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THE EFFECT OF RADIATION SCREENS ON NORDIC TIME SERIES OF MEAN TEMPERATURE

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ABSTRACT

A short survey of the historical development of temperature radiation screens is given based upon research in the archives of the Nordic meteorological institutes. In the middle of the nineteenth century most thermometer stands were open shelters, free-standing or fastened to a window or wall. Most of these were soon replaced by wall or window screens, i.e. small wooden or metal cages. Large free-standing screens were also introduced in the nineteenth century, but it took to the 1980s before they had replaced the wall screens completely in all Nordic countries. During recent years, small cylindrical screens suitable for automatic weather stations have been introduced. At some stations they have replaced the ordinary free-standing screen as part of a gradual move towards automation.

The first free-standing screens used in the Nordic countries were single louvred. They were later improved by double louvres. Compared with observations from ventilated thermometers the monthly mean temperatures in the single louvred screens were 0·2–0·4°C higher during May–August, whereas in the double louvred screens the temperatures were unbiased. Unless the series are adjusted, this improvement may lead to inhomogeneities in long climatic time series.

The change from wall screen to free-standing screen also involved a relocation from the microclimatic influence of a house to a location free from obstacles. Tests to evaluate the effect of relocation by parallel measurements yielded variable results. However, the bulk of the tests showed no effect of the relocation in winter, whereas in summer the wall screen tended to be slightly warmer (0·0–0·3°C) than the double louvred screen. At two Norwegian sites situated on steep valley slopes, the wall screen was *ca*. 0·5°C colder in midwinter.

The free-standing Swedish shelter, which was used at some stations up to 1960, seems to have been overheated in spring and summer (maximum overheating of about 0·4°C in early summer).

The new screen for automatic sensors appears to be unbiased compared with the ordinary free-standing screen concerning monthly mean temperature. © 1997 Royal Meteorological Society. *Int. J. Climatol*., 17, 1667–1681

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KEY WORDS: Temperature screens; Scandinavia; Denmark; temperature.

INTRODUCTION

As part of the North Atlantic Climatological Dataset (NACD) project (Frich *et al*., 1996), eleven countries in the North Atlantic region co-operated in creating a data set of supposedly homogeneous climatic series for the period 1890–1990. Analysis of the data set shows that annual temperature in this region has increased by about 0·5°C

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during the last 100 years (Hanssen-Bauer *et al*., 1996). However the variability in temperature due to natural fluctuations relative to the trend is high, and consequently a climatic change is not easy to detect. Detection is also obscured by problems associated with the measurements themselves.

To make accurate measurements of air temperature, it is necessary to screen the thermometer from direct and reflected radiation from the sun and also from the exchange of longwave radiation with the surrounding environment. However, a perfect screening method has not yet been invented, so there may be a temperature difference between the thermometer bulb and the adjacent air outside the screen. National meteorological institutes attached importance to improving radiation protection so as to approach the objective of obtaining true air temperature measurements. In so doing, however, they have also introduced some inhomogeneities into the time series which may lead to biases in studies of long-term trends.

Comparisons between different screens were made as early as the nineteenth century (e.g. Schouw, 1826; DNMI, 1875; Mawley, 1897), and numerous examples have been reported in the present century. Recently, Parker (1994) has studied the available world-wide literature concerning screen changes. Particular emphasis was given to changes of exposure during the late nineteenth and early twentieth centuries. In the extratropical region he found that the early series may be biased 0·2°C warm in summer and by day, and similarly cold in winter and by night, relative to modern observations.

Although the present report deals with screen changes only, it should be kept in mind that this is not the only reason for inhomogeneities in temperature series. Others include: changes of exposure due to vegetation and buildings, relocation of the screen, urbanization of the area near the screen, changes of observation hours or the number of observations per day, shrinking of the glass in thermometers, changes in formulae for calculating daily and monthly mean temperature and changes in screen height above the ground. In many cases these can be of greater importance than screen changes.

After an outline of the screen history in the Nordic countries, test results are reviewed for the different types of screens, respectively, open shelters, free-standing screens, wall screens and sensor screens used at automatic stations. The tests reported have been carried out predominantly in the Nordic countries. If the influence of the screens on mean temperature is not calculated in the available literature, it is calculated by us. We conclude with a discussion of the adjustments required to correct for screen effects across the entire Nordic station network.

SCREENS USED IN LONG TIME SERIES

When a thermometer is placed in the air it will very seldom record the true air temperature. The difference between the bulb temperature and the air temperature may reach 25°C under extremely unfavourable conditions (WMO, 1983). Therefore, it is necessary to protect the thermometer from radiation by a screen. The main role of the screen is to prevent shortwave radiation reaching the thermometer and to shield the thermometer from precipitation, while allowing adequate ventilation. These contradictory criteria are a challenge to screen designers. During the last 150 years improved compromises have been found between ventilation and protection.

Experience has shown that screen errors appear most frequently during daytime under a clear sky with little or no wind, when the temperature inside the screen may exceed the true air temperature. Conversely, during clear, calm nights the screen temperature may be slightly lower than the true value. Errors are commonly in the range −0·5°C to +2·5°C (WMO, 1983).

In the Nordic countries four main types of radiation screening are, or have been, widely used:

(i) shelters—open structures;
(ii) wall screens—small cages fastened to a wall of a building;
(iii) free-standing screens—wooden screens placed above a surface of short grass, often called Stevenson screens;
(iv) sensor screens—small, cylindrical free-standing screens constructed for automatic weather stations.

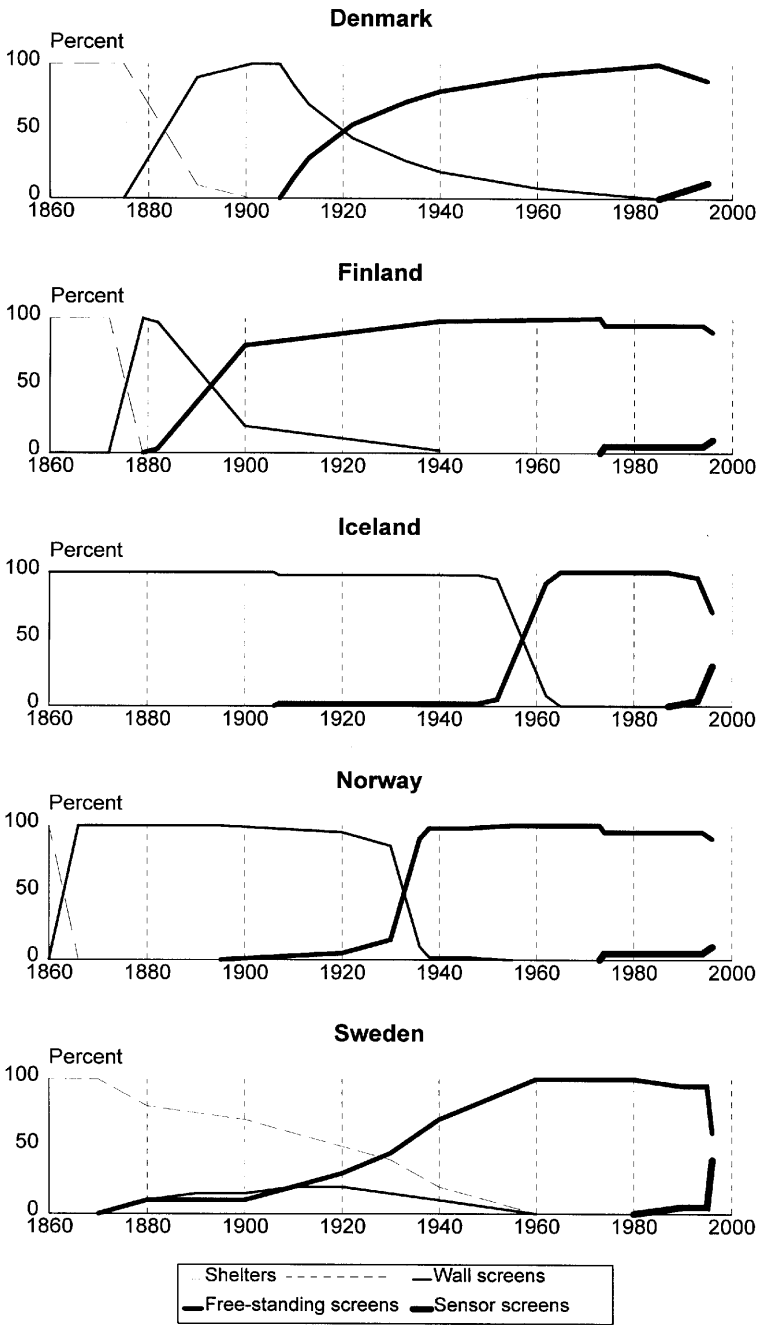

Figure 1. Schematic time evolution of the relative number of the main types of screen

The terms used in this paper are underlined. The word screen refers to structures intended to protect the thermometers from radiation in all directions, except (in some cases) directly from below (cf. Middleton, 1966). More open structures are referred to as shelters. The relative number of the different types in operation since 1860 are shown schematically in Figure 1.

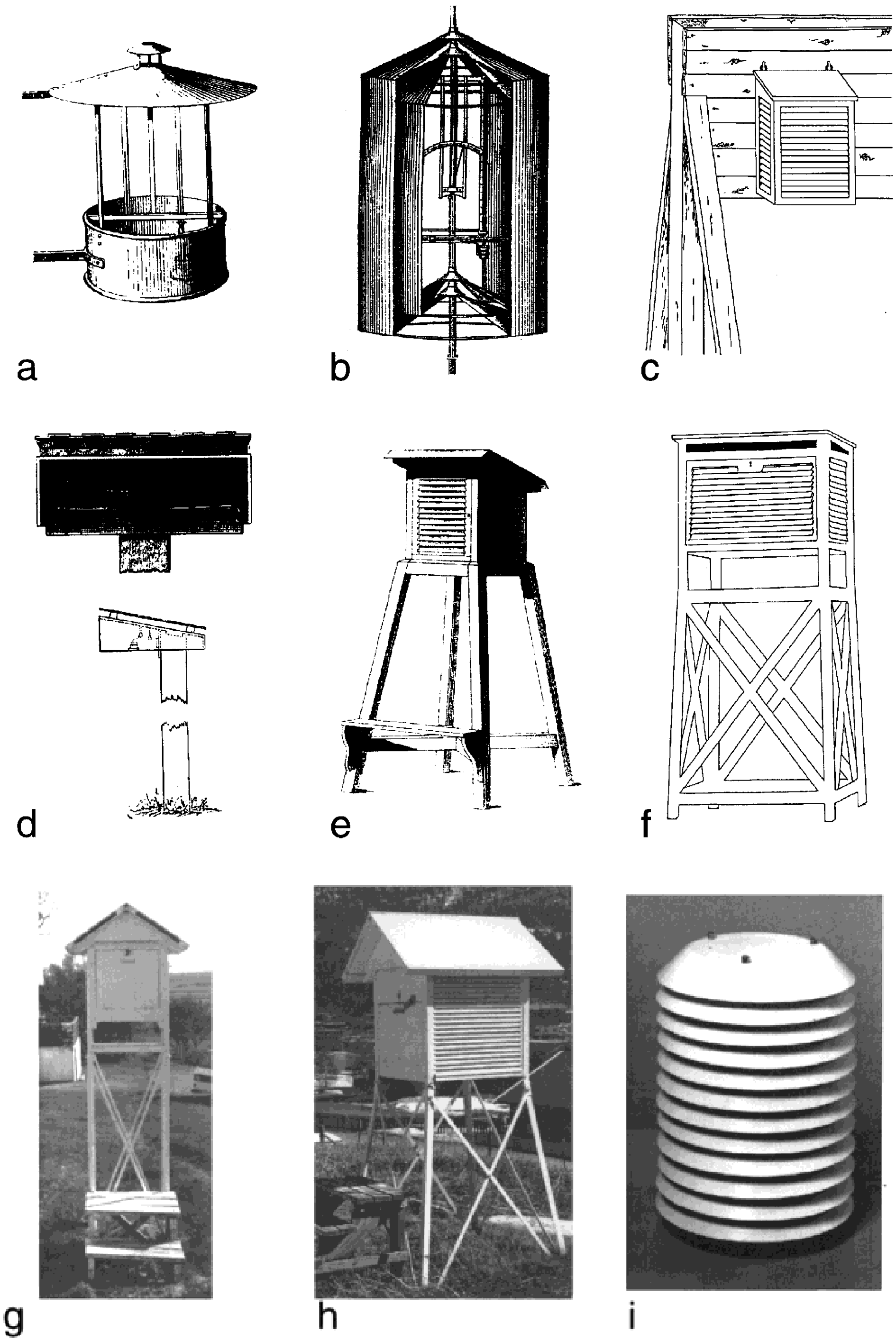

Figure 2. Illustrations of different types of screen used in the Nordic countries. (a) Swedish window shelter (Edlund and Hamberg, 1882). (b) Wild's cylindrical cage used in Finland from 1871 until the early 1900s (Wild, 1879). (c) Danish trellised wall screen fastened on a wooden, double fence in Upernavik, Greenland (Brandt, 1994). (d) Swedish free-standing shelter used mainly at third-order stations (Edlund and Hamberg, 1882). (e) Swedish single louvred Stevenson screen used at lighthouse stations (Nautisk Meteorologiska Byrån, 1879). (f) Double louvred Danish Stevenson screen erected after World War 2. The sketches are based on photographs (Brandt, 1994). (g) Icelandic free-standing screen with solid double walls. (h) Norwegian free-standing screen, pattern of 1946 (MI-46). (i) Vaisala sensor screen, type DTR 13, in current use in Finland and Sweden

Shelters

In the middle of the nineteenth century shelters were in common use in the Nordic countries (Figure 2(a)). In Helsinki, four thermometers were fastened outside windows on each side of the building and the thermometer in shade was read. The thermometer bulb was protected against shortwave radiation. At the Royal Veterinarian and Agricultural University in Copenhagen, a horseshoe shaped free-standing shelter was used.

The early types of shelters used in Sweden were white-painted metal window shelters. A similar type of shelter was probably also used in Norway, but was replaced in the 1860s. The Swedish window shelters were used up to around 1880 at smaller stations and up to the late 1890s at major stations. A free-standing white wooden shelter (Figure 2(d)) was adopted from about 1880 to 1930–1960, mainly at smaller stations, after which Stevenson screens were gradually introduced.

Wall screens

According to the installation instructions for the wall screens (Figure 2(b and c)) these were to be placed on walls that would be in shadow at all hours of observation. That might be possible if the station was situated on a south-facing slope. However, on flat, open terrain in the Nordic countries it was not possible to find a wall that was permanently shaded throughout the year at all observation hours, although obstacles, such as trees and buildings, might provide sufficient shadow.

If it was not possible to find a wall permanently in shadow, outer screens could be mounted on the wall, thus preventing direct sunshine from falling on the cage. This method was often used where the sun's angle to the wall was small at the hours of observation. In other cases it was found necessary to use two cages mounted on differently oriented walls, so that, at all times at least one would be shaded. Normally these instructions were followed but from station histories a few occasions are known where the sun was allowed to shine on to the cages.

Some cages had only three walls, because they were designed for mounting outside a window. The observers were instructed to read the thermometers through the glass of the window. Other cages had four walls, with front doors which enabled the thermometers to be read from outside. The cages were made of tin, zinc or wood and painted white or yellow. Some of their walls were louvred but not necessarily all of them. It is important to note that the cages had no floors, allowing radiation exchange between the ground and the thermometer.

Some early cages were made of plates that were bent into a cylinder. There was a split in the cylinder allowing the thermometers to be read without opening the cage. In Norway this type of screen was used at lighthouse stations up to about 1920. After 1871 the Finnish climatic stations were also equipped with cylindrical wall screens (Figure 2(b)) of the type devised by Heinrich Wild in 1861 and also used in Switzerland, Baden and Russia (Wild, 1879; Heino, 1994). Some of the Finnish cages also contained a ventilation apparatus, i.e. Wild's construction of 1874. The material was enamelled white zinc. During the time interval between observations the cylinders were closed, but could be opened before the reading of the thermometers.

The wall screen was introduced into the Norwegian network in the 1860s and in Denmark at the main climatic stations from 1873, following recommendations from Mohn (1872). Before 1920 Danish screens were also used in Iceland, and the Icelandic wall screens that gradually replaced them were very similar to these. In Greenland several louvred wall screens were mounted on wooden fences.

Free-standing screens

These normally consist of a wooden cage located above a short grass surface at some distance from buildings or other obstacles. Photographs of screens in use about 1970 are shown by Sparks (1972), with about 75 countries represented in his collection, among them all the Nordic countries.

The term Stevenson screen is often used as a synonym for the free-standing screen, although Thomas Stevenson did not invent the louvred screen. However, he seems to have been the first to adopt double louvres sloping in opposite directions (Middleton, 1966). This feature was an important improvement of the screens.

Stevenson's oldest screen, referred to by Buchan in his figures 15 and 16 (Buchan, 1868), has double louvred walls 2 cm apart (Langlo, 1947), so that a ventilation channel is established between them. In the newer

Stevenson screen the double louvred walls are set closer together. There are also major construction differences in the roof and the floor. Whereas the new one has a double roof and a floor, the old one has only a single roof and no floor (Føyn, 1915).

Another early designer of screens was Heinrich Wild, whose construction of 1874 was widely adopted in Russia and Germany and, with some modifications, also in Finland from 1882. It consisted of two concentric cylinders (which could be used as a wall screen as well, see above) installed inside a huge wooden construction with thermometer bulbs about 3.2 m above the ground. The east and west side were single louvred, the south side had a double wall of closed boards, while the northern side was open. During the 1890s the number of Wild screens increased in Finland. The Wild screen was also used at the Oslo Observatory from 1877, in parallel with a wall screen.

The national institutes in the Nordic countries made their own screens, mostly modelled on the Stevenson screen. Often several modifications were made. In Denmark, Finland and Sweden the free-standing screens in current use are of Stevenson type (Figure 2(f)). A Stevenson screen was also designed in Norway in 1895 but was not widely adopted.

Stevenson screens were installed at many Danish stations during the period 1913–1928. Several models have been used, the first one was a copy of a 1911 Fuess screen, which later on was replaced by larger models and finally by a pattern designed in 1971. In Finland a modification of the Stevenson screen was installed at ordinary climatic stations between 1909 and 1912 and at Helsinki in 1923.

In Sweden, single louvred Stevenson screens were introduced as early as about 1880, although probably only at lighthouse stations (Figure 2(e)). At inland stations Stevenson screens with double louvres gradually replaced the older screen types. At major land stations most of these were introduced in the 1930s, whereas at most smaller stations they were introduced within the period 1930–1960. At lighthouses the old screens were also gradually replaced by the newer type, mainly between 1930 and 1950.

In 1920 a single louvred screen type constructed at Tromsø came into use in the northern part of Norway and in the Arctic. In 1930 another single louvred screen was built in Oslo. Like the Wild screen, this one also included the standard wall cage set inside the outer cage. These screens were replaced between 1933 and the 1950s by the ones in use nowadays. One of them, MI-46 (Figure 2(h)) has Stevenson's double louvred walls to the east and west but double boarded walls to the south and north. The other one, MI-33, designed for harsh weather conditions, has double boarded walls facing all directions. Both of them have double floors of overlapping boards of conventional type also used in modern Stevenson screens.

A screen very similar to the Norwegian MI-33, but slightly smaller (Sparks, 1972), is currently used in the Icelandic network (Figure 2(g)). The choice of design reflects the problem of penetrating snow and rain so prevalent at the more exposed Icelandic locations. It replaced wall screens and, at a few stations, also English screens of the Stevenson type or Norwegian screens.

Sensor screen

Traditional screens contain several types of rather large manual instruments such as thermometers, hygrometers and even thermographs and hygrographs. Automatic sensors can be run almost continuously so one temperature sensor can replace the main thermometer and the two extreme thermometers as well as the thermograph. With fewer sensors to be screened and given the smaller size of modern sensors, it is more cost effective to construct small separated radiation screens designed for each sensor.

The screens used in the Nordic countries have cylindrical forms built of concentric plastic rings with a space for ventilation between them. Thus, they are louvred like earlier screens, one of them even double louvred. The outward facing surface is white in order to reflect as much radiation as possible and on many screens the inner surface is painted black to absorb any remaining radiation before it reaches the sensors. The screens presently used are, in Denmark, various versions of the Aanderaa Instruments type and, in Finland and Sweden, Vaisala's DTR 13 (Figure 2(i)). In Norway, a double louvred screen designed by the meteorological institute (MI-74) is currently in use.

In recent years some of the old free-standing screens have been replaced by sensor screens in connection with automation and the present station network in the Nordic countries is a mixture of manual and automatic stations.

At some automatic stations the temperature sensors are placed inside free-standing screens for homogeneity reasons, but at a large number of automatic stations the more cost effective sensor screen is the only one in use. A more detailed description and illustration of Nordic screens is available in Nordli *et al*. (1996).

FREE-STANDING SHELTER COMPARED WITH MODERN FREE-STANDING SCREEN

The Stevenson free-standing screen and the free-standing shelter (Figure 2(d)) were compared during seven years of measurements on a flat meadow at Henstad (59°22′N, 13°23′E) outside Karlstad, Sweden (Modén, 1954). The free-standing shelter was open from below and overestimated temperatures in spring (especially with reflecting snow) and summer, with the noon temperature and maximum temperature influenced the most. Monthly mean differences are presented in Table I, which indicates a maximum difference of 0·4°C in early summer, with higher values in the shelter than in the Stevenson screen. For minimum temperatures no significant differences were found. A similar overheating in spring and summer was also found for the British Glaisher stand (Parker, 1994).

Table I. Monthly mean differences (in 0·01°C) between the Swedish free-standing screen and shelter based upon seven years of measurements

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
0	−10	−20	−20	−30	−40	−40	−30	−20	0	0	0	−20

FREE-STANDING SCREENS COMPARED WITH VENTILATED THERMOMETERS

In many of the comparative tests reported, ventilated thermometers were used as a measure of the true air temperature. The commonly used Assmann psychrometer has less inertia and consequently reveals greater fluctuations in temperature than free-standing screens. The different inertia leads to greater standard deviations of the difference but not to biases in its daily mean values. The standard deviation can be reduced by taking a mean of more than one reading of the ventilated thermometer (Langlo, 1947). A more serious problem is that ventilation draws up air from lower layers which may be cooler or warmer than the air at the measuring level. This is a possible source of bias in the mean values of the differences. Nevertheless ventilated thermometers still provide the best common reference temperature available for comparison of test results from various sites.

Comparisons have been made at fixed clock hours, often at the same hours as the ordinary observations. In the literature, average temperature differences from these comparisons are available but usually not monthly average differences representative for the whole day. If the formulae for monthly mean temperature are linear, the calculation of the monthly differences can be done by simply replacing clock mean temperatures by clock mean temperature differences.

Before describing the Nordic comparisons, we will look briefly at two made outside the Nordic countries. Köppen (1913) quoted comparisons in the years 1910–1912 of a ventilated thermometer and a Stevenson screen at Bergedorf, Hamburg Observatory. Based upon mean values at observation hours 0700, 1400 and 2100 hours in his publication, the monthly mean differences are calculated by adding the values at 0700 and 1400 hours, and two times that at 2100 hours, and dividing the sum by 4. This formula has been used in Germany (Berlin-Brandenburgishce Akademie der Wissenshaft, pers. comm. and Finland (Heino, 1994) for calculating monthly mean temperature. The largest differences occurred in July/August when the Stevenson screen was overheated by 0·2°C, whereas the differences in the months November–April were less than 0·1°C.

The Wild screen (also used in Finland and Oslo) was compared with ventilated thermometers at the Pavlovsk Observatory in Russia (Wild, 1885). The ventilation seems to have been poor as there are large differences (often 1°C) between values of the sling thermometer exposed to sunshine and values obtained in the shadow of the Wild screen. Later Wild performed comparisons with Assmann's apparatus (Wild, 1889), which led to results that have been subject to much criticism (Middleton, 1966). However, results from Pavlovsk in 1898 and 1899, quoted by

Table II. Monthly mean differences (in 0·01°C) of temperature of forced ventilated air minus temperature in free-standing screens

Country	Screen	Test	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Finland	Wild, ventilated	1[b]	−2	−5	−11	−18	−30	−37	−37	−23	−9	−3	0	2	−14
	English screen	2[c]	8	7	6	3	−4	−12	−11	0	6	6	7	8	−2
Norway	Norwegian screen[a]	3[d]	6	−3	−6	−6	−15	−21	−26	−16	−9	−4	0	−5	−9
	MI-30[a]	4[e]	−5	1	−5	−15	−21	−33	−36	−34	−16	3	−4	5	−13
	MI-33[a]	4[e]	−8	−4	−4	0	7	−12	−13	−10	−7	3	−4	−3	−5
	MI-33[a]	5[f]	3	2	−1	−6	−31	−16	−26	−18	−10	6	6	9	−7
	MI-33[a]	6[g]						−12	−12	−8	−18				
	MI-46[a]	5[f]	5	1	1	4	−18	6	−3	−2	5	6	7	11	−2
Sweden	SMHI large	7[h]	2	2		−1	−1	−2	6	−1	0	0	−2	−1	0
	SMHI small	7[h]	0	0		−5	−5	−8	1	−4	−2	−2	−4	−3	−3

[a] The minimum temperature term in the formula of monthly mean temperature is omitted. This will add an additional uncertainty to the results of 0·1°C or less.
[b] Helsinki (60°10′N, 24°57′E), southern Finland. Period: 1898–1904 (Johansson, 1906).
[c] Helsinki (60°10′N, 24°57′E), southern Finland. Period: 1923–1946, altogether 8766 daily observations (Heino, 1994).
[d] Bergen (60°24′N, 5°19′E), Fredriksberg Observatory, western Norway. Period: March 1911 to March 1912 (Føyn, 1915).
[e] Ås Observatory (59°41′N, 10°47′E), south-eastern Norway. Period: February 1938 to January 1939 (Langlo, 1947).
[f] Oslo (59°55′N, 10°43′E), Norwegian Meteorological Institute, south-eastern Norway. Period: June 1946 to May 1947 (Langlo, 1947).
[g] Kleppe (60°31′N, 5°33′E) on Osterøya, western Norway. Period: June 1952 to September 1954. Data comprise the season June to September only (Utaaker, 1956).
[h] Norrköping (58°58′N, 16°15′E), central Sweden, Swedish Meteorological and Hydrological Institute. Period: April 1989 to February 1990. (Andersson and Mattisson, 1991).

Köppen (1913), reveal a difference of mean temperature between the ventilated thermometer and the Wild screen of −0·27°C in July/August. In January/February the difference is negligible.

The Nordic comparisons are presented in Table II as the difference of monthly mean temperature in ventilated air minus monthly mean temperature in different types (patterns) of free-standing screens. They represent a variety of tests obtained over a rather long time span (see notes underneath the table).

Test results from Helsinki (test 1) representing comparisons of the Wild screen, are in good agreement with test results from Pavlovsk. In contrast the Stevenson screen tested in Bergedorf seems to be more overheated than the modern screens in current use, although its results resemble those obtained from the outdated, double-louvred Norwegian Screen (test 3).

For all months except May, the Norwegian standard screen MI-46 is subject to very little overheating compared with forced ventilated air (test 5 in Table II). In May, however, the sun's radiation reached the louvred walls at approximately perpendicular angles at the morning and evening observing time and may have penetrated into the cage. This is confirmed by the fact that the entire difference in May resulted from the morning and evening observations (not shown in the table). Similar overheating is not present in August, probably because of a higher frequency of cloudiness. Overheating at low solar angles is also in agreement with measurements at Vågåmo, Norway (62°N, 9°W) (Høgåsen, pers. comm).

Similar results are also found by Andersson and Mattisson (1991) for two of the standard SMHI screens (test 7). The largest overheating of the screens occurred around the time of sunset and to a lesser degree, at sunrise. The large values at sunset can also be attributed to a back lag caused by the screens' inertia, but this will be levelled out when integrating to obtain the monthly mean temperature. The monthly mean differences of the SMHI screens are less than 0·1°C in all months.

In Figure 3 the test results have been grouped mainly according to the shape of the screens' walls: single louvred, old double louvred, double louvred and double walls. During the months from October to March the monthly mean temperature from all groups follows the temperature measured in ventilated air very well, the differences being less than 0·1°C. This is also true for the individual test results (except for two values, Table II).

During the months May–September, however, the Norwegian MI-33 screen is overheated by 0·1–0·2°C, the result based upon comparisons at three sites around 60°–61°N. This screen, for harsh weather conditions, seems

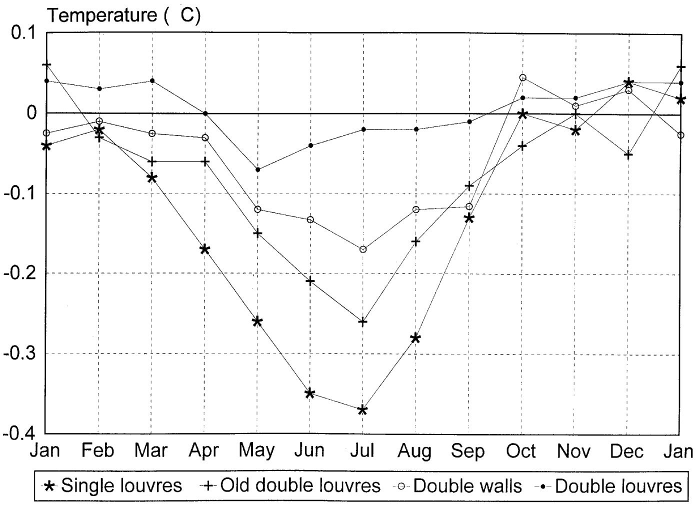

Figure 3. Monthly mean differences for the temperature of forced ventilated air minus temperature in ordinary free-standing screens. Mean values for four different groups of screens, i.e.: single louvres—Finnish Wild screen and Norwegian pattern of 1930 (MI-30); old double louvres—Norwegian Screen; double walls—Norwegian pattern of 1933 (MI-33); double louvres—'English' Screen used in Finland, Norwegian pattern of 1946 (MI-46), large and small SMHI screens

to be somewhat better than the old double louvred 'Norwegian' Screen. During May–August the latter is overheated by about 0·2°C but for the rest of the year the differences are within an interval of 0·1°C. As expected the greatest overheating during summer is found for the group of single louvred screens, reaching at most 0·3–0·4°C in June and July.

Monthly mean temperature differences for the group of double louvred screens are within the range 0·1°C throughout the year. In this group, the 'English' Screen used in Finland has a small overheating of about 0·1°C in June and July.

Most of the comparisons were performed in areas of continental climate; Bergen and Kleppe being the exceptions. For the MI-33 screen, test results from both a maritime climate (Kleppe, test 6) and a continental climate (Ås and Oslo, tests 4 and 5) are available. From Table II it is seen that the results from Kleppe do not differ systematically from those in eastern Norway. Kleppe, however, is situated in a fjord district in western Norway about 40 km from the coast. The overheating is expected to be less at coastal sites, where calm, fair weather situations do not occur so frequently.

Direct use of test results at latitudes other than around 60°N, where these comparisons were made, is questionable. At high latitudes radiation reaches the louvred walls at greater angles than at the test sites and may penetrate more readily into the interior of the screens.

COMPARISONS OF FREE-STANDING SCREENS AND WALL SCREENS

Before the new free-standing screens replaced wall screens, comparison measurements were often performed at the observatories and also at some station sites. The test results are summarized in Table III. In Figure 4 these results are averaged for each country except Sweden, where data only comprises one year and one station. Regardless of the methods used in the original papers, all differences between the screens are calculated as follows: $T_{\text{free-standing screen}} - T_{\text{wall screen}}$, thus positive (negative) differences mean that the free-standing screen is warmer (colder) than the wall screen. The results of the comparisons differ considerably for individual tests. An essential factor for explaining these differences is the radiation balance, which is positive in summer and negative in winter. Different local or microclimates at the measuring sites are also important.

During the *summer* the bulk of the measurements reveal somewhat higher temperatures in the wall screen than in the free-standing screen. Thus, the mean differences from eight Icelandic comparisons were 0·3°C in June and July (Figure 4), with similar results obtained from test field experiments at Stockholm Observatory and at

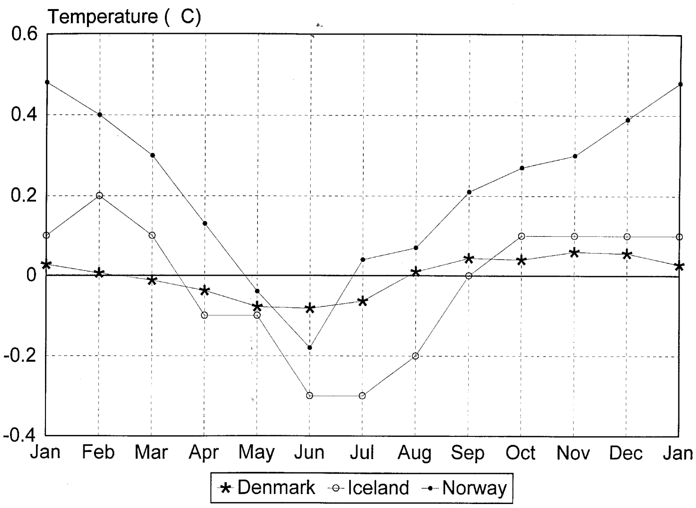

Figure 4. Monthly mean temperature differences: free-standing screens minus wall screens from Denmark (tests 2–6), from Iceland (test 7), and from Norway (tests 9 and 10). For details of tests, see Table III

Table III. Monthly mean differences (in 0·01°C) between free-standing screens and wall screens. All free-standing screens are double louvred. In test 8 the outdated 'Norwegian Screen' was used

Country	Test	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Denmark	1[a]	−34	−51	−39	−59	−82	−108	−99	−72	−45	−36	−32	−34	−58
	2[b]	−3	−3	−4	−5	−19	−16	−12	−1	−5	−13	−9	−3	−8
	3[c]	1	−1	2	7	8	6	7	6	12	8	4	1	5
	4[d]	8	8	5	−4	−2	−5	−1	10	17	20	20	16	8
	5[e]	5	−3	−10	−20	−27	−26	−12	−10	2	3	12	10	−6
	6[f]	3	3	1	3	1	0	−1	0	1	2	3	4	2
Iceland	7[g]	10	20	10	−10	−10	−30	−30	−20	0	10	10	10	−3
Norway	8[h]	28	21	20	9	5	7	1	5	18	32	30	37	18
	9[i]	60	50	50	20	10	−10	20	20	30	40	50	50	33
	10[j]	36	30	10	5	−18	−25	−12	−6	11	13	9	28	7
Sweden	11[k]	−10	−10	0	0	−10	−20	−20	0	10	0	−10	−10	−7

[a]Bovbjerg Fyr (24020) (56°31′N, 08°07′E), western Jutland, Denmark. Period: 1971–1987.
[b]Skjoldnæs Fyr (28490) (54°58′N, 10°12′E), Ærø, Denmark. Period: 1971–1983.
[c]Keldsnor (28550) (54°44′N, 10°43′E), Langeland, Denmark. Period: 1971–1987.
[d]Rudkøbing (28590) (54°57′N, 10°43′E), Langeland, Denmark. Period: 1971–1987.
[e]Spodsbjerg Fyr (30110) (55°59′N, 11°51′E), Sjælland, Denmark. Period: 1971–1974.
[f]Gedser Fyr (31612) (54°34′N, 11°58′E), Falster, Denmark. Period: 1971–1982.
[g]Mean values from eight Icelandic stations in the period 1948–1962 (VI 1962).
[h]Fredriksberg observatory (50560), Bergen, western Norway. Period: January 1907 to December 1914 (Føyn, 1915).
[i]Glomfjord (80700) (66°49′N, 13°59′E), northern Norway. Period: January 1956 to December 1956 (Bruun, 1957).
[j]Dombås (16550) (62°04′N, 9°08′E, 653 m a.s.l.), central mountain area, southern Norway. Period: June 1989 to March 1995 (Nordli *et al.*, 1996).
[k]Stockholm Observatory, eastern Sweden. Period: October 1960 to December 1961 (Modén, 1963).

Dombås, Norway (tests 10 and 11 in Table III). Three of six Danish tests also show significantly higher temperatures in the wall screens than in the free-standing screens, and the remainder reveal differences of less than 0·1°C during summer (tests 1–6). However, some of the Danish comparisons were performed at locations that are known to reduce the bias, i.e. windy, coastal sites and/or stations located in the shadow of large trees. The real biases for the whole network could thus be significantly larger, if account is taken of the number of inland stations and stations more exposed to direct sunshine.

At one Danish station, 24020 Bovbjerg (test 1), there are marked differences from the others. Here the wall screen is up to 1·1°C warmer in summer (Table III). However, photographs and maps of the station show that the cage was placed on a wall in a yard surrounded by buildings. Only a narrow east-facing sector was open, whereas the Stevenson screen was placed in an open area. A local heat source, i.e. the exhaust pipe from a generator, might also have contributed to the difference and the test is included in Table III as an example of the effect of bad exposure.

During *winter*, differences are less than $\pm 0{\cdot}1$°C for most of the tests. Thus, the homogeneity of time series seems in most cases to be maintained in winter through a change from wall screens to free-standing screens. However, the three Norwegian comparisons differ substantially from the others. Pitfalls may therefore exist even for the winter season if time series are used without adjustments for this kind of screen change. It is therefore essential to understand the reason for the different results.

One of the three divergent Norwegian comparisons was carried out at Fredriksberg Observatory in Bergen around 1910. The original observations are lost and the reason for the large winter differences is unknown. The original data from the remaining two at Glomfjord and Dombås (tests 9 and 10 in Table III and averaged in Figure 4) are available for analysis. The free-standing screens (MI-46) were warmer than the wall screens (metal cage of 1876), the largest average difference being 0·5°C in January. Large individual differences were especially found during inversion situations (Nordli *et al*., 1996).

Two possible mechanisms by which inversions can cause the wall screen to be colder than the free-standing screen are:

(i) different screens—The thermometer in the wall screen exchanges radiation with the colder (snow covered) ground through its open floor;
(ii) different microclimate—A shallow drainage flow is established on the slope, with the upslope, northern side of the building (where the wall screen is located), impeding the flow of air, which stagnates and may be colder than the air some metres away from the building (where the free-standing screen is located).

In order to evaluate these effects, two additional sensors, protected by identical screens, were placed in the Dombås test field, one near the wall screen and the other near the free-standing screen. At night the difference between the two sensor screens did not differ significantly from the difference between the free-standing screen and the wall screen. Thus, the difference between the two sites is mainly a consequence of different microclimate and not of differences between the screens.

Especially in the mountain areas of Scandinavia there are valleys where temperature is a limiting factor to agriculture. The majority of the farms are optimally situated on southern faced slopes. Thus, when weather stations were located at these farms, shadows for the cages were found at the upper side of the houses (as at Glomfjord and Dombås) where cold air can accumulate. Therefore the problem of too cold wall screens during winter should not be overlooked. It may bias most of the series originating from mountain valleys.

The station at Síðumúli, Iceland (64°43′N, 21°22′W), like Dombås, is situated in a valley, but unlike Dombås the winter differences are near zero (Nordli *et al*., 1996). It is suggested that this discrepancy is caused by different local climates. During inversion situations, Síðumúli experiences a strong and thus turbulent drainage flow, whereas the air at Dombås in fair weather situations is typically calm.

In general a change from wall screen to free-standing screen also involves a relocation and may therefore lead to different results at different sites. The results may depend on the characteristics of the building (orientation, colour, winter heating, size), or other factors such as height above the ground of the thermometers, latitude, local topography and horizon. When transferring comparison results from one site to another, differences in microclimate must also be taken into account. The factors involved are many and each of them may be difficult to assess. Therefore we cannot recommend general adjustment terms for this change that would be applicable, for example, to national networks.

COMPARISONS OF FREE-STANDING SCREENS AND SENSOR SCREENS

Parallel measurements in free-standing and sensor screens were performed above a fairly unobstructed grass surface close to the Swedish Meteorological and Hydrological Institute in Norrköping during the period April

1989 to February 1990 (Andersson and Mattisson, 1991). The main issue was to evaluate the new type of screens used to protect platinum resistor thermometers at automatic stations. One of the screens under test was Vaisala's type DTR11, a type very similar to DTR13 in current use in Finland and Sweden (Figure 2(i)). The sensors were compared with a Teledyne ventilated thermometer.

In spite of large individual differences, the magnitude of the monthly mean differences was negligible, i.e. of the same magnitude as the measurement accuracy, which was estimated to be about 0·04°C. The standard deviation of individual differences was about 0·2°C.

Ventilation due to wind minimized the screen effect. With wind speeds higher than about $1\,\mathrm{m\,s^{-1}}$ (somewhat depending upon the screen type and irradiation), the differences were close to zero. Under cloudy weather they were also close to zero.

At the Norwegian Meteorological Institute in Oslo, parallel measurements were performed over the period 14 October 1982 to 15 December 1983. Those measurements involved only two screens, the Institute's new sensor screen, type MI-74, and the ordinary free-standing screen, type MI-46 (Nordli *et al*., 1996). Similar results were obtained as in Norrköping. The mean values of all observations were not biased more than 0·03°C. The monthly mean differences (free-standing − sensor screen) ranged from −0·04°C to 0·11°C.

The MI-74 screen cannot be compared directly with those used in Norrköping because of the lack of a common reference. However, measurements quoted earlier in this paper (cf. Table II) show that monthly mean temperature from the ordinary SMHI screen as well as the MI-46 are not biased compared with ventilated thermometers. The tests described here indicate that they are not biased compared with the sensor screens either. Therefore, ordinary free-standing screens may probably be replaced by sensor screens without causing inhomogeneity in the series of monthly mean values. However, as the test material is rather limited, the possibility of biases in months with unusual weather conditions cannot be excluded, e.g. calm weather in early spring when the ground is covered with snow.

Although outside the scope of this paper, it should be mentioned that sensor screens are biased compared with ordinary screens concerning the diurnal temperature range: for MI-74 this amounts to more than 1°C in the summer months from June to September (Nordli *et al*., 1996). The largest contribution to this bias comes in summer from the maximum temperature. Replacement of the ordinary free-standing screens with sensor screens will therefore cause inhomogeneities in time series of maximum and minimum temperatures (e.g. see Quayle *et al*., 1991). The sensor screens therefore should be tested thoroughly because they are now commonly used in the national station networks.

ADJUSTMENTS APPLIED TO TEMPERATURE SERIES CAUSED BY SCREEN CHANGES

Long time series of mean temperature often have to be adjusted for inhomogeneities by adding an adjustment term to some parts of the series. For practical reason this should be done before the shift so that new data can be added without adjustments.

Many of the oldest parts of long series contain observations made in shelters, free-standing or fixed to a wall. The test results show that the Swedish free-standing shelter is overheated during spring and summer and consequently the series requires negative adjustments in those seasons. In the Swedish network, shelters were also used in the present century (see above).

Thermometers in wall screens are not only screened by the cage but also by the building or structure they are mounted upon. A relocation from one building to another may change the irradiation reaching the cage at given observation hours if the orientation of the buildings is not the same. This kind of inhomogeneity is, for example, detected in the Norwegian network (Nordli *et al*., 1996). On the other hand, wall screen arrangements are probably not sensitive to changes of wall screen type. We know that a variety of types has been used but test results are very sparse. In 1875 an old Norwegian wooden cage was tested against a new type made of metal. The original figures are lost, but the conclusion is known. For mean temperature 'no important differences between the cages were found' (DNMI, 1875).

Adjustments for changes from wall screens to free-standing screens are not needed in winter for most of the series. However, the two Norwegian comparisons at Glomfjord and Dombås, carried out on valley slopes revealed 0·5°C colder wall screen than free-standing screen in midwinter, i.e. positive adjustments are needed

(Figure 4). In four of the Nordic countries, wall screens were gradually replaced by free-standing screens, and possible adjustment terms (if needed) may be estimated by nearby reference stations or by parallel measurements. Generally, the change from wall screen to free-standing screen also involved relocation from a building's wall to an open grassed surface. The appropriate adjustments therefore vary from place to place. The optimal solution to this homogeneity problem is parallel measurements at all stations, as is done in Iceland.

Practically all wall screens were replaced in Norway in the early part of the 1930s and consequently it is almost impossible to establish reference groups of unchanged stations within the country. However, the most inhomogeneous series may be excluded from the groups, i.e. inland stations with cages fixed on walls facing upslope. With that precaution, test results indicate that reference groups may be unbiased in winter.

A preliminary analysis of the adjustments required for NACD temperature series in Finland, Norway and Sweden (Tuomenvirta, pers. comm.) is in general agreement with results presented in this paper. However, during wintertime some of the NACD temperature series needed statistically significant mean adjustments (−0·1 to −0·2°C) for changes related to radiation screen (type, height, maintenance, etc.). According to the various tests reported in this paper, radiation screen type changes did not generally cause discontinuities during winter, although there were exceptions at individual stations, e.g. Dombås. One possible explanation for negative adjustments is related to screen heights. In old shelters and walls screens, thermometers were not always situated at the present standard height of 2 m above ground, and, for example, in Finland the majority of them were located 3 to 4 m above the ground. Thus, during the prevailing winter inversion conditions over Fennoscandia, the old screens are likely to have been warmer than the free-standing screens at a standard height of 2 m. However, it is possible also that some other local factors, e.g. heat transfer from the supporting building to a wall screen, could have contributed to systematic negative adjustments.

The test results revealed overheating of the single louvred free-standing screens in spring and summer but not of the double louvred screens. When the outdated single louvred screens were replaced by double louvres (or double walls), adjustments ranging from −0·2°C to −0·4°C should be applied to the series in those seasons for inland stations. The single louvred Wild screen was used mainly in Finland in the period from 1890 to the 1910s, whereas the single louvred MI-30 was used in Norway from 1930 to the 1950s.

In Sweden, single louvres were used only at lighthouse stations, where the effect on mean temperature may have been negligible due to adequate ventilation by wind, as indicated by Norwegian test results. Tested against reference groups, the series from the inland station Karasjok was biased due to the screen change, whereas the series from Vardø, an island adjacent to the Barents Sea, was not. Single louvred screens were never introduced in the station networks of Denmark and Iceland.

The most probable sign of the adjustments, which should be applied to mean temperature, is summarized in Table IV. It is based on the tests presented in this article but excluding two of the tests in Table III (test 1—very different environments of the wall screen and the free-standing screen; test 8—old-fashioned double louvred

Table IV. Summary of the sign of adjustment to be added to monthly mean temperatures before the change of screen during the seasons spring (March–May), summer (June–August), autumn (September–November), winter (December–February)

Change of screen		Sign of the adjustment terms[c]			
From	To	Spring	Summer	Autumn	Winter
Wall screen	Single louvred[a]	n.c.	+	n.c.	n.c.
Wall screen	Double louvred[a]	n.c.	−	n.c.	n.c.
Single louvred[a]	Double louvred[d]	−	−−	−	0
Shelter[b]	Double louvred[a]	−	−−	0	0
Double louvred[a]	Sensor screen	0	0	0	0

[a]Different types of free-standing screen.
[b]Swedish free-standing shelter.
[c]++(−−) means positive (negative) adjustments found by an overwhelming majority of the tests. +(−) means a tendency of positive (negative) adjustments. 0 means that practically no adjustment is required and n.c. means that the test results are non-conclusive.

screen). The tendency of warmer wall screen than single louvred screen (row 1 in Table IV) is not found directly by tests. It follows, however, from the two next rows where both the wall screen and the single louvred screen are compared with double louvres.

CONCLUSIONS

It should be stressed that this paper considers only mean temperature; the task of analysing the screen effect on temperature maxima, minima and diurnal range still remains. For monthly mean temperature we are able to conclude that most screen changes do not cause inhomogeneities in winter. The individual tests collected here show that it is not possible to be too precise about the effects of screen changes at a specific site. Especially in hilly and mountainous terrain the spatial variation of temperature is very complex. However, in late spring and summer the change from wall screen to single louvred screen most probably requires positive adjustments, the change from wall screen to double louvred screen will usually require negative adjustments to the earlier data, the change from single louvred to double louvred screen requires adjustments at inland stations of about $-0{\cdot}2^{\circ}$C to $-0{\cdot}4^{\circ}$C, and the change from double louvred to sensor screen probably requires no adjustment.

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