

HERDIS M. GJELTEN^{1,2}, ØYVIND NORDLI²,
ARNE A. GRIMENES¹ AND ELIN LUNDSTAD²

¹Department of Mathematical Sciences and Technology,
Norwegian University of Life Sciences, Ås, Norway

²Norwegian Meteorological Institute, Oslo, Norway
e-mail: herdismg@met.no

THE ÅS TEMPERATURE SERIES IN SOUTHERN NORWAY–HOMOGENEITY TESTING AND CLIMATE ANALYSIS

Abstract: Homogeneity is important when analyzing climatic long-term time series. This is to ensure that the variability in the time series is not affected by changes such as station relocations, instrumentation changes and changes in the surroundings. The subject of this study is a long-term temperature series from the Norwegian University of Life Sciences at Ås in Southern Norway, located in a rural area about 30 km south of Oslo. Different methods for calculation of monthly mean temperature were studied and new monthly means were calculated before the homogeneity testing was performed. The statistical method used for the testing was the Standard Normal Homogeneity Test (SNHT) by Hans Alexandersson. Five breaks caused by relocations and changes in instrumentation were identified. The seasonal adjustments of the breaks lay between -0.4°C and $+0.5^{\circ}\text{C}$. Comparison with two other homogenized temperature series in the Oslo fjord region showed similar linear trends, which suggests that the long-term linear temperature trends in the Oslo fjord region are not much affected by spatial climate variation.

Key words: homogenization, monthly temperature mean, formula for monthly mean temperature, rural temperature data, long-term climate data, temperature trend, AnClim

Introduction

The temperature series from Ås offers an important opportunity to study long-term variations in the climate near the Oslo fjord, as there have been observations at Ås since 1874. The measurements have been taken at the Norwegian University of Life Sciences, which started as an agricultural college in 1859. This long observation series is outstandingly valuable because Ås is located in a rural environment, in contrast to the Oslo series only 30 km to the north. The observation series is unique, as other time series of important climate variables dating back to the 19th century also exist, e.g. soil temperatures, precipitation, snow days/depths, sunshine hours, air pressure and humidity.

In order to study how climate has changed over time, long-term series of climate data are a prerequisite. When using a time series in climate analyses and modelling, the time series has to be homogeneous, i.e. the variation in the time series is not affected by changes in equipment, relocations of the meteorological station, changes in observation hours, urbanization or other changes in the surroundings of the observation site. This is of paramount importance as inhomogeneities may be of the same order of magnitude as long term trends.

One source of inhomogeneities in temperature series is a change in the formula for calculation of monthly mean temperature (e.g. Heino 1994, pp. 37–42; Nordli and Tveito 2008). Due to an early automation of the Ås weather station, a long series of hourly observations is available. This will be used in the present article to assess the uncertainties and biases of old formulae.

Thanks to the HistKlim project at the Norwegian Meteorological Institute (MET Norway), the entire Ås series has been digitized on sub-daily resolution. Knowledge of the station's metadata has been improved by merging two files of information, one from each of the institutions. The metadata was further completed with data directly extracted from the observational protocols during the digitization. These data had not earlier been systematically collected.

Some Norwegian long-term temperature series have been homogenized by Nordli (1997). Ås was not included because the station at that time was run by the Norwegian University of Life Sciences as a private station, and not present in the network of MET Norway. Andresen (2011) homogenized

all Norwegian temperature series of more than 20 years in length, among them also Ås, using the Standard Normal Homogeneity Test (SNHT) (Alexandersson 1986) imbedded in the program package ProClimDB (Štěpánek 2008b). This was done before the digitization of the whole Ås series was finished, so it was based on old, hand-calculated, monthly means in the period 1874–1956. The present homogenization is unique in the sense that it uses the fully digitized series and also includes the period of private observations, i.e. May 1984 to December 2009.

The SNHT is the predominant method in use in the Nordic countries (Alexandersson 1986, 1995; Alexandersson and Moberg 1997; Moberg and Alexandersson 1997; Tuomenvirta 2001, 2002). Comparisons of the SNHT with other methods (Pettersson et al. 1998; Ducré-Robitaille et al. 2003; Domonkos 2013) have shown that the SNHT performs well, which may be the reason why it has been widely used for a considerable amount of time. However, recently developed methods (Szentimrey 2007; Domonkos 2011; Mestre et al. 2013; Guijarro 2013) are now giving it strong competition.

The scope of this study is to compare formulae for calculation of monthly mean temperatures, to calculate new monthly means for Ås, to perform homogeneity testing on the Ås temperature series and then to compare the homogenized temperature series to other nearby long-term series.

Data and methods

Formulae for calculation of monthly mean temperature

Today, monthly mean temperature is calculated directly from high-resolution temperature data registered at automatic weather stations. Automatic registrations have existed at Ås since May 1988, whereas earlier registrations are manual.

Calculating monthly mean temperature from manual temperature observations, which in Norway normally consists of three observations at fixed hours during daytime together with the minimum temperature, can be carried out according to different formulae (Nordli and Tveito 2008). In this study the formulae of Köppen, Føyn, and Hansteen are tested, as well as the formula called “the classic formula” (see Table 1).

Table 1. Formulae for calculating monthly mean temperature, T_m , based on three daily temperature registrations, T_1 (morning), T_2 (midday) and T_3 (evening), and the daily minimum temperature, T_{\min}

Köppen	$T_m = T_f - k(T_f - T_n)$	T_f – monthly mean of T_1 , T_2 and T_3 T_n – monthly mean of T_{\min} k – Köppen’s constant
Føyn	$T_m = T_g + k(T_2 - T_g)$	T_g – monthly mean of T_1 and T_3 k – constant
Hansteen	$T_m = \frac{17T_1 + 14T_2 + 17T_3}{48} + k$	For observations hours 06, 13, 20 UTC. Weight factors are the time span between proceeding and following observation. k – constant
Classic	$T_m = T_g + k$	T_g – monthly mean of T_1 and T_3 k – constant

Köppen’s formula (Köppen 1888) was already introduced in Norway for calculation of monthly mean temperatures in 1890, but monthly means were also recalculated for earlier data meaning that the same formula was used for all manual stations from 1876. With only daytime measurements, the k -term (often called Köppen’s constant or the k -value) should correct for the missing part of the daily temperature cycle. During winter, when the daily temperature range is small, the k -value is close to zero, whereas during summer, when the daily temperature range is pronounced, the k -value reaches its maximum value. The k -value lies within the interval 0 and 0.3 and varies with location, month and observation hours (Nordli and Tveito 2008). The observation hours at Ås have changed several times, hence several sets of k -values had to be calculated for each month in each period. In order to calculate the monthly mean temperature for time periods without minimum temperature measurements, Føyn’s formula, Hansteen’s formula and the classic formula can be used.

Standard Normal Homogeneity Test (SNHT) for single breaks

When homogenizing the Ås temperature series, the Standard Normal Homogeneity Test (SNHT) developed by Hans Alexandersson was

used. This is a statistical test which uses neighboring weather stations as a reference in order to detect homogeneity breaks in the time series of the candidate station, which is the series to be tested (Alexandersson 1986). AnClim (Štěpánek 2008a), a software with the SNHT imbedded, was used in the homogeneity testing.

Reference stations

The 25 meteorological stations used as reference stations for the SNHT in this study can be seen in Figure 1. Ås meteorological station is also included in this map. Table A.1 in the supplementary material lists the period with data coverage for each of the reference stations in addition to the national station identifier (i.e. station number) and station name.

Results and discussion

Comparing the formulae for calculation of monthly mean temperature

In order to use and compare the four formulae for calculation of monthly mean temperature, the constants in the formulae first had to be calculated. These constants had, for most of the period, previously been calculated at MET Norway using geographical interpolation from sites where hourly observations were extracted from thermograph registrations (Birkeland 1935, p.10). These constants could now be calculated directly using hourly observations from Ås. Automatic hourly measurements began in 1988, but due to many gaps in the period 1988–1994, the period 1995–2011 was chosen. The arithmetic mean of the hourly observations, i.e. the international definition of mean temperature, hereafter called the «true mean», was inserted as T_m in the formulae. The hourly observations were also used to calculate T_1 , T_2 , T_3 , T_n , T_f and T_g in the formulae, see Table 1 for notations and formulae. Thus, the only unknown quantity in the formulae was the constant, which could then be calculated.



Fig. 1. An overview of the meteorological stations used as reference stations in the homogeneity testing. The meteorological station at Ås is also displayed. Basis map: © Kartverket (<http://www.kartverket.no>, 30-Oct-14)

For the period 1874–1877, when minimum temperature was not measured, there have traditionally been three formulae in use in Norway, (see Table 1) In order to test the skill of the formulae, all of the formulae were used to calculate the monthly mean temperatures in the period 1995–2011. The differences between the true means and the monthly means were calculated, as well as the standard deviations of the differences. Part one of Table 2 shows the standard deviation of the difference per month and year for Köppen's, Føyn's, Hansteen's and the classic formula. From the table it is evident that the classic formula has the highest standard deviation, i.e. the lowest skill, which is consistent for all months. Both Føyn's and Hansteen's formula perform well with standard deviations lower than 0.1°C for most of the months. Føyn's formula has the highest skill for the majority of the months.

MET Norway uses Köppen's formula when daily minimum temperature is available. It is therefore of great interest to study the skill of this formula compared to the other ones. As expected, due to the use of one extra daily observation, Köppen's formula has the overall best skill, see part one of Table 2. It should be noted, however, that for the winter months (November, December and January), which have the smallest daily temperature range, Føyn's formula performs slightly better than Köppen's formula. This may not be very surprising as Köppen constructed his formula in order to deal with the systematic variation of temperature during the day, knowing that the observation times were biased against daytime (Høgåsen 1993; Nordli and Tveito 2008).

Table 2. The first part of the table shows the standard deviations of the differences between the monthly mean temperatures calculated by various formulae and the true means for the period 1995–2011. Formulae by Köppen, Føyn and Hansteen and the classic formula are represented. Part two shows the standard deviations and the average of the differences between the monthly means calculated by Köppen's and Føyn's formula and the true means in the period 2004–2011. Units are °C

Period	Complete dataset 1995–2011				Validation dataset 2004–2011			
	Standard deviation				Standard deviation		Average difference	
	Köppen	Føyn	Hansteen	Classic	Köppen	Føyn	Köppen	Føyn
January	0.08	0.07	0.07	0.12	0.09	0.07	-0.04	-0.04
February	0.08	0.08	0.08	0.21	0.07	0.08	0.03	0.03
March	0.07	0.09	0.10	0.39	0.10	0.12	-0.05	-0.03
April	0.03	0.06	0.07	0.25	0.03	0.03	-0.01	0.07
May	0.05	0.09	0.10	0.16	0.04	0.06	0.01	0.03
June	0.06	0.11	0.11	0.16	0.07	0.13	0.00	0.02
July	0.06	0.08	0.12	0.12	0.05	0.06	0.02	-0.03
August	0.06	0.09	0.07	0.28	0.04	0.06	0.02	0.04
September	0.06	0.08	0.07	0.27	0.06	0.08	0.03	0.06
October	0.07	0.07	0.07	0.37	0.07	0.07	0.05	0.04
November	0.05	0.05	0.05	0.20	0.07	0.07	0.00	-0.01
December	0.06	0.06	0.07	0.10	0.04	0.03	-0.01	0.01
Annual	0.06	0.08	0.08	0.23	0.07	0.08	0.00	0.02

The testing so far has revealed that Føyn's is the best formula to use for Ås for the period without minimum temperature measurements, whereas Köppen's formula is the best one when minimum temperature measurements are available. However, the skill of the formulae has not been tested on an independent dataset. Therefore the testing procedure was repeated with the hourly dataset split into two parts. The first part (training dataset, 1995–2003) was used to calculate new constants. The second part (validation dataset, 2004–2011) was used to test the new constants by calculating

monthly means for this period using the new constants and comparing these monthly means to the true means.

Part two of Table 2 shows that the standard deviation of the difference is 0.10 °C or lower for Köppen's formula and 0.13 °C or lower for Føyn's formula. This is of the same order as the errors of mercury thermometers or modern temperature sensors. The average of the differences for the validation period are small and show no biases in the monthly means. Thus, when it comes to monthly means, the lack of hourly observations in the past is not a big disadvantage when the correct constants in the formulae can be calculated from modern hourly observations.

Summing up: The constants which were finally adopted in Føyn's and Köppen's formulas were calculated from the whole dataset of hourly observations (1995–2011). Føyn's formula was chosen for the calculation of the monthly means for the period January 1874 to July 1877, when there was no registration of minimum temperature, whereas Köppen's formula was chosen for the period August 1877 to April 1988. The last part of the series contains arithmetic means of the hourly observations. These new monthly means are now stored in the database of MET Norway, and were also used in this study for the homogeneity testing.

Homogeneity testing

The Ås temperature series was expected to have several breaks of homogeneity due to station relocations, changes in observation hours and changes in measuring equipment. The version of the SNHT used could only handle one homogeneity break at a time. Hence the time series from Ås was split into shorter time series called subseries containing only one potential breakpoint. The potential breakpoints were found by studying the metadata of the station. However, the metadata available might not be complete, so if the test results gave indications that there might be several breaks in a subseries, this subseries was divided yet again in order to isolate the break points.

In the homogeneity testing, 25 neighbouring weather stations were used as reference stations. Different stations were used in the reference series corresponding to each subseries. The only criteria deciding whether or not a reference station should be included was continuous data in the time span of the subseries. Table A.2 in the supplementary material shows the subseries and the number of reference stations in each subseries period.

Annual and seasonal means of the Ås temperature series were homogeneity tested. The seasons were defined as follows: winter (DJF), spring (MAM), summer (JJA), autumn (SON).

The SNHT detected several homogeneity breaks in the Ås series. In order to check whether or not a break was real, the reference station group in each reference series was split into two new groups, and testing was repeated separately for each group. If the break appeared in the test results from both groups, then one could be quite sure that it was a real break. In addition, metadata was used in order to find the precise time and cause of the break. The metadata can be found in Table A.3 in the supplementary material.

Results of the homogeneity testing

The homogeneity testing discovered several breaks of homogeneity in the Ås temperature series. Four of the breaks were supported by the metadata and therefore adjusted, see Table 3. The breaks in 1894 and 1925 were thought to be caused by a new minimum thermometer. A new minimum thermometer should normally not lead to breaks as there are procedures to correct minimum temperature readings according to the readings of the main thermometer. However, a new minimum thermometer may be an indication of a change in radiation screen, which may have an effect on the reading of all thermometers. The breaks in 1918 and 1988 were caused by station relocation, which is a common reason for homogeneity breaks, as documented in other works (e.g. Nordli 1997; Andresen 2011). In addition, a break in 1967 was adjusted for. There was not quite enough relevance in the metadata supporting this break; however, the test statistic was 12.1, 9.7 and 16.7 for winter, spring and autumn, respectively. The critical value of the test statistic at 95% significance level is 7.6, so the break was too significant to be ignored.

Table 3. Homogeneity breaks in the Ås temperature series and their respective seasonal adjustments (°C)

Year	Winter	Spring	Summer	Autumn
1894	0.0	0.3	0.3	0.2
1918	-0.3	-0.1	-0.2	-0.2
1925	-0.4	-0.4	-0.2	0.0
1967	0.5	0.2	0.0	0.3
1988	-0.3	-0.2	-0.3	-0.2

The homogenized temperature series

A homogenized temperature series for Ås was established by applying the adjustments obtained by the SNHT in the period 1874–2011, which gives the opportunity to calculate reliable temperature trends for this rural site in Southern Norway. The method used was linear least square regression analysis with years as predictor and temperature as predictand. The results are shown in Table 4 where the trends per 100 years are given as the slope of the linear regression line. The root mean square error (RMSE) and p-value for the linear regression trend line are also given. For comparison, the annual mean temperature change per 100 years for the inhomogeneous series is 0.66°C and Figure A.1 in the supplementary material shows the inhomogeneous time series. The trend is largest during spring and smallest during winter. Winter has the largest RMSE, which is also evident in Figure 3. The estimated linear trend lines for the annual, spring, summer and autumn data are statistically significant on a 0.01 significance level, while the estimated trend line for winter is only statistically significant on a 0.1 significance level. Figure 2 shows the homogenized Ås temperature series for annual means for the period 1874–2013. A linear regression trend line is also shown. Figure 3 shows seasonal means for the homogenized temperature series for the period 1874–2013. Linear regression trend lines are also shown.

Table 4. Mean temperature change per 100 years based on linear regression for the homogenized Ås temperature series. The corresponding RMSE for the regression is also given. Units are °C

Statistic	Winter	Spring	Summer	Autumn	Annual
Change per 100 years	1.02	1.46	0.82	0.86	1.01
RMSE	0.54	0.28	0.22	0.23	0.20
p – value	0.06	5e-07	1e-04	9e-05	4e-07

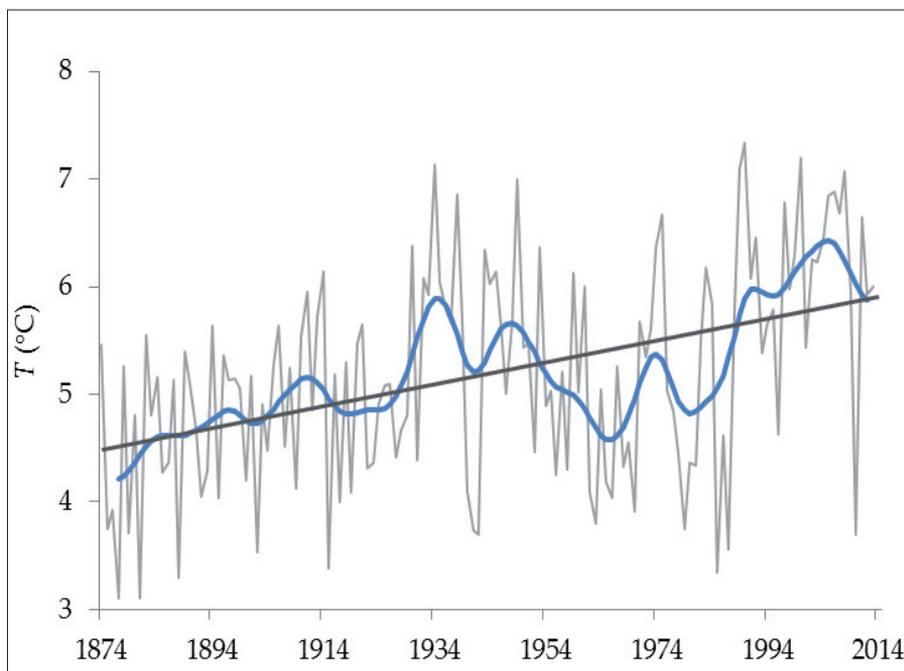


Fig. 2. The homogenized temperature series of annual means for the period 1874–2013 with a 10-year Gaussian filter (blue curve) and a linear regression trend line. The series has interpolated values between 1988 and 1994, obtained by the use of multiple linear regression

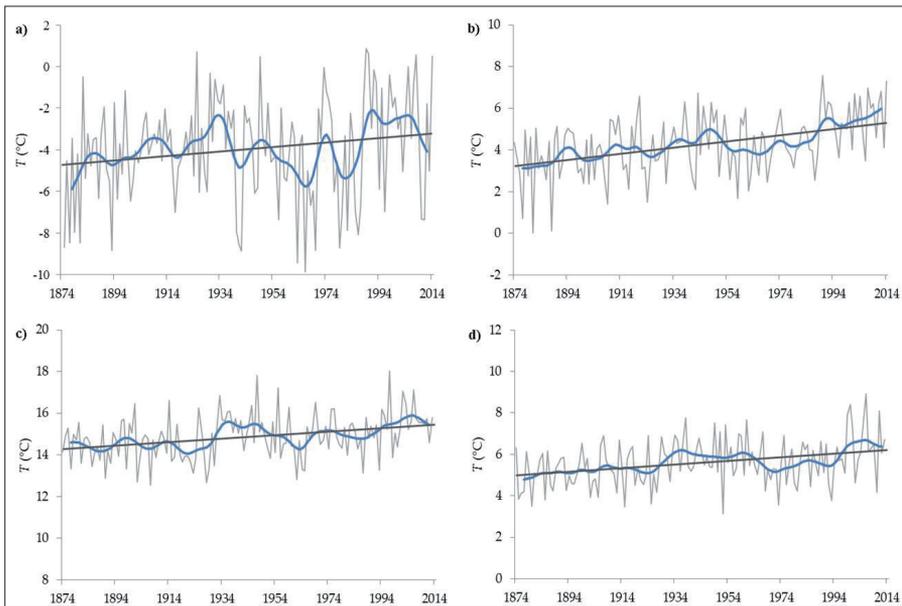


Fig. 3. The homogenized temperature series for winter (a), spring (b), summer (c) and autumn (d) for the period 1874–2013 with a 10-year Gaussian filter (blue curve) and linear regression trend lines

From Figures 2 and 3 one can see the early twentieth century warming, especially between 1930 and 1950. This warming period is followed by a cooling period in the 1950s and 1960s before another warming period begins around 1970. The highest temperatures are found mainly in the two last decades, but also in the 1930s and 1940s, especially in winter and summer.

There are two other long-term series in the Oslo fjord region: Færder and Oslo. Færder lies roughly 70 km to the south of Ås and Oslo lies roughly 30 km to the north of Ås. For locations, see Figure 1. Both stations are homogenized, Færder by Andresen (2011) and Oslo by Nordli et al. (submitted). Lying on a small island, Færder lighthouse station has a maritime environment whereas Ås lies 9 km inland from the coast in an agricultural area. Oslo has an urban environment, but the urban trend is removed in the homogenized data (Nordli et al., submitted).

The differences between the two homogenized series and Ås are shown in Figure 4. There are appreciable differences for individual years as well as for some sub-periods, but the trends in the series of differences

are insignificant (-0.07 and -0.09°C per 100 years). For the whole period (1874–2013) the annual linear trend for the homogenized series from Færder and Oslo is 0.9°C per 100 years and for Ås nearly the same, 1.0°C per 100 years. A larger trend for Oslo is not to be expected as the urban influence is removed from the homogenized series, which is necessary if the series is to be representative for a rural area. The long-term linear temperature trends in the Oslo fjord region do not seem to be much affected by spatial climate variations, although the differences in continentality are apparent.

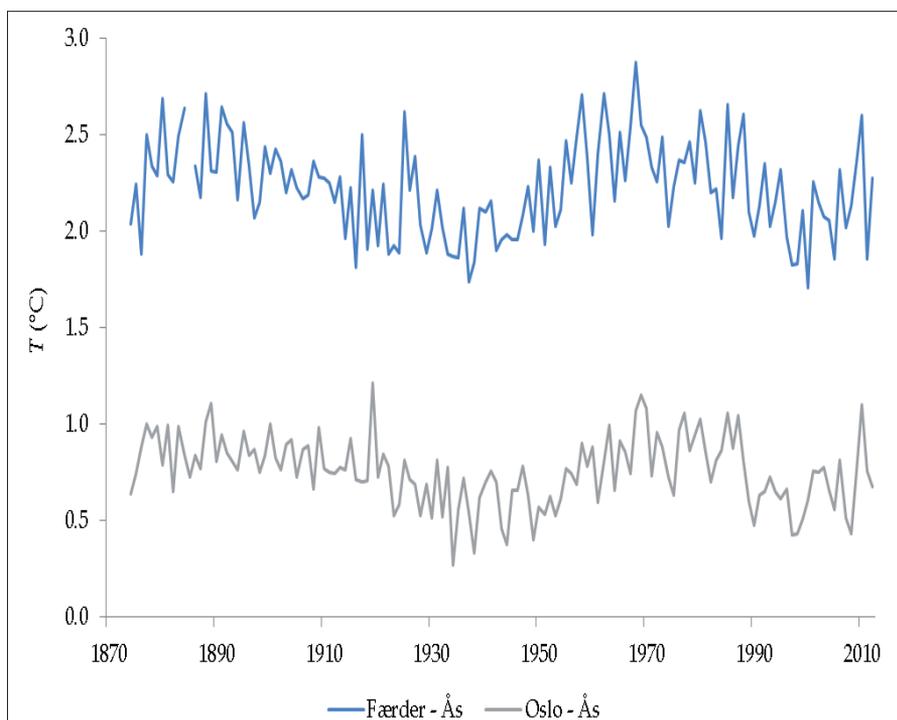


Fig. 4. The difference ($^{\circ}\text{C}$) between the homogenized annual mean temperature in the period 1874–2013 between Færder and Ås (top) and Oslo and Ås (bottom)

Conclusion

Comparison of several formulae showed that Köppen's formula gave the most accurate monthly means for the period with daily minimum temperature measurements, while Føyn's formula proved to give the most

accurate monthly means for the period without daily minimum temperature measurements. The Ås temperature series was adjusted for five homogeneity breaks. The seasonal adjustments of the breaks lay between -0.4°C and $+0.5^{\circ}\text{C}$. The linear regression trend of the homogenized Ås temperature series is $1.0^{\circ}\text{C}/100\text{y}$, which is about $0.3^{\circ}\text{C}/100\text{y}$ higher than the Ås raw data series and $0.1^{\circ}\text{C}/100\text{y}$ higher than the trends of the homogenized Oslo and Færder series.

Acknowledgements

The authors thank Marjit Vinjerui Christenson for a beautifully made map. We also thank Signe Kroken and Tom Ringstad for providing observation data. Petr Štěpánek is much acknowledged for providing us with the AnClim software. We also thank three anonymous reviewers and an anonymous proofreader for improving this article. Finally, we acknowledge the HistKlim activity at MET Norway for digitizing the Ås series, a prerequisite for the present article.

References

- ALEXANDERSSON H., 1986, A homogeneity test applied to precipitation data, *Int. J. Climatol.*, 6, 661–675.
- ALEXANDERSSON H., 1995, Homogeneity testing, multiple breaks and trends. *Proceedings of the Sixth International Meeting on Statistical Climatology*, Galway, Ireland, 439–441.
- ALEXANDERSSON H., MOBERG A., 1997, Homogenization of Swedish temperature data. Part 1: A homogeneity test for linear trends, *Int. J. Climatol.*, 17, 25–34.
- ANDRESEN L., 2011, Homogenization of monthly long-term temperature series of mainland Norway, met.no note No. 02/2011, Norwegian Meteorological Institute.
- BIRKELAND B.J., 1935, Mittel und Extreme der Lufttemperatur, *Geofysiske Publikasjoner*, XIV, No. 1, 153 pp.
- DOMONKOS P., 2011, Adapted Caussinis-Mestre Algorithm for Networks of Temperature series (ACMANT), *Int. J. Geosci.*, 2, 293–309.

- DOMONKOS P., 2013, Measuring performances of homogenization methods, *Időjárás-Quarterly Journal of the Hungarian Meteorological Service*, 117, 1, 91–112.
- DUCRÉ-ROBITAILLE J., VINCENT L.A., BOULET G., 2003, Comparison of techniques for detection of discontinuities in temperature series, *Int. J. Climatol.*, 23, 1087–1101.
- GUIJARRO J. A., 2013, Climatological series shift test comparison on running windows. *Időjárás-Quarterly Journal of the Hungarian Meteorological Service*, 117, No.1, 35–45.
- HEINO R., 1994, Climate in Finland during the period of meteorological observations, *Finnish Meteorological Institute Contributions*, No. 12, 209 pp.
- HØGÅSEN S., 1993, Mean temperature in meteorology, DNMI report No. 40/93 *Klima*, Norwegian Meteorological Institute.
- KÖPPEN W., 1888, Über die Ableitung wahrer Tagesmittel aus den Beobachtungen um 8^h a.m., 2^h p.m. und 8^h p.m., *Annalen der Hydrographie und Maritimen Meteorologie*, 16, 341–354.
- MESTRE O., DOMONKOS P., PICARD F., AUER I., ROBIN S., LEBARBIER E., BÖHM R., AGUILAR E., GUIJARRO J., VERTACHNIK G., KLANCAR M., DUBUISSON B., STEPANEK P., 2013, HOMER: a homogenization software-methods and applications, *Időjárás-Quarterly Journal of the Hungarian Meteorological Service*, 117, 1, 47–67.
- MOBERG A., ALEXANDERSSON H., 1997, Homogenization of Swedish temperature data. Part II: Homogenized gridded air temperature compared with a subset of global gridded air temperature since 1861, *Int. J. Climatol.*, 17, 35–54.
- NORDLI Ø., 1997, Homogenitetstesting av norske temperaturserier II [Homogeneity testing of Norwegian temperature series II], DNMI report No. 29/97 *Klima*, Norwegian Meteorological Institute.
- NORDLI Ø., TVEITO O., E., 2008, Calculation of monthly mean temperature by Köppens formula in the Norwegian station network, *Met.no report No. 18/2008*, Norwegian Meteorological Institute.
- PETERSON T., C., EASTERLING D., R., KARL T., R., GROISMAN P., NICHOLLS N., PLUMMER N., TOROK S., AUER I., BOEHM R., GULLET D., VINCENT L., HEINOR., TUOMENVIRTAH., MESTRE O., SZENTIMREY T., SALINGER J., FØRLAND E., J., HANSSEN-BAUER I., ALEXANDERSSON H., JONES P., PARKER D., 1998, Homogeneity adjustments of *in situ* atmospheric climate data: A review, *Int. J. Climatol.*, 18, 1493–1517.

-
- ŠTĚPÁNEK P., 2008a, AnClim-software for time series analysis: Dept. of Geography, Fac. of Natural Sciences, MU, Brno, Czech Republic, 1.47 MB. <http://www.climahom.eu/AnClim.html>
- ŠTĚPÁNEK P., 2008b, ProClimDB-software for processing climatological datasets, CHMI, regional office Brno, Czech Republic. <http://www.climahom.eu/PocData.html>
- SZENTIMREY T., 2007, Manual of homogenization software MASH v3.02, Hungarian Meteorological Service.
- TUOMENVIRTA H., 2002, Homogeneity testing and adjustment of climatic time series in Finland, *Geophysica*, 38 (1–2), 15–41.
- TUOMENVIRTA H., 2001, Homogeneity adjustments of temperature and precipitation series-Finnish and Nordic data, *Int. J. Climatol.*, 21, 495–506.

Supplementary material

Table A.1. List of meteorological stations used as reference stations in the homogeneity testing. The station number is the national station identifier. The stations elevation and data period is also shown

Number	Name	m a.s.l.	Observation period
1500	Krappeto	105	1884–1914
3400	Eidsberg	140	1927–1964
17150	Rygge	40	1955–present
4780	Gardermoen	202	1941–present
4930	Hvam	162	1945–1983
19400	Fornebu	10	1941–1998
19480	Dønski	59	1970–2003
19710	Asker	163	1913–present
18650	Oslo 1	25	1877–1937
18651	Oslo 2	25	1837–1933
18700	Oslo Blindern	94	1937–present
5500	Åbogen	145	1890–1926
5650	Vinger	175	1942–2004
6040	Flisa	184	1919–1998
12300	Hamar	139	1883–1998
12550	Kise	128	1951–present
11500	Østre Toten	264	1930–present
20880	Kutjern	493	1918–1954
27450	Melsom	26	1959–present
27500	Færder fyr	6	1885–present
30450	Løveid	29	1884–1907
32100	Gvarv	26	1919–1989
34120	Jomfruland fyr	12	1940–1993
37230	Tveitsund	252	1944–present
36200	Torungen fyr	12	1867–present

Table A.2. The sub-periods used in the homogeneity testing and the number of reference stations for each subseries period

Sub-period	Number of reference stations
1874–1893	2
1887–1906	6
1900–1923	5
1920–1933	9
1931–1951	6
1941–1960	9
1953–1980	10
1971–2011	5

Table A.3. Metadata for Ås meteorological station

1874	The temperature is measured in Reaumur. Observation hours: 06, 13, 20 UTC
1877	Temperature measured in Celsius from 1 st of July. The station was equipped with a minimum thermometer in August.
1881	New observation hours from November: 07, 13, 19 UTC.
1885	New observer.
1888	New observer.
1894	New definition of minimum temperature: From nightly minimum to 24-h minimum.
1895	New observer from 18 th of October.
1910	New thermograph in October.
1915	New screen in July.
1918	Relocation 1 st of July. New observer. Maximum temperature was from now on found from the thermograph. The air temperature was from now on found from the thermograph on Sundays, public holidays and the evening observations. New thermometer height (1.8 m. Old: 1.6 m).
1920	New observation hours from July: 07, 13, 18 UTC.
1921	New observer from 21 st of August.

[26]

Table A.3 (Continued)

1925	New minimum thermometer from 10 th of June.
1931	New thermometer height (2.1 m)
1942	New observer.
1949	New observation hours from January: 07, 12, 18 UTC.
1951	The station was again equipped with a maximum thermometer. New screen in June.
1967	New observer in April.
1983	Relocation in May. Parallel measurements in the period 1978–1987. New thermometer 23 rd of September.
1988	Automatic registrations from 7 th of May.
1993	New screen.
1997	New PT100-thermometer September 16 th .
1998	New PT100-thermometer August 17 th .

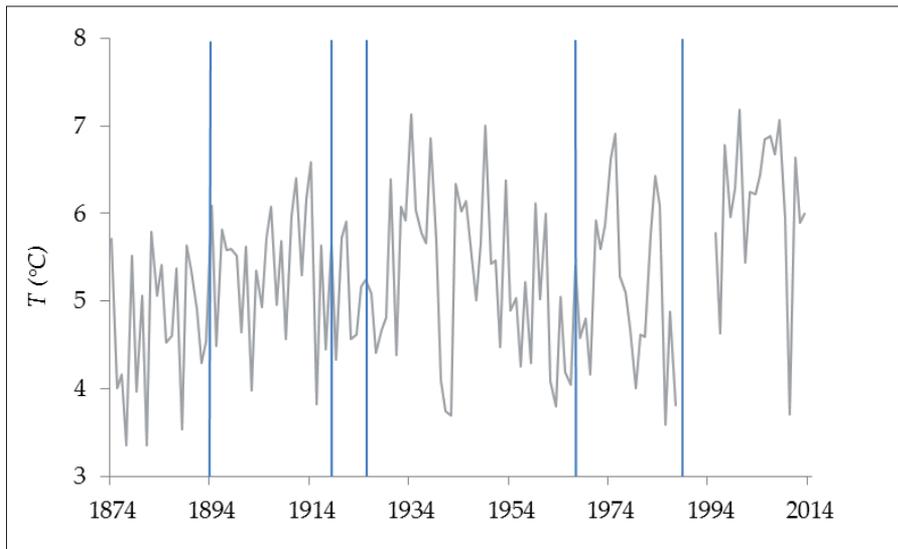


Fig. A.1. The raw data temperature series of annual means for the period 1874–2013. The vertical lines mark the breaks of homogeneity