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Extending Greenland temperature records into the late eighteenth century

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[1] At present, continuous instrumental temperature records for Greenland reach back to the late nineteenth century at a few sites. Combining early observational records from locations along the south and west coasts, it has been possible to extend the overall record back to the year 1784. The new extended Greenland temperature record is 9% incomplete. There are, however, sufficient new data (an additional 74 complete winters and 52 complete summers) to provide a valuable indication of late eighteenth century and nineteenth century seasonal trends. Comparison of the previously published records with additional observational series digitized from Danish Meteorological Institute Yearbooks has also revealed inhomogeneities in some of the existing twentieth century temperature records. These problems have been eliminated in the new extended Greenland temperature record. A long homogeneous west Greenland instrumental temperature record is of great value for the interpretation of the growing number of Greenland ice core records. A first comparison of the new record with highly resolved Greenland ice core data is presented. Correlations between west Greenland winter temperatures and the ice core winter season proxy are found to be r = 0.67 and r = 0.60 for the periods 1785–1872 and 1873–1970, respectively.

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1. Introduction

[2] When reconstructing past climatic conditions from the ever increasing archives of natural proxies, it is essential to establish rigorous statistical relationships between the proxy data and modern climatic observations. Efforts to establish such relationships are however often hampered by the relatively short period of available instrumental observations. The extension of the homogeneous series of instrumental observations is often not considered, even though earlier records often exist in many regions. Not only do such series facilitate an extension of global instrumental climatic data sets, they are also of particular value for increasing the scope of long-timescale comparisons with proxy records [*Osborn and Briffa*, 2004; *Jones and Mann*, 2004]. During the past 20 years, a substantial effort has been devoted to the extension and homogenization of instrumental data series in projects such as IMPROVE [*Camuffo and Jones*, 2002], ADVICE [*Jones et al.*, 1999], EMULATE [e.g., *Ansell et al.*, 2006] and ALPIMP [*Auer et al.*, 2005].

[3] None of these has focused on the extension of Greenland instrumental records. Available temperature and pressure data from Greenland are therefore limited to the period from 1873 to present [see, e.g., *Box*, 2002]. The founding of the Danish Meteorological Institute (DMI) in late 1872 marks the beginning of official Greenland instrumental records, even though many published nineteenth-century sources provide data back to 1866 and earlier [e.g., *Hann*, 1890]. As climatic proxies derived from Greenland ice core records provide a rare source of high-resolution environmental information, covering more than 100 millennia [e.g., *NGRIP members*, 2004; *Andersen et al.*, 2006], it is particularly unfortunate to have relatively short Greenland instrumental series with which to compare them.

[4] Because of collaboration between the late H. H. Lamb and former staff at DMI, a compilation of pre-1873 Greenland instrumental data from non-official observers is available at the Climatic Research Unit (CRU at University of East Anglia, UK) from DMI archives. The observations were made at various locations along the south and west coasts of Greenland but often they cover only relatively short time intervals of 5 to 10 years. Through searches of additional observation records at DMI, it has been possible to find longer and newer data for all the locations in question. Using the newer data, relationships between different observation sites can be established facilitating the merging of the older data into longer periods of continuous observations.

[5] Here we present three long series of Greenland temperature observations, for the south coast, the south-

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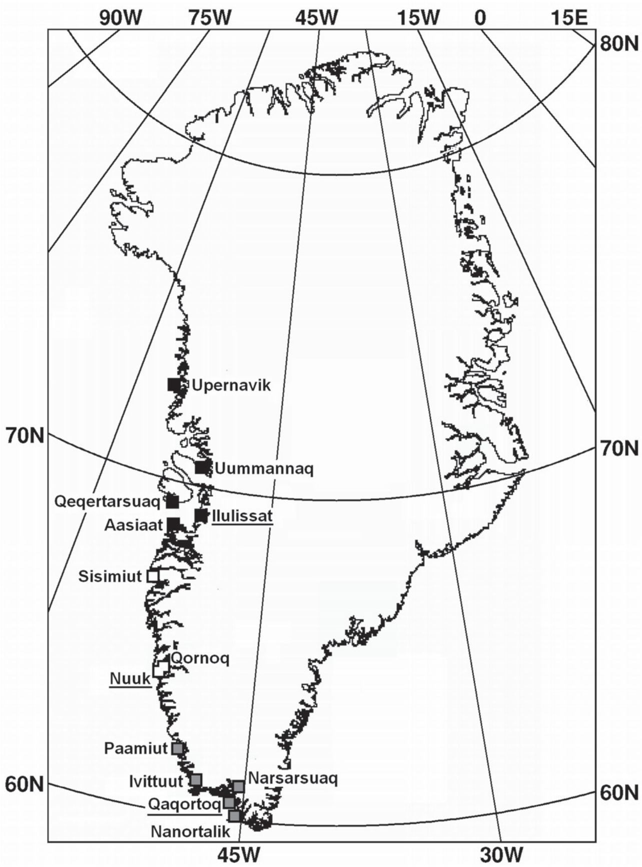

Figure 1. Locations of observation sites used in this study. Colors indicate groupings. Ilulissat group stations are black, Nuuk group stations are white and Qaqortoq group stations are grey. The three stations providing master records are underlined.

west coast and the west coast. As the series are found to contain a strong common temperature signal, we use the three series to create one merged south-west Greenland temperature record covering the period from 1784 to 2005. The merged record is complete from 1829 to 2005 for winters and from 1855 to 2005 for summers. The 71-year period from 1784 to 1854 contains gaps corresponding to ~20 years of observations and is thus 72% complete. A comparison between the merged Greenland temperature series and an ice core based index of southern Greenland winter temperatures [*Vinther et al.*, 2003] is also presented.

2. Greenland Temperature Data

[6] During the past decade, DMI has made a great effort to digitize and document Greenland weather and climate observations [*Frich et al.*, 1996; *Cappelen et al.*, 2001; *Laursen*, 2003a, 2003b; *Jørgensen and Laursen*, 2003; *Cappelen et al.*, 2005]. In this study, extensive use has been made of the data and documentation presented in these reviews (all available from the DMI website: http://www.dmi.dk/dmi/index/viden/dmi-publikationer/tekniskerapporter.htm). Supplemental temperature data have also been digitized in this study for a number of stations from DMI Yearbooks. Furthermore, the pre-1873 temperature data from the CRU archive (based on photocopies of the DMI archive made in the 1970s) have been digitized. We have, therefore, been able to use an extraordinary collection of Greenland temperature observations in an effort to extend and improve existing Greenland temperature series.

[7] The spatial distribution of observation sites is shown in Figure 1 and listed in Table 1, while the temporal distribution of observations used for this study is shown in Figure 2. All place names are given in the local Inuit language, as used by *Cappelen et al.* [2001] (former Danish names for some stations are listed in Table 1). The Inuit name for Greenland is Kalaallit Nunaat, but for reasons of clarity, it was decided to stay with the commonly used name, Greenland, throughout the paper. The following sections discuss the various data sources.

2.1. North Atlantic Climatological Data Set (NACD)

[8] The NACD data compilation [*Frich et al.*, 1996] includes a number of Greenland temperature series. In the NACD data report [*Frich et al.*, 1996] the Greenland data were all marked as being "not perfectly homogeneous". The data set is generally superseded by the NARP data

Table 1. Greenland Observation Sites[a]

Site Name	Former Name	Elevation, m a.s.l.	Latitude, °N	Longitude, °W	First Obs.[b] MM-YYYY	Last Obs.[b] MM-YYYY	Station No. DMI
Nanortalik	-	20	60.13	45.22	01-1883	10-1946	04283
Qaqortoq	Julianehaab	32	60.72	46.05	11-1807	09-2005	04272
Narsarsuaq	-	27	61.17	45.42	01-1961	09-2005	04270
Iviituut	Ivigtut	30	61.20	48.17	01-1880	08-1966	34262
Paamiut	Frederikshaab	13	62.00	49.67	10-1828	09-2005	04260
Nuuk	Godthaab	80	64.17	51.75	09-1784	09-2005	04250
Qornoq	Kornok	31	64.50	51.32	01-1874	12-1960	04247
Sisimiut	Holsteinsborg	12	66.92	53.67	01-1961	05-2001	04230
Aasiaat	Egedesminde	43	68.70	52.75	01-1958	09-2005	04220
Ilulissat	Jakobshavn	29	69.23	51.07	11-1835	09-2005	04221
Qeqertarsuaq	Godhavn	8	69.23	53.52	08-1807	12-1960	04218
Uummannaq	Umanak	39	70.67	52.12	10-1829	12-1956	04212
Upernavik	-	120	72.78	56.17	08-1807	12-1986	04210

[a]As many observation sites have been slightly relocated during their period of observation, this table gives the latest location of all stations.
[b]Data used in this study. For some stations, periods of inhomogeneous observations have been omitted (see text for details).

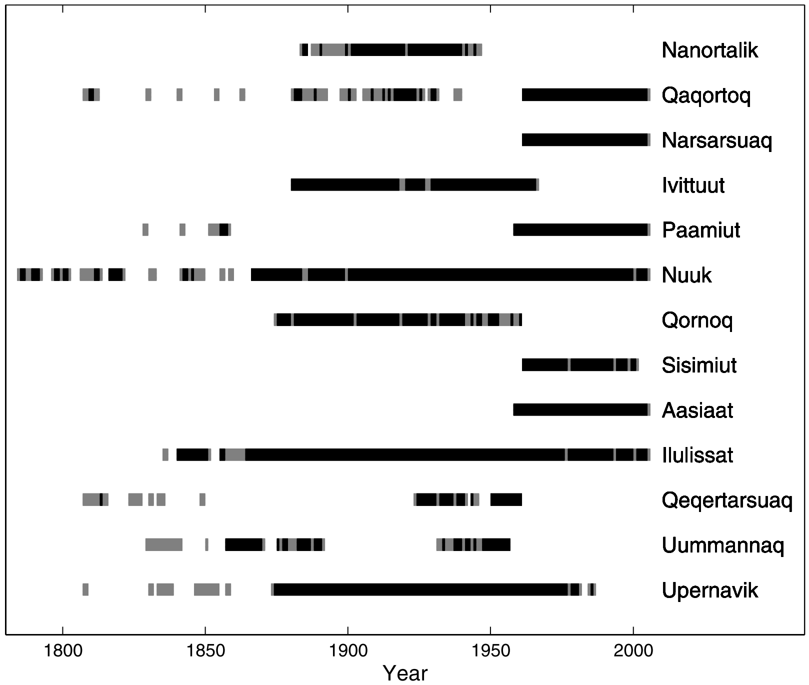

Figure 2. Temporal distribution of the observations used in this study. A black bar indicates complete observation years, and a grey bar indicates incomplete observation years.

set (see below), but as very few adjustments to the Greenland series were introduced in NACD, the data are closer to the original observations than later NARP records.

2.2. Collection of Synoptic Data

[9] In the work of *Cappelen et al.* [2001], a collection of data from a large number of Greenland synoptic stations was presented. Modern synoptic stations carrying out several observations a day were set up all over Greenland during the 1950s and early 1960s. The *Cappelen et al.* [2001] data set covers the period from 1958 to 1999. Many of the synoptic stations were subsequently shut down, relocated or suffered changes in observation hours during this period, leaving only a limited number of stations with homogeneous observation records.

2.3. Nordic Arctic Research Programme (NARP) Data

[10] As part of the NARP initiative, a number of Greenland weather records were released through Danish Meteorological Institute Technical Reports [*Laursen*, 2003a, 2003b; *Jørgensen and Laursen*, 2003]. The NARP data set is mainly a combination and update of NACD and the synoptic data of *Cappelen et al.* [2001]. In the NARP effort numerous corrections were made in order to homogenize the NACD/synoptic data. A large amount of metadata concerning the Greenland stations was released by *Laursen* [2003a]. The *Cappelen et al.* [2005] report presents the latest revision of the NARP data set.

2.4. Global Historical Climatological Network (GHCN) Data

[11] The GHCN data [*Peterson and Vose*, 1997] includes a number of Greenland stations of which most are included in the NARP and *Cappelen et al.* [2001] data sets. Beside the homogenized records, GHCN provides pre-homogenized station data (Goddard Institute for Space Studies web page: http://data.giss.nasa.gov/gistemp/station_data) and is therefore a useful reference when evaluating subsequent homogenization efforts.

2.5. Data From DMI Yearbooks

[12] From 1873 to 1960, DMI published an annual series of Yearbooks. These Yearbooks contain observations from a number of Greenland stations which have never been

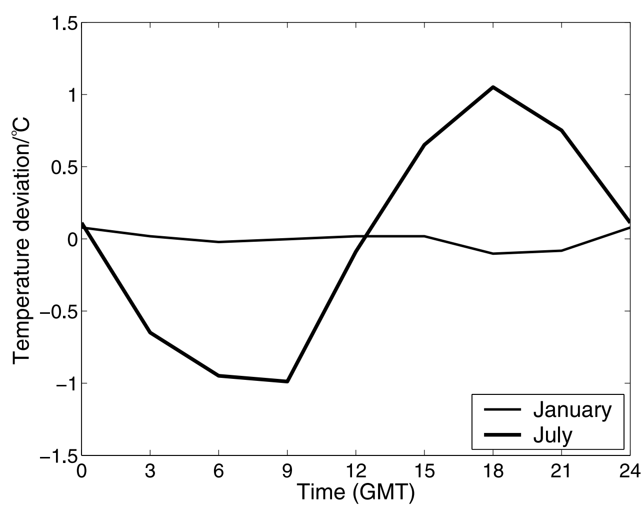

Figure 3. Mean Upernavik air temperature deviation from the daily mean at different observation hours (1961–1965).

Table 2. Monthly Corrections (°C) Applied to Ilulissat Data Sets, to Form a Homogeneous Series

Period	Data Set	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1835/11–1872/12	CRU	Private Obs.	0.1	0.2	0.8	0.7	0.6	0.1	0.1	0.3	0.5	0.2	−0.3	0.1
1873/01–1936/10	NARP	34216	0.1	0.3	0.8	1.1	0.6	0.9	0.8	1.0	0.6	0.2	−0.2	0.1
1936/11–1946/08	NARP	34216	0.8	1.0	1.5	1.8	1.3	1.6	1.5	1.7	1.3	0.9	0.5	0.8
1947/09–1955/12	NARP	34216	0.1	0.3	0.8	1.1	0.6	0.9	0.8	1.0	0.6	0.2	−0.2	0.1
1956/01–1966/07	CRU	34216	0.1	0.2	0.8	0.7	0.6	−0.5	−0.5	−0.3	0.5	0.2	−0.3	0.1

digitized. All stations for which pre-1873 observations were available in the CRU archive were therefore digitized from these Yearbooks.

[13] In an attempt to estimate the true mean temperature from the thrice daily observations carried out before the introduction of the synoptic stations, a weighted average of the observations has been used to calculate monthly mean temperatures (T_m) in the Yearbooks:

$$T_m = \frac{2 \cdot T_8 + 2 \cdot T_{14} + 5 \cdot T_{21}}{9} \qquad (1)$$

where T_8, T_{14} and T_{21} are the monthly mean temperatures measured at 8, 14 and 21 hours local time respectively. The Yearbook of 1874 states that (1) is based on hourly observations from the Greenland east coast carried out during the second German Polar Expedition. As this way of averaging has been used in every Yearbook, the series from the Yearbooks are internally consistent.

2.6. Pre-1873 Observations

[14] All the pre-1873 data had been written into monthly mean tables before being archived at CRU. The archive consists of photocopies of DMI sheets made in the 1970s. These sheets must have been based on calculations made by earlier DMI staff. Cross-checking the monthly data with original observational series published by *Östergaard et al.* [1856] clearly indicates that only months having gaps of a maximum of 4 observation days were used for the monthly means. Further, all months not being 100% complete were clearly marked in the monthly mean tables. From comparison with the original observations it is also clear that the monthly mean temperatures were all calculated to conform with the standard formulae (1) used in the Yearbooks of DMI (see previous section). Temperature series based on observations not in agreement with Yearbook standard observation hours had all been corrected, probably using the Greenland diurnal cycle standards derived during the second German Polar Expedition. The earlier staff at DMI who prepared the monthly mean sheets available at the CRU had therefore gone to great lengths to ensure that the pre-1873 data conform with the Yearbook data.

3. Homogeneity of the Temperature Records

[15] A number of circumstances can lead to non-climatic shifts in temperature records. The most important include changes in station location or instrumentation, changes in observation methods and observation hours, and changes in the surrounding environment (such as urbanization).

[16] The Greenland data in the recently released NARP data set [*Laursen*, 2003a, 2003b; *Cappelen et al.*, 2005], as well as the supplemental data set released by *Cappelen et al.* [2001], have been subjected to a high level of quality control. Given that the NARP and NACD data sets did not include the observations digitized especially for this study, it was decided to check data for homogeneity for the complete period from 1784–2005, exploiting the many overlapping records.

3.1. Correcting Inhomogeneities

[17] To check for inhomogeneities, intercomparisons between temperature series from neighboring stations were carried out. Statistical homogeneity tests have already been applied to the bulk of the temperature data during the NACD and NARP efforts, hence it was decided to ascertain homogeneity by visually inspecting plots of normalized temperature differences between stations. To enable later verification of the homogeneity of the series, the station data were divided into three groups (see Figure 1) and comparisons were carried out only within each group of stations. This ensures that the resulting series from each of the 3 groups are independent of the other groups allowing later verification of homogeneity between the individual group records. Using this methodology, three series were found to contain unresolved homogeneity problems: the series for Ilulissat, Ivittuut and Qaqortoq.

3.1.1. Ilulissat

[18] Comparing the Ilulissat series to neighboring stations, three homogeneity problems were discovered. A station relocation and change of observer from November 1936 to August 1946 [*Laursen*, 2003a] led to artificially low Ilulissat temperatures during this period (revealed by comparing with Qeqertarsuaq, Upernavik and Uummannaq

Table 3. Monthly Corrections (°C) Applied to Ivittuut Data Sets, to Form a Homogeneous Series

Period	Data Set	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1880/01–1889/12	GHCN	34262	0.0	0.0	−0.4	−0.7	−1.2	−1.2	−1.2	−1.2	−0.5	0.0	0.0	0.0
1890/01–1920/12	NACD	34262	0.0	0.0	−0.4	−0.7	−1.2	−1.2	−1.2	−1.2	−0.5	0.0	0.0	0.0

Table 4. Monthly Corrections (°C) Applied to Qaqortoq Data Sets, to Form a Homogeneous Series

Period	Data Set	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1880/10–1892/04	Yearbooks	04272	−0.2	−0.2	−0.6	−0.6	−1.0	−1.3	−1.3	−1.3	−1.1	−0.4	−0.4	−0.2

data). As mean monthly minimum and maximum temperatures have been routinely recorded at the Ilulissat station, it was possible to use the Ilulissat monthly average of these measures to establish the offset and correct the Ilullisat mean temperature data.

[19] Both in January 1961 and in August 1966 changes in observation hours took place at the new Ilulissat synoptic station [*Laursen*, 2003a]. Fortunately the old Ilulissat thrice daily observations overlap those from the synoptic station during the period from January 1956 to October 1971. It was therefore possible to use the data from the old station from January 1956 to July 1966, and calculate the monthly offset between the two stations using the period from August 1966 to October 1971. Compared to the NARP data set [*Laursen*, 2003b], the largest changes in the Ilullisat series occurs during summer months, with almost no changes evident during winter months. This is due to the fact that there is no discernible diurnal cycle in Greenland winter temperatures (see Figure 3), hence Greenland winter temperature estimates are very robust with respect to inhomogeneities arising from changes in observation hours. Corrections applied to the Ilulissat data are shown in Table 2.

3.1.2. Ivittuut

[20] A single inhomogeneity was identified in the Ivittuut series. In January 1921, a change in observation hours took place [*Laursen*, 2003a] as the evening observations were carried out one hour later from 1921 and onwards. Delaying the evening observation leads to a significant cooling of the measured evening temperature during summer, hence the pre-1921 data had to be corrected downwards to conform with later observations (see Table 3). The corrections were derived through comparison with records from Nanortalik and Qaqortoq. Again, it is the change in observation hours and the summer diurnal cycles that are responsible for the shift in mean temperature. As there is no diurnal temperature cycle during winter months, no corrections were necessary for the months from October to February.

3.1.3. Qaqortoq

[21] Comparison against Ivittuut and Nanortalik temperatures revealed that the Qaqortoq record had elevated temperatures before April 1892. The sparse metadata in the DMI Yearbooks (from which the 1881 to 1939 Qaqortoq record was digitized) reveals that a change in instrumentation and observer took place after April 1892. As there is a gap of a couple of years in the Qaqortoq observation series after April 1892, it is quite possible that the observation site changed as well. The correction pattern in Table 4 (large corrections during summer, small corrections during winter) also suggests that a change in observation hours took place. There is, however, no evidence for this in the Yearbooks. Corrections were calculated through comparison with Nanortalik and Ivittuut data.

3.1.4. Pre-1873 Observations

[22] To assure continuity, adjustments were made to all the pre-1873 data, in accordance with corrections imposed on the earliest post-1873 data (see Table 5), under the assumption that the pre-1873 data are most similar to those in the earliest post-1873 period.

[23] After this adjustment, no clear discrepancies were found between temperature series before and after 1873. It should, however, be noted that periods of overlap between data before 1873 are very few and last only for a few months to a few years in some cases, so that it is generally difficult to asses in a statistically robust sense, whether small inhomogeneities are still present. Only marked outliers can therefore be identified within the pre-1873 data. Further scrutiny of these data was therefore deferred to the later step of verification, involving the inter-group series comparison.

3.1.5. Discarded Observations

[24] It was decided to leave out a few periods of inhomogeneous observations from four of the stations (periods left out are not shown in Figure 2). These observations were for different reasons difficult to homogenize. As homogeneous series were available from other stations, the apparent risk of introducing inhomogeneities was considered to outweigh the possible benefit of including the observations. A short description of the problems follows.

[25] The Upernavik station moved in January 1987. Comparisons with Ilulissat and Aasiaat suggest that an inhomogeneity remains in the Upernavik record despite corrections applied to the Upernavik series in the NARP data set. All post-1986 data from Upernavik were discarded.

[26] The Uummannaq station was relocated (without any overlapping observations) in January 1957. Therefore all post-1956 data were left out. The station closed in 1989.

[27] The Qeqertsuaq station changed observation hours and location in 1961 (no overlap), hence all post-1960 data were discarded. The station closed in 1980.

Table 5. Monthly Corrections (°C) Applied to the pre-1873 Observation Series

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qaqortoq	−0.2	−0.2	−0.6	−0.6	−1.0	−1.3	−1.3	−1.3	−1.1	−0.4	−0.4	−0.2
Nuuk	−0.1	0.0	−0.1	−0.2	−0.3	−0.6	−0.4	−0.1	−0.1	−0.1	−0.1	−0.1
Ilulissat	0.1	0.2	0.8	0.7	0.6	0.1	0.1	0.3	0.5	0.2	−0.3	0.1

Table 6. Mean Monthly Correlations Between Observed and Regressed Values in the (Variable) Regression Period

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qaqortoq	0.96	0.97	0.98	0.90	0.87	0.90	0.85	0.83	0.88	0.92	0.94	0.95
Nuuk[a]	0.94	-	0.94	0.95	0.95	-	-	-	-	-	0.92	0.95
Ilulissat	0.97	0.97	0.93	0.94	0.81	0.87	0.83	0.80	0.87	0.86	0.91	0.94

[a]For some of the months, no infilling was carried out in the Nuuk record.

[28] Temperature at Iviituut was only measured once a day from January 1873 to December 1879 [*Laursen*, 2003a], and so this period was not used.

4. Three Long Greenland Temperature Series

[29] For each of the three groups of station records, a combined temperature series was created. The combined series were developed by choosing a single master record and then filling in the gaps in this record through linear regression with the neighboring temperature series. When selecting the master record, two criteria were used: the observation site should still be active, and the record should be as complete as possible. This allows the three new records to be easily updated, and minimizes the amount of infilling necessary. The records found to best meet these criteria were the series from Qaqortoq, Nuuk and Ilulissat. These stations are underlined in Figure 1.

[30] The regressions are generally more significant for winter as opposed to summer months. Typical correlations between regressed estimates and observations are r = 0.94–0.97 during winter and r = 0.80–0.90 during summer (see Table 6); sufficient to make the regression approach valid.

[31] Winter, summer as well as annual temperature averages for the infilled Qaqortoq, Nuuk and Ilulissat temperature records are shown in Figures 4, 5, and 6, respectively. It can be clearly seen in all series that winter temperatures are much more variable than those in summer. It is also evident that the record from the northern station of Ilulissat is more variable than the records for Qaqortoq and Nuuk.

4.1. Verification of the Series

[32] Having independently created three long Greenland temperature series, a final homogeneity check is possible by comparing the three new series. Before comparison all monthly temperature series were normalized to have the same variance. Summer, winter and annual averages were used to create difference plots for Nuuk and Qaqortoq (Figure 7), Nuuk and Ilulissat (Figure 8) and Qaqortoq and Ilulissat (Figure 9). These figures indicate that there are no apparent inhomogeneities remaining in the three series. The apparently anomalous 1917 winter difference in Figure 8 is related to a very warm Nuuk winter and is probably an effect of both sea ice extent and the more inland position of the Ilulissat observation site. The warmth of the 1917 Nuuk winter is supported by the parallel series from the nearby Qornoq station.

[33] With respect to the pre-1873 data, it is reassuring that all difference values in the (albeit few) overlapping sections are within the range spanned by post-1873 difference values. It is still possible that the pre-1873 data are not perfectly homogeneous, as the sparse difference data would only allow inhomogeneities of about one standard deviation (corresponding to 1.2°C for Qaqortoq and Nuuk and 1.7°C for Ilulissat annual temperatures) to be detected. It is, however, encouraging that no such spurious inhomogeneities can be found before 1873.

5. A Merged Greenland Temperature Record

[34] To obtain a Greenland temperature record containing as few gaps as possible, it is tempting to merge the three long Greenland temperature series into one common record. Before any such merging can be carried out, it is necessary to investigate if the three series contain a dominant common signal, as merging significantly different climatic records is not appropriate.

[35] Assuming that the records consist of a common regional climatic signal and uncorrelated local climatic noise, the variance (v_i) of the record i can be written as:

$$v_i = s_i + n_i \tag{2}$$

where s_i and n_i represent the variances of the signal and noise respectively. The mean signal-to-noise variance ratio

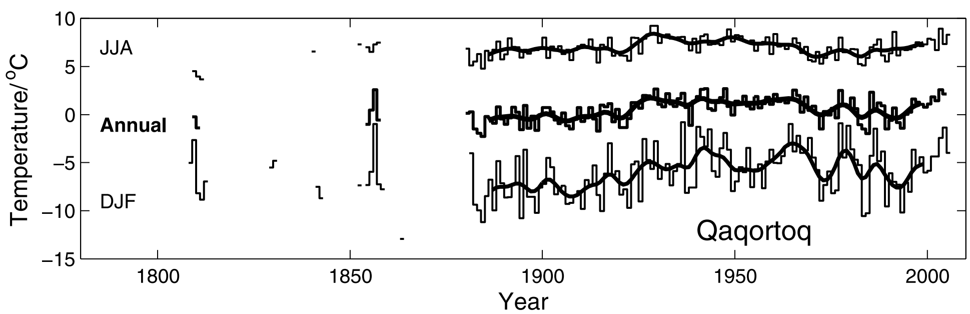

Figure 4. Summer, annual and winter temperatures for Qaqortoq. Thick lines are decadally filtered data. Gaps in the Qaqortoq observation series have been in filled with regression estimates based on data from neighboring stations whenever possible.

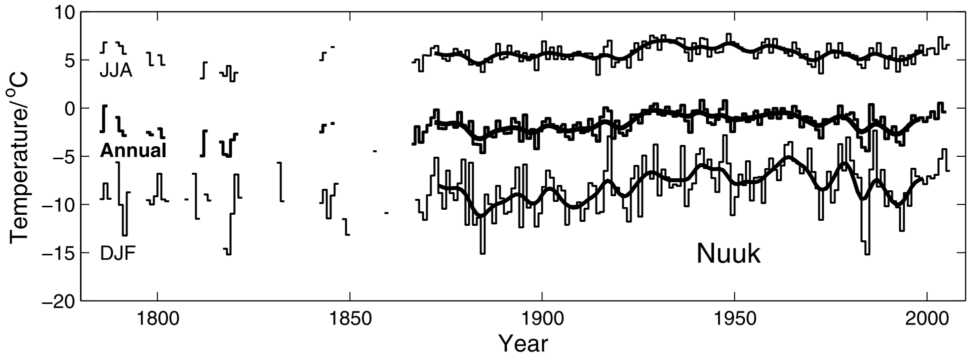

Figure 5. Summer, annual and winter temperatures for Nuuk. Thick lines are decadally filtered data. Gaps in the Nuuk observation series have been in filled with regression estimates based on data from neighboring stations whenever possible.

(SNR) of the (N = 3) series can then be calculated as [*Johnsen et al.*, 1997] (derivation in Appendix A):

$$SNR = \frac{\overline{s_i}}{\overline{n_i}} = \frac{v_A - \frac{1}{N}\overline{v_i}}{\overline{v_i} - v_A} \quad (3)$$

[36] Here overbars represent averages and v_A is the variance of the record obtained by averaging all the N = 3 data series. SNR for each month of the year for the three series is given in Table 7. It can be seen that the three temperature series contain strong common signals during all months of the year. The winter months have SNRs larger than 5, while summer months generally have SNRs between 1.5 and 3.

[37] The strong common signals for all months of the year in the three temperature series, justify the merging of the series into one master record. As the three series have different variances (the northerly temperature observations being more variable than the southern observations) it was decided to normalize the series before merging, to avoid a northerly bias.

[38] The merged series was constructed as the average of the three normalized series. As different months in the merged record can consist of averages of 3 or 2 series, or simply the value taken from one of the series, it is necessary to "variance correct" the merged series [*Osborn et al.*, 1997; *Jones et al.*, 2001]. The correction (c) necessary to offset the effect of the changing number of contributing series can be expressed in a simple manner in terms of the SNR and the number of available series M, for a given month (derivation in Appendix A):

$$c = \sqrt{\frac{SNR}{SNR + \frac{1}{M}}} \quad (4)$$

[39] Multiplying all monthly values in the merged series by c, the record is adjusted to produce a series whose variance relates to one based on an infinite sample replication, corresponding to the particular signal-to-noise ratio SNR. The expression is equivalent to the methodology described by *Jones et al.* [2001] if all series are normalized, i.e., v_i = 1 for all i (see Appendix A).

[40] The average of monthly standard deviations and means for Ilulissat, Nuuk and Qaqortoq were finally used to scale the variance-corrected series back to an average temperature record. The merged and variance-corrected Greenland temperature record is presented in Figure 10. It is seen that winter and spring seasons have few gaps, while the summer and autumn series are patchy before 1840. Only 15 winters are absent between 1784 and 2005, all of them before 1829.

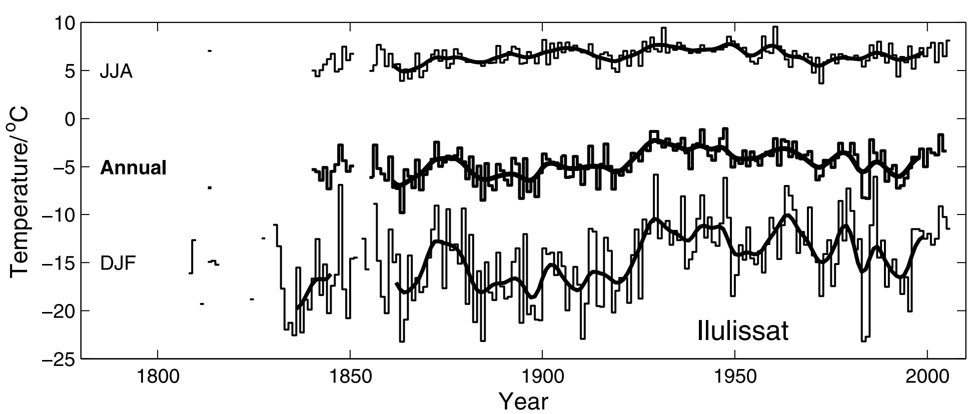

Figure 6. Summer, annual and winter temperatures for Ilulissat. Thick lines are decadally filtered data. Gaps in the Ilulissat observation series have been in filled with regression estimates based on data from neighboring stations whenever possible.

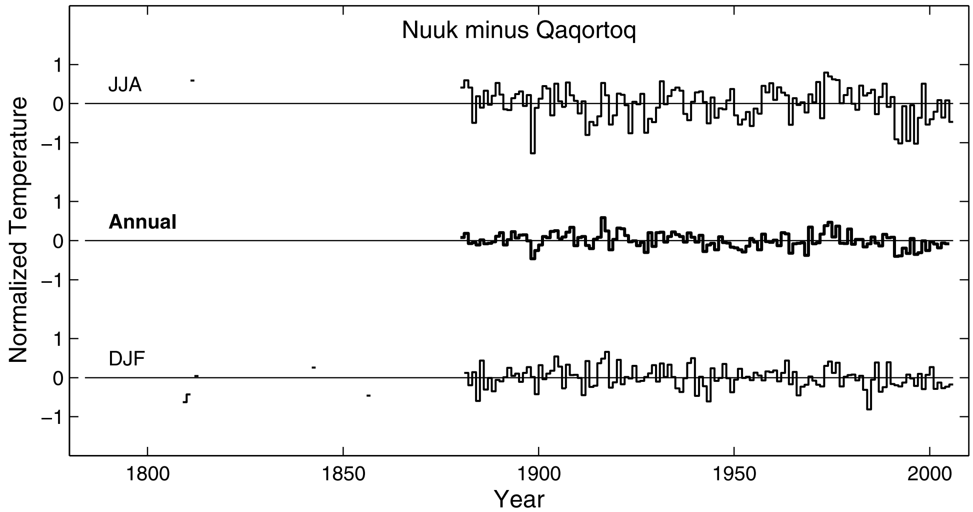

Figure 7. Difference between normalized temperature in the Nuuk series and normalized temperature in the Qaqortoq series.

[41] The warmest year in the merged record is 1941, while the 1930s and 1940s are the warmest decades (Table 8). The coldest year is 1863, while two cold spells (1811 and 1817–18) make the 1810s the coldest decade (Table 8 and Figure 10). The marked cool periods in 1811 and 1817–18 follow two large volcanic eruptions in ~1809 (unidentified) and 1815 (Tambora). The coolings after the two eruptions are in line with the general observation of *Box* [2002] (based on post-1873 observations), that western Greenland cools in response to large volcanic eruptions.

6. Discussion

[42] The main concern with regard to the extended Greenland temperature record is the homogeneity of the pre-1873 data. It would therefore be prudent to compare the extended record to other nearby temperature records that reach as far back in time. Unfortunately no such data are presently available.

[43] The second-best option is to look for relevant proxy records for comparison, and in fact an annually resolved ice core based southern Greenland winter temperature index is readily available for comparison [*Vinther et al.*, 2003]. The $\delta^{18}O$-based ice core winter temperature index was reported to be highly correlated (r = ~0.7) with Greenland south and west coast (Ivittuut and Nuuk) December–March temperatures for the 1895 to 1966 period. The last year in the index is 1970, and it is based on 7 ice cores: 6 from the southern half of the Greenland ice sheet and one from the Renland ice cap, which is situated in eastern Greenland. Hence running 30-year correlations were calculated between the *Vinther et al.* [2003] ice core data and December–February, respectively, December–March averages of the merged Greenland temperature series (see Figure 11). The running correlations are remarkably stable, consistently above the 99% significance level for all 30-year periods. The running correlations are highest in the early period of the data set, suggesting that the winter temperatures in the pre-1873 data

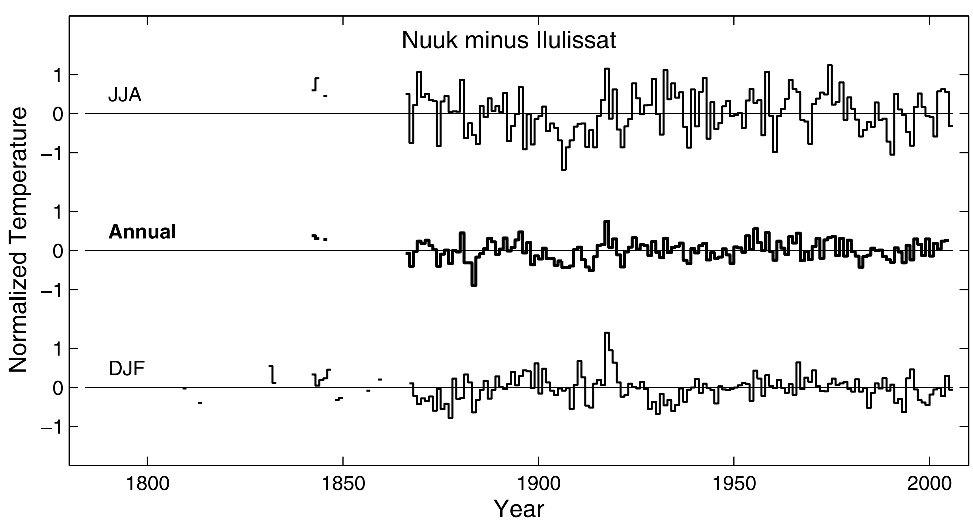

Figure 8. Difference between normalized temperature in the Nuuk series and normalized temperature in the Ilulissat series.

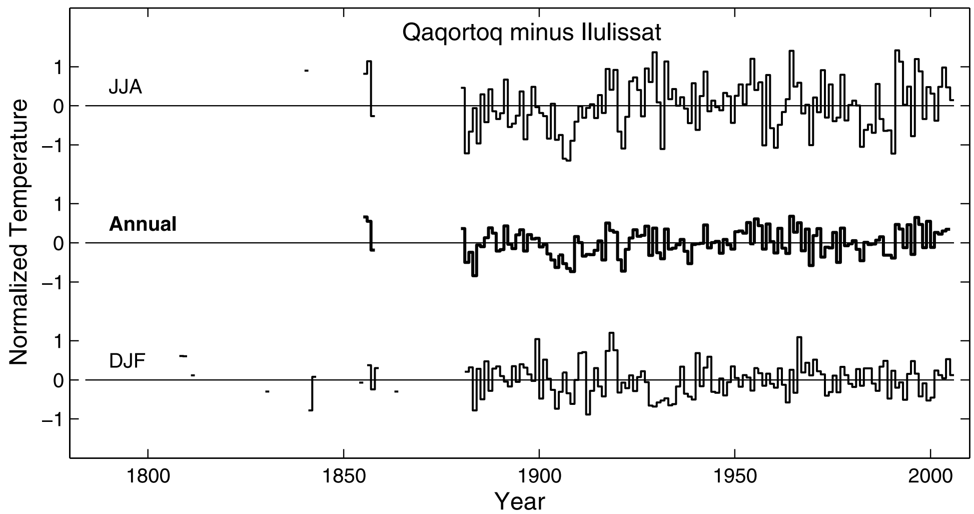

Figure 9. Difference between normalized temperature in the Qaqortoq series and normalized temperature in the Ilulissat series.

are very robust. The fact that correlations for the 1784–1872 and 1873–1970 periods (for December–March temperatures) are r = 0.67 and r = 0.60 respectively, further strengthens that perception.

[44] It should also be mentioned that the extraordinary stability of the running correlations in Figure 11 is a clear verification of the dating of the ice core series, which must be exact in order to achieve this level of consistency.

[45] As has been shown, the winter temperature observations are much more robust with respect to inhomogeneities than the summer data. Furthermore it can be seen from Figures 4, 5, and 6 that Greenland summer temperatures are much less variable than the winter temperatures, making even relatively small inhomogeneities significant.

[46] Unfortunately, annually resolved proxies for Greenland summer temperatures have still to be derived from Greenland ice cores. Furthermore, a preliminary investigation into a small number of Greenland ice core records does suggest that summer season $\delta^{18}O$ is generally more sensitive to regional-scale changes in sea surface temperatures south of Iceland and in the Greenland and Norwegian Seas rather than to the (relatively small) variations in summer temperature along the west Greenland coast. This is consistent with the fact that summertime atmospheric cyclogenisis is generally much more erratic and disorganized compared to the more persistent regional-scale wintertime circulation.

[47] The nearest temperature observations are from the Icelandic site at Stykkisholmur, still far away from southwest Greenland. Having no better option, a comparison with Stykkisholmur temperature data [*Jónsson*, 1989] was carried out despite its remote location.

[48] In Figure 12, winter, summer and annual differences between normalized temperatures in the merged Greenland record and in the Stykkisholmur series are presented back to the start of the Stykkisholmur record (1830). It is encouraging that no significant trends or spurious values can be seen for the oldest summer data. An increase in variability does however suggest a slight decrease in the accuracy of the oldest Greenland (or the Icelandic) summer data. The 1881 peak in winter difference is driven solely by 1881 being the coldest winter (by far) on record for Stykkisholmur.

7. Conclusion

[49] Using old temperature observations from early observers, the existing Greenland temperature records have been extended back to the year 1784. Gaps remain, mostly during summer and autumn. In the process of creating the long record, a few inhomogeneities were identified and corrected. Most of the homogeneity problems were due to changes in the hours at which temperature observations were carried out.

[50] Comparison against winter season ice core proxy data showed stable and highly significant correlations throughout the period covered by the extended Greenland temperature series. This marked consistency, r = 0.67/0.60 for the extended/existing data, shows that both the ice core data and the extended temperature series are very robust.

[51] The warmest year in the extended Greenland temperature record is 1941, while the 1930s and 1940s are the warmest decades. Two distinct cold periods, following the 1809 ("unidentified" volcanic eruption and the eruption of Tambora in 1815 make the 1810s the coldest decade on record.

8. Online Data Access

[52] The merged Greenland temperature record as well as the three long series from Ilulissat, Nuuk and Qaqortoq can

Table 7. Monthly Signal-to-Noise Variance Ratios (SNRs) for the Three Long Greenland Temperature Series (Period 1880 to 2004)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6.3	7.2	4.7	3.0	3.0	2.9	1.6	2.5	3.3	3.8	5.4	5.8

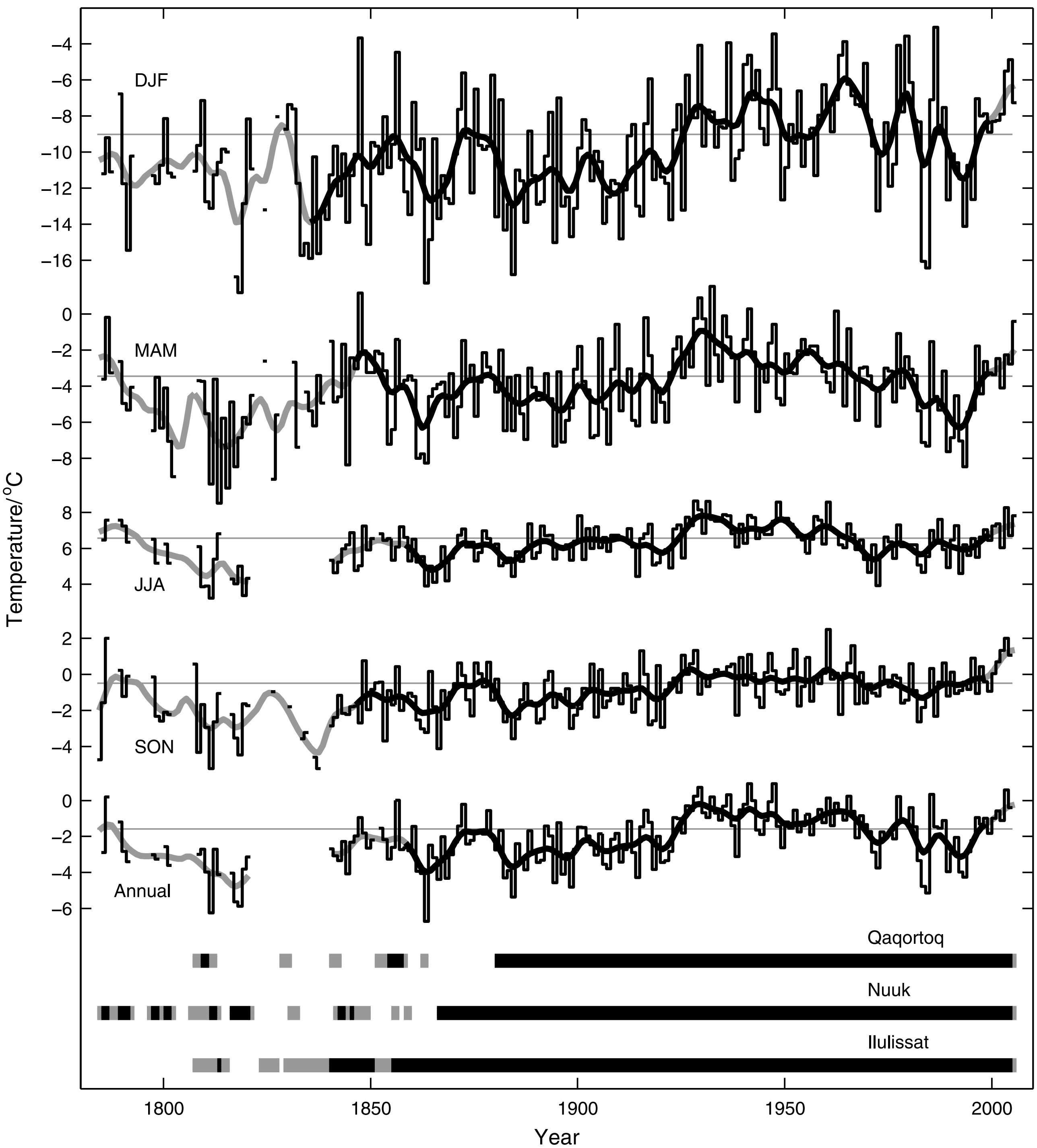

Figure 10. Seasonal and annual Greenland temperatures merging the long Qaqortoq, Nuuk and Ilulissat records. Thick lines are decadally filtered data (lines are grey if the filtered data are based on incomplete data). Thin grey lines give twentieth-century average temperatures. Data coverage for each of the three records is shown at bottom of the figure. Black bars indicate complete observations, and a grey bar indicates incomplete observation years.

Table 8. Decadal Merged Greenland Temperatures[a]

Decade	Annual, °C	DJF, °C	MAM, °C	JJA, °C	SON, °C
1811–20	(−4.4)	(−13.1)	(−7.1)	(4.6)	2.8
1821–30	-	-	-	-	-
1831–40	-	−12.3	(−4.5)	-	-
1841–50	−2.5	−10.1	−3.2	5.8	−1.6
1851–60	(−2.1)	−9.4	−3.7	(6.3)	−1.3
1861–70	−3.6	−11.8	−5.6	5.0	−1.9
1871–80	−1.7	−9.1	−3.5	6.3	−0.4
1881–90	−3.3	−11.7	−4.6	5.6	−2.0
1891–1900	−2.9	−10.9	−4.6	6.4	−1.5
1901–10	−2.6	−11.1	−4.4	6.4	−1.0
1911–20	−2.4	−9.9	−4.0	6.1	−1.1
1921–30	−1.1	−8.4	−2.1	6.9	−0.1
1931–40	−0.8	−8.0	−2.1	7.3	−0.1
1941–50	−0.8	−7.2	−2.8	7.4	−0.3
1951–60	−1.1	−8.4	−2.5	7.0	0.1
1961–70	−1.0	−6.9	−3.1	6.3	−0.4
1971–80	−1.7	−8.6	−3.6	6.0	−0.6
1981–90	−2.5	−10.1	−5.2	6.0	−0.9
1991–2000	−2.1	−10.3	−4.6	6.3	−0.4

[a]Numbers in parenthesis are based on at least 8 or 9 years/seasons.

be downloaded from http://www.cru.uea.ac.uk and http://www.icecores.dk.

Appendix A

[53] *Johnsen et al.* [1997] presented a formula for calculating the mean single series signal-to-noise variance ratio (SNR) having $N \geq 2$ data series, but offered no derivation of the expression. Here the *Johnsen et al.* [1997] formula is derived and extended to cover the subject of variance correction [*Jones et al.*, 2001] as well.

[54] The basic assumption is that N data series with variances (v_i) are available. Each series contains a signal with variance s_i and some noise (uncorrelated with the signal) with variance n_i:

$$v_i = s_i + n_i \tag{A1}$$

The noise in each series is assumed to be independent, random and white, while the signal is assumed to be identical for all series.

[55] Defining the mean noise and signal variances of the series as:

$$\overline{n_i} = \frac{1}{N}\sum_{i=1}^{N} n_i \qquad \overline{s_i} = \frac{1}{N}\sum_{i=1}^{N} s_i \tag{A2}$$

the following expression for the mean variance of the series $\overline{v_i}$ can be obtained:

$$\overline{v_i} = \frac{1}{N}\sum_{i=1}^{N} v_i = \frac{1}{N}\sum_{i=1}^{N}(s_i + n_i) = \overline{s_i} + \overline{n_i} \tag{A3}$$

[56] Now using the N series, it is possible to create an average record. As the signals in all the series are the same, while the noise in each series is uncorrelated, the variance of the average record (v_A) is given by:

$$v_A = \overline{s_i} + \frac{1}{N}\overline{n_i} \tag{A4}$$

[57] Using (A3) and (A4), it is possible to obtain the following expression for the mean single series signal-to-noise variance ratio (SNR):

$$SNR = \frac{\overline{s_i}}{\overline{n_i}} = \frac{v_A - \frac{1}{N}\overline{v_i}}{\overline{v_i} - v_A} \tag{A5}$$

This is identical to the expression for SNR given by *Johnsen et al.* [1997] (except for a printing error in that paper).

[58] In the following, we will consider a merged record consisting of values that are obtained through averaging a varying number (N) of series. It is evident from (A4) that the variance of such a record will be dependant on N. To

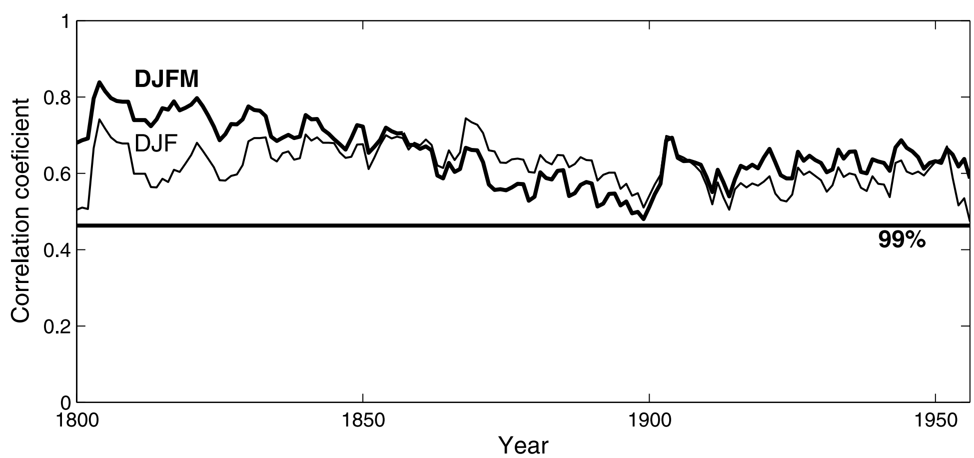

Figure 11. Running 30-year correlations between December–February/December–March averages of the merged Greenland temperature record and the southern Greenland winter temperature index derived from winter season ice core δ^{18}O. The 99% significance level for 30-year correlations is indicated by the straight line.

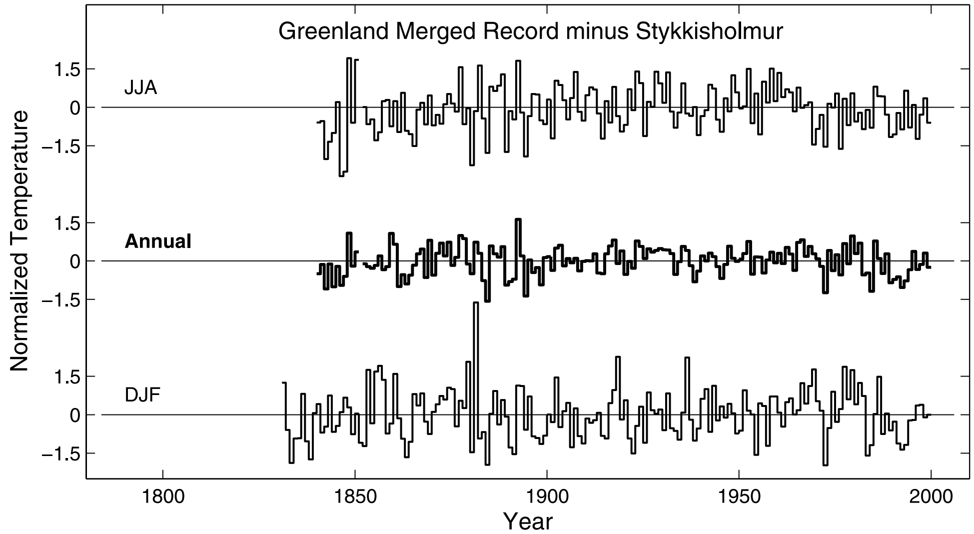

Figure 12. Difference between normalized temperature in the merged Greenland record and normalized temperature in the Stykkisholmur series.

overcome this, *Jones et al.* [2001] suggested the approach of correcting each value in the merged record to the infinitely sampled case (i.e., $N \rightarrow \infty$). The variance (v_∞) of the average of an infinitely replicated series is seen from (A4):

$$v_\infty = \overline{s_i} \tag{A6}$$

[59] Hence the correction (c) to be applied to a value based on an average of N series is given by:

$$c^2 = \frac{v_\infty}{v_A} = \frac{\overline{s_i}}{\overline{s_i} + \frac{1}{N}\overline{n_i}} = \frac{1}{1 + \frac{1}{N}\frac{n_i}{s_i}} \tag{A7}$$

[60] Multiplying numerator and denominator by SNR, the final expression of c only in terms of SNR and N is obtained:

$$c = \sqrt{\frac{SNR}{SNR + \frac{1}{N}}} \tag{A8}$$

[61] If all series are normalized ($v_i = 1$ for all i) it turns out that c is equivalent to the correction factor described by *Jones et al.* [2001]. The *Jones et al.* [2001] paper finds the following formulae for c:

$$c = \sqrt{\frac{N\overline{r}}{1 + (N-1)\overline{r}}} \tag{A9}$$

where $\overline{r}$ is the mean correlation between the series.

[62] In the following the equivalence of (A8) and (A9) will be shown. The correlation (r_{ij}) between two series i and j can be expressed as:

$$r_{ij}^2 = \frac{v_{ij}^2}{v_i v_j} = \frac{\left(v_{i+j} - \left(v_i + v_j\right)\right)^2}{4\overline{v}^2} \tag{A10}$$

[63] Here v_{ij} is the covariance between the two series, v_{i+j} is the variance of the sum of the two series and the overbar signifies an average as in (A3). Note that it is assumed that the variances are normalized and therefore of the same magnitude, i.e., $v_i = v_j = \overline{v}$.

[64] Expanding v_i, v_j and v_{i+j} into variances of signal and noise (A10) takes the form:

$$r_{ij}^2 = \frac{\left(2\left(s_i + s_j\right) + n_i + n_j - \left(s_i + n_i + s_j + n_j\right)\right)^2}{4\overline{v}^2} \tag{A11}$$

where the signal-terms are perfectly correlated and the noise-terms are uncorrelated, both to each other and to the signal-terms. Equation (A11) can thereafter be reduced to:

$$r_{ij} = \frac{s_i + s_j}{2\overline{v}} \tag{A12}$$

[65] The average correlation ($\overline{r}$) (as defined by *Briffa and Jones* [1990]) can then be derived using (A12):

$$\overline{r} = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} r_{ij} = \frac{\sum_{i=1}^{N} s_i}{N\overline{v}} = \frac{\overline{s}}{\overline{v}} \tag{A13}$$

Note that in the above the following summation relation has been used:

$$\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} s_i + s_j = (N-1) \sum_{i=1}^{N} s_i \tag{A14}$$

[66] This is easily seen to hold, because the left hand side summation is simply a sum over all elements in the lower half (not including the diagonal) of the $N \times N$ matrix with entries $s_i + s_j$. Equation (A13) can be rewritten in terms of SNR:

$$\overline{r} = \frac{\overline{s}}{\overline{v}} = \frac{\frac{\overline{s}}{\overline{n}}}{\frac{\overline{s}+\overline{n}}{\overline{n}}} = \frac{SNR}{SNR + 1} \tag{A15}$$

[67] A relationship that was also derived by *Wigley et al.* [1984] in a slightly modified form (SNR in that study was defined for the average record, i.e., N times the SNR used here). Inserting (A15) into (A9), (A8) is readily derived.

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