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EFFECTS OF CHANGING EXPOSURE OF THERMOMETERS AT LAND STATIONS

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ABSTRACT

In view of the implications for the assessment of climatic changes since the mid-nineteenth century, systematic changes of exposure of thermometers at land stations are reviewed. Particular emphasis is laid on changes of exposure during the late nineteenth and early twentieth century when shelters often differed considerably from the Stevenson screens, and variants thereof, which have been prevalent during the past few decades. It is concluded that little overall bias in land surface air temperature has accumulated since the late nineteenth century: however, the earliest extratropical data may have been biased typically 0·2°C warm in summer and by day, and similarly cold in winter and by night, relative to modern observations. Furthermore, there is likely to have been a warm bias in the tropics in the early twentieth century: this bias, implied by comparisons between Stevenson screens and the tropical sheds then in use, is confirmed by comparisons between coastal land surface air temperatures and nearby marine surface temperatures, and was probably of the order of 0·2°C.

KEY WORDS Climatic change Surface air temperatures Exposure of thermometer screens

1. INTRODUCTION

Long-term surface air temperature records, extending back to the late seventeenth century, have required careful compensation for the changes of design and siting of thermometers (Manley, 1974). However, even since observations at land stations became widespread in the mid-nineteenth century, there have been substantial and systematic changes in exposure of thermometers. The impact of these changes on perceived climatic trends may not have been negligible. A review of the changes of exposure, and of their probable effects, is therefore an essential part of any assessment of world-wide climatic change.

This brief study will comprise four parts:

(i) a résumé of the principles of thermometer exposure;
(ii) an account of documented changes of exposure;
(iii) a survey of published comparisons between observations with differing exposures;
(iv) a discussion of some of the observed trends in regional temperatures in terms of changes of thermometer exposure.

2. THE PRINCIPLES OF THERMOMETER EXPOSURE

The frequent changes and international variety in thermometer exposure during the second half of the nineteenth century were a result of a growing realization of the conditions that should be fulfilled by a 'perfect' exposure. Mawley (1897) quotes a list of conditions formulated in 1873 by the Royal Meteorological Society after extensive consultation and discussion. These included:

(i) the thermometers must at all times be shielded from the direct rays of the Sun;

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(ii) the thermometers must be unaffected by heating of the outside of the screen;
(iii) reflected radiation must be excluded;
(iv) other exterior influences (e.g. heat from buildings) must be excluded;
(v) there must be free access of air round the thermometers;
(vi) the thermometres must not be wet by rain or covered by snow.

As a result the old-style Stevenson screen with an open base (Figure 1(a)) was recommended by the Society in 1873 for general adoption in the UK. However, it was soon superseded by a newer version (Mawley, 1884), with a double roof, and with staggered boards across the base so as to exclude reflected radiation more effectively. Stevenson's screen, along with a special stand used at Kew, were the only screens employing louvres to ensure good ventilation and adequate screening from radiation in Gaster's (1882) comparison of screens in 1869.

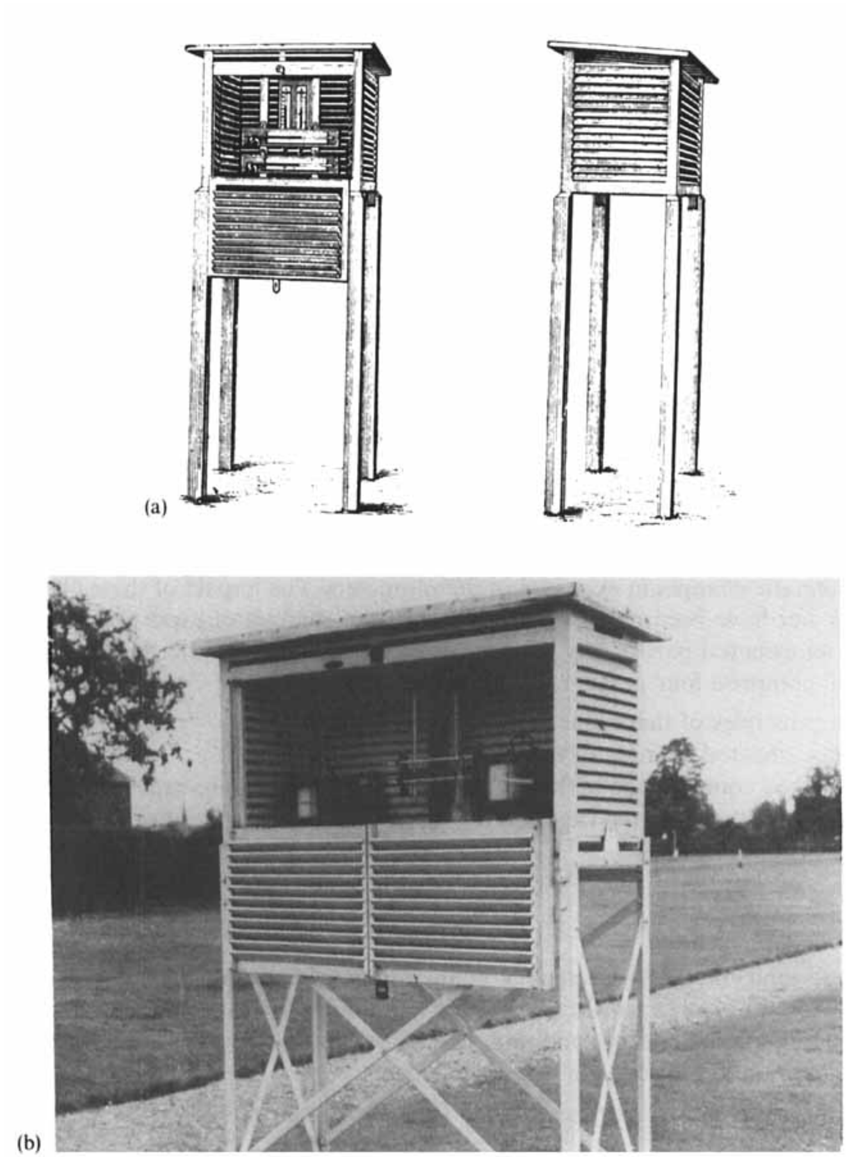

Figure 1. (a) Stevenson screen, old version (from Mawley, 1897) © Royal Meteorological Society. (b) Modern Stevenson screen © HMSO

Many of the observed differences between exposures (see section 4) were attributed to greater or lesser adherence to these conditions. The extensive comparisons also indicated the need for two further conditions (Köppen, 1913):

(vii) the thermal inertia of the screen plus contents should be as low as possible, to minimize lag of the observed behind the true temperatures;

(viii) the site of the screen must be representative of the true climate. This can be regarded as partly an extension of (iv). It excludes sites in the shadow of a building, which are unrepresentative of open fields.

Köppen found that, of existing screens, the Stevenson screen was, although imperfect, still the best. Its readings were, however, somewhat affected by heating, or cooling, of its exterior. To reduce these influences,

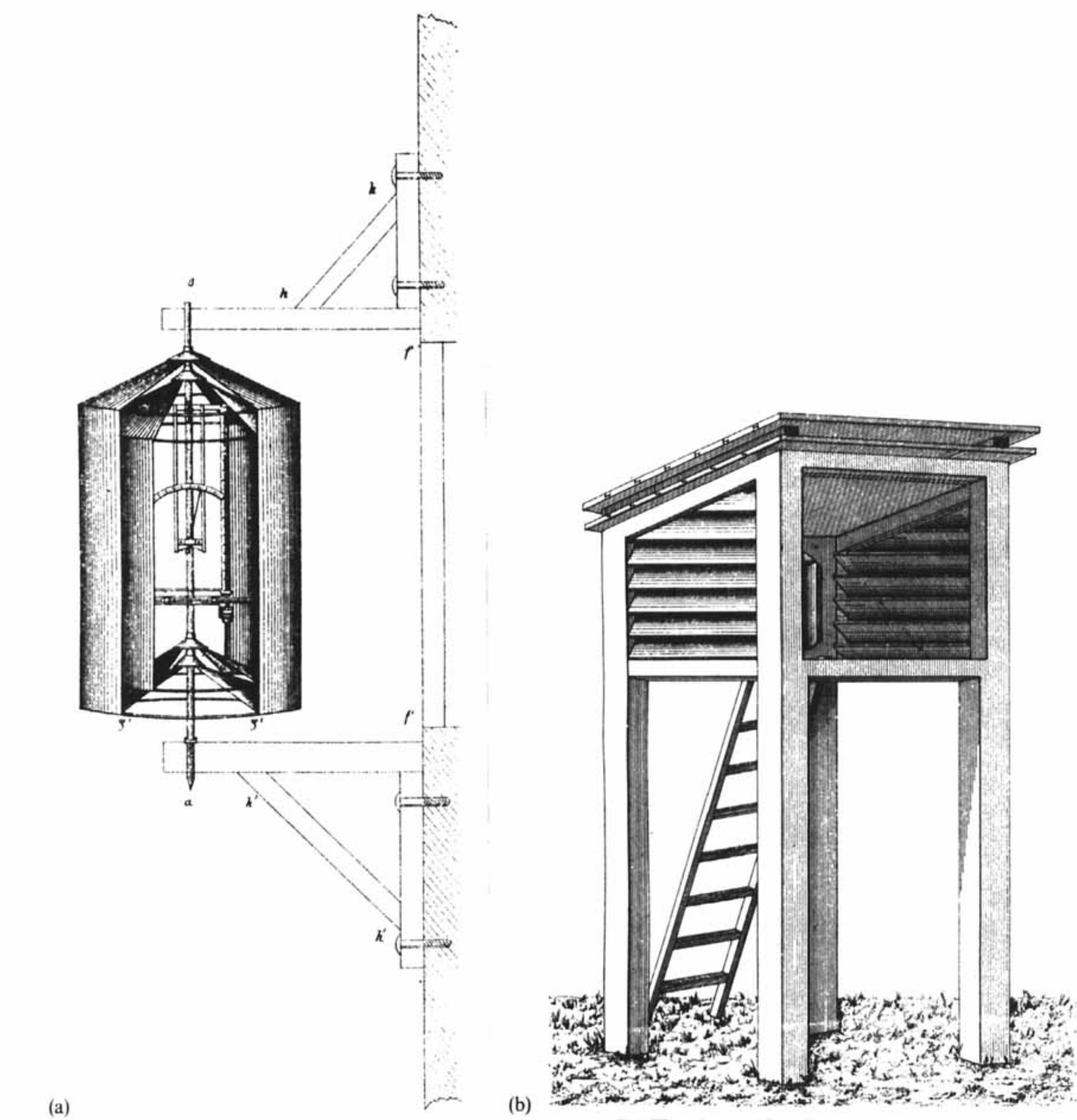

Figure 2. (a) Wild's cylindrical zinc shield (1874) (from Wild, 1879). (b) Wild's screen to house his shield (1874) (from Wild, 1879)

Köppen designed special shelters to protect a version of the screen from receipt or loss of radiative heat. Different shelters were proposed for different latitudes because of the different combinations of solar elevation and azimuth, but did not come into general use (Sparks, 1972). A belief in the inadequacy of Stevenson screens in the tropics had, nevertheless, already resulted in the use of cages beneath thatched shelters in parts of southern Asia, Africa, and Australia (see Section 3). Ultimately, however, Stevenson screens in various forms became almost universal (Sparks, 1972).

An extension of condition (viii) was cited by Köppen as the reason that the thermometers in mainland Europe were about 2 m above the ground, as opposed to about 1·2 m (4 ft) in the UK. Köppen stated that 'the purely local influences are greater, the nearer the instrument is brought to the ground, and a "climatic" temperature is to be found in the more disturbed air at some height above the ground'. Hazen (1885) in the USA had the same opinion. A further consideration was the greater depth of snow in these countries (Gorczynski, 1910). In Wild's screen (Figure 2) the hygrometer bulbs were to be 12 ft (3·7 m) above the ground (Wild, 1879). The world-wide survey by Sparks (1972) shows that thermometers in the UK and in formerly British locations (e.g. Australia, Canada, Cyprus, Kenya, Tanzania, Uganda, Ghana, India, Kuwait, New Zealand, Nigeria, South Africa) continued to have their bulbs at 1·25–1·5 m, as opposed to 1·5–2 m in most other countries.

Diurnal ranges are greater at lower thermometer-elevations (Sparks, 1972). Sparks summarized studies by Hellmann (1922), Ramanathan (1929), and Nawa (1965). In Hellman's investigation, a screened thermometer at 1·4 m above the ground, in Potsdam, Germany, yielded monthly mean maxima up to 0·4°C higher and monthly mean minima up to 0·28°C lower than an identically screened thermometer 2·08 m above the ground. Individual differences did not exceed 1°C. Ramanathan's (1929) measurements in Agra, India yielded similar results, but the monthly mean maxima in the lower screen, at 1·5 m, were up to only 0·17°C higher, whereas the monthly mean minima were up to 0·44°C lower, than in the screen at 1·85 m. Finally, to quote from Sparks.

> 'During two winters at Obanazwa, Japan, Nawa (1965) compared screens with their bottoms 1·0 m and 2·5 m above the ground with a special shelter that could be adjusted to keep it 1·0 m above the snow surface. Over the period for which the results are given the depth of snow varied from 30 cm to 150 cm. He found that the higher screen was in much better agreement with the adjustable screen. The maximum temperature in the lower screen differed by more than 0·6°C from that in the adjustable screen on about 20 per cent of occasions, while that in the higher screen differed by the same amount on only 3 per cent of occasions. The minimum temperature in the lower screen was considerably lower than that in the adjustable screen, the largest difference was 2·0°C and (estimating from the published graph) about 9 per cent of the differences were greater than 1·0°C. The differences decreased with increasing wind speed'.

Nevertheless, for monitoring climatic changes, international differences in observing exposure or procedure are less important than changes in exposure or procedure at a particular location. Documented changes of exposure are therefore dicussed in the following section.

3. DOCUMENTED EARLY THERMOMETER EXPOSURES

A selection of national information on early thermometer exposures is presented here. It is limited by the availability of published documentation, but is probably sufficient to reflect the dominant exposures in world-wide use between the mid-nineteenth and mid-twentieth century. It complements the more complete catalogue of Sparks (1972) of thermometer screens in use around 1970.

The user of data should be aware that not all stations may have followed the national pattern and that observatories in particular may have been atypical. Thus, estimates of temperature trends, particularly for small regions, should be assessed in the light of any available documentation for the stations chosen. *World Weather Records* (Smithsonian Institution, 1927, 1944, 1947) provides useful information for some stations. For analyses of the hemisphere and globe, the overall picture presented here should, however, be a useful guide.

3.1. Argentina

North American pattern Stevenson screens (see section 3.30) were used from the late nineteenth century onwards (Smithsonian Institution, 1927).

3.2. Australia

The use of a Lawson stand (Figure 3) in Melbourne in 1858–1862 is documented by Neumayer (1864). The stand was raised on a platform about 5 ft high. Until 1865 the stand could be rotated: thereafter, a fixed Lawson stand was used, until 1880 when a French-type shelter, open to poleward, was built (Ellery, 1881; Hazen, 1885). In Sydney, a stand 'similar to that at Greenwich' (i.e. a Glaisher stand) was in use in the early 1860s (Scott, 1862). Wooden sides had been added to ensure shading. By 1870, however, this stand had been replaced by a specially built shed in which 'the minimum temperature is not so low on fine nights as in the Greenwich stand, where the instrument is exposed to the effect of radiation' (Russell, 1871). In 1888, a motion at the Intercolonial Meteorological Conference held in Melbourne, to install Stevenson screens at all Australian stations was not passed (Ellery, 1888), though by this time Stevenson screens were standard in Queensland (Donaldson, 1888). Hunt (1925) specified the use of a Stevenson screen in general, but a cage suspended under a thatched shelter (see Figure 4) was to be used at tropical stations.

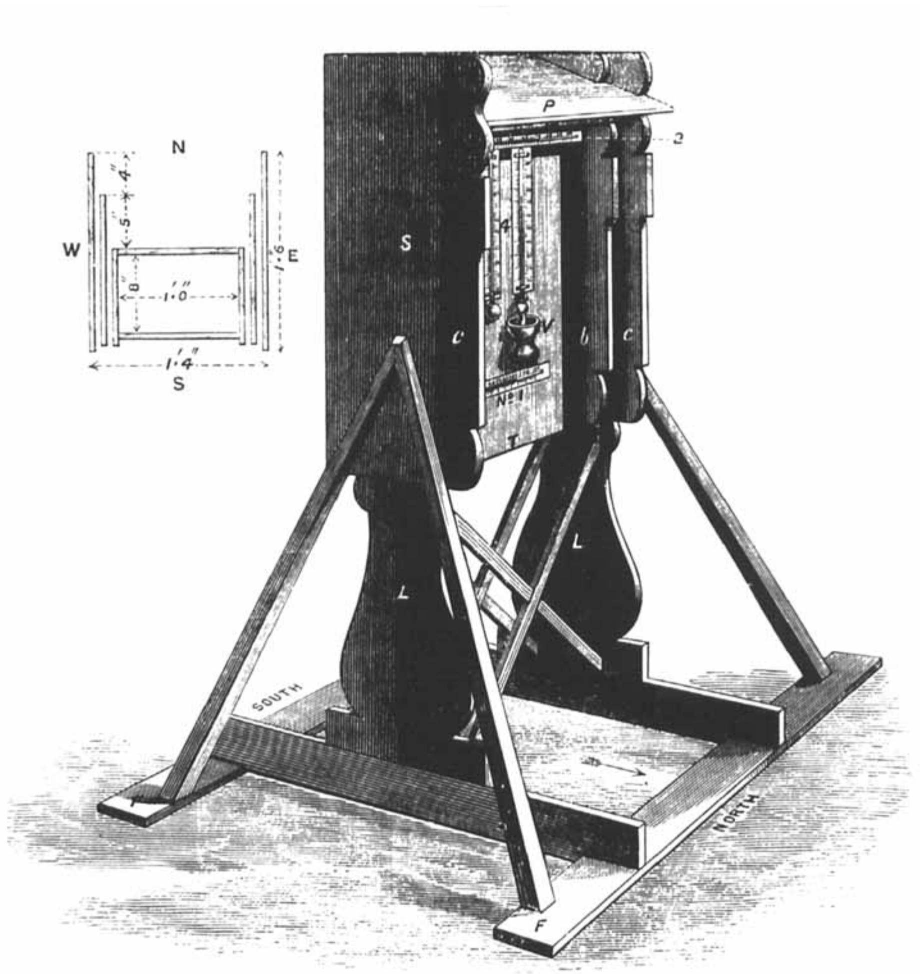

Figure 3. Lawson's stand (from Gaster, 1882) © HMSO

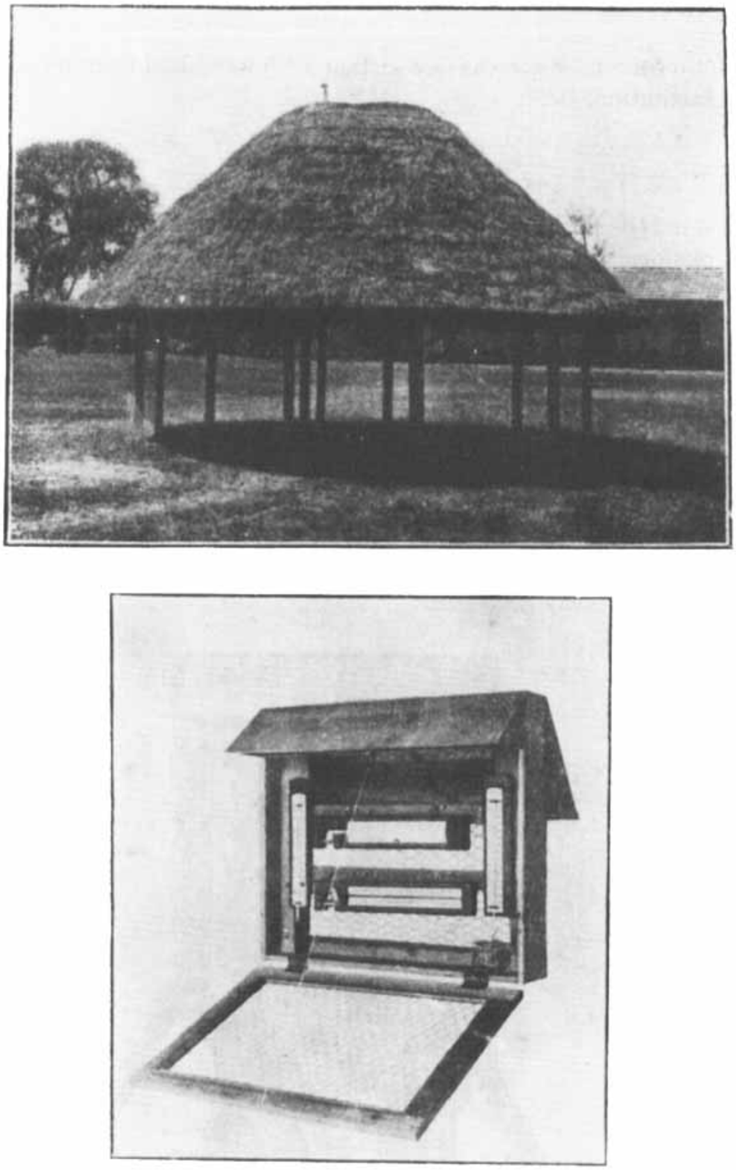

Figure 4. Thatched shelter and associated thermometer cage for use in the tropics (from Field, 1920) © HMSO

3.3. Austria

Wild (1879) states: 'the sheet metal screen ⋯ in Austrian stations offers the thermometers insufficient protection against radiation, particularly against that emanating from the ground'. Wild's cylindrical zinc shields (Figure 2(a)), outside a north-facing window of a building and without Wild's surrounding screen (Figure (2b)), were subsequently introduced (Gorczynski, 1910). Note, however, that Wild had designed Figure 2(a) to be inside Figure 2(b): this was done in Russia, see below. By 1920, double-louvred white wooden screens were in use at two of the three observatories providing data to the Smithsonian Institution (1927). Information for other individual stations is given in inspection reports in the Austrian Meteorological Service yearbooks, e.g. Zentral-Anstalt für Meteorologie und Geodynamik (1907).

3.4. *Belgian Congo*

Vandenplas (1947) illustrates several screens in use in the Belgian Congo, including a shed similar in design to Figure 4. However, Stevenson screens were used at first-order stations in the network, which was almost entirely set up in the 1930s.

3.5. *Belgium*

At Brussels, the thermometers were fixed to one of the windows of the north side of the east wing of the Observatory, 3 m above ground level, from 1833 until 1877. Thereafter, a Stevenson screen was used at Brussels and, on transfer of the Observatory, at Uccle (Lancaster, 1901).

Between 1901 and 1910, louvred boxes, open to the north, were used at many Belgian stations. These afforded insufficient protection against radiation, as did the simpler shelters generally used between 1910 and 1920. Improved screens, louvred on all sides, were installed in the 1920s. Precise details of dates of changes of screens at individual stations appear to have been lost. Only at Uccle and Denée-Maredsous was the same exposure used throughout the period 1901 to 1930 (Poncelet and Martin, 1947). Three varieties of 'Stevenson' screen were in use in Belgium in 1970 (Sparks, 1972).

3.6. *Brazil*

A large louvred pavilion was used in Rio de Janeiro from 1870 until at least 1920 (Rotch, 1894). A double-layered louvred shelter was recommended by De Carvalho (1917) for main stations and a form of Stevenson screen for third order stations. De Carvalho commented that most of the shelters in the Sao Paulo network were covered with a thatched shading rather like English colonial stations (see Figure 4).

3.7. *British colonies in Africa*

Ravenstein *et al.* (1892) and the Meteorological Office (1907) recommended thatched sheds, as did Marriott (1902), but there is no reference to these in Marriott (1892). In 1924 Marriott recommended a change to Stevenson screens, as did an unpublished Meteorological Office memorandum in 1935 on the basis of Field (1920). Some stations in Africa were, however, already using Stevenson screens in the 1920s and before (Gamble, 1881; Smithsonian Institution, 1927, 1944).

3.8. *Canada*

Kingston (1878) instructed that the exposure be a louvred screen attached to the north side of a 'shed' or insulated board, as shown in Figure 5. However, from 1840 until 1889 the thermometers at Toronto 'were exposed on the north wall of the observatory in a shed formed of Venetian slats which extended to a distance from the ground of 3 to 4 feet' (Morley Thomas, pers. comm.). A shelter free of the building was used from July 1899 until the end of 1906. The Stevenson screen became the official screen at Toronto, and probably throughout Canada, in 1907 (Morley Thomas, pers. comm.).

3.9. *Ceylon (now Sri Lanka)*

Until about 1880, thermometres were exposed on verandahs. Cages under thatched shelters (see Figure 4) then became standard until 1904–1905, when wood or tiles replaced the thatch. By 1913, felt roofs were in use, with a ventilator. The cages had shielding against low-elevation insolation if necessary. Enlarged Stevenson screens in the open were installed in the late 1920s (Bamford, 1928).

3.10. *China*

A form of Stevenson screen was recommended for the 'Treaty Ports' by Doberck (1883), but a French screen (see Figure 6) was used at Zi-ka-wei near Shanghai (LeLec, 1875).

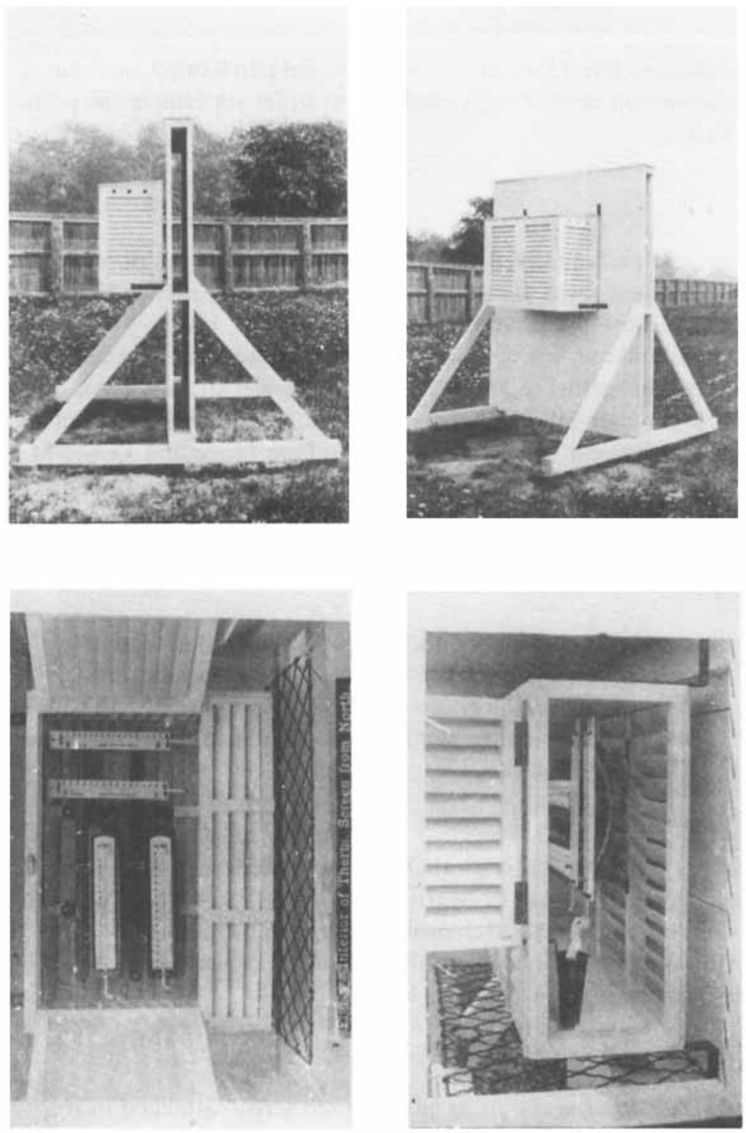

Figure 5. Canadian screen and 'shed' as recommended by Kingston (1878) © HMSO

3.11. Denmark, The Faeroes, Iceland, and Greenland

In 1873 the thermometers, 1·25 m above ground level, were placed in spacious wooden boxes with double trellised walls. The boxes were north-facing, with additional trellised attachments to shade against direct solar radiation if necessary (Danske Meteorologiske Institut, 1874). Subsequently, Stevenson screens were gradually introduced (Danske Meteorologiske Institut, 1933).

3.12. Egypt

Around 1910 a network of large Stevenson screens was established, replacing a Russian screen which had itself replaced an arrangement similar to the French shield (Figure 6; Köppen, 1913).

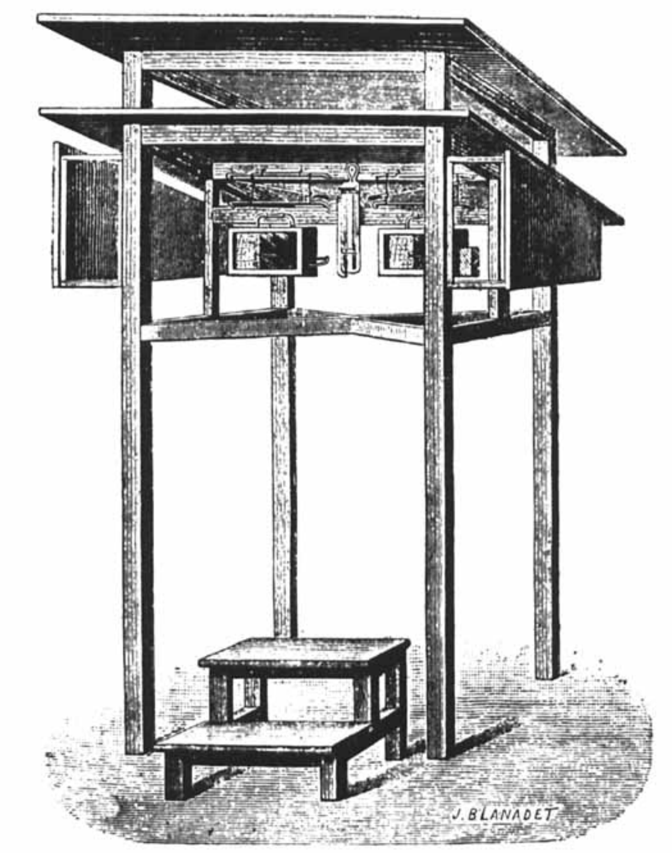

Figure 6. French shield (from Gorczynski. 1910)

3.13. France

In the nineteenth century French screens, open to the north (Figure 6), were used (Mawley, 1897; Gorczynski, 1910), sometimes in the shade of a tree (Köppen, 1913). In the 1930s, both French and Stevenson screens were in use, with the thermometer bulbs above 2 m above the ground (Office National Météorologique de France, 1932). At Montsouris (Paris) the French type of screen was used, unshaded, until 1948 when a form of Stevenson screen was introduced (Sparks, 1972; Dettwiller, 1978).

3.14. German colonies (in Africa)

These were using instrument cases in thatched or boarded sheds according to Köppen (1913). The height of the thermometer bulbs was something over 2 m above the ground.

3.15. India

Cages under thatched shelters (Figure 4) became general in India in the 1870s (Blanford, 1876). The standard height of the thermometer bulbs above the ground was 1·3 m (Field, 1920). There was shielding against direct low-elevation insolation if necessary (Bamford, 1928). Stevenson screens in the open were adopted in the 1920s as a result of the comparisons made by Field (1920), which are discussed in Section 4, though some minor stations already used Stevenson screens by 1920 (Field, 1920).

3.16. Italy

Denza (1882) specified a large louvred cage (Figure 7(a and b)), generally to be attached to a building outside a north-facing window, though open-field locations were permitted, as were balcony locations in the tropics. The side of the cage furthest from the building, i.e. to the north, was to be left open except during storms or in locations where reflected radiation might penetrate. The side of the cage facing the building was to be open, and the window of the building was to be kept shut. Wild (1879), however, stated that a wet and dry bulb thermometer with a fan but exposed thermometer had been introduced in Italy.

3.17. Japan

Stevenson screens were in use at Nemuro in 1889 and Sapporo in 1890 (Itabashi, 1890; Kuji, 1891), in approximate accord with instructions, probably dated 1887, that louvred screens with a ventilating pipe should be used over grass (Observatoire Météorologique Central du Japon, 1899). An example (Figure 8) illustrated by Okada and Sato (1905) shows that these screens may have differed significantly in design from Figure 1, but they will have been of the same genre. In 1950, ventilated psychometers were introduced into the screens in the Japanese network (Sparks 1972;Yonetani, 1992).

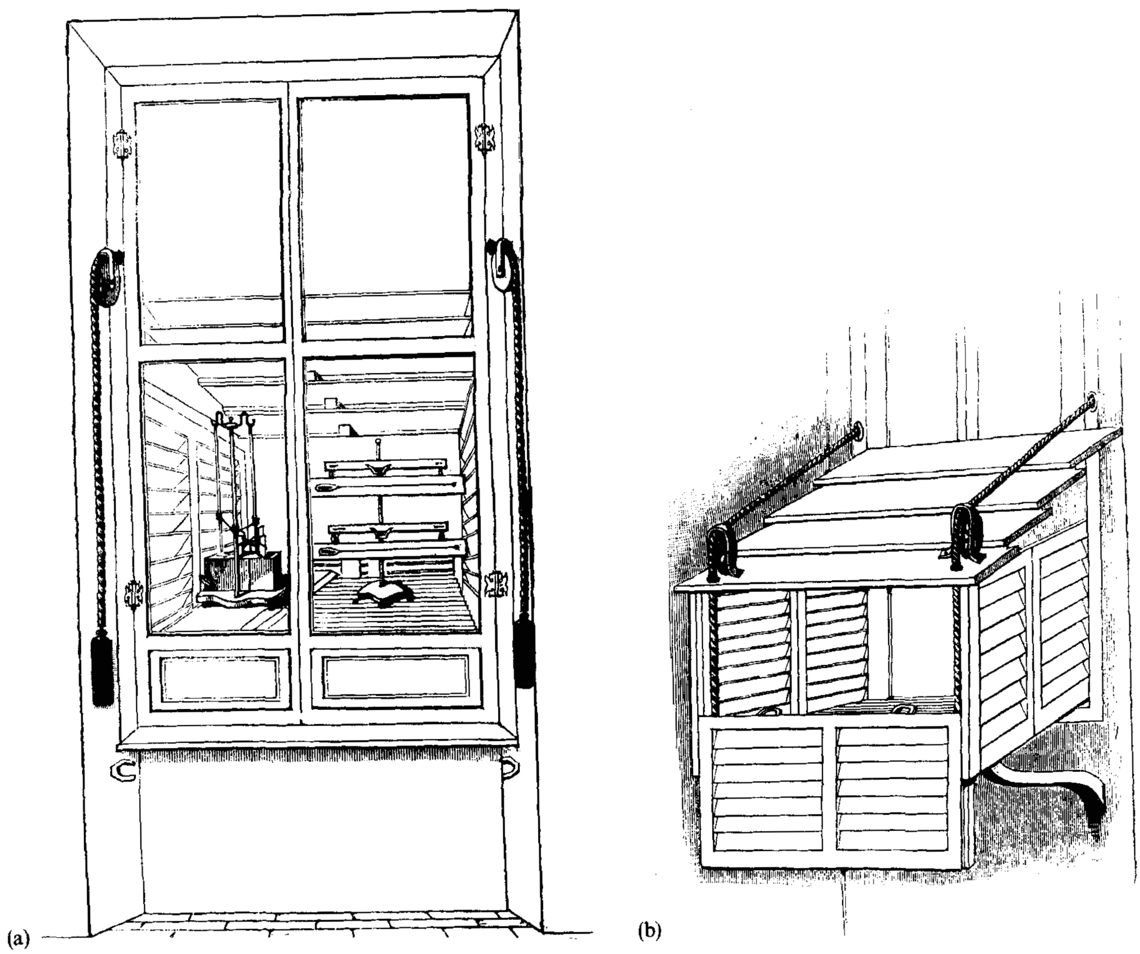

Figure 7. Italian screen for use outside a north-facing window (from Denza, 1882). (a) View from inside window; (b) exterior view

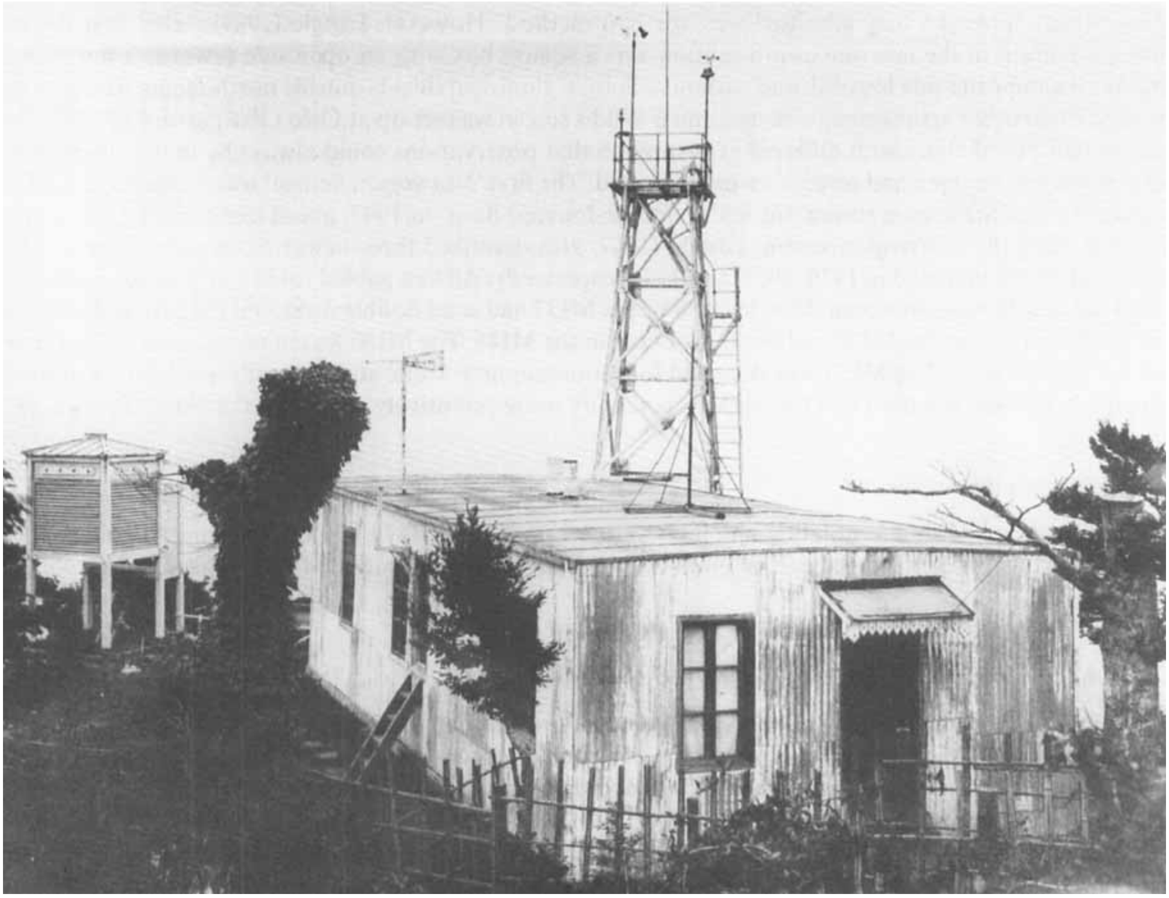

Figure 8. Tsukubasan Meteorological Observatory, Japan (from Okada and Sato, 1905)

3.18. The Netherlands

Koninklijk Nederlandsch Meteorologisch Instituut (KNMI) (1916) indicates that enlarged Stevenson screens were in use at three of five main stations, but De Bilt had a specially constructed screen, and one station had an arrangement similar to Wild's full apparatus. Stevenson screens were introduced at the latter station in 1930 (KNMI, 1931) and at De Bilt in 1950 (KNMI, 1968). The latter reference indicates that the thermometer-elevations in The Netherlands were reduced from 2·2 m to 1·5 m between 1958 and 1962. The KNMI yearbooks for the nineteenth century do not specify the instrumentation used.

3.19. New Zealand

Stevenson screens, with the door hinges at the top instead of at the bottom so as to exclude rain during observations, have been in use since 1870 (Hector, 1871).

3.20. Norway

According to Gorczynski (1910), Wild's cylindrical zinc shield (Figure (2a)), outside a north-facing window and without Wild's surrounding screen, was popular in Scandinavia: the Norwegian Meteorological Institute had recommended this arrangement in 1871, with due precautions, as 'far more convenient' than a Stevenson screen, which, however, they admitted was 'the best method'. However, Langlo (1947) stated that the most common pattern in the late nineteenth century was a square box with an open side towards a north-facing window, the opposite side louvred, and without a floor. Cylindrical shields outside north-facing windows were amongst three other arrangements in use, and a Wild's screen was set up at Oslo Observatory in 1877. Some stations had two shelters with different exposures so that observations could always be in the shade. Before 1920, only a few stations had screens on open ground. The first 'Norwegian Screen' was designed in 1895 and was similar to a Stevenson screen but had a double-louvred floor; in 1947, about eight Norwegian stations were still using the Norwegian screen. Langlo (1947) also described three newer Norwegian screens, MI30, MI33, and MI46, invented in 1930, 1933, and 1946 respectively. All had gabled roofs and had floors similar to that of the new Stevenson screen (Mawley, 1884): the MI33 had solid double walls, but the east and west walls were single louvred in the MI30 and double louvred in the MI46. The MI30 was in use at about 70 per cent of stations with screens. The MI33 was designed for mountain and Arctic stations with wind-driven snow. By 1970, the MI30 was not used and the MI46 was slightly more extensively used than the MI33 (Sparks, 1972).

3.21. Portugal and Angola

Louvred screens with a ventilating chimney were set up around 1879 in Portugal and Angola (Capello, 1879). In Portugal these replaced earlier types of shelter, possibly the ventilated boxes described cursorily by Lobo (1867).

3.22. Prussia (Western Poland and Northern Germany)

Mahlmann (1847) instructed that the north side of an uninhabited building be used: the thermometer should be at least 12–15 ft above the ground and 1 ft from a closed window, through which it could be read. It should be moved, or a duplicate site be used, to avoid solar radiation. If possible, it should be unscreened, except from rain, etc. from above.

In Germany, up to about 1880, thermometers were usually sited directly in the shade, with only the bulbs being protected by a double conical screen (Gorczynski, 1910).

After 1880, Prussian stations were chiefly equipped with Wild's cylindrical zinc shields (Figure 2(a)), (Wild, 1879), or variants thereof, e.g. Hellmann's (Sprung, 1890), positioned directly outside north-facing windows of buildings, without Wild's surrounding screen (Figure 2(b)) (Gorczynski, 1910). In Baden (south-west Germany) these shields were introduced somewhat earlier (Wild, 1879). However, Hellmann (1881) recommended an arrangement similar to Wild's full apparatus, i.e. Figure 2(a) inside Figure 2(b), and a few of these were used (Sprung, 1890). The suggestion of Wild (1887) that his shields be ventilated was soon taken up (Sprung, 1890). However, Gorczynski (1910) stated that use of a fan had proved to be unreliable in observational practice. A modified English (i.e. Stevenson) screen was introduced in newly opened stations of the Warsaw meteorological network in 1909 (Gorczynski, 1910). This screen differed from the English standard in having the thermometers 2–3 m above the ground and in having a side-hinged door and a hinged roof (Figure 9).

3.23. Russia

Wild (1879) reports the recent or current use of combined wood, metal, and glass housings fixed to the north side of buildings, or, with appropriate sheltering wooden walls at a distance, to the east or west sides of buildings. He, however, introduced his own cylindrical zinc shields with a surrounding louvred screen open to the north. An early version of this, introduced in 1869, afforded insufficient protection against radiant heat emanating from the ground. The version shown in Figure 2(a and b) was introduced in 1874. In 1910 Gorczynski stated that Wild's screened shield 'is found chiefly in the Russian network'. In *1912 the* St Petersburg Central Observatory was experimenting with Stevenson screens of different sizes (Köppen, 1913). However, the network was then adversely affected by war, and there was little new instrumentation much before 1930. (Sternzat, 1967).

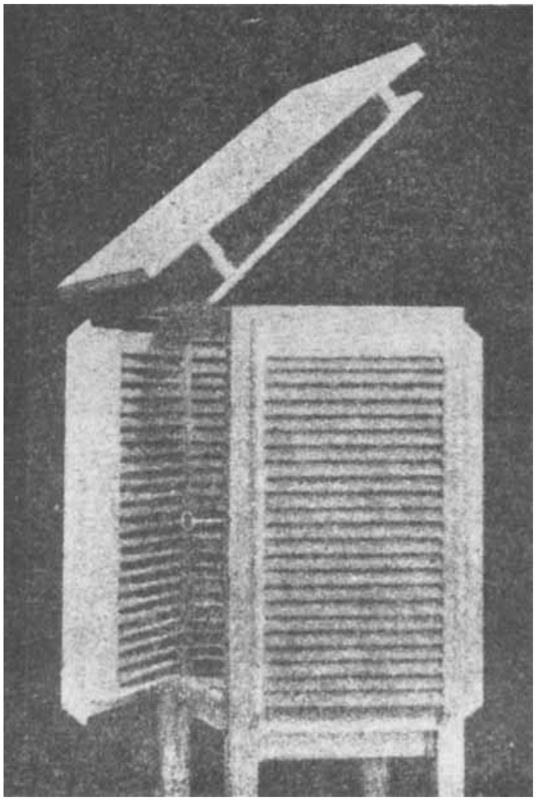

Figure 9. New type of English screen, side view (from Gorczynski, 1910)

3.24. Samoa

A Stevenson screen, set up in 1902 at Apia Observatory, was replaced at sometime between 1908 and 1920 by a tropical screen (Figure 10), which was louvred in a manner similar to a Stevenson screen, but had an auxiliary thatched, gabled shelter about 0·35 m above its roof (Sapsford, 1940). Parallel readings were taken in a Stevenson screen from 1932.

3.25. South Africa

Diverse exposures were being replaced by Stevenson screens in 1881 (Gamble, 1881).

3.26. Spain

According to Hazen (1885), a double metallic louvred shelter was used, with a vane ventilator.

3.27. Sweden

Wild's cylindrical zinc shields, outside north-facing windows of buildings, were replaced by Stevenson screens relatively recently (e.g. at Karlshamn in 1951; at Holmogadd in 1941; at Pitea in 1941; at Haparanda in 1942) but a few stations used free-standing screens from about 1920 or earlier (Alexandersson and Eriksson, 1989).

Figure 10. Tropical and Stevenson screens at Apia, Samoa (from Sapsford, 1940). © SIR Publishing, Wellington, New Zealand.

3.28. Switzerland

Wild's cylindrical zinc shields were fixed outside north-facing windows of buildings, without a surrounding screen, from 1861 onwards (Wild, 1879). At Zürich, the shield was placed in a wooden shelter in 1874, but the apparatus was replaced by a thermometer in a wooden screen in 1891 and in an iron screen in 1895 (Smithsonian Institution, 1927).

3.29. United Kingdom

In the period 1840–1880, there was a wide variety of exposures (Symons, 1868; Gaster, 1882). At some observatories, louvred frames were slightly offset from the north wall (Royal Society, 1868). Glaisher's revolving stand was often used: this was open away from the sun (Figure 11) so long as the observer remembered to rotate it. The Stevenson screen was recommended by the Royal Meteorological Society in 1873 for general adoption (Mawley, 1897). However, at some observatories, Glaisher's stands were used for much longer, e.g. until 1938 at Greenwich (Laing, 1977) and 1902 at Stonyhurst Lancashire (Sidgreaves, 1903), though generally in parallel with Stevenson screens. Nevertheless, Stevenson screens rapidly became standard from the mid-1870s, e.g. 1876 at Cambridge Observatory (Meteorological Committee, 1877); 1878 at Radcliffe Observatory, Oxford (Knox-Shaw and Balk, 1932); 1875 at Ross-on-Wye (unpublished documentation in Meteorological Office Archives). The screens at over 100 stations illustrated by Royal Meteorological Society (1884–1888) are overwhelmingly of the Stevenson pattern. For individual stations, useful information can be gleaned from the Inspectors' reports for the Meteorological Council (1882), and in corresponding volumes for subsequent years: some non-standard exposures are noted.

Even after the adoption of the Stevenson screen, there were progressive changes to its design. In particular a 'new' screen described by Mawley (1884) was slightly larger than the 'old' one, and had a base of boards, staggered to allow ventilation, instead of an open base. Bilham (1937) designed a smaller screen, but many modern screens are large because modern thermometers tend to be longer than nineteenth century ones (Bilham, 1937), and also because the screens need to house autographic equipment. The thermal inertia of such screens is greater than that of small screens, and the ventilation may be impeded by the equipment in them (Köppen, 1913). The diurnally varying and seasonally varying effects of heating of the air passing over louvres warmed by the sun are discussed in section 4.4.

3.30. United States of America

A latticed window-box 10–15 ft above the ground, partly open to the north and open towards the closed window through which it was to be read, was recommended by the Smithsonian Institution (1860). The US

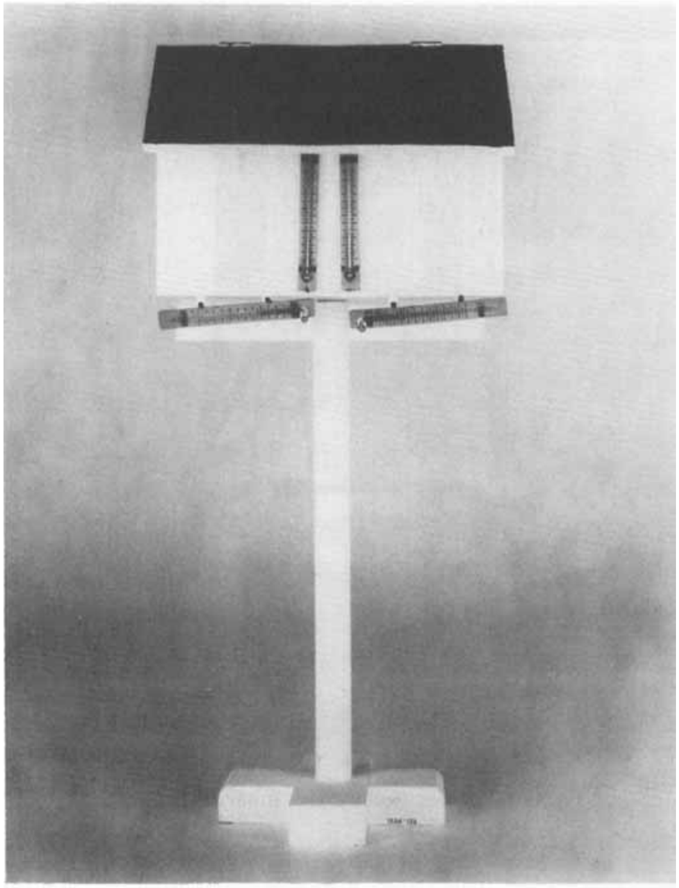

Figure 11. Glaisher's stand © HMSO

Signal Service (1871) recommended this arrangement, although it allowed a shelter on a roof-top as an alternative. The US Signal Service (1875), however, suggests that a shelter on a roof-top was the first choice. Many individual observers, however, used thermometers without a shelter (Hazen, 1885). Hazen himself recommended a roof-top shelter, which could, however, be used in a field if the bottom of the shelter were at least 16 ft above the ground.

A form of Stevenson screen, the 'cotton-region shelter', was adopted by the US Weather Bureau in the early 1890s (Flora, 1920) and was still standard in the early 1970s, with the thermometer bulbs 1·5 m above the ground (Figure 12; Sparks, 1972).

4. COMPARISONS BETWEEN EXPOSURES

In view of the multiplicity of exposures, only comparisons between major types of exposure are described. Other comparisons are documented in the references, e.g. Langlo (1947) for various Norwegian screens, and Poncelet and Martin (1947) for Belgian screens. The results below should be interpreted in the light of the following.

(i) Screens of a particular type, e.g. Stevenson or Wild, had several, or many, variations (section 3). In particular, the height of the thermometers above ground level was not fixed. Also, the 'Assmann' psychometer used as reference instruments could vary considerably in their rate of ventilation and their

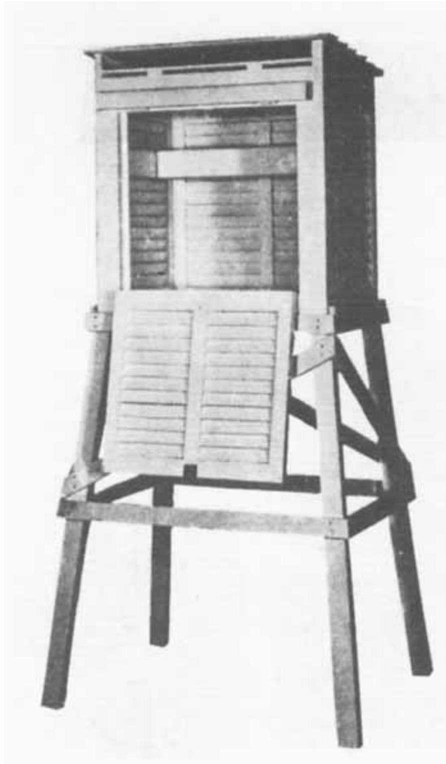

Figure 12. Cotton-region shelter (from Sparks, 1972)

shielding from radiation (Sparks, 1972), and their readings could even be affected by solar heating of the clothing of the observer (Vincent, 1891).

(ii) The deviations of measured from true air temperature depend on weather conditions, in particular insolation, outward radiation, and wind. Comparisons are thus subject to sampling error, and the results depend on the climate of the chosen location.

(iii) The local micro climate can affect the results (Wild, 1887), leading in some cases to systematically unrepresentative comparisons. Köppen (1913) had to discard a comparison of English screens with an aspirated psychometer in southern Russia in 1911, and also cast doubt on some of the comparisons made between the Indian screen (i.e. a cage under a thatched shed) and the Stevenson screen in Hong Kong in 1889–1890.

4.1. Stevenson screen versus the 'open' Glaisher stand

Gaster (1882) compared a wide range of exposures at a rural site at Strathfield Turgiss (now Stratfield Turgis), England (51°20′N, 1°1′W), in 1869. The Stevenson screen used was of the old type with an open base. The elevation of the thermometer bulbs was 1·2 m–1·3 m in the screen and in the Glaisher stand. Table I shows mean values of Glaisher stand minus Stevenson screen readings.

The open exposure of the Glaisher stand yielded higher daytime temperatures in spring and summer because of reflected insolation, and lower night-time temperatures throughout the year because of loss of radiant heat to space or to the cold ground. The annual average bias for the maxima was significant at the 95 per cent level according to a one-sided t-test on the monthly biases: that for the minima was significant at the 99·9 per cent level. The differences were accentuated when the sky was clear by night, but not when it was clear by day. This latter result may indicate a role of diffuse radiation. The overall annual mean temperature differed very little between the two exposures, and the difference was statistically insignificant according to a one-sided *t*-test on the monthly differences.

Gaster (1882) reported, furthermore, that Lawson's stand (Figure 3) showed an accentuated diurnal range, to an even greater degree than Glaisher's. However, he did not publish the results for Lawson's stand. The original data have been located and are being analysed by N. Nicholls (pers. comm.) in Australia, in view of the use of a Lawson stand in Melbourne before 1880 (section 3).

Ellis (1891) compared the new type of Stevenson screen, with the boarded base, with the Glaisher stand at Greenwich, London, a semi-urban park site, between 1887 and 1889 (Table II). These results are broadly consistent with the results obtained at Strathfield Turgiss. On an annual mean using 1/2 (maximum + minimum), the Glaisher stand read 0·21°C higher than the Stevenson screen, whereas at Strathfield Turgiss it had read 0·03°C lower. The statistical significances of the annual average biases, calculated as for Table I, were: maxima, 99·9 per cent; minima, 99·9 per cent; overall mean, 99 per cent.

Mawley (1884) had found that in summer the new Stevenson screen was colder than the old one by day, but by less than 0·1°C on average. The night-time temperatures were almost identical. Thus the differences between new and old Stevenson screens were much smaller than those between Stevenson and Glaisher screens, and should not have made Gaster's and Ellis's results as different as Tables I and II show. The difference between new and old Stevenson screens by day was a result of the elimination of radiation entering through the base.

Mawley (1897) obtained the results in Table III using the old version of the Stevenson screen in his garden in a suburban area of Croydon, 15 km south of central London. The same general features are evident. The annual average biases of maxima and minima were significant at the 99 per cent and 99·9 per cent levels respectively, but the overall annual mean difference was statistically insignificant, according to one-sided *t*-tests on the monthly biases.

Margary (1924) compared an old-style Stevenson screen with a Glaisher stand at Camden Square (an urban site in central London) from 1881 to 1915 (Table IV). Yet again the same features were evident. The annual average bias of the maxima was statistically insignificant but that of the minima was significant at the 99·9 per cent level and that of the mean was negative and significant at the 99 per cent level. The minimum thermometer in the Stevenson screen was at 1·4 m: this may have accentuated the relative coldness of the Glaisher stand readings at a little over 1·2 m.

In Margary's experiment, the Glaisher screen was 0·15° colder on an annual overall mean. The average difference for the four investigations quoted here was, however, only 0·01°C, with the Glaisher value colder. The indications are thus for an insignificant annual mean difference between the exposures, but for a significant raising of daytime and summer-mean temperatures, and a significant lowering of night-time and possibly winter-mean temperatures, in the Glaisher stand relative to the Stevenson screen.

Laing (1977) discusses the occurrence of extremely high summer maxima in Glaisher stands. She suggests that about 2°C should be subtracted to make the data compatible with values from Stevenson screens, on the basis of distributions of (Stevenson minus Glaisher) maxima at Greenwich along with the observation that the larger differences, around 2°C, occurred on the sunny dry days.

4.2. Stevenson screen versus French screen

Mawley (1897) also compared temperatures in a new-style Stevenson screen with those in a French screen (Figure 6) in a garden at Berkhamsted, 50 km north-west of London, during April to December 1896. The thermometer bulbs in the French screen were at about 1·6 m above the ground as against 1·2–1·4 m in Stevenson screens and Glaisher stands. Like the Glaisher stand, the French screen was open away from the Sun, but it was constructed so as to require no turning to shade the thermometers. Mawley's results (Table V) were similar to those in Table III (Glaisher versus old-style Stevenson), but were generally less accentuated, especially at night, because of better shielding from radiative effects. Overall, the French screen was nearly 0·1°C warmer than the Stevenson screen.

Young (1920) in the USA compared the performance of the 'cotton-region shelter' (Figure 12) and a newly designed 'fruit-region shelter', which was patterned after the French type. In a very small sample for the winter

Table I. Average deviations of daily maximum and minimum temperatures (°C) in a Glaisher stand from those in a Stevenson screen at Strathfield Turgiss, 1869 (from Gaster, 1882)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Maximum	– 0·2	– 0·3	0·3	0·1	0·7	0·8	0·7	0·5	0·4	0·1	0·0	0·2	0·27
Minimum	– 0·4	– 0·3	– 0·1	– 0·4	– 0·3	– 0·5	– 0·3	– 0·3	– 0·4	– 0·3	– 0·4	– 0·2	– 0·32

Table II. Average deviations of daily maximum and minimum temperatures (°C) in a Glaisher stand from those in a new-type Stevenson screen at Greenwich, 1887–1889 (from Ellis, 1891)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Maximum	0·2	0·2	0·5	0·9	1·0	1·1	1·2	1·1	0·7	0·5	0·3	0·1	0·64
Minimum	– 0·1	– 0·2	– 0·2	– 0·2	– 0·2	– 0·3	– 0·3	– 0·3	– 0·3	– 0·3	– 0·2	– 0·1	– 0·23

Table III. Average deviations of daily maximum and minimum temperatures (°C) in a Glaisher stand from those in an old-style Stevenson screen at Croydon, 1877–1881 (from Mawley, 1897)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Maximum	0·0	0·0	0·2	0·5	0·6	0·8	0·8	0·6	0·4	0·2	– 0·1	– 0·1	0·33
Minimum	– 0·4	– 0·4	– 0·5	– 0·5	– 0·4	– 0·4	– 0·4	– 0·3	– 0·4	– 0·4	– 0·4	– 0·4	– 0·42

Table IV. Average deviations of daily maximum and minimum temperatures (°C) in a Glaisher stand from those in an old-style Stevenson screen at Camden Square (London), 1881–1915 (from Margary, 1924)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Maximum	– 0·2	– 0·2	– 0·1	0·2	0·4	0·7	0·7	0·6	0·4	0·1	– 0·2	– 0·2	0·18
Minimum	– 0·4	– 0·5	– 0·5	– 0·6	– 0·6	– 0·5	– 0·6	– 0·6	– 0·6	– 0·6	– 0·4	– 0·4	– 0·52

Table V. Average deviations of daily maximum and minimum temperatures (°C) in a French screen from those in a new-style Stevenson screen at Berkhamsted, 1896 (from Mawley, 1897)

	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Maximum	0·2	1·0	0·6	0·4	0·2	0·0	− 0·2	− 0·1	− 0·1
Minimum	0·0	0·0	0·0	0·0	− 0·1	0·0	− 0·1	− 0·1	− 0·1

Table VI. Average deviations of daily maximum and minimum temperatures (°C) in French screens and Glaisher stands from those in Stevenson screens (from Köppen, 1913)

	FRENCH			GLAISHER	
	Gr. Licheterfelde (Berlin) 1886–1887 (Sprung, 1890)	Pavlovsk 1898–1899 (Rykachev, 1909)	Hamburg Observatory (Bergedorf) 1910–1912	Strathfield Turgiss (England) 1869 (Gaster, 1882)	Cape Town Observatory 1881 (Gill, 1882)
Maximum					
January–February	0·3	0·1	0·2	0·0	1·7
July–August	0·7	0·9	1·1	0·5	0·3
Minimum					
January–February	− 0·2	− 0·1	− 0·2	− 0·4	− 0·5
July–August	− 0·4	− 0·1	− 0·3	− 0·6	− 1·3

of 1917–1918, obtained in a grove of orange and olive trees in California, daily maxima were generally lower in the fruit-region shelter, while daily minima were very similar in the two shelters. On clear nights in the springs of 1919–1920 over suburban grassland in Oregon, the fruit-region shelter's minima averaged 0·16°C higher. Nevertheless, readings in the fruit-region shelter were, in a very small sample of clear nights at both sites, sometimes 1°C or lower than those of a whirling psychrometer, with an opposite tendency by day, at least at the Oregon site.

These results suggest that there is overheating by day and overcooling by night in the French screen, but that these effects may not be much different than in Stevenson screens. The results are tentative because the samples were small.

Köppen (1913) summarized results of comparisons between Stevenson screens and French screens or Glaisher stands (Table VI). Note that at Gr. Lichterfelde the thermometer-elevations were greater (1·75 m) in the Stevenson screen than in the French screen (1·5 m). At Pavlovsk the elevations were 1·2 m in the new-style Stevenson screen and 1·8–1·9 m in the French screen. Apart from the rural Strathfield Turgiss site, the locations were either suburban (Gr. Lichterfelde and Pavlovsk) or city observatories, according to the authors cited in Table VI.

The Strathfield Turgiss results quoted in Table VI are for occasions with a clear sky, so they differ from those given in Table I, which are for all weather conditions. The indications are for enhanced diurnal and annual cycles in French screens and Glaisher stands, with little overall annual bias in the Glaisher stands and a small positive bias ($< 0·2$°C) in the French screen. The daytime overheating reported by Gill (1882) at Cape Town may have been accentuated because the stand was over bare soil.

Dettwiller (1978) suggested that readings in the old French screen at Montsouris Observatory (in a park in Paris) required no correction to the minimum temperatures to make them consistent with readings in a Stevenson screen. However, the maximum temperatures had to be reduced, according to Table VII. Based on the same test as used on Table I, the bias in the annual average maximum was significant at the 99·9 per cent level. These results again suggest enhanced diurnal and annual cycles in French screens, with an overall

Table VII. Biases of maximum temperatures (°C) in the French screen at Montsouris (Paris) relative to a Stevenson screen (based on Dettwiller, 1978)

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0·1	0·2	0·4	0·5	0·8	0·9	0·9	0·8	0·6	0·3	0·2	0·1	0·48

Table VIII. Average deviations of daily maximum and minimum temperatures (°C) in Wild's shield and screen from those in an old-style Stevenson screen at Kew (London), 1879–1881 (from Whipple, 1883)

	Spring	Summer	Autumn	Winter	Year
Maximum	0·2	0·2	0·1	0·1	0·15
Minimum	− 0·3	− 0·2	− 0·4	− 0·4	− 0·33

Table IX. Average deviations of daily maximum and minimum temperatures (°C) in Wild's shield and screen from those in a new-style Stevenson screen (from Köppen, 1913). The thermometer-elevation in Wild's apparatus at Gr. Lichterfelde and Pavlovsk was 3·2 m

	Jan-Feb		July-Aug	
	Gr. Lichterfelde (Berlin) 1886–1887 (Sprung, 1890)	Pavlovsk 1898–1899	Gr. Lichterfelde (Berlin) 1886–1887 (Sprung,1890)	Pavlovsk 1898–1899
Maximum	0·1	0·5	0·3	0·8
Minimum	0·2	0·3	0·2	0·3

positive bias of about 0·2°C. French screens may not, however, have given similar results when sited under trees (Köppen, 1913).

4.3. Stevenson screen versus Wild's shield and screen

Whipple (1883) compared temperatures in an old-style Stevenson screen with those in an unventilated Wild's shield and screen at Kew Observatory between June 1879 and November 1881 (Table VIII). The thermometer bulbs were 3·6 m above the ground in Wild's apparatus, but 1·3 m above the ground in the Stevenson screen. The daytime differences were accentuated in clear weather, suggesting overheating of Wild's apparatus, which should have been sampling colder air owing to its greater height. The night-time differences were accentuated in clear and calm weather, suggesting excessive radiative cooling of Wild's apparatus, which should have been sampling warmer air than the Stevenson screen during night-time temperature inversions.

Köppen (1913) was unable to explain Whipple's results (Table VIII) as he had obtained the different results shown in Table IX. Not only do these results differ from Whipple's but they also diverge in that the Pavlovsk results indicate excess daytime overheating, whereas the Gr. Lichterfelde results do not. An explanation may be that the Wild's apparatus in Pavlovsk was without artificial ventilation, whereas Sprung in Gr. Lichterfelde had small ventilators, though these only served to set the air inside the casing in motion, not to replace it. Gorczynski (1910) cited measurements suggesting only 0·2°C daytime overheating of Wild's apparatus relative to a new-style Stevenson screen in an annual mean. The daytime overheating was concentrated in the summer. Wild (1887) recognized that daytime overheating affected his apparatus, along with thermal lag, which could have yielded the overall warm bias in Table IX (Köppen, 1913). Wild (1887) therefore recommended that the metal shield be ventilated. Hazen (1885), in experiments made in Virginia in summer 1884, found that ventilation reduced the overheating of a version of Wild's apparatus. Wild's original assessment of his apparatus (Wild, 1879) may have been too lenient because he tested it at 60°N (Hazen, 1885).

4.4. Stevenson screen versus north-wall exposures

Marriott (1879) compared temperatures in a north-facing wall-screen with those in an old-style Stevenson screen in a suburban garden at an unspecified location 'on London clay 184 ft above sea level' (Figure 13). The wall-screen was 43 cm wide, 22 cm high and 14 cm deep with single louvres on three sides and the bottom, and a plain board at the top and back. The thermometer-elevations were about 1·2–1·3 m in both screens. Table X shows Marriott's results. The annual average biases of maxima and minima were significant at the 99·9 per cent and 99 per cent levels, respectively, according to the one-sided t-test. Note the marked reduction of the diurnal cycle in the wall-screen. The temperature in the wall-screen was on an annual average about 0·15°C colder than that in the Stevenson screen, but this fell slightly short of significance at the 95 per cent level on the one-sided t-test. There is evidence of heat-retention by the wall at night in summer.

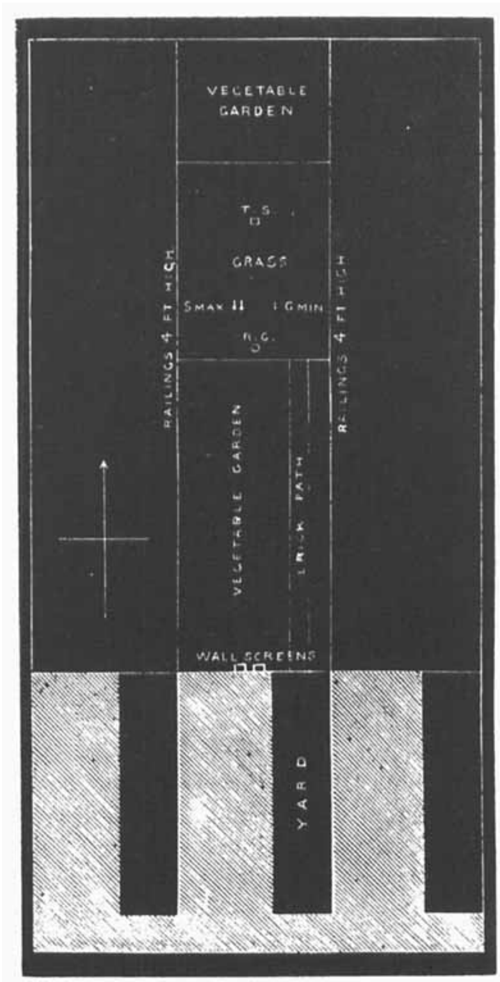

Figure 13. Site plan of Marriott's (1879) experiments. The Stevenson screen (T.S.) is about 14 m north of the wall screen © Royal Meteorological Society

Table X. Average deviations of daily maximum and minimum temperatures (° C) in a north-wall screen from those in an old-style Stevenson screen, 1878-1879. (from Marriott, 1879)

	April 1878	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan 1879	Feb	Mar	Year
Maximum	− 0·6	0·0	− 0·1	− 0·4	− 0·6	− 1·2	− 1·1	− 0·3	− 0·3	− 0·3	− 0·7	− 1·0	− 0·54
Minimum	0·0	0·4	0·6	0·7	0·4	0·4	0·2	− 0·1	0·1	0·0	0·2	0·2	0·26

Table XI. Average deviations of daily maximum and minimum temperatures (°C) in a screen outside a south-facing window from those in an old-style Stevenson screen at Cape Town Observatory, 1881 (from Gill, 1882)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Maximum	− 2·2	− 2·5	− 3.0	− 1·9	− 0·9	− 1·6	− 1·4	0·2	− 1·7	− 1·9	− 2·0	− 2·6	− 1·80
Minimum	0·8	1·0	1·0	1·1	1·0	1·6	1·9	1·5	1·7	2·2	1·9	1·4	1·42

The lowering of the daily maxima appeared to follow a biannual rather than an annual cycle, though the significance of this is hard to assess from 1 year's data. The biannual cycle shows highest relative values in the Stevenson screen around September and March. It may have resulted from the heating of the air by the sun-warmed south-facing louvres of the Stevenson screen, on days with southerly wind components to advect the warm air through the screen (Painter, 1977). At the latitude of London (51°N), such heating is greatest around the equinoxes when the insolation on to a south-facing vertical plane is greatest. In addition, around the equinoxes, the insolation would be most perpendicular to the louvres, enhancing the effect (C.K. Folland, pers. comm.)

Gill (1882) obtained the results in Table XI when he compared readings in a window-screen with readings in an old-style Stevenson screen. Again a strong reduction of the diurnal range was evident in the window-screen, in which the overall mean was 0·2°C lower than that in the Stevenson screen. The lowering of the daily maxima was greatest in summer, with no suggestion of a biannual cycle. There was no evidence of enhanced heat-retention by the building at night in summer. The annual average biases of maxima and minima were significant at the 99·9 per cent level according to the one-sided *t*-test: that of the mean was statistically insignificant.

Hazen (1885) also found reduced diurnal ranges in window-shelters by comparison with roof-top shelters and shelters near the ground. In addition, he had observations made from September 1883 to August 1884 comparing temperatures inside roof-top shelters with those given by unscreened, north-facing thermometers, at seven stations in the USA. Hazen only presented results for 0700, 1900 and 2300 hours. At 0700 hours, the unscreened thermometers often read higher in summer because of direct exposure to insolation, and even on the annual average they read 0·14°C higher than those in the shelters. At 1700 and 2300 hours the unscreened thermometers read colder by an annual average of 0·29°C and 0·44°C respectively. The relative coldness was slightly greater in summer. Thus an enchanced diurnal range is suggested, with possibly a reduction of mean temperature.

Sprung (1890) obtained differences between Hellman's variant of Wild's shield outside a north-facing window and a new-style Stevenson screen (Table XII).

The results again show a strong reduction of the diurnal range with the north-wall exposure. The mean temperature was nearly 0·2°C higher in the north-wall apparatus than in the Stevenson screen. The lowering of daily maxima in the north-wall location was greatest in summer, and particularly in the sunny September of 1886, when overheating of the Stevenson screen may have been greatest (Painter, 1977; and discussion of Table X). The results suggest enhanced heat-retention by the building at night in summer.

Mawley (1897) compared the performance of a new-style Stevenson screen with that of Wild's shield, unscreened and attached outside a north-facing window of his home, probably in Croydon. This form of exposure was common in Austria, Prussia, Scandinavia, and Switzerland (Section 3). The shield was nearly a metre from the wall in Mawley's experiment. Unfortunately the experiment only ran through part of 1896 (Table XIII).

The results are rather incoherent but suggest retention of heat by the building at night in summer. Mawley found also that the Wild's shield was heated by early morning insolation in summer. Overall, the Wild's shield gave a mean temperature very close to that in the Stevenson screen, with a slightly reduced diurnal range.

Köppen (1913) cited comparisons made at Potsdam (Germany) which indicated that Hellmann's variant of Wild's shield, with a north-wall exposure, yielded temperatures 0·1°C lower and 0·4°C higher than a

Table XII. Average deviations of daily maximum and minimum temperatures (°C) in Hellman's variant of Wild's shield outside a north-facing window from those in a new-style Stevenson screen at Gr Lichterfelde (Berlin) (from Sprung, 1890)

	July 1886	Aug	Sept	Oct	Nov	Dec	Jan 1887	Feb	Mar	Mean
Maximum	− 0·4	− 0·8	− 1·4	− 0·6	− 0·2	0·0	0·3	− 0·1	− 0·3	− 0·38
Minimum	1·2	1·1	1·1	0·5	0·7	0·6	0·8	0·4	0·4	0·76

Table XIII. Average deviations of daily maximum and minimum temperatures (°C) in a Wild's shield outside a north-facing window from those in a new-style Stevenson screen, 1896 (from Mawley, 1897)

	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean
Maximum	−0·5	−0·3	0·4	−0·1	−0·1	-	−0·2	−0·1	0·6	−0·05
Minimum	0·1	0·3	0·2	0·3	0·1	−0·2	−0·2	−0·2	−0·2	0·01

Stevenson screen at 1400 and 2100 hours in winter. Corresponding values in summer were 1·0°C lower and 0·9°C higher. The reduction of the diurnal range found in the earlier investigations is thus confirmed.

Unpublished comparisons by J. M. Stagg of the north-wall screen and a Stevenson screen at Kew Observatory (London) between April 1923 and March 1926 show that day maxima in the former averaged about 0·3°C lower, whereas night minima averaged 0·9°C higher. There was slight evidence of greater retention of heat by the wall at night in summer; but the depression of the day maxima followed no clear annual cycle. The thermometer elevations in the north-wall screen were 3·0 m.

In summary, screened north-wall exposures give reduced diurnal cycles and, in most cases, enhanced night-time retention of heat in summer. The overall annual-mean temperature bias appears to be near zero. The results are likely to have been very site-dependent because of the different characteristics of the buildings and elevations of the thermometers above ground-level, which are not specified in most of the papers quoted.

Unscreened north-wall exposures, on the other hand, may give enhanced diurnal cycles and possibly a reduced overall annual-mean temperature.

4.5. Canadian screen and shed

Comparisons between the Canadian apparatus in Figure 5 and Stevenson screens were, apparently, never made. However, Kingston (1878) provided precise specifications, from which the Canadian screen and shed could be reconstructed and used to make comparisons. These would be valuable in view of the geographical area covered by Canadian data in the late nineteenth century (figure 7 of Jones *et al.*, 1986). The thermal retention of the Canadian apparatus would probably be small, giving night-time temperatures similar to those in a Stevenson screen; but on calm sunny days the shading of the ground beneath the screen might yield lower temperatures than in a Stevenson screen.

4.6. Stevenson screen versus tropical shed exposures

Field (1920) compared temperatures in a slightly enlarged Stevenson screen with those in a cage suspended beneath a thatched shed (Table XIV: see also Figure 4). Thermometer-elevations were in each case 1·3 m. Annual average biases of maxima, minima and mean are all significant at the 99·9 per cent level according to the one-sided t-test. The daytime overheating of the shed exposure was mainly caused by radiation reflected from the unshaded ground outside the area of the eaves. This in turn would depend on vegetation and soil type. At night, downwards longwave radiation from the thermally inert roof of the shed prevented cooling. Occasionally, stagnant warm air trapped beneath the eaves affected the data. Field found greater daytime overheating, but less retention of heat at night, in experimental tiled sheds. However, the Stevenson screen agreed best with an aspirated thermometer, and was therefore subsequently adopted as standard (section 3), despite a slight tendency to overheating when the wind was light and from the sunny side of the screen.

Bamford (1928) conducted similar experiments using a felted shed in Colombo (Sri Lanka) (Table XV). His Stevenson screen A differed from screen B in having a more open base. Both screens were somewhat enlarged versions. Annual cycles in the differences were weak. The daytime overheating relative to screen A was slightly less because screen A itself was overheated slightly by reflected radiation entering through the base. The results agree well with Field's for tiled sheds. For overall mean temperature, Field's and Bamford's results suggest overheating of about 0·4°C relative to Stevenson screens.

Table XIV. Average deviations of daily maximum and minimum temperatures (°C) in a cage suspended beneath a thatched shed from those in a slightly enlarged new-style Stevenson screen at Agra Observatory (India). (from Field, 1920)

	July 1917	Aug	Sept	Oct	Nov	Dec	Jan 1918	Feb	Mar	Apr	May	June	Year
Maximum	0·4	0·3	0·3	0·3	0·3	0·3	0·4	0·4	0·4	0·4	0·5	0·5	0·39
Minimum	0·2	0·2	0·3	0·7	0·7	0·7	0·7	0·6	0·5	0·5	0·3	0·3	0·46

Table XV. Average deviations of daily maximum and minimum temperatures (°C) in a cage suspended beneath a felted shed from those in Stevenson screens at Colombo (Sri Lanka) (from Bamford, 1928)

	Annual mean, shed minus screen A April 1923 to March 1926	Annual mean, shed minus screen B April 1926 to March 1927
Maximum	0·54	0·66
Minimum	0·15	0·14

By contrast, Sapsford (1940) found that the tropical screen at Apia, Samoa, gave temperatures on average 0·08°C lower than the Stevenson screen, with a reduction in the mean daily range of 0·46°C. However, the apparatus he was investigating (Figure 10) was very unlike those considered by Field (1920) and Bamford (1928), being much more similar to a Stevenson screen, but with an extra protective roof.

4.7. *Summary of comparisons*

Table XVI summarizes the biases that are likely to have resulted from the differing exposures of thermometers. The biases are expressed relative to temperatures measured in Stevenson screens. Section 3 has been used to specify the geographical areas that are most likely to have been affected.

5. OBSERVED TRENDS IN REGIONAL TEMPERATURES

Figure 14 (from Folland *et al.*, 1990) shows trends in land air temperatures relative to a 1951–1980 climatology, for the Northern Hemisphere, for the four seasons (winter = December to February, etc.). The data were provided by P. D. Jones, University of East Anglia. The series have been smoothed with a 21-year term low-pass binomial filter, which passes fluctuations longer than about 20 years almost unattenuated. There is good agreement between the seasons after the 1890s, although winter shows somewhat more marked interdecadal variability, as expected in view of the enhanced variance of continental surface temperatures in winter. However, before 1880 summer appears to have been systematically warm, and winter sytematically cold. The same effect occurs weakly in Southern Hemisphere data (not shown). The relative warmth of summer before 1880 was particularly marked over Europe, but was also apparent over most other extratropical parts of the Northern Hemisphere and in Australia. We have already shown (section 4) that 'open' screens (e.g. the French screen, Glaisher's stand) and Wild's screens overheat by day, especially in summer, whereas the open screens tend to be too cold at night and therefore particularly in winter.

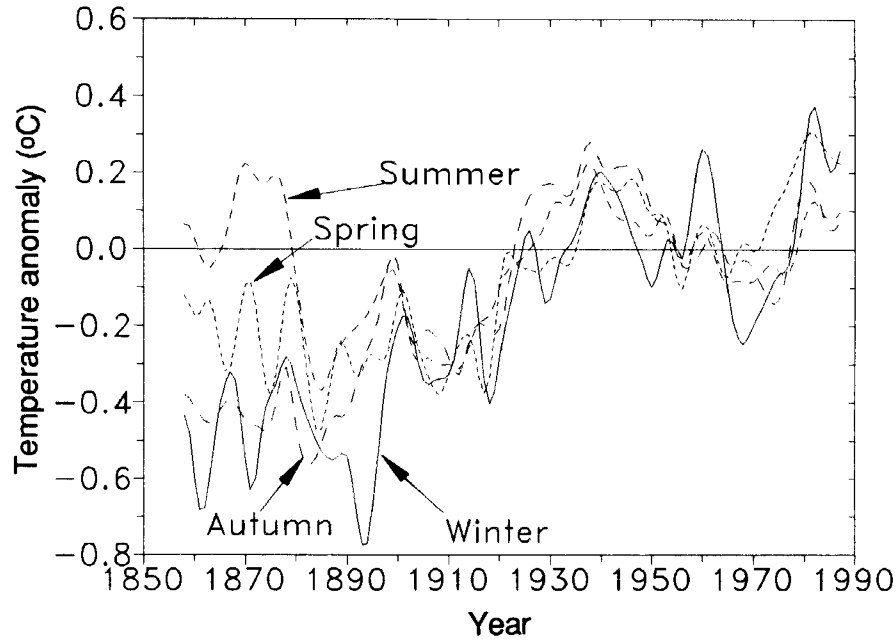

Figure 14. Smoothed seasonal land surface air temperature anomalies, relative to 1951–1980, for the Northern Hemisphere. Data from P. D. Jones, University of East Anglia (from Folland *et al.*, 1990) © HMSO

Table XVI. Summary of the effects of differing exposures of thermometers, relative to exposure in a Stevenson screen

Exposure	Seasonal effects: Winter	Seasonal effects: Summer	Overall mean effect	Effect on diurnal cycle	Principal regions and dates affected
Glaisher stand	Colder	Warmer	Near zero	Enhanced	UK until 1870s: later at some observatories
French screen	Near zero	Warmer	Warmer (≤ 0·2°C)	Enhanced	France, late nineteenth and early twentieth century. Egypt, Australia late nineteenth century
Wild's screened shield	Slightly warmer	Warmer	Warmer (0·1–0·2°C)	Enhanced	Russia 1870s until 1910s
North-wall screens	Slightly colder	Slightly warmer	Near zero	Reduced	Scandinavia, central and Eastern Europe, Italy, late nineteenth and early twentieth century. Russia until 1870s. USA until 1890. Canada, late nineteenth century
Unscreened north-wall sites	Possibly slightly colder	Possibly near zero	Possibly slightly colder	Enhanced	USA until early 1890s. Prussia until 1880
Canadian apparatus	?	?	Unknown; possibly colder	Possibly reduced	Canada, late 19th century
Cage suspended in shed	(Warmer at all seasons)		Warmer (0·4°C)	Unchanged in thathched shed. Enhnaced in felted shed	Tropics until 1920–1935

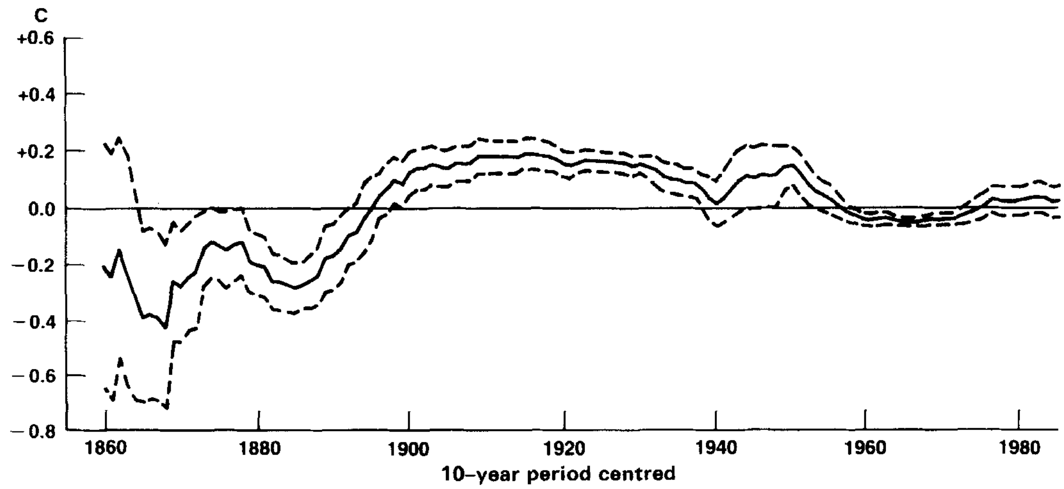

Figure 15. Ten-year running mean differences (solid line) between coastal and island air temperatures and nearby sea-surface temperatures for the tropics (20°N–20°S), relative to 1951–1980. The dashed lines are ±two standard errors estimated from the variability of the differences between sites. Land data were provided by P. D. Jones, University of East Anglia © HMSO

Furthermore, the north-wall sites may be slightly too warm in summer and slightly too cold in winter. Therefore it is suggested that the summer temperatures before 1880 shown by Figure 14 are too high, and the extratropical winter temperatures slightly too low. The annual mean may be nearly correct or marginally too high (section 4). There is likely to be a geographical pattern, albeit indistinct, of biases in the extratropical Northern Hemisphere in view of the distribution of exposures. In the earliest years, non-standard sites without adequate protection from radiation (Symons, 1868; Gaster, 1882) will have increased the uncertainties in the biases.

Figure 15 shows 10-year running mean differences between coastal and island air temperatures and nearby sea-surface temperatures for the tropical zone 20°N to 20°S. All values are anomalies referenced to 1951–1980. The sea-surface temperatures were taken from the Meteorological Office Historical Sea Surface Temperature (MOHSST5) data set which had been corrected for the use of uninsulated or partly insulated buckets before 1942, following Folland *et al.* (1992). The theory of the corrections for the use of buckets is given by Folland (1991). The relative warmth at land stations between about 1890 and 1935 suggests bias, relative to modern data, resulting from the use of the cages under sheds at some stations (sections 3 and 4). The bias may have extended into the 1930s, rather than only into the 1920s when Stevenson screens were introduced, because some stations issued their data in the 1920s and 1930s adjusted to the earlier exposure (Smithsonian Institution, 1944, 1947). Figure 15 is unreliable before 1880 because there were fewer than 10 locations for comparison.

6. CONCLUSIONS

It will be difficult to assess (and adjust) the data before about 1875 because in many countries standardized procedures were not followed.

The use of open screens led to enhanced diurnal ranges and annual cycles in mid-latitudes. Diurnal ranges will also have been enhanced, and annual cycles slightly amplified, in Wild's screened shield and at unscreened north-wall sites. Diurnal ranges, but not annual cycles, will have been reduced in north-wall screens. Overall mean observed mid-latitude temperatures in the late nineteenth century are likely to have been unaffected or very slightly raised by the exposures used.

Tropical temperatures before the late 1920s were too high, relative to modern standards, because of the use of cages under sheds. Because data published in the 1920s and 1930s were sometimes adjusted to be consistent with earlier records, the excess warmth may extend into the 1930s in the data.

Mean adjustments may not be applicable to particular days' data, because of natural variations in radiation balance and in ventilation. Extreme maxima and minima, which are usually associated with extreme radiative environments, are particularly likely to require larger adjustments, as documented by Laing (1977) and by Poncelet and Martin (1947).

The exposure and instrumental design of thermometers continue to change. Some of these developments have affected the readings significantly. In particular, recent changes in the USA have lowered apparent daytime temperatures and raised those at night, yielding observed reductions of 0·7°C in the diurnal range (Quayle *et al.*, 1991). However, at some stations the reverse bias has been observed (Gall *et al.*, 1992). Biased estimates of changes in diurnal range could lead to misinterpretation of the climatic effects, and therefore the economic impacts, of the increasing atmospheric concentrations of greenhouse gases and other pollutants (Folland *et al.*, 1992). It is therefore essential that, when instrumentation or exposure are changed, new and old systems be operated in parallel for at least 2 years, to enable reliable comparisons to be made, especially at Reference Climatological Stations. At a recent workshop (Frich and Cappelen, 1992) it was also recommended that if a station is automated, the new thermometer be placed inside the original screen.

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