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RECENT CHANGES IN THERMOMETER SCREEN DESIGN AND THEIR IMPACT

by

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FOREWORD

The *Commission of Instruments and Methods of Observation* (CIMO) considered at its eleventh session (Geneva, 1994) matters related to improvement of observations, especially in support of research in the field of climate change. As is well known, accurate and homogeneous temperature measurements are very essential in this respect. In addition to representative siting, the correct exposure of the thermometers or sensors is of highest importance for obtaining reliable measurements. The Commission therefore stressed the importance of more information on the performance characteristics of thermometer screens or other shieldings, considering especially new designs used for automatic weather stations.

The requested study became the responsibility of the *Working Group on Surface Measurements* of CIMO. The Group agreed that first a report should be prepared, reflecting the main results obtained from previous national or regional tests. This will serve as a basis for further recommendations on how best to proceed for most effectively guaranteeing homogeneous temperature observations in all climatic regions.

This report, prepared under the supervision of Mr D.W. Jones (UK), provides an excellent and concise overview of the main results of tests of thermometer screens, some of which date from the previous century. The report provides useful information especially if further activities in this regard are planned, such as national or regional tests. It is also a useful reference for those who intend to develop new thermometer screens or to improve the design of existing ones for various applications and for use in different climatic zones.

The report generally shows that:

- The basic Stevenson screen design has been in use already for a century.
- Over this time there have been many attempts to modify the design of screens with the intention of improving their performance and to determine their influence on the temperature measurement.
- The differences in measurements caused by the condition of the surface of a good design of screen can be as important as the differences between different screen designs.
- Changes to screen designs may change climatological records.
- Different screen designs suit different climatological regions.

I wish to thank Messrs A. Barnett, D.B. Hatton and D.W. Jones (all UK) for their contributions to the preparation of this report. I also thank the Meteorological Office of the United Kingdom for the support given to this undertaking.

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Recent Changes in Thermometer Screen Design and Their Impact

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1. Introduction

Recent changes to thermometer screen design and a heightened awareness of global climate changes have focused the mind of the meteorological world, in particular climatologists, on the effects these changes are bringing about. There is concern that any changes that take place could influence the homogeneity of the temperature records. The purpose of this report is to examine the recent published work on instrument screens, intercomparisons and theoretical studies and to make recommendations on how to proceed with ensuring continuity in the meteorological records.

The practice of temperature screen intercomparison is not new. The first reference documented, and probably the first coordinated study was performed in the grounds of Strathfield Turgiss (now known as Stratfield Turgis in southern England) by the Reverend C.H. Griffith F.M.S. 'Who himself kindly undertook the laborious task of conducting the observations, consisting of readings of all of the instruments at 9 a.m., 3 p.m. and 9 p.m., from November 1868 to April 1870 inclusive, broken only by an absence of one month in January 1870.' (Gaster 1882)

Throughout this report a 'Stevenson screen' will be referred to several times; this is to be read as the country's standard size, louvered, often wooden thermometer enclosure. It is acknowledged that some countries, such as Iceland will not use such a screen as their standard because of the climate.

2. Why change the design of screens?

The drive for changes in meteorological measurements is based primarily on economic factors, whether it be manifest as automation or smaller changes to decrease maintenance costs. But in many ways the changes are both inevitable and desirable on scientific terms. Recent changes in technology are enabling more accurate meteorological measurements when compared to the current and recent methods, which often date back decades.

The advent of more modern methods of temperature measurement, including automation, has resulted in smaller sensors to be used in screens. It follows that the traditional Stevenson screen or box designed to house several liquid in glass thermometers and possibly thermographs are unnecessarily large. These screens are also expensive to build and maintain and it is therefore advantageous that smaller more cost-effective screens should be sought.

2.1 The development of screen design

In 1873 the Royal Meteorological Society produced a list of conditions that should be fulfilled by a thermometer screen;

1. The thermometers must be protected from the rays of the sun at all times.
2. The thermometers must be unaffected by the heating of the outside of the screen.
3. Reflected radiation must be excluded.
4. Other exterior factors (e.g. heat from nearby buildings) must be excluded.
5. There must be free access of the air around the thermometers.
6. The thermometers must not be wet by precipitation.

The result was the screen attributed to Stevenson. It was soon realised by Mawley (1897) that the Stevenson screen had shortcomings. Namely that the bottom of the box was open and could let reflected radiation in from underneath causing overheating on 'sunny afternoons' (something which recent tests at the UK Meteorological Office have confirmed (Barnett 1997) and that the roof was not ventilated enough, causing a build up of heated air. He proposed alternatives that resulted in the Stevenson screen that is now recognised throughout the world, and has remained largely unchanged.

Further tests showed the need for two more conditions (Köppen 1913);

7. The thermal inertia of the screen plus contents should be as low as possible to minimise the lag of the observed temperature relative to the true air temperature.
8. The site of the screen must be representative of the true climate.

Several changes have been suggested for the Stevenson screen since then, however most have not come into use and the screen has become almost universal.

There are some well known problems with the Stevenson screen that cause systematic errors and have resulted in meteorological instrument makers being kept occupied in the design of new screens for many years. The main problem with the traditional wooden screen is simply its bulk. This large bulk equates to a thermal inertia on the observed temperature.

Tests in 1947 by Langlo used measurements made in 56 screens throughout Norway which resulted in the estimation of a lag coefficient equation. Evaluating this equation gives an estimated 5+ minute lag for a wooden Stevenson screen in a 5 knot wind. This combined with the lag of the instrument inside the screen and lower wind speeds can lead to a much higher lag, possibly as much as 15 minutes or more. It has also been suggested by the team developing the Israeli screen (Thaller et al. 1967) that different wood used in the construction of the screen may also affect the lag of the screen. To extend this it could be said that any material used in the construction will behave differently from other materials that could be used and thus the choice of materials is very important.

Degradation of the outer surface of the screen is also a problem. It was shown, in a field test of thermometer screens (Andersson & Mattisson 1991), that with even a slightly degraded screen the temperature differences were significantly large. This was not a 'rotten' screen that had been left for years, as in the words of the report - 'The painting was old, some paint had flaked off, but otherwise no difference could be detected at visual inspection.' The overall results are presented in Table 1; the screens were compared to a Teledyne 327B reference psychrometer.

Screen	RMS • °C	Skewn • °C	Max. °C	Min. °C
Poor Condition	0.295	0.32	1.00	-0.75
Good Condition	0.241	0.26	0.87	-0.62

- RMS is the root mean square of the difference.
- Skewn is a measure of the lack of symmetry about a mean value, a positive or negative higher value indicates more data to the positive or negative side of its mean respectively.

Table 1

The figures show that the screen was warmer with more scatter in its observed temperatures. To date no reference of a comparison to the WMO standard reference has been found.

Amongst the other problems with the Stevenson screen is that of a microclimate within the screen itself (Lin and Hubbard 1996). There may be vertical gradients of air temperature, and on days of high direct solar radiation there may also be a vertical gradient toward the direction of the radiation.

Sparks (1972) and Parker (1994) brought together data on the effect of thermometer (screen) height on observed temperature, and through several studies demonstrated that the lower screens produce greater diurnal ranges than higher screens. They also showed that the increase in range was largest in mid-summer and smallest in winter. No averages for daily temperatures were given. This report will not go into detail on this subject because it is well documented in both papers.

It is worth noting that the WMO standards still indicate that a height of 1.25 - 2 m is acceptable for thermometer exposure, and the UK and many former British locations still use 1.25 m as opposed to 1.5 - 2 m for most other countries. Nevertheless D.E. Parker (1994) states that international differences are less important than changes in procedure or exposure at individual locations for monitoring climatic changes.

In the paper by W.R. Sparks (WMO 315), he cites that the error caused by the tolerance in observation time with regard to temperature measurement can cause significant and sometimes large errors. Tests at Kew Observatory between 1901-1930 showed that the mean rise in temperature between 0800 UTC and 0900 UTC was 1.33°C. Consequently errors of up to 0.2°C could be produced by the tolerances in the nominal time of reading the thermometer. This result is for a temperate country; the errors may be larger for less temperate regions. In reality, of course, the errors would be random, or at least random on a large scale and are therefore not systematic. An automatic system of temperature measurement would largely eradicate these errors.

3. Experiences with some modern screens

There have been several National Intercomparisons in the last 5-6 years and several introductions of new design screens into national networks. The main types of new designs are:- replacement non-wooden Stevenson screens, small cylindrical screens and 'sandwich' screens. There are also other types under research and development, but too little information is available to comment.

3.1 Non-wood screens in the Stevenson pattern (boxes)

These screens came about to solve some of the problems with the wooden Stevenson screen as listed above without reducing the volume within the box for instruments.

There are three designs of these screens that have been recently documented; the Israeli screen (around for some time now and in service in Israel), the KNMI screen (in service in the Netherlands) and the French 'Socrima' screen also in service.

The UK Meteorological Office recently tested a KNMI screen in its program to investigate more cost effective solutions to the Stevenson screen (Bridgman 1997). This screen is larger than the UK Large Stevenson screen, is made of plastic and is more cube shaped than most Stevenson screens. Its louvres are numerous and closer together than a traditional box type screen with the inner and outer roofs at a larger distance apart and more sloping. The design was to incorporate existing plastic manufactured parts and therefore the louvres are at 90° to each other and do not overlap in the same way as a wooden Stevenson screen. The UK trial used a Vector Instruments T302 psychrometer as the reference, an instrument designed within the UK Meteorological Office and one which has a respectable comparison to the Teledyne 372B (Moore and Callander 1987). In trials the screen performed well, see Table 2.

Table for the KNMI screen referenced to the Vector T302

	Mean °C	Max. °C	Min. °C	Mean Difference °C	RMS Difference °C	Skewn °C	Maximum Difference °C	Minimum Difference °C
Large Stevenson	10.19	26.72	-4.21	0.02	0.16	0.12	1.76	-2.10
KNMI	10.20	26.82	-4.23	-0.02	0.13	0.13	1.87	-1.89
T302(Ref.)	10.22	26.89	-4.40					

Table 2

The trial also investigated the levels of solar radiation within the screen; the KNMI let in very slightly less radiation than the large Stevenson screen.

The French 'Socrima' screen has been in use for some time and is currently being investigated by the UK Met. Office. It is plastic and larger than some standard Stevenson screens, but over the years has shown itself to have a smaller thermal inertia than wooden ones.

The Israeli screen was designed after extensive testing of a 'standard' screen (Thaller et al. 1967). The most obvious difference is that it is cylindrical with a diameter of 0.55 metres. It is effectively double floored with instruments on both floors. It is made of fibreglass and was designed to overcome the ventilation problems of the standard 'rectangular' Stevenson. This was found to be effective, yielding slightly lower temperatures in American National Weather Service tests.

Though there has been work on improving large screens the majority of recent work is in the field of small cylindrical screens designed to house only one or two small electrical thermometers, or hygrometers.

3.2 Cylindrical screens

These screens are small and light and relatively cheap to manufacture; much work has gone into this type of screen. Several countries have performed tests on this type of screen. They are usually made of white plastic disks shaped to make louvres, with a cut out through the centre of all but the top plate to hold a vertically held temperature sensor. There are also designs which use grey anodised aluminium; these will be commented on later. These types of screen can only hold one electrical temperature sensor.

Sweden (SMHI) performed a field intercomparison of thermometer screens in 1989 (Andersson and Mattisson1991). Their main conclusion is that the smaller cylindrical screens had less lag associated with them, with the observed temperature changes only lagging behind real temperature changes by a short time. SMHI also concluded that they represented a better temperature measuring environment. They generally produced slightly larger ranges throughout the day, yielding slightly lower minimum temperatures and slightly higher maxima, with the exception of the Vaisala screen which exhibited the opposite effect. Tables 3 and 4 show some of the differences found between cylindrical screens when compared to the reference, a Teledyne 327D psychrometer.

Table of Average Differences referenced to the Teledyne 327B

Screen	Mean °C	RMS °C	Skewn °C	Max. °C	Max. °C
Vaisala	-0.01	0.154	-0.12	2.08	-1.58
Young	0.00	0.168	0.17	3.36	-1.86
Lambrecht 1	0.04	0.215	0.24	2.51	-1.70
Lambrecht 2	0.01	0.209	0.17	2.49	-1.95

Table 3

Table of Average Daily Differences at Maximum and Minimum Temperatures referenced to the Teledyne 327B

Screen	Maximum Temperature °C		Minimum Temperature °C	
	Mean	RMS	Mean	RMS
Vaisala	-0.11	0.215	0.10	0.151
Young	0.00	0.179	0.00	0.142
Lambrecht 1	0.20	0.304	-0.08	0.164
Lambrecht 2	0.18	0.304	-0.13	0.208

Table 4

It is interesting to note that the figures given in the last two columns in Table 3 are larger than the WMO Guide to Meteorological Instruments and Methods of Observation suggest you should find; "the temperature of the air in a screen can be expected to be higher than the true air temperature on a day of strong sunshine and calm wind and slightly lower on a clear calm night, with errors perhaps reaching +2.5°C and -0.5°C respectively in extreme cases". The SMHI report, however, does not state how many times these extremes were exceeded. In the report they also concluded that wind speed is very important and that above a certain 'threshold' for a particular screen its efficiency at measuring the true air temp is greatly increased.

Another point of interest in the report is the work done on the times of greatest difference with the reference. It was concluded that the time of maximum differences in the positive was not at the time of highest solar irradiance, as one might expect, but at times of sunset and sunrise. This, it was proposed, was because of the relatively high temperature changes brought on by the sudden increase, or decrease, in radiation and the normally lower wind speeds at dawn and dusk. It could also be, however, that these designs permit the direct entry of solar radiation onto the thermometer, a factor which could at least contribute to the errors. Included in this trial was a cylindrical screen not made out of plastic but made of grey anodised aluminium, the Lambrecht. This screen had a tendency to over read in direct solar radiation, especially that reflected by snow. The silver/grey colour absorbed short wave radiation which heated the materials of the screen much more than the white screens and this was passed by conduction and radiation to the sensor.

The Australian Bureau of Meteorology conducted tests for five different cylindrical screens in 1994 (Huysing et al 1995). Preliminary results only are available but they echo the results of the above trial that the screens tend give lower minimum temperatures and higher maximum temperatures. The reason that the Vaisala instrument shows a different pattern is puzzling but the Australian researchers suggest that it also has quite a large thermal lag also because of its bulk, although it is only 21cm diameter x 30cm high.

The UK recently performed a field intercomparison on a Gill multiplate radiation shield (RM Young) of which the results are presented in Table 5;

Table for the Gill screen referenced to a Vector T302

	Mean °C	Max. °C	Min. °C	Mean Difference °C	RMS Difference °C	Skewn °C	Maximum Difference °C	Minimum Difference °C
Large Stevenson	10.19	26.72	-4.21	0.02	0.16	0.12	1.76	-2.10
Gill	10.22	27.17	-4.35	0.01	0.15	0.22	2.85	-1.36
T302(Ref.)	10.22	26.89	-4.40					

Table 5

The results regarding the lower minima and higher maxima can be attributed to the fact that the Stevenson screen has a large bulk and therefore a large thermal inertia slowing down its response to shorter term temperature changes.

Brock and Richardson performed extensive theoretical and practical research into cylindrical design of screen (1995) to ascertain those aspects of design which were most important. They concluded that optimum shield design is a function of the climatology of where it is to be used as well as that of the characteristics of the sensor contained within. Factors that caused most errors in reading air temperature in screens were solar elevation and azimuth angle (a factor that was suggested earlier), as larger temperature errors were seen when the solar radiation comes from the same direction as the wind, ground reflectance and the occurrence of high insolation with low wind speeds. The last confirms the experiences of the SMHI screen trials. They concluded that screen characteristics to consider were diameter, length, thermal conductivity, absorptivity and the location of the sensing element within the screen. Most screens that block radiation effectively also block air flow but if there is to be a trade off Brock and Richardson suggest that the latter should have priority. Also the screen should have as small a diameter as possible so as not to heat the air passing over the louvres.

3.3 Sandwich screens

These are similar in external appearance to the cylindrical screen reported above, but they do not have their centre portions cut away. The only publicised results of these types of screen in recent years emanate from the UK Meteorological Office (Bridgman 1997). The screens tested were developed for use in a marine environment (ODAS), and are in service with this organisation on meteorological data buoys. The screens consist of circular disks of fibreglass, white on the upper side, black underneath, except the bottom one which is all white. The disks are turned down at the edges to form louvres, and the temperature and humidity sensors are mounted horizontally between the disks.

Three types of these screens were tested, a standard one, one without the black undersides on the disks, and one with fewer disks containing only one instrument (effectively half height). The results are presented in Table 6.

Table of results for ODAS screens tested by the UK Met. Office against a Vector T302.

Screen	Mean	Max.	Min.	Mean Diff.	RMS Diff.	Skewn	Max. Diff.	Min. Diff.
Standard Sandwich	10.21	26.67	-4.23	-0.01	0.10	0.07	1.24	-1.28
Non-Black Sandwich	10.25	26.94	-4.20	0.04	0.14	0.17	1.43	-1.23
Half Height	10.18	26.99	-4.65	-0.04	0.17	-0.18	1.83	-2.09

Table 6

It can be seen from these results that halving the number of disks has a considerable impact. It is also worth noting that the standard sandwich screen performed better, when compared to a Vector T302 reference psychrometer, than any other screen, including the KNMI screen, two sizes of Stevenson screen, and a Gill cylindrical screen.

4. Theoretical Work

The recent work by Brock, Richardson and Semmer (1995) demonstrate that new techniques can be used to quickly evaluate proposed designs of screen and give valuable insight into the behaviour of the screen. Not even Brock et al. suggest that these techniques can replace the empirical methods so far used to evaluate screens. In fact they explicitly say they cannot but can produce guidelines as to screen design.

The techniques used are optical ray tracing, numerical fluid flow modelling and analytical heat transfer analysis. Optical ray tracing is used to estimate the radiative power absorbed by the screen and sensor by tracing the path of radiation through the screens together with absorption figures for the materials. Fluid flow techniques can be used to assess the flow efficiency, the ratio of flow speed around the sensor to the upwind speed, and can estimate the heat transfer from the plates to the sensor. Analytical heat transfer is used to estimate the errors caused in the screen by radiation, convection and radiation.

Their conclusions for the study were outlined in the last paragraph in section 3.2. The studies are ongoing and they are hoping to improve the models with the next phase of the work. This method could provide an excellent opportunity for analysing screens quickly, removing the problems of performing year long environmental experiments which show the screen clearly to be poor.

5. Air Temperature References

In order to fully understand the measurement capabilities of any system of screen and thermometer a reference has to be used. In 1981 CIMO recommended that the psychrometer designed by the Australian National Standards Laboratory was adopted as the reference instrument for determining the relationship between the air temperature measured by conventional surface instruments and the true air temperature. It was adopted in 1982. It is of complex design (Wylie and Lalas 1992) and since its acceptance there have been many screen trials but none published that used the reference. Many have used the Teledyne 372B and some have even designed their own reference psychrometer, the UK being one of them.

To ensure continuity between regions, global and local references must be actively used ensuring worldwide traceable air temperature measurements.

6. Conclusions

We have seen that modern screens can represent air temperature in a more realistic way than traditional wooden Stevenson screens but they also represent a split from the tried and tested methods of temperature observation that have been used for decades, or in some cases over a century.

The dangers of introducing new instrumentation into networks can hardly be better illustrated than by the recent American experience (Quayle et al. 1991) with the Maximum-Minimum Temperature System (MMTS). It involved changing the traditional screens with small cylindrical screens and replacing the liquid in glass thermometers with thermistor based sensors. Nearly 3000 were exchanged in four years. This resulted in a step change in the apparent climatolgy, with a REDUCTION in daily range by 0.7°C, a value that is highly significant in any climatological study. Those implementing these changes realised that while it was troublesome for climatologists it represented an improvement in the accuracy of reading air temperature, and algorithms were developed for adjusting the bias of the new systems in the records. The conclusion was that while the change was needed there needed to be a scientific infrastructure to monitor these changes and to develop adjustment methods for climatological records.

In 1972 W.R Sparks wrote that even excluding systematic errors 'the standard error of individual temperature measurements with equipment then in routine use was about ±0.13°C, and that to decrease this random error by a significant factor (Sparks suggested 2.6) would be a difficult and expensive task'. (This would indicate that Sparks was looking to reduce the random errors to ±0.05°C or less.) This error is, in fact, now reduced in many places by the introduction of automation. The problems that now face temperature measurement are systematic errors that are induced by screen design and thermometer construction. The figure given by the WMO for the accuracy, systematic and random errors combined, is currently ±0.1°C. This paper shows that operationally this is still not possible even with modern measuring equipment because of the errors induced by screens and the nature of the measurement.

Automatic observations represent a conceptual change in meteorological measurement. It is important to remember that automatic systems are not merely observation making equipment but can be systems which monitor the atmosphere constantly. This is most useful when analysing the changes that take place during equipment change, and used carefully, the changing face of meteorological observations need not impact greatly on climatological records. In the UK, the Meteorological Office has continued to use its standard Stevenson screen, even at most new sites and after a former manual site is automated. This also has the advantage that any effects due to other changes in the measurement chain can be identified and resolved, eliminating the problem of dissaggregrating the cause(s) when whole new systems are put in at one time.

It is also important to remember that temperature measurements are still taken manually in many places and that this is likely to continue for some years yet, continuing to influence the screen design.

7. Recommendations

It is clear from Sparks (1972) that large differences in the behaviour of individual screens in different climates can be seen. The many studies that have been referenced here, whilst all addressing various aspects of the same basic problem, temperature measurements generally and screen performance specifically, have all addressed these topics from slightly different standpoints, with no single methodology.

It is therefore recommended that, in future, reports of such studies should emphasise local climate, ground reflectivity and wind directions, as well as the more technical details that they tend to concentrate on now.

Other recommendations that will help to reduce errors are;

- A tighter definition of air temperature measurement for routine meteorological use as recommended by W.R. Sparks in 1972. This should include a standard height for the measurement, an averaging time for the observation and tighter controls over when the reading is made.

- References used in intercomparisons should be traceable to accepted (WMO?) standards.

- When changing instruments, overlapping comparisons should be made with the current equipment.

- The use of analytical modelling techniques for the assessment of screen performance should be encouraged, and development of these techniques themselves should be continued in order to improve their effectiveness and thereby reduce the effort required in the future to determine performance empirically, particularly in relation to extreme events.

With regard to temperature measurements and their impact on global climate studies it is clear that the first step should be undertaken at national level. This should determine the performance in absolute terms of the measurement system(s) currently in operational use, and relate these to the measurement system(s) used previously.
With regard to intercomparisons on larger scales (i.e. international ones) it seems unwise to contemplate a single global intercomparison, as different climatological regions have different requirements from their screens; see Sparks (1972). However it is also clear that intercomparisons on a regional basis can provide invaluable information for normalising data sets across international boundaries. Ideally for this there should be an accepted international reference, but the use of regional representative screens should also be considered.

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