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Standardization of data and methods for calculating daily Tmean, Tn and Tx in the Netherlands for the 1901-1970 period

Theo Brandsma, Rudmer Jilderda and Rob Sluijter

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Auteurs	Theo Brandsma (theo.brandsma@knmi.nl) Rudmer Jilderda Rob Sluijter

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Foreword

The quality of meteorological measurements deserves continuous attention. KNMI therefore follows as close as possible the regulations of the World Meteorological Organization and the guidelines for climate monitoring for these measurements. Sometimes it is possible to improve the quality of historical measurements with retroactive effect, for instance due to methodological improvements. This is the case for the study in this report.

At the start of this work, it was known that for the five principal stations in the Netherlands several methods had been used in the 1901-1970 period to calculate daily minimum and maximum temperatures (Tn and Tx) from the available measurements. It was, however, not completely clear which methods had been used for each of the stations and how this affected the time series. In addition, for the 1946-1970 period climatological and synoptical hourly temperature data were available for the principal stations. So far, it was unclear which data type is closest to the real temperature of that time. The type of hourly data may affect, however, the Tn and Tx and the daily mean temperature (Tmean). The heterogeneity of data and methods is undesirable and limits the usefulness of the time series. The work described in this report was performed to standardize the data and the methods used for calculating Tmean, Tn and Tx and thus obtain a more robust dataset.

A reconstruction is made here of the data and methods used to calculate Tmean, Tn and Tx for the five principal stations. The methods and data are standardized and new daily Tmean, Tn and Tx time series are calculated for the five principal stations. These time series will be implemented by KNMI as the new operational daily temperature series for the five stations. The update improves the quality of the existing series substantially.

Measured daily temperature time series are commonly used when informing the general public on temperature extremes. The standardized time series can be considered as an update of the measured time series. The updated series will now serve as basis for the calculation of extreme values. The changes in extremes are described in this report.

The standardization does not remove inhomogeneities due to for instance station relocations. Currently there is no generally accepted method to correct for inhomogeneities on a daily basis.

1 Introduction

1.1 Problem description

Meteorological time series may become inhomogeneous for various reasons. Some important causes are: relocations of the stations and/or instruments, slow or abrupt changes in the environment and changes in instruments and measurements practices. For climate change and variability studies it is important to deal with these potential sources of inhomogeneities and obtain homogenized datasets.

Nowadays many studies are being undertaken that homogenize time series before calculating trends and variability (Venema et al., 2012). Homogenization is then mostly done in a statistical way by calculating corrections from mutual comparisons of stations. However, sometimes it is possible to improve the quality of the time series directly. For instance, it is known that methods for calculating daily mean temperature from sub-daily observations have changed in the past. When the metadata shows when and how these methods changed, it may be possible to apply a method that calculates the daily mean temperature in a uniform way. Although the remaining time series may still be inhomogeneous due to other causes, this important source of inhomogeneity is removed and it becomes easier to trace other sources of inhomogeneity.

This report deals with the daily mean, minimum and maximum temperatures (Tmean, Tn and Tx) in the Netherlands. Until 1932, daily Tn and Tx were determined for the 8-8 Mean Local Time (MLT)[1] interval and thereafter for the 19-19 MLT interval. Since 1971, daily Tn and Tx are determined for the 0-0 UTC interval. For reasons of consistency, Tn and Tx in the 1901-1970 period have then also been calculated for the 0-0 interval. These values are being used operationally. Several methods have, however, been applied for calculating the daily 0-0 Tn and Tx. Some of these methods are not well described but may still be inferred from the data itself.

Besides using several methods, also two different data sources have been used. From 1946 onwards there was a transition from the so-called climatological measurements to synoptical measurements. For the principal stations in the Netherlands, often both the climatological and synoptical measurements are available in conjunction in the 1946-1970 period. For the operationally used time series, from 1951 onwards mainly the synoptical measurements have been used. The reason for using one of the two was not completely clear. It is therefore necessary to reconsider the choice for climatological or synoptical measurements.

The uncertainty about data and methods for calculating Tmean, Tn and Tx and the lack of standardization reduces the confidence in the data for climate applications. The work in this report addresses these problems and presents a solution.

1.2 Scope and objectives

The main objective of this study is to improve the quality of temperature time series in the Netherlands by standardizing the methods for calculating Tmean, Tn and Tx and using the best quality data source. This improves the suitability of the series for climate change and variability studies.

1 Corresponding to about 7:40 – 7:40 UTC. Sometimes also Netherlands Time (NLT) has been used (corresponding the 5E meridian). At maximum MLT and NLT differ about 8 min.

We restrict ourselves to the five principal stations: 1. Den Helder/De Kooy, 2. De Bilt, 3. Groningen/Eelde, 4. Vlissingen, and 5. Maastricht/Beek. For the Bilt the 1901-1970 period will be considered, for the other stations the 1906-1970 period. When of interest, information will also be presented about other stations. However, at present standardization is only feasible for the five principal stations. The temperature changes due relocations are not dealt with in this study.

Chapter 2 describes the data sources and summarizes the current methods and data used for calculating Tmean, Tn and Tx. In that chapter we also describe the method used for standardizing the calculation of Tmean, Tn and Tx. Chapter 3 presents results of the standardization action. This focuses mainly on changes in trends and changes in reported extreme events in Tmean, Tn and Tx. Chapters 4 and 5 present a discussion and a summary and conclusions.

2 Data and methods

In this chapter we describe the data available for calculating daily Tmean, Tn and Tx in the 1901-1970 period and we reconstruct the data and methods that have been used for calculating these variables. We show the effect of the chosen interval (8-8, 19-19 and 0-0 MLT) on the climatological Tn and Tx values. The reconstruction mainly applies to how the Tn and Tx values for the 0-0 interval were calculated in the 1901-1970 period. In addition, a comparison is made between the climatological and synoptical temperature data for the 1951-1970 period to enable an objective choice of one of them. Finally, a standard procedure for calculating Tn and Tx for the 0-0 interval is presented.

2.1 Data

For the principal stations of KNMI in the 1901-1970 period there are two data sources available for calculating Tmean, Tn and Tx. The first data source consists of the climatological measurements. These are available for the whole period and consist of three readings per day of a mercury thermometer and a minimum/maximum mercury thermometer at 8, 14 and 19 MLT[2]. Tn and Tx apply to the intervals between the observations times and are further denoted as Tn8, Tn14, Tn19, Tx8, Tx14 and Tx19. The temperature values at the remaining hours were deduced from thermograph readings. The thermograph readings were corrected towards the readings at 8, 14 and 19 MLT. Both the values of the regular thermometer and the minimum/maximum thermometer were used. As an illustration, Figure 1 shows for De Bilt the climatological means of the hourly temperatures and the several Tn and Tx values.

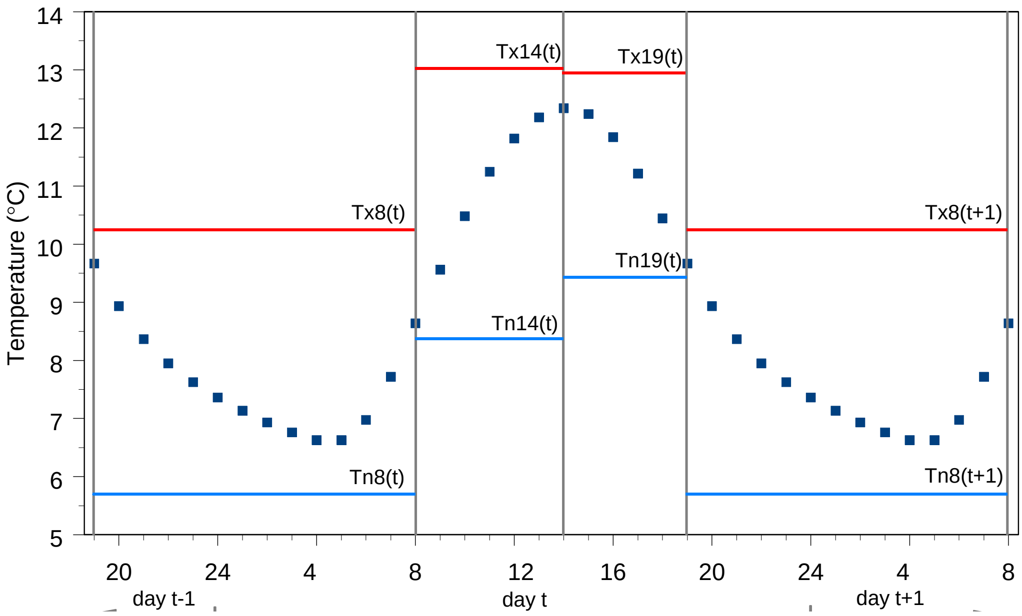

Figure 1. Mean hourly temperatures and mean values of Tn8, Tx8, Tn14, Tx14, Tn19. and Tx19 for De Bilt in the 1901-1970 period.

2 Corresponding to about 7:40, 13:40 and 18:40 UTC.

The second data source consists of the synoptical measurements. From 1946 onwards these measurements were done hourly at synoptic hours (1,2,…,24 UTC) mainly taken for weather forecasting purposes. First the instruments were read hourly in a Stevenson screen from a mercury thermometer but later resistance thermometers were used that could be read remotely. Till 1971, the synoptic measurements did not contain enough information to calculate 24 hour Tn Tx values for the 0-0 UTC interval.

On 1 January 1971 the climatological and synoptical networks were combined into one network. This implied that the use of MLT for the observations hours at climatological stations had to be discontinued and that UTC was used instead.

Figure 2 shows the locations of the five principal stations and nine additional stations that are mentioned in this report. The details of the stations are presented in Table 1.

Figure 2. Situation of the five principal stations, Den Helder/De Kooy, Groningen/Eelde, De Bilt, Vlissingen and Maastricht/Beek and 9 additional airport stations (in gray).

Table 1. Details of the stations shown in Figure 2.

Station	LAT (N)	LON (E)	ALT (m)	Operational period	Current name (WMO station nr.)
Den Helder / De Kooy	52.967 52.924	4.750 4.785	4.4 0.5	1843-1972 1958-present	De Kooy (235)
Groningen / Eelde	53.217 53.125	6.550 6.586	2.1 3.5	1839-1952 1945-present	Eelde (280)
De Bilt	52.101	5.177	2.0	1897-present	De Bilt(260)
Vlissingen / Souburg	51.442 51.467	3.596 3.583	8.0 -0.5	1855-present* 1947-1962	Vlissingen (310)
Maastricht / Beek	50.850 50.910	5.693 5.768	49.4 114.0	1811-1952 1946-present	Maastricht (380)
Valkenburg	52.165	4.419	-0.2	1947-present	Valkenburg (210)
Schiphol	52.301	4.774	-4.4	1937-present	Schiphol (240)
Soesterberg	52.130	5.274	13.9	1951-2005	Soesterberg (265)
Leeuwarden	53.225	5.755	1.5	1950-present	Leeuwarden (270)
Deelen	52.061	5.888	50.0	1949-present	Deelen (275)
Twenthe	52.273	6.897	34.5	1946-present	Twenthe (290)
Gilze-Rijen	51.568	4.933	11.1	1947-present	Gilze-Rijen (350)
Eindhoven	51.446	5.414	20.3	1947-present	Eindhoven (370)
Volkel	51.657	5.706	21.1	1951-present	Volkel (375)

*Gap in the period 1947-1958, filled in with Souburg.

2.2 Reconstruction of data and methods for calculating Tmean, Tn and Tx in the 1901-1970 period

2.2.1 Calculation of Tn and Tx for different intervals

Until 1932 KNMI published the daily Tn and Tx values in the KNMI meteorological year books (KNMI). These followed directly from the climatological 3 times daily Tn and Tx values, Tn8, Tn14, Tn19, Tx8, Tx14 and Tx19. The daily Tn and Tx values related to the 8-8 interval. For day t they are defined as:

$$\text{8-8Tn}(t) = \min[\text{Tn14}(t-1), \text{Tn19}(t-1), \text{Tn8}(t)] \tag{1}$$

and

$$\text{8-8Tx}(t) = \max[\text{Tx14}(t-1), \text{Tx19}(t-1), \text{Tx8}(t)] \tag{2}$$

From 1 January 1932 onwards a switch was made to the 19-19 interval and the daily Tn and Tx values on day t were then defined as:

$$\text{19-19Tn}(t) = \min[\text{Tn8}(t), \text{Tn14}(t), \text{Tn19}(t)] \tag{3}$$

and

$$\text{19-19Tx}(t) = \max[\text{Tx8}(t), \text{Tx14}(t), \text{Tx19}(t)] \tag{4}$$

From 1 January 1971 onwards the distinction between climatological and synoptical measurements disappeared. The decision implied that the use of MLT for the observation hours at climatological stations was discontinued and UTC was used instead. In addition, temperature for many stations[3] became readings from electrical resistance thermometers recordings. The 0-0Tn and 0-0Tx as well as the hourly temperatures could directly be determined from these readings. Since then the 0-0Tn and 0-0Tx are the standard for daily Tn and Tx[4]. Consequently, there was a need to calculate these values also for the 1901-1970 period. As mentioned, these calculations were not standardized and not well documented. In addition, sometimes it is not clear which data source has been used. Both problems will be discussed further in Section 2.2.3.

2.2.2 *Climatological differences Tn and Tx for different intervals*

For the highest or lowest recorded daily temperature extremes the choice of the interval does not affect the extremes themselves, although the date attached to these values may change. However, the monthly mean Tn and Tx values may be affected. For instance, Tn in winter frequently occurs close to the time of the reading of Tn8. Consequently, when using 8-8Tn instead of 19-19Tn, low Tn values often affect two consecutive days causing the mean 8-8Tn in winter to be lower than 19-19Tn.

To illustrate the above, we calculated the mean monthly Tn and Tx values for the 8-8, 14-14 and 19-19 intervals and compared them with the corresponding Tn and Tx values for the 0-0 interval. The 14-14 interval is added for comparison purposes. The values were calculated using 10-min Tn and Tx data of De Bilt for the period 2008-2012. The results for Tn in Figure 3 show indeed that the monthly mean 8-8Tn in winter is smaller than 19-19Tn. Note further that during the summer half year (Apr-Sep) Tn for all intervals is mostly more than 0.5°C larger than the 0-0Tn. Figure 4 illustrates that the time of occurrence of Tn occurs very often around midnight throughout the year, which explains the deviation from zero for the graphs in Figure 3. The results for Tx in Figure 5 show that 14-14Tx is larger (0.4-0.9°C) than Tx for the other intervals. This was expected because Tx mostly occurs around 14 MLT (Figure 6).

The results show that the choice of the interval used to calculate daily Tn and Tx may significantly affect the monthly mean Tn and Tx values. For climate change studies it is important to take this into account. In the remainder of the this study we focus on the calculation of Tn and Tx for the 0-0 interval. In contrast to the calculation of Tn and Tx for the 8-8 and 19-19 intervals, the calculation of Tn and Tx for the 0-0 interval is not unambiguous for the 1901-1970 period.

3 Beek, De Bilt, Deelen, Eelde, Eindhoven, Gilze-Rijen, Den Helder, Leeuwarden, Rotterdam, Schiphol, Soesterberg, Twenthe, Valkenburg (ZH), Vlissingen and Volkel (see introduction KNMI meteorological year book 1971).

4 Until 1980 these values are published in the KNMI meteorological year books and from 1981 onwards in the Monthly review of the weather in the Nederlands (currently 'Maandoverzicht van het weer in Nederland')

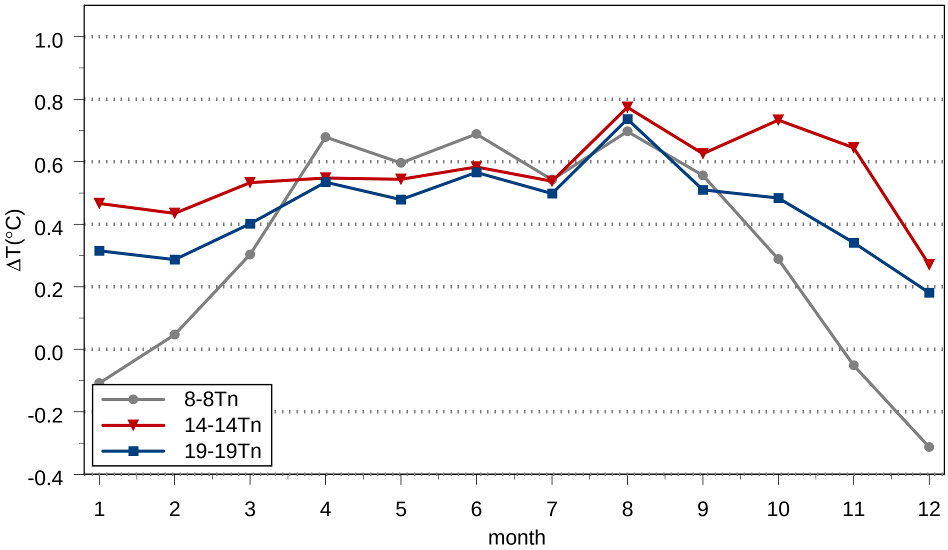

Figure 3. Monthly mean differences between Tn for the intervals 8-8, 14-14, and 19-19 MLT relative to 0-0Tn for De Bilt 2008-2012.

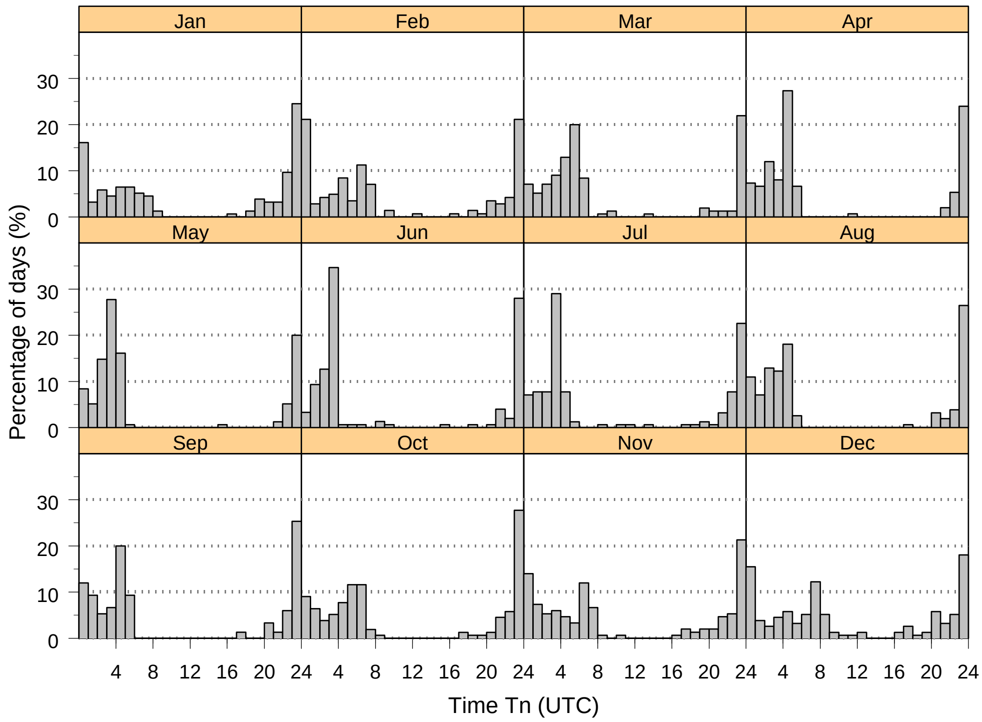

Figure 4. Time of occurrence of Tn for De Bilt 2008-2012

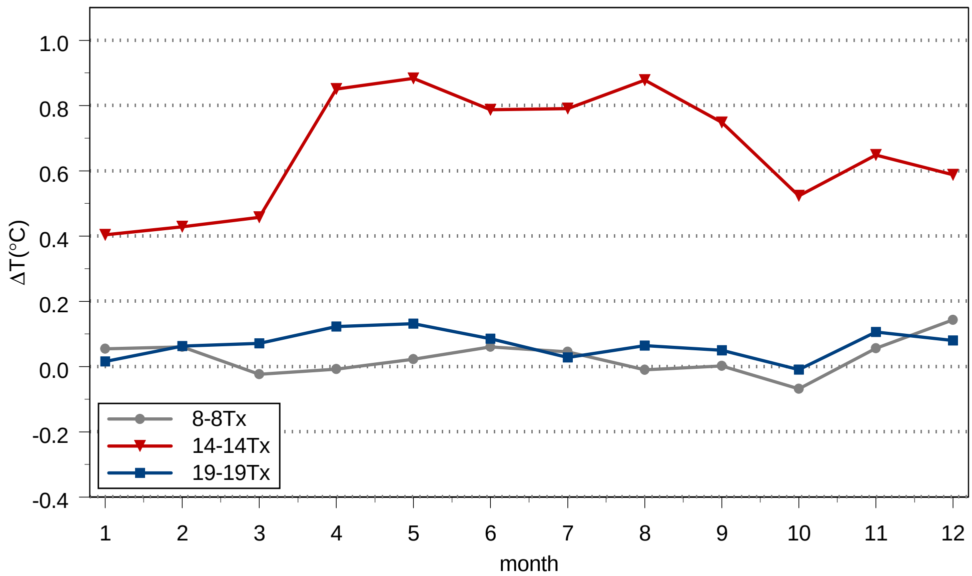

Figure 5. Monthly mean differences between Tx for the intervals 8-8, 14-14, and 19-19 MLT relative to 0-0Tx for De Bilt 2008-2012.

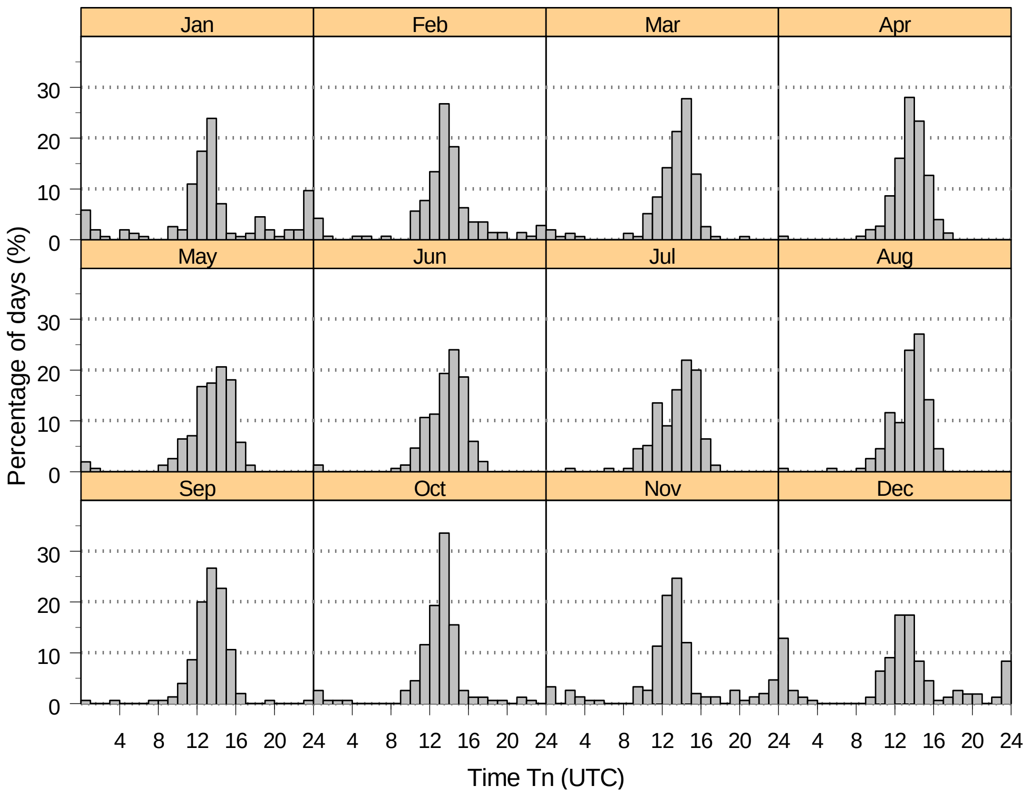

Figure 6. Time of occurrence of Tx for De Bilt 2008-2012

2.2.3 *Reconstruction of 0-0Tn and 0-0Tx calculation*

For Maastricht and Den Helder an earlier action was undertaken to improve the quality of the calculated historical 0-0Tn and 0-0Tx values. This was done in 2003 by Verkaik (Verkaik, unpublished internal document). The method was meant to make optimal use of the available information, the hourly temperature values and the 3xdaily Tn and Tx measurements. The method presented in this report (see Section 2.5) is based on the same assumptions as the method used by Verkaik.

The reconstruction of data and methods that have been used to calculate Tmean[5], 0-0Tn and 0-0Tx for the 1901-1970 period was a laborious work. For each station many comparisons had to be made with all available data sources. To illustrate this, consider for instance the case of Vlissingen in the period August 1947 to December 1962. From 15 August 1947 till 30 April 1958 the operational location at Vlissingen was temporarily relocated to Souburg (about 1.8 km NNW of the Vlissingen location, see Figure *7* for details). The Souburg location was in operation from 16 August 1947 to 31 December 1962. In addition to the climatological measurements at Souburg, from 1 January 1951 onwards also synoptical measurements were carried out at that location. Beforehand it was not clear how the daily Tmean, Tn and Tx values (as stored in the KNMI database) had been calculated and which data source had been used.

Figure 8 shows a comparison between the monthly mean Tmean, Tn and Tx values calculated for Souburg (climatological data) and the data stored in the KNMI data base for Vlissingen. For the sake of this comparison, Tmean, 0-0Tn and 0-0Tx of Souburg were calculated as Tmean = mean(T1.clim,T2.clim,…,T24.clim), Tn =

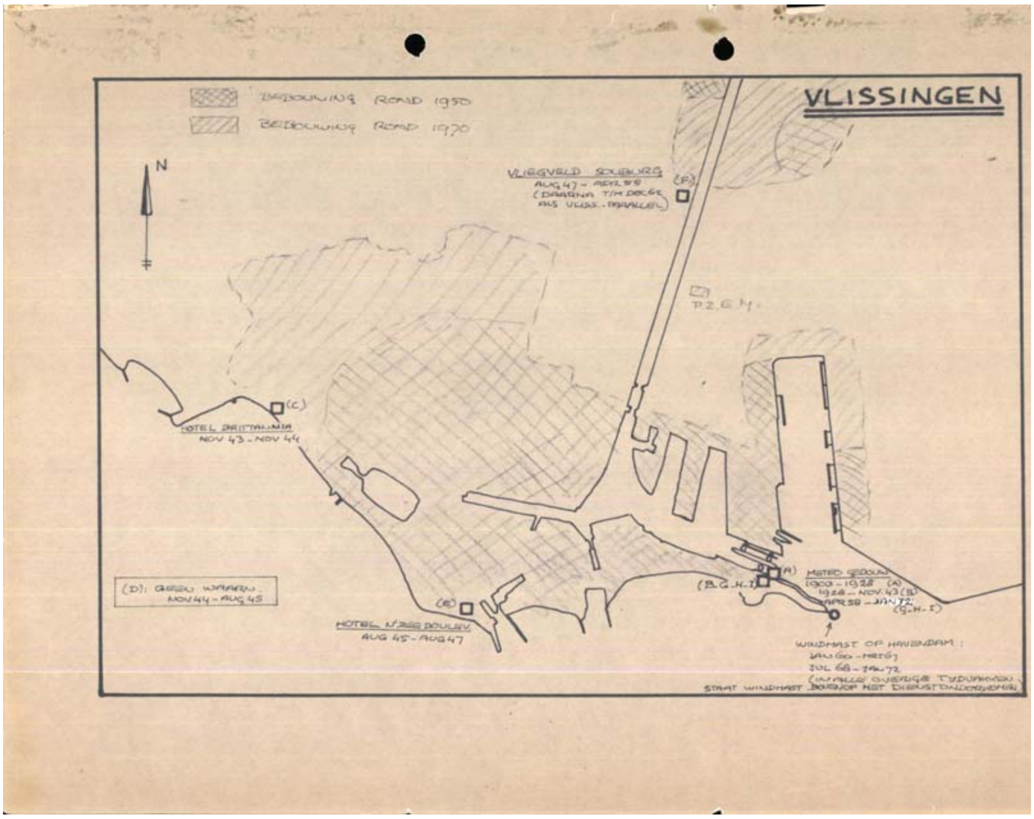

Figure 7: Map of Vlissingen showing the locations of the stations in different periods including the Souburg location (F).

5 Tmean always refers to the 0-0 interval.

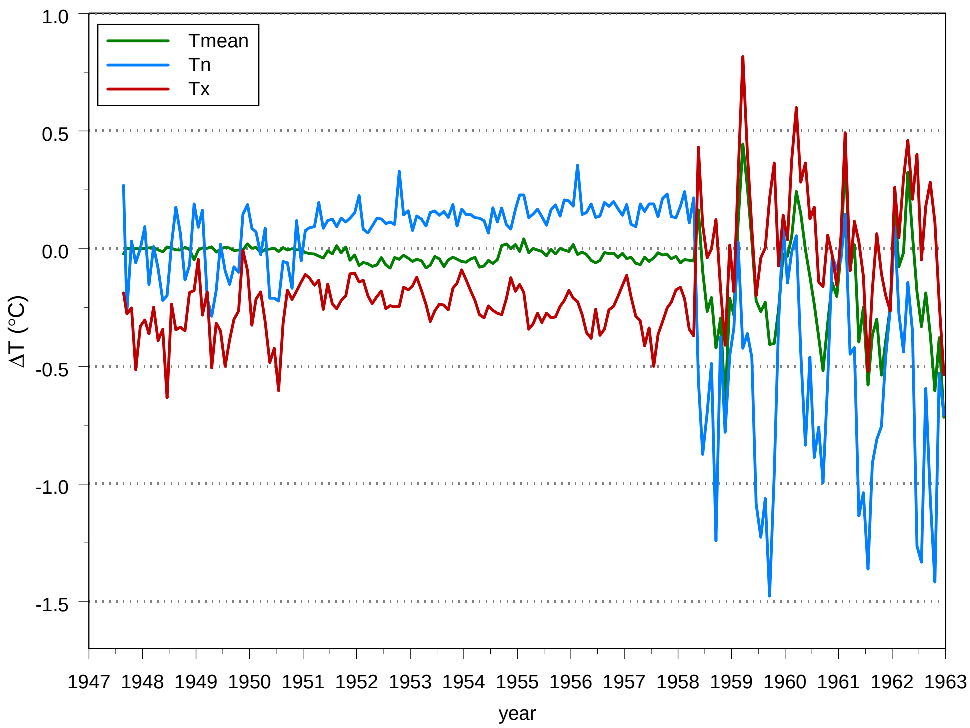

Figure 8: Comparison of monthly mean values of Tmean, Tn and Tx of the Souburg location near Vlissingen (derived from the hourly climatological data) and the Tmean, Tn, Tx data for Vlissingen stored in the KNMI database for the period September 1947-. December 1962.

min(T1.clim,T2.clim,…,T24.clim), and Tx = max(T1.clim,T2.clim,…,T24.clim). The results for Tmean show that in the period August 1947 – December 1950 the climatological measurements of Souburg have been used. Thereafter, the differences in Tmean slightly deviate from zero till April 1958. Comparison (not shown) with the Tmean values calculated from the synoptical measurements of Souburg, revealed that the synoptical measurements have been used from 1 January 1951 to 30 April 1958 to calculate Tmean (Tmean = mean(T1.syn,T2.syn,…,T24.syn). From May 1958 onwards, there is a large deviation between the Tmean of Souburg and the Tmean in the database, indicating a change of location. Comparison (not shown) with the climatological and synoptical Tmean of Vlissingen revealed that from 1 May 1958 onwards the synoptical data of the Vlissingen location has been used.

For Tn and Tx the temperature difference curves in Figure 8 show a strange behaviour till 1 January 1951. After some trail and error it was found that the data that was labelled as the 0-0Tn and 0-0Tx in the database were actually the 19-19Tn an 19-19Tx as derived from the 3xdaily measurements of Tn and Tx (equations 3 and 4). From 1 January 1951 onwards the 0-0Tn and 0-0Tx have been calculated from the climatological data with a method similar to the method proposed in this report, first for the Souburg location till 30 April 1958 and from 1 May 1958 onwards from the Vlissingen location. The practice where Tmean is calculated from synoptical measurements and 0-0Tn and 0-0Tx from climatological measurements sometimes leads to inconsistencies.

Appendix A summarizes the results of the reconstruction of methods that have been used to calculate Tmean, 0-0Tn and 0-0Tx for the 1901-1970 period. For each station, the appendix presents the basic data that have been used, the calculation methods and some remarks. The appendix includes also the airport stations (see Figure 2 and Table 1) that have daily temperature data in the 1951-1970 period and that are available in the KNMI database. For these stations there is no climatological data available.

The appendix shows that Tmean, 0-0Tn and 0-0Tx have not been calculated in a consistent manner. There are important differences between stations and within a single station the methods may differ for different time periods. 0-0Tn and 0-0Tx have been calculated using a large range of methods, for instance as:

a) the minimum and maximum of the 24 hourly temperatures,
b) the minimum and maximum of the 24 hourly temperatures with 0.5°C subtracted for the 0-0Tn and 0.5°C added for the 0-0Tx,
c) a combination of the climatological 3xdaily Tn and Tx measurements and the hourly climatological temperatures,
d) a combination of the climatological 3xdaily Tn and Tx and the synoptical hourly temperatures, etc.

In addition, for Vlissingen in the period 1 January 1918 – 31 December 1930, no hourly data has been used. We could not find digital hourly data for that period. Fortunately, these data are still available as hardcopy and could be digitized within this study (see Section 2.4). The method used for calculating 0-0Tn and 0-0Tx in the 1918-1932 period is clearly wrong.

In summary, there are inconsistencies in the calculation of Tmean, 0-0Tn and 0-0Tx for each station and between stations and in the type of data used for the calculations. It is obvious that no optimal use has been made of the digitally available data.

2.3 Selection of data type

From 1946 onwards, there was a transition from the so-called climatological measurements to synoptical measurements. For the principal stations in the Netherlands often both the climatological and synoptical measuremens are available in conjunction in the 1946-1970 period. For the operationally used time series, from 1951 onwards mainly the synoptical measurements have been used for the calculations of Tmean. Because synoptical Tn and Tx values were only partly available in the 1951-1970 period, some unfortunate combinations of synoptical and climatological measurements have been used for that period (see Appendix A). From the presently known information, it is not clear why it was decided to use one of the two data types. It is therefore necessary to reconsider the choice for climatological or synoptical measurements.

For the five principal stations both climatological and synoptical hourly temperatures are available in the 1951-1970 period (for some stations the hourly synoptical data go even back to 1946). Daily mean values were calculated from the 24 hourly values for both Tclim and Tsyn. Figure 9 compares the monthly Tclim and Tsyn values for the five principal stations. The figure shows that for De Bilt and for Beek the monthly mean temperature differences can be up to 0.6°C. While for De Bilt the differences comprise the whole 1951-1970 period, for Beek the largests differences are mainly found in the 1964-1970 period. For the other stations the monthly mean temperature differences are small and of the same magnitude as the measurements uncertainty.

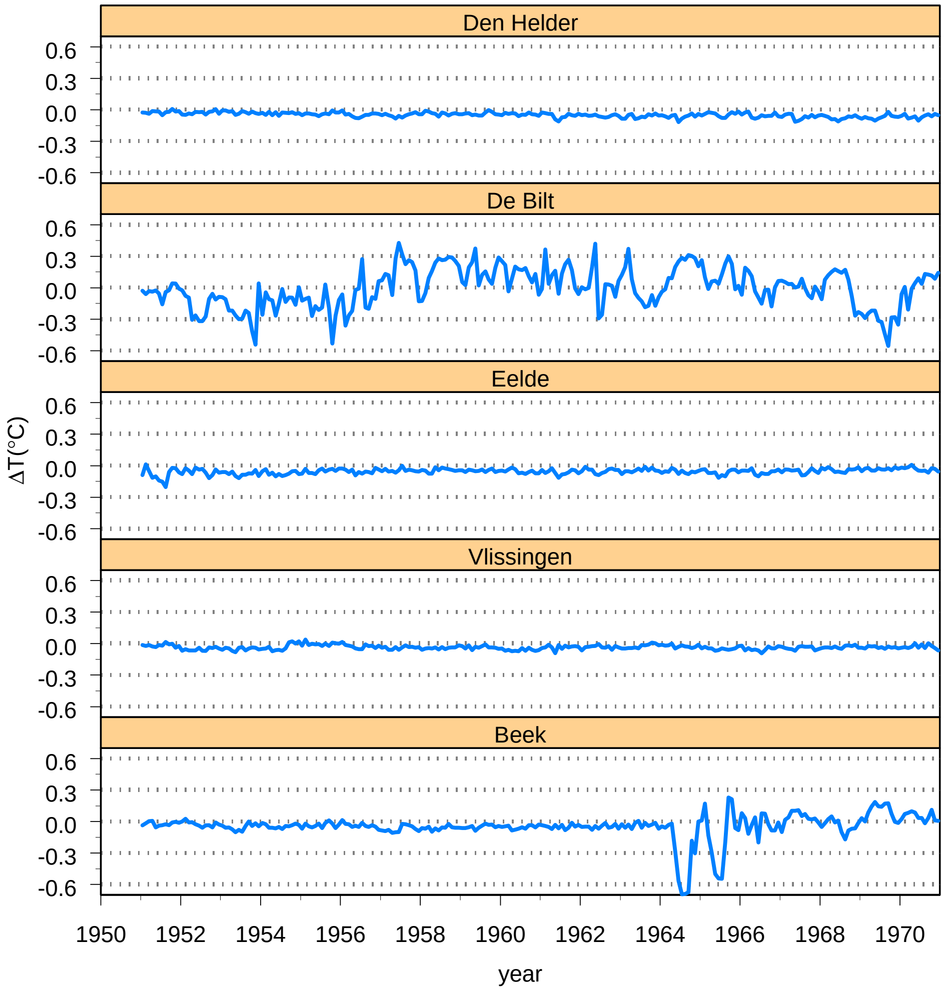

Figure 9: Monthly temperature differences between the climatological and synoptical Tmean for the 1951-1970 period. Before May 1958 the graph of Vlissingen refers to the Souburg location.

Table 2 presents information on the spread of the daily differences between climatological and synoptical Tmean. As expected the table shows the largest spread for De Bilt and Beek.

Table 2: Percentiles of the daily differences between the climatological and synoptical Tmean.

	Percentiles (°C)						
Station	**0th**	**5th**	**25th**	**50th**	**75th**	**95th**	**100th**
Den Helder	-0.48	-0.17	-0.10	-0.05	0.00	0.07	0.27
De Bilt	-1.32	-0.41	-0.15	0.01	0.16	0.36	0.92
Eelde	-0.70	-0.23	-0.12	-0.05	0.01	0.11	0.41
Vlissingen	-0.35	-0.15	-0.08	-0.04	0.01	0.08	0.30
Beek	-1.33	-0.31	-0.11	-0.03	0.05	0.18	0.96

For De Bilt and Beek it is important to determine which of the two temperatures, Tclim or Tsyn, causes the fluctuations in the temperature differences. For both locations we therefore compared the annual mean Tclim and Tsyn with the annual mean temperatures of the mean of the 3 stations Den Helder, Eelde, Vlissingen for both the climatological and synoptical data, denoted as clim(3stat) and syn(3stat), respectively. In addition, we compared De Bilt and Beek with the Central England Temperature (CET; Parker and Horton, 2005) and the Central Netherlands Temperature (CNT, Schrier et al., 2011). All these temperatures can be considered as reference temperatures. The annual mean temperatures of De Bilt and and Beek may be expected to be linearly related to the reference temperatures. Errors in Tclim or Tsyn will detoriate the relationship with the references. Note that the CNT series is composed of several other series in the Netherlands, and contains for the 1951-1970 period also the climatological temperatures of De Bilt. CNT is thus not a completely independent reference.

Table 3 presents the percentages of explained variance of the linear fits between the annual mean temperatures of De Bilt and Beek with the references temperatures. The table clearly shows that in all comparsions the climatological data explain more of the variance than the synoptical data. For Beek the 1964-1970 period is added because Figure 9 showed that the problems with Beek are confined to that period.

The results indicate that for De Bilt and Beek in the 1951-1971 period, the climatological temperatures are of higher quality than the synoptical temperatures. For Den Helder, Eelde and Vlissingen the climatological and synoptical temperatures may be considered of equal quality in the 1951-1970 period. Earlier we noted that the use of synoptical temperatures in the 1951-1970 period sometimes required a forced combination with climatological observations. This sometimes resulted in inconsistencies in the data.

In conclusion, to use the best quality data and to avoid inconsistencies we decided to use the climatological hourly temperature data for the calculation of Tmean, 0-0Tn and 0-0Tx for all five principal stations.

Table 3: Percentages of explained variance of the linear fit between the annual mean temperatures in the 1951-1970 period for De Bilt and Beek with 4 reference series. For Beek also the values for the 1964-1970 period are added.

	De Bilt		**Beek**		**Beek (1964-1970)**	
Time series	**clim**	**syn**	**clim**	**syn**	**clim**	**syn**
clim (3stat)	98.2	93.1	94.4	91.7	78.2	53.7
syn (3stat)	98.2	93.1	94.3	91.6	78.1	53.9
CET	83.3	75.9	87.7	87.3	71.5	61.4
CNT	99.0	92.6	98.5	96.6	96.7	77.3

2.4 Digitization of hourly data for Vlissingen

In Appendix A it is shown that for Vlissingen in the period 1 January 1918 – 31 December 1930 no hourly data was used for the calculation of Tmean, Tn and Tx. This resulted in serious errors in Tn and Tx while Tmean was not calculated at all. From the KNMI yearbooks of that time it is known that these measurements have been undertaken. Inspection of the KNMI hardcopy archive revealed that the original handwritten tables with these measurements were still available. For this study we therefore digitized these 13 years of hourly temperature data from the handwritten tables. After quality control the hourly temperatures were included in the Vlissingen file and could then be used in the standardization process.

2.5 Standard procedure for calculating 0-0Tn and 0-0Tx in the 1901-1970 period

2.5.1 *Automatic procedure*

To determine 0-0Tn and 0-0Tx we use the Tn and Tx measured three times a day at 8, 14 and 19 MLT and the hourly temperatures as derived from the thermograph (and corrected using the thermometer measurements at 8, 14 and 19 MLT (see also Figure 1).

Points of departure:

1. The Tn and Tx values measured at 8, 14, and 19 MLT represent the real extremes of the preceding intervals (the hourly temperatures in those intervals are ≥ Tn and ≤ Tx).
2. Tn8(t) and Tx8(t), for the interval 19 MLT (t-1) until 8 MLT (t), are ascribed to day (t-1), t or to both day t-1 and day t (the latter when minimum or maximum of the hourly temperatures is at midnight or equal on both sides).
3. The times where Tn8(t) and Tx8(t) are closest to an hourly values in the sequence of hourly temperatures [T19(t-1), T20(t-1),…,T24(t-1),T1(t),T2(t),…,T8(t)] determines to which day(s) Tn8(t) and Tx8(t) should be ascribed.

For the calculation of 0-0Tn and 0-0Tx the main point is the calculation of the Tn and Tx values in the period before midnight (19-24 MLT) and the period after midnight (24-8 MLT). The extremes in the interval 19-24 will further be denoted as $Tn8(t)^-$ and $Tx8(t)^-$ and the extremes in the interval 24-8 as $Tn8(t)^+$ and $Tx8(t)^+$. We use Tn8, Tx8 and the hourly temperatures in the preceding 19-8 MLT interval to calculate these extremes.

To determine 0-0Tn and 0-0Tx for day t now requires the following steps:

1. Determine for each day t: (a) the position of Tn8(t) from the location of the minimum of the hourly temperatures in the sequence [T19(t-1), T20(t-1),…,T24(t-1),T1(t),T2(t),…,T8(t)] and (b) the position of the Tx8(t) from the location of the maximum of the hourly temperatures in the sequence [T19(t-1), T20(t-1),…,T24(t-1),T1(t),T2(t),…,T8(t)].
2. If Tn8(t) occurs in day t-1 then $Tn8(t)^-$ = Tn8(t) and $Tn8(t)^+$ = min[T24(t-1),T1(t),T2(t),…,T8(t)].
3. If Tn8(t) occurs in day t then $Tn8(t)^-$ = min[T24(t-1),T1(t),T2(t),…,T8(t)] and $Tn8(t)^+$ = Tn8(t).
4. If Tx8(t) occurs in day t-1 then $Tx8(t)^-$ = Tx8(t) and $Tx8(t)^+$ = max[T24(t-1),T1(t),T2(t),…,T8(t)].
5. If Tx8(t) occurs in day t then $Tx8(t)^-$ = max[T24(t-1),T1(t),T2(t),…,T8(t)] and $Tx8(t)^+$ = Tx8(t).
6. If the hourly temperarures show a minimum at midnight (24 MLT) then $Tn8(t)^-$ = $Tn8(t)^+$ = Tn8(t); and if they show a maximum then $Tx8(t)^-$ = $Tx8(t)^+$ = Tx8(t).
7. For day t the 0-0Tn = min[$Tn8(t)^+$,Tn14(t),Tn19(t),$Tn8(t+1)^-$] and 0-0Tx = max[$Tx8(t)^+$,Tx14(t),Tx19(t),$Tx8(t+1)^-$].

In many cases 0-0Tn and 0-0Tx can be determined exactly. For Tn this happens when :

$$Tn14(t) \leq \min[Tn8(t),Tn19(t),Tn8(t+1)] \tag{5}$$

or

$$Tn19(t) \leq \min[Tn8(t),Tn14(t),Tn8(t+1)] \tag{6}$$

For Tx this happens when:

$$Tx14(t) \geq \max[Tx8(t), Tx19(t), Tx8(t+1)] \tag{7}$$

or

$$Tx19(t) \geq \max[Tx8(t), Tx14(t), Tx8(t+1)] \tag{8}$$

In practice this occurs in about 35% of the days for 0-0Tn and 83% of the days for 0-0Tx. In all other cases 0-0Tn and 0-0Tx depend on Tn8(t), Tn8(t+1), Tx8(t) and Tx8(t+1) for which the location (in day t-1, t or t+1) has to be estimated from the hourly temperatures.

The degree of exactness of the 0-0Tn and 0-0Tn can be expressed by quality flags. These flags are described in Appendix B and are stored together with the data.

Before performing the automatic procedure, the data are checked for possible inconsistencies between the hourly temperatures on the one hand and the Tn and Tx values for each interval on the other. For instance, the hourly temperatures in the 14-19 interval should be ≤ Tx19 and ≥ Tn19. In a minor amount of days this resulted in corrections of the original data. These corrections have been obtained from the original hardcopy data.

For the five principal stations there are no missing data within the days, although sometimes short periods might be missing during World War II. These periods are omitted in the analysis.

2.5.2 *Comparison with manual procedure*

In case 0-0Tn and 0-0Tx can not be determined exactly, 0-0Tn and 0-0Tx may sometimes be estimated more accurately by inspection of the thermograph strip charts than from the automatic procedure described above. The inspection of the strip charts is, however, a labour-intensive task. To quantify the differences between the two approaches, we performed a test with the data of Maastricht in the period 1906-1945. The automatic procedure was used to calculate 0-0Tn and 0-0Tx. For each day where 0-0Tn and/or 0-0Tx could not be calculated exactly, we estimated 0-0Tn and 0-0Tx from both the automatic procedure and manually from the charts.

For 0-0Tn, adaption of the automatically calculated values was needed in only 1.4% of days, for 0-0Tx this was even smaller and amounted 0.3% of the days. The mean difference between the automatic procedure and the manual method on these days was −0.11°C (sd = 0.34°C) for 0-0Tn and 0.03°C (sd = 0.37°C) for 0-0Tx. The monthly mean temperature differences of 0-0Tn and 0-0Tx for both approaches are < 0.02°C in 95% of the months while the annual mean temperature differences are < 0.01°C. The differences between the automatic procedure and the labour-intensive manual method are thus mostly negligible.

The extended procedure, with manual checking of values that could not be determined exactly with the automatic procedure, is in principle preferable above the automatic procedure. However, differences between the approaches are infrequent and when there are differences they are almost always smaller than the detection accuracy of the thermograph (about 0.2°C).

2.5.3 *Comparison with modern data*

The validity of the automatic procedure to determine 0-0Tn and 0-0Tx where they can not be determined exactly, can be tested using modern data. Here we use the 10-min data for De Bilt in the 2004-2012 period. The basis for the calculation of the temperatures are 12-sec sample values. For each 10-min interval Tn and Tx are known from 1-min running mean temperatures (5 samples). In addition, for each 10-min interval a temperature T is specified as the mean temperature of the last minute (5 samples) of the 10-min interval. These calculations are in line with the handbook for meteorological observations of KNMI (HaWa[6]).

The operational daily 0-0Tn and 0-0Tx values can easily be calculated from, respectively, the minimum of the 10-min Tn values and the maximum of the 10-min Tx values. For the automatic procedure we first calculated Tn8, Tn14, Tn19, Tx8, Tx14 and Tx19 from the 10-minute Tn and Tx values and we selected the hourly temperatures as the 1-minute temperature of the last minute before each hour.

For 0-0Tn there is a difference between the automatic procedure used here for standardizing the pre-1971 data and the currently used operational method on 24.6% of the days. For 0-0Tx this is 3.3%. The mean difference between the automatic procedure and the operational method on these days is 0.17°C (sd = 0.26°C) for 0-0Tn and -0.12°C (sd = 0.17°C) for 0-0Tx. The 0-0Tn and 0-0Tx of the automatic procedure are thus slightly less extreme than the operational values on these days. The effect of the differences on monthly mean values is negligible. For 0-0Tn the absolute monthly mean temperature differences are < 0.08°C in 95% of the months. For 0-0Tx the differences are < 0.08°C in 95% of the months.

The 10-min temperatures can also be used to assess the effect of the change in measurement times. Until 1970 we calculated 0-0Tn and 0-0Tx from about 23:40 to 23:40 UTC using the climatological temperatures. Today 0-0Tn and 0-0Tx are calculated from 00:00 to 00:00 UTC, while in the period of the manual observers it was 23:50-23:50 UTC. For a 20-time difference (23:40 instead of 00:00), we found that only the 0-0Tn becomes slightly biased. The bias ranged from 0.01°C in the three winter months to 0.06°C in June (old – new). The bias in 0-0Tn results from the time of occurrence of Tn, which is often around midnight (see Figure 4).

2.6 Composition of the standardized time series

Table 4 summarizes the composition of the standardized time series. The main differences with the old composition (see Appendix A) are: (a) the use of climatological data for the 1951-1970 period instead of synoptical data, and (b) the extension of Maastricht to 1950.

Table 4. Composition of the standardized time series of the five principal stations.

Station	**Period**	**Data type**
De Helder / De Kooy*	1906-1970	Den Helder: clim
Groningen / Eelde	1906-1950 1951-1970	Groningen: clim Eelde: clim
De Bilt	1901-1970	De Bilt: clim
Vlissingen	1906-1947,1958-1970 1947-1958	Vlissingen: clim Souburg: clim
Maastricht / Beek	1906-1950 1951-1970	Maastricht:clim Beek: clim

*From 1 August 1972 onwards the measurements come from airport De Kooy

6 www.knmi.nl/samenw/hawa/download.html

3 Results

In this chapter we compare the newly standardized series with the old time series. The annual mean temperature differences are discussed first and thereafter we focus on extreme values. The introduction of the standardized time series as the new operational time series of KNMI may change recorded extreme values. Changes in monthly and daily extremes are therefore presented.

3.1 Annual mean temperature differences

Figure 10 presents the annual mean temperature differences between the standardized series and the original values. For Den Helder the figure shows hardly any change. For De Bilt there are some small changes in 1951-1970 period. This is mainly due to the use of climatological data instead of synoptical data. Note that the differences in monthly mean temperatures for De Bilt were relatively large (see Figure 9). The annual mean absolute differences are ≤ 0.3°C and not systematic. For

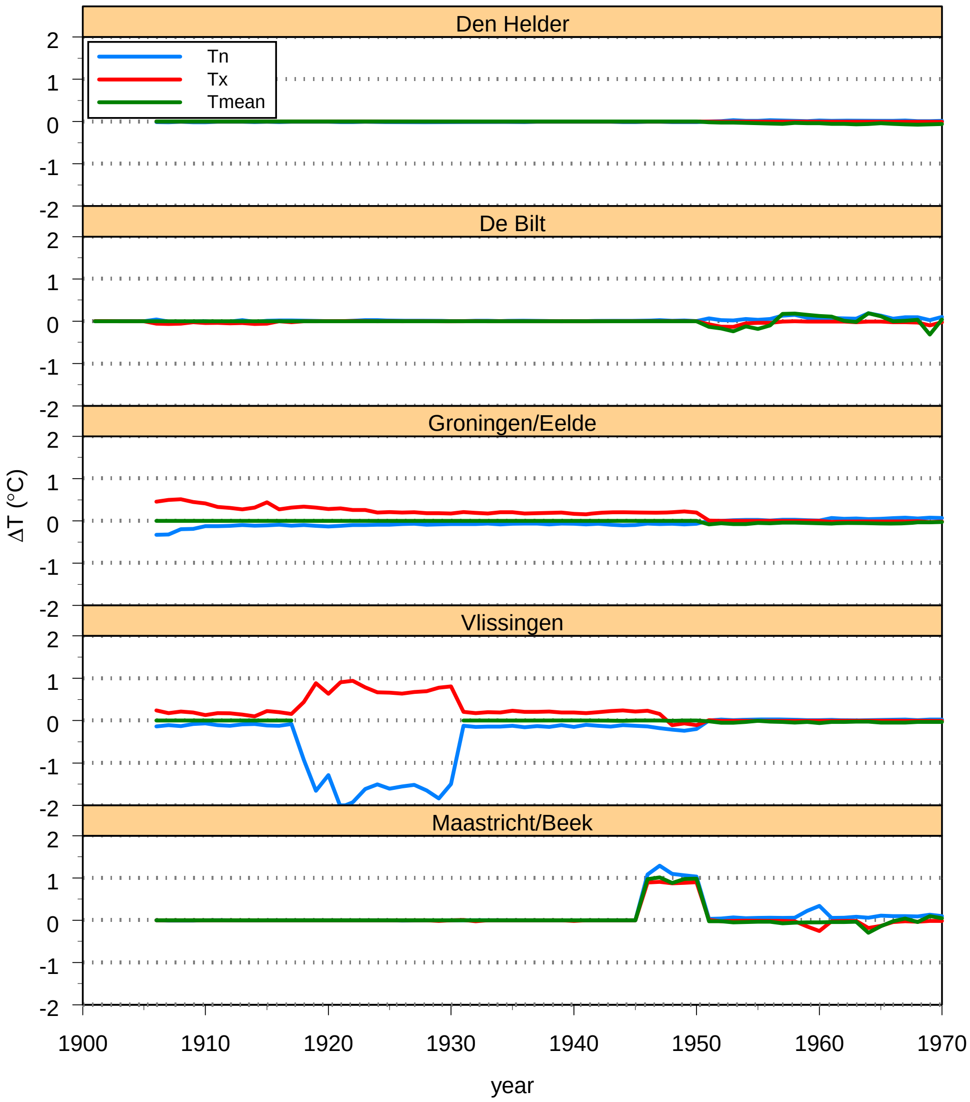

Figure 10: Annual mean temperature differences between the standardised and original series for Tmean, Tn and Tx.

Groningen/Eelde the standardized 0-0Tn and 0-0Tx values are more extreme than the original values for the pre-1951 period. This was expected because the old method used for calculating 0-0Tn and 0-0Tx severely underestimates the extremes (Appendix A). The same applies to Vlissingen where for the 1918-1930 period the annual mean 0-0Tn and 0-0Tx values change considerably by an amount of 1-2°C. Finally, for Maastricht/Beek the main change is in the 1946-1950 period where instead of the Beek data now the Maastricht data has been used.

It is of interest to know if the standardization resulted in changes in the trends of Tmean, 0-0Tn and 0-0Tx. The linear trends in the ΔT values (standardized – original series) are presented in Table 5. The table shows that in general the changes are small but for Groningen/Eelde (0-0Tn and 0-0Tx), Vlissingen (0-0Tn and 0-0Tx) and Maastricht/Beek (0-0Tn) there are changes that may be important for some applications.

Table 5: Trend in the ΔT values (standardized – original series) in Figure 10 (p-values in brackets). Trends apply to the periods presented in Figure 10.

	Linear trend (°C/10 year)		
Station	**Tmean**	**0-0Tn**	**0-0Tx**
DenHelder/DeKooy	-0.010 (0.000)	0.005 (0.000)	-0.001 (0.000)
De Bilt	0.000 (0.957)	0.014 (0.000)	-0.001 (0.498)
Groningen/Eelde	-0.010 (0.000)	0.038 (0.000)	-0.072 (0.000)
Vlissingen	-0.007 (0.000)	0.138 (0.001)	-0.083 (0.000)
Maastricht/Beek	0.013 (0.462)	0.044 (0.024)	0.009 (0.583)

3.2 Changes in extremes of monthly Tmean values

The extreme values of monthly Tmean are often referred to in climate services news items. The standardized series can be considered as updated versions of the observed values and as such they may change the ranking and values of record warm or cold monthly Tmean.

Tables 6 and *7* show the extremes of the warmest and coldest monthly Tmean for each month for the standardized series (new) and the original series (old). For the warmest months there is only one change (September for Maastricht/Beek). For the coldest months there are more changes in extreme values, especially for Vlissingen and Maastricht/Beek. For Vlissingen there are seven changes in the extremes and five of them also result in a changed value and a changed year of occurrence. For Maastricht/Beek there are six small changes in extreme values but no changes in the year of occurrence.

Tables 8 and 9 compare for De Bilt the top-10 of warmest and coldest months for each calendar month for the new and old series. The tables show that sometimes reordering of the top-10 values occurs because of the changes, of mostly a few tenths of a degree Celsius, in Tmean in the 1951-1970 period.

Table 6: Warmest months for Tmean for De Bilt (January 1901- June 2013) and the other four stations (January 1906 - June 2013) for the standardized data (new) and the original data (old). Changes are shaded in grey. When there is only a change in position or when the new and old values rounded to one decimal are equal, the changes are give in light grey.

	Den Helder/De Kooy				De Bilt				Groningen/Eelde				Vlissingen				Maastricht/Beek			
	new		old		new		old		new		old		new		Old		new		old	
Month	year	T	year	T	year	T	year	T	year	T	year	T	year	T	year	T	year	T	year	T
Jan	2007	7.59	2007	7.59	2007	7.09	2007	7.09	2007	6.39	2007	6.39	2007	7.81	2007	7.81	1921	6.69	1921	6.69
Feb	1990	7.32	1990	7.32	1990	7.62	1990	7.62	1990	6.90	1990	6.90	1990	7.91	1990	7.91	1926	8.12	1926	8.12
Mar	1990	7.99	1990	7.99	1991	8.76	1991	8.76	1938	7.72	1938	7.72	1990	8.70	1990	8.70	1938	9.21	1938	9.21
Apr	2007	11.65	2007	11.65	2011	13.12	2011	13.12	2011	11.96	2011	11.96	2011	13.12	2011	13.12	2007	13.57	2007	13.57
May	1992	14.73	1992	14.73	2008	15.67	2008	15.67	1992	14.71	1992	14.71	2008	15.82	2008	15.82	1917	16.72	1917	16.72
Jun	2003	16.96	2003	16.96	1917	18.34	1917	18.34	1917	18.44	1917	18.44	2003	18.19	2003	18.19	2003	19.40	2003	19.40
Jul	2006	20.87	2006	20.87	2006	22.31	2006	22.31	2006	21.39	2006	21.39	2006	22.16	2006	22.16	2006	22.91	2006	22.91
Aug	1997	20.54	1997	20.54	1997	20.55	1997	20.55	1997	20.29	1997	20.29	1997	21.05	1997	21.05	1911	21.17	1911	21.17
Sep	2006	18.19	2006	18.19	2006	17.92	2006	17.92	2006	17.38	2006	17.38	2006	18.72	2006	18.72	1949	18.72	2006	18.29
Oct	2001	14.61	2001	14.61	2001	14.22	2001	14.22	2001	13.69	2001	13.69	2001	14.89	2001	14.89	1921	14.51	1921	14.51
Nov	2006	10.25	2006	10.25	1994	10.18	1994	10.18	2006	8.85	2006	8.85	1994	11.06	1994	11.06	1994	9.94	1994	9.94
Dec	2006	7.71	2006	7.71	1974	7.25	1974	7.25	2006	6.67	2006	6.67	1934	7.90	1934	7.90	1934	8.23	1934	8.23

Table 7: Coldest months for Tmean for De Bilt (January 1901- June 2013) and the other four stations (January 1906- June 2013) for the standardized data (new) and the original data (old). For shading see Table 6.

	Den Helder/De Kooy				De Bilt				Groningen/Eelde				Vlissingen				Maastricht/Beek			
	new		old		new		old		new		new		new		old		new		old	
Month	year	T	year	T	year	T	year	T	year	T	year	T	year	T	year	T	year	T	year	T
Jan	1963	-4.12	1963	-4.04	1940	-5.51	1940	-5.51	1940	-6.29	1940	-6.29	1963	-4.13	1963	-4.07	1963	-5.45	1963	-5.42
Feb	1947	-5.71	1947	-5.71	1956	-6.72	1956	-6.37	1929	-6.64	1929	-6.64	1956	-4.84	1956	-4.82	1956	-7.64	1956	-7.63
Mar	1942	1.11	1942	1.11	1955	1.93	1917	1.94	1987	0.49	1987	0.49	1917	2.05	1917	2.05	1962	1.77	1962	1.82
Apr	1917	4.15	1917	4.15	1917	4.61	1917	4.61	1917	4.05	1917	4.05	1917	4.85	1917	4.85	1917	5.17	1917	5.17
May	1941	8.88	1941	8.88	1902	9.36	1902	9.36	1987	9.08	1987	9.08	1941	9.61	1941	9.61	1962	9.99	1962	10.02
Jun	1923	10.79	1923	10.79	1923	11.63	1923	11.63	1923	10.71	1923	10.71	1923	11.85	1916	12.44	1923	12.17	1923	12.17
Jul	1919	13.47	1919	13.47	1919	13.88	1919	13.88	1907	13.57	1907	13.57	1919	13.45	1907	14.03	1954	14.28	1954	14.35
Aug	1956	14.70	1956	14.73	1956	14.02	1912	14.14	1956	13.19	1956	13.25	1920	14.74	1912	14.98	1956	14.50	1956	14.53
Sep	1912	11.88	1912	11.88	1912	10.73	1912	10.73	1912	10.47	1912	10.47	1912	11.77	1912	11.77	1912	10.83	1912	10.83
Oct	1922	8.09	1922	8.09	1905	6.47	1905	6.47	1922	6.26	1922	6.26	1919	7.70	1915	8.65	1974	6.46	1974	6.46
Nov	1921	2.52	1921	2.52	1921	1.25	1921	1.25	1921	0.95	1921	0.95	1919	3.33	1993	4.17	1921	1.60	1921	1.60
Dec	1995	-0.57	1995	-0.57	1933	-2.15	1933	-2.15	1969	-2.46	1969	-2.42	1933	-1.14	1933	-1.14	1933	-2.23	1933	-2.23

Table 8: Top-10 of warmest months for Tmean for De Bilt (January 1901- June 2013) for the standardized data (new) and the original data (old). For shading see Table 6.

Jan				Feb				Mar				Apr				May				Jun			
year	new	year	old	year	new	year	old	year	new	year	old	year	new	year	old	year	new	year	old	year	new	year	old
2007	7.09	2007	7.09	1990	7.62	1990	7.62	1991	8.76	1991	8.76	2011	13.12	2011	13.12	2008	15.67	2008	15.67	1917	18.34	1917	18.34
2008	6.50	2008	6.50	2002	7.11	2002	7.11	1990	8.46	1990	8.46	2007	13.06	2007	13.06	1992	15.61	1992	15.61	1976	17.98	1976	17.98
1975	6.20	1975	6.20	1995	6.68	1995	6.68	1957	8.38	2012	8.29	2009	12.18	2009	12.18	1947	15.08	1947	15.08	2003	17.84	2003	17.84
1921	6.17	1921	6.17	1998	6.35	1998	6.35	2012	8.29	1957	8.26	1993	11.15	1993	11.15	1998	14.94	1998	14.94	1930	17.80	1930	17.80
1983	6.17	1983	6.17	1961	6.28	1926	6.28	1989	8.24	1989	8.24	1987	10.73	1987	10.73	2000	14.73	2000	14.73	1970	17.58	1947	17.49
1916	5.96	1916	5.96	1926	6.28	1997	6.24	1981	8.14	1981	8.14	1961	10.50	1952	10.61	1917	14.70	1917	14.70	1947	17.49	1970	17.49
1988	5.86	1988	5.86	1997	6.24	2007	6.04	1997	8.00	1997	8.00	1943	10.48	1943	10.48	1989	14.64	1989	14.64	2007	17.48	2007	17.48
1990	5.69	1990	5.69	2007	6.04	1945	6.00	2007	7.96	2007	7.96	1949	10.40	1949	10.40	2006	14.50	2006	14.50	1950	17.30	1950	17.30
2005	5.25	2005	5.25	1945	6.00	1961	5.91	1938	7.73	1938	7.73	2005	10.39	1961	10.39	2012	14.45	2012	14.45	1992	17.23	1992	17.23
1999	5.20	1999	5.20	2000	5.86	2000	5.86	1998	7.55	1998	7.55	2004	10.35	2005	10.39	1988	14.37	1988	14.37	1905	16.92	1905	16.92

Jul				Aug				Sep				Oct				Nov				Dec			
year	new	year	old	year	new	year	old	year	new	year	old	year	new	year	old	year	new	year	old	year	new	year	old
2006	22.31	2006	22.31	1997	20.55	1997	20.55	2006	17.92	2006	17.92	2001	14.22	2001	14.22	1994	10.18	1994	10.18	1974	7.25	1974	7.25
1994	21.35	1994	21.35	1975	19.87	1975	19.87	1999	17.35	1999	17.35	2006	13.58	2006	13.58	2009	9.47	2009	9.47	1934	7.18	1934	7.18
1995	20.12	1995	20.12	1947	19.76	1947	19.76	1949	17.17	1949	17.17	2005	13.34	2005	13.34	2006	9.16	2006	9.16	1988	7.02	1988	7.02
1983	20.12	1983	20.12	1995	19.69	1995	19.69	1947	16.80	1947	16.80	1921	12.74	1969	13.03	1938	8.66	1938	8.66	2006	6.51	2006	6.51
2010	19.87	2010	19.87	1911	19.41	1911	19.41	1961	16.62	1961	16.35	1969	12.74	1921	12.74	1951	8.44	1951	8.50	2011	6.48	2011	6.48
1976	19.34	1976	19.34	1944	19.28	1944	19.28	1929	16.03	1929	16.03	1995	12.68	1995	12.68	1913	8.39	1963	8.45	1918	5.83	1918	5.83
1941	19.22	1941	19.22	2003	19.25	2003	19.25	1934	16.00	1934	16.00	1989	12.35	1989	12.35	1963	8.27	1913	8.39	1985	5.74	1985	5.74
1999	19.13	1999	19.13	1932	18.93	1932	18.93	2000	15.82	2000	15.82	1990	12.02	1954	12.03	1984	8.17	1984	8.17	1910	5.68	1910	5.68
1991	19.01	1991	19.01	2004	18.84	2004	18.84	1958	15.76	2005	15.72	1954	11.94	1990	12.02	1982	8.15	1982	8.15	1954	5.45	1954	5.45
1982	18.92	1982	18.92	2002	18.60	2002	18.60	2005	15.72	2011	15.64	1942	11.86	1967	11.86	1992	8.00	1992	8.00	1912	5.45	1912	5.45

Table 9: Top-10 of coldest months for Tmean for De Bilt (January 1901- June 2013) for the standardized data (new) and the original data (old). For shading see Table 6.

Jan				Feb				Mar				Apr				May				Jun			
year	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**
1940	-5.51	1940	-5.51	1956	-6.72	1956	-6.37	1955	1.93	1917	1.94	1917	4.61	1917	4.61	1902	9.36	1902	9.36	1923	11.63	1923	11.63
1963	-5.19	1963	-5.31	1947	-5.46	1947	-5.46	1917	1.94	1962	1.97	1929	5.46	1929	5.46	1941	9.65	1962	9.56	1916	12.24	1916	12.24
1942	-5.12	1942	-5.12	1929	-5.42	1929	-5.42	1962	1.97	1955	2.02	1903	5.58	1903	5.58	1955	9.97	1941	9.65	1991	12.72	1991	12.72
1979	-3.23	1979	-3.23	1942	-4.24	1942	-4.24	1969	2.24	1958	2.18	1956	5.70	1956	5.93	1962	9.98	1991	10.01	1956	12.82	1956	12.84
1985	-3.05	1985	-3.05	1986	-3.61	1986	-3.61	1958	2.27	1987	2.30	1922	6.07	1922	6.07	1991	10.01	1957	10.03	1927	13.22	1927	13.22
1987	-2.73	1987	-2.73	1963	-3.21	1963	-3.41	1987	2.30	1931	2.39	1973	6.07	1973	6.07	1987	10.18	1955	10.15	1909	13.25	1909	13.25
1941	-2.51	1941	-2.51	1917	-1.49	1917	-1.49	1931	2.39	2013	2.45	1908	6.11	1908	6.11	1957	10.30	1987	10.18	1972	13.41	1972	13.41
1945	-1.56	1945	-1.56	1940	-1.27	1940	-1.27	2013	2.45	1969	2.50	1970	6.12	1970	6.12	1923	10.35	1923	10.35	1918	13.49	1918	13.49
1947	-1.45	1947	-1.45	1979	-0.91	1979	-0.91	1964	2.66	1964	2.58	1936	6.17	1936	6.17	2010	10.49	2010	10.49	1907	13.69	1907	13.69
1929	-1.36	1929	-1.36	1901	-0.91	1901	-0.91	1942	2.69	1942	2.69	1986	6.17	1986	6.17	1984	10.56	1984	10.56	1962	13.73	1985	13.74

Jul				Aug				Sep				Oct				Nov				Dec			
year	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**	**year**	**new**	**year**	**old**
1919	13.88	1919	13.88	1956	14.02	1912	14.14	1912	10.73	1912	10.73	1905	6.47	1905	6.47	1921	1.25	1921	1.25	1933	-2.15	1933	-2.15
1907	13.91	1907	13.91	1912	14.14	1920	14.15	1952	11.47	1931	11.55	1922	6.47	1922	6.47	1919	1.78	1919	1.78	1969	-1.70	1969	-1.35
1954	14.28	1954	14.29	1920	14.15	1956	14.21	1931	11.55	1986	11.56	1974	6.96	1974	6.96	1993	2.18	1993	2.18	1927	-1.25	1927	-1.25
1962	14.68	1965	14.77	1924	14.37	1924	14.37	1986	11.56	1952	11.57	1919	7.01	1919	7.01	1985	2.65	1985	2.65	1950	-1.21	1950	-1.21
1913	14.82	1913	14.82	1902	14.82	1902	14.82	1925	11.79	1925	11.79	2003	7.46	2003	7.46	1965	2.68	1965	2.70	2010	-1.15	2010	-1.15
1909	14.85	1909	14.85	1922	14.85	1922	14.85	1972	11.86	1972	11.86	1915	7.56	1915	7.56	1925	2.76	1925	2.76	1963	-1.13	1963	-1.05
1965	14.89	1962	14.95	1941	15.01	1941	15.01	1904	12.38	1904	12.38	1939	7.57	1939	7.57	1915	2.86	1915	2.86	1995	-0.88	1995	-0.88
1922	15.15	1922	15.15	1940	15.17	1965	15.05	1996	12.49	1996	12.49	1912	7.92	1964	7.62	1923	2.91	1923	2.91	1981	-0.70	1962	-0.74
1910	15.28	1960	15.25	1963	15.19	1940	15.17	1922	12.57	1965	12.50	1964	7.94	1912	7.92	1952	2.97	1952	3.09	1962	-0.67	1981	-0.70
1916	15.33	1910	15.28	1993	15.23	1993	15.23	1974	12.68	1922	12.57	1926	7.99	1926	7.99	1920	3.16	1920	3.16	1946	-0.33	1946	-0.33

3.3 Changes in extreme values of daily Tmean, Tn and Tx

As for the monthly extreme values, the absolute extreme values in daily Tmean, Tn and Tx are based on the observed values. Again, these might change due to the standardization described in this report.

Tables 10 and 11 show the record values of the highest and lowest Tmean, Tn and Tx for the standardized series (new) and the original series (old). For the lowest values, the changes are restricted to Tmean on 16 February 1956 where the values slightly change due to the use of climatological data instead of synoptical data. For the highest values the changes are restricted to Groningen/Eelde and Vlissingen (Tn) and Maastricht/Beek (Tmean and Tx).

One of things that triggered this study was a record high 0-0Tn value for Vlissingen on 11 July 1923 of 23.3°C (see Table 10). This value was clearly wrong because of the erroneous method for calculating 0-0Tn and 0-0Tx in the 1918-1930 period for Vlissingen. Due to the standardization and the inclusion (after digitization) of the hourly temperatures for this period, the 0-0Tn value for this particular day decreased by an amount of 4.8°C to a value of 18.5°C. The new record high 0-0Tn value for Vlissingen is now on 9 August 2004 amounts 22.2°C.

Table 10: Highest daily values of Tmean, 0-0Tn and 0-0Tx for De Bilt (1901-2012) and the other four stations (1906-2012) for the standardized data (new) and the original data (old). For shading see Table 6.

	New				Old				New				Old				New				Old			
	yr	**mo**	**Da**	**Tmean**	**yr**	**mo**	**da**	**Tmean**	**yr**	**mo**	**da**	**Tn**	**yr**	**mo**	**da**	**Tn**	**yr**	**mo**	**da**	**Tx**	**yr**	**mo**	**da**	**Tx**
DenHelder/DeKooy	1925	7	22	26.5	1925	7	22	26.5	1925	7	22	23.0	1925	7	22	23.0	1923	7	12	33.9	1923	7	12	33.9
De Bilt	1947	6	27	27.9	1947	6	27	27.9	2004	8	9	20.8	2004	8	9	20.8	1947	6	27	36.8	1947	6	27	36.8
Groningen/Eelde	1941	7	10	27.7	1941	7	10	27.7	1944	8	24	20.7	1941	7	10	20.8	1944	8	23	36.8	1944	8	23	36.8
Vlissingen	2006	7	19	26.9	2006	7	19	26.9	2004	8	9	22.2	1923	7	11	23.3	2006	7	19	35.5	2006	7	19	35.5
Maastricht/Beek	1947	6	27	30.1	2003	8	12	28.8	2012	8	19	23.1	2012	8	19	23.1	1947	6	27	38.4	1944	8	23	38.0

Table 11: Lowest daily values of Tmean, 0-0Tn and 0-0Tx for De Bilt (1901-2012) and the other four stations (1906-2012) for the standardized data (new) and the original data (old). For shading see Table 6.

	New				Old				New				Old				New				Old			
	yr	**mo**	**da**	**Tmean**	**yr**	**mo**	**da**	**Tmean**	**yr**	**mo**	**da**	**Tn**	**yr**	**mo**	**da**	**Tn**	**yr**	**mo**	**da**	**Tx**	**yr**	**mo**	**da**	**Tx**
DenHelder/DeKooy	1956	2	16	-13.0	1956	2	16	-12.8	1979	1	1	-18.8	1979	1	1	-18.8	1938	12	20	-10.6	1938	12	20	-10.6
De Bilt	1956	2	16	-14.9	1956	2	16	-14.5	1942	1	27	-24.8	1942	1	27	-24.8	1938	12	20	-11.3	1938	12	20	-11.3
Groningen/Eelde	1956	2	16	-17.4	1956	2	16	-17.2	1956	2	16	-22.9	1956	2	16	-22.9	1942	1	26	-12.8	1942	1	26	-12.8
Vlissingen	1938	12	20	-11.8	1938	12	20	-11.8	1956	2	21	-19.6	1956	2	21	-19.6	1938	12	20	-10.4	1938	12	20	-10.4
Maastricht/Beek	1929	2	14	-15.4	1929	2	14	-15.4	1929	2	14	-20.2	1929	2	14	-20.2	1956	2	1	-12.7	1956	2	1	-12.7

4 Discussion

We restricted the standardization in this report to the temperatures of the five principal stations (Den Helder/De Kooy, De Bilt, Groningen/Eelde, Vlissingen, and Maastricht/Beek). The other stations listed in Appendix A show significant biases in the 0-0Tn and 0-0Tx temperatures during the 1951-1970 period with respect to the values in the proceeding period. Unfortunately, there is not enough data available for these stations to perform the standardization described in this report.

The standardization for daily Tmean, 0-0Tn and 0-0Tx does not remove inhomogeneities due to for instance station relocations. It is important to keep this in mind when evaluating extreme values. Currently there is no generally accepted method to correct for inhomogeneities on a daily basis. For the study of long-term changes, series of Tmean, 0-0Tn and 0-0Tx series are mostly homogenized on a monthly basis. For De Bilt and Central Netherlands there are homogenized monthly Tmean series available. Currently we are working on the homogenization of the monthly mean Tmean, 0-0Tn and 0-0Tx series of the five principal stations. For the major stations relocations, KNMI usually performed parallel measurements in order to calculate corrections.

5 Summary and conclusions

In this report we made a reconstruction of the data and methods used to calculate Tmean, 0-0Tn and 0-0Tx for the five principal stations in the Netherlands in the 1901-1970 period. We found that a variety of approaches was followed for calculating 0-0Tn and 0-0Tx and that it was not completely clear what type of data, climatological or synoptical, had to be preferred in the period that both types were available.

A standard approach for calculating 0-0Tn and 0-0Tx was introduced. This approach automatically calculates 0-0Tn and 0-0Tx from all available data. Further improvement of the method by (labour-intensive) manually checking the thermograph strip charts, does not result in significantly improved 0-0Tn and 0-0Tx values. Quality flags were defined to indicate the degree of exactness of the automatically calculated 0-0Tn and 0-0Tx values. For De Bilt and Maastricht/Beek it was found that the quality of the climatological temperatures was better than that of the synoptical temperatures. So far, the latter had been used operationally for the 1951-1970 period. For the other stations there was no indication of quality differences between both data types. It was decided to solely use climatological temperatures for calculating the operational Tmean, 0-0Tn and 0-0Tx in the 1901-1970 period. The main reasons for this decision are: (a) improved data quality for De Bilt and Maastricht/Beek, (b) uniformity of data type for the whole 1901-1970 period, and (c) prevention of illogical combinations of both data types in the 1951-1970 period.

The standardized series of daily Tmean, 0-0Tn and 0-0Tx will serve as the new operational time series of KNMI for the five principal stations. As a result, some of the record values of Tmean, Tn and Tx change. The standardized series also serve as the basis for calculating trends in Tmean, 0-0Tn and 0-0Tx for the Netherlands. For that purpose the data needs to be studied further in conjunction with corrections for stations relocations. This is the subject of a subsequent study.

6 References

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Appendix A. Summary of Tmean, Tn, Tx calculation in the 1901-1970 period

Station	Period	Basic data	Tmean, Tn, Tx calculation method[7]	Remarks
De Bilt (260)	1901-1950	- File (H001, 1901-1970) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). The 24 hours measurement in the file gives the 0-0Tn.clim and 0-0Tx.clim as calculated in the past	Tmean = mean(T1.clim,T2.clim,…,T24.clim). The 0-0Tn and 0-0Tx equal the 0-0Tn.clim en 0-0Tx.clim in de H001 file. These have been calculated from the hourly temperatures and the 3xdaily Tn and Tx.	The method used for calculating the 0-0Tn and 0-0Tx in de H001-file is analogous (but not well described) to the method proposed in this report. The annual mean bias is negligible (< 0.01°C).
	1951-1970	- 260-file with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn) - H001 (see above)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = min(T1.syn, T2.syn,…,T24.syn,0-0Tn.clim) 0-0Tx = max(T1.syn, T2.syn,…,T24.syn,0-0Tx.clim)	The combination of the hourly synoptical temperatures and the de climatological 0-0Tn and 0-0Tx causes inhomogeneous Tn and Tx in this period. Annual differences with the previous period can be up to 0.4°C.
Vlissingen (310)	1906-1917	- File (H003, 1906-1970; interuption from 15/08/1947 till 30/04/1958) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). From 01/05/1958 onwards the 24 hour measurement in the file gives the 0-0Tn.clim en 0-0Tx.clim as calculated in the past. From 1918-1930 there only the 3xdaily measurements are in the file	Tmean = mean(T1.clim,T2.clim,…,T24.clim) 0-0Tn = min(T1.clim,T2.clim,…,T24.clim) 0-0Tx = max(T1.clim,T2.clim,…,T24.clim)	The method used here for calculating 0-0Tn and 0-0Tx results in a systematic underestimation of those values with an annual mean bias of about 0.2°C.
	1918-1930	- H003 (see above)	Tmean = not calculated 0-0Tn = min(T8.clim,T14.clim,T19.clim) 0-0Tx = max(T8.clim,T14.clim,T19.clim)	The method used here for calculating 0-0Tn and 0-0Tx results in a large underestimation of those values.
	1931-14/08/1947	- H003 (see above)	See above (1906-1917)	
	16/08/1947-31/12/1950	- File (H010 file, 16/08/1947 - 31/12-1962, Souburg location) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). From 01/01/1951 onwards the 24 hour measurement in the file gives the 0-0Tn.clim en 0-0Tx.clim as calculated in the past	Tmean = mean(T1.clim,T2.clim,…,T24.clim) 0-0Tn = min(Tn8.clim,Tn13.clim,Tn19.clim) 0-0Tx = max(Tx8.clim,Tx13.clim,Tx19.clim)	Tn and Tx apply here to the 19-19 interval as given in the yearbooks since 1932. The climatological measurements on location Vlissingen have temporarily been relocated to location Souburg (16/08/1947 - 01/05/1958). Since 1951 synoptical measurements are also

7 This concerns the daily Tmean, Tn and Tx stored in the Climatological Information System (KIS) of KNMI and as published on the KNMI internet site before the transition to the standardized series.

				available at that location. From 01/05/1958 onwards both climatological as synoptical measurements come from location Vlissingen. The climatological measurements in Souburg have been continued till 31/12/1962.
	1951-1970	- 310-file with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn) - H003 file (see above) - H010 file (see above)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn and 0-0Tx agree with the 0-0Tn.clim en 0-0Tx.clim in de H010 file (t/m 30/04/1958) en H003 file (from 01/05/1958 onwards). These have been calculated from the hourly temperatures and the 3xdaily Tn and Tx.	The method used for calculating the 0-0Tn and 0-0Tx in de H003 and H010 files is analogous (but not well described) to the method proposed in this report. The used combination of synoptical (Tg) and climatological measurements (0-0Tn and 0-0Tx) results in a datasets that may sometimes be inconsistent.
Maastricht/Beek (380)	1906-1950	- File (H007, 1906-1952, Maastricht location) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). There are no 0-0Tn.clim and 0-0Tx.clim values in the file - File (H005, 1946-1970, Beek location) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). From 01/01/1951 onwards the 24 hour measurement in the file gives the 0-0Tn.clim en 0-0Tx.clim as calculated in the past	Tg = mean(T1.clim,T2.clim,…,T24.clim) 0-0Tn and 0-0Tn agree with values generated by Job Verkaik from the hourly temperatues and the 3xdaily values of Tn and Tx Untill 01/01/1945 location Maastricht has been used and thereafter location Beek.	On 21 February 2003 the existing 0-0Tn and 0-0Tx in het database have been replaced with values generated by Verkaik
	1951-1970	- 380-file with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn) - H005 (see above)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = min(T1.syn, T2.syn,…,T24.syn,0-0Tn.clim) 0-0Tx = max(T1.syn, T2.syn,…,T24.syn,0-0Tx.clim)	Here the same method has been used as for De Bilt in this period.
	Jun 1959 - dec 1960	See above	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = min(T1.syn, T2.syn,…,T24.syn) – 0.5 0-0Tx = max(T1.syn, T2.syn,…,T24.syn) + 0.5	The reason for changing the method for calculating 0-0Tn and 0-0Tx in this period is unclear.
Den Helder (235)	1906-1950	- File (H002, 1906-1970) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). From 01/01/1951 onwards the 24 hours measurement in the file gives the 0-0Tn.clim and 0-0Tx.clim as calculated in the past	Tmean = mean(T1.clim,T2.clim,…,T24.clim) 0-0Tn and 0-0Tn agree with values generated by Job Verkaik from the hourly temperatues and the 3xdaily values of Tn and Tx	On 24 February 2003 the existing 0-0Tn and 0-0Tx in het database have been replaced with values generated by Verkaik.

	1951-1970	- 235- file with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn) - H002 (see above)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = 0-0Tn.clim 0-0Tx = 0-0Tx.clim	The method used for calculating the 0-0Tn and 0-0Tx in de H002-file is analogous (but not well described) to the method proposed in this report. The used combination of synoptical (Tg) and climatological measurements (0-0Tn.clim and 0-0Tx.clim) results in a datasets that may sometimes be inconsistent.
Groningen/Eelde (280)	1906-1960	- File (H006, 1906-1952, Groningen location) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC). There are no 0-0Tn.clim and 0-0Tx.clim values in the file - File (H004, 1946-1970; Eelde location) with hourly climatological measurements (T1.clim,T2.clim,…,T24.clim) and 3xdaily measurements of Tn and Tx (at 8, 14 and 19 UTC).From 01/01/1951 onwards the 24 hours measurement in the file gives the 0-0Tn.clim and 0-0Tx.clim as calculated in the past	Tmean = mean(T1.clim,T2.clim,…,T24.clim) Tn = min(T1.clim,T2.clim,…,T24.clim) Tx = max(T1.clim,T2.clim,…,T24.clim) Until 31/12/1950 location Groningen has been used, thereafter location Eelde.	The method used here for calculating 0-0Tn and 0-0Tx results in a systematic underestimation of those values an annual mean bias of about 0.2°C.
	1961-1970	- 280-file with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn) - H004 (see above)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = min(T1.syn, T2.syn,…,T24.syn,0-0Tn.clim) 0-0Tx = max(T1.syn, T2.syn,…,T24.syn,0-0Tx.clim)	Comparable systematic as for De Bilt. The 0-0Tn.clim and 0-0Tx.clim in the H004 file have been calculated in the same way as the Verkaik method.
Valkenburg (210) Soesterberg (265) Leeuwarden (270) Deelen (275) Twenthe (290) Gilze-Rijen (350) Eindhoven(370) Volkel (375)	1951-1970	- 210, 265, 270, 275, 290, 350, 370, 375 files with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = min(T1.syn, T2.syn,…,T24.syn) – 0.5 0-0Tx = max(T1.syn, T2.syn,…,T24.syn) + 0.5	Comparison with post-1970 0-0Tn and 0-0Tx data shows that the used method results in too extreme values of 0-0Tn and 0-0Tx with an annual mean bias of 0.1–0.3°C.
Schiphol (240)	1951-1970	- 240-file with hourly synoptical measurements (T1.syn,T2.syn,…,T24.syn)	Tmean = mean(T1.syn,T2.syn,…,T24.syn) 0-0Tn = min(T1.syn, T2.syn,…,T24.syn) 0-0Tx = max(T1.syn, T2.syn,…,T24.syn)	The method used here for calculating 0-0Tn and 0-0Tx results in a systematic underestimation of those values with an annual mean bias of about 0.2°C

Appendix B. Quality flags for Tn, Tx

Section 2.5 mentioned the existence of quality flags that are stored together with the 0-0Tn and 0-0Tx data. Four flags have been defined (0,2,3,4) that are described in the table below.

Flag	**Description**
0	The extreme was determined exactly from the available data
2	The extreme on day t depends on Tn8 or Tx8 for day t or day t+1 and the hourly temperatures indicate that the corresponding Tn8 or Tx8 value is situated in day t. The real 0-0Tn on day t may be higher and the real 0-0Tx may be lower than the calculated values.
3	The extreme on day t depends the extreme of the hourly temperatures [T24(t-1),T1(t),T2(t),…,T8(t)] or [T19(t), T20(t),…,T24(t)]. The real 0-0Tn on day t may be lower and the real 0-0Tx may be higher than the calculated values.
4	The extreme on day t depends on Tn8 or Tx8 for day t or day t+1 and the hourly temperatures indicate that the corresponding Tn8 or Tx8 value may be situated in both the day of measurement or the preceding day. The real 0-0Tn on day t may be higher and the real 0-0Tx may be lower than the calculated values.

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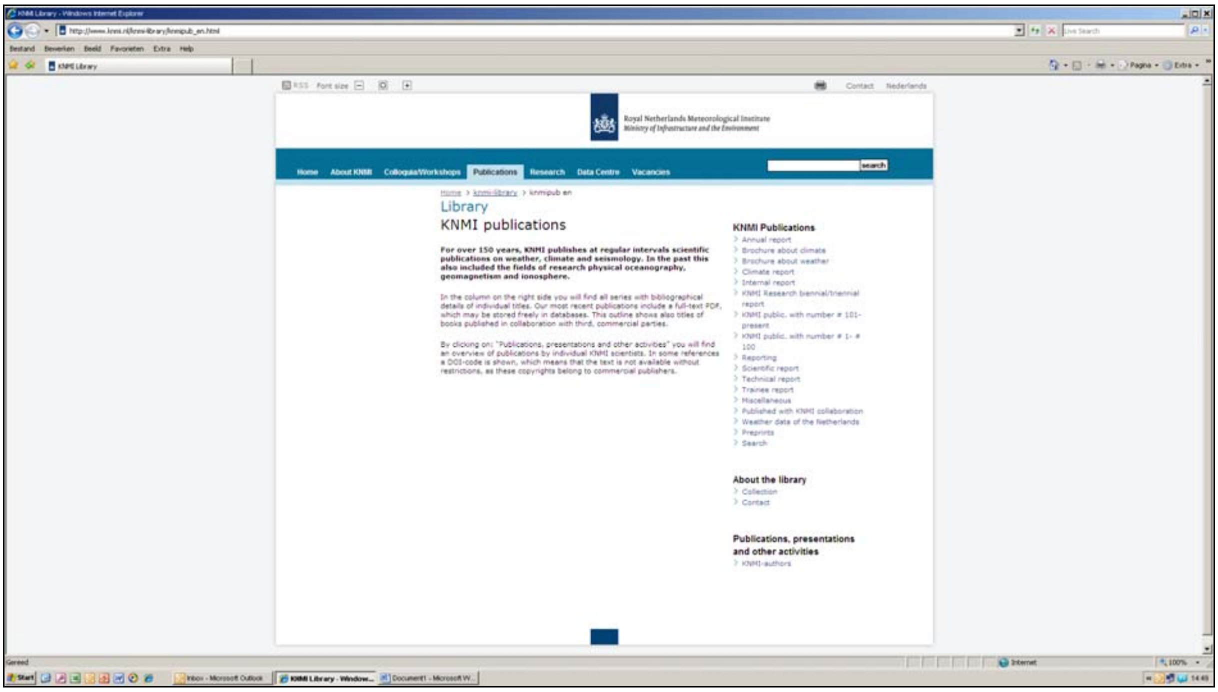

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