FOURTH SEMINAR FOR HOMOGENIZATION AND QUALITY CONTROL IN CLIMATOLOGICAL DATABASES

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Preface

The Hungarian Meteorological Service has the honour fourth time to organize the Seminar on Homogenization and Data Quality Control. Since the First Seminar it has been changed a lot.

The Third IPCC Assessment Report states, that there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. WMO issued a Press Release about the extreme events. By this paper the extreme weather events might increase. These statements show, that the changeability of climate is higher than it was earlier. It means, that our measurements, observations have to be more accurate, than earlier. Even this time, a large change in the observing system is going on due to the economical necessity and technical development. The human work is redistributed, it is reducing on the observational area (automatization), and growing on the modelling and computing parts of the meteorology.
Recently, WMO issued a statement on the occasion of the opening of the World Climate Change Conference (WCCC). In this statement declared, that the WMO's system ensures the standardization and archiving of meteorological and hydrological data and products. This should be extended to cover data from other data gathering programmes. During this Conference it became clear, that there is a large development on the field of modelling which is not accompanied by the development of similar size on the field of data management.
By our opinion, the lag in the data management area will set back the development of modelling, because of lower quality of data and time series can not assure the requested level for parametrization of processes and evaluation of model results. Decisions will be made established on model results, and the shortcomings of the mentioned processes can seriously influenced the final outcome.
We believe, that a standardization, or at least a comparability is essential in the data management methods. WMO made a good start by establishing of expert groups. This process has to be continued. This seminar will be hopefully a small addition on the long way we have to do.
We are grateful for the support of the World Meteorological Organization and the Hungarian Meteorological Service making possible the organization of this meeting. The success of the Fourth Seminar is thanks to the contributions of the participants, whose active work helped to reach the results can be read in this volume.

Sándor Szalai

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OPENING ADDRESS AT THE FOURTH SEMINAR FOR HOMOGENIZATION AND QUALITY CONTROL IN CLIMATOLOGICAL DATABASES

By

Dr. Iván Mersich

President of the Hungarian Meteorological Service

Dr. Yadowsun Boodhoo, President of the Commission for Climatology,
Dear Participants,
Ladies and Gentlemen,

It is a great pleasure for us to host for the fourth time the Seminar for Homogenisation. The highlights of the meeting have been enlarged; as new parts, the data quality control procedures appeared at the third Seminar. The possible climate change, the origin of the global warming became one of the most important questions of the environment, and our future. We can not answer these questions without good measurements, well established database.

Unfortunately, there is not enough resources spent for the development in this field and we can recognize the lack of necessary international co-operation. WMO supports this seminar, and established a small group for writing the basis of a guidance, but many countries prefer their own way for both the homogenisation and data quality control. And what we have as a result? We have national databases, which quality procedures had not been compared, and consequently, the managed data could have contain different from the natural tendencies.

How can we find a way out of this problem? The basic activity should be done in the frame of an expansive project, where the strict mathematical and climatological reliability has to be controlled, and the accepted methods have to be compared and guided. Otherwise, the solution of this problem will be shifted, and appropriate database will fail for the modelling community.

The modelling is one of the best way to learn our future, but it badly requests good data for verification. Verification based on a not (good) controlled database could lead to false results of modelling, and not appropriate decision of the fundamental problems of the economy.
We have some other, very often mentioned, but still not solved problems. I have to mention here on the first place the automation, which changes the methods of observation, but very often the observed parameter, too. This problem exists already ten years, but still exists. As a next problem, I can mention the homogenisation of the daily data. We have several better or worse methods for homogenisation of monthly or yearly data, but very few methods for daily data. The homogenisation of extreme events is also a problem, and I could continue this series for a quite long time.

I have not yet spoken about the interactions of the different statistical methods applied in the climatology. I give a simple example: the possible use of spatial interpolation in the homogenisation, and the request for the homogenised time series for interpolation purposes shows, that in the most simple case, these algorithms request a common management.

I told you last time, that the meteorological community needs your effective work to improve the homogenisation and data quality control procedures. Now, I have to say, that not only the experts, but the whole humankind have a live interest for the analysis of good time series, which could give answers to very important questions. And you can give a substantial contribution in this process.

Therefore, I would like to wish you success with your work, and a beneficial meeting here at the Hungarian Meteorological Service.

Thank you for your attention.

OPENING SPEECH AT THE FOURTH SEMINAR ON HOMOGENISATION OF CLIMATE DATA SERIES

By

Yadowsun Boodhoo

President of Commission for Climatology

Dr Mersich, Dr Szalai, Colleagues

It gives great pleasure to attend the Conference on Homogenisation of Climate Data Series in Budapest. I must seize the opportunity to congratulate the Hungarian Meteorological Services for keeping up with the tradition of organizing this type conference which is the fourth of the series.

WMO Congress which convened last May/June in Geneva advised all its Members to carefully collect, archive and analyse their climate data. These data can only yield reliable if the collection has been done in a systematic way and the data homogenized for inconsistencies.

Climate data has emerged as an important commodity which can even be traded. It is increasingly utilized by planners and policy-makers to decide developmental policies . But it is even more important in assessing the climate itself. As we all know, WMO has, in collaboration with UNEP, sponsored the IPCC. This and other UN organizations are engaged in the monitoring of climate, its variability and change because these factors go even as far as determining the survival of many nations. For example, global warming by even half a degree taken globally over a whole decade is significant. But if climate data is not collected systematically and correctly, this half degree change will become so common that scientist will have difficulties in deciding whether to attribute it to global warming or to errors in measurement.
However, homogenization of climate data is not within the reach of all WMO Members. It is therefore essential that you, as experts, help in devising guidance material which will assist Members to decide on homogenisation methods and procedures. Such an exercise has been started by the Commission_s appropriate Expert Team. Your contribution and the outcome of this seminar will help further consolidate the work of this Team.

So I wish you success in your task.

Thank You.

SOMETHING LIKE AN INTRODUCTION

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INTRODUCTION

In general the topics such as the data quality control, homogenization, spatial interpolation, examination of representativity of station networks and the (statistical) climate change detection are treated separately. However these topics form together a complex system. Another important question is to clarify the role of the meteorology, the mathematics and the software in managing of the above complex system.

1 SURFACE METEOROLOGICAL DATA AND TOPICS

The meteorological observing station networks are constantly changing.
To illustrate this problem the Fig. 1 is presented.

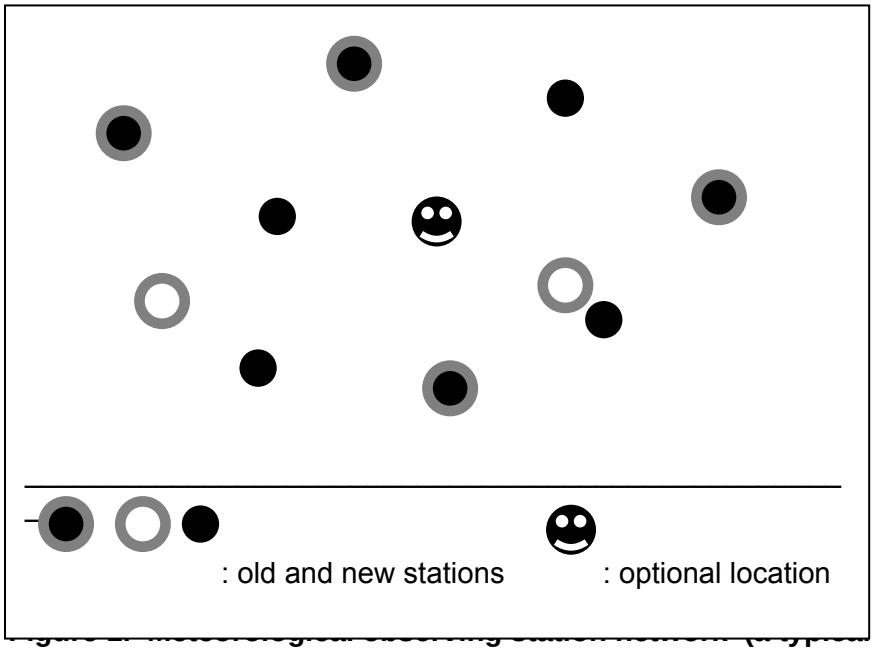


Figure 1. Meteorological observing station network (a typical situation)

○ : Closed Old Manual Station with Long Data Series,
(“Sample” in space and in time!)

● : New Automatic Station with Short Data Series

◉ : Closed Old Manual Station and a New Automatic Station
(“Sample” in space and in time!)

☺ : Optional Location without Data

The Statistical Parameters (e.g. expectation, standard deviation, correlation) can be estimated or modeled on the basis of the Sample ○ ◉ !!!

Meteorological Problems and Topics

Spatial Interpolation (Remark: the geostatistical methods are not recommended because these methods neglect the sample in time.)

Examination of Representativity of Station Network

Data Quality Control, Homogenization of Data Series

Climate Change Detection

Connection between the Topics

Spatial Interpolation

Necessary Condition: Homogeneous Data Series (“sample”)
Efficiency: depends on the Representativity of Station Network
Methodological Requirement: consideration of the possible Climate Change

Examination of Representativity of Station Network

Definition, Interpretation: can be based on the Spatial Interpolation
Necessary Condition: Homogeneous Data Series (“sample”)
Methodological Requirement: consideration of the possible Climate Change

Data Quality Control, Homogenization of Data Series

One of the Tools: Spatial Interpolation
Efficiency: depends on the Representativity of Station Network
Methodological Requirement: consideration of the possible Climate Change

Climate Change Detection

Necessary Condition: Homogeneous Data Series
Efficiency: depends on the Representativity of Station Network

2 STATISTICAL FORMULATION OF THE TOPICS

2.1 Additive Model of Data Series (e.g. temperature)

$$Z(\mathbf{s},t) = C(t) + E(\mathbf{s}) + D(\mathbf{s}) \cdot \varepsilon(\mathbf{s},t) \qquad \left(\mathbf{s} \in D\text{: space ; } t\text{: time} \right)$$

$C(t)$: climate change signal

$\varepsilon(\mathbf{s},t) \in \mathrm{N}(0,1)$: standard normal noise term

<u>Statistical parameters:</u>

Local parameters:

$E(\mathbf{s})$: expectations or spatial trend

$D(\mathbf{s})$: standard deviations

Stochastic connection:

$r(\mathbf{s}_1,\mathbf{s}_2) = corr(\varepsilon(\mathbf{s}_1,t), \varepsilon(\mathbf{s}_2,t))$: correlations

First: let us assume we have Long Observed Data Series:

$Z(\mathbf{s}_i,t)$ $\left(i = 1,...,M; t = 1,.....,n \right)$, sample in space and in time:

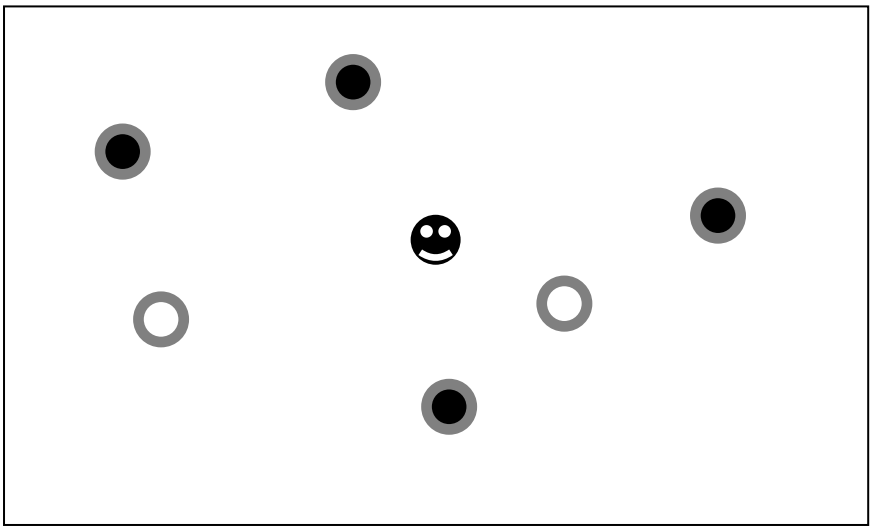


Figure 2. Meteorological observing stations with long data series

The general case that is we have old stations with long data series as well as new stations with short data series (see Fig. 1) will be discussed in Section 4.

2.2 Spatial Interpolation

<u>Predictand:</u> $Z(\mathbf{s}_0, t)$; <u>Predictors (stations):</u> $Z(\mathbf{s}_i, t)$ $(i = 1,..., M)$

<u>Additive Interpolation Formula:</u>

$$\hat{Z}(\mathbf{s}_0, t) = w_0 + \sum_{i=1}^{M} w_i \cdot Z(\mathbf{s}_i, t) \quad ,$$

where $\sum_{i=1}^{M} w_i = 1$, because of the **Climate Change** signal $C(t)$.

<u>Interpolation Error (RMSE):</u> $ERR(\mathbf{s}_0; \mathbf{w}, \mathbf{E}, \mathbf{D}, \mathbf{r})$
depends on the parameters: $\mathbf{w} = \{ w_i \mid i = 0,.., M \}$,
$\mathbf{E} = \{ E(\mathbf{s}_i) \mid i = 0,.., M \}$, $\mathbf{D} = \{ D(\mathbf{s}_i) \mid i = 0,.., M \}$, $\mathbf{r} = \{ r(\mathbf{s}_i, \mathbf{s}_j) \mid i, j = 0,.., M \}$

<u>The structure of the optimum solution (Optimum Interpolation, minimum error):</u>
Weighting factors w_i $(i = 0,..., M)$ depend on the statistical parameters $\mathbf{E}, \mathbf{D}, \mathbf{r}$

<u>Estimation or modelling of the Statistical Parameters</u> $\mathbf{E}, \mathbf{D}, \mathbf{r}$:
Statistical estimation if we have long data series for the predictand.
Modelling if we have no long data series for the predictand. ☹ (see Section 3.2)
Both statistical estimation and modelling can be based on the **Homogenized Data Series**:
$Z(\mathbf{s}_i, t)$ $(i = 1,..., M; t = 1,....., n)$

<u>Efficiency:</u>
The Optimum Interpolation Error $ERR(\mathbf{s}_0; \mathbf{D}, \mathbf{r})$ depends on the **Representativity of Station Network:** $\mathbf{s}_i$ $(i = 1,..., M)$

2.3 Examination of Representativity of Station Network

2.3.1 Spatial Interpolation inside the Network

Interpolation of $Z(\mathbf{s}_j, t)$: $\hat{Z}(\mathbf{s}_j, t) = w_{j,0} + \sum_{i \neq j} w_{j,i} \cdot Z(\mathbf{s}_i, t)$ $(j = 1,..., M)$

where $\sum_{i \neq 0, i \neq j} w_{j,i} = 1$, because of the **Climate Change** signal $C(t)$.

<u>Optimum Interpolation:</u>
Estimation of the Statistical Parameters on the basis of the **Homogenized Data Series**:
$Z(\mathbf{s}_i, t)$ $(i = 1,..., M; t = 1,....., n)$

Interpolation Error for Station $\mathbf{s}_j$: $ERR(\mathbf{s}_j)$ $(j = 1,..., M)$

Representativity Value for Station $\mathbf{s}_j$: $REP(\mathbf{s}_j) = 1 - \dfrac{ERR(\mathbf{s}_j)}{D(\mathbf{s}_j)}$ $(j = 1,..., M)$

The Interpolation Error and the Representativity Value depend on the interpolation method. The Optimum Interpolation method is recommended!
(See Section 3.1)

2.3.2 Spatial Interpolation for Optional Location $\mathbf{s}_0$ ☺

Optimum Interpolation:
Modelling of the Statistical Parameters on the basis of the **Homogenized Data Series**:
$Z(\mathbf{s}_i, t)$ $(i = 1,..., M; t = 1,....., n)$

Interpolation Error and Representativity Value for Location $\mathbf{s}_0$:

$$ERR(\mathbf{s}_0) \quad , \; REP(\mathbf{s}_0) = 1 - \frac{ERR(\mathbf{s}_0)}{D(\mathbf{s}_0)}$$

2.4 Data Quality Control, Homogenization of Data Series

Candidate Series: $Z(\mathbf{s}_0, t) = Z_H(\mathbf{s}_0, t) + IH(\mathbf{s}_0, t)$ $(t = 1,....., n)$
Reference Series: $Z(\mathbf{s}_i, t) = Z_H(\mathbf{s}_i, t) + IH(\mathbf{s}_i, t)$ $(i = 1,..., M; t = 1,....., n)$
($Z_H(\mathbf{s}, t)$: the homogeneous series, $IH(\mathbf{s}, t)$: the inhomogeneity)

Multiple Comparison of the Series:
Multiple **Optimum Interpolation** (without common Reference Series):

$$\hat{Z}^{(k)}(\mathbf{s}_0, t) = w_0^{(k)} + \sum_{i=1}^{M} w_i^{(k)} \cdot Z(\mathbf{s}_i, t) \qquad (k = 1,....., K; t = 1,....., n)$$

where $\sum_{i=1}^{M} w_i^{(k)} = 1$, because of the **Climate Change** signal $C(t)$.

Estimation of the Statistical Parameters:
on the basis of the data series $Z(\mathbf{s}_i, t)$ $(i = 0,..., M; t = 1,....., n)$

Interpolation Errors, Representativity Values: $ERR^{(k)}(\mathbf{s}_0)$, $REP^{(k)}(\mathbf{s}_0)$ $(k = 1,., K)$

Filling the Gaps
Missing Candidate Data $Z(\mathbf{s}_0, t_0)$ can be completed on the basis of estimations:

$$\hat{Z}^{(k)}(\mathbf{s}_0, t_0) \qquad (k = 1,..., K)$$

Data Quality Control, Homogenization of Data Series
Can be based on the examination of Difference Series System:

$$Z(\mathbf{s}_0,t) - \hat{Z}^{(k)}(\mathbf{s}_0,t) \qquad (k=1,...,K;\ t=1,.....,n)$$

Time Series Analysis (see Section 3.3):
Outlier Detection, Break Point Detection, Estimation of Shifts etc.

Efficiency:
Depends on the **Representativity of Station Network**:
Interpolation Errors $ERR^{(k)}(\mathbf{s}_0)$, Representativity Values $REP^{(k)}(\mathbf{s}_0)$

3 EXAMPLES

3.1 Examination of Representativity

Data:
Homogenized monthly mean temperature series (57 stations, 1971-2000).
The series were homogenized by the MASH method.
Area: Hungary ($\approx$93 000 km^2), a relatively flat ground.
Distances between the nearest stations:
minimum: 5 km, mean: 30 km, maximum: 56 km
Height differences between the nearest stations:
minimum: 0 m, mean: 139 m, maximum: 890 m

Spatial interpolation inside the Network (between the stations).

Interpolation Error and Representativity for Station s **and Month** m **:**

$$ERR(m,s) \quad , \quad REP(m,s) \qquad (s=1,...,57\,;m=1,..,12)$$

Mean monthly Error and Representativity (Figures 3,4):

$$ERR(m)=\frac{1}{57}\sum_{s=1}^{57}ERR(m,s)\ , \quad REP(m)=\frac{1}{57}\sum_{s=1}^{57}REP(m,s) \qquad (m=1,...,12)$$

Mean station Error and Representativity:

$$ERR(s)=\frac{1}{12}\sum_{m=1}^{12}ERR(m,s)\ , \quad REP(s)=\frac{1}{12}\sum_{m=1}^{12}REP(m,s) \qquad (s=1,..,57)$$

The Compared Interpolation Methods:
Inverse Distance Method with the nearest 1 station: ERR_{inv1} , REP_{inv1}
Inverse Distance Method with the nearest 6 stations: ERR_{inv6} , REP_{inv6}
Optimum Interpolation with the nearest 6 stations: ERR_{opt6} , REP_{opt6}

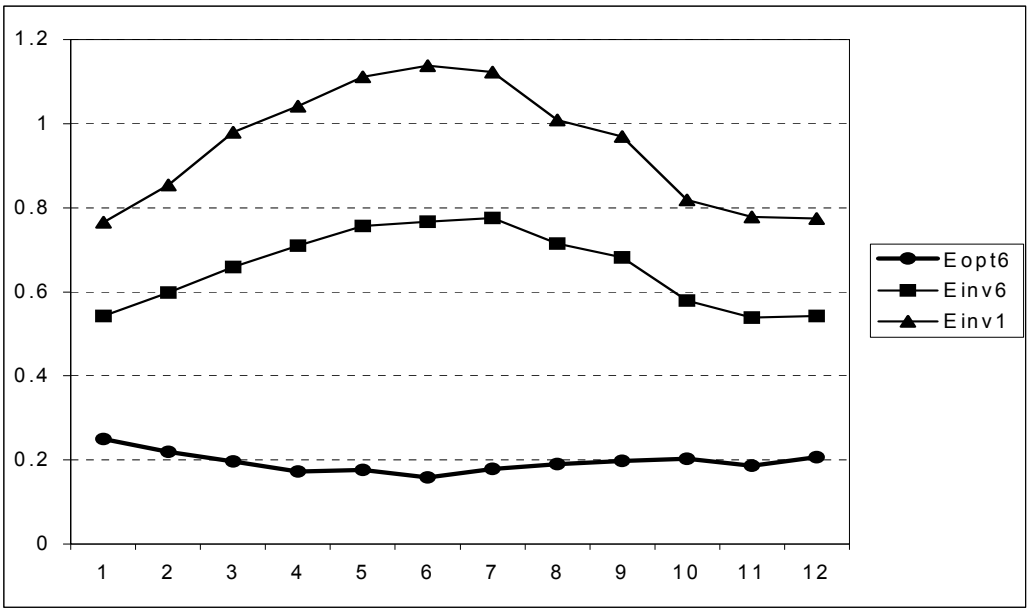


Figure 3. Spatial mean monthly Errors $ERR(m)\ (m = 1,..,12)$ obtained by different spatial interpolation methods

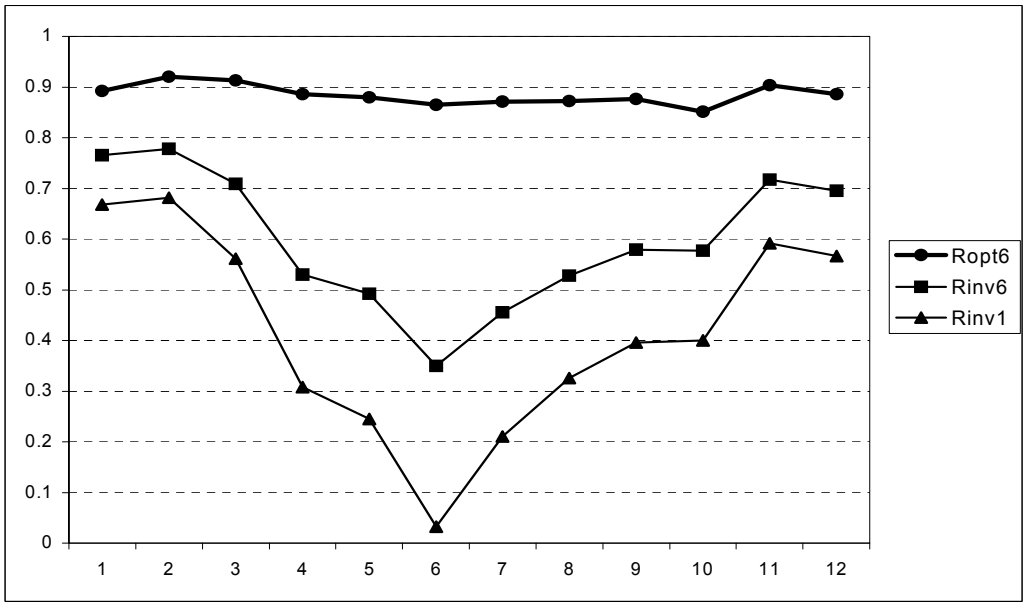


Figure 4. Spatial mean monthly Representativity Values $REP(m)\ (m = 1,..,12)$ obtained by different spatial interpolation methods

3.2 Benchmark Study for Modeled Spatial Interpolation (for COST719)

Data: The data series are the same that examined in Section 3.1.

Interpolation with the nearest 6 stations, the Compared Interpolation Formulas:

(i0) Optimum Interpolation (theoretical lower limit for errors)
(i1) Optimum Interpolation with modeled covariances and with real spatial trend
(i2) Optimum Interpolation with modeled covariances and with modeled spatial trend
(i3) Optimum Interpolation with modeled covariances and without spatial trend
(i4) Inverse Distance Method (empiric upper limit for errors)

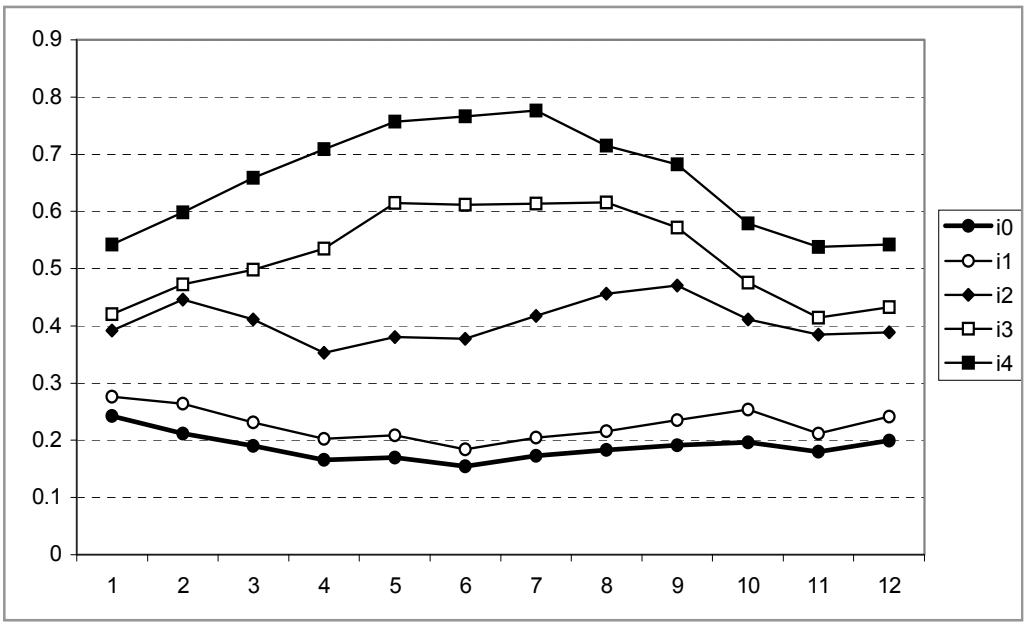


Figure 5. Spatial mean monthly Errors $ERR(m)\ (m=1,..,12)$ obtained by different interpolation formulas (i0, i1, i2, i3, i4)

3.3 Quality Control, Homogenization of Data Series (Result Files of MASH: Multiple Analysis of Series for Homogenization; T. Szentimrey)

Examined Series: Hungarian annual mean temperature series (1901-1999)
Candidate Series: Miskolc (Mi)
Reference Series: Kecskemét (Ke), Mosóvár (Mo), Debrecen (De), Sopron (So)

Two Difference Series (NO common Reference Series!):

Difference Series 1: $\mathrm{Mi} - (0.66 \cdot \mathrm{Ke} + 0.34 \cdot \mathrm{Mo})$

Difference Series 2: $\mathrm{Mi} - (0.78 \cdot \mathrm{De} + 0.22 \cdot \mathrm{So})$

Time Series Analysis:

Outlier Detection, Break Point Detection, Estimation of Shifts etc. (Figures 6. 7.)

Point Estimation as well as Confidence Intervals!

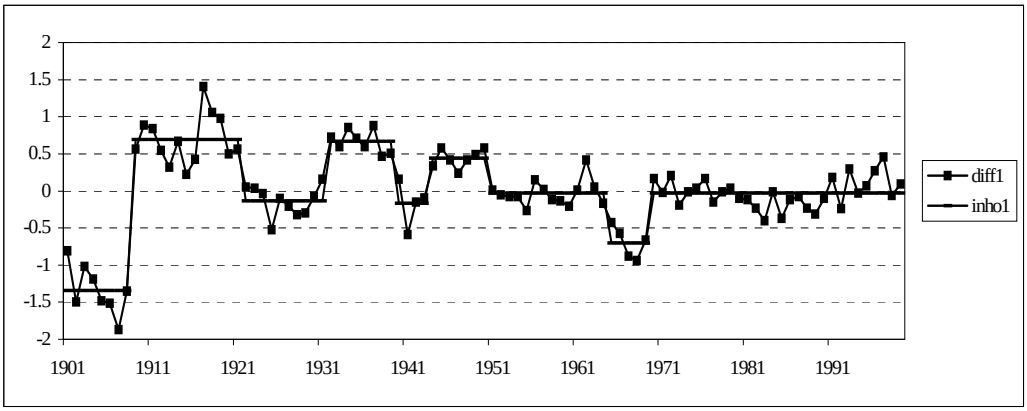


Figure 6. Difference series 1 with its estimated Inhomogeneity series

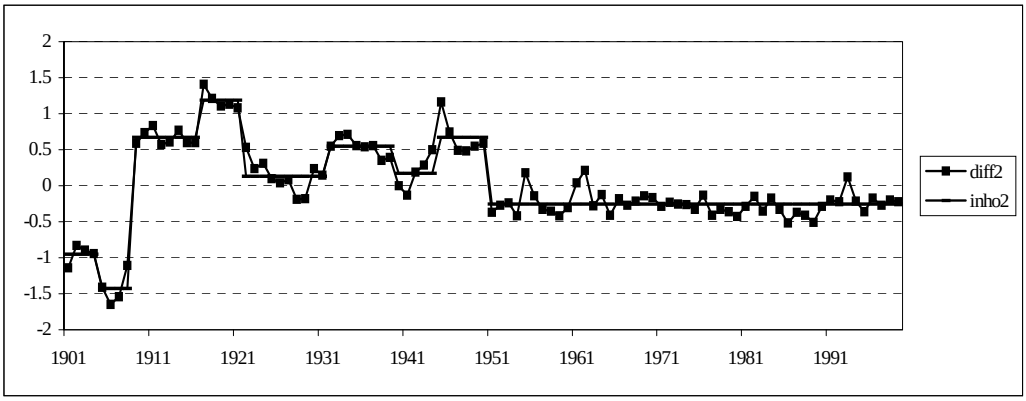


Figure 7. Difference series 2 with its estimated Inhomogeneity series

RESULT of MASH: ESTIMATED BREAK POINTS and SHIFTS of the CANDIDATE SERIES (Mark M: META DATA)

1908:-1.78,M1922: 0.78, M1930:-0.41, M1938: 0.38,1944:-0.35, M1950: 0.47

4 GENERAL CASE OF OBSERVING STATION NETWORK

4.1 Spatial Modelling of the Statistical Parameters $(\mathbf{E}, \mathbf{D}, \mathbf{r})$

According to the Section 2 the spatial interpolation is a basic topic in respect of the other topics as well furthermore the optimum mathematical solution of the spatial interpolation is a function of the statistical parameters in space. Consequently modelling of the statistical parameters in space is a key-question if we have old stations with long data series as well as new stations with short data series (Fig. 1).

<u>Sample in space and in time:</u>

$Z(\mathbf{S}_i, t) \quad (i = 1,..., N; t = 1,....., n)$

$\mathbf{S}_i \ (i = 1,..., N)$: stations with **long Homogeneous Data Series**!

<u>The following Statistical Parameters are essentially known :</u>

$E(\mathbf{S}_i)$, $D(\mathbf{S}_i) \ (i = 1,..., N)$: Local parameters

$r(\mathbf{S}_i, \mathbf{S}_j) \ (i, j = 1,..., N)$: Stochastic connection

<u>Modelling on the basis of the above known Parameters</u>:

$\tilde{E}(\mathbf{s})$, $\tilde{D}(\mathbf{s}) \ (\mathbf{s} \in D)$, $\tilde{r}(\mathbf{s}_1, \mathbf{s}_2) \ (\mathbf{s}_1, \mathbf{s}_2 \in D)$

The distances between stations and the topography can be used as model parameters for modelling the Statistical Parameters.

<u>For example some Tricks can be used for Modelling:</u>

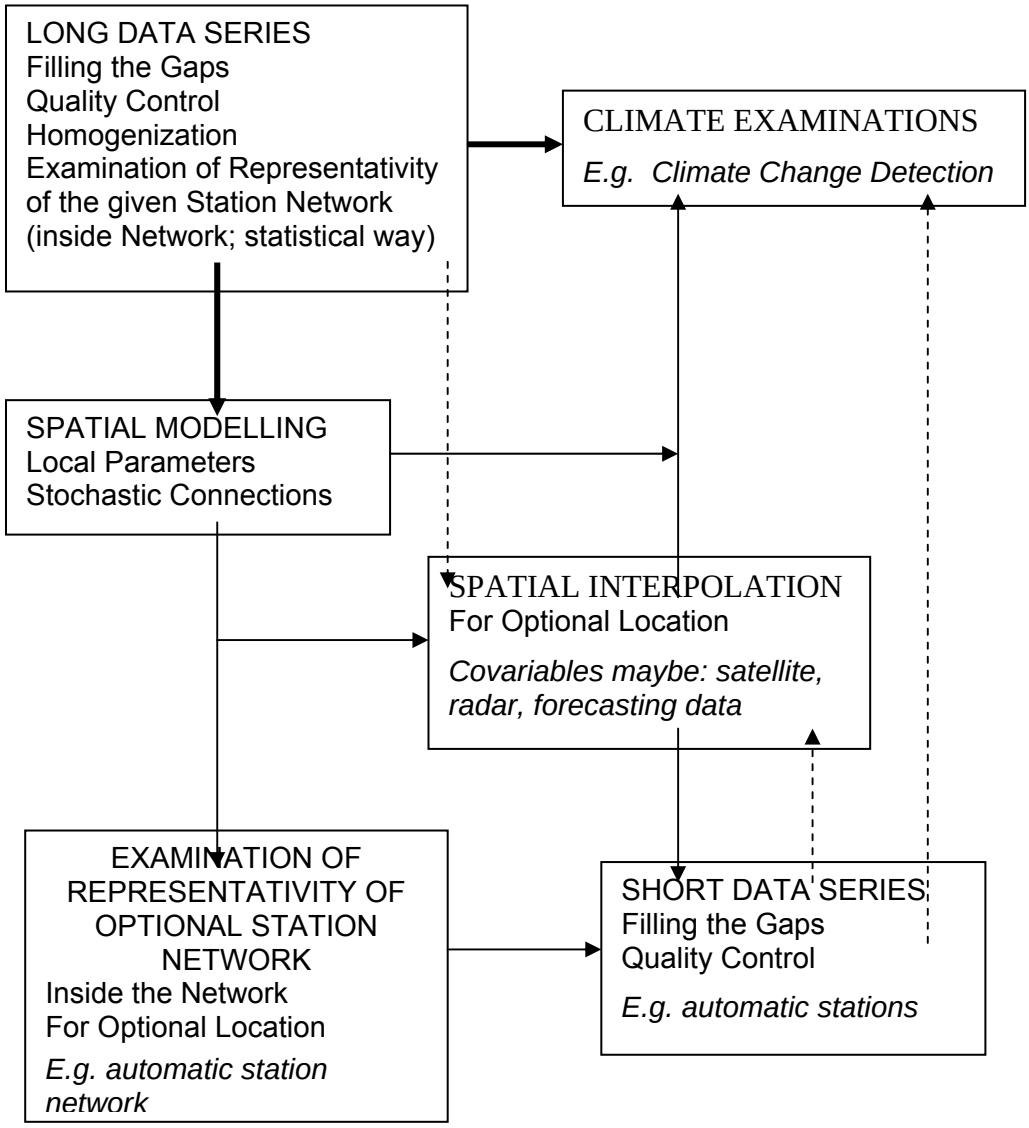
– Modelling only in the neighborhood of predictand (candidate): $D_{pr} \subset D$

– The optimum interpolation formula depends on the differences $E(\mathbf{s}_1) - E(\mathbf{s}_2)$ $\left(\mathbf{s}_1, \mathbf{s}_2 \in D_{pr}\right)$. If $E(\mathbf{s}) \equiv E \ \left(\forall \mathbf{s} \in D_{pr}\right)$ the formula does not depend on E.

– The optimum interpolation formula depends on the quotients $D(\mathbf{s}_1) / D(\mathbf{s}_2)$ $\left(\mathbf{s}_1, \mathbf{s}_2 \in D_{pr}\right)$. If $D(\mathbf{s}) \equiv D \ \left(\forall \mathbf{s} \in D_{pr}\right)$ the formula does not depend on D.

4.2 Possible Connection of Different Systems and Topics

To illustrate a possible solution the following flow diagram is presented.



: Data and Method or/and Result
: only Method or/and Result
: only Data

5 THE ROLE OF METEOROLOGY, MATHEMATICS AND SOFTWARE

Without mathematics and software the above outlined meteorological problems can not be solved. According to the one of the greatest mathematicians John von Neumann – who was also a Hungarian –: without quantitative formulation of the meteorological questions we are not able to answer the simplest qualitative questions either. Our motto on homogenization is also presented by way of illustration.

Problem of Homogenization

Data Series: the basis
Mathematics : abstract formulation
Meta Data: historical, climatological information
Software: automatization

Solution = Mathematics + Meta Data + Software

(i) without Software: Mathematics + Meta Data = Theory without Benefit
(ii) without Meta Data: Mathematics + Software = Gambling
(iii) without Mathematics: Meta Data + Software = "Stone Age" + "Bill Gates"

Finally we suggest programmed statistical procedures instead of picture-books.

Example: Let us assume that there is a difficult stochastic problem.
In case of having relatively few statistical information:
– an intelligent man is possibly able to solve the problem, but it is time-consuming,
– the solution of the problem can not be programmed.
In case of increasing the amount of statistical information:
– one is unable to discuss and evaluate all the information,
– but then the solution of the problem can be programmed. (**Chess!**)
Aim, Requirement: to develop the mathematical methodology in order to increase the amount of statistical information furthermore to develop the algorithms for optimal using of both the statistical and the meteorological information.

Conclusion: *There is No Royal Road (Archimedes)*

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METADATA AND THEIR ROLE IN HOMOGENISING

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INTRODUCTION

During the last years the question of climate variability and change has moved more and more into the public eye. Although the climate debate aims more to future climate the knowledge of past climate variability is the indispensably solid basis to understand the mechanisms of climate variability for the changes of future climate. In order to achieve this goal historical climate time series have to be analysed, however, inhomogeneities can bias the series and the results will not reflect only natural climate variability. The best way to avoid inhomogeneities in climate time series is to keep the record homogeneous, nevertheless we have to accept that even at present some changes cannot be avoided and the history of a station cannot be changed. In order to ascertain the homogeneity of a series a number of good tools have been developed (comp. Szalai et al, 1999 or Peterson et al., 1998 a.o.) and progress has been going on to improve and refine these methods. Also WMO has stressed its strong interest in this topic. For that purpose WMO initiated that “Guidelines on Metadata and Homogenisation” (Aguilar E et al., 2003) should be worked out. The draft version is available at:
http://www.bom.gov.au/wmo/climate/ccl/CCl_HM_250603.doc:

At the Central Institute for Meteorology and Geodynamics in Vienna during the last ten years a number of climate variability projects have been finished or are carried out at present focussing on time series analyses in the Alpine region (ALOCLIM, ALPCLIM, ALP-IMP, CLIVALP). During these projects, apart from the use of homogeneity tests an intensive study of metadata has been performed. The paper intends to put together some results provided by these projects and to underline the importance of metadata studies.

THE SPATIAL DE-CORRELATION OF CLIMATE TIME SERIES IN THE GREATER ALPINE REGION

Relative methods for homogenisation of data sets assume that there exists a minimum of common variance, e.g. 0.5 between neighbouring stations. Based on this criterion it can be decided a priori whether a series is suited for homogenisation or not.

Based on the network of 57 long-term air pressure series (begin of first series 1760), 135 long-term temperature series (begin of the first series 1760) and of 192 long-term precipitation series (begin of first series 1800) -all in monthly resolution- it turned out that our network density is sufficient for monthly air pressure and temperature series since its

beginning, however for precipitation only since 1860. Before that time we have to justify our adjustments only on metadata.

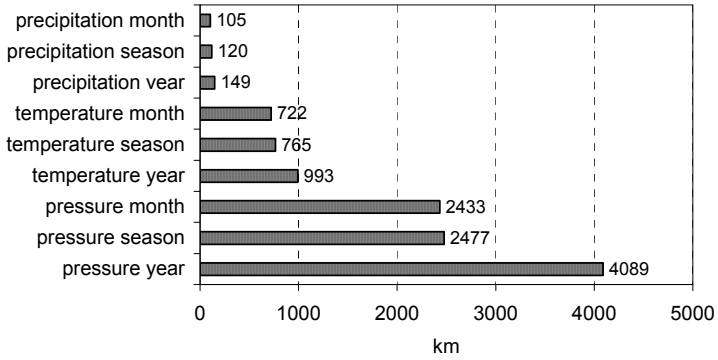

Fig.1 Average spatial de-correlation distances (common variance less than 0.5) of air pressure, temperature and precipitation for annual, seasonal and monthly series derived from Central European series.

In the near future there will be an increasing need for daily series. Besides the fact that up to now no appropriate methods for testing and adjusting daily series have been developed the question of network density will become important too. As an example it should be mentioned that for daily precipitation the average spatial de-correlation distance shrinks to 42 km.

GENERAL NETWORK INFORMATION

The list of possible factors biasing our series in the sense of inhomogeneities is a long one (Aguilar et al., 2003) and we never can be sure to know all of them. Some inhomogeneities will be only station specific (e.g. relocation, change of instrument etc.) and most probably identified by relative homogeneity testing. However, general information concerning the whole network within a country or a specific region often seems to be trivial. That's why often it is not documented -because it is thought to be well known. However, such information is at least as important as the individual station information because larger areas may be affected systematically. Especially, for historical long-term series this topic becomes more and more important. Some examples of many can be shown here.

Responsibility of a station due to its national history

Due to the history of some countries the responsibility for a station may have changed several times including country specific regulations for the network management. This could cause prominent inhomogeneities within the time series, which are not very easy to detect by relative homogeneity tests as larger regions are affected at the same time. As an example, consider the station Pula, which is now managed by the Croatian Hydrometeorological Service. Its turbulent history started with the K.K. Central-Anstalt für Meteorologie und Erdmagnetismus. From 1918 until 1930 it was managed by the Ufficio Centrale in Rome, from 1931 until 1941 it belonged to the Federal Republic of Yugoslavia. During World War II it was occupied by the Germans and after 1945 it belonged to the Socialistic Republic of Yugoslavia. Since 1991 it has been part of the network of Croatia (The first part of the precipitation series will be shown later in Figure 4).

Observation hours and calculation of means

It was in 1873 at the Meteorological Congress in Vienna when first suggestions were made to define observation hours in order to get daily and monthly means as consistent as possible (Authority of the Meteorological Committee, 1874). But even after 1873 observation hours and regulations for the calculations of means have been objects of changes. E.g. in the Austrian network it was decided to change the evening observation from 9 p.m. to 7 p.m. after January 1st, 1971 and based on this to use a new algorithm for the calculation of daily and monthly means. Figure 2 shows the impact of using different rules for determining temperature means for the inner-alpine station Puchberg. Compared to the 24hours true mean the various algorithms deviate within a range of –0.6 and + 0.8°C.

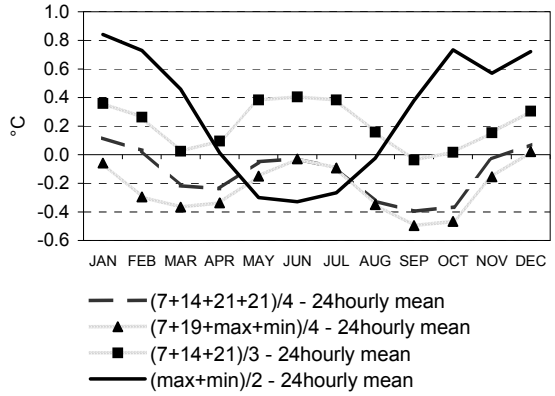

Figure 2: Seasonal variation of the differences between various ways of calculating daily mean temperature and 24-hourly observations average for the inner-alpine station Puchberg in Austria, 1987-1996. Data source: Central Institute for Meteorology and Geodynamics, Vienna, Austria.

Systematic changes in mounting of instruments

Sometimes it is argued that inhomogeneities of a greater number of stations are random and therefore by calculating regional means or gridpoints etc. the new series can be regarded to be homogeneous. This is necessarily not true. For the sample of the Alpine long-term temperature series it turned out that the average time series of the adjustments reveal an increasing trend of approximately 0.5 K from the mid 19th to the end of the 20th century (Böhm et al., 2001).

One systematic bias in long-term series is connected to the heights of instruments above ground which for temperature and precipitation used to be higher in former times than today.

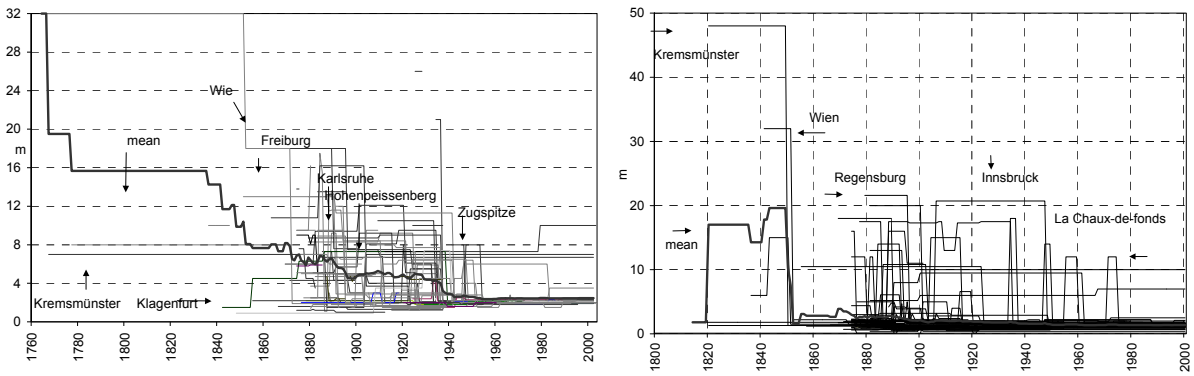

Fig 3 Evolution of mounting of instruments (heights above ground: left thermometers, right rain gauges)

Due to systematic errors in precipitation measurements (Sevruk, 1989) old precipitation data are consequently too low compared to those measured today. Roof exposures which were preferred in the first half of the 19th century cause a marked deficiency of precipitation amounts as it is shown in Figure 4. In Pula Monte Zaro (today in Croatia) measurements were taken on the roof of the building of the K.K. Hydrograhical Office from July 1871 and also in the courtyard from 1873. The period of parallel measurements lasts from 1873 until 1897. The mean precipitation amount of April at the roof exposure shows a deficiency of 35% compared to courtyard exposure**.**

For barometers a reverse evolution was found. A study of east Alpine baromter heights showed a systematic mean trend from lower to higher altutudes from the 19th to the late 20th century. Early barometer sites were approximately 10m lower than modern ones. Thus, the original Austrian long-term pressure series have been sytematically biased by more than 1 hPa. (Auer et al., 2001)

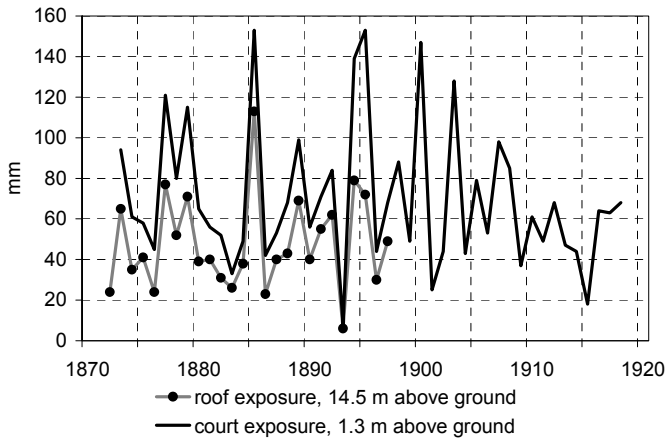

Figure 4: Precipitation series for April at Pula Monte Zaro (Croatia). Data sources: Jahrbücher der K. K. Central-Anstalt für Meteorologie und Erdmagnetismus 1871-1915, Wien, Beiträge zur Hydrographie Österreichs, X. Heft, Lieferung II, Wien and Archivio del Ufficio Centrale di Meteorologia e Geofisica Italiano, Roma.

Urbanisation and land-use changes

Today the global population is significantly greater than it was in the past, and will continue to increase for many decades to come. Urbanization often leads to less green space within a town or city and increased use of concrete and steel, more vehicles and industries, higher concentrations of pollutants etc. This results in a built-up of heat commonly known as the

“urban heat island”. Growing population numbers and changes in land-use can show an impact on our meteorological series. But urbanization effects in our meteorological time series do not cause sudden breaks in homogeneity if the local environment remains unchanged, but instead a gradual trend. However, this trend cannot be regarded as a trend for a city as a whole; it is strongly influenced by the local surroundings. The change in urbanization over time may be smaller for a station which originally was established in a densely built-up area or in an urban park than for a station originally installed in a rural or only light urbanized environment that has experienced growth as the example of Vienna can demonstrate. Figure 5 shows Time series of the annual mean urban temperature excess (relative to rural mean 1951 to 1995) based on height reduced temperature records. The station in the densely built-up area shows a stable temperature excess against the rural surroundings, whereas the trend of temperature excess at the station in the urban development area is 0.18 °C per decade (Böhm, 1998).

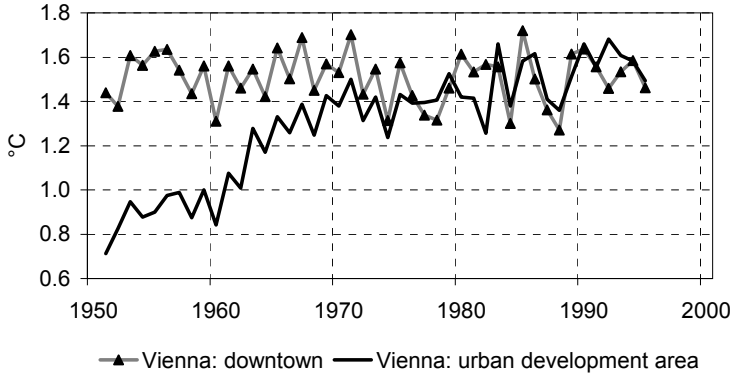

Figure 5: Time series of annual mean urban temperature excess (relative to rural mean 1951 to 1995) based on height reduced temperature records.

Network Automation

The number of Automatic Weather Stations has been increasing worldwide and will do so for the foreseeable future. If the conventional station and the AWS co-exist at the same location for a sufficiently long period the magnitude of breaks can be determined. With the introduction of the automatic weather station in Graz Univeristy a Haenni solar system (curve with triangles) was installed next to the Campbell-Stokes, which in February systematically records an excess of sunshine. Sunshine has increased since 1970: for the unchanged Campbell Stokes 2.13 hours per year, continuing the series with Haenni solar since 1989 the trend would be biased with an excess of 0.45 hours per year.

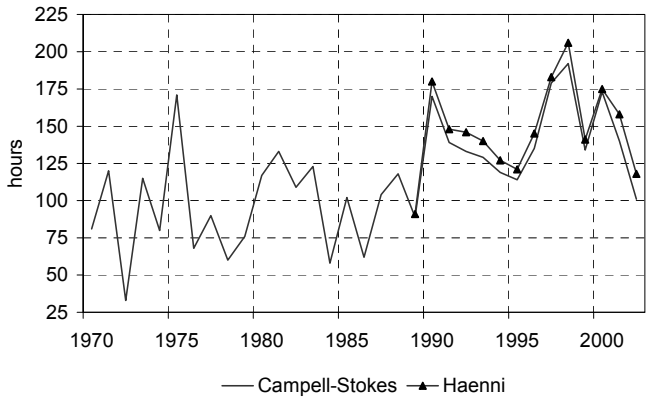

Figure 6: Time series of hours of bright sunshine for February in Graz-University (366m asl.) since 1970: Campell-Stokes sunshine autograph (grey curve), and Haenni solar (grey curve with triangles).

VERIFICATION OF BREAKPOINTS BY METADATA

For a sample of 15 multiple historical climate time series in Austria a study about the verification of test results by metadata was carried out (Auer et al., 2001). 72% of the detected breaks were documented and could be verified by metadata. The majority of breaks could be traced back to observer changes followed up by instrument changes and relocations.

METADATA STORAGE FOR HISTORICAL TIME SERIES AT THE AUSTRIAN WEATHER SERVICE

Although most historical metadata are in hand-written or printed form we have decided to create the database HISTALP permitting a combined collection and archiving of original and homogenised time series as well as of metadata. In parallel to the data a time dependent list of metadata is kept up. This enables to include metadata into the process of decisions during the work of homogenisation and to precise unclear test results. HISTALP was designed as a relational databank using MySQL. At present HISTALP contains about 200 historical time series and an extensive amount of metadata of about 140 stations within the Alpine region. Metainformation was provided by the national Weather Services or was digitised from yearbooks (Ungersböck et al., 2003).

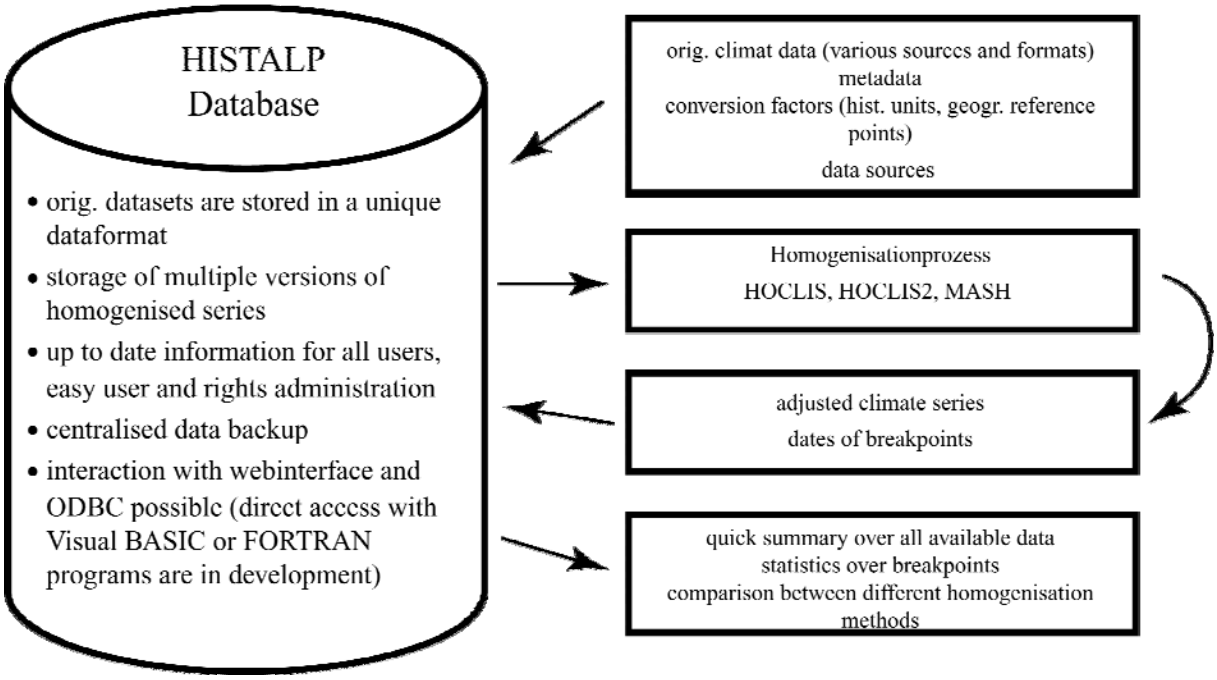

Figure 7: Scheme of HISTALP

CONCLUSIONS

Metadata are an independent tool to detect breakpoints. That's why they should be an integrative part of homogenising procedures. They provide the first indications about the feasibility of homogenising and are a useful tool to confirm homogeneity test results. Moreover they are of great help to precise the test results of break points.

Due to the spatial representativity of climate elements for periods with sparse data density metadata are the only tool to identify inhomogeneities.

A database of original data, homogenised data (version 1 to …..) and metadata is of great advantage.

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STATISTICAL ANALYSIS OF RESULTS OF HOMOGENEITY TESTING AND HOMOGENISATION OF LONG CLIMATOLOGICAL TIME SERIES IN GERMANY

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INTRODUCTION

Like most meteorological services the German weather service possesses a large archive with long climatological time series. Unfortunately many long time series contain inhomogeneities caused by changes in instrumentation, observing practices, relocations and changes in the environment of the stations. These inhomogeneities are of the same size as the climatic variations to be expected. Therefore a check of homogeneity and eventually a homogenisation of the time series is necessary before it can be used for such investigations.

As temperature and precipitation are the basic parameters for investigations in climatic trends, in a first step all long time series have been checked and several shorter series have been tested as well.

STATISTICAL PROCEDURE

As statistical test to find out inhomogeneities the Standard Normal Homogeneity Test described by Alexandersson (1986) has been chosen. For temperature it is applied to the time series of differences between the time series to be tested and the reference time series. For precipitation the time series of quotients is tested. In both cases an error level of 10 % is used.

To compute the reference series a special procedure has been developed, which selects the best neighbouring stations and produces a mean of these time series
As the test can only find one inhomogeneity, the time series is homogenized, when an inhomogeneity has been detected, and is tested again. This procedure is continued until no further inhomogeneity is found.

This procedure is applied independently on the time series of the 12 calender months.

As the statistical procedure is applied independently to each month, the results are not always consistent. The size and the date of the detected inhomogeneity may vary from month to month. In some months an inhomogeneity may not be detected at all, and the relatively large error level may cause the indication of some inhomogeneities, even when the time series is homogeneous.

Therefore a manual revision of the statistical results is necessary. For this purpose the station history files are looked through and all events, which might possibly produce some inhomogeneity, are compiled. Unfortunately the meta data are far from complete and quite often apparently small changes in observing procedures, location of the instruments and changes in the surroundings, which did not seem relevant to the observers, have not been reported.

As far as possible inhomogeneities found by the statistical procedure are allocated to plausible causes detected in the station history. Differences in date between inhomogeneity and cause of up to 10 years are accepted, as the statistical results may vary widely between the months.

As the correction factor is computed independently for each month by the statistical procedure, it may vary unrealistically from month to month. Therefore outliers are reduced to achieve a smooth variation around the year.

As far as inhomogeneities have not been detected in some months, these gaps are filled by interpolation of the correction factors of the neighbouring months. Usually an inhomogeneity is constituted for the whole year, when at least six months distributed equally over the seasons show a statistically significant inhomogeneity of the same direction. In other cases inhomogeneities only during a part of the year are assumed. If inhomogeneities appear only in one month or two months in different seasons or at very different dates or with different direction they are assumed to be artefacts of the high statistical error level.

RESULTS

505 time series of precipitation and 115 temperature series lasting at least 80 years have been investigated as well as 105 temperature series with a length of 50 - 80 years and 26 shorter temperature series have been tested.

Because of the special temporal and spatial structure of the two parameters investigated, the results concerning the number, size, distribution within the year as well as the frequency of causes for the inhomogeneities detected became rather different, so that they will be presented separately.

Temperature

Temperature is the parameter with a rather large spatial correlation and relatively small variations from year to year which made it quite easy to detect inhomogeneities.

The relative frequency of inhomogeneities per station for time series with morer than 80 years of observation is given in figure 1.

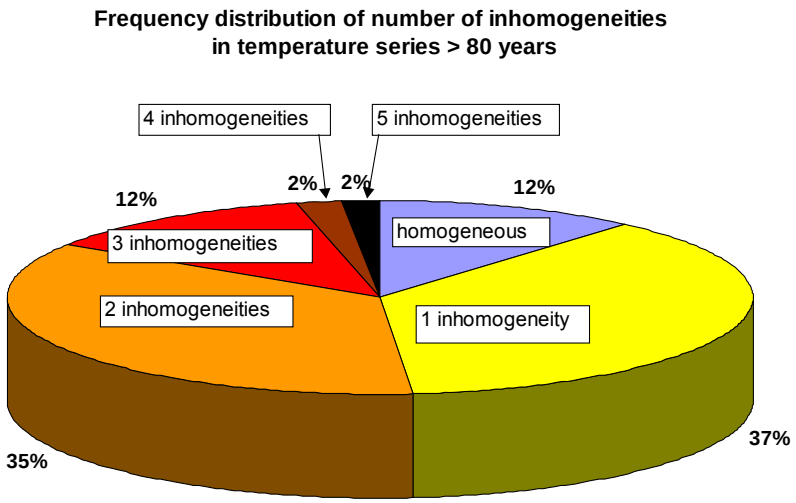


Figure 1

Only 12 % of the 115 stations investigated were homogeneous. 37 % showed one inhomogeneity. 51 % had several inhomogeneities with a maximum of 5 inhomogeneities (2 %).

The number of inhomogeneities detected by the statistical test is not constant during the year. Figure 2 shows the variation of the frequency distribution for the number of inhomogeneities in the different months.

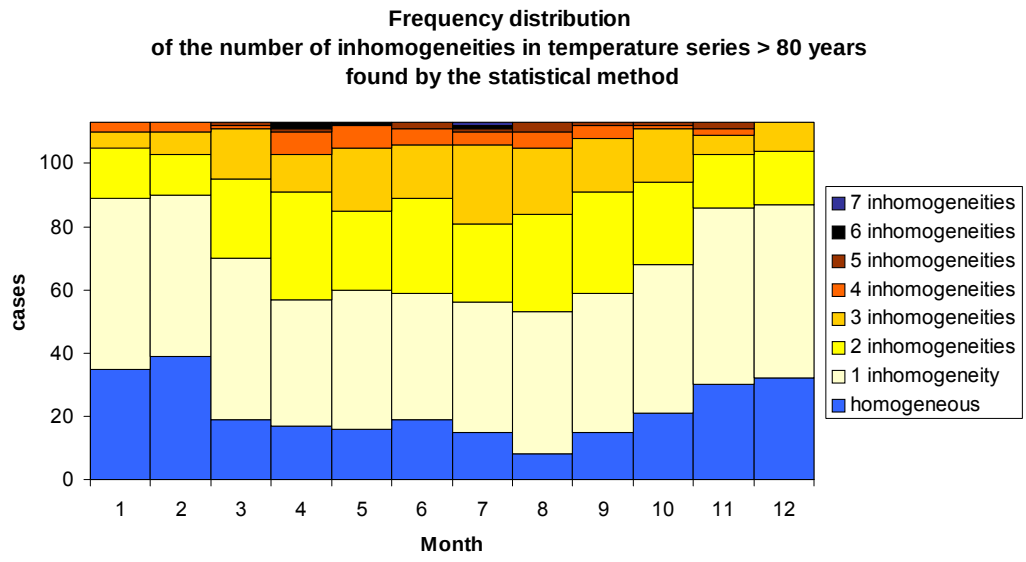


Figure 2

One can see that there is a maximum of inhomogeneities detected in summer, while during the period November to February the percentage of apparently homogeneous stations is rather high. This is caused by the larger variance of monthly mean temperature in winter compared to the summer half year.

The situation after manual revision of the statistical results is given in figure 3.

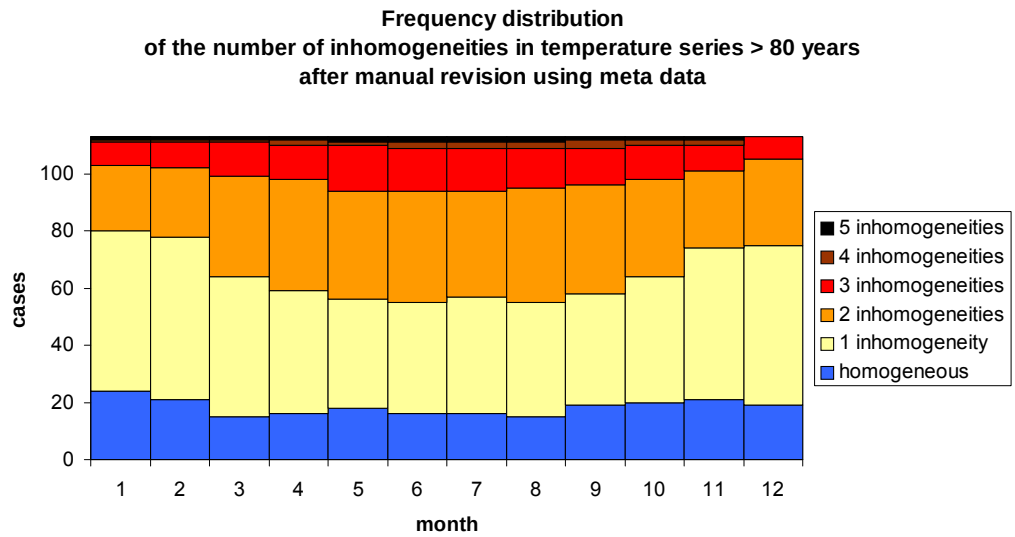


Figure 3

The annual variation is still visible, but weaker. The number of cases with two inhomogeneities is increased, while the cases with several inhomogeneities are reduced, because quite a lot of the cases with a large number of inhomogeneities found by the statistical test are due to some kind of oscillation, when one inhomogeneity found is widely cancelled by the inhomogeneity found next.

Also for temperature time series of 50 - 80 years inhomogeneities could be found in the majority of cases, but time series with only one inhomogeneity become more frequent (s. Figures 4 - 6)

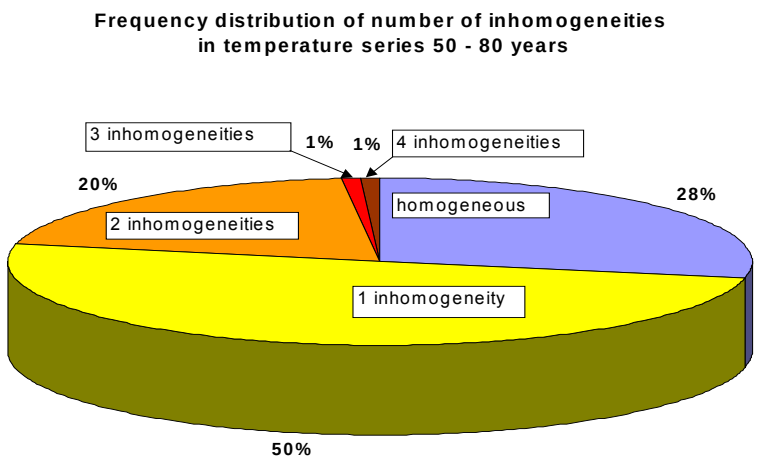


Figure 4

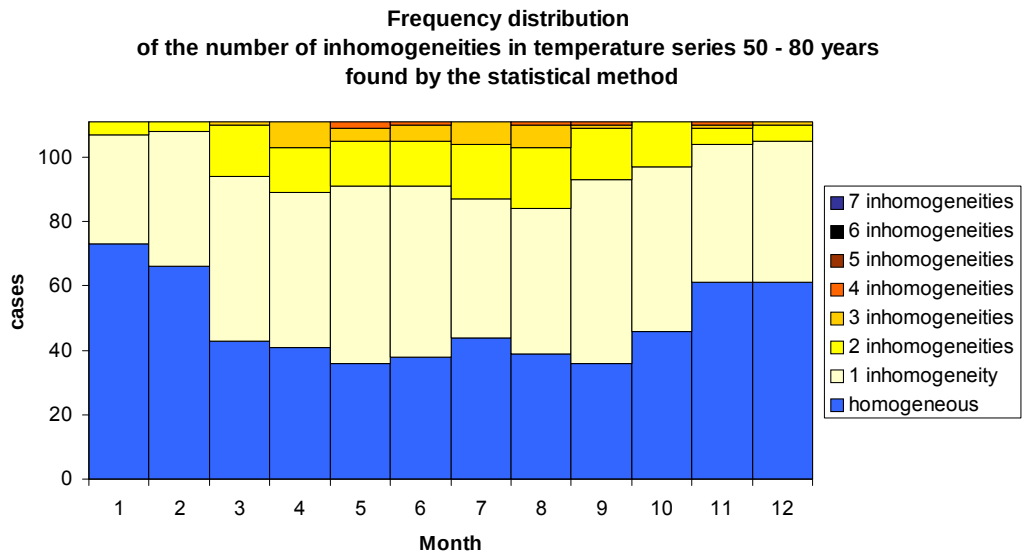


Figure 5

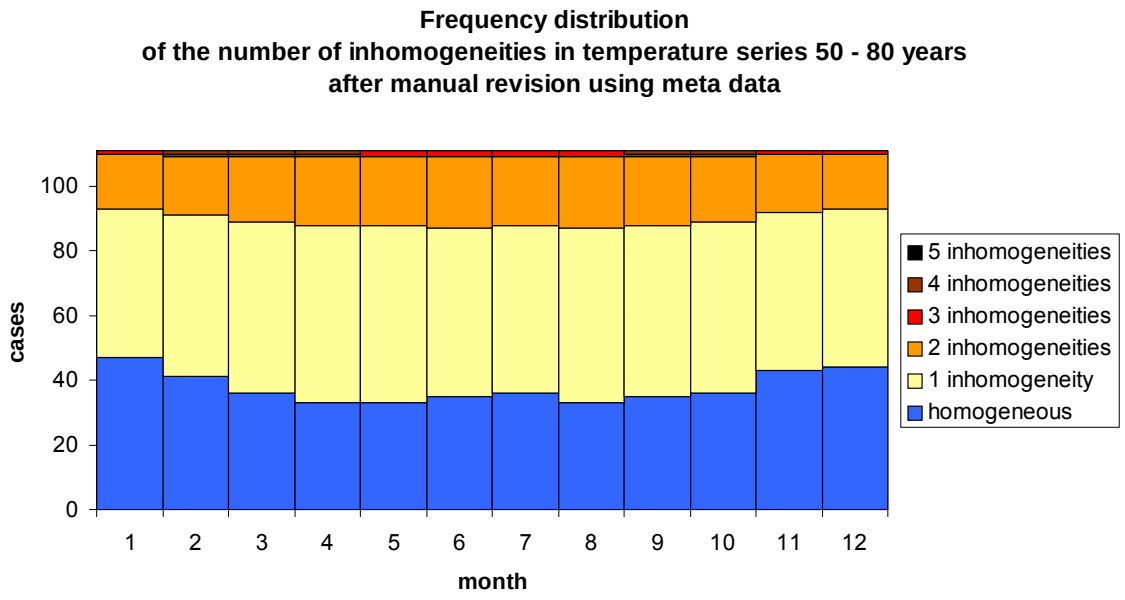


Figure 6

For shorter time series the majority of stations is homogeneous and usually not more than one inhomogeneity can be found (s Figures 7 - 9)

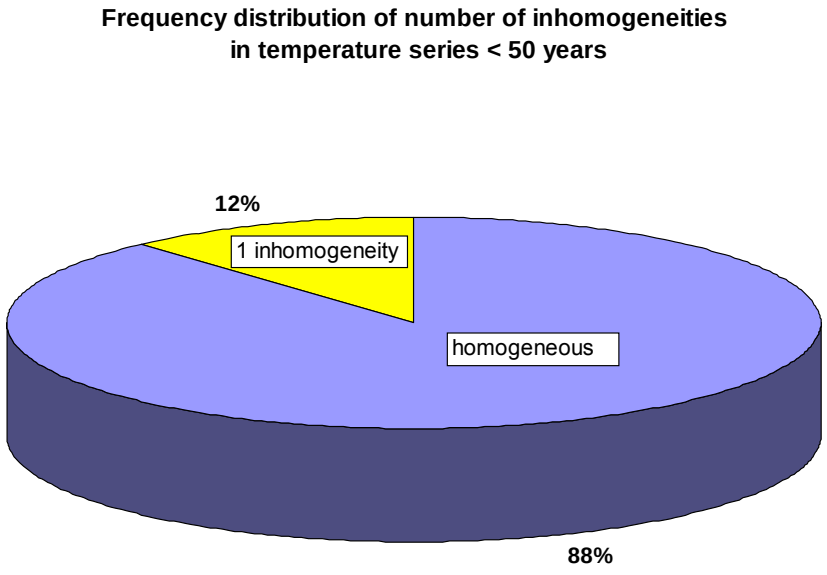


Figure 7

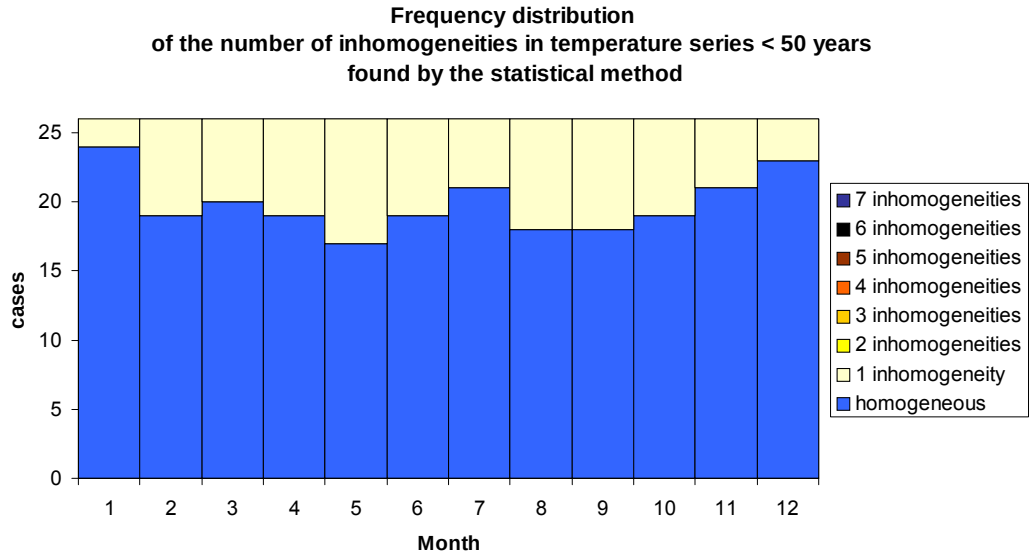


Figure 8

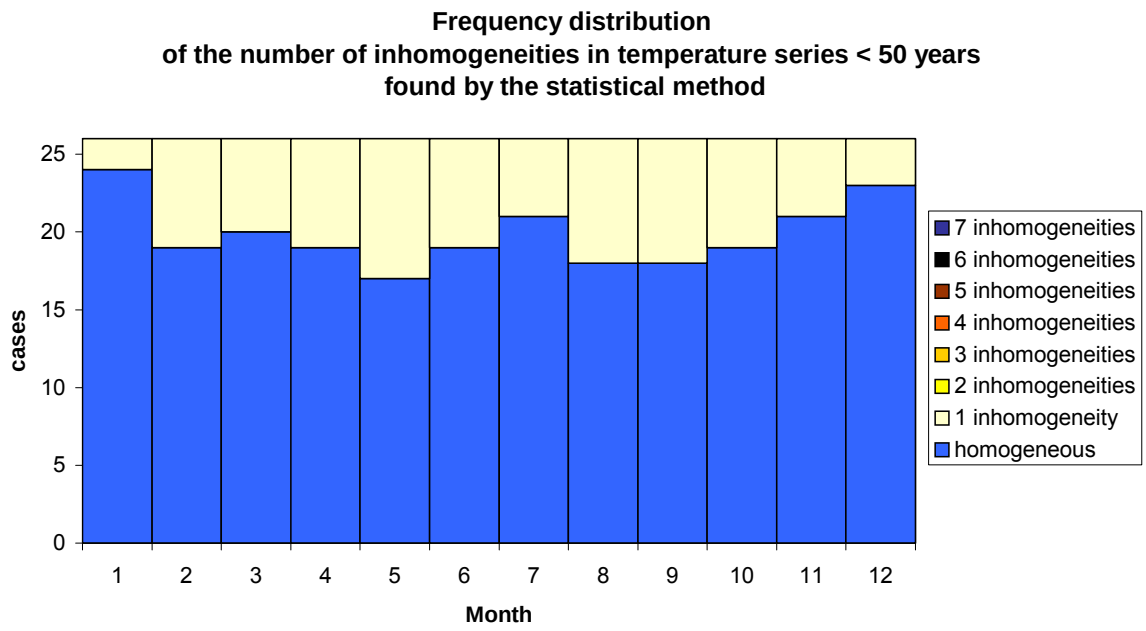


Figure 9

Figure 10 shows the frequency distribution of the size of the inhomogeneities found by the statistical test and after manual revision

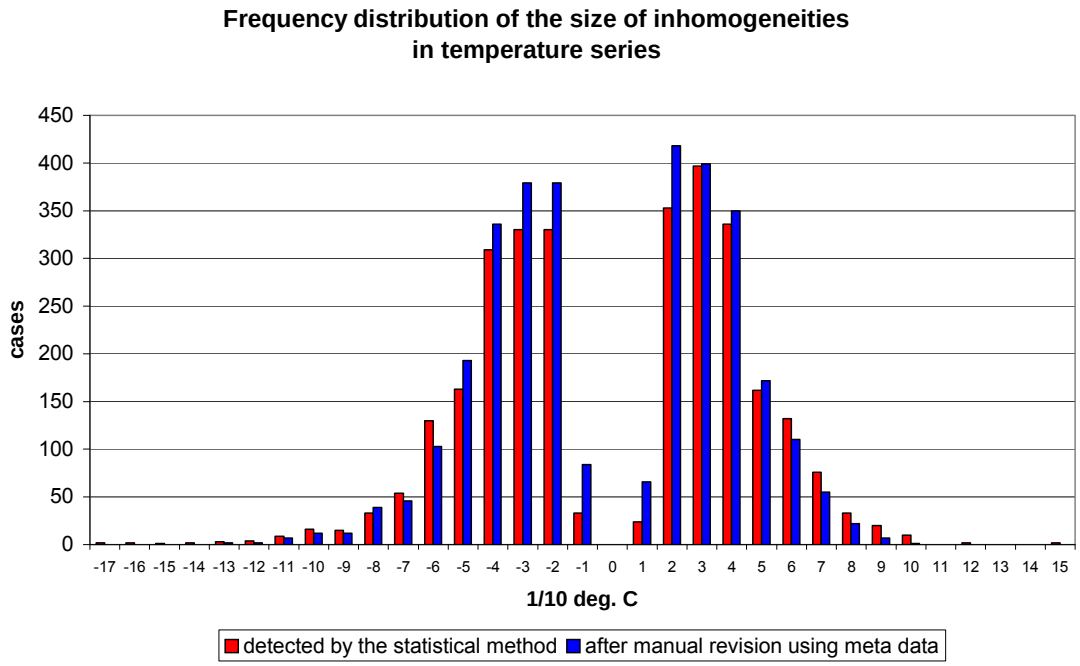


Figure 10

The correction factors for the inhomogeneities in the series of mean monthly temperature detected by the statistical test vary between –1.7 K and +1.5 K. Very small inhomogeneities usually cannot be found, because of the random variations in the time series to be tested and in the reference time series. Therefore there are only few cases with correction factors of 0.1 K and the maxima are +/- 0.2 K.

The revised correction factors are usually a bit smaller in absolute size, as extremes in the annual variation are reduced. Correction factors of moderate size become more frequent. Their number is increased by interpolated values for cases, when the test could not detect inhomogeneities in individual months.

For most stations some reasonable cause for the inhomogeneities detected by the statistical test could be found in the station history files. The dominant factor was relocation of the stations. Other detected causes are changes of instrument shelters, especially the transition from window screens to the Stephenson screen.

Nevertheless in nearly one quarter of the cases no cause for statistically significant inhomogeneities could be detected. Figure 11 gives an overview over the relative frequency of the causes for the inhomogeneities.

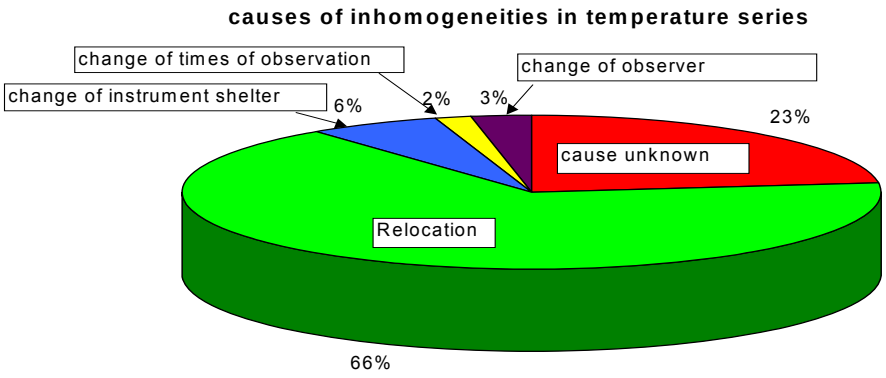


Figure 11

A comparison of the year of inhomogeneity detected by the statistical method and the year allocated after manual revision is given in Figure 12. Only in about 25 % of cases these dates coincide and in roughly 13 % of cases the difference between the two dates is 10 years or more, so that it must be assumed that the inhomogeneity detected by the statistical method is just an artefact caused by the large error level and has noting to do with the inhomogeneity found in station history.

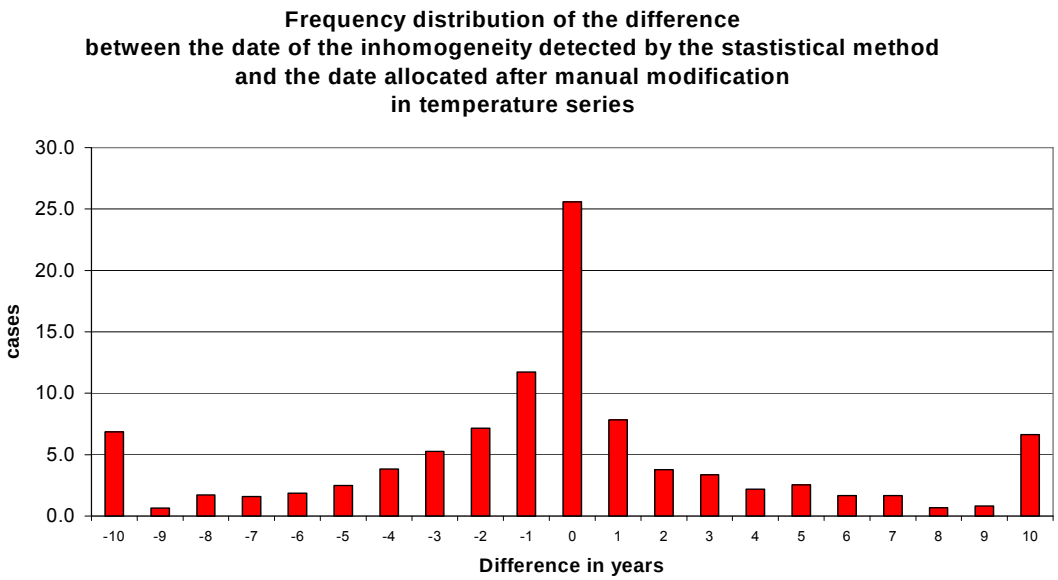


Figure 12

Precipitation

Precipitation is a parameter with much larger spatial and temporal variation than temperature. This makes it much more difficult to detect inhomogeneities.

So the number of inhomogeneities detected is relatively small. Figure 13 gives an overview of the frequency of inhomogeneities that could be found. The majority of stations seems to be homogeneous. Usually not more than two inhomogeneities per station could be found.

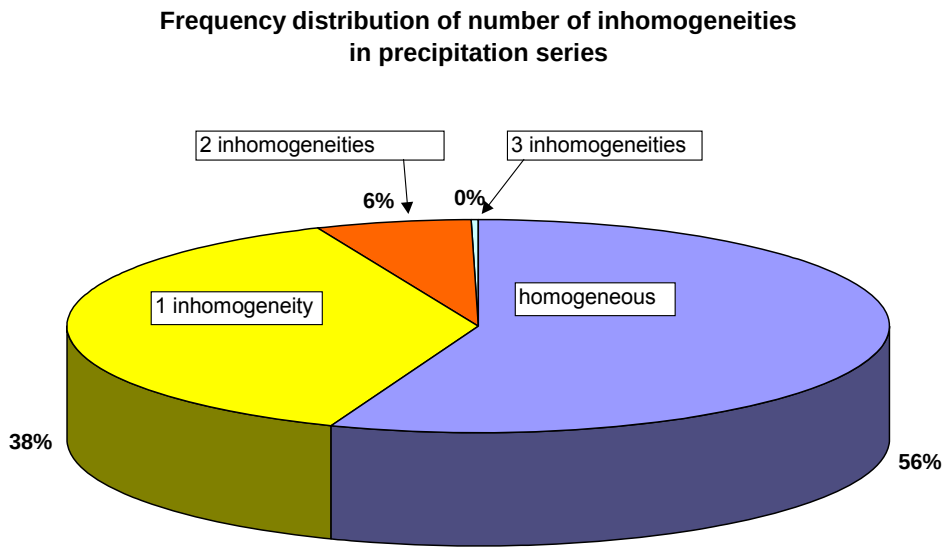


Figure 13

In figure 14 the annual variation of the number of inhomogeneities per station is presented. One can see a clear minimum of inhomogeneities in the summer half of the year. Cases with more than one inhomogeneity are nearly completely restricted to the winter months. This is mostly caused by the annual variation of the temporal and spatial variance of precipitation with high values during the summer months with their dominantly convective precipitation. Special problems with the measurement of solid precipitation may add to the maximum of inhomogeneities during winter.

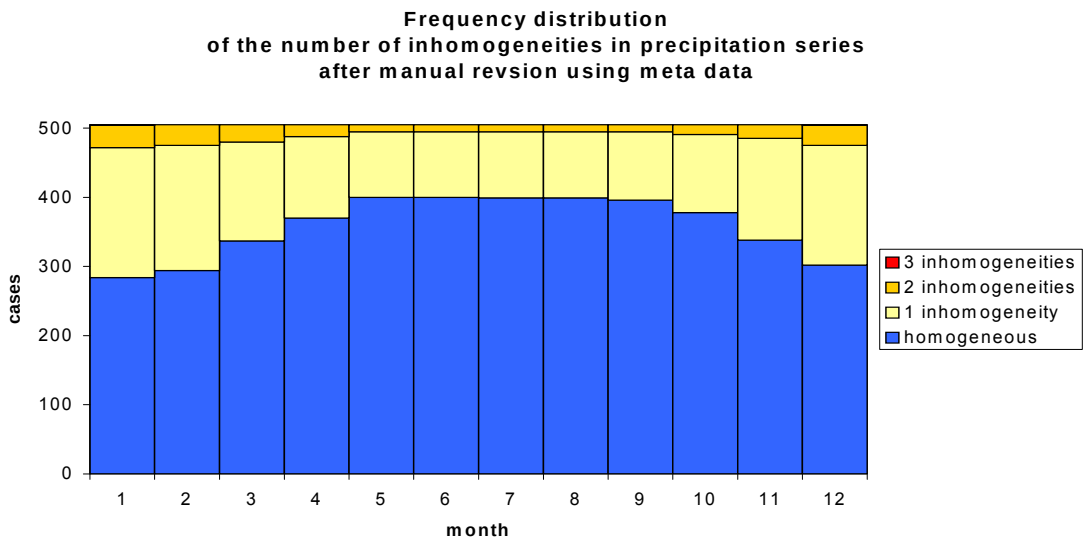


Figure 14

Only a minority of stations is without statistically significant inhomogeneities, but in most cases these inhomogeneities detected by the test are limited to less than six months. Therefore many of the inhomogeneities had to be attributed to an artefact caused by the relatively high error level of the statistical test.

Figure 15 shows the situation after manual revision. It shows a much larger number of stations without inhomogeneities and the number of cases with more than one inhomogeneity has clearly decreased.. On the other hand also the number of cases with inhomogeneities all around the year is increased. The cases with inhomogeneities only during a part of the year are rare, but relatively more frequent than for temperature.

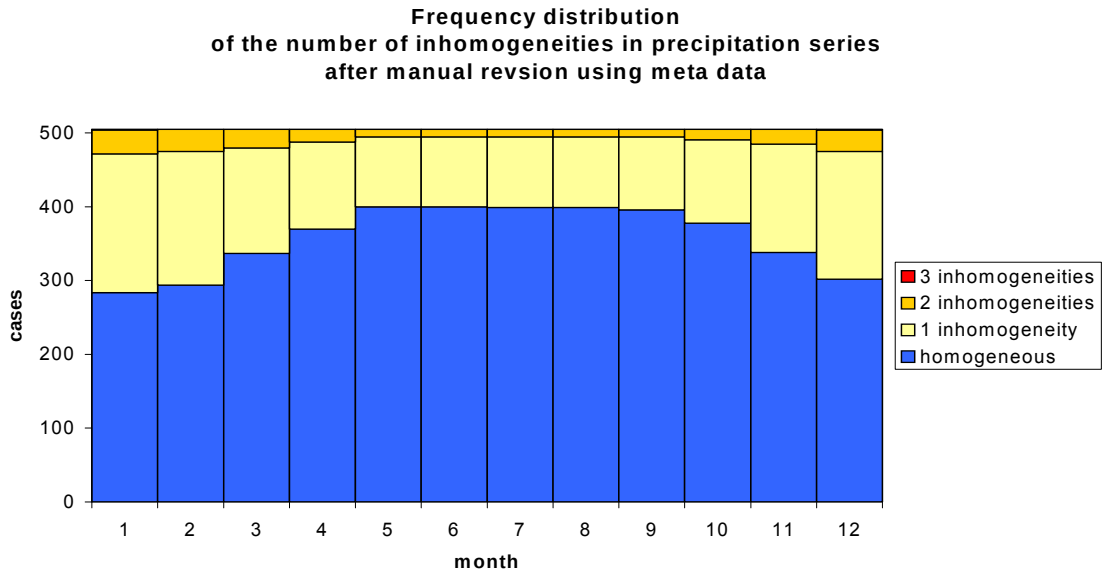
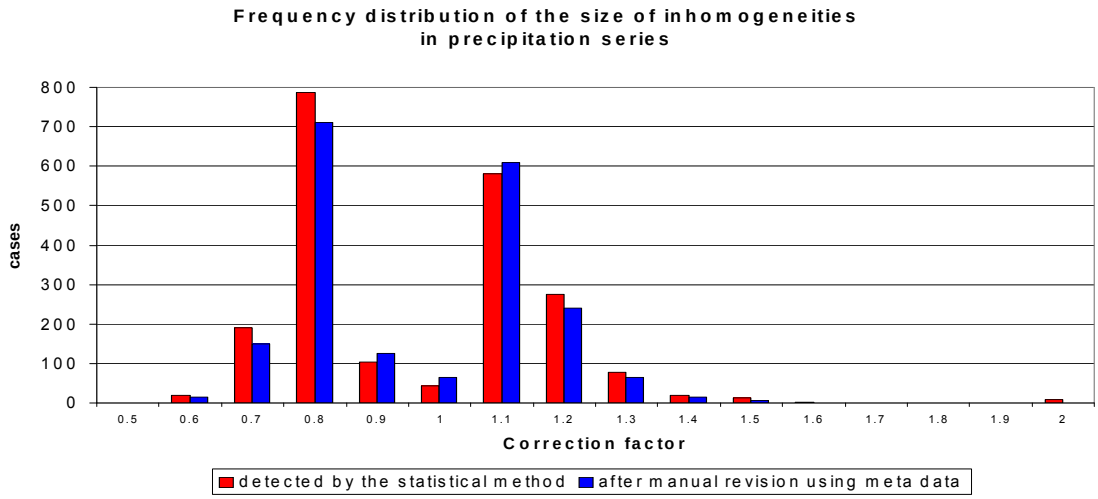


Figure 15

The percentual correction factors vary between 60 and 380 %. However mostly they lie between 70 and 140 %. As small inhomogeneities can hardly be detected because of the large random variability of precipitation, correction factors between 90 and 110 % are seldom. The maxima are found around 85 and 115 % (s. figure 16).
Figure 16



Like with temperature the major cause of inhomogeneities are relocations (61 %) Other reasons like changes of observer, instrument type and surroundings of the stations play only a minor role. However for a large part of the inhomogeneities (30 %) the causes remained unexplained. Figure 17 gives the frequency distribution of the causes of inhomogeneities.

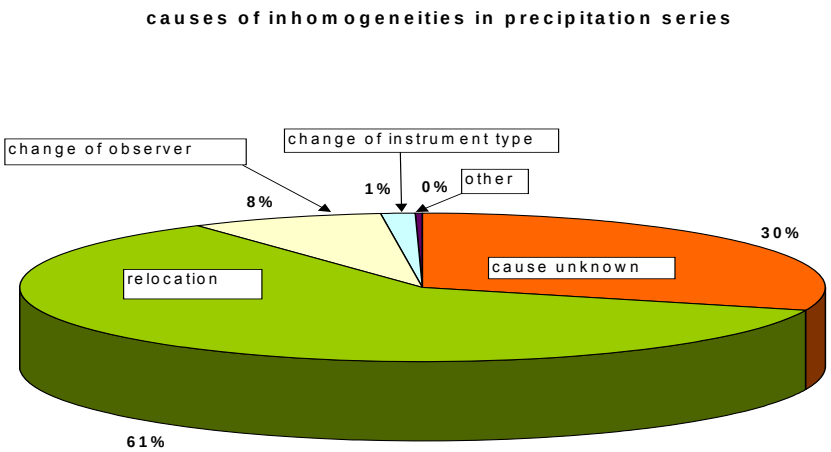


Figure 17

Similar to the situation for temperature the reliability of the time of the inhomogeneity detected by the statistical method is not large. (s. figure 18). In only 20 % of cases this date fits with the date of some cause detected in station history.

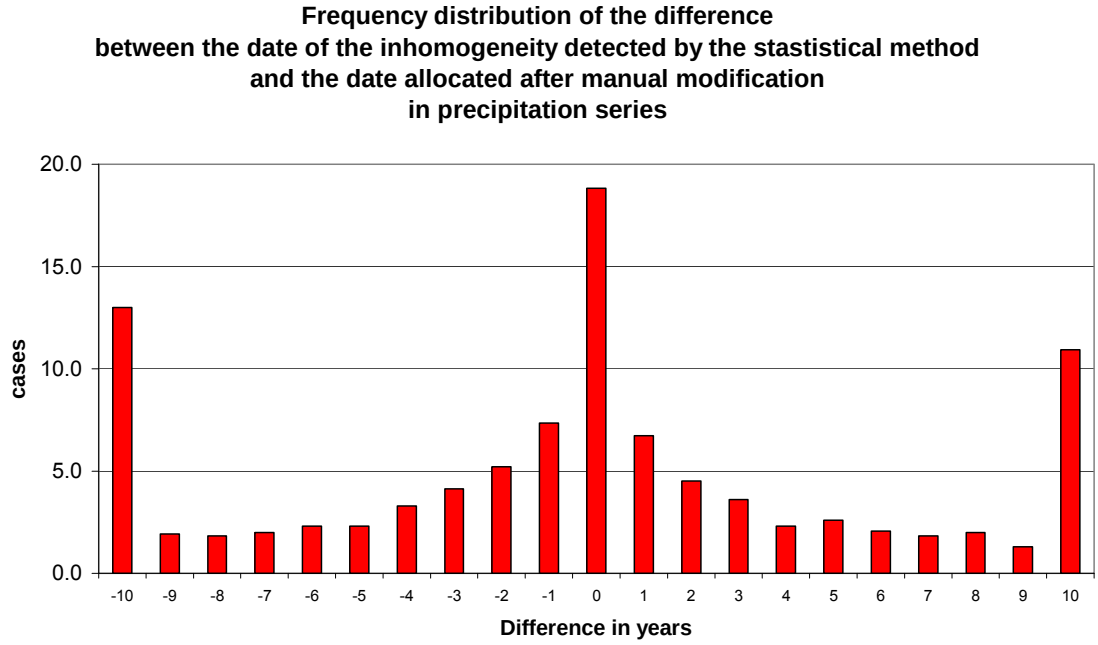


Figure 18

CONCLUSIONS

Most long time series are inhomogeneous and the size of the inhomogeneities is similar to the climatic variations and trends to be expected. The ability of statistical tests to detect inhomogeneities depends widely on the size of random variations within the time series. Especially the large spatial and temporal variability of precipitation makes it difficult to detect inhomogeneities for this parameter.
The temporal location of an inhomogeneity as well as the assessment of the size of the correction factors by the statistical procedure is not very exact. Therefore a manual supervision of the statistical results is absolutely necessary.
Only after a modification of the statistical results via an analysis of station history the homogenization gets real value. A pure statistical approach would only transfer information from the reference time series to the time series tested.

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New Developments in the Homogenization of Temperature and Precipitation series in Canada

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1. Introduction

The more recent development of the ongoing projects related to homogenization of temperature and precipitation datasets are presented here. The starting point is the publication issued for the Third Seminar for Homogenization and Quality Control in Climatological Databases (Mekis and Vincent, 2000) where basic information related to the homogenization procedures applied on temperature and precipitation measurements were summarized. Since then new improvements were achieved on both fields and the objective is to share and discuss the new results with the climate research science community. An overview of the procedures is presented in this report, more details on how to apply them can be retrieved directly from the referenced documents. At the end a short comparison of several techniques and the most recent study on the climate indicators in Canada are also presented.

2. Temperature

A technique was developed to identify inhomogeneities in annual temperature time series (Vincent, 1998). The inhomogeneities were identified as steps in the difference between the tested and surrounding station series. The method was based on the successive application of several regression models: an independent variable was introduced in the model to determine the position and magnitude of a step. Database of long-term and homogenized monthly mean, maximum, and minimum temperatures was assembled for 210 locations across Canada (Vincent and Gullett, 1999). Joining of stations observations was often needed due to station relocation to airports in the 1940s and to the introduction of automated observations in the 1990s (Fig. 1). The datasets were recently updated for the period 1995-2001. These datasets can be used with confidence in the detection and quantification of trends at regional, national and global levels. In the present report, two new improvements - the adjustments performed on daily records (Vincent et al., 2002) and an examination for the new definition of the climatological day - are discussed.

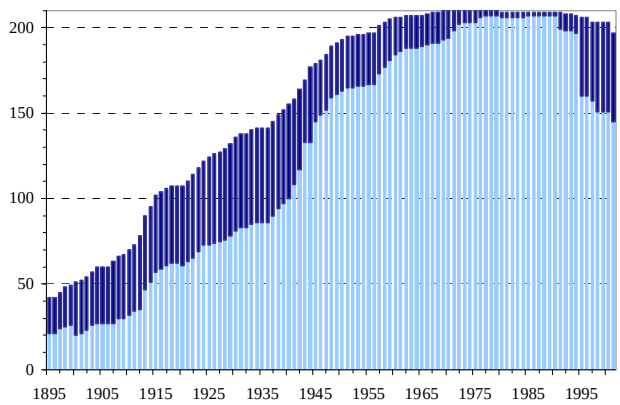


Figure 1. Total number of homogenized temperature stations classified by joining (light – not joined, dark – joined)

2.1 Homogenization of daily temperatures in Canada

Most of the work on Canada's temperature homogeneity assessments and adjustments has been carried out on annual and monthly time scales with relatively little consideration given to daily adjustments. Several climate change detection studies have clearly identified the need for daily homogenized datasets in order to analyze changes in the frequency and intensity of extreme climate events. Recent work has therefore focused on the investigation and application of various approaches to adjust daily maximum and minimum temperatures.

Monthly adjustment factors were obtained by fitting regression models to individual monthly series both before and after each step change. The adjustments were then applied to bring each segment into agreement with the most recent homogeneous part of the series. The magnitude of the individual monthly adjustment factors can vary considerably. The application of these factors to every day within the corresponding month would therefore create artificial steps in the day to day temperatures, particularly near the beginning and end of each month. An interpolation approach based on Sheng and Zwiers (1998) was used. Their main objective was to provide an improved time-interpolation scheme that preserves monthly values and does not yield to artificial steps at the joining of the calendar months.

Daily adjustments are derived from the monthly adjustments. They are obtained using linear interpolating between mid-month "target" values which are objectively chosen so that the average of the daily adjustments over a given month is equal to the monthly adjustment. The target values are related to the monthly adjustment factors by the system of equations:

$AT = M$, where A is a tridiagonal 12 x 12 matrix,

$$A = \begin{vmatrix} 7/8 & 1/8 & & & \\ 1/8 & 6/8 & 1/8 & & \\ & . & . & . & \\ & & 1/8 & 6/8 & 1/8 \\ & & & 1/8 & 7/8 \end{vmatrix}$$

T is a 12 x 1 vector of the target values and M is a 12 x 1 vector of the monthly adjustment factors. The target values are then obtained by solving the equations:

$T = A^{-1}M$.

This approach has several advantages. First, it does not require the creation of a daily reference series, which is often time consuming since inhomogeneities can be found in

surrounding stations. The procedure does not require the identification of inhomogeneities in daily temperatures, which may be difficult due to the large variability in daily data. Finally, the homogenized daily temperatures are compatible with the homogenized monthly datasets. As a result, the homogenized daily temperatures can be used to compute the homogenized monthly data, and both datasets contain the same long-term trends and variations presented by the annual time series.

Figure 2 shows the monthly adjustments (in grey), the targets values (black dots), and the daily adjustments obtained by interpolation (black line) for the step of 1.1°C identified in 1943 in the tested series of Mont Joli.

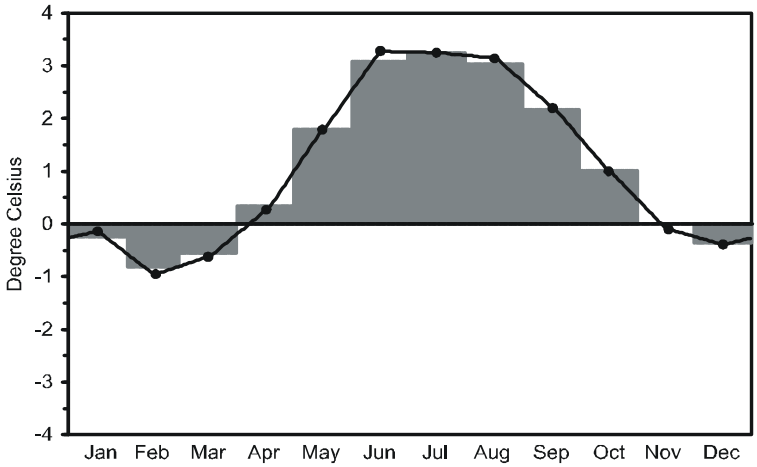


Figure 2. Example of daily adjustment factors.

2.2 Impact of adjustments on trends in extremes

To assess the impact of the daily adjustments on extremes, trends in the frequency of extreme low and extreme high temperatures were determined on a seasonal basis at each of the 210 stations, both before and after adjustment. Trends in extreme low temperatures are represented by the percentage of days with minimum temperature less than the 5th percentile. This threshold is obtained by averaging the 5th percentiles over the period 1961-1990 for each season. Similarly, trends in extreme high temperatures are represented by the percentage of days with the maximum temperature greater than the 95th percentile.

Fig. 3 presents an example of the impacts on the trends produced by the daily adjustments. The before and after adjustment trends in the percentage of days with minimum temperature below the 5th percentile during summer are shown for the period 1950-1998. The before map shows a mixture of decreasing and increasing trends across the country with several positive values over eastern Canada. The after map shows a more consistent pattern of decreasing trends across the entire country.

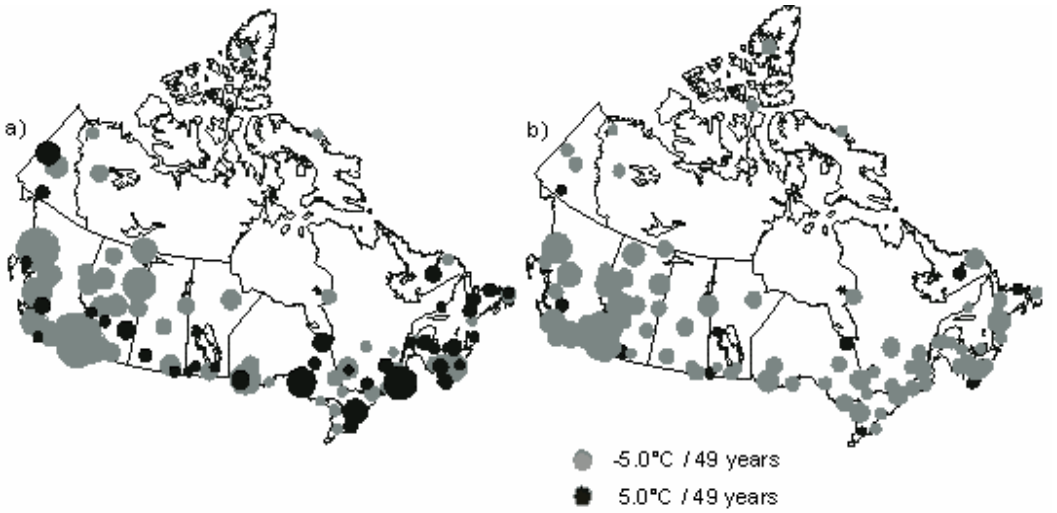


Figure 3. Trends in percentage of days with minimum temperature below the 5th percentile during summer for 1950-1998, a) before adjustment and b) after adjustment. Grey and black dots indicate negative and positive trends only for the stations experiencing a change in trend caused by the adjustment. Size of the dots is proportional to the magnitude of the trend.

2.3 Bias in the minimum temperatures introduced by a redefinition of the climatological day

At principal stations (often airport stations) throughout eastern Canada, the homogeneity procedure has identified a decreasing step of about 0.6 to 0.8°C in 1961 in annual mean minimum temperature series. This bias resulted from a nation-wide redefinition of the climatological day at principal stations in July 1961. At that time, it was decided to change the reporting of the daily maximum and daily minimum temperatures from the 00Z-00Z climatological day to the 06Z-06Z window. Since the 06Z hour correspond more closely to the time when the actual minimum temperature is more likely to occur in eastern Canada, the same minimum was often recorded on two successive days thus leading to more days with lower minimum temperatures. This change has resulted in a decreasing step in the annual minimum temperatures at principal stations. This inhomogeneity also accentuated the cooling trend in the annual minimum temperatures and in the frequency of extreme low temperatures over eastern Canada over the past 50 years. An example is presented in Fig. 4. A preliminary assessment of this issue has been presented in Cameron and Wilson (1996).

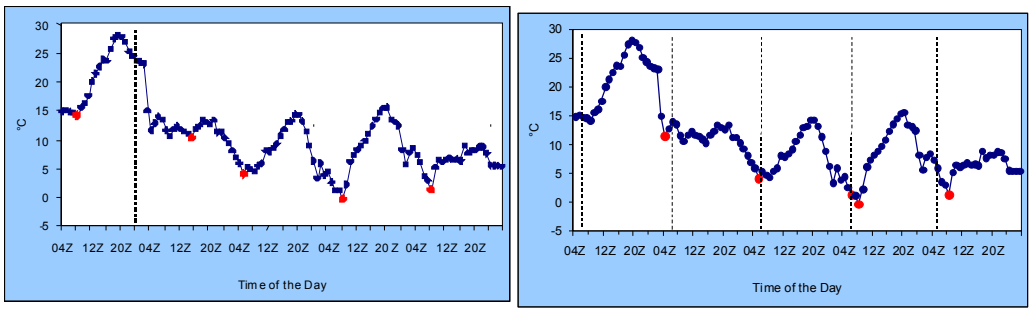


Figure 4. Hourly temperatures of Mont Joli, May 21 to May 25, 1980; a) for the 00Z-00Z and b) for the 06Z-06Z. The minimum temperature identified in red is different depending on how the climatological day is defined.

3. New improvements in precipitation adjustments

The adjusted daily precipitation time series created for the First Generation Historical Adjusted Climate Database was produced in 1996 and updated annually since then (Mekis and Hogg, 1999). Adjustments were applied on daily rain and snow separately at 495 stations across the country. For each rain gauge type, corrections to account for wind undercatch and evaporation, gauge specific wetting loss corrections were implemented. For snowfall, density corrections based upon coincident ruler and Nipher measurements were applied to all ruler measurements. Great care was taken to properly account for the trace measurement as well. Since then it was possible to revisit some of the issues part of the method and more detailed or extended studies were completed.

It is extremely important to update the datasets regularly, revise the selected stations and include new methodologies when new instruments or measurement practices are introduced. A crucial problem presently in Canada is the replacement of manual observing stations with fully automated stations (Milewska and Hogg, 2002). Several of our best records are broken due to the fact, that separate rain and snow measurements are not available any more. In case of total precipitation measurements resulted from an auto station, the lack of overlapping measurements or known instrument problems like wind pumping are causing further serious headaches to the climate research community. We did mot make any attempt to include the measurements originated from auto gauges into the adjusted precipitation database yet.

The three topics discussed here in further details are the new developments achieved on 3 related fields: snow water equivalent adjustment factor (SWEAF) map recomputation (Mekis and Hopkinson, 2004), sensitivity study for proper adjustments of wetting loss at the rain gauge and the most recent results of precipitation station joining (Mekis and Vincent, 2002).

3.1 Derivation of an improved snow water equivalent adjustment factor map for application on snowfall ruler measurements in Canada

The depth of freshly fallen snow measured by ruler has been the standard measurement of snowfall since Canadian snowfall measurements began. For all stations, prior to the 1960's, and for most non-synoptic stations over the entire record, total precipitation (water equivalent) for snowfall events is determined by assuming a standard density for freshly fallen snow of 100 kg m^{-3}. At synoptic stations, a Nipher shielded snow gauge was introduced in the 1960's to directly measure snow water equivalent for determination of precipitation amount, but depth of snowfall measurements with a ruler were continued. The adjustment of ruler measurements to be homogeneous with Nipher gauge data would raise a number of difficulties, including that of the snow density in the past. The limiting factor for the use of Nipher shielded snow gauge data is its restricted availability both in time (Nipher gauges were first installed in the 1960's) and space (there are almost 10 times more ruler measurement stations). As well, inherent to the Nipher measurements are all the problems associated with gauge undercatch due to wind and wetting loss. Because the process of ruler measurement has undergone fewer changes over time, the use of daily snow ruler data is more appropriate for climate change studies. The Canada-wide map for the Snow Water Equivalent Adjustment Factor (SWEAF) could be applied on any snow ruler measurements available for over 2000 locations across Canada. For the computation of snow water equivalent the use of the standard density of freshly fallen snow is rejected. The use of the SWEAF map can provide appropriate snow water equivalent values suitable for hydrologic studies, for example.

3.1.1 Data and methodology

The snowfall water equivalent computation method follows Metcalfe et al. (1994) and is based on the ratio of adjusted Nipher gauge measurements to snowfall ruler depth measurements for all events greater than trace values during the period of record when snow ruler and Nipher gauge measurements were made coincidentally. The adjustment procedure

accounts for gauge undercatch due to wind and for wetting and evaporation losses. The rain gauge correction values originated from the publications by Metcalfe et al. (1997) and Routledge (1997).

Using the Canadian National Archive of Climatological Observations, all stations with hourly and synoptic programs were selected for the period 1960-2001. The applied condition was the co-existence of the six-hourly and daily precipitation measurements and the six-hourly wind measurements.

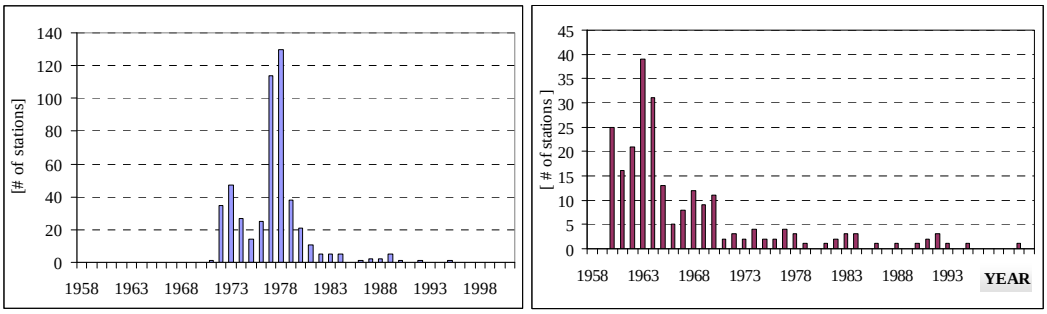


Figure 5a and b: Distribution of the Type B rain (495 stations) and Nipher (233 stations) gauge installation year across Canada

For the proper adjustment procedure, the following metadata information is required: precipitation gauge installation dates for Nipher gauge and MSC Type B rain gauge, anemometer height and wind exposure code. The distributions of Type B and Nipher gauge installation years are plotted on Figures 5a and 5b.

The wind-related metadata is required for the proper adjustment of the Nipher gauge data for undercatch associated with windy conditions. Although the Nipher shield was designed to minimize the disturbance of airflow around the orifice to the gauge, Goodison (1978) demonstrated that the Nipher shield reduced the undercatch but did not eliminate it. Anemometer height is a highly variable value within the range of 5 to over 30 m. The most difficult task was to get wind exposure codes in each direction. The 7 possible exposure codes applied in the study are: (1) fully open, (2) flat, open, (3) flat, open with some obstructions, (4) small building or trees, (5) building nearby, airport, (6) buildings, towers, trees or hills, (7) sheltered in all direction, on the top of building. Final exposure code is given by the average of all 4 directions at any station. Exposure code sensitivity on the SWEAF was studied for 50 stations. The result clearly showed that a small change in the exposure code does not have significant effect on the final results.

3.1.2 Station selection, search for outliers

The stations were classified based on the continuity of measurements and missing records. Different classes based on station quality and longetivity are introduced. The location of stations with over 20 years of data, additional stations with 15 to 20 years of data and the location of the original 63 stations used in the Mekis and Hogg, (1999) study are presented in Fig. 6. It was decided that in the final map, only the best quality stations (stations with more then 20 years of continuous measurements) would be included.

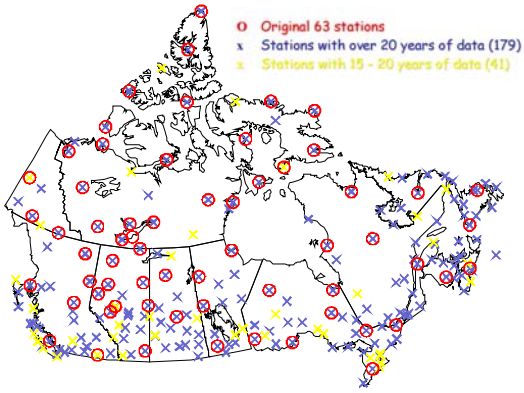


Figure 6. Station locations used in the SWEAF study.

The SWEAF ratios are computed for each location for each greater than trace precipitation events. The final interpolated map was developed using Kriging with a linear variogram model. The applied resolution is 100 km, no significant difference had been found for greater grid resolution computations (e.g. 50 km). The first version of contoured adjustment factor maps is plotted in Fig. 7. This map contains all 179 stations which qualified (met the requirement of more than 20 years of continuous measurements). The next step was the evaluation of the resultant contour map based on spatial consistency, in other words searching for outliers by comparing close-by stations. The locations mentioned in the paper below are also plotted.

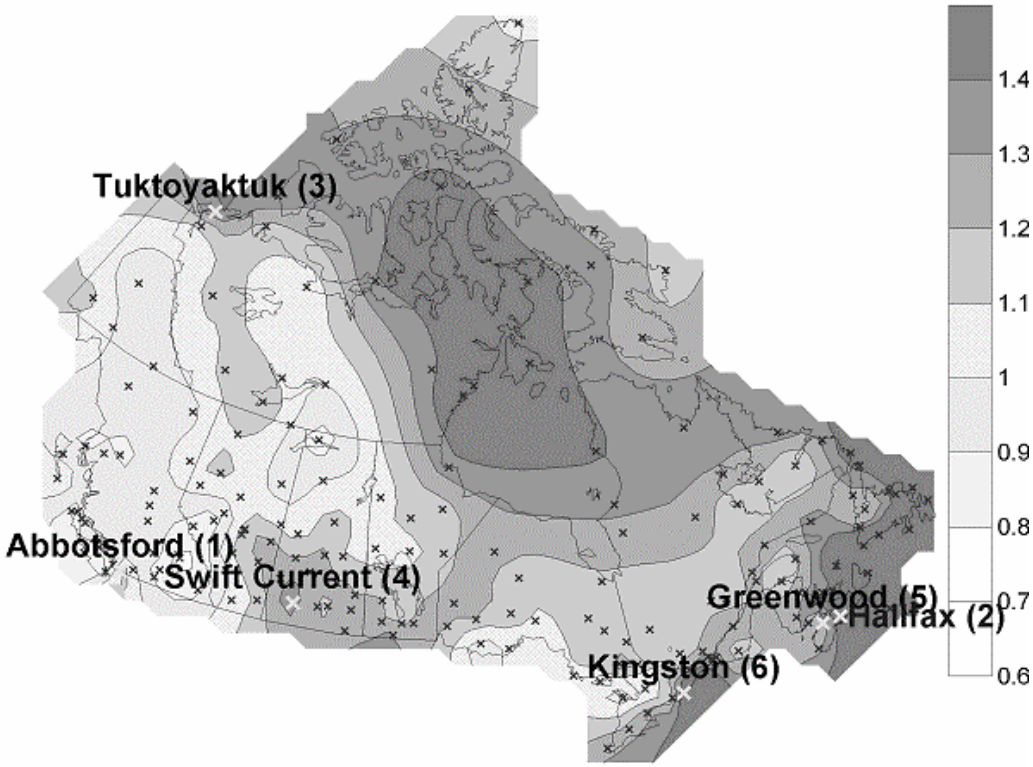


Figure 7. New SWEAF map with outliers included in the analysis.

(1) On the west coast *Abbotsford* was removed after careful comparison with two nearby locations Vancouver and Victoria.

(2) The anemometer heights at *Halifax* looked anomalous. After an extensive metadata search it was revealed that the anemometer was not installed at the standard 10 m because of a local airport planning restriction. The metadata reflected the real situation; it was retained in the SWEAF analysis.

(3) The situation with *Tuktoyaktuk* was less obvious. After the comparison of daily measurements from different resources, it turned out, that there was no Nipher

program at this location so the station data could not be used for the SWEAF analysis. The station was removed from the final selection.

(4) The case of *Swift Current* is just the opposite. The reason of discrepancy between Moose Jaw and Swift Current is the probable use of Nipher gauge measurements to estimate snowfall measurements as well, for part of the observing period. For this reason, this station had to be removed.

(5) The relatively lower values at *Greenwood* compared to the area initiated further metadata search. Greenwood has a good reputation for careful and consistent measurements. It is located in an area which receives a lot of "lake-effect" type snow from the Bay of Fundy, much like the area around the Great Lakes. The behaviour of this station compared to other locations in Nova Scotia is shown to be different. Greenwood was kept in the selection.

(6) *Kingston* in Ontario had to be removed as well. It is a clear outlier but the specific reason for its anomalous value could not be determined.

The final map after removing the outlier locations of Abbotsford, Tuktoyaktuk, Swift Current and Kingston is plotted on Fig. 8.

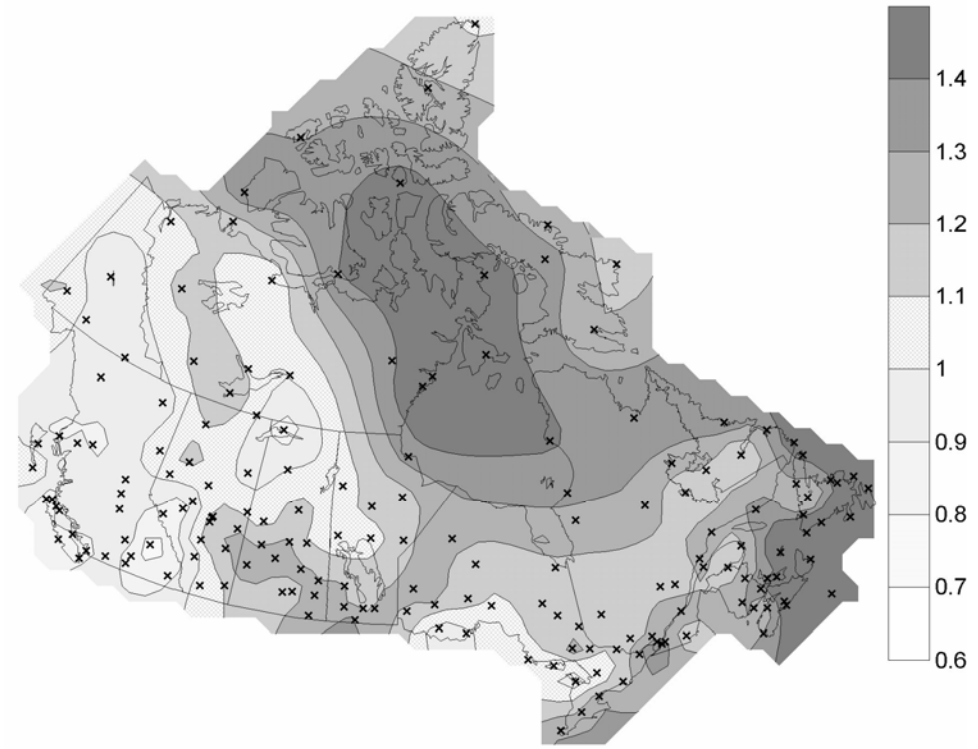


Figure 8. Final SWEAF map based on 175 locations across Canada.

3.1.3. Snow Water Equivalent Adjustment Factor map

A comparison of the original figure published by Mekis and Hogg, 1999 and a new SWEAF figure using the same 63 locations revealed some differences. It could be explained by the fact that the actual computation period became longer and the metadata were occasionally updated based on new evidence.

The major achievement of the improved SWEAF map is a higher station density, an extensive metadata search and a very thorough search for outliers. Using spatial interpolated data based on 175 locations across Canada, the SWEAF map provides an excellent tool to estimate realistic snow water equivalent from snowfall measurements. The resultant snow water equivalent estimates provide a good basis for several climate research studies, including climate change.

3.2 Wetting loss corrections sensitivity study of different rain gauges

In the Canadian literature, three different set of numbers were suggested for correcting the losses associated with retention on the gauge container and the evaporation (Ref_1: Metcalfe et all, 1994; Ref_2: Metcalfe et all, 1997, Ref_3: Routledge, B., 1997). It was agreed, that Ref_2 is an improvement over Ref_1. In the present status of the adjustment procedure the correction factors found in Ref_3 was applied. Different adjustment factors may have a significant effects on the dataset used for climate change studies. The proper assessment of the issue is possible only through a sensitivity study using all cases.

The adjustments associated with the instrument changes at specific dates for daily rain measurements for wetting loss corrections are:

	$date_1$		$date_2$		
MSC Copper liner	↓	MSC Plastic liner	↓	Type-B	
	↓		↓		
----------	o		•----------		
	•----------		o		
"measured"× 1.04		× 1.04	× 1.02	gauge undercatch	
					same for $Ref_{2\&3}$
+ 0.36 [mm]		+ 0.17 [mm]	+ 0 [mm]	retention & evap:	Ref_1
+ 0.17 [mm]		+ 0.14 [mm]	+ 0 [mm]		Ref_2
+ 0.21 [mm]		+ 0.19 [mm]	+ 0.12 [mm]		Ref_3

3.2.1 Effect on trend

The adjusted time-series are computed using wetting loss correction from References 2 & 3. For trend computation the Mann-Kendall test was used. The autocorrelation was NOT removed. In the study the complete time period was included at each location (which varies by locations), since the effect of different wetting loss corrections on trends are studied, and the actual trend values at different locations are not compared to each other.

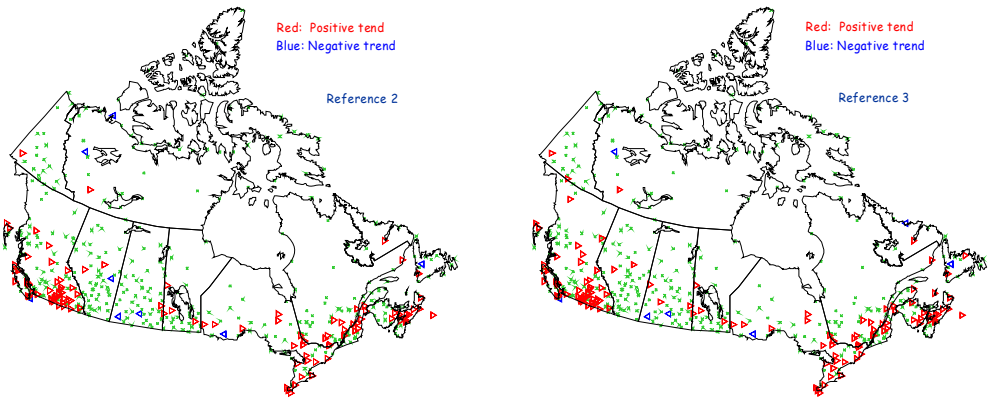


Figure 9a and b: Trend computation using wetting loss correction factors from Ref_2 and Ref_3 respectively.

The negative / not significant / positive trends for Ref_2 respectively are: 8 / 384 / 103 and using adjusted data with factors suggested from Ref_3 are as follows: 7 / 369 / 119 (Fig. 9a and b). The trend changed in any direction only for 23 stations, which is less then 5 % of all the cases. As a conclusion, the adjustments due to wetting loss calculated from Ref_2 and Ref_3 do not have significant impact on the trends.

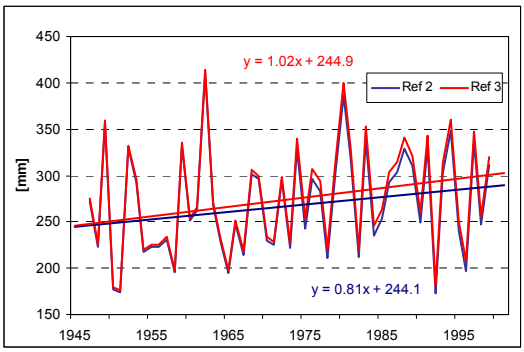
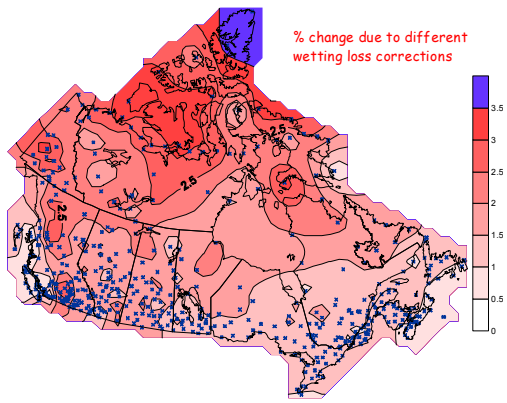


Figure 10. Annual Rain Trends for Dease Lake

The case study of Dease Lake (one of the 23 stations where the trend became significant) plotted on Fig. 10 is a good example to show the effect of two different wetting loss corrections on the result. In most cases the trend increased slightly due to the higher correction factor towards the end of the time-series (Type-B correction). If the original series were close to the significant limit, the trend using Ref_3 wetting loss adjustment may become significant.

3.2.2 Effect on magnitude

The total mean annual rain for the interval 1961 – 1990 was computed first using Ref_2 & Ref_3 wetting loss corrections. The ratio of results (Ref_3 / Ref_2) expressed in % is plotted on Fig. 11a and the difference (Ref_3 - Ref_2) is mapped on Fig. 11b. The largest change in percentage 3.8% located at Eureka on the high Arctic, the actual value of it is only 1.1 mm here (the mean annual rain total is ~30 mm). As another extreme, the biggest change in the absolute value of mean annual total rain obviously occurred on the West coast in British Columbia where the annual mean rain is over 3000 mm, the difference of 20 mm means here less then 1% of total rain. The final conclusion is that the difference between Ref_2 and Ref_3 wetting loss correction are negligible.



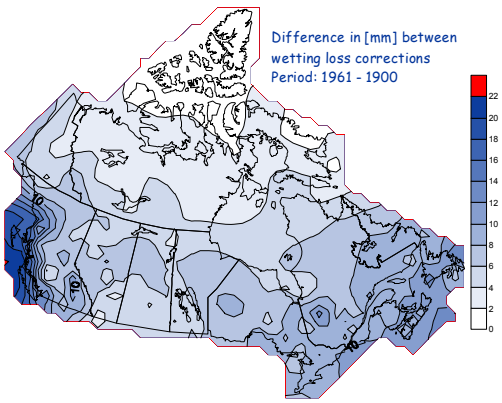


Figure 11a. Percentage change **Figure 11b. Difference in [mm]**

3. 3 Station Joining

In Canada station joining is inevitable. During station relocations new station identification number was assigned to the new location, but for climate change studies after proper adjustments the two locations should be united. The task is to find the connected segments and adjust the possible inhomogeneities caused by the relocation.

The list of possible segment was identified based on metadata. Out of the originally selected 495 stations, 186 contain more then one segments. When common observations

over a period of time were available, adjustments could be derived from Simple Ratio Method (Thom, 1966). The main objective of this work is to investigate alternative methods (such as homogeneity methods) to determine the factors needed for the adjustment of joined precipitation observation segments. Here the already widely used Alexandersson (1986) and the newly developed Vincent (1998) methods for precipitation are applied to specified case studies and the results are compared. Since automation of all climate observations is now a priority, it is hoped that a new procedure could eventually be used for combining human and automated precipitation observations. The major difference between a conventional homogeneity test run and the application for the joined station is that the year of possible problem is known here, namely the joining year. That is why it is called “Forced Year Method”.

Homogeneity techniques were applied on monthly and annual total rain and snow series computed from daily rain and snow. Using the condition of data availability around the joining year (typically 20 or 30 years were applied), all surrounding stations was selected within a given radius. Interpolated grid values were also derived for whole Canada including all station information at a given time. Three types of reference series were produced: the average of all surrounding stations, the average of the highest correlated and longest series (called “Best”) and average of grid values around the base station. The highest correlated stations may be different for rain and snow. Any outliers were removed from the computation and the missing values are decided not to be estimated.

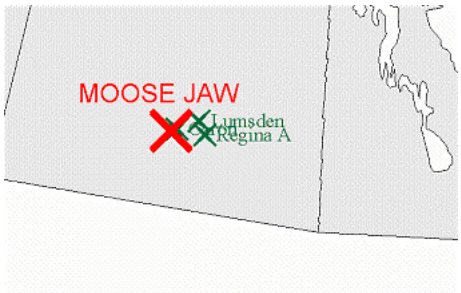


Figure 12. Moose Jaw map

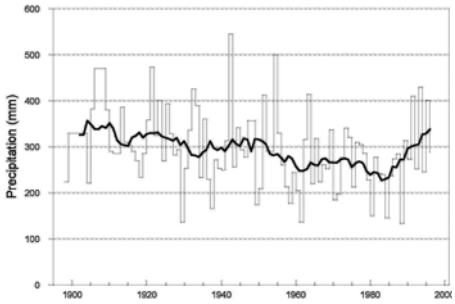


Figure 13. Moose Jaw rain annual plot

For easier understanding of the whole process, one case study is presented here. Moose Jay Chab is located on the Canadian Prairies, close to the US border (Fig. 12). New station Moose Jaw was opened in 1943 located 12 km away from the original Moose Jaw Chab station which was closed in 1954. The two locations have over 10 years of overlapping period (Table 1). The time-series of the joined station (joining year is 1944) for rain is plotted on Fig. 13. For the purpose of surrounding station, within 60 km radius, 3 stations were found, Caron, Lumsden and Regina. The reference series was computed using the cross correlation analysis results. For rain, the base station was best correlated with Lumsden, for snow it was Caron (Table 2). These are the series used for the “Best” stations then.

Station Name	Province	Overlap Exist?	Overlaping days # Snow	Overlaping days # Rain	Periods	Station Identification	Max Elevation Difference [m]	Distance between segm.	Joining Year	Snow to Total ratio
MOOSE JAW MOOSE JAW CHAB	SASK	Y	789	802	1895/1-1954/5 1943/1-1998/8	4015325 4015320	22	12.0	1944	34

Table 1. Metadata information

					RAIN								SNOW			
St_id	Station_name	Region	Dist.	Elev	An_Corr	Lgth	Su_Corr	Lgth	Au_Corr	Lgth	From	To	An_Corr	Lgth	W_Corr	Lgth
4015325	MOOSE JAW	1944		577							1895	1954				
4011280	CARON	SASK	25.9	579	0.72	38	0.61	60	0.88	57	1915	2001	0.8	37	0.67	48
4014720	LUMSDEN	SASK	59.8	497	0.84	48	0.73	66	0.84	58	1922	2001	0.8	48	0.63	52
4016560	REGINA A	SASK	63.6	577	0.73	89	0.67	97	0.78	96	1898	2001	0.67	84	0.64	87
	4015320_Average				0.83	90	0.82	100	0.9	98	1895	2001	0.86	84	0.8	87
	4015320_Grid				0.81	90	0.79	100	0.88	98	1895	2000	0.82	84	0.75	87
	4015320_Best				0.84	48	0.73	66	0.84	58			0.84	31	0.68	39

Table 2. Correlation Analysis – Moose Jaw

The homogeneity test results are summarized in Table 3. For the actual computation of the Alexandersson method, the AnKlim software was used (Štepánek, 2000). The values are the actual adjustment factors should be applied in the joining year (1944) for the given month or year and for the specific element. The significant step change was identified through the test value (Fig. 14b) and highlighted in Table 3. In case of Moose Jaw, the joining of the two annual rain series caused significant step change which should be corrected.

	Joined: 1944 30 yr.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Moose Jaw - RAIN	Vincent - Aver.				1.14	0.94	**0.66**	0.93	**0.29**	0.87	0.56			**0.78**
	Vincent - Best				0.54	0.77	**0.64**	0.99	**0.18**	0.70	0.37			**0.79**
	Vincent - Grid				1.07	0.95	**0.69**	0.97	**0.40**	0.82	0.54			0.76
	Alex - Average				1.23	1.17	**0.79**	1.09	**0.65**	0.83	0.76			**0.88**
	Alex - Best				0.68	0.87	**0.64**	0.92	0.52	0.88	0.93			**0.90**
	Alex - Grid				0.97	1.14	**0.79**	1.06	**0.66**	0.76	0.79			**0.85**
	SRM				0.88	0.85	**1.24**	0.95	**1.36**	0.61	1.12			**1.07**
Moose Jaw - SNOW	Vincent - Aver.	1.20	1.35	**0.97**	**2.20**	1.22				1.00	0.95	1.31	1.26	1.23
	Vincent - Best	0.84	**1.63**	**0.57**	**1.96**	0.40				1.00	0.78	1.07	1.08	1.15
	Vincent - Grid	1.44	1.51	1.10	1.63	1.30				1.00	0.92	1.51	1.44	1.32
	Alex - Average	1.01	0.87	**0.76**	1.76	1.54				1.00	0.73	0.86	1.00	0.90
	Alex - Best	0.70	1.31	**0.53**	1.42	0.63				1.00	1.08	0.86	0.74	0.99
	Alex - Grid	0.91	0.79	0.71	0.82	2.99				0.90	1.37	0.72	0.77	0.85
	SRM	1.32	0.83	1.39	1.00	0.84				1.36	1.36	1.42	8.04	1.36

Table 3. Homogeneity test results – suggested adjustment factors - Moose Jaw.

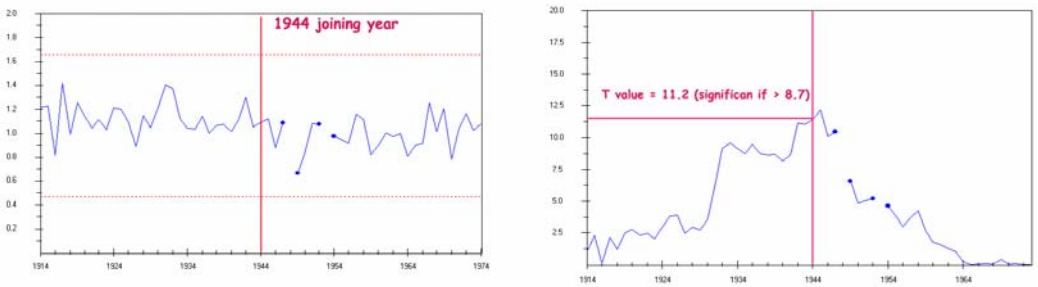


Figure 14a and b. Plot of ratios (base station and average of reference series) and test values for annual rain.

The homogeneity testing of joined 186 precipitation stations has started but it is far from completion. The results should also be compared to the Simple Ratio Method, which can be improved by computing gradually changing adjustment factors as well. The final decision about the suggested adjustment factors applied on the daily rain and snow data will also be a difficult task.

4. A comparison of methods for the identification of steps in temperature series

Over the past years, many techniques were presented in the scientific literature for the identification of discontinuities in climatological time series. Most of them have been tested for their ability of detecting a single step. However, very few methods have been evaluated for the detection of multiple steps or to determine whether the series is homogeneous. In this study, seven methods were compared for the identification of homogenous series, series with one step and series with a random number of steps using simulated annual temperature datasets. A detailed description of the methods and of the analysis is provided in Ducré-Robitaille et al., 2003.

4.1. Simulation of temperature series

To simulate an homogenous series, random numbers normally distributed with mean zero and variance one were generated from an AR(1) model with an autocorrelation equal to 0.1. This process was repeated 1000 times to produce 1000 homogenous series of 100 values (or years). To simulate series with one discontinuity, a step was artificially introduced in the homogenous series. Its magnitude varied from 0.25°C to 2.0°C with an incremental increase of 0.25°C, and its position was set to 5, 10, 15, 20, 35 and 50. To simulate the series with a random number of steps, the magnitude of the step (ranging from 0.25°C to 2.0°C) followed a normal distribution whereas the time interval between two consecutives steps followed a truncated exponential. A reference series was also created for each candidate series. A homogenous series was first generated and then it was cross-correlated with the candidate series (before the introduction of the discontinuity) by multiplying the candidate values by 1.5 and adding them to the reference series. Each series were then re-standardized to have similar mean and variance of those of the candidate series.

4.2. Overview of the methods

Seven methods were selected for the comparison study. They are:

- Standard Normal Homogeneity Test (SNHT) without trend (Alexandersson, 1986)
- Standard Normal Homogeneity Test (SNHT) with trend (Alexandersson and Moberg, 1997)
- Multiple Linear Regression (MLR) (Vincent, 1998)
- Two-Phase Regression (TPR) (Easterling and Peterson, 1995)
- Wilcoxon Rank-Sum (WRS) (Karl and Williams, 1987)
- Sequential Testing for equality of means (ST) (Gullett et al., 1990)
- Bayesian Approach (Perreault et al., 2000).

4.3 Identification of homogenous series

To assess the ability of each method to determine if a series is homogeneous, the methods were applied to homogeneous series and the frequency of the steps falsely detected was recorded (Table 4). The SNHT with trend, TPR and WRS are not as dependable as the others since their percentage of false detection reach 13.3%, 41.3% and 56.3%, respectively. The percentage of false detection represents the percentage of series for which the null hypothesis of no step is rejected when in fact this assumption is true and it is expected to be 5%. The SNHT no trend, MLR, and Bayesian with reference are found to be the most reliable techniques for the identification of homogeneous series since they have a relatively low rate of false detection and the detected steps tend to be very small.

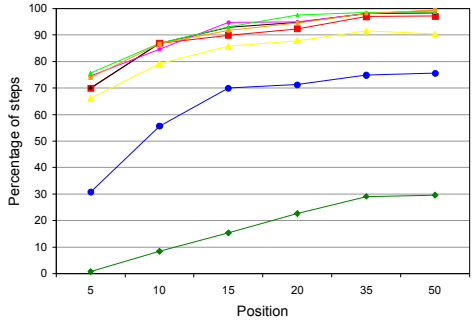
4.4 Identification of a single step

To evaluate the performance of the methods to detect the position and magnitude of a single step, the methods were applied to the series with a step. A step was identified when its position was within ±2 years and its magnitude within ±0.2°C. Fig. 15 summarizes the results. Two methods are definitely less precise than the others: ST and Bayesian without reference. The ST uses a 5-years window to detect a step and the length of the window is probably insufficient to determine its statistical significance. As for the Bayesian approach without reference, the difficulty for detecting the step is due to the absence of reference series. The results also show that steps greater than 1.0ºC are identified by SNHT with and without trend, MLR, TPR, WRS and Bayesian with reference more than 80% of the time at position 20. For the steps less 1.0ºC, it is the SNHT without and with trend and the Bayesian with reference that seem to offer the best precision.

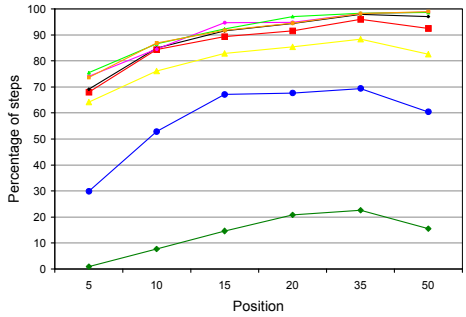
Magnitude (°C)	SNHT no trend	SNHT with trend	MLR	TPR	WRS	ST	Bayes no ref.	Bayes with ref.
0.0 - 0.1	0.2	0.0	0.2	12.9	6.6	0.0	0.0	0.5
0.1 - 0.2	1.8	3.0	1.0	15.0	22.0	0.0	0.0	2.5
0.2 - 0.3	4.0	4.4	1.4	8.2	16.7	0.0	0.0	2.1
0.3 - 0.4	1.4	2.8	0.6	3.9	8.1	0.3	0.0	0.9
0.4 - 0.5	0.9	1.9	0.3	1.0	1.7	0.3	0.5	0.4
0.5 - 0.6	0.3	1.1	0.1	0.2	1.0	0.3	1.5	0.4
> 0.6	0.0	0.1	0.0	0.1	0.2	3.5	3.8	0.0
Total	8.6	13.3	3.6	41.3	56.3	4.9	5.8	6.8
Total > 0.4	1.2	3.1	0.4	1.3	2.9	4.6	5.8	0.8

Table 4. Percentage of steps falsely detected by each method when applied to 1000 homogeneous series (%).

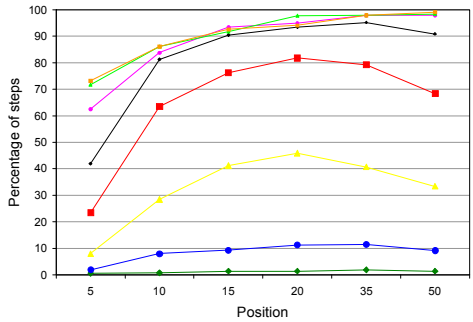
a) SHNT no trend



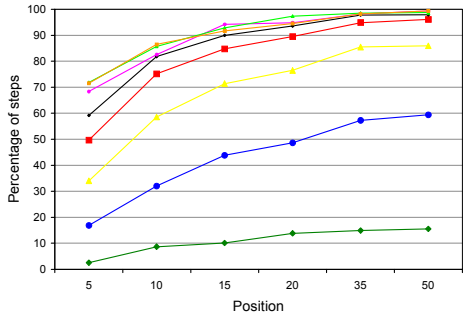
b) SNHT with trend



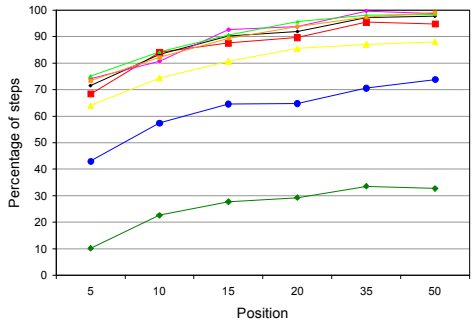
c) MLR



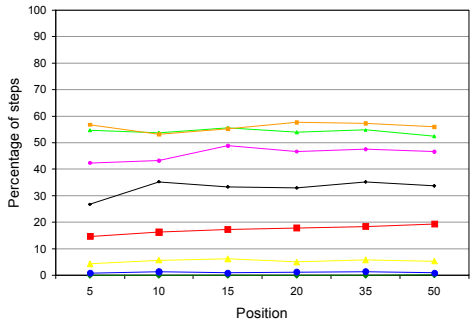
d) TPR



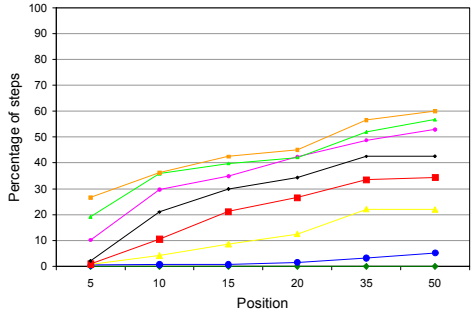
e) WRS



f) ST



g) Bayes no reference



h) Bayes with reference

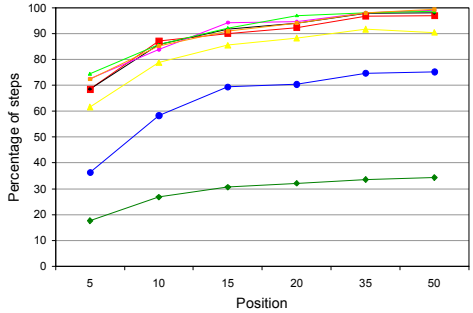


Figure 15. Percentage of steps identified when one artificial step is introduced. The magnitude is represented by a color (0.25-dark green, 0.5- blue, 0.75-yellow, 1.0-red, 1.25-black, 1.5-pink, 1.75-light green, 2.0-orange).

4.5 Identification of a random number of steps

The methods were also tested to identify a random number of steps. After detecting the first step, the series is divided into two segments at the position of the step and each segment is re-tested separately. This process continues until each segment is assessed to be homogeneous or its length is less than 10. The percentage of series with the number of steps detected versus the number of steps artificially introduced in the candidate series was recorded. The results showed that the SNHT without trend is definitely the best method for detecting the correct number of steps randomly introduced in the tested series, followed by SNHT with trend and MLR. A detailed description of this analysis is provided in Ducré-Robitaille et al., 2003.

5. Variations and trends in climate indices for Canada

Climate indices are valuable to evaluate the potential impact of climate change on our activities, agriculture and economy and they are also useful to monitor the climate change on a global basis (Peterson et al. 2001). The summary of the study of the variations and trends in selected climate change indices for Canada over 1950-2001 and 1900-2001 is presented. A paper with a more detailed analysis of the trends and variations in the climate indices is under preparation. Additional indices and seasonal distribution will also be examined on local and regional scale. A few initial results will also be presented in the Poster session of AMS (Vincent and Mekis, 2004).

5.1 Temperature indices

The indices are based on daily maximum, minimum and mean homogenized temperatures for 210 stations across the country (Vincent et al. 2002). Table 5 presents a list of the indices assembled into categories. The frost-free season is the maximum number of days with daily minimum temperature above 0°C, whereas the growing season length is the number of days starting with mean temperature above 5°C for 5 consecutive days and ending with mean temperature below 5°C for again 5 consecutive days. The extreme temperature range and the standard deviation of the daily mean (computed from the daily 1961-1990 averages) were analyzed. The cold extremes are given by the frost days, cold nights, cold days and cold wave duration index while the warm extremes are given by the summer days, warm nights, warm days and heat wave duration index. The percentile used for the above variables is obtained from 150 values: five equally space day's window centered at the calendar day over 1961-1990. The cold (heat) wave duration index is the maximum number of consecutive days during the year with the minimum temperature 5°C below the daily normal (maximum temperature 5°C above the daily normal): the daily normal is also calculated from 150 values as for the percentiles.

5.2 Precipitation indices

In the study the Canadian Historical Rehabilitated Precipitation dataset (Mekis and Hogg, 1999) was used. A list of the precipitation indices is presented in Table 6, the indices are also classified into categories to provide different and independent information. The indicator computation was applied only for greater then trace events (except the snow to total ratio). To determine the frequency of precipitation events, trends are computed on the annual number of days with total precipitation, rain, and snow. The number of maximum consecutive dry days in every year is used to characterize long dry spells at each location. To measure the intensity of the events, the simple day intensity index for total precipitation and rain is examined. The simple day intensity index for rain is the ratio between annual total rain amount and the number of days with rain (same calculation is applied for total precipitation). The ratio of snowfall to total precipitation describes the change in the form of precipitation. To represent extreme wet conditions, the time series of the highest 5-day total precipitation, rain and snow were analyzed. The very wet days (number of days with total precipitation above 10 mm) and the number of days with total precipitation above the 95th percentile (calculated from the 1961-1990 average) are also included in the study.

5.3. Methodology

The non-parametric Kendall's test was used to estimate the slope of the trend at any individual station. This method is less sensitive to the non-normality of a distribution and it is less affected by extreme values and outliers, as compared to the least squares method. Since serial correlation is often present in many climatological time series, the procedure also takes into account the first lag autocorrelation: a detailed description of the trend computation can be found in Zhang et al. 2000. The 3/5 rule was applied for both temperature and precipitation indices (in any month if more than 3 consecutive days or more than 5 random days are missing, then the month is missing for the year). For each station trends are computed only if less than 20% of the years are missing. A single time series is also produced for the entire country by averaging the stations anomalies (departures from the 1961-1990 average). Since very few stations have climate observations prior 1945 in the northern regions of the country (north of 60°N), trends are analyzed for two separate time periods: 1950-2001 and 1900-2001.

5.4 Trends in temperature indices

Table 5 summarizes the findings by presenting the number of stations with significant decreasing trends, no significant trends and significant increasing trends for each temperature indices. For 1950-2001, the frost-free season has increased by 15 to 20 days at many stations across the country whereas the growing season length has significantly increased only at a few stations. The variability defined by the extreme temperature range and the standard deviation of the daily mean has not changed much at most stations over the same period. The results also show that more stations have changed in their cold extremes than in their warm extremes. For example, the number of frost-days and cold nights (Fig. 16a) has significantly decreased by 15 to 30 days at many stations whereas the number of cold days and the cold wave duration have decreased mostly in the west. Conversely, the summer days and heat wave duration have not greatly changed while several stations have experienced significant increasing trends in the number of warm nights and warm days (Fig. 16b) over the past 50 years.

Over 1900-2001, similar trends were found with a few exceptions. The frost-free season has increased by 20 to 30 days while the growing season has not significantly changed. The extreme temperature range has decreased by 4 to 6°C at more than half of the

stations. The results also show many stations with significant decreasing trends in the cold extremes. The average anomaly series of the whole country for the number of cold nights has also been decreased by 30 days throughout the century (Fig. 18a). The warm extremes have not greatly changed (Fig. 18b) with the exception of the warm nights where the time series for the whole country shows an increase of 18 days over the past century.

		1900-2001			1950-2001		
Categories	Indices	negative	not sign.	positive	negative	not sign.	positive
Season length	Frost-free season	1	29	**36**	0	133	30
	Growing season length	0	53	10	0	138	19
Variability	Extreme temperature range	**24**	40	0	9	147	2
	Standard deviation of Tmean	17	54	1	10	140	17
Cold extremes	Frost days	**44**	22	0	**48**	113	2
	Cold nights: days with Tmin < 10th perc.	**60**	12	1	**69**	102	0
	Cold days: days with Tmax < 10th perc.	**32**	42	0	37	129	3
	Cold wave duration index	**24**	47	2	13	158	0
Warm extremes	Summer days: days with Tmax > 25°C	5	53	8	0	123	28
	Warm nights: days with Tmin > 90th perc.	0	34	**39**	1	127	**43**
	Warm days: days with Tmax > 90th perc.	2	57	15	1	139	29
	Heat wave duration index	3	67	4	3	156	10

Table 5. Number of stations with significant negative, not significant and significant positive trends for the temperature indices over 1900-2001 and 1950-2001 respectively (significant at 5% level). The number in bold indicates that more than 25% of the stations have significant trend. Shaded results are presented in Fig. 16.

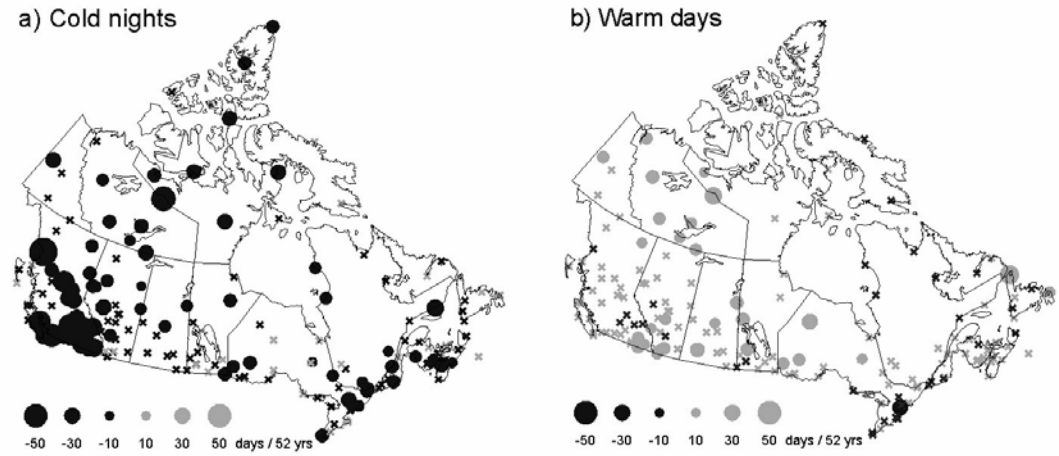


Figure 16. Trends in four temperature indices over 1950-2001.

5.5 Trends in precipitation indices

The results are summarized in Table 6. For the 1950-2001 period, the number of days with total precipitation has increased by 20 to 40 days: this increasing is mostly due to the increasing number of days with rain almost everywhere (Fig. 17a). The number of days with snow has decreased in the southern regions of the country (south of 60°N) whereas it has substantially increased on the north and northeast. The negative trends observed at many stations in the number of maximum consecutive dry days are in agreement with the positive trends in days with precipitation. Over the same period, the intensity of the precipitation events has significantly decreased at most stations while the ratio of snowfall to total precipitation has decreased in the south and increased at a few stations in the north. The findings also show that there are no consistent changes in the extremes precipitation. Only a few stations displayed significant change in the highest 5-day precipitation (Fig. 17b), rain and snow.

Categories	Indices	1900-2001 negative	1900-2001 not sign.	1900-2001 positive	1950-2001 negative	1950-2001 not sign.	1950-2001 positive
Frequency	Days with total precipitation	1	18	**55**	6	121	**110**
	Days with rain	1	15	**60**	3	90	**151**
	Days with snow	2	41	**36**	31	187	28
	Maximum number of consecutive dry days	**51**	23	0	35	198	4
Intensity	Simple day intensity index for total prec.	**42**	29	3	**60**	169	8
	Simple day intensity index for rain	**40**	33	3	**76**	162	6
	Ratio of snowfall to total precipitation	17	49	9	56	176	6
Extremes	Highest 5-day precipitation	1	65	9	5	222	11
	Highest 5-day rain	0	68	9	3	230	12
	Highest 5-day snow	7	64	9	33	203	11
	Very wet days (prec. > 10 mm)	4	54	18	9	214	21
	Days with total prec. > 95th percentile	3	64	9	2	229	13

Table 6. Number of stations with significant negative, not significant and significant positive trends for the precipitation indices over 1900-2001 and 1950-2001 respectively (significant at 5% level). The number in bold indicates that more than 25 % of the stations have significant trend. Shaded results are presented in Fig. 17.

The pattern of increasing frequency, decreasing intensity and no changes in extremes remains the same over 1900-2001. The number of days with rain anomalies for the entire country (Fig. 18c) shows that there are over 30 more days with rain in Canada since the beginning of the century. The increase in the number of days with rain and snow is consistent across the country. Most stations show decreasing trends in the simple day intensity index for total precipitation and for rain whereas the ratio of snowfall to total precipitation does not show as consistent trends as it displayed for the last half of the century (it could be analyzed only for the southern stations). Only a few stations show any significant trend in the form of extreme precipitation, and the time series for the country does not display any considerable change either (Fig. 18d). Overall the changes in precipitation events are mainly due to more frequent rain and not to a change in the form of extremes.

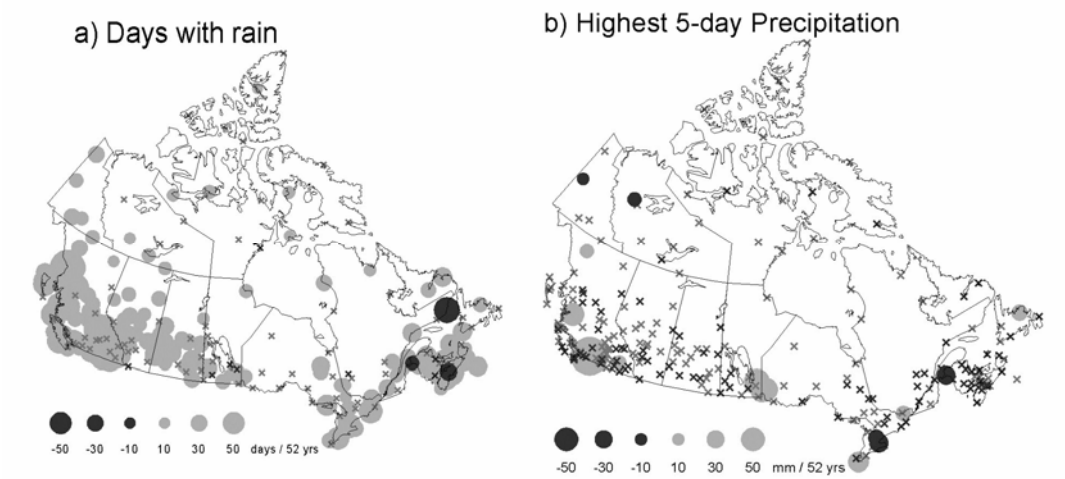
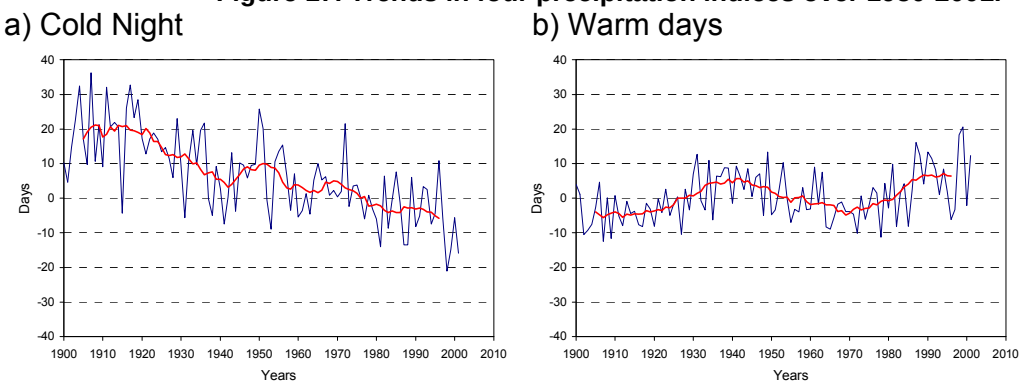
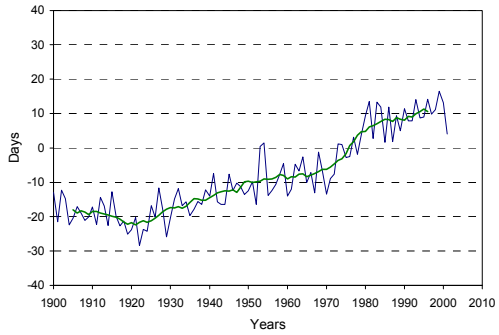


Figure 17. Trends in four precipitation indices over 1950-2001.



c) Days with Rain



d) Highest 5-day precipitation

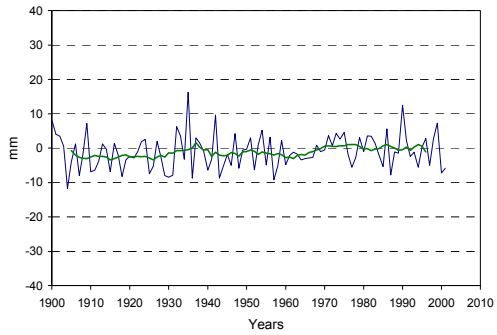


Figure 18. Temperature and precipitation indices anomalies over 1900-2001 for Canada. The red (green) line is the 11-year running mean for the given temperature (precipitation) index.

6. Summary and Future

The issues related to homogenization and quality control of Canadian measurements are often displaying local characteristics due to the sparse area of our country with diverse types of climate regions and due to the specific instruments involved in the measurement science. The existence of separate snow measurements is extremely important especially in the Cryosphere, which become endangered by automation. Many sites in Canada have already ceased human observations and begun automated observations. Any separate studies related to snow measurements (like change in the precipitation phase) will face further difficulties. Since a main objective of the database is to create long-term time series, further study will also required whether human and automated observations can be joined together to produce reliable, homogeneous time series.

The type of adjustments required for real-time application of measurements (for example North American Drought Monitor) is becoming increasingly important nowadays. The inhomogeneities at the state borders caused by the different measurement practises and measuring devices are also adding to the difficulties of getting uniform picture for any continent. The work presented in this report describe the current state of the precipitation and temperature data homogenization and further research and new methodologies are needed to address all new issues. It is an ongoing process to achieve improved datasets representing the variations in climate. The WMO plays important roll by comparing measuring devices (Goodison et al., 1999), organizing workshops and suggesting generalized homogeneity techniques for the participating countries.

7. Acknowledgements

The authors would like to offer their special thanks to Xuebin Zhang, Barrie Bonsal and Bill Hogg for their contribution in chapters 2.1 and 2.2, to Ron Hopkinson for his contribution in chapter 3.1, to Jean-Francois Ducré-Robitaille and Gilles Boulet for their contribution in chapter 4 and to the second generation adjusted precipitation working group members for all their useful advice and guidance.

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HOMOGENISATION OF A CANADIAN SURFACE PRESSURE DATABASE

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ABSTRACT

This paper describes the collection, checking and homogenisation of a Canadian atmospheric surface pressure database. The object of the exercise was to create a database of monthly mean surface pressure for as many stations as possible across Canada as far back in time as possible. Data sources included the World Weather Records, Monthly Climatic Data for the World Bulletins, the Global Historical Climate Network and the electronic meteorological report archives of Environment Canada. Much of the earlier data was in paper form and had to be digitized by hand. Over 66,000 individual mean monthly pressure values were obtained, with a missing value rate of 5.9%. The homogenisation procedures used were the Standard Normal Homogeneity Test (SNHT; Alexandersson and Moberg 1997) and Multiple Comparison Analysis (MCA; as used by Slonosky et al 1999). In addition, simple subtraction of sea-level pressure from station-level pressure revealed a major inhomogeneity which took place in 1977, when computer generated pressure reduction tables were used for the first time by the Meteorological Service of Canada, and when the meteorological reporting procedure was brought into alignment with the World Meteorological Organisation's guidelines. As a result, the final homogenised database shows appreciable differences in trends compared to the unhomogenised series. The final database has been used by Slonosky & Graham (2003) in the statistical analysis of trends and variability of surface pressure across Canada during the 20th century.

1. INTRODUCTION

This project was conceived with the aim of analysing decadal to century scale variability of surface pressure over Canada. For the study of atmospheric circulation dynamics over these timescales, an extensive temporal, spatial and homogenous surface air pressure database is necessary. Many observations of surface pressure for Canada exist back to the 19th century, but the majority are in paper form. This project was the first attempt to gather all the different data sources together, and to digitise, quality control and homogenise them. The homogenisation methods are especially important as non-climatic changes, such as site relocations, instrument replacement, or changes in the observation practice, including changes in the time of observation or calculation procedure, can introduce biases of the same magnitude as the long term climatic variability of pressure into the series, leading to spurious trends and variability (Vincent et al. 2002, Slonosky et al. 1999, Peterson et al. 1998, Young 1993). This paper describes the collection, quality control and homogenisation part of the Canadian pressure database project. For a more detailed climatological analyses of the final database, readers are referred to Slonosky and Graham (2003), who have used the database in the analysis of decadal scale circulation variability over Canada and Greenland.

2. SOURCES OF DATA

The climatic variable of interest in this study was mean monthly surface air pressure. These data were all recorded at official observing stations of the Meteorological Service of Canada observational network, starting in 1841 for Toronto and in 1873 for a selection of other stations across Canada. In this project, we used data from 1873 onwards. There were four primary sources of data, namely:

a) The World Weather Records, published each decade by the Smithsonian Miscellaneous Collections. These contain monthly mean sea and station level air pressure data in paper form for assorted Canadian and Greenland stations from 1874 to 1990. Digitisation by hand was necessary.
b) The Monthly Climatic Data for the World Bulletins. These are individual monthly bulletins, containing sea and station level air pressure records in paper form from 1959 to 1999. Digitisation by hand was also necessary.
c) Global Historical Climate Network; a few Canadian stations are available in digital format from 1873-2000.
d) Environment Canada electronic database. This archive contains data for most Canadian reporting stations from 1953 onwards, but in hourly synoptic format. It is accessible in digital format on the internet by user interface (password-protected). Due to the hourly nature of the data, it was necessary to calculate monthly means of air pressure for each station from this data. In the interests of data quality, months with fewer than 21 reporting days of data were discarded, as were days with fewer than three different synoptic reports.

Other miscellaneous sources of data included Climate Research Unit of the University of East Anglia. Data from Greenland was also included in this study, due to the existence of a few long term pressure records located in southern Greenland and the Davis Strait, close to north-eastern Canada. In total, over 66,000 individual mean monthly pressure values were obtained during the course of this project, with a missing value rate of 5.9%.

3. COMMON PROBLEMS AND EXAMPLES

As was to be expected, there were many problems encountered during the preliminary checking and quality control procedure. Table 1 lists the main problems in order of magnitude. The biggest problems encountered were related to unreported changes in station or barometer location and elevation. In the absence of metadata (information on the barometer or station history), we had to use standard homogenisation techniques to correct for such changes (these techniques are outlined in section 5).

Another major problem encountered was the so-called “50-foot” rule. This was a bizarre rule which had been introduced into Canada during the 1930s (at the start of aviation). It stated that stations with an altitude of between 0 and 50 feet above sea level should report station pressure as being identical to sea-level pressure i.e. station pressure was also reduced to sea level (McMaster 1975, Upton 1972). However, stations at an altitude greater than 50 feet did not have this correction applied. Furthermore, a site re-location of less than 50 feet in height resulted in no new established elevation for the station in question – a correction factor was assumed to have been added. This rule was abolished in 1976 under World Meteorological Organisation guidelines (Environment Canada 1976). It also coincided with metrification and computerisation of the pressure reduction tables at same time, adding to additional complications. McMaster (1975) states that mean sea level pressures would not be affected, but station pressures (for those stations previously at an altitude between sea level and 50 feet) would experience a slight drop (McMaster 1975). Infact, analysis of this database shows that the correction to station level pressure records was often the order of 1mb or more. As a result of these reporting changes between 1976 and 1977, the vast majority of station records (77%) showed some sort of spurious jump at the 1976/1977 boundary.

Other errors uncovered during the course of this project included differences between the World Weather Record values and the Environment Canada electronic archives, due to differences in the rounding procedure.

There were also frequent errors resulting from confusion between sea and station level pressures, and between metres and feet in altitude (see Table 1).

Problem	Example
Unreported changes in station location and/or station /barometer elevation	Standard homogenisation techniques were used to correct for these errors.
“50-foot” rule	All Canadian stations with an altitude between 0 and 50 feet were affected from ~1930 to 1976 (see text for more details).
Computerisation	Computer generated pressure reduction tables were used for the first time in 1976 (replacing primitive desk calculators) – the majority of Canadian stations were affected.
Conversion/rounding errors	Between 1951 and 1970, the World Weather Records (WWR) were rounded to the nearest millibar; the averages are 0.05mb higher than the Environment Canada synoptic archives (which were rounded to the nearest 0.1mb).
Confusion between feet and metres	This is a common problem (but especially in 1976 when metrification was adopted in Canada). For example, Clyde station was given an altitude of 26 feet in the WWRs of the 1940s but the WWRs of the 1990s were still listing it as 26 metres.
Confusion between “sea” and “station”	Sea level pressure was sometimes given as station pressure, and vice versa (human typing error).
“sea” and “station” data transposed	The WWR for Greenland have identical values for sea and station level pressure, regardless of station location or altitude.
Random differences between GHCN and WWR (e.g. typos, outliers)	These were usually easily identified by visual analysis.

Table 1: common problems and errors uncovered during the collection and preliminary quality control of the Canadian atmospheric pressure database. Examples of each problem are given in the right-hand column.

4. PROVENANCE

After a rigorous procedure of preliminary checking and quality control, 73 individual station series were retained from Canada and Greenland. The stations selected are shown in Figure 1. As can be seen, the longest station series (with start dates before 1900; red colour) are to be found primarily in southern Canada and southern Greenland. Those stations with records from between 1900 and 1930 (blue colour) are generally clustered in north-western Canada. The stations with the shortest series (only 50 or 60 years) are found almost exclusively in the Canadian Arctic i.e. we do not have reliable data from the Arctic from before the second world war.

Station level observations were selected in preference to sea level values, as it was considered that station level pressures were more reliable. Fewer calculations are involved in obtaining station level pressures, and therefore there were fewer opportunities for calculation related inhomogeneities to occur. In several cases only sea or station level observations were available for certain portions of a station record; in these cases, either the station information or, if the station information was unavailable, monthly transfer functions were used to relate the segments and produce a uniform station or sea level record.

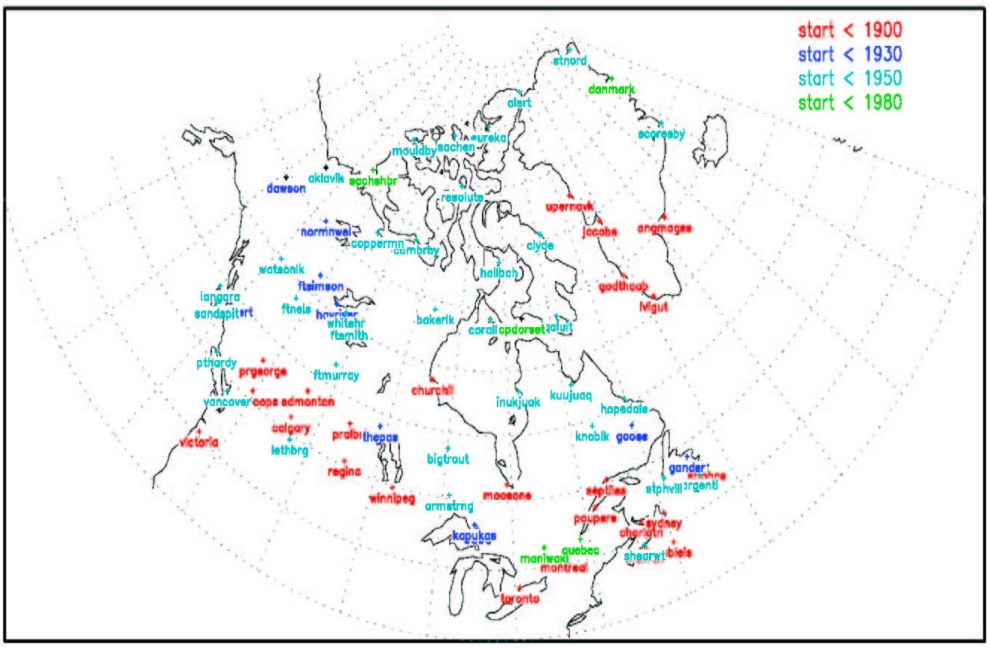
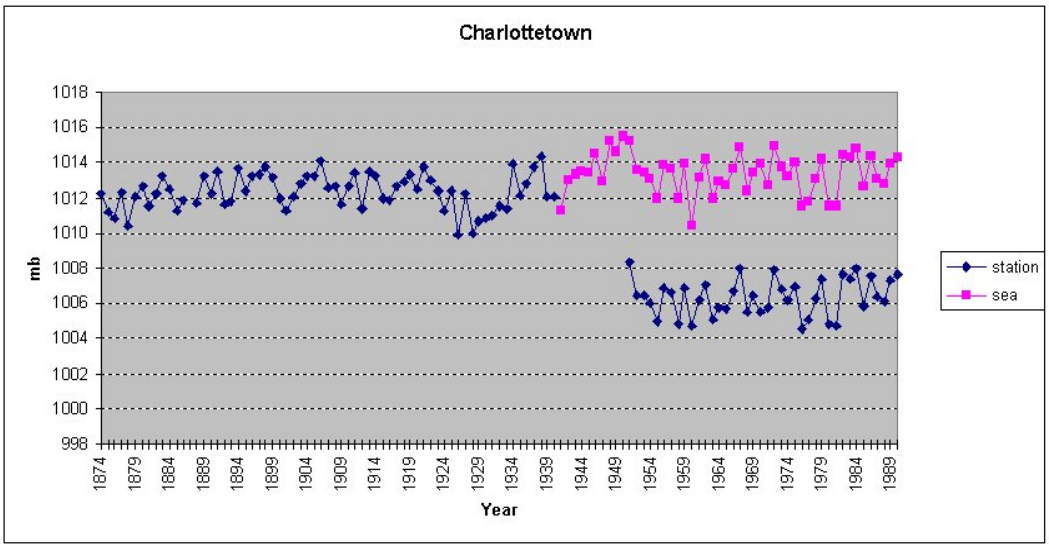


Figure 1. Location of station series.



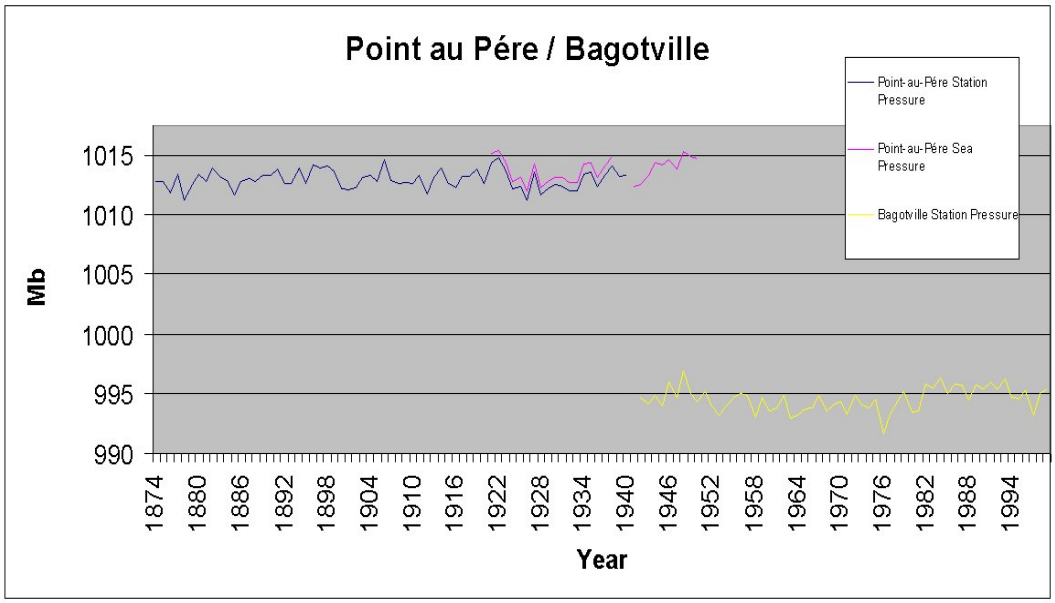


Figure 2: a) Mean annual atmospheric pressure (mb) records for Charlottetown, Prince Edward Island, 1874-1998. Station pressure is available from 1874-1940 and 1951-1998, but there is a gap from 1941 to 1950. Fortunately, a sea-level pressure record overlaps with the station pressure record, and using monthly transfer functions a complete station level pressure record is obtainable. b) Point-au-Père is available as a combination of station level and sea level series from 1874 to 1950, but records then cease. However, the nearby station of Bagotville commences in 1942, and using monthly transfer functions for the overlapping period, a complete station level pressure record is obtainable.

The example of Charlottetown (Prince Edward Island) is shown in figure 2(a). Station level pressure was available from 1874 onwards but stopped in 1940. Station data resumed again in 1951, but with a mean long term value of about 6mb lower than before, most likely due to a station re-location. Fortunately, a sea level pressure record overlaps the broken period, and using monthly transfer functions, a complete station level pressure record was obtained.

Several observation series which started relatively early ended abruptly; when possible, nearby stations were used to complete the series and produce a composite series of longer duration. Monthly transfer function were again calculated using the overlapping portions of both series to produce the composite series; the earlier segments were reduced to conform with the later, most modern segment. The example of Point-au-Père, Québec, is shown in figure 2(b). Station level data are available from 1874 to 1940, with a sea level pressure record from 1921 to 1950, after which records cease. However, the nearby station of Bagotville started recording data in 1942, and using monthly transfer functions, all three segments of atmospheric pressure can be reduced to one continuous record through to the present.

With regard to sea-level pressure reports, it is worth noting that J.G. Potter (1955) made a decision to exclude all data prior to 1940 when constructing monthly mean sea level pressure maps for Canada (Potter 1955). Potter notes that prior to 1940s, barometers were not inspected regularly, and “periods of 20 years or more passed without reports on the index”.

5. HOMOGENISATION METHODS

A database is said to be “homogenous” if the internal variations are caused by weather and climate. In reality, however, the internal variability caused by weather and climate may be large enough to mask or obscure step changes or trends caused by inhomogenieties. In order to track down such inhomogenieties, the following methods were employed in this project.

5.1. Subtraction of Station Pressure from Sea Level Pressure

Simple and straightforward, this method gave considerable insight into an individual station’s history. The subtraction of the station level series from the sea level series was plotted visually. Several inhomogeneities were discovered using this technique, including a nation-wide inhomogeneity which otherwise may have gone undetected.
In November 1976, computer generated pressure reduction tables were used for the first time by the Meteorological Service of Canada (formerly the Atmospheric Environment Service), replacing the previous calculations which were made either manually or by using primitive desk calculators. The algorithms used to calculate the station pressure correction and the station to sea pressure corrections were also adapted to World Meteorological Organisation (WMO) guidelines at this time, including the addition of plateau correction (Savdie 1982). Also at the same time, the “50-foot” rule (as discussed in section 3) was abolished (Environment Canada 1976, McMaster 1975, Upton 1972). The result was a noticeable jump in both sea level and station level pressure records, but especially in the sea level record across almost all parts of Canada. The sea level correction was sometimes of the order of several millibars. Coastal and low-lying stations which had been subject to the “50-foot” rule saw a strong drop in station pressures at this time. These discontinuities were usually noticeable upon subtraction of station pressure from sea level pressure (see figures 3a and 3b). If undetected, this would have led to spurious trends of atmospheric pressure across large parts of Canada. A total of 50 stations (more than three-quarters) showed some

sort of jump across this discontinuity, with a mean correction factor of 0.92mb. The highest correction factor was 5.5mb at Dawson in north-western Canada.

5.2. Standard Normal Homogeneity Test and HadSLP

The Standard Normal Homogeneity Test (SNHT; Alexandersson and Moberg 1997) is a test which uses differences in standard deviations between a candidate series and a "pure" reference series to find breaks. As we did not have a reference series in this project, we compared our Canadian pressure dataset with the UK Met Office Hadley Centre's northern hemisphere HadSLP gridded dataset, which is available for the period 1873-1998. It is acknowledged, however, that the HadSLP dataset is by no means homogenous – especially for the data sparse regions of northern Canada and the Arctic. It transpires that the HadSLP grid was digitised from old weather charts (Vicky, is this true?), in which meteorologists may have over-extrapolated the extension of lower latitude weather features, and may also have assumed the predominance of a virtual, quasi-permanent "Arctic High" (see Jones 1987). In practice, this method of homogenisation was suitable only in the detecting of significant jumps and outliers. Often, it demonstrated the shortcomings of the HadSLP gridded dataset. This procedure also assumed that no change in climate occurred between periods of jumps

To compare the datasets, a fortran program called gridcheck was run on the database, using the HadSLP grid as a reference series (the HadSLP grid has a size of 5° by 10°). The nearest value of the grid was interpolated for each station location. Outliers and jumps were detected by using the following equation (differences of greater than 4mb were flagged):

$$outlier = (stnvalue - stnmean) - (gridvalue - gridmean)$$

e.g. (980mb – 990mb) – (1014mb – 1020mb) = -10 – (-6) = -4

Sometimes, we had to infill data from the HadSLP grid, in order to make a continuous station record (but it was only undertaken in special circumstances for a few stations). Smoothing of the infilled HadSLP values was necessary, however, as the internal variability of HadSLP grid was greater than that of the station series that needed infilling. The following two equations were used:

$$gridvalue = gridraw - (\Delta diff)$$

$$newstnvalue = \frac{(gridvalue - \overline{grid})}{grid\sigma}.stn\sigma + \overline{grid}$$

gridvalue is simply the raw interpolated grid value (*gridraw*) minus the mean difference between grid and station data for each month. Then we subtract the mean value of the grid for that point, and divide by the grid's standard deviation. Then we multiply by the station series standard deviation and re-add the mean value for the grid at that point again. This gives is a new value for the station record. This method simply reduces the variability of the infilled period.

5.3. Multiple Comparison Analysis

Due to the shortcomings of the previous method, Multiple Comparison Analysis (MCA; Slonosky et al,1999) was used as the next stage in the homogenisation procedure. The method involves the selection and comparison of data from the four nearest stations in each

direction from a candidate station. It is a semi-objective iterative technique based upon graphical inspection of difference series between neighbouring stations. For each candidate station, four neighbouring stations were chosen for comparison, one in each cardinal direction (if a station was at a boundary or edge, simply the four nearest stations were chosen). Four difference series were calculated, and the graphical results plotted together (see figure 4 for an example). If a jump or discontinuity occurred in more than two difference plots, the jump was attributed to the candidate station. All stations were inspected, and all stations were then adjusted, and the process repeated to ensure that the discontinuities were correctly attributed. Adjustment factors were calculated to adjust identified inhomogeneous periods to the modern portion of the series. This method also assumes that no change in climate occurs between periods of jumps. An evaluation of this method, compared to the SNHT method (Alexandersson and Moberg 1997) and the Bayesian method developed by Caussinus and Mestre (CMT; 1996) is given in Slonosky et al. (1999). For pressure data, generally speaking, MCA is better than CMT, which in turn is better than the SNHT and the raw data series respectively.

As a final method of homogenisation, we did a visual check for "bulls eyes" –these are outliers that escaped the above homogenisation methods. This is a rather subjective method and only a few corrections were made.

Figure 3; a) Clyde mean annual sea level (dotted pink line) and station level (dark blue solid line) atmospheric pressure 1953-1999. b) subtraction of the two series. Note the discontinuity in late 1976 when computer generated pressure reduction tables were used for the first time (these introduced new algorithms in the calculation of sea level pressures, causing a rise). The "50-foot" rule was also abolished in 1976, leading to a drop in station-level pressure.

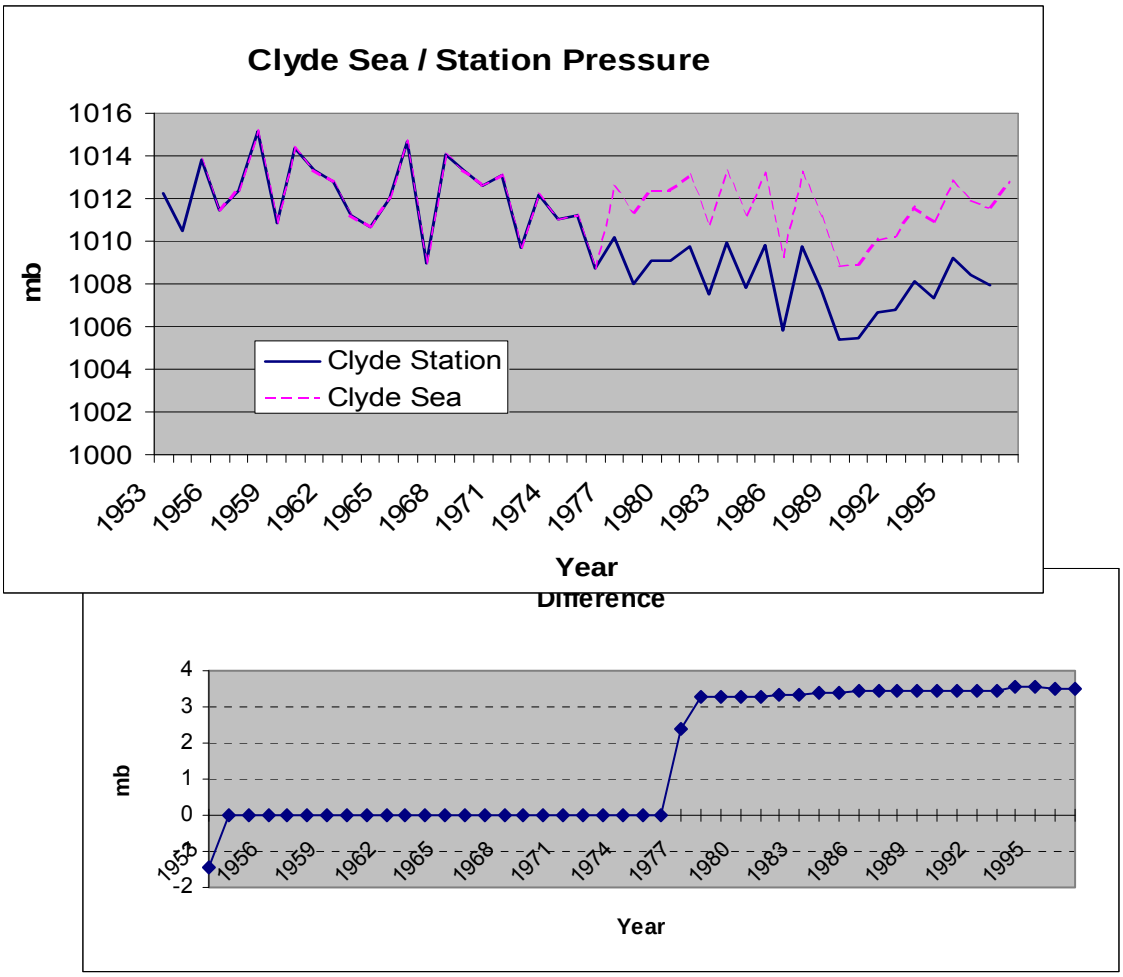
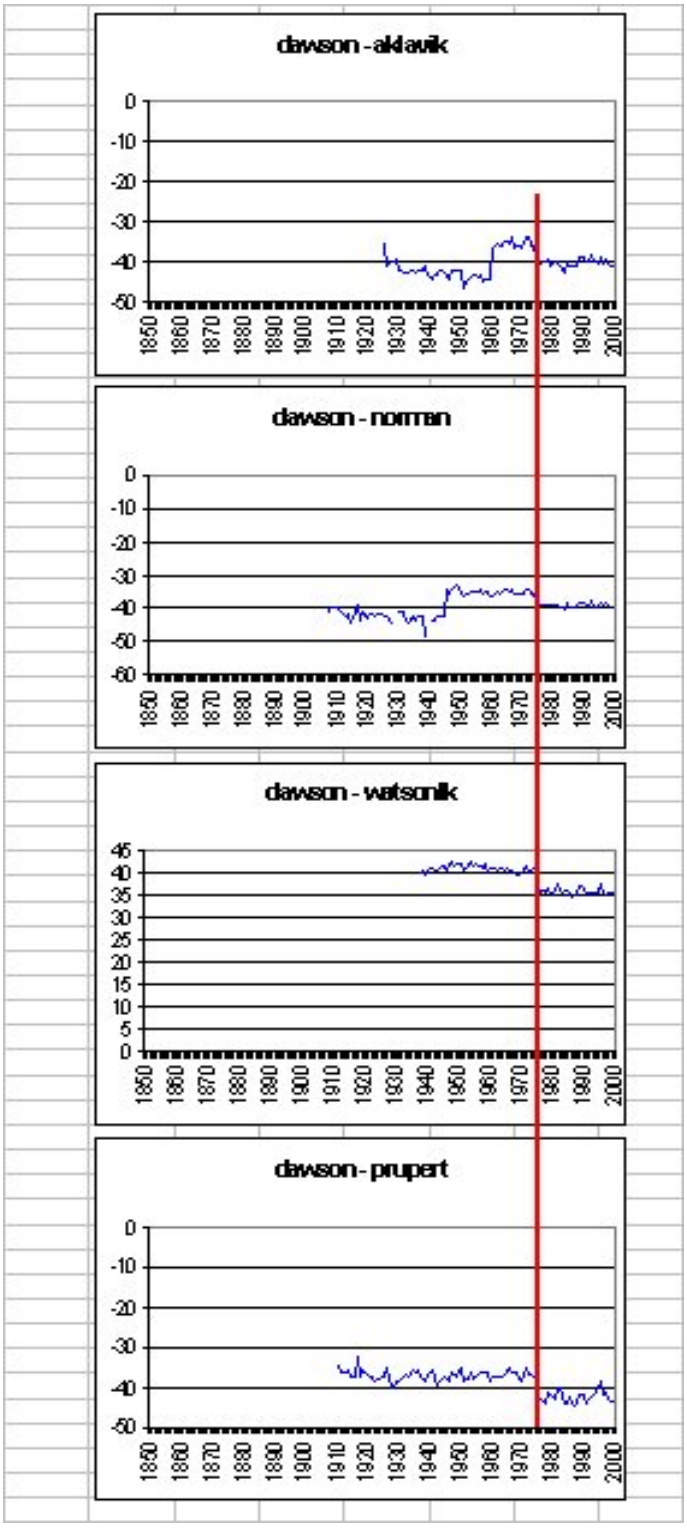


Figure 4: Multiple Comparison Analysis (MCA) for Dawson (Yukon). When the station series is compared with that of the four neighbouring stations (Aklavik, Norman Wells, Watson Lake and Prince Rupert) a distinct jump occurs in 1976 in all four comparisons (marked by the red line) – this jump can therefore be attributed to Dawson.



6. A FEW RESULTS

The final homogenised database shows appreciable differences in trends of atmospheric pressure when compared to the unhomogenised data. Table 2 lists the regional trends of standardized anomaly pressure data before and after the homogenization process. In the unhomogenised series, statistically significant trends (at the 95% confidence level, p-value < 0.05) are evident in south-eastern and south-western parts of Canada (South of 55N, east of 100W; South of 55N, west of 100W, respectively). The final database (after homogenisation), however, shows that these trends are spurious, and that no significant trends in atmospheric pressure are evident in any part of Canada during the 20th century.

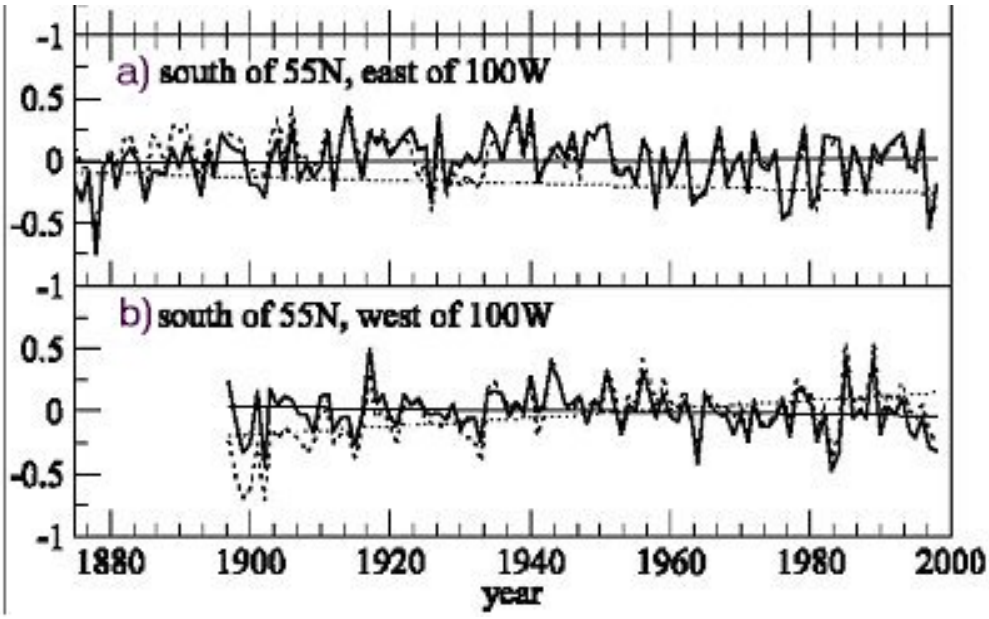
Table 2. Trends in original and homogenized data

All stations:	Original (mb per decade)	Homogenized (mb per decade)
North of 67N	-0.0285	-0.0123
North of 55N	0.0000	-0.0121
North of 55N, east of 100W	0.0053	-0.0078
South of 55N, east of 100W	-0.0117*	0.0030
North of 55N, west of 100W	-0.0130	-0.0128
South of 55N, west of 100W	0.0324*	-0.0130

*statistically significant at the 95% confidence level

These results emphasise the extreme importance of rigorous homogenisation in any climate data analysis, as there are statistically significant trends in the unhomogenised series for southern Canada. Figure 5 shows these trends more clearly in a graphical format for south-eastern and south-western Canada. The dotted lines show the spurious significant trends in the unhomogenised data (upward trend in southwestern Canada, downward trend in southeastern Canada); the solid lines show the final non-significant trends in the all areas of the homogenised series. EOF analyses has also be performed on the Canadian Stations pressure dataset, and a full statistical and climatological analyses of the database is given in Slonosky & Graham (2003), where they present and analyse trends and variability of surface pressure across Canada during the 20th century.

Figure 5; area-averaged standardized pressure anomalies for before and after homogenisation, for a) all stations south of 55N, east of 100W, and b) all stations south of 55N, west of 100W. The dotted lines show the statistical significant trends before homogenisation; the solid lines show the no-significant trends after homogenisation.



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