of corrected temperature readings made at 0600 and 1500 GMT - times likely to be near periods of maximum and minimum relative humidity - and also at other times during the day if the difference, D - C, between readings of the dirty and clean wet bulb thermometers was greater than that recorded at either 0600 or 1500. Wind speed and direction were also listed and any relevant remarks. Readings were continued until 31st October, 1964. At Bracknell, after approximately six months, the dirty muslin and wick was replaced by a clean set on 1st July and a second series of readings was started. At Manchester Weather Centre a similar change was made on 8th July. At all the other land stations the muslin on the dirty wet bulb thermometer was left unchanged throughout the experiment.

Ocean Weather Ship Weather Surveyor made three voyages between May and September, 1964 with the same muslin and wick on the second wet bulb thermometer. The (portable) marine type Stevenson screen was removed inside during spells in harbour. A fourth voyage was made in September/October with new equipment and with clean muslins and wicks on both wet bulb instruments at the beginning of the voyage.

Ocean Weather Ship Weather Monitor also made four voyages between May and October. On this ship clean muslins and wicks were fitted at the beginning of all four voyages. New thermometers and screens were fitted for the fourth voyage.

3. Sources of error in psychrometry

The determination of humidity with a psychrometer depends on the measured air temperature and the temperature depression of the wet element. The uncertainty in the derived relative humidity (or dew point) is due principally to that in the temperature depression. For example, at 10°C, with a true depression of 5°C, a one degree error in dry bulb temperature leads to an error in relative humidity of about 2%, while a one degree error in temperature depression yields an error of about 12%. At the same dry bulb temperature, corresponding errors in dew point are approximately 1.5°C and 4°C, with errors in the depression of the dew point below the dry bulb reading - which is of importance to the forecaster - of 0.5°C and 4°C. The magnitude of the error in relative humidity, for a given error in depression of the wet bulb, increases with decrease in dry bulb temperature, the increase becoming marked at temperatures near and below 0°C. Thus, for a certain error in wet bulb depression the resulting error in relative humidity may be acceptable at dry bulb temperatures greater than a particular value, but not at temperatures lower than such a value. The results to be discussed contain very few readings of temperature near or below 0°C, but instruments mounted on masts up to 1000 ft or so in height will be exposed frequently to temperatures of this order during the winter. Table 1 shows the approximate change in relative humidity and in dew point for a change in the wet bulb temperature of 0.5°C at different dry bulb temperatures.

/Table 1

Table 1. Approximate change in relative humidity and in dew point when the wet bulb depression increases by 0.5°C

Dry bulb °C	Change in RH %	Change in Dew Point °C
20	4	1
15	5	1
10	6	1
5	8	2
0	10	2
-5	13	3
-10	18	4

Errors occurring in the temperature depression are of two kinds, those which are effectively equal to a constant fraction of the temperature depression and those which form a constant additive part of the depression. Errors of the first kind may be unimportant at high humidities while being serious at low humidities; errors of the second kind may be important at all humidities. The forecaster is most interested in accurate measurements of high humidities, though climatologists and others may wish for a similar accuracy at all values of humidity.

A detailed list of errors in psychrometry is given by Wylie (12). Those most likely to be significant in measurements made in Stevenson screens are due to:-

a. inadequacy or imperfection of the covering of the wet bulb and of the water supply to it.

b. the presence of substances which affect the vapour pressure over the water on the wet bulb.

c. variation of the assumed rate of ventilation (due to opening of the screen door and/or length of time it is left open).

d. the temperature of the wet bulb influencing that of the dry either by free or forced convection, or by radiation.

e. temperature gradients in the neighbourhood of the wet and dry elements.

f. a high rate of change of atmospheric conditions (involving the time lag of the thermometers).

The last two sources of error lead to errors of the second kind mentioned above, the others give rise to errors of the first kind.

The object of the experiment described in Section 2 was to discover the time taken for errors due to a. and b. above to become significant. The interpretation of the results is complicated by the presence of errors due to other causes.

/4.

4. Discussion of results

4.1. Readings during the first week

The instructions contained in the Observer's Handbook (4) and the Marine Observer's Handbook (13) suggest that it is permissable to leave a muslin and wick unchanged for one week (a fortnight in rural districts of the British Isles) unless there is reason to believe that the instrument is contaminated by, for example, heavy weather at sea with spray reaching the instrument, or a storm at coastal stations with on-shore winds. Table 2 below is made up from returns covering the first week of readings at each station and shows the range of the difference, D - C, between the corrected readings of the two wet bulb instruments. Since the effect of contamination is to reduce the depression of the wet bulb, the difference, D - C, should be positive and increase, after an initial period of zero differences, or small differences due to other errors.

From Table 2 it is seen that at most stations negative as well as positive differences were recorded; at Manchester Weather Centre, for example, during the first week of both runs, at all observations but one, the depression of the additional wet bulb thermometer was greater than that of the standard. Since at this station new muslins and wicks were fitted to both the standard and additional wet bulb thermometers at the beginning of the experiment, the negative differences cannot be explained on the grounds of the additional theromometer, with clean muslin and wick, being temporarily more efficient than the standard instrument, with a muslin polluted after several days use. At five other land stations clean muslins and wicks were fitted to both thermometers on the first day of the experiment. At the remaining stations, clean muslins were fitted to the standard instrument in accordance with normal station routine, but in no case could negative D - C values during the first few days be explained by assuming pollution to be affecting the efficiency of the standard wet bulb thermometer. The effects of changes of the muslin on the standard wet bulb thermometer during the week are further considered below.

Table 2 shows that minimum differences of $\pm 0.1^{\circ}C$ occurred at Bracknell, Kew, Eskdalemuir and Wick. An error of only this magnitude during the first week of the experiment is likely to be due to causes other than contamination of the wet bulb muslin, especially as at Kew and for both runs at Bracknell, the muslin on the standard wet bulb thermometer was left unchanged. At three more stations, Leuchars, Valley and Benbecula, differences during the first week ranged over $\pm 0.2^{\circ}C$. (This excludes one reading at Benbecula, giving a difference of $+0.4^{\circ}C$, because the additional wet bulb thermometer was recording $+0.2^{\circ}C$ above the dry bulb instrument - see section 4.3 below). All three stations are in coastal areas, but winds were mostly light or moderate and, at Leuchars and Valley, generally off the land. The probability of pollution due to salt deposits affecting the readings is therefore small.

/Table 2.

Table 2. Extreme D - C values °C for each station during first week of experiment

Station	Range of D - C, °C	Remarks
Bracknell(1)	-0.1 to 0.0	Three 0.0, two -0.1.
Bracknell(2)	-0.2 to 0.0	All differences but one, 0.0.
Kew	-0.1 to +0.1	Eight 0.0, one +0.1, two -0.1.
Eskdalemuir	-0.1 to 0.0	All differences but one, 0.0.
Birmingham Airport	-0.3 to +0.4	Difference of +0.4 on first day. All differences but one +ve.
LWC	-0.5 to +0.4	Difference of -0.5 on second day.
MWC(1)	-0.4 to -0.1	All differences -ve. First difference -0.1.
MWC(2)	-0.6 to +0.1	All differences but one -ve. First difference -0.3.
Acklington	-0.4 to 0.0	Winds light or moderate and mainly off the land. -0.2 on second day.
Benbecula	-0.2 to +0.2	First difference -0.2. One difference of +0.4 rejected - see text.
Leuchars	-0.1 to +0.2	Winds light or moderate and mainly off the land. +0.2 on third day.
Mount Batten	-0.2 to +0.5	Wind mainly moderate or fresh between NW and NE.
Valley	0.0 to +0.2	Wind moderate, occasionally fresh to strong, mostly off the land. +0.2 on 4th day.
Wick	0.0 to +0.1	Winds mainly moderate, occasionally off the sea.
Surveyor(1)	-0.8 to +0.2	+0.2 to -0.4 in first six days. -0.2 on first day. -0.4 on third day.
Surveyor(4)	-0.1 to +0.5	+0.1 at first reading. ±0.1 first four days.
Monitor(1)	-1.2 to +0.7	-0.3 at first reading. -1.2 on third day with gale force winds. First +ve reading of +0.4 on fourth day.
Monitor(2)	-0.4 to +0.2	-0.3 on second day.
Monitor(3)	-0.3 to +0.3	+0.3 on third day.
Monitor(4)	-0.1 to +1.6	+1.2 to -0.1 on first day. Strong to gale force winds.

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At Benbecula, the first reading after the additional wet bulb thermometer was mounted in the screen gave D - C equal to -0.2°C. At this time the muslin and wick on the standard wet bulb thermometer had been in use for about four days. Negative or zero differences were then logged until the muslin on the clean wet bulb was changed during the afternoon of the third day of the experiment. Differences then became positive between zero and +0.2°C until negative differences were logged again on the sixth day.

At Valley zero differences were recorded during the first three days. On the fourth day the muslin and wick of the standard wet bulb thermometer were changed. The first few readings taken thereafter gave D - C equal to +0.2°C, with a relative humidity higher than some of those previously recorded. Later readings, however, did not maintain a positive difference. At both Benbecula and Valley therefore it is not altogether certain that the change of about +0.2°C can be attributed solely to pollution effects. Alternatively, if this is the case, routine practice in the changing of wet bulb muslins at some coastal stations will permit errors in wet bulb temperatures of about +0.2°C.

The remaining stations listed in Table 2, excluding the returns from the weather ships, show D - C differences ranging over ±0.5°C. The stations are either near the sea, or in urban areas where smoke pollution may be high, but the differences noted above cannot be attributed entirely, if at all, to pollution effects. This is clear from the following considerations, which also rule out as a prime cause errors made by the observers in reading the thermometers.

a. A difference of +0.4°C was recorded at Birmingham on the first day of the experiment.

b. At London Weather Centre the difference varied from -0.5°C recorded on the second day, to +0.4°C on the fifth day, being negative on the second and third days, zero or +0.1°C on the first and fourth days, and positive on the fifth, sixth and seventh days. Relative humidity varied between 41% and 92%, but with no systematic relationship between it and the D - C difference. Table 3 shows some of the values of relative humidity occurring with various differences.

Table 3. Relative humidity at various D - C values during first week of the experiment at LWC

D - C °C	RH%	D - C °C	RH%
0.0	92	-0.1	54
0.0	61	-0.2	89
+0.1	44	-0.2	54
+0.1	90	-0.5	65
+0.2	41		
+0.2	68		
+0.3	86		
+0.4	48		

/c.

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c. At Manchester Weather Centre all the differences in the first experiment, and all but one in the second, were negative. A difference of $-0.4^{\circ}C$ was recorded on the fifth day of the first experiment. The first difference in the second experiment was $-0.3^{\circ}C$. These differences were associated with wide ranges of relative humidity, some of the largest negative differences occurring with relative humidities as low as 44%.

d. At Plymouth, during the first four days, differences ranged over $\pm 0.2^{\circ}C$. On the fifth day, the muslin and wick on the clean wet bulb thermometer were changed and the differences, now all positive, rose to $+0.4^{\circ}C$, with $+0.5^{\circ}C$ being recorded on the sixth day. The positive increase in D - C could be associated with effects due to contamination, made obvious after the change of muslin, but it is to be noted that winds during this period were mostly moderate, from between northwest and northeast, and consequently any contamination of the muslin is more likely to be due to smoke than to salt. (Saunders, (14) has described the exposure at Mount Batten, and sources of smoke pollution, in a paper on diurnal variation of visibility). Readings taken after the first week, discussed in the following sections, also indicate that if the increase in D - C is due to pollution, then the effects are very complex.

e. At Acklington, differences during the first week were all negative except during the first day when D - C was zero. The muslin on the standard wet bulb thermometer was changed on the fourth day without any significant change in the negative D - C values.

f. The returns from the weather ships are difficult to interpret and there is little doubt, that although pollution effects can be large, and, in stormy weather build up fairly quickly, other sources of error were important. On one ship, Weather Monitor, for the first three voyages the dirty wet bulb thermometer was mounted in a separate portable screen which was moved as necessary to the windward side of the bridge. On the Weather Surveyor, an extra wet bulb thermometer was mounted in each of the two small screens then in use, one on either side of the bridge. The instruments to windward are read, the results from the two sets of instruments being presented as one series of readings. The Meteorological Officer has commented on the unsatisfactory exposure of the additional wet bulb thermometers and also pointed out that, as the ship normally lies stopped with port side to the wind, the port screen receives salt spray and the starboard screen funnel smoke contamination. For the fourth voyages larger screens were used on both ships, with an additional wet bulb thermometer mounted more satisfactorily in each port and starboard screen.

The results during the first week indicate that, unless large effects due to pollution from either funnel smoke or salt spray are in evidence from the very first day, which is unlikely since both wet bulbs should be equally affected, quite large errors in the reading of the thermometers must be attributed to other causes. The largest errors, $+1.6^{\circ}C$ and $-1.2^{\circ}C$, both occurred on days of gale force winds; and the larger errors were usually, though not always, associated with high winds, suggesting that ventilation effects, and possibly observer error, are significant under these conditions.

Table 4 summarises for all participating stations the arithmetic mean and root mean square of the differences during the first week, at various relative humidities.

/Table 4.

Table 4. Arithmetic mean and root mean square D - C values °C at various ranges of relative humidity during first week

Range RH% / Station	100 - 91		90 - 71		≤70		All Values	
	AM	RMS	AM	RMS	AM	RMS	AM	RMS
Bracknell(1)	-.03	.06	-.05	.07	-	-	-.04	.06
Bracknell(2)	-	-	.00	.00	-.05	.10	-.04	.09
Kew	-.07	.08	+.04	.06	-.02	.04	-.01	.06
Eskdalemuir	.00	.00	.00	.00	-.05	.07	-.01	.03
Birmingham AP	-.03	.18	+.08	.09	+.30	.31	+.16	.24
LWC	.00	.00	+.09	.18	-.01	.26	+.03	.22
MWC (1)	-	-	-.09	.09	-.20	.23	-.15	.18
MWC (2)	+.06	.06	-.09	.11	-.32	.36	-.23	.29
Acklington	-.15	.16	-.15	.16	-.10	.12	-.14	.15
Benbecula	+.05	.14	-.06	.15	.00	.00	-.01	.13
Leuchars	-	-	+.01	.03	-.02	.05	+.03	.07
Mount Batten	.00	.00	+.02	.16	+.18	.30	+.07	.20
Valley	.00	.00	+.15	.17	+.08	.13	+.11	.14
Wick	.00	.00	+.02	.04	+.04	.06	+.01	.03
Surveyor (1)	-.15	.29	-.08	.14	-	-	-.13	.26
Surveyor (4)	+.20	.20	+.14	.27	+.10	.10	+.13	.20
Monitor (1)	+.27	.33	+.35	.58	-	-	+.33	.54
Monitor (2)	-	-	-	-	-	-	-.02	.18
Monitor (3)	-	-	-.03	.18	-.07	.11	-.03	.16
Monitor (4)	+.28	.31	+1.03	1.14	-	-	+.72	.89

The following conclusions may be drawn from an examination of Tables 2 and 4 and the readings on which they are based.

The most consistent readings were obtained from Eskdalemuir, where it may be assumed that within one week there was virtually no pollution, but results were very nearly as consistent from Wick, Bracknell and Kew. At the latter two stations there was no change of muslin and wick during the week, so we infer that differences of ± 0.1°C can arise from causes other than pollution.

From the coastal stations, Acklington and Leuchars, differences ranging from -0.4 to +0.2°C cannot be attributed to the effects of pollution acting in any simple way following a change of muslin on the clean thermometer, since this cannot account for negative differences occurring after the change.

At London Weather Centre and Manchester Weather Centre, negative differences are larger and occur more frequently than positive differences. The differences are too large to be attributable entirely to observer error. Even larger differences, of both signs, are reported from the weather ships where ventilation errors may be significant.

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At Benbecula, Mount Batten and Valley, observations immediately following a change of muslin on the standard wet bulb thermometer, perhaps suggest a degree of pollution resulting in an error in the wet bulb of about +0.2°C. The positive difference was not long maintained. Therefore either the effect is not a simple pollution effect, or at a coastal station a clean muslin becomes contaminated within a day or two, and immediately thereafter positive and negative differences arise from other sources of error.

4.2. Readings during the first five weeks

Table 5 shows the (numerically) largest positive and negative differences occurring at each station in each of the first five weeks. Where the differences in any one week are all of one sign, and a zero difference was also recorded, this is indicated by entering 0.0 in the appropriate positive or negative column. Where the differences are all of one sign, but a zero difference was not recorded, the (numerically) minimum difference is shown with a positive or negative sign, as appropriate, before the observation.

Table 5. Range of D - C °C for each week during first five weeks.

Station	1st Week		2nd Week		3rd Week		4th Week		5th Week	
	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve
Bracknell (1)	0.1	0.0	0.2	0.0	0.1	0.0	0.2	-0.1	0.1	0.1
Bracknell (2)	0.2	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.1
Kew	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.4
Eskdalemuir	0.1	0.0	0.2	0.0	0.1	0.1	0.0	0.1	0.0	0.1
Birmingham	0.3	0.4	0.2	0.1	0.0	0.3	0.0	0.4	0.0	0.3
LWC	0.5	0.4	0.1	0.5	0.0	0.4	0.0	0.4	0.1	0.4
MWC (1)	0.4	0.0	0.2	0.4	0.2	0.2	0.0	0.2	0.0	0.4
MWC (2)	0.6	0.1	0.3	0.0	0.3	0.0	0.2	0.0	0.2	0.3
Acklington	0.4	0.0	0.4	-0.1	0.3	0.0	0.3	0.0	0.3	0.2
Benbecula	0.2	0.2	0.3	0.2	0.5	0.3	+0.1	0.3	0.2	0.2
Leuchars	0.1	0.2	0.2	0.0	0.1	0.0	0.0	0.1	0.2	0.2
Mount Batten	0.2	0.5	0.0	0.5	0.3	0.1	1.0	0.0	0.3	0.0
Valley	0.0	0.2	0.1	0.2	0.5	0.6	0.1	0.5	0.1	0.5
Wick	0.0	0.1	0.0	0.3	0.0	0.2	0.0	0.6	+0.2	0.7
Surveyor (1)	0.8	0.2	0.2	0.2	0.7	0.6	0.5	0.1	0.2	0.2
Surveyor (4)	0.1	0.5	+0.1	1.4	+0.1	1.2	+0.1	1.6	-	-
Monitor (1)	1.2	0.7	0.8	0.9	0.0	0.9	+0.2	1.5	-	-
Monitor (2)	0.4	0.2	0.0	0.5	0.2	0.3	0.1	0.5	-	-
Monitor (3)	0.3	0.3	0.3	0.3	0.7	0.3	0.4	0.2	-	-
Monitor (4)	0.1	1.6	1.0	1.0	1.0	1.3	0.8	1.2	-	-

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At most stations it will be seen that there is little systematic trend towards larger positive D - C values from the first to the fifth week. Table 6, which shows arithmetic mean and root mean square D - C values for various humidity ranges during the fifth week and which may be compared with Table 4, also provides little evidence for a systematic deterioration in efficiency of the dirty wet bulb thermometer, except at Wick. At this station, positive differences of +0.2 and +0.3°C were recorded during the second week and these increased to +0.5 and +0.6°C during the fourth week and to +0.7°C in the fifth week. Winds varied considerably in speed and direction and included onshore winds at some time during each week. There is some indication in the observations from Valley of a progressive deterioration in the dirty wet bulb thermometer at coastal stations. Here positive and negative differences were recorded until half way through the third week, after which only positive differences occurred increasing to +0.5°C. However, in subsequent weeks, negative differences were again recorded.

Table 6. Arithmetic mean and root mean square D - C values °C at various ranges of relative humidity during fifth week

Range RH% / Station	100 - 91		90 - 71		≤ 70		All Values	
	AM	RMS	AM	RMS	AM	RMS	AM	RMS
Bracknell (1)	-.03	.10	-.10	.10	-.10	.10	-.06	.10
Bracknell (2)	-	-	-.10	.10	.00	.10	-.05	.10
Kew	+.10	.10	.00	.07	+.11	.17	+.08	.14
Eskdalemuir	+.01	.04	+.03	.05	+.04	.06	+.03	.05
Birmingham AP	+.05	.07	+.08	.11	+.15	.18	+.11	.15
LWC	-.05	.07	+.16	.21	+.10	.14	+.11	.17
MWC (1)	+.20	.22	+.17	.18	+.33	.35	+.26	.28
MWC (2)	.00	.00	+.03	.07	-.02	.15	+.01	.11
Acklington	.00	.00	-.05	.09	-.09	.17	-.06	.12
Benbecula	+.03	.12	+.11	.18	-	-	+.08	.16
Leuchars	.00	.00	+.03	.05	+.02	.11	+.02	.09
Mount Batten	-.11	.14	-.36	.45	-	-	-.21	.31
Valley	+.23	.27	+.19	.26	-	-	+.21	.27
Wick	+.36	.40	+.49	.50	+.55	.55	+.49	.51
Surveyor (1)	-.07	.11	+.07	.14	-	-	-.01	.13

Observations from the other coastal stations do not indicate any systematic change during the period. At Leuchars differences throughout were zero or -0.1°C except for two observations of -0.2°C. At Mount Batten, differences, mainly positive at first, were zero or negative for the latter half of the five week period. At Benbecula, differences were positive and negative during the first half of the period and then became positive, but a series of negative differences were recorded during the fifth week. From Acklington, apart from a few zeros, differences were negative until the last day of the fifth week when +0.2°C was reported.

/Turning

Turning now to the inland stations, at Eskdalemuir a difference D - C not equal to zero was reported on eleven days. On all but one of these eleven days, the difference was either ±0.1°C. On one day with a relative humidity about 40%, differences of -0.2°C were reported. This is interesting in that the lower the humidity, the more likely is the size of D - C to increase, but here the sign is in the wrong sense. If observational error is excluded, this result suggests that the dirty instrument was acting more efficiently than the clean one, or that other sources of error were significant on this occasion.

At Bracknell only two positive differences were reported during the first five weeks of each run, one in each fifth week. During the first run, 25 observations were recorded in the first five weeks and in the second run 24; these gave differences shown in Table 7.

Table 7. Number of occurrences of each D - C value recorded during first five weeks of each run at Bracknell

D - C °C	0.0	+0.1	-0.1	-0.2
1st Run	5	1	14	5
2nd Run	15	1	7	1

At Kew, for the first four weeks, differences were either zero, or ±0.1°C. During the fifth week also, for relative humidities near or above 70%, the differences lay between ± 0.1°C. At relative humidities of 65% and 57% on the second and third days of the week, differences were +0.2 and +0.4°C respectively, but on the fourth and seventh days at humidities of 61% and 37%, the differences were zero. Wind speeds on the two occasions of 57% and 37% relative humidities were 040/17 and 070/21 knots. The increased positive differences are therefore unlikely to be due simply to pollution effects, especially as a difference greater than +0.1 was not reported again until the tenth week.

Birmingham Airport reported during the fourth week a difference equal to the largest occurring during the first week, otherwise from the second to the fifth week differences were less than during the first week.

At the more urban areas of London Weather Centre and Manchester Weather Centre, the differences are slightly indicative of a possible pollution effect. At London, mainly negative differences in the first few days were followed by mainly positive differences for the rest of the period, but without any increase in magnitude. During the first run at Manchester differences were all negative during the first week, positive and negative during the second and third week, and all postive during the fourth and fifth weeks. Second run differences, apart from one +0.1°C in the first week, were all zero or negative until the fifth week, when positive differences up to +0.3°C were recorded.

The returns for the weather ships, with the exception of the third voyage of the Weather Monitor, show a trend to more numerous and larger positive differences with time. (On the third voyage of the Monitor differences were all negative or zero during the last five days of the voyage after a series of postive readings in the third week). As can be expected, the larger differences are associated with relatively low humidities, but there are many anomalies. Two of these are discussed below, both occurring during the fourth voyage of the Weather Surveyor. At midday on 9th October, 1964, during the second week of the voyage, a difference of +1.4°C was recorded with dry bulb temperature 7.3°C and

/relative

relative humidity 58%. At 1500 GMT, with the same dry bulb temperature, and a rise of humidity to only 68%, the difference was +0.1°C. Winds at the two observations were 290/14 and 280/11 kt. As the relative humidity had been low for some time previous to midday, and was therefore unlikely to be changing rapidly, the large positive difference is unlikely to be due to instrumental lag - increased on the dirty wet bulb by reason of pollution - unless the humidity is varying considerably and rapidly on a small scale. The second case occurrred towards the end of the fourth week, when with a humidity of 75% a difference of +0.1°C was recorded at 1500 GMT. Before the 1800 GMT observation was made, new muslins and wicks were fitted to the clean wet bulb thermometers. The differences then recorded increased to +1.3°C. Part of this increase may be due to a drop in relative humidity to 59%, but twelve hours later with 77% relative humidity the difference was +1.6°C. At 92% relative humidity the difference, later in the same day, decreased to +0.2°C. If the change in the difference before and after the changing of the muslins is to be attributed to pollution, and since the muslins on the clean instruments were changed in accordance with normal practice, then clearly errors of this magnitude may occasionally be incorporated in routine observations.

The broad conclusions to be reached from a study of the results over the first five weeks are that where pollution effects can be expected to be small they do not build up sufficiently to be a significant source of error over this period. Where pollution is likely to be large, in urban and coastal areas and at sea, although there is some evidence that its effects may become significant, errors occurring within a day or two of fitting a clean muslin and wick are likely to be almost as large as those occurring later in the period.

4.3. Readings after the first five weeks

Since, at many of the participating stations, errors in the wet bulb depression from all causes are not significantly increased by increasing pollution during the first five weeks, it is of considerable interest to examine readings in the subsequent weeks of the experiment.

At Eskdalemuir, at the end of the tenth week a difference of +0.3°C was recorded; otherwise the majority of differences were zero with some +0.1 and occasional differences +0.2°C. Towards the end of the eleventh week, and again in the twelth week differences of +0.4°C occurred on two occasions with relative humidities of 60% and 49%. Resulting errors in relative humidity are three or four per cent. In subsequent weeks very occasional differences of +0.3 or +0.4°C were recorded on occasions of low humidity, but the majority of differences from the eleventh to the twenty-fourth week were +0.1°C. From the twenty-fifth to the twenty-ninth week, when readings stopped, the mean difference was +0.2 with a maximum of +0.4°C. Although only these comparatively small errors were recorded at the end of the experiment, the muslin on the dirty wet bulb thermometer by this time was stained a dirty yellow colour.

During the first run at Bracknell, a difference of +0.5°C was recorded on one occasion in the seventh week when the dry bulb thermometer was -0.4°C. Otherwise differences lay mainly between ±0.1, occasionally ±0.2, with two -0.3°C, until the eleventh week. From then until the seventeenth week differences were all negative, apart from one zero, and mainly about -0.2°C. The (numerically) maximum difference in this period was -0.6°C, (twice) with relative humidities between 65 and 75%. From the eighteenth until the twenty-fifth week, when the run ended, differences were either zero or negative, mostly about -0.1 or -0.2°C. A difference of -0.3°C occurred on six days, and -0.4°C on two days when relative humidity was 70 to 75%. The increased negative difference with rather low humidities suggests that the dirty wet bulb thermometer is more efficient than the clean one, or is ventilated more strongly, neither explanation being very credible.

/The

The second run at Bracknell showed even less variation in the differences than the first. The experiment extended over nearly thirty weeks from 1st July, 1964 to 22nd January, 1965 and, with one exception, no difference numerically greater than $\pm 0.2^{\circ}$C was recorded, most differences being zero or $\pm 0.1^{\circ}$C. The exception was a difference of $+0.3^{\circ}$C with a relative humidity of about 70% and a dry bulb temperature of 19°C.

It should be remembered that at Bracknell only the 0900 GMT reading was recorded; consequently there will be a bias towards high relative humidities and their smaller differences. What readings are available with low humidities (mostly negative differences) do not, however, suggest errors that would be of much concern to the forecaster. By the end of each run the muslin on the wet bulb thermometer was green where it was not stained a dark grey with encrusted dirt.

The returns from Kew extended over a period of 39 weeks, all but two days. Up to the fourteenth week differences lay between $\pm 0.2^{\circ}$C, there being many negative values up to the eighth week, many positive, but some negative differences from the ninth to the eleventh week and then all positive values to the fourteenth. Positive differences then continued to the twenty-seventh week, by which time many were about $+0.3^{\circ}$C, with occasional differences of +0.4, +0.5 and $+0.6^{\circ}$C. The larger differences were generally associated with low relative humidities (about 50% or less), but some humidities of this order occurred with small differences (zero or $+0.1^{\circ}$C). From the thirtieth week, to the end of the experiment in the thirty-ninth week, differences remained mostly +0.1 or $+0.2^{\circ}$C with occasional higher values up to $+0.4^{\circ}$C on occasions of low humidity.

London Weather Centre showed a remarkable consistency throughout the thirty weeks of the experiment, with differences in the first week almost as large as occurred at any other time. In the second, sixth, seventh and thirteenth week some positive differences were 0.2°C greater and some negative differences 0.1°C (numerically) greater than the largest differences recorded during the first week. Otherwise differences throughout were less than the extremes during the first week. Differences in the last five weeks of the experiment were mostly between $\pm 0.2^{\circ}$C with occasional differences of $\pm 0.3^{\circ}$C.

At Manchester, during the first run, following all postive differences during the fourth, fifth and sixth weeks, negative differences up to -0.5°C were recorded during the seventh week. Differences were then all positive, and mostly less than $+0.5^{\circ}$C, until the eleventh week when D - C values increased to between +1.0 and $+3.0^{\circ}$C. The first run ended after fourteen weeks by which time a difference of $+4.4^{\circ}$C had been recorded at 44% relative humidity and 24°C dry bulb temperature, yielding an error in humidity of 32%.

During the second run, only positive differences were recorded after the seventh week and during the ninth week a difference of $+4.0^{\circ}$C was recorded at a relative humidity of 44% and a dry bulb temperature of 22°C. At lower temperatures much smaller differences, of the order of $+0.5^{\circ}$C, were recorded until the eleventh week after which the dirty wet bulb thermometer acted virtually as a dry bulb instrument.

Readings at Birmingham Airport during the sixth, seventh and eighth week were all positive. From then on, until the twenty-second week, a few negative differences were recorded, but most differences were +0.1 or $+0.2^{\circ}$C with some values +0.3 or $+0.4^{\circ}$C, generally at low humidities. From the twenty third week onwards large positive differences were recorded, at first +1.0 to +1.5, but later +3.0 to $+4.0^{\circ}$C, and it was obvious that the dirty wet bulb thermometer was completely unreliable.

/Considering

Considering the returns from the six coastal stations, none of them showed the very marked rise in the value of the difference which was characteristic of the later stages in the experiment at Manchester and Birmingham.

At Leuchars during the last fortnight, the twenty-ninth and thirtieth weeks, differences ranged from -0.4°C to zero. Throughout the thirty weeks differences were mostly in the range ±0.3°C with many days of zero differences, mostly at high humidities, and some rather larger differences, between +0.5 and +1.0°C, generally at low humidities. There were, however, some anomolies. One of these is discussed in Section 5 below. In the tenth week, up to which time the largest positive difference was +0.2°C, differences between +1.0 and +2.0°C occurred. Similar large differences were reported on a few isolated occasions in later weeks. These large differences may have been due to an inadequate water supply on those occasions, but not all of these differences occurred at high temperatures and low humidities. Another feature of the returns from Leuchars was the occurrence of differences nearly all negative over a period of several days, sometimes weeks, after long spells when differences were positive.

This phenomenon also occurred at Benbecula. Positive and negative differences of about ±0.3°C up to the beginning of the eighth week were followed by six weeks (except for one night) of positive differences, many about +0.5°C or more, and two of +1.0°C, the largest differences which occurred throughout the whole thirty weeks. In the fifteenth week differences of both signs occurred about equally and then followed a week when they were all positive and during which the dirty wet bulb thermometer occasionally read higher than the dry bulb.

An explanation for the phenomenon of the wet bulb temperature exceeding that of the dry bulb, other than when there is supersaturation with respect to ice, has been given by Gregory and Rourke (15). Briefly:

from the psychrometric equation

$$T - T' = f\,(e'_w - e)$$

where

T is the temperature of the dry bulb

T' is the temperature of the wet bulb

e'_w is the saturation vapour pressure of pure water at the temperature of the wet bulb

e is the vapour pressure.

If e'_s is the saturated vapour pressure of a contaminated solution at the temperature of the wet bulb;

we have

$$T - T' = f\,(e'_s - e).$$

Now the saturated vapour pressure over a solution is less than over a pure solvent, so e'_s is always less than e'_w and, if sufficiently depressed, may be less than e thus making $T - T'$ negative.

It would seem from the above that, at Benbecula, from about the eighth week pollution effects were marked, but the re-occurrence of negative values later in the run indicates that the effects are not straightforward. There is some evidence that negative differences occurred during or following a period of gale force winds from the Atlantic, but not all negative values are associated in this way with the wind. In the last four weeks of the experiment differences ranged from -0.8 to +0.3°C, not very dissimilar from those reported in the first three weeks.

/A

A notable feature of the returns from Wick, when compared with the returns from most other stations, is the absence of negative D - C values, only two (each -0.1°C) being reported. These occurred at 1500 and 0600 GMT on successive days. Following the relatively large difference of +0.7°C reported in the fifth week, the maximum differences occurring up to the eleventh week rose only to +0.8°C. In the eleventh week differences up to +1.3°C were reported and after the sixteenth week differences greater than +2.0°C occurred. In the seventeenth and eighteenth week the majority of differences were about +1.5°C for various humidities, but such values occurred only occasionally thereafter. Low differences, about +0.2 or +0.3°C, in the eighteenth week were accompanied by high humidities with winds mainly off the sea and there were several cases, at near saturation, of the dirty wet bulb thermometer reading higher than the dry bulb one. In the last four weeks of the experiment (weeks 27 to 30) differences were between +0.5 and +1.0°C for a wide range of humidities.

At Acklington the mainly negative differences reported during the first five weeks were followed by six days of positive differences up to +0.6°C. This was a period of rather high temperatures, up to about 20°C, and generally low relative humidities. The period ended on 16th May when the following reports were made:

Table 8. Temperature and humidity reports from Acklington, 16th May 1964

Time GMT	Dry Bulb °C	Clean Wet Bulb °C	RH%	Difference D - C °C	Wind ddd/ff
0600	8.2	6.8	80	+0.1	240/07
1100	15.0	10.2	50	+0.4	200/08
1500	16.6	11.5	50	+0.2	220/13
1600	17.1	11.8	49	-0.1	230/07

The decrease in the difference from that at 1100 GMT to that at 1500, and still more at 1600 GMT, with slowly rising temperatures and with no significant change in relative humidity, or in wind speed or direction, is difficult to account for, unless perhaps it followed a replenishing of a rather impoverished water supply. Differences remained small and of both signs until the ninth week when another series of all positive differences began with values up to +0.7°C at relative humidities near 70%. This pattern was repeated several times up to the sixteenth week when a long series of positive values began which lasted until the twenty third week. During this period differences up to +0.9°C were recorded and there were several reports of the dirty wet bulb reading higher than the dry bulb. Another short period of negative differences followed and thereafter D - C values were nearly all positive, but without any further increase in magnitude.

From Mount Batten differences remained negative from the fifth week until the tenth, with no value numerically greater than the -1.0°C recorded in the fourth week. From the tenth week to the fourteenth week differences of both sign were recorded, the largest positive value being +0.4°C. There followed a fortnight of negative differences and then three weeks of positive values with a maximum of +1.2°C at 19.4°C dry bulb and 67% relative humidity in the seventeenth week of the experiment. Three weeks of zero or small negative differences were then followed in the twenty third week by positive values which persisted until the twenty-seventh week and rose to a maximum of +3.4°C. Although there were several differences of this order, they did not persist, as did eventually the large positive differences recorded at Birmingham and Manchester. The last three and a half weeks saw a return to negative differences with values lying between zero and -0.3°C.

/Returns

Returns from Valley showed, for the first eleven weeks, positive and negative differences no larger, and generally much smaller, than the range -0.5 to +0.6°C recorded during the third week. In the twelfth and thirteenth week mainly positive differences were recorded with a maximum of +0.9°C at 15.2°C dry bulb temperature and relative humidity 81%. From the fourteenth to the seventeenth week positive and negative differences were observed with extreme values ranging from -0.8 to +1.0°C. Thereafter, until the end of the experiment in the thirty first week, only occasional negative values were observed. The largest difference reported was +1.1°C in the twenty first week with a dry bulb temperature of 16.1°C and a relative humidity of 55%.

The Weather Surveyor maintained a comparison between the readings of the standard wet bulb thermometer and a dirty instrument during almost twelve weeks at sea extending over three voyages. Throughout this time the differences were mainly negative with only a few positive values. Most of these were small, but some differences up to +0.7°C were recorded with relative humidities about 65%. The exposure arrangements have already been described and it is probably significant that during the fourth voyage, when with new equipment both clean and dirty wet bulb thermometers were housed in the same screen, differences were all positive, apart from two of -0.1°C in the first week.

4.4. Summary of observations

The detailed discussion of results given in Sections 4.1., 4.2. and 4.3. above is summarised below.

Of the land stations, the shortest run was at Manchester Weather Centre where the first experiment ended after fourteen weeks. Table 9 shows for that week arithmetic mean and root mean square D - C values at various humidities which may be compared with Tables 4 and 6. The last column in each table is of most interest and shows the very large increase with time in the root mean square differences for all humidities at Manchester. Smaller but significant increases also occur at Wick, Valley and Benbecula.

Table 9. Arithmetic mean and root mean square D - C values °C at various ranges of relative humidity during fourteenth week

Station \ Range RH%	100 - 91		90 - 71		≤ 70		All values	
	AM	RMS	AM	RMS	AM	RMS	AM	RMS
Bracknell (1)	-	-	-.20	.22	-.30	.34	-.28	.30
Bracknell (2)	.00	.00	+.03	.05	-	-	+.02	.04
Kew	-	-	+.07	.08	+.11	.12	+.10	.11
Eskdalemuir	+.07	.08	+.10	.10	+.10	.12	+.09	.10
Birmingham AP	+.20	.20	+.08	.14	+.07	.13	+.08	.14
LWC	-	-	+.07	.10	-.12	.22	-.04	.19
MWC (1)	-1.44	1.44	+.31	.33	+1.99	2.20	+.87	1.46
MWC (2)	+.39	.37	+1.00	1.05	+3.10	3.14	+2.08	2.44
Acklington	+.10	.10	+.05	.07	-.01	.09	+.03	.08
Benbecula	+.22	.30	+.35	.37	+.57	.57	+.34	.39
Leuchars	.00	.00	-.04	.08	-.24	.29	-.13	.20
Mount Batten	.00	.08	-.03	.23	-.23	.35	-.12	.28
Valley	+.15	.21	+.18	.31	+.48	.51	+.25	.36
Wick	+.64	.75	+.48	.60	+.84	.98	+.66	.79

/Tables

Tables 4, 6 and 9 are based on available information, normally three observations per day (0600, 1500 and the time of greatest D - C value), but not all stations reported in this detail. The mean values at various humidities are not very soundly based because of the paucity of observations, particularly at Bracknell (1) and (2) with only five observations per week. The variation in D - C values with varying humidity is discussed later in this Section and in Section 5.

Tables 10a and 10b show for each station, for weeks up to the thirteenth, and for all humidities, arithmetic mean and root mean square D - C values based on 0900 GMT observations at Bracknell, 0900 and 1500 GMT observations at Kew and 0600 and 1500 GMT observations at all other stations.

Table 10a. <u>Arithmetic mean D - C value °C for weeks up to the thirteenth (all humidities)</u>

Station \ Week	1	2	3	4	5	7	9	11	13
Bracknell (1)	-.04	-.12	-.08	-.16	-.06	+.10	-.06	-.14	-.24
Bracknell (2)	-.04	-.04	-.04	.00	-.05	-.06	+.02	+.12	-.04
Kew	-.01	+.04	-.01	+.02	+.08	-.06	.00	+.05	+.11
Eskdalemuir	-.01	-.01	-.01	+.01	.00	+.02	.00	+.11	+.13
Birmingham	+.16	+.01	+.11	+.11	+.07	+.10	+.16	+.04	+.10
LWC	+.06	+.11	+.11	+.16	+.05	-.16	+.14	+.08	+.09
MWC (1)	+.13	-.03	-.06	+.10	+.19	-.01	+.17	+.71	+1.16
MWC (2)	-.18	-.16	-.01	-.04	-.02	-.01	+.52	+.33	+2.54
Acklington	-.15	-.17	-.11	-.13	-.05	+.05	+.21	+.05	+.10
Benbecula	-.05	.00	+.08	+.17	+.08	-.01	+.55	+.36	+.28
Leuchars	.00	-.03	.00	+.01	+.01	.00	+.01	+.08	-.18
Mount Batten	+.06	+.17	-.01	-.26	-.16	-.33	-.19	+.04	-.04
Valley	+.11	+.09	+.09	+.14	+.16	-.23	+.11	+.08	+.22
Wick	.00	+.04	+.06	+.27	+.43	+.32	+.25	+.59	+.89
Surveyor (1)	-.15	+.07	-.04	-.16	-.02	+.04	-.05	-.08	-

Table 10b.

Table 10b. Root mean square D - C values °C for weeks up to thirteenth (all humidities)

Station \ Week	1	2	3	4	5	7	9	11	13
Bracknell (1)	.06	.14	.09	.17	.10	.22	.10	.17	.25
Bracknell (2)	.09	.06	.06	.00	.10	.08	.05	.15	.14
Kew	.05	.06	.08	.06	.15	.12	.07	.11	.12
Eskdalemuir	.08	.01	.04	.01	.00	.05	.00	.16	.14
Birmingham	.21	.08	.14	.14	.11	.10	.20	.13	.44
LWC	.16	.19	.15	.19	.10	.29	.19	.11	.24
MWC (1)	.17	.09	.12	.12	.22	.20	.18	1.17	1.71
MWC (2)	.24	.18	.07	.07	.09	.06	.90	.37	3.20
Acklington	.15	.20	.14	.16	.11	.12	.33	.09	.17
Benbecula	.15	.10	.21	.18	.14	.13	.58	.40	.33
Leuchars	.01	.05	.00	.04	.02	.00	.09	.10	.37
Mount Batten	.18	.21	.08	.38	.22	.42	.24	.10	.19
Valley	.15	.22	.22	.19	.16	.36	.46	.14	.89
Wick	.00	.09	.09	.34	.44	.35	.30	.67	.93
Surveyor (1)	.28	.12	.28	.23	.10	.18	.35	.14	-

Although an observer is trained to read thermometers to one tenth of a degree, errors of this order can be expected to arise occasionally in temperature readings. Consequently there may be occasional errors in wet bulb depression of ±0.2°C when possible errors in reading the two thermometers are not self cancelling. Thus a D - C value equal to or between ±0.2°C may be due to observer error alone. Inspection of Tables 5 and 10, which give overall extremes and mean values, shows that during the first five weeks most stations had mean values between, or at least not significantly far outside the range of, ±0.2°C while Bracknell (1) and (2), Eskdalemuir and Leuchars, had extreme values in this range. Kew should also be included with these stations as it is virtually certain that the +0.4°C observed during the fifth week is not representative. During weeks after the fifth, up to the thirteenth, Table 10b shows only slight increases in root mean square values at Bracknell (1) and (2), Kew and Eskdalemuir where no RMS difference greater than +0.25°C occurs. London Weather Centre's are not very much larger (+0.29°C in seventh week), and although the extreme values reported during the first five weeks lie outside the range ±0.2°C, the results, as discussed in Section 4.3 above, remain fairly consistent throughout thirty weeks. Table 11 shows arithmetic mean and root mean square differences in the last fortnight of the experiment at these four stations and indicates that little systematic increase in pollution effects is occurring.

/Table 11.

Table 11. Arithmetic mean and root mean square D - C values °C for selected stations in each of last two weeks of experiment

Station	Weeks		Arithmetic Mean		Root Mean Square	
Bracknell (1)	23	24	-.16	-.12	.19	.13
Bracknell (2)	28	29	-.02	+.02	.08	.08
Kew	37	38	+.05	+.09	.08	.11
Eskdalemuir	28	29	+.13	+.18	.15	.19
LWC	29	30	+.01	+.01	.13	.13

The results shown in Table 10 may be compared with those obtained by Sutcliffe (6) in experiments on the Air Ministry Roof, Kingsway. Sutcliffe's experimental arrangements were different from those described here; he compared readings taken each day up to 21 days after a change of muslin (standard), with readings of a wet bulb thermometer fitted with a clean muslin each day (additional). He was thus able to compute mean differences between readings of the additional and standard wet bulb thermometers for each day up to the twenty-first after a change of muslin on both thermometers. The results show a slow but fairly steady rise in the size of the mean difference from +0.01°F on the first day to +0.17°F on the seventeenth day followed by a drop to +0.10°F on the twenty-first day. Combined into mean differences over three weekly periods the results were +0.04°F, +0.08°F and +0.12°F for the first second and third weeks respectively. These results are most closely matched by the root mean square D - C values for the first three weeks at Kew; the corresponding figures for London Weather Centre, though larger, do not show a steady increase during the period, nor do those for Bracknell and Eskdalemuir.

Because the differences at Bracknell (1) and (2), Kew and Eskdalemuir were small and remained small throughout the experiment, and because differences at London Weather Centre, although larger during the first five weeks, remained consistent or if anything decreased, the observations from these stations (as detailed for Table 10) were combined and re-analysed into humidity ranges to give results more firmly based than those shown in Tables 4, 6, and 9. The combined results for various weeks are shown in Table 12 which includes the standard deviation as well as the arithmetic mean and root mean square of the D - C values. For humidities greater than 70% there is no significant increase in mean differences up to the fourteenth week and very little in later weeks. Below 70% humidity mean differences increase slightly in the later weeks of the experiment, but the resulting error in relative humidity would be only 3% or 4%.

/Table 12.

Table 12. Arithmetic mean, root mean square and standard deviation of D - C values °C at various humidities: Bracknell (1) and (2), Kew, Eskdalemuir, and London Weather Centre, combined

Range RH% / Week	Arithmetic Mean			Root Mean Square			Standard Deviation		
	100-91	90-71	≤70	100-91	90-71	≤70	100-91	90-71	≤70
1	-.02	+.03	-.01	.05	.12	.11	.05	.12	.11
2	-.01	+.03	+.02	.05	.11	.15	.05	.11	.15
3	-.02	+.04	+.03	.06	.10	.14	.06	.09	.14
4	-.01	+.06	+.06	.07	.13	.14	.07	.12	.13
5	-.01	+.01	+.05	.06	.09	.12	.06	.09	.11
6	-.04	-.01	-.11	.07	.10	.21	.06	.10	.18
7	+.02	-.05	-.08	.20	.09	.23	.20	.07	.22
8	.00	+.01	-.02	.11	.09	.09	.11	.09	.09
9	+.04	+.03	+.01	.12	.10	.05	.11	.10	.05
14	+.06	+.03	.00	.07	.11	.16	.04	.11	.16
15	+.07	+.09	+.07	.09	.25	.21	.06	.23	.20
16	+.05	+.04	+.06	.09	.13	.17	.07	.12	.16
17	+.03	+.08	-.02	.10	.19	.25	.10	.17	.25
21	+.01	+.05	+.07	.08	.09	.22	.08	.07	.21
22	+.04	+.02	+.09	.09	.11	.32	.08	.11	.31
23	+.07	+.02	+.13	.17	.11	.28	.15	.11	.25
24	+.05	+.06	+.15	.10	.18	.34	.09	.17	.31
25	+.03	+.11	+.18	.14	.17	.31	.14	.13	.25

The final table in this section, Table 13, gives the time from the beginning of the experiment, in weeks from the start, at which various events occurred.

/Table 13

Table 13. Week after start in which stated events occurred

Station \ Event	1	2	3	4	5	6	7	8	9
Bracknell (1)	7	-	-	5	5	6	-	-	25
Bracknell (2)	11	-	-	5	5	11	9	1	29
Kew	5	22	-	1	5	20	2	8	38
Eskdalemuir	10	-	-	3	3	7	4	1	29
Birmingham AP	1	23	23	23	23	23	3	-	29
LWC	1	13	-	1	2	13	3	30	30
MWC (1)	2	2	10	2	2	6	4	8	14
MWC (2)	5	8	8	1	5	8	8	8	16
Acklington	6	6	15	5	5	6	13	25	30
Benbecula	3	8	9	1	3	7	9	26	30
Leuchars	10	10	10	1	10	10	4	-	30
Mount Batten	1	16	17	1	16	16	17	-	30
Valley	3	3	21	1	3	13	1	29	30
Wick	2	4	6	1	2	6	1	1	30
Surveyor (1)	3	3	-	1	3	6	-	-	12
Surveyor (4)	1	2	2	1	2	-	2	1	4
Monitor (1)	1	1	1	1	2	-	3	3	4
Monitor (2)	2	-	-	1	2	-	2	2	4
Monitor (3)	1	-	-	1	-	-	-	-	4
Monitor (4)	1	1	1	1	-	-	-	-	4

Key to events

1. D - C $<$ +0.2°C.
2. D - C $<$ +0.5°C.
3. D - C $<$ +1.0°C.
4. D - C $<$ largest positive difference occurring on first day.
5. D - C $<$ largest positive difference occurring in first week.
6. D - C $<$ largest positive difference occurring in first five weeks.
7. First week of all positive differences.
8. Week from which no negative difference numerically greater than -0.2°C occurred.
9. Last full week of experiment.

/5.

5. Some additional results

At Kew during the twenty-eighth week, 11th to 17th August, a remarkable discontinuity occurred in the differences which decreased to lie mostly between ±0.2°C for about the next fortnight. The discontinuity was commented on by Superintendent, Kew Observatory, who calculated for the periods 1st to 13th and 14th to 31st August, mean differences, (0900 + 1500 GMT), of +0.30 and +0.05°C respectively. Comparison with the standard North Wall observations indicated that, if anything, the clean wet bulb in the Stevenson screen was reading slightly high during the first period and slightly low during the second period, which would aid a change in the recorded difference D - C in the opposite way to that which actually occurred. Any change would therefore seem to have taken place in the dirty wet bulb installation, though this had not been disturbed since the experiment began.

The tendency for the D - C value to diminish after a period during which it increased, as well as the reversion to negative values after quite long intervals with positive differences, has been noted at other stations and can be seen in the root mean square values in Tables 10 and 12. A period of high humidity following a dry spell with low humidity would result in a decrease of the D - C values, but Table 12 indicates that the effect also occurs without significant change in humidity. The effect is suggested after the seventeenth day in Sutcliffe's (6) results. It has also been noted by Garnett (7) who analysed returns from Wick. These showed that with muslins changed weekly on a wet bulb therometer there was a decrease in efficiency of the instrument for the first two days in winter and the first three days in summer, followed by an improvement. The initial rise in relative humidity was 4 or 5% and the subsequent fall 2 or 3%. Garnett suggested that accumulation on the muslin of salt from sea spray, building up faster in winter than in summer, resulted in a roughened surface which enhanced evaporation.

Another factor which affects the size of the difference D - C, and one which was not rigorously controlled during the experiment, is the rate at which water is supplied to the wet bulb. Commenting on large differences recorded at Birmingham, the Meteorological Officer reported that when the bottle feeding the dirty wet bulb was full to the very top differences were small. When the water-level in the bottle was down to the bottom of the neck differences were often large and it was observed that although moisture extended along the wick it did not always reach the muslin which at times dried out. The Meteorological Officer at Manchester Weather Centre also commented that on occasions of large differences "it would appear that the wick has become so dirty it cannot supply sufficient water to the muslin". The effect of the level of the water supply on the readings of a wet bulb thermometer has previously been discussed by Durward (8) who describes experiments conducted in Egypt where high temperatures and low humidities give rise to a high rate of evaporation from the wet bulb muslin. Whipple (9), describing experiments at Kew, comments on the need for water to pass freely through the pores of the wet bulb muslin and achieved this by arranging for the free surface of the water supply to be raised a millimetre or so above the bottom of the thermometer bulb, resulting in a slow drip from the wet bulb. A somewhat similar arrangement has also been used at Valencia (11) where a wet bulb thermometer wearing the same muslin throughout, but constantly washed by a syphon process, was used as the standard for comparison with a wet bulb thermometer with a muslin changed fortnightly.

The recording of many negative differences in this experiment was surprising. Middleton and Spilhaus (16) state that all the errors of a psychrometer, apart from ventilation errors and errors in the thermometers themselves (but specifically including errors due to dirty muslin or impure water), operate in such a direction as to increase the observed relative humidity. But the many negative differences recorded at different stations in various conditions of temperature, humidity and wind cannot all be explained by selective over-ventilation of the dirty instrument.

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An interesting series of negative differences increasing up to -0.7°C was recorded over three or four days in the sixth week at Leuchars. These differences were considerably larger (numerically) than those previously reported and occurred immediately after a change of muslin on the clean wet bulb. The muslin was then changed twice without significantly altering the negative differences, while a third wet bulb thermometer mounted in the screen compared well with the dirty instrument. After a few days all three wet bulb thermometers were giving comparable readings.

The dependence on humidity of the error in wet bulb depression has already been commented on. The Meteorological Officer at Valley has made an interesting analysis of three-hourly observations between 3rd July and 30th September, 1964 (fourteenth to twenty-sixth week) which is presented in Table 14. This shows a diurnal variation in the mean value of D - C in sympathy with the diurnal variation of the average relative humidity.

Table 14. Average relative humidity and average D - C value °C at three-hourly intervals at Valley

Time GMT	00	03	06	09	12	15	18	21
Average RH%	93	93	93	87	81	79	85	91
Average D - C °C	0.17	0.16	0.15	0.18	0.20	0.21	0.19	0.17

Another suggestion from Valley was that many of the negative differences recorded might be explained by assuming an increase in the lag of the dirty wet bulb thermometer such that a sharp rise in relative humidity left the temperature of the dirty instrument below that of the clean. With a decrease in humidity an increased positive difference would result. Although an examination of the records at Valley support this explanation on many occasions, not all negative differences can be thus accounted for, for instance those occurring at some stations on the first day, or in the first few days, of the experiment, as well as others occurring in later weeks.

An attempt was made at Valley and Birmingham Airport to discover whether rapid fluctuations of temperature and/or humidity could be observed. This was done by quickly reading the thermometers in the following order:

dry bulb thermometer (first reading)

clean wet bulb thermometer (first reading)

dirty wet bulb thermometer

clean wet bulb thermometer (second reading)

dry bulb thermometer (second reading).

The screen door was thus open slightly longer than usual and differences in the two readings of the dry bulb therometer or the clean wet bulb thermometer may therefore be due to: observer error, the presence of the observer, genuine fluctuations of temperature and humidity, or the effect (especially on the wet bulb) of increased ventilation due to the open screen door. At both stations the readings were taken over a period of seventeen weeks from early July to the end of October. Table 15 shows during this period the number of occasions, for both stations combined, in which the two readings of the same instrument differed by stated amounts.

/Table 15a.

Table 15a. Number of occurrences of differences °C between two quick readings of dry bulb thermometer (first minus second) at Birmingham AP and Valley combined

Difference °C	0.1	0.2	0.3	0.4	≥0.5	≥0.1
Positive	11	4	2	0	2	19
Negative	116	22	9	5	5	157

Table 15b. Number of occurrences of differences °C between two quick readings of clean wet bulb thermometer (first minus second) at Birmingham AP and Valley combined

Difference °C	0.1	0.2	0.3	0.4	≥0.5	≥0.1
Positive	18	5	1	1	1	26
Negative	83	11	5	5	2	106

For both stations combined, and for both wet and dry bulb thermometers, the total number of differences other than zero between first and second readings of the same instrument recorded over seventeen weeks was 308, between two and three per day, or rather more than one per day per station. The majority of the differences are 0.1°C, but these are unlikely to be due to observer error since there should be approximately equal numbers of positive and negative differences if this was the case. The preponderence of negative differences is rather surprising since the effect of increased ventilation, especially on the wet bulb, is most likely to be a lowering of the temperature giving a positive difference (first minus second reading).

6. Summary and conclusions

The experiment described and discussed above was primarily an attempt to obtain information on how long a muslin and wick on a wet bulb thermometer may be left unchanged without introducing unacceptable errors. For thermometers exposed in Stevenson screens at ground level the results enable an estimate to be given dependent on some assumptions about the type of pollution. From these results we may infer how instruments exposed on tall masts 1000 ft or more in height may possibly be affected.

Where pollution concentration is very small (Eskdalemuir) errors are negligible for some weeks, and small, 3% or 4% at 50% relative humidity, after two or three months. There is no indication, even after five or six months, of the instrument becoming completely inefficient. At the other extreme (Manchester), where pollution is industrial or urban in origin, the wet bulb may completely fail to function after about nine weeks and is probably too inefficient to be of use to the forecaster after about three or four weeks (though errors from other sources make this difficult to estimate). For inland stations, between these two extremes, returns from Bracknell, Kew, London Weather Centre and Birmingham Airport suggest that pollution effects do not become an important source of error within a period of two or three months. (That London Weather Centre should be more like Kew than Manchester Weather Centre may possibly be a result of the Clean Air Act. A report on the investigation of atmospheric pollution by the Department of Scientific and Industrial Research (17) shows similar smoke concentrations both in the vicinity of Kew and London Weather Centre).

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The returns from coastal stations and the weather ships show a wide variation in the rate at which effects likely to be due to the accumulation of salt pollution become significant, and clearly wind speed and, at a coastal station, wind direction are important. Except, however, for instruments at the foot of a mast on or very near the coast line, the accumulation of salt on instruments several hundred feet above ground level is likely to be slow.

It may be inferred, therefore, that wet bulb thermometers exposed on tall masts situated in areas not in the immediate neighbourhood of sources of heavy industrial pollution, are likely to remain effective instruments for up to one month or more, and may retain an efficiency acceptable to forecasters for periods as long as two or three months, assuming that the instrumental error in the electrical resistance thermometers proposed for tall masts is no greater than the observer error when reading mercury in glass thermometers.

A secondary result of the experiment with wet bulbs was an indication of how errors, sometimes quite large, can occur in readings of temperature and humidity made by experienced observers following standard practice.

A most surprising result was the number, the size and at times the persistence of differences between the standard and additional wet bulb thermometers when the reading of the additional instrument was depressed below that of the standard (D - C negative). Errors due to ventilation and to differences in the lag coefficients of the clean and dirty wet bulb thermometers may account for some negative differences, but there remains an inexplicable residue.

Another result, difficult to account for, is the improvement in efficiency of the dirty wet bulb thermometer after a period during which its efficiency becomes impaired. This phenomenon is paralleled by the re-occurrence of a series of negative differences after a long series of increasing positive ones.

It is also surprising that even after the muslin on a wet bulb thermometer becomes visibly polluted (as at Eskdalemuir) the resulting errors may be very small. In smokier areas errors may be somewhat larger, but nevertheless can remain quite small for long periods of time. And at coastal stations and ships at sea, for several weeks errors may occur no bigger than those apparently occurring on the first day of fitting a clean muslin and wick.

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