DETECTING OF INHOMOGENEITIES IN TIME SERIES USING REAL PRECISION METHOD

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INTRODUCTION

The Real Precision Method, introduced in previous Seminars for homogenisation of surface climate data (Petrovic, 1998 and 2000), showed how to determine data quality in time series using observed measurement precision. This is done by using counts of specific read-out values (i.e. decimal values) and putting them into a simple equation deriving new data precision attribute, the Real Precision Index (RPI):

$$RPI = \frac{2N}{2N - \sum_{i=1}^{n} |d_i|} \cdot x_{def}$$

where N is total number of processed cases, d_i is difference of i-th count from the expected number of cases, n is the number of specific read-out value categories (i.e. 10 for decimal values) and x_{def} is the pre-defined measurement precision (usually 0.1 for measurement precision of one decimal value).
Since the RPI values represent data quality through actual, real measurement precision, their use in homogeneity tests (instead of values of a meteorological element) was expected to be successful. In practice, only a small number of runs of the method those refer to obvious changes in precision showed inhomogeneity in desired way. Thus, the method had to be developed further in order to obtain such information.

DEVELOPMENT OF THE REAL PRECISION METHOD

Different types of non-precision might have more or less the same RPI values (Petrovic, 2000). Therefore, applications of homogeneity tests do not always produce satisfactory results.

Variation of the basic assumption

The aim of the Real Precision Method is not only to detect data quality by precision, but also to detect changes of the precision in time series. Types of non-precision could not be easily detected yet. Therefore, a variation of basic assumption is made.
The variation assumes that the reference measurement precision is not the defined one (i.e. uniform distribution of decimal values), but the *observed* one. This means that the reference distribution is derived from the subset of N members preceding the equally long subset that determines present measurement precision at one point. In this case, half of the sum of all absolute values of differences d_i between the reference and the observed counts for each i-th specific read-out value of n values (i.e. every one of ten decimal values) is no longer called the

number of non-precision cases, but the *number of redistributed cases* (N_r) in the processed dataset.

$$N_r = \frac{\sum_{i=1}^{n} |d_i|}{2}$$

Relation between the number of redistributed cases (N_r) and the total number of cases (N) is the ReDistribution Index (RDI):

$$RDI = \frac{N_r}{N}$$

Comparing to the definition of the Real Precision Index (RPI), the ReDistribution Index (RDI) has dimensions of relative precision. Relativity of the RDI value is shown through its theoretical maximum and minimum values. The "ideal best case" with the unchanged distribution returns the zero value of RDI, since there are no redistributed cases ($N_r = 0$). On the other hand, if all cases are redistributed ($N_r = N$), the returned value of RDI is 1.

Use of the ReDistribution Index

The Real Precision Method uses observed values only, because it examines measurement precision. Calculated values (i.e. monthly, seasonal, annual or long-term values) are not processed because these are the results of data processing, not the result of observations or measurements. Therefore, at least daily data should be available for this kind of data processing.
In order to get the complete precision information, calculation of the ReDistribution Index (RDI) should be performed together with the calculation of the Real Precision Index (RPI) wherever possible. It is equally important to know both data quality and changes in data quality. Weather elements that are not measured by any instrument cannot always produce satisfactory RPI results. In such cases, distribution of specific read-out or observed values should be available (a sort of Real Precision Scale, a distribution function or, in case of wind direction, a wind rose). The ReDistribution Index allows processing any weather element data, either measured with an instruments or observed (non-measured). Thus, it is now possible to examine changes in observed precision for any weather element.
Number of cases in processed data set should cover sufficiently long period of measurements in order to get a good sample. It is recommended to set the number of processed cases to number of observations in one period of time (i.e. one year for one value per day, N=365), or to multiply such number with appropriate number of such periods.
Values of RPI and RDI should move through the series in order to get the break point as precise as possible. Naturally, it is hard to expect the very day of change detected, but present experiences with the Real Precision Method show differences not larger than 15 days, frequently under 10 days from the change indicated in meta data.
Peaks of the RDI values indicate possible break points in measurement precision. Higher peaks (over 0.250) indicate drastic changes in precision, while lower peaks (between 0.130 and 0.250) cannot always certainly indicate a break point. RPI values are used for detecting data quality between the break points. For closer looks at the precision problems, a Real Precision Scale or any convenient graphic presentation of distribution of observed specific read-out values is welcome.

Example of daily extreme temperature data

Maximum and minimum daily temperature time series are easy for examination in described way. An example that uses daily series of Bologna for the period 1814-2002 shows many

different problems in data precision (Bologna time series were available at Internet address http://www.isac.cnr.it/~climstor/data.html).
Both series were processed the same way. Since differences in results were not significant, only maximum daily temperature series are shown. Number of cases in processed dataset was 365 both for RPI and for RDI, and both were moving through the series. Peaks in RDI values indicate changes in precision that occurred one year earlier, but explanations that follow will notify real break point years.
The beginning of series in 1814 are featured with RPI values around 0.125. These RPI values do not change until the end of 1866 (Fig. 1). On the other side, RDI values do not peak over 0.185 until the same year, when it peaks until 0.359. Such values indicate temperature measurements that were originally performed using 80-grade Reaumur temperature scale. This break point is verified in meta data (Brunetti et al., 2001). In order to get the real precision information, this part of series was reprocessed with temperature converted back into Reaumur degrees.
The next significant break point appears in July 1880 with RDI values peaking up to 0.452. This indicates a change in rules of measurement and instrumentation in Italy, which is also confirmed in meta data. The period between 1867 and 1880 features significantly lower precision, which is a consequence of experiments with instrumentation at the site of measurements.

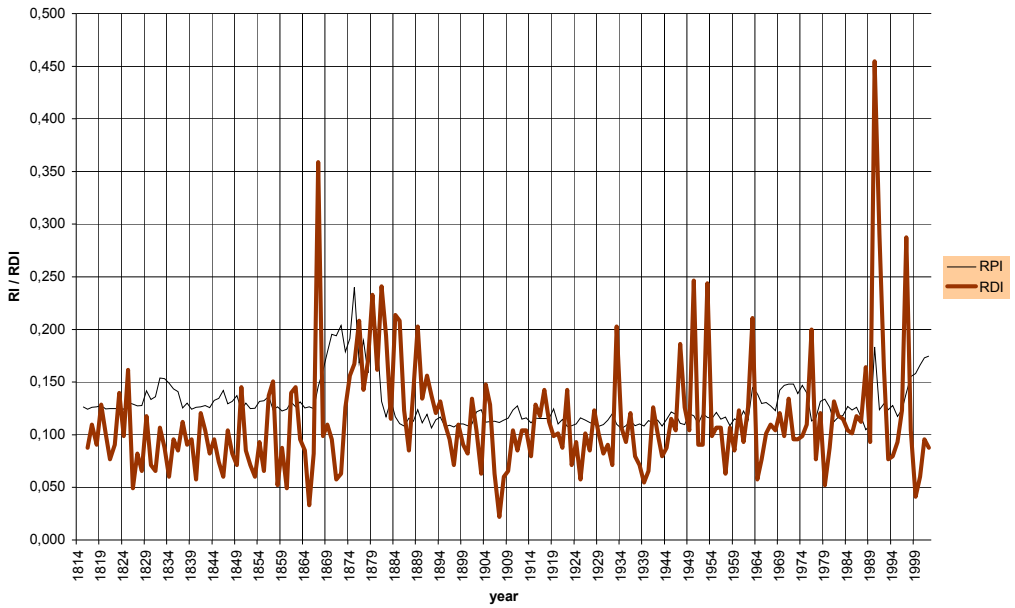

Figure 1. Real Precision Index (RPI) and ReDistribution Index values for daily maximum temperature, Bologna, 1814-2002

The next significant break point is by the end of 1945 (RDI=0.260), which corresponds to the end of the World War II and, probably, consequent change in personnel. This break point is not verified in available meta data. The period between 1880 and 1945 is marked with several minor peaks of RDI values (between 0.201 and 0.236), that might correspond to minor changes in personnel. Nevertheless, the type of non-precision remained the same: data set with effects of rounding to even decimal values and very good precision (Fig. 2).

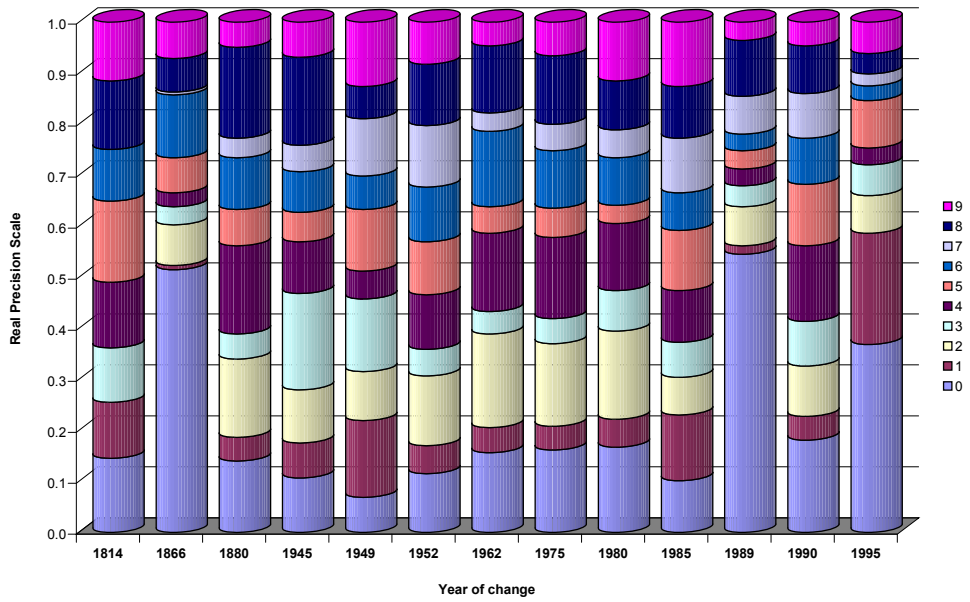

Figure 2. Real Precision Scale for break points, daily maximum temperature, Bologna, 1814-2002

The next two peaks indicate changes in non-precision type. Rounding to even decimal values are temporarily replaced with rounding to odd decimal values. This period is indicated with RDI peaking up to 0.301 in 1949 and RDI peak value of 0.285 in 1952 (Fig. 2). RPI values indicate good precision data ever since 1880 (Fig. 1). Nevertheless, these subtle changes of precision indicate possible homogeneity breaks due to replacement of observers that might have their own systematic errors.
The next significant peak of RDI value (RDI=0.236) appears in 1962, coming after minor RDI peak values in 1957 (RDI=0.183) and 1959 (RDI=0.153) (Fig. 1). On the other side, meta data show "problematic situation with instrumentation" in 1959 and "solving the instrumentation problem" in 1962. On the contrary, RPI values show a bit different situation. There was a little improvement of precision in 1957 (RPI values are rather small, around 0.107), while RPI values of 1962 suddenly rise to about 0.145, indicating lower precision instead of improvement of the situation with instruments! Nevertheless, break points are detected, but the explanations of changes did not respond correctly.

April 1975 brings another peak of RDI value (RDI=0.236) (Fig. 1). Since RPI values go down again to nearly 0.110, this confirms real improvement of the situation with instruments. However, meta data give no available comments so far for this precision break point.

The next RDI peak value (RDI=0.282) appears in 1980 (Fig. 1). Rounding to even decimal values remains the main type of non-precision, while some decimal values are redistributed. Decimal values 6 are disappearing, while decimal values 9 are significantly greater in number (Fig. 2). Meta data show changes of both location and personnel of the weather station. Homogenisation of the series showed the same break point (Brunetti et al., 2001).

Introducing automatic weather station in 1985 is indicated with minor peak of RDI value (RDI=0.186 in 1986). Measurement precision returns the best results ever (the lowest RPI values in series, between 0.103 and 0.108) (Fig. 1).

The highest peak of RDI values in series appeared in 1989 (RDI=0.463) (Fig. 1). This clearly indicates change of personnel education and quality at that time, which was recorded in meta data. Significantly high RPI and RPI2 values (for the first time in series) show poor measurement precision. Due to these changes, frequent problems with data feature this part of series. The Real Precision Scale for that period shows zero decimal values prevailing in data,

which confirms these problems (Fig. 2). Smaller, but still high RDI peak in 1990 (RDI=0.304) is assigned as the end of this non-precision period, which is supported by lower RPI (from 0.185 to between 0.120 and 0.130) and RPI2 values (from 0.318 back to around 0.220).

The last RDI peak in series appears in 1995 (RDI=0.301) (Fig. 1). At this point, measurement precision grows poor. The RPI value rises to over 0.150, even up to 0.187, and RPI2 value rises to between 0.278 and 0.324. This is obviously a consequence of non-professional personnel performing observations, which is confirmed in meta data.

Reprocessing data: As stated in the beginning of the analysis of this series, the original temperature observations were performed using 80-grade Reaumur scale until 1866. In order to examine measurement precision at that time, all temperature values were converted back to Reaumur temperature scale and the data were reprocessed. Some unseen details of observations are now discovered.

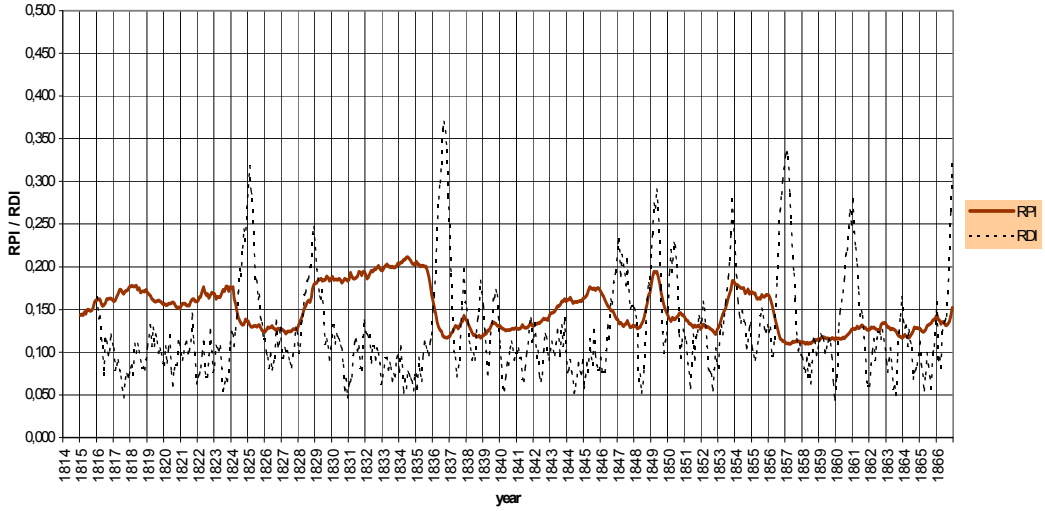

Figure 3. Real Precision Index (RPI) and ReDistribution Index (RDI) values for daily maximum temperature, Bologna, 1814-2002

The first RDI peak (RDI=0.326) appears in 1824 (Fig. 3), indicating first observations with rounding to decimal values 0, than 5, 3 and 7 (Fig. 4). In this order, these decimal values clearly indicate thermometer with tick marks on 0 (thicker) and 5 (thinner). The precision required for reading out values on the scale was half of the tick mark. Description of the instrument's scale is verified in meta data.

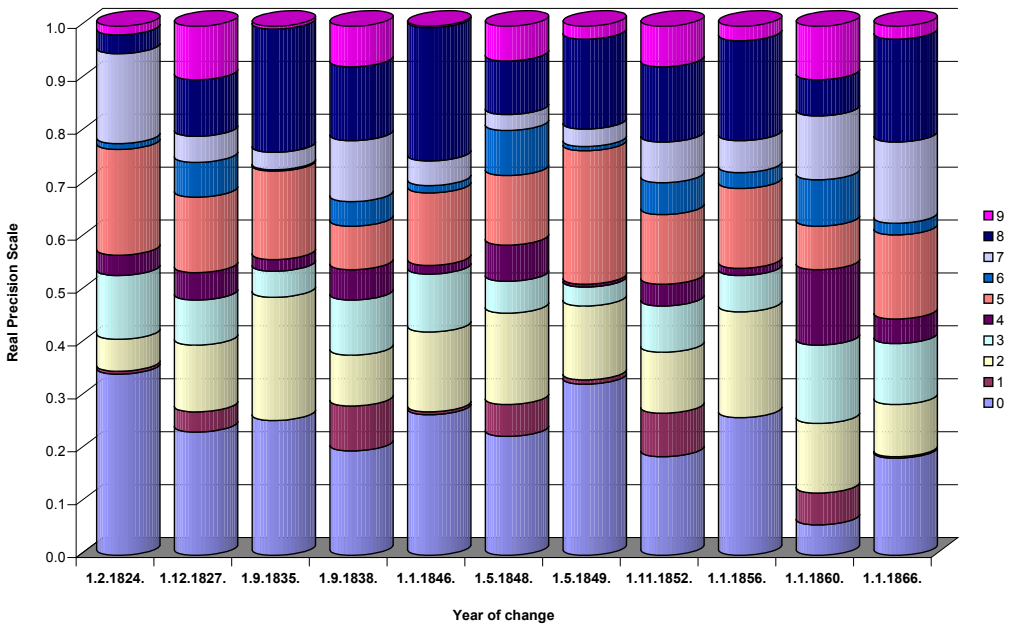

Figure 4. Real Precision Scale for Precision break points of original Reaumur scale, daily maximum temperature, Bologna 1814-1866

After this break point, measurement precision has improved, most probably due to more precise instrument. Still, the same rounding effect was present (Fig. 4). In 1827, measurement precision returned to the initial one (Fig. 3). This precision break point is indicated with peak of RDI value (RDI=0.260). Like in most cases in the period 1814-1866, meta data for this break point were not available.

The next break point was in 1836, where RDI value peaks at 0.384 (Fig. 3). This peak was also present in previously processed data set with values converted into centigrade, but it had smaller magnitude (less than 0.185). Similar rounding effect was present, but the leading number of cases belonged to decimal values 2 instead of 3 and 8 instead of 7 (Fig. 4). This might indicate change in valid rules of rounding at that time, but there is no certain way to verify this presumption. At this point, meta data indicate change of thermometer.

Series of minor peaks of RDI value appear in the following three years, but this might indicate only minor changes in precision due to frequent changes of observers. Other peaks of RDI value have greater magnitude. These are 0.236 in 1846, 0.299 in 1849, 0.285 in 1853 and 0.356 in 1856 (Fig. 3). These precision break points even clearly point out changes in data quality. Meta data for this period confirms these changes of thermometer type for years 1853 and 1856.

The most significant break point that was fully verified in meta data was in 1860. The RDI value peaks up to 0.279 (Fig. 3). At this point, new instrument with higher precision (thermometergraph) was introduced. This change might also be viewed through RPI values, which are significantly low. The Real Precision Scale shows almost uniform distribution of decimal values, which confirms the high quality of the new instrument (Fig. 4).

Finally, the end of this period is clearly marked with the highest RDI peak in reprocessed dataset (RDI=0.375) (Fig. 3). As described, the source of such redistribution is switching from Reaumur 80-grade to centigrade scale.

This data reprocessing has discovered new precision features of the data set successfully. Therefore, it is necessary to discover the source of possible changes first, using both meta data and various data processing procedures, such as the Real Precision Method.

Example of wind data

The Real Precision Method is capable to process other, non-decimal weather elements in order to get an information about changes in precision. Wind direction data, for example, might also be successfully examined. Even changes in precision (number of wind directions in such case) might be successfully detected using new features of the method.
Wind speed data might also be tested in the same manner. The only difference is that it is not necessary to test measurement precision, but also distribution of these values. Using the same series, but of wind speed data, a similar results of testing might appear. With adding new calculations, combination of these two applications of the Real Precision Method might bring development of new homogeneity method for wind direction and speed data.
An example of Belgrade Observatory is used as an illustration of using the Real Precision Method for detection of inhomogeneities of wind direction and speed data. The data are processed in similar manner as in previous case: length of tested series is 365 days, but three observation terms a day make 1095 long processed data subset.

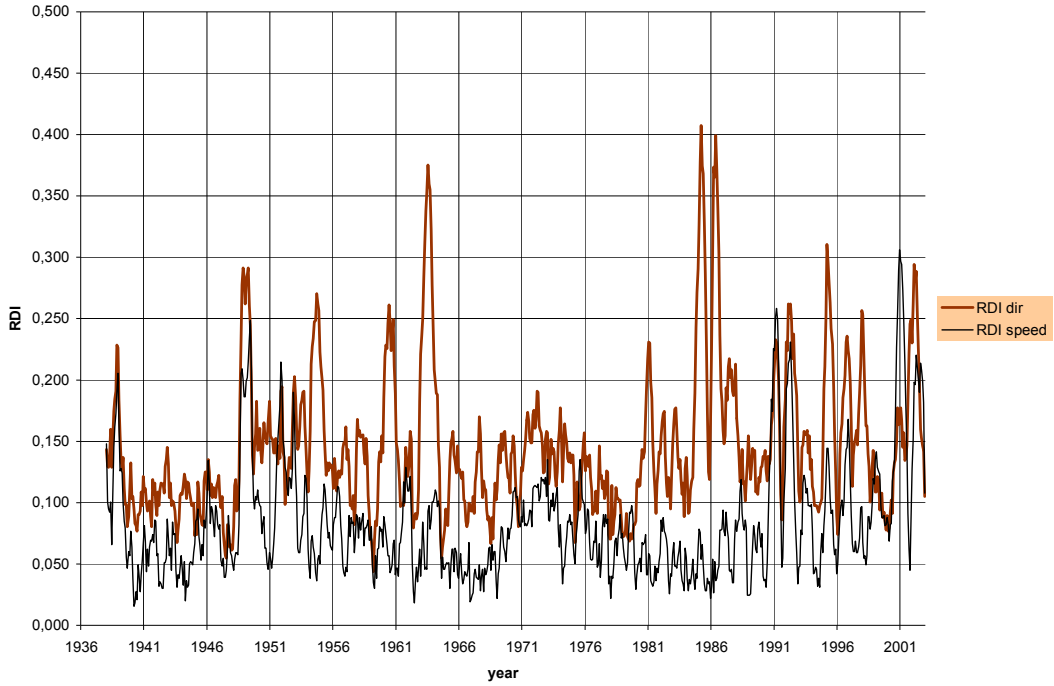

Figure 5. ReDistribution Index (RDI) values for wind direction and speed, Belgrade, 1936-2002

Briefly viewed, there are many significant RDI peaks in examined data, both for wind direction and for wind speed (Fig. 5). A great number of peaks match in time, which indicate change of an instrumentation (between 1991 and 1992) or precision (note the "starry" shape of the wind rose in 1948, fig. 6). On the other side, there is also significant number of RDI peaks for wind direction only, while RDI values for wind speed remain low. The most possible reason for this is change in orientation of wind vane. The wind rose appears to be "rotated" for a certain angle (between 1985 and 1986). The last two peaks of RDI values in both series (in 2000 and 2002) are caused by changing of the surroundings (making one more floor to a hospital building some 30-40 meters from an instrumentation).

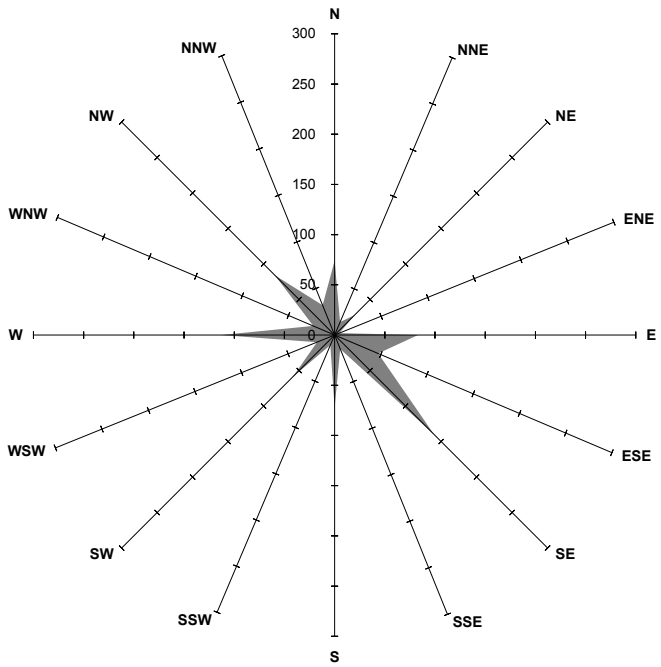

Figure 6. "Starry" wind rose as a consequence of lack of wind direction precision, Belgrade, 1948

Peaks of RDI values in wind speed series indicate changes of data distribution (Fig. 7). This consequently leads to changes in resulting wind speed, but also shows source of changes. This might be a step forward in explanation of inhomogeneities of wind speed data.

SUMMARY

The Real Precision Method has new features that enables successful detection of measurement precision break points in time series. This is the ReDistribution Index (RDI), which peaks in time series indicate break points.
The use of ReDistribution Index is no longer limited to observed values only. It might be also applied to calculated values in order to examine rank distribution of the values.

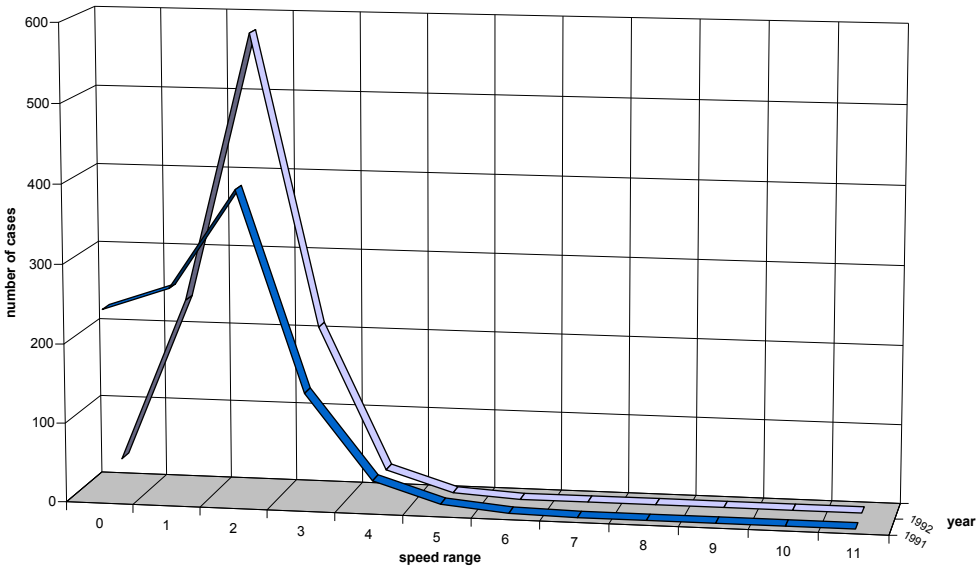

Figure 7. Distribution of wind speed data at the time of changing instrumentation, Belgrade, 1991-1992

Careful use of the Real Precision Method might lead to detecting of the day of homogeneity break point, with error not larger than a few days. This feature might help in detecting causes of inhomogeneity, which is one of the most valuable informations. Inhomogeneity must have a cause to be justified.

The Real Precision Method is one of seldom data homogeneity tests that might use high-resolution data (daily or higher) as well as low-resolution data (monthly, seasonal, annual or longer).

The Real Precision Method might be complete at the moment, but it draws more questions about testing time series in many different manners. These tests might bring a new homogenisation method, since there are some embryonic stages of such methods.

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Detecting multiple change-points in a gaussian sample using dynamic programming

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1. PRESENTATION

We consider n normal random variables Y_i (i=1,...,n is the time index) and let Y denote the column vector of the Y_i's. We assume that the probability distribution of Y is n-dimensional normal, with covariance matrix I_n (identity matrix of order n) up to the unknown variance. The mean μ is constant between two change-points, but varies from time to time (Fig. 1).

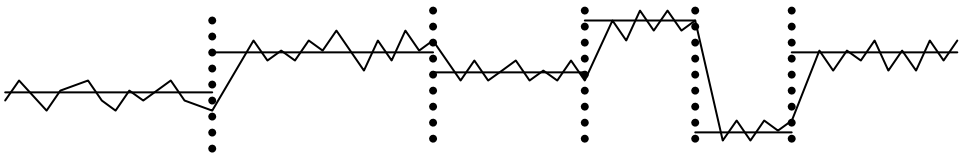


Fig.1 : ***example of a series with 5 change-points.***

2. NOTATIONS

Let k be the number of change-points. Let $\tau_1,\tau_2,\ldots,\tau_k$ be the positions of the k change-points. Let $K=\{\tau_1,\ldots,\tau_k\}\subset\{1,\ldots,n\}$ be the set of change-points and outliers, and H_K the corresponding model. To simplify the notation, we will set $\tau_o=0$, and $\tau_{k+1}=n$.

We denote: $n_j = \tau_j-\tau_{j-1}$ $\quad \overline{Y}=\frac{1}{n}\sum_{i=1}^{n}Y_i$ and $\overline{Y}_j=\frac{1}{n_j}\sum_{i=\tau_{j-1}+1}^{\tau_j}Y_i$ for j=1,…,k+1.

$$\overline{Y}_{hm}=\frac{1}{m-h}\sum_{i=h+1}^{m}Y_i \qquad W_{hm}=\sum_{i=h+1}^{m}\left(Y_i-\overline{Y}_{hm}\right)^2$$

When considering abrupt shifts in the mean: $IE[Y_i]=\mu_j$ for any $\tau_{j-1}+1<i\leq\tau_j$

Beware that by convention, the shift occurs on the data following immediately the change-point index.

The Maximum Likelihood (ML) estimates of the μ_j are given by: $\hat{\mu}_j=\overline{Y}_j$, *i.e.* by the empirical mean between the two change-points. For a given fixed value of k, we try to maximize the likelihood, which is equivalent to maximizing deviance D_k:

$$D_K=\frac{\sum_{j=1}^{k+1}\sum_{i=\tau_{j-1}+1}^{\tau_j}\left(Y_i-\overline{Y}_j\right)^2}{\sigma^2}+2n\cdot\ln\left(\sqrt{2\pi}\sigma\right)$$

3. DYNAMIC PROGRAMMING AND THE « COMBINATORIAL WALL »

The naïve way to search for the minimum of D_k is to consider all possible hypotheses, *i.e.* every combination of the position of the changes-in-mean. But the number of hypotheses rises very fast with n, the length of the series, and k, the number of accidents.

When detection is performed for change-points in a normal sample, a dynamic programming algorithm can be used (Lavielle, 1998, Hawkins, 2001). Computation time then becomes only linear in k and quadratic in n.

This approach based on dynamic programming is strictly equivalent to the exhaustive search of the best solution.

It relies on a recurrence relation between k and k-1 solutions. If variance σ^2 is constant, minimizing D_k is equivalent to minimize:

$$Q=\sum_{j=1}^{k+1}\sum_{i=\tau_{j-1}+1}^{\tau_j}\left(Y_i-\overline{Y}_j\right)^2=\sum_{j=1}^{k+1}W_{\tau_{j-1}\tau_j}$$

Initially, W_{hm} has to be computed for every m=1,…,n and 0<h<m. The following recurrence then gives the solution:

$F_{1,m}=W_{0m}$ for m=1,n
For r=2,…,k+1, calculate $F_{r,m}=\underset{0<h<m}{\mathrm{MIN}}\left[F_{r-1,h}+W_{h,m}\right]$ for m=1,n

For every value $F_{r,m}$ we keep record in table $H_{r,m}$ the value of h for which the minimum $F_{r,m}$ is obtained. he estimates of the positions of the breaks are given by: $\tau_{k+1}=n$, and for r=k, k-1,…,1 we have $\tau_r=H_{r+1,\tau_{r+1}}$.

4. SELECTING THE NUMBER OF BREAKS

The previous paragraph allows to select, for a given number k of shifts their most probable location. We have now to set k, since the absolute minimum of Q is obtained when k=n.

To obtain a realistic number of breaks, we use the following criterion, proposed by Caussinus and Lyazrhi (1997). Using previous notations, let:

$$C_{\varnothing}(Y)=0 \qquad \text{and} \qquad C_K(Y)=\ln\left[1-\frac{\sum_{j=1}^{k+1}n_j\left(\overline{Y}_j-\overline{Y}\right)^2}{\sum_{i=1}^{n}\left(Y_i-\overline{Y}\right)^2}\right]+\frac{2k}{n-1}\ln(n) \qquad (1)$$

The proposed procedure is: select K* such that $K^*=\mathrm{Argmin}_K(C_K(Y))$ (2)

In practise, the dynamic programming algorithm gives for every number k the optimal position of the change-points. Corresponding statistics $C_K(Y)$ is then calculated.

The solutions for various number of shifts are then compared together using criteria (1) through procedure (2). Detection ends when $C_K(Y)$ stops decreasing. Usually we let the algorithm proceed a few steps ahead in order to verify that the final solution corresponds to the absolute minimum $C_{K^*}(Y)$.

5. SIMULATION STUDY

To illustrate the efficiency of the proposed procedure, we use randomly generated series which resemble the real data. Here n=100 and there are six changes-in-mean with amplitude ±*a* at positions 20, 40, 50, 70, 75 and 85, as shown in Table 1 (broken line).

The standard deviation is constant and equal to one. 1000 normal test series with artificial changes in mean have been generated. The number k of detected change-points and the histograms of their positions are given in Table 1 for *a*=1.0, 2.0 and 3.0.

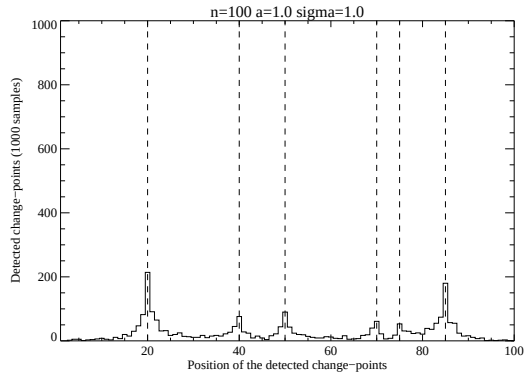
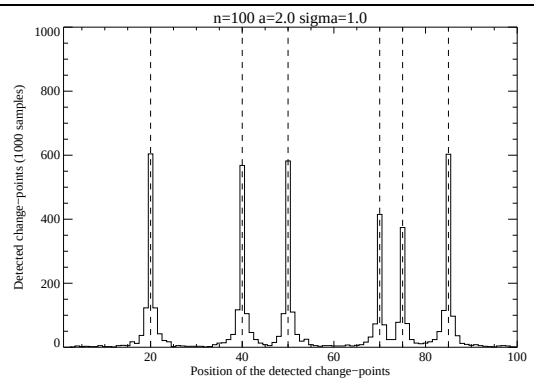
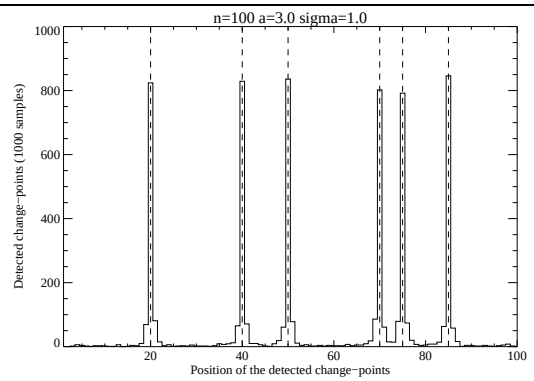
Histograms of the position of the detected breaks	Percentage of observed values of k	
	k	*a*=1.0
	k=0	0.7%
	k=1	25.4%
	k=2	19.6%
	k=3	38.1%
	k=4	12.2%
	k=5	3.1%
	k=6	0.6%
	k=7	0.0%
	k>7	0.0%
	k	*a*=2.0
	k=0	0.0%
	k=1	0.0%
	k=2	0.5%
	k=3	2.0%
	k=4	35.1%
	k=5	7.9%
	k=6	43.4%
	k=7	8.3%
	k>7	2.8%
	k	*a*=3.0
	k=0	0.0%
	k=1	0.0%
	k=2	0.0%
	k=3	0.0%
	k=4	1.2%
	k=5	0.5%
	k=6	80.9%
	k=7	13.1%
	k>7	4.3%

Table. 1: *number and position of the detected change-points*

Of course the results improve when the amplitude *a* of the breaks increases. For low values of *a*, the change-points are drowned by the residual variance and thus cannot be well detected (in number and position). For *a*=2.0, the procedure detects 4 or 6 change-points which are correctly placed most of the time. The detection of breaks in position 70 and 75 is always poorer, since these change-points are very close to each other. When *a*=3.0, the percentage of cases where six

change-points are detected reaches 80%, while the number of cases where k>6 remains moderate.

CONCLUSION

Usual step-by-step procedures are often inefficient in some cases, especially for breaks close in position. The proposed solution, based on dynamic programming, is **strictly equivalent to the calculation of every possible combination**, at a moderate computation cost.

Combined with Caussinus & Lyazrhi's Criterion, the resulting procedure is a powerful tool for automatic detection of multiple change-points in a gaussian sample.

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Correcting climate series using ANOVA technique

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1. MODEL

We present below an overall two factors model, that allows us to correct a whole set of non homogeneous series, without using a "reference" series.

Let us consider p series belonging to the same climate area in such a way that all the series are affected by the same climatic conditions at the same time. This assumption is realistic when considering monthly or annual observations at a regional scale.

We assume that each series of observations is the sum of a climate effect, a station effect and random white noise. The station effect is constant if the series is reliable. If not, the station effect is piecewise constant between two shifts.

Let X be a matrix of n observations X_{ij} on p series where i=1,...,n is the time index and j=1,...,p is the station index. Let k_j be the number of change-points and let $\tau_{1,j},\tau_{2,j},\ldots,\tau_{k_j,j}$ be the positions of these k_j change-points. In the following, *level* denotes an homogeneous sub-period between two discontinuities of a given series. For a series j with k_j breaks, let L_{jh} be the hth level ($h=1,\ldots,k_j+1$), that is L_{jh} is the interval: $[\tau_{h-1,j}+1, \tau_{h_j,j}]$. Note that the level h for the observation X_{ij} depends both on time i and station j: when necessary it will be written h(i,j).

Let μ_i be the climate effect at time i and ν_{jh} the station effect of station j for level L_{jh}. The data are described by the linear model (Caussinus & Mestre, 2003):

$$IE(X_{ij})=\mu_i+\nu_{jh(i,j)} \qquad Var(X)=\sigma^2 I_{np}. \qquad (1)$$

The parameters are identified by $\sum_{i=1}^{n}\mu_i=0$. The number of independent parameters of the model without discontinuities is n+p-1.

Examples: No break in series 1: $IE[X_{i1}]=\mu_i+\nu_1$

One break at i_o for series 2: $\begin{cases} IE(X_{i2})=\mu_i+\nu_{21} & \text{for } i\le i_o \\ IE(X_{i2})=\mu_i+\nu_{22} & \text{for } i>i_o \end{cases}$

Remark: the climate signal is treated as a fixed parameter so that *no assumption is made about the shape of this signal*. Moreover, conditionally to the climate signal, the disturbances may be considered independent. Finally, the local variability are very similar, which leads to the expression of Var(X).

2. ESTIMATION

2.1. Classical least squares estimation

Let β bet the vector of parameters of the model, and q its dimension. We denote $\hat{\beta}$ the usual least square estimate of β, T being the design matrix of the model, so that $X=T\beta+e$, e being the vector of residuals (independent, identically distributed $N(0,\sigma^2)$).

$\hat{\beta}$ is given by: $\hat{\beta}=({}^tTT)^{-1}{}^tTX$ (2)

Properties of $\hat{\beta}$ are given by Gauss-Markov theorem, that is:

(a) $\hat{\beta}$ is unbiased : $IE(\hat{\beta})=\beta$

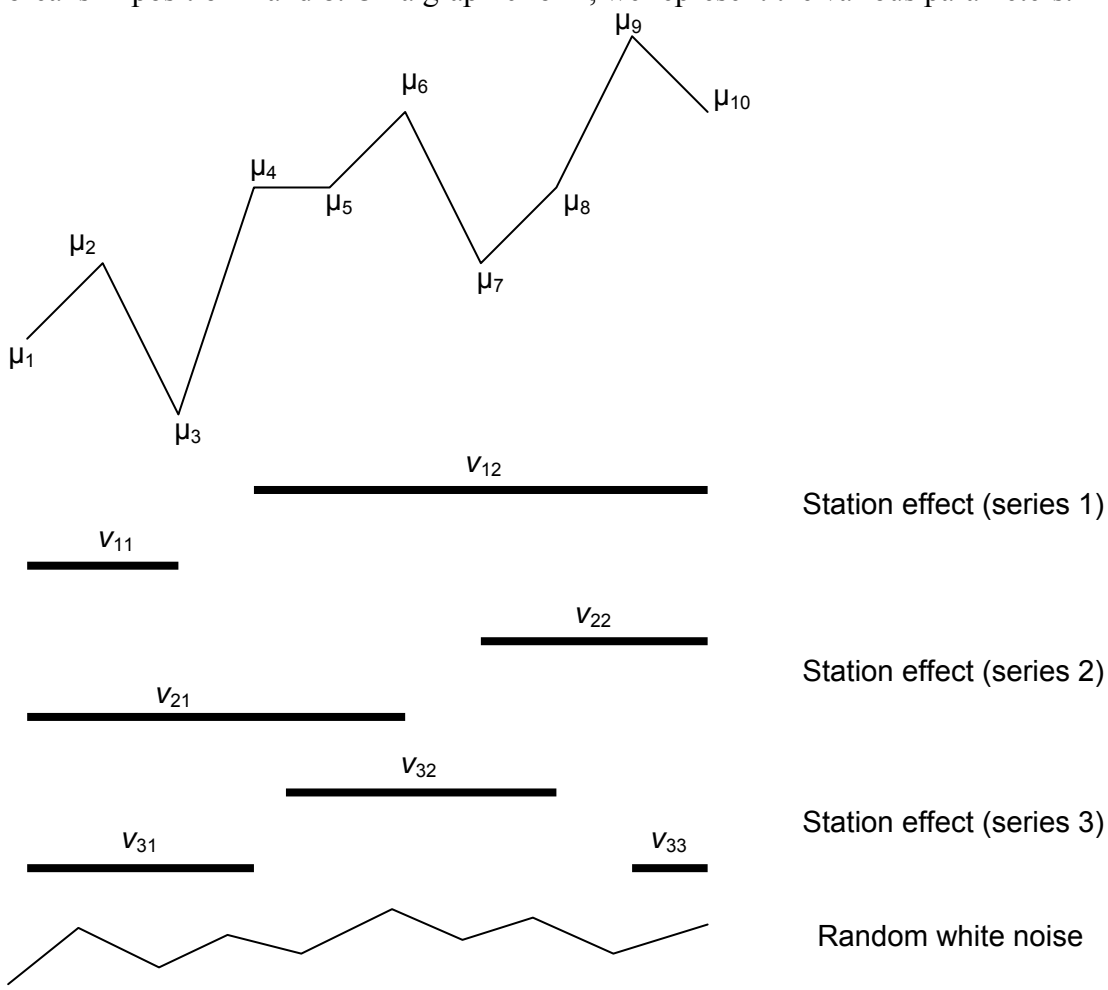
(b) $Var(\hat{\beta})$ is minimum (optimality)

If X is normal, $\hat{\beta}$ is q-dimensional normal : $\hat{\beta} \sim N_q(\beta, ({}^tTT)^{-1}\sigma^2)$

The estimation of variance σ^2 is given by $\hat{\sigma}^2=\frac{\left\|X-T\hat{\beta}\right\|^2}{n-q}$, which is also unbiased and optimal.

2.2. Example

Let us give a simple example in the case of our model. We consider three series of length 10: n=10, p=3. First series has a break in position 3, second series a break in position 6, third series two breaks in position 4 and 8. On a graphic form, we represent the various parameters:



Under matrix form, the model is written as : X=Tβ+e where:

$$X=\begin{pmatrix} X_{11}\\ X_{21}\\ X_{31}\\ X_{41}\\ X_{51}\\ X_{61}\\ X_{71}\\ X_{81}\\ X_{91}\\ X_{101}\\ X_{12}\\ X_{22}\\ X_{32}\\ X_{42}\\ X_{52}\\ X_{62}\\ X_{72}\\ X_{82}\\ X_{92}\\ X_{102}\\ X_{13}\\ X_{23}\\ X_{33}\\ X_{43}\\ X_{53}\\ X_{63}\\ X_{73}\\ X_{83}\\ X_{93}\\ X_{103} \end{pmatrix} \quad T=\begin{pmatrix}
1&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
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0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&1&0\\
0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&1\\
0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&1
\end{pmatrix} \quad \beta=\begin{pmatrix} \mu_1\\ \mu_2\\ \mu_3\\ \mu_4\\ \mu_5\\ \mu_6\\ \mu_7\\ \mu_8\\ \mu_9\\ \mu_{10}\\ \nu_{11}\\ \nu_{12}\\ \nu_{21}\\ \nu_{22}\\ \nu_{31}\\ \nu_{32}\\ \nu_{33} \end{pmatrix} \quad e=\begin{pmatrix} e_{11}\\ e_{21}\\ e_{31}\\ e_{41}\\ e_{51}\\ e_{61}\\ e_{71}\\ e_{81}\\ e_{91}\\ e_{101}\\ e_{12}\\ e_{22}\\ e_{32}\\ e_{42}\\ e_{52}\\ e_{62}\\ e_{72}\\ e_{82}\\ e_{92}\\ e_{102}\\ e_{13}\\ e_{23}\\ e_{33}\\ e_{43}\\ e_{53}\\ e_{63}\\ e_{73}\\ e_{83}\\ e_{93}\\ e_{103} \end{pmatrix}$$

But here matrix T is not full rank, so that $({}^tTT)^{-1}$ cannot be computed. We then have to use $\sum_{i=1}^{n}\mu_i = 0 \Leftrightarrow \mu_{10}=-\mu_1-\mu_2-\mu_3-\mu_4-\mu_5-\mu_6-\mu_7-\mu_8-\mu_9$. Under matrix form, the problem then becomes:

$$X=\begin{pmatrix} X_{11}\\ X_{21}\\ X_{31}\\ X_{41}\\ X_{51}\\ X_{61}\\ X_{71}\\ X_{81}\\ X_{91}\\ X_{101}\\ X_{12}\\ X_{22}\\ X_{32}\\ X_{42}\\ X_{52}\\ X_{62}\\ X_{72}\\ X_{82}\\ X_{92}\\ X_{102}\\ X_{13}\\ X_{23}\\ X_{33}\\ X_{43}\\ X_{53}\\ X_{63}\\ X_{73}\\ X_{83}\\ X_{93}\\ X_{103} \end{pmatrix} = \begin{pmatrix}
1&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
0&0&1&0&0&0&0&0&0&1&0&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&1&0&1&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&1\\
-1&-1&-1&-1&-1&-1&-1&-1&-1&0&0&0&0&0&0&1
\end{pmatrix} \bullet \begin{pmatrix} \mu_1\\ \mu_2\\ \mu_3\\ \mu_4\\ \mu_5\\ \mu_6\\ \mu_7\\ \mu_8\\ \mu_9\\ \nu_{11}\\ \nu_{12}\\ \nu_{21}\\ \nu_{22}\\ \nu_{31}\\ \nu_{32}\\ \nu_{33} \end{pmatrix} + \begin{pmatrix} e_{11}\\ e_{21}\\ e_{31}\\ e_{41}\\ e_{51}\\ e_{61}\\ e_{71}\\ e_{81}\\ e_{91}\\ e_{101}\\ e_{12}\\ e_{22}\\ e_{32}\\ e_{42}\\ e_{52}\\ e_{62}\\ e_{72}\\ e_{82}\\ e_{92}\\ e_{102}\\ e_{13}\\ e_{23}\\ e_{33}\\ e_{43}\\ e_{53}\\ e_{63}\\ e_{73}\\ e_{83}\\ e_{93}\\ e_{103} \end{pmatrix}$$

β is estimated using (2), the last parameter being set by $\mu_{10}=-\mu_1-\mu_2-\mu_3-\mu_4-\mu_5-\mu_6-\mu_7-\mu_8-\mu_9$.

CONCLUSION

Model (1) is the translation of the relative homogeneity principle in terms of a linear model. It is quite simple to use, and its good properties are ensured by the Gauss-Markov theorem.

It allows a direct correction of a set of *non-homogeneous* series, without using any reference, once detection of the shifts has been fully performed (which is another problem).

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EXPERIENCE WITH SPATIALISATION METHODS IN THE CLIMATIC INHOMOGENEITY DETECTION

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INTRODUCTION, AIM OF THE STUDY

GIS (Geographic Information System) has recently became a very important and widespread tool serving a variety of functions in several areas of scientific endeavor. Its importance can be easily seen in the environmental sciences including meteorology and climatology. GIS tools afford also some techniques for climatic inhomogeneity detection. They are not originally orientated for that purpose however, in some cases can be easily helpful for quick meteorological data quality control. The main aim of the study is to present some examples of the application of the GIS spatialisation methods in the climatic inhomogeneity detection. It is showed on the examples of the air temperature series which have been used for the construction of climatic maps for territory of Poland. These maps have been created for the mean monthly and seasonal temperature as well as different thermal characteristics (e.g. growing season, effective temperature seasons etc.). The mentioned maps have been created with the application of few spatialisation methods including ordinary kriging and residual kriging. Several geographic parameters, including elevation, latitude, longitude, and distance to the Baltic coast (for stations located within 100 km) were used as predictor variables for air temperature (Ustrnul, Czekierda 2003).

DATA

Application of GIS tools requires 2 types of data: firstly, the relevant climatic data; and secondly, environmental data allowing spatial representation of the particular climatic component. Of course, for the professional presentations, other auxiliary “layers” of data are often required (e.g. administrative structures, road placements, etc.). In the present study, the first data set contains mean monthly temperatures from 168 stations (synoptic and climatological type) from the entire territory of Poland. The location of reporting stations is relatively consistent with an emphasis on mountainous areas where temperature conditions are most complex. The mentioned data originate from the so-called normal period 1961-1990 as well as for the entire period of 50 years 1951-2000. The basic Digital Terrain Model (DTM) for Poland had a spatial resolution of about 250 m. Additional, basic layers contained hydrographic and administrative network.

GENERAL REMARKS

Using GIS approach in climatology one always refers to the general question what the „real surface" denotes. So, the real problem is how the presented (modeled) surface represents the real natural conditions. But initially, one can be sure what means the real surface and how much it can be known. The knowledge of the "real surface" is always limited and only such one can be taken into account. It means that all modeling and spatialisation tools are being employed for the reconstruction of not quite well known surface. But that problem is not quite solved yet and must be neglected in further considerations.

Another problem is the verification of the approximated surfaces created with the application of different spatialisation methods. In these cases there are some well-examined tools described in the literature (Cressie 1991, Wackernagel 1995, Dobesch, Tveito, Bessemoulin 2001, Tveito et al. 2000, Tveito 2002). Among them the semivariogram and cross validation tools are the most efficient. However, in the author's opinion testing of the independent samples is the most objective and important method. It should be always used after application of the traditional ones.

Using GIS tools one must realize that there can be also some inhomogeneities in the input not only climatic data. The source of them can be found in the environmental data like in: digital elevation model, land use, hydrographic data etc. Errors can be located even in the world known databases. For example Figure 1 presents examples of some typical inhomogeneities and discontinuities in the GTOPO base (Global…). They are located in the western part of Poland but similar can be also found in other countries and regions. These types of errors are important when particular environmental data are being used as the predictor for the climatic element spatial analysis.

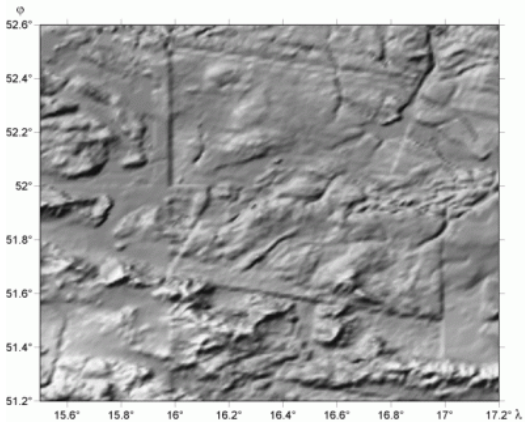

Fig. 1. Example of the inhomogeneity in the GTOPO database for Poland

APPLIED METHODS

Latin motto says: "natura non facit saltum" ("Nature does not make a leap") what means that there should not be any rapid changes (breaks) in the spatial distribution of the particular climatic elements. Temperature being so called continuous element especially should not have any breaks, so each separate closed isopleths ("bowl's eyes") can suggest some discontinuities and possible errors. There are a couple of simple tools for detection of such inhomogeneities.

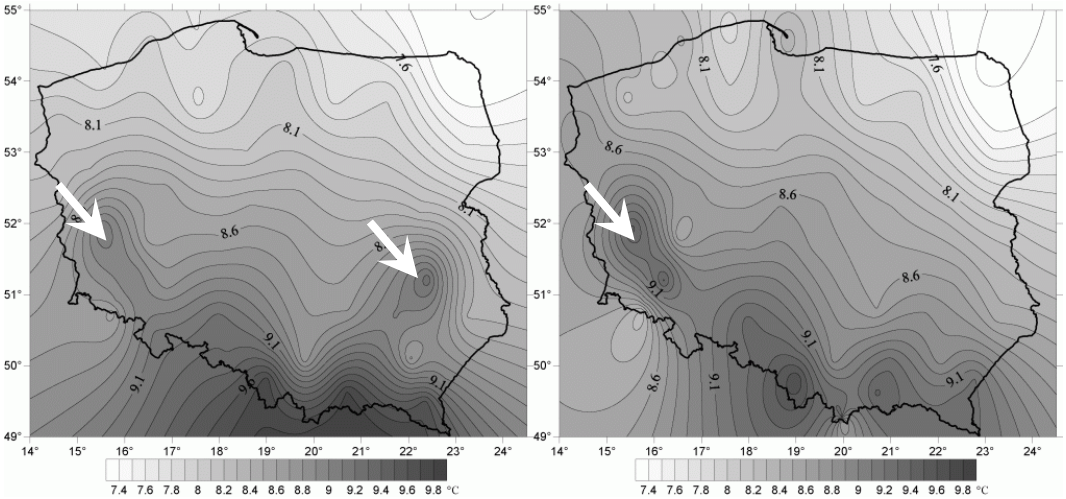

Fig.2. Mean annual temperature reduced to sea level and constructed by the kriging method: 1972 (left), 1973 (right)

First one is the well known method of the climatic data reduction to the specific level (e.g. for atmospheric pressure, air temperature). That method is well known in meteorology and being used for the synoptic maps. Thanks to reduction of the station atmospheric pressure to the sea level the baric system can be easily presented. In a slight similar way reduction of particular climatic elements to one common level can be done. Application of the ordinary kriging is quite sufficient for the spatial visualisation of that element. Figure 2 shows spatial distribution the mean annual temperature reduced to one level located close to the sea level. It is not important which exact level was taken and what reduction rates have been used. It has been applied such as a method to exclude the influence of the altitude on the temperature which is basically associated just with the elevation (Hess, Niedzwiedz, Obrebska-Starkel 1975, Ishida, Kawashima 1993). As one can see there are two inhomogeneous points (series) in 1972 i.e. in the Western and Eastern parts of Poland (left part of the figure). In 1973 (right part of the figure) there is already only one “break” point in the Western part. The second “break” disappeared due to station relocation. That station (Lublin, WMO No. 12495) was shifted from the deep valley to the upper part of plateau. Of course on the Fig. 2, there are some other points in the Southern part with the closed isopleths but they are only results of the location of mountain stations. Using ArcView there is possible to write script calculating and indicating on the map the exact gradient (ratio) exceeding the specific required threshold. The gradient *(gt)* is defined as follows:

$$gt = \frac{\Delta t}{\Delta z}$$

where, Δt denotes difference between temperature and Δz the distance between the respective points.

The method mentioned above is especially reliable for the introductory testing of the large data points when the data analyses of the singular stations require much time.

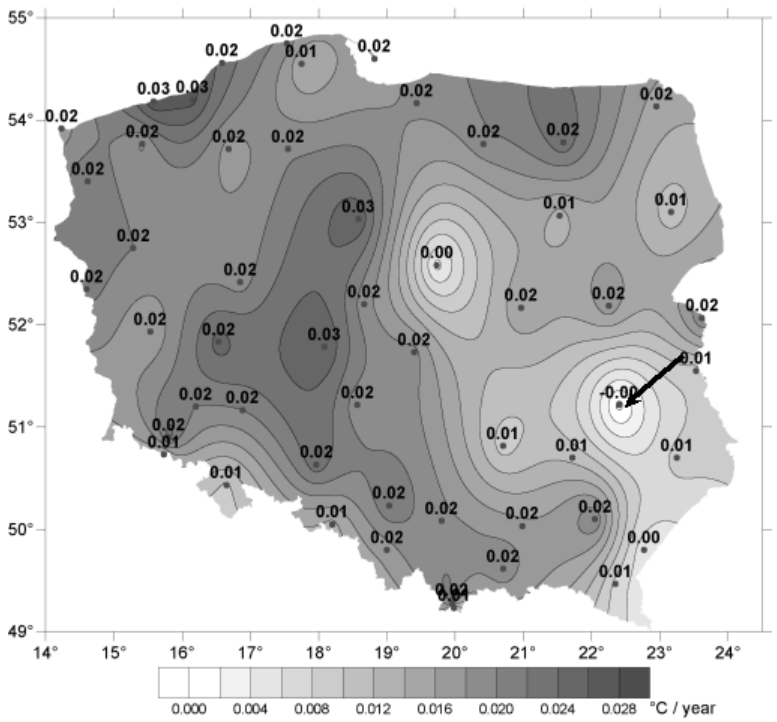

Fig. 3. Linear trends of the mean annual temperature (°C/year) (based on 1951-2000 period)

The next - almost the same simple - tool is the spatial analysis of the linear trends of the particular stations. It turned out that linear trends are quite sensitive indicator of air temperature series (Quiel, Sobik Rosinski 2002, Ustrnul Czekierda 2003). First, the linear trends should be calculated by external software, then the spatial analysis using ordinary kriging must be done. Figures 3-4 present the

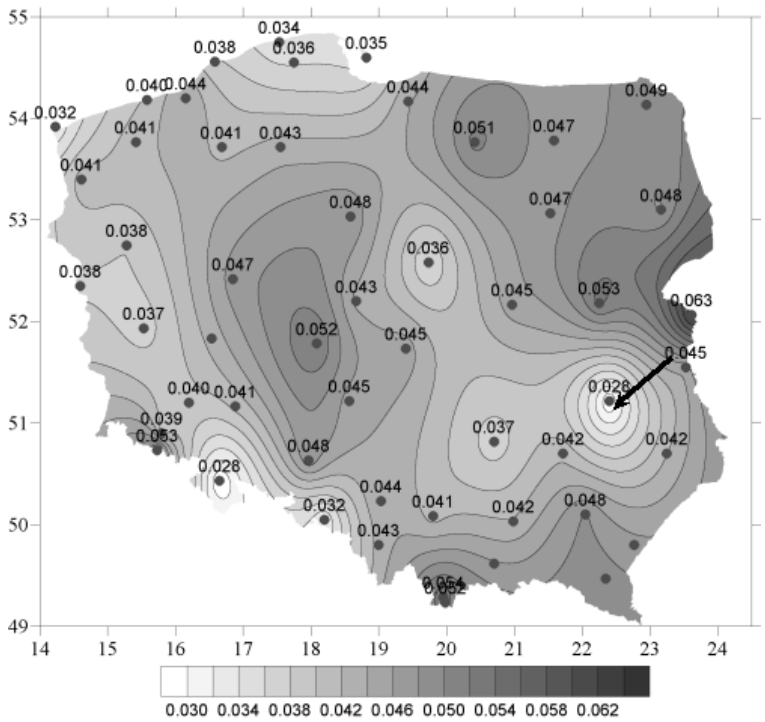

Fig. 4. Linear trends of the mean January temperature (°C/year)

(based on 1951-2000 period)

spatial distribution of the linear trends of the annual and January mean temperature calculated on the basis of 50 years (1951-2000). Inhomogeneities can be noticed for similar stations and they are caused by the real climatic data “breaks”. Sometimes, they resulted from different, not equal time series.

Figure 5 presents some inhomogeneities detected for the earlier mentioned stations: 12495 (Lublin; testing station) and 12595 (Zamość; reference station).

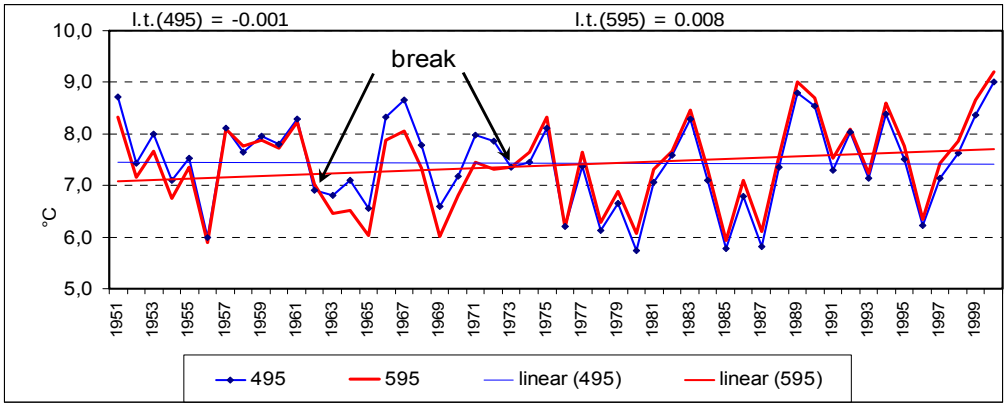

Fig. 5. Linear trends of the mean annual temperature (stations: 12495, 12595)

All above presented tools allow for introductory but very quick analysis of spatial data. Of course, they give quick answer what quality of data has been used. However, for particular detailed analysis they can not be substituted for traditional, well worked out tests for climatic inhomogeneity detection. Sometimes, stations can be situated in very specific local conditions where climatic conditions including temperature can be different than in the surrounding areas. Such situation is rather quite unique but always probable. So, all traditional tests can be applied for further detection and verification. There is no problem to choose the proper test due to the large set of contemporary existing adequate methods (Alexandersson 1986, Szalai 1997, Szalai, Szentimrey, Szinell 1999, Wijngaard, Klein Tank, Koennen 2003). Some examples of these methods can be found in the “AnClim” software (AnClim...). That programme was chosen due to its user-friendly form which is quite open also for students without any larger computer experiences. However, it does not mean that other software can not be applied for detailed testing. Figure 6-7 confirm “break” points which have been detected on the analysis of the above series (12495 and 12595). They give precise test value and dates of breaks in the 12495 series.

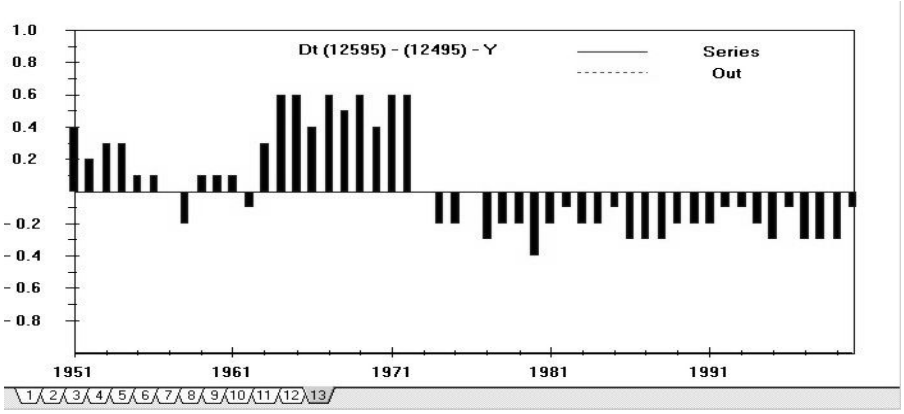

Fig. 6. Deviations of the mean annual temperature (station: 12595 vs. 12495) (According to 'AnClim')

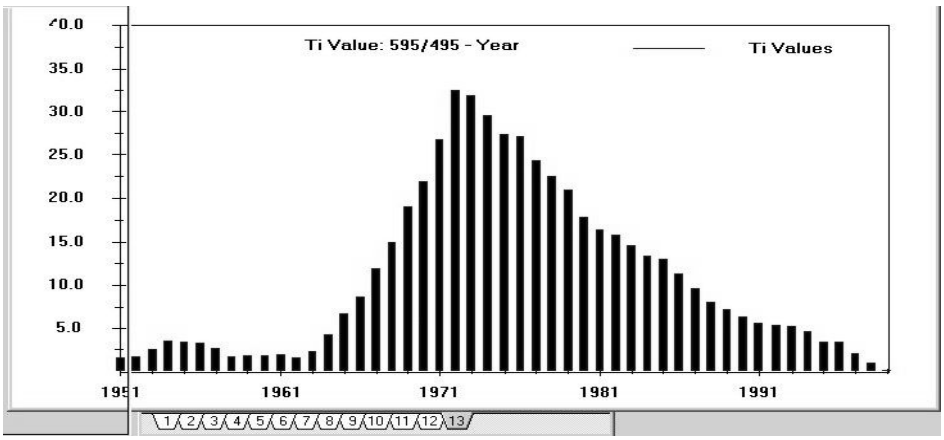

Fig. 7. Ti Values of the SNHT – annual data (station: 12595 vs. 12495) (According to 'AnClim')

CONCLUSIONS

Each climatic/weather map reveals as the another type of data (series), more or less poorly modeling the real conditions. It can be another source of inhomogeneities and therefore firstly must be checked using cross-validation as well as independent samples.

GIS - spatialisation methods using the internal (spatial) dependencies create the particular group of the data quality control tools.

Climatic data reduction to the specific level (e.g. for atmospheric pressure, temperature and also few other climatic parameters) is very simple but quick and efficient manner of homogeneity detection. They are especially reliable for the preliminary testing of the large data points when data analyses of the singular stations require very long time.

Ordinary kriging and linear trend visualisation are quite promising as the inhomogeneity indicators. It is especially useful for large set of series. Some other statistical measurements (e.g. standard deviation) can be also helpful for inhomogeneity detection.

Final inhomogeneity detection can be only done with the help of meta data and they are the same crucial like in the other traditional approaches.

'AnClim' software seems to be very useful and reasonable tool for homogeneity detection of particular stations for different users including undergraduate students.

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MONTHLY PRECIPITATION DATA BASE IN MEDITERRANEAN CLIMATE AREA OF SPAIN. RECONSTRUCTION PROCESSES AND QUALITY CONTROL

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ABSTRACT

Rainfall data analysis under Global Change scenarios in Mediterranean landscapes are under specifically constrains, given the paucity, torrentially, seasonality and irregularity of rainfall regime in these areas. So the approach to rainfall analysis is needed of a very dense data base to control the spatial diversity of rainfall regime.

From 2000, we are trying to construct, by using complete original data base stored at National Meteorological Institutions (INM), a monthly precipitation data base as dense as possible for Spanish Mediterranean climate area. The original INM source is composed by a big amount of data (near 4000 rainfall series for an area of 150.000 km^2) but presents many quality problems. There exist more than 300 series older than 1930, but no one of them continuous recording data today. Moreover, gaps higher than 20 years are frequent. In contrast, redundancy and overlapping are common and usually more than one observatory in the same location is available. Thus, reconstruction process is the first steep in order to obtain a dense, complete and homogeneous data base for this area. For these purpose, we have adopted a general procedure for reconstruction, using Geographical Information System, at two spatial levels: the local level, i.e. rainfall observatories in the same place or far away under specific threshold (less than 5 km) and the subregional level using reference stations.

The quality control of reconstructed series is checked by common homogeneization procedures (i.e. SNHT and others) following the general scheme proposed by Štepánek (2003), and considering the meta-data information produced by reconstruction processes itself. The homogeneization analysis is carried out by AnClim software available at Internet.

The initial results produce a very dense data base (overall mean 1 station per 200 km^2) in the Valencia Region and in the central Ebro Basin (the coastland east and north east inland area). The percentage of observed inhomogeneities let us to indicate that reconstruction process used do not produce a noticeable amount of inhomogeneities in the final series. The global data base is at present under construction, so we present some results of the analysis of such a previous subregional data base for 1951-2000.

1. INTRODUCTION

Recent IPCC recommendations suggested, between others, as principal objectives for the next years the subregional analysis of Global Change and the precipitation analysis (Houghton et al, 2001; Parry 2001). Such task implies the research for links between GCM and empirical records, and has two main problems. First, precision of GCM´s decrease when scales

are changed to high resolution (Matyasovszky *et al.*, 1999; Mcnamara, 1999), because models still have limitations that affect the simulations of rainfall in terms of spatial resolution, some times because precipitation regimes are dependent on local factors (Bhaskharan and Mitchell, 1998). Model values are acceptable in homogeneous and extended areas but they are not able to show the subregional and local details (Zorita and González Rouco, 1999; Prudhoumme *et al.*, 2002).

In the case of precipitation the above mentioned problems are especially relevant, because precipitation is more variable than other climate variables, and because from regional to global scale they are needed for model evaluation and for the construction of climate scenarios for climate changes impacts studies (New et al., 2002; Houghton *et al.*, 2001; Parry, 2001). These is specially true where they are affected by paucity, variability, and torrentially and seasonal regime, as mediterranean climate areas (Groisman and Legates, 1994; Balairón, 2000; Wilby and Wigley, 2000). In such environments GCM predictions represent a simplified view (Palutikof *et al.*, 1996; Sulzman *et al*., 1995), with high uncertainty in spatial and temporal detailed (Mearns *et al.*, 1995; Barrow *et al*., 1996) that should be valuated by studies of empirical records.

The second problems relates with empirical records and GCM outputs. Their comparison needs detailed information both in time and space, and again such constrains affect particularly rainfall analysis because it is one of the most variable climate elements given that precipitation changes in a region only can be detected if a dense data base is analyzed (Groisman and Legates, 1994; Hulme, 1995; Vinnikov *et al.*, 1990). Again the problems increase in areas as above mentioned, as mediterranean ones, where precipitation from one observatory is concentrated in time and many times represents only a reduced space (Cosgrove and Garstang, 1995).

As provisional conclusions, to analyze the Climatic Change on precipitation at subregional level we should be cautious in transitional climate areas, we should avoid a priori spatial and temporal generalizations, and finally there exists a prior necessity for local studies with historical records to contrast outputs of global models. All aforementioned questions implies the need for a dense data base as much as possible both in terms of spatial density and temporal records.

2. PRESENT STATUS OF CLIMATE INFORMATION IN SPAIN

At present, the Instituto Nacional de Meterología (National Meteorological Agency of Spain, I.N.M.)

- Preserve and store a big amount of data of different climatic elements, mainly temperature and precipitation
- Record series are high variable in characteristics (gaps, missing, length, etc)
- It is very common the existence of different series in the same location (from different observatories), or different observatories from towns located very close in space (< 5 km)
- Spatial density of observatories is high, except for altitudes higher than 2000 m o.s.l.
- Data stored offer the possibility to obtain hundred of series by local reconstruction
- The processes of reconstruction produces the only metadata information available.

Under such circumstances, we present the general approach for reconstruction of precipitation monthly data base of Mediterranean area of Spain following the partial approach developed in Valencia Region and Middle Ebro Basin. The study analyze more than 3800 monthly series for a total amount of 181,330 km^2, 36.8% of National area. The final objective is to analyze precipitation at different spatial and temporal scales (year, season, month) in Mediterranean area of Iberian Peninsula, by exhaustive use of the INM information, to study the natural systems response to Global Change.

In previous year different efforts has been made in such direction. Between others, Pérez Cueva (1994) in Valencia Region of Spain (east coastland central area), Romero et al., (1998) for spanish mediterranean littoral area (1963-1994), and González Rouco et al., (2000)

for Iberian Peninsula, Southern France and Northern Africa using 95 station for 1899-1989 period.

3. THE APPROACH

The approach has the following steps:

Reconstruction at local level

- Initial evaluation of data and selection of Potential Candidate series (CC) for reconstruction and filling series (R). The criteria for select series as candidate include present status, minimum length of records (10 years), missing and gaps (less than 25%).
- Local reconstruction of CC series, filling missing values with data from R station using the minimum distance criteria.
- Quality control (Step 1), looking for typing errors, false 0, extreme values and outliers by using overlapping data between CC series and R series in each case, when overlapping period exist, and other nearest stations not so far > 10 km.

The analysis of reconstructed series is as follows:

- Creation of Reference series of each CC series by using the 5 CC nearest (correlated) stations.
- Quality control, Step 2 (as before) in this case with reference series
- Homogeneity test (SNHT)
- Criteria for correction
    - Metadata originated during processes
    - Beginning and ending series not considered
    - Repeated in different months
    - Summer problem (July and August)

Such approach follows the general scheme proposed by Štepánek in Czech temperatures data base, (Štepánek, 2003) with some modifications given the characteristics of precipitation data, and using the Anclim program (Štepánek, 2001) available at internet.

4. DESCRIPTION OF ORIGINAL DATA BASE

The total amount of series stored at INM for Mediterranean areas of Spain are 3980, from which we selected 1196 as CC series following the previous criteria. The information is summarized in Table 1 for total observatories, and CC series prior and after reconstruction. Figure 1 shows the number of observatories in time; from the beginning of XXth century the amount of observatories increase until the Spanish Civil War (1936-1939), then increase again until 1970´s, reaching the maximum value, and then decrease. Rural exodus, reorganization and abandon are the main causes of such final decreasing. The spatial distribution of CC series is shown in Figure 2.

	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Total	4	8	11	17	15	19	278	609	777	959	1553	1979	2474	2287	2108	1695
CC	1	1	1	1	1	4	97	184	238	331	562	803	1066	1184	1186	1032
CC rec.	4	8	10	15	13	18	218	418	490	606	882	1034	1165	1197	1197	1117

CC rec. series CC after local reconstruction

Table 1. Total number of observatories. Decade analysis

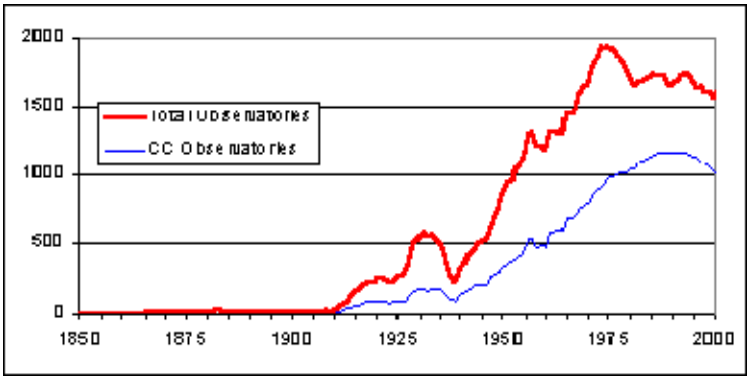


Figure 8. Time evolution of precipitation observatories. Total amount and CC series

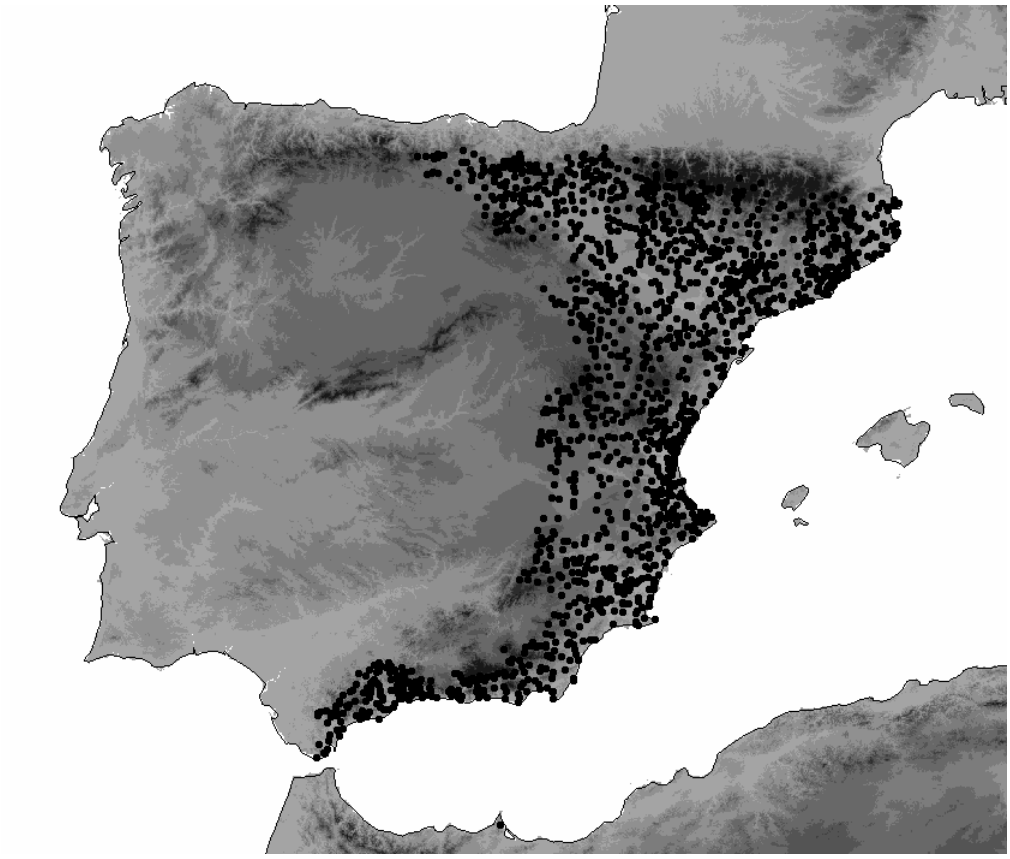
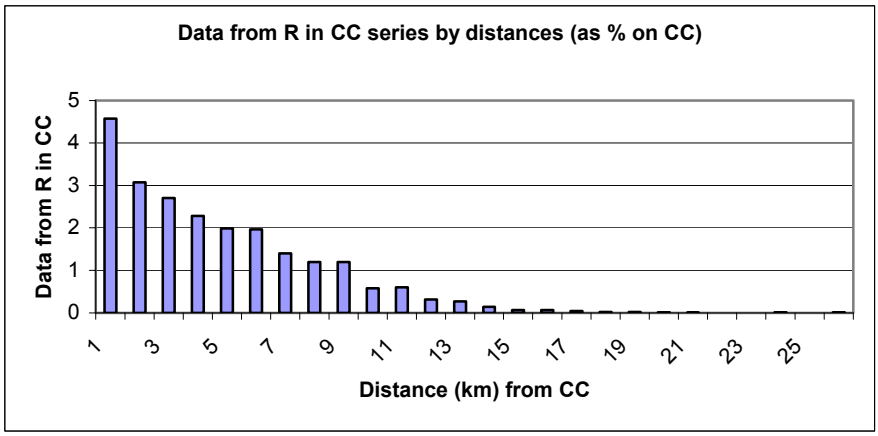


Figure 9. Spatial distribution of CC precipitation series.

The local reconstruction processes consider distance criteria between CC series and R series as guideline. In Figure 3 it is shown the distribution of R series with respect to their CC series accordingly distance in km. Data are shown as percentage of reconstructed CC series produced by different R series at different distances. The most interesting result is that more than 80% of R series are less than 5 km far, and data from those R series and original CC in reconstructed CC are 92% of total data.

Figure 10. Local reconstruction processes. Data amount from R series in CC series accordingly distance (in km). Data are expressed in % of R over CC series.

The total amount of data month (a data month is defined as "total amount of precipitation



for a given month, in a given year, in one observatory") is 1,054,807. Data month included in original CC are 564,922 and final data month in CC reconstructed are 729,546. Then reconstruction processes supposed 22.6 % of data reconstructed, and more than 50% of such a data come from R series less than 5 km far. In Table 2 it is shown the CC series by length in years prior and after reconstruction. The most noticeable result is the amount of series with 60-80 years in length. Such results also produce a noticeable spatial density, increasing along the century.

Length (years)	10-20	20-40	40-60	60-80	80-100	>100
Prior	112	375	582	111	15	5
After	15	183	679	254	54	12

Table 2. Distribution of CC series by length (years) prior and after reconstruction

5. PRELIMINARY RESULTS AT SUBREGIONAL LEVEL

In a previous years we have developed this approach in two different areas of Mediterranean landscapes of Spain, the Middle Ebro Valley (NE inland) and the Valencia Region (E coastland), for the 1951-2000 period. A brief presentation of some results let us to check the global value of such approach.

5.1. Precipitation evolution in the eastern coast of Valencia Region

Such a data base consist of a 95 reconstructed series from a total of 210 original series. The period analyzed is 1951-2000, and global spatial density is about 1 observatory per 200 km^2. After reconstruction, series were checked for inhomogeneities using metadata information produced during reconstruction processes, specially joining points. The global results are shown in Table 3.

	E	F	M	AB	MY	JN	JL	AG	S	O	N	D
Total	10	24	11	18	9	27	10	2	9	7	20	1
First years	5	20	1	6	4	15	2	1	2	0	18	0
Ending years	4	0	5	4	3	4	2	0	3	6	0	0
Accepted	**1**	**4**	**5**	**8**	**2**	**8**	**6**	**1**	**4**	**1**	**2**	**1**

Table 3. Subregional precipitation data base for Valencia Region. Inhomogeneities results

The accepted and corrected inhomogenities (43) correspond with such cases as those indicated by metadata information given by reconstruction processes. We note the big amount of such inhomogeneities at the beginning (74) and ending (31) of series, not accepted in our case. The inhomogeneities detected and accepted are less than 5% of monthly series

Such data base let us to analyzed the behavior of the last decade of XXth century. In Figure 4 it is shown the precipitation evolution between comparison of the mean value 1991-2000 and 1951-1990. Positive and negative marks indicate variation over the 15% (positives or negatives). The most important results is the coherency of spatial patterns at seasonal and annual scale.

5.2. Teleconnection patterns

The above subregional data base of precipitation, combined with the subregional ones for the Middle Ebro Valley is composed for the same period 1951-2000 of 141 observatories for 40,000 km^2. This second subregional data base has been constructed following the same criteria.

In Figure 5 the relationship between NAO and Polar teleconection paterns is shown. Winter NAO pattern relates negatively and significantly (Spearman rank test, p 0.05) with inland observatories, and Polar pattern relates positive and significantly at coastland areas. Again spatial results are coherent, and western flows (indicated by NAO negative value at Iberian Peninsula latitude) are related to inland winter precipitation, while coastland areas are out of its influence. Polar pattern in coastland areas produce east-west flows and relates with a specifically coastland area. Finally the most interesting results is that both winter pattern seems not to be overlapped in the space.

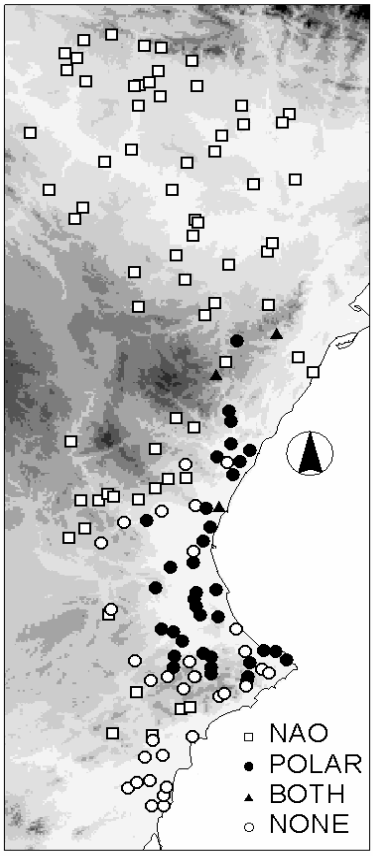
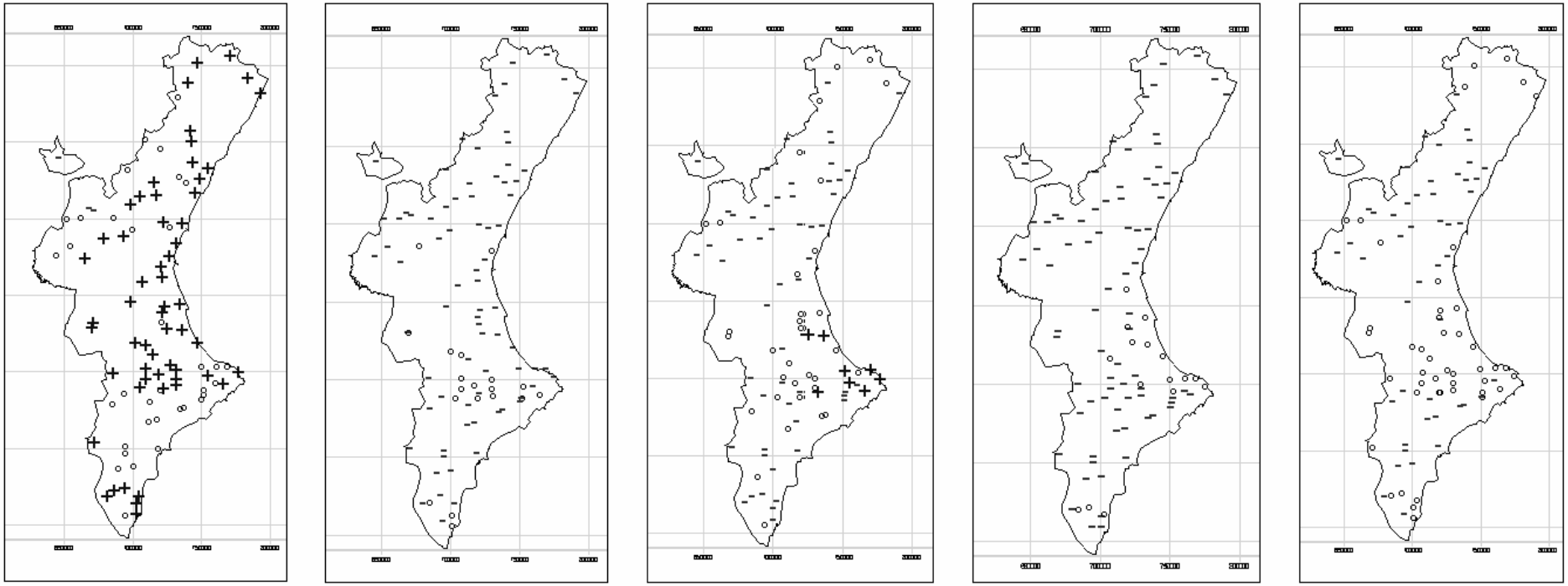


Figure 5. Winter teleconnection

Figure 11. Precipitation evolution in Valencia Region. Variations (+/- 15%) in mean values between 1991-2000 and 1951-1990. From left to right winter, spring, summer, autumn and annual results.



5.3. The natural systems response

As has been previously indicated, one of our final objectives is to analyzed the natural systems response to global change evaluated by mean of precipitation analysis. To do that dendroecological research is being done at the same time as climate analysis. Figure 6 show the relationship between tree ring index (TRI) and standardized precipitation index (SPI) at 6 month scale prior to June (Figure 6 a), and TRI with precipitation from September to October (Figure 6 b). The first case is an example from Middle Ebro Basin and the second ones from eastern coast of Valencia Region. Data are expressed in deviation from mean value. Both relationships are significant (p 0.05).

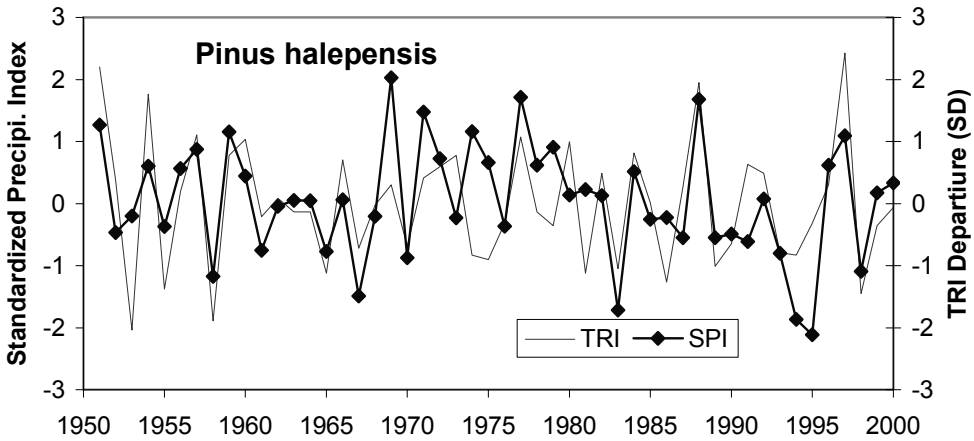


Figure 6a. Relationships between TRI and SPI. (Ebro basin)

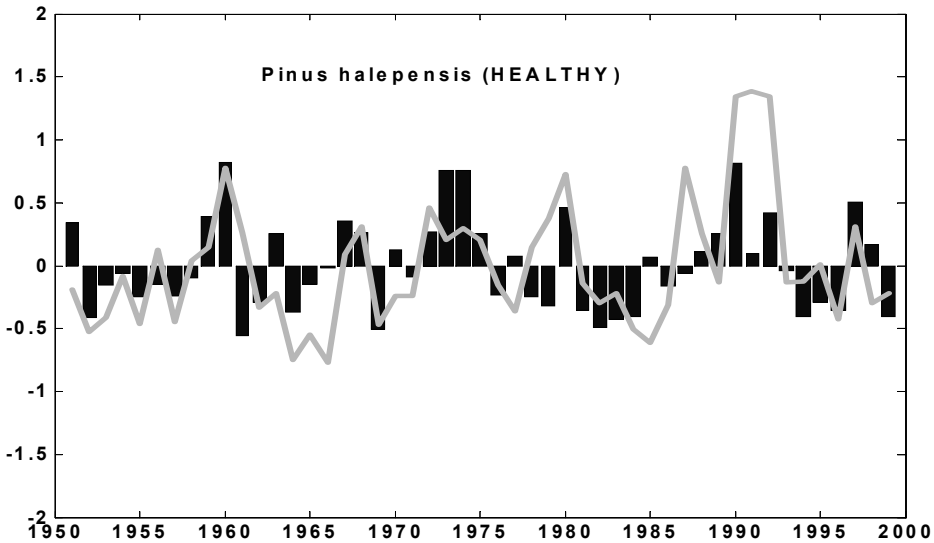


Figure 6b. Relationships between TRI and precipitation (SE Spain)

6. **FINAL REMARKS**

Quality control, homogeneization procedures, filling missing values are previous task to ensure the quality of climate data series to avoid miss interpretation of climate change (González Rouco *et al,.* 2000). With respect to filling missing data differents methods has been

presented (Rodriguez *et al.*, 1999; Valero *et al.*, 1996) all of them dealing with nearest or reference stations (see Vincent and Gullet, 1999; WMO, 1990; Karl and Williams, 1987).

By the other hand, homogeneity control is a well known problems not solved until present. There are many test (see revision in Szalai *et al.*, 1999; Peterson *et al.*, 1998; Lanzante, 1996), with differents examples in Rhoades and Salinger (1993, CUSUM test), Rodríguez *et al.*, (1999, von Neuman test), Tayanç *et al.*, (1998, Kruskal-Wallis test), Easterling and Peterson (1995, *likelihood ratio test*), Gan (1995, Kendall test), Lanzante (1996, Wilkoxon-Mann-Withney test), Tarhule and Woo (1998, Pettit, Man Withney and Man Kendall test), and of course the most well known test SNHT of Alexanderson (Alexanderson 1986; for a nice exposition see Keiser andy Griffits, 1997). But different test implies different results many times. Secondly, some meteorological services has developed their own procedure (see Vincent and Gullet, 1999; Tuomenvirta, 2001; Peterson *et al.*, 1998; Szalai *et al.*, 1999), but unfortunately the software is not ever available.

In our case, after differents tentatives in two areas of Iberian Peninsula, we are developing a general procedure to reconstruct as much as possible the precipitation monthly series of mediterranean area to ensure the analysis of climate change at subregional level and to study de natural systems response. To do that we adopt a general scheme that try to use the total amount of data stored at National Meteorological Agency of Spain (INM), using the software Anclim and two steps procedure, first the local analysis (reconstruction and quality control), and second the subregional analysis dealing with reference series. The practical absence of metadata information is overpass by generating our own metadata during the reconstruction processes. The initial results obtained for the second half of XXth seems to be promising because of coherence of spatial patterns.

Acknowledgments

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HOMOGENIZATION OF AIR TEMPERATURE SERIES IN THE CZECH REPUBLIC DURING A PERIOD OF INSTRUMENTAL MEASUREMENTS

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Abstract
This paper describes homogenization of monthly, seasonal and annual air temperature series of almost 200 stations of the Czech Republic measuring during a period of instrumental measurements (since 1771). As a matter of fact, stations metadata are rarely complete so it is more or less necessary to rely upon the results of statistical tests for homogeneity. But in most cases the results of the tests cannot be relied on with complete certainty to find the inhomogeneities in the series. By using various statistical tests along with various types of reference series etc. in this work it was possible to considerably increase the number of homogeneity test results for each tested series which made assessing homogeneity and inhomogeneities determination more reliable. It is only in recent years that such a task can be efficiently accomplished thanks to new technologies (faster computers) and new software development. All data processing and analysis in this paper were carried out by means of software called AnClim and ProcData (software package for automatic processing of climatological data, analyzing, homogeneity testing, adjusting, etc.) which has been created by the author.

Key words: tests of homogeneity, homogenization, series processing, AnClim and ProcData software.

1. INTRODUCTION

There is a reasonable presumption that an investigation of so much discussed climatic change should be based on homogeneous climatological time series. However analyzed long time series very often suffer from non-climatic effects. These effects include station relocations, change of observer, instruments, observational procedures etc. Information on changes of this type should be mentioned in station metadata, but there are a lot of cases where the metadata are not complete or even are missing, so we have to rely then mainly upon statistical tests results. A large number of statistical techniques have been developed for detecting inhomogeneities in climatological time series. List of the techniques used in recent years together with approaches of individual states towards this problem are described e.g. in Peterson (1998) or Szalai (1999).

This paper follows the effort of such works and presents the results and experiences of homogenization of air temperature series (monthly averages) in the Czech Republic for a period of instrumental measurements (1771-2000). Created database consist of almost 200 stations measuring within the area of the Czech Republic. Long-term

measurements of air temperatures from neighbour states of the Czech Republic (Austria, Germany, Poland, Slovakia) were also used in order to improve the homogenization of the series. These series were important mainly in the early years of measurements when there were not enough available stations in the Czech Republic for construction of reference series. For sources of gathered data and problems that had to be solved regarding the data (e.g. different observation hours etc.) see Štěpánek (2003a).

So far inhomogeneities detected and adjusted in this work were only those of single shift. This type of inhomogeneity is the easiest one to detect and it occurs the most frequent in the series. For homogeneity testing and time series analysis software AnClim developed by Štěpánek (2003b) have been used. For preparing and processing data for/from AnClim, created database software ProcData have been used (Štěpánek 2003c).

2. BACKGROUND FOR USED APPROACH TO HOMOGENIZATION

One of the problems when dealing with homogenization of climatological time series is a lack of complete metadata (information about station relocation, change of observer, etc.). In case of missing metadata we then have to fully rely upon statistical tests for homogeneity. Unfortunately the results of statistical tests are not satisfactory in most of the cases - correct inhomogeneity detection is quite problematic (detected year of inhomogeneity is often given with some error or not at all).

Before starting homogenization, the ability of the statistical tests to correctly detect inhomogeneities in the series was investigated. For this purpose, series of random numbers were generated (with properties of air temperature series for annual, summer and winter averages of the Czech Republic). The length of the generated series varied from 10 to 100 values. Artificial steps were introduced into these series, which had various amounts of change in level, these steps were situated in various positions of the series etc. Almost 1000 series were obtained by combining the results from the series with these artificial breaks. These series were then passed through tests for homogeneity available in AnClim (Štěpánek, 2003b) in order to determine the abilities of these tests to detect inhomogeneities.

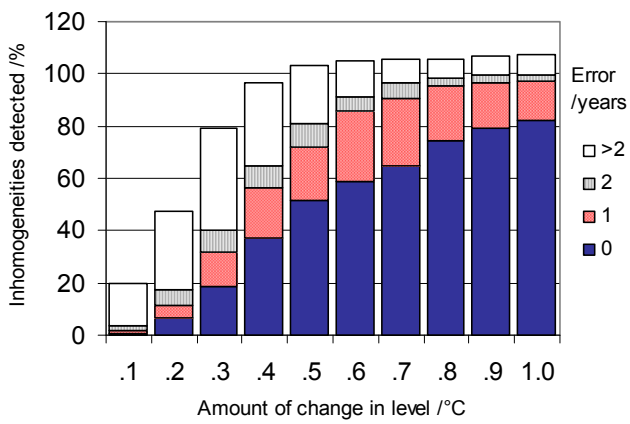


Fig. 1. Percentage of detected inhomogeneities (from all inhomogeneities present in the series), for various amounts of change in level, Alexandersson SHNT – single shift, α=0,05. For generated series with annual standard deviation and length of series less

than 50 years. Differentiated are right detections (0 – blue – inhomogeneities detected correctly for a given year), and erroneous detections (1, 2 and more years fault). The number of tested series was 180 for each category of amount of change. More than 100% of detections is given by dividing the series into more parts during homogeneity testing.

Fig. 1. shows the output of one such investigating of reliability of inhomogeneities detection (relative homogeneity testing, the reference series were guaranteed to be homogeneous). The given results are appropriate for Alexandersson SNHT test – single shift (Alexandersson, 1986), but similar results were also obtained using Bivariate test (Potter, 1981), Easterling and Peterson test (Easterling and Peterson, 1995) etc. There is a lot of information hidden in the figure. We can, for example, conclude that correct inhomogeneity detection (i.e. error of right year determination is 0) with magnitude less than 0.5°C occurs in less than half of the cases, in the rest of the cases we are given false years of inhomogeneity or no detection at all. According to these results, inhomogeneities less than 0.5°C are very problematic to detect. For further details see Štěpánek (2003a).

Because of this uncertainty of homogeneity tests results, an approach was searched for that would increase the reliability of inhomogeneity determination. The idea was to get as many test results for each candidate series as possible. By statistical processing of large numbers of these test results it was possible to calculate probability of each inhomogeneity of a given series (probability calculated as a portion of number of detected inhomogeneities - for each year, group of years or whole series - in amount of all theoretically possible detections). Among the advantages of such an approach is that we know relevance of each inhomogeneity (we can compare inhomogeneities and to say which inhomogeneities are more relevant), moreover we can assess the quality of measurements for a series as a whole (when we sum the number of all detected inhomogeneities in the series and express them relative to the number of all theoretically possible detections).

In order to carry out the approach outlined above for homogenization, several statistical tests for homogeneity were applied, various types of reference series were calculated for each candidate, and monthly series as well as seasonal and annual averages of the series were tested. By combining all of these it was possible to considerably increase the number of test results for each tested series, thereby increasing the reliability of the homogenization process.

3. SERIES PROCESSING DURING HOMOGENIZATION

Processing of the series during quality control and homogenization included the following steps: detection, verification and possibly correction of outliers (extreme values), creation of reference series (3 ways), homogeneity testing (using 3 homogeneity tests), inhomogeneities (years) determination according to test results and metadata, adjustment of inhomogeneities and, only at the end, filling missing values. These steps are outlined in the fig. 2. and are discussed further in the text.

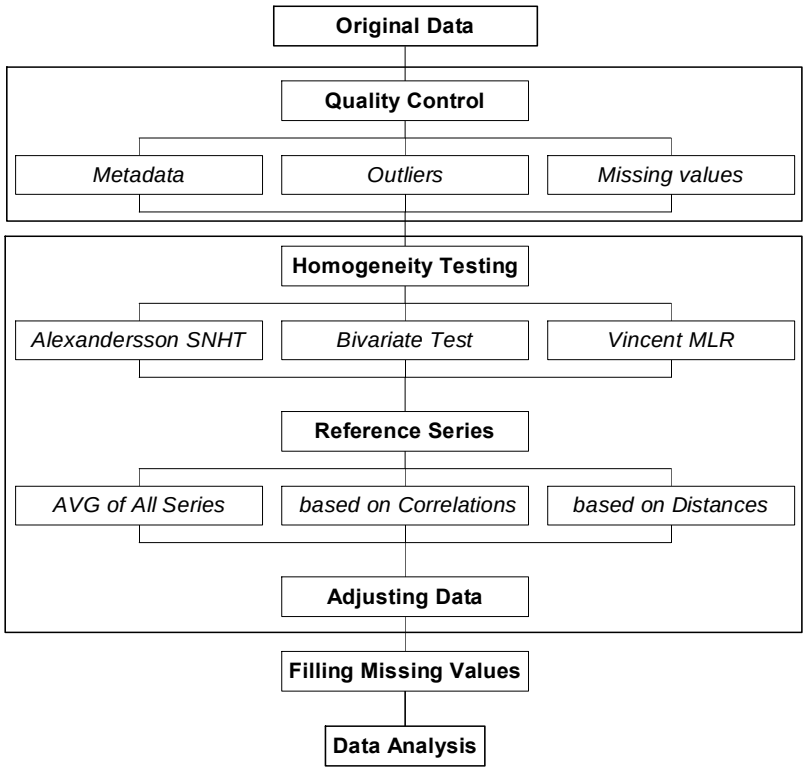


Fig. 2. Scheme of data processing during quality control and homogenization of the series.

3.1 Data Quality control

Before homogenization it was necessary to check the data for the presence of outliers. The outliers (extremes) were detected in difference series between candidate and several types of reference series of this candidate (to increase reliability of the outliers/extremes detection; for creating reference series see chapter 3.3). Detected outliers were then verified (also using information from metadata). In the case where a value was verified correct but classified as an outlier (defined as a value exceeding 1.5 multiple of interquartile range from quartiles), the value was left in the series. In the case where it was classified as an extreme value (value exceeding 3 multiple of the interquartile range), it was replaced by a missing value and after the homogenization the gap was filled (see chapter 3.6).

3.2 Homogeneity testing

The homogeneity was tested by means of the software AnClim (Štěpánek, 2003b) using these tests for relative homogeneity (significance level α=0,05):

- Alexandersson test (SNHT for a single shift) (Alexandersson 1986, 1995) - applied for monthly, seasonal and annual data.
- Bivariate test of Maronna and Yohai (Maronna and Yohai 1978, Potter 1981) - applied for monthly, seasonal and annual data.
- Vincent multiple linear regression method – model 3 - a step (Vincent, 1998) - applied for seasonal and annual averages only.

The first two tests are based on cumulative deviations from the mean, the third one is very similar to Easterling and Peterson test (Easterling and Peterson 1995) and is based on two-phase linear regression model.

Tests for finding inhomogeneities were applied on 40-year long parts of tested series because the alternative hypothesis of the Alexandersson and Bivariate test suppose the presence of only one inhomogeneity in the series (there exist modifications of the Alexandersson test for several steps - see e.g. Alexandersson 1995, but they were not used in this work). In cases where the length of a series was greater than 40 years, the series was divided into several parts. These parts were created with an overlap of 10 years (overlapping is important due to the overestimation of detected inhomogeneities near the ends of series - see Alexandersson 1995 e.g.). Reference series were created individually with regard to each 40-year long part of a candidate series.

The use of series with lengths of 40 years seems to be reasonable for homogeneity testing. Shorter lengths would not be so suitable from statistical point of view, whilst on the other hand longer series usually contain more than one inhomogeneity (a typical length of period with one inhomogeneity usually does not exceed 30-40 years, see e.g. Auer, 2001).

To ensure that only one inhomogeneity was present in a series when using Alexandersson or Bivariate test, a further modification was introduced into AnClim software, which divides the series at the position of the found inhomogeneity and test the parts before and after the detected inhomogeneity separately. If no other inhomogeneity was found in these two parts, we can rely on the results of the given test for a whole length of the series (especially the significance of a test statistic).

3.3 Reference series

For improved homogenization, the reference series used should fulfill some requirements. Among the most important are that they are highly correlated with the tested series and they are homogeneous. In case of temperature there is no problem finding series with sufficiently high correlations within the whole area of the Czech Republic. For calculation of reference series, averages of several selected stations (5 at least) were used, thus the influences of possible inhomogeneities in selected individual series were suppressed and the reference series could be regarded as truly homogeneous.

In order to get more homogeneity test results and thus a better assessment of the homogeneity of the tested series (see chapter 2.), three different calculations of reference series were performed:

- a simple average of all available series
- a simple average from selected stations based on correlations
- a weighted average from selected stations based on distances

Generally homogeneity testing using these three types of reference series gives results which are a little bit different and thus gives a more comprehensive view of inhomogeneities present in the tested series. Each of these types of reference series has its advantages and disadvantages. For the first type of reference series (average of all available series), possible inhomogeneities in the reference series are suppressed the most of the three types, but it is the least correlated with the tested series (but still the correlations are higher than 0.9 for the series of the Czech Republic). For the second type of reference series – by using correlations, the reference series created is

the most similar to tested series (and thus suppressing variability in the differences/ratios series the best), but stations with similar inhomogeneities to the tested series can be selected (however this danger can be diminished by using the first difference series for calculation of correlation coefficients). For the third type of reference series – by using distances, geographical vicinity of the selected stations is preserved, but there can be different climatic conditions even for near stations (due to different altitude etc.).

For calculation of reference series, stations outside the Czech Republic were also used (21 stations from neighboring states). These stations were important mainly during the period of early measurements when there was only a small number of stations available within the Czech Republic to create reference series.

Calculation of the different types of reference series is discussed further in the text.

3.3.1 Reference series calculated from all available series

All available series in the database for a given year were taken and from all these values an averaged series was computed. First the series had to be converted into series of anomalies from their means (for 1961-1990) so that the values of different stations were comparable within the whole period of instrumental measurements.

In the first step, the series measuring within the period 1961-1990 have been converted into series of anomalies, which have zero mean for this period (each month).

In the second step, series that did not have measurements during the period 1961-1990 have been converted into series of anomalies by using the series already converted into anomalies. 10 stations with the highest correlation coefficients were selected for each station to be converted. Then averages were calculated for the last 30-year period of the converted series, both for the station in question and its reference series (created by averaging all the selected stations series). These two averages were then compared using differences (ratios for precipitation) and an adjustment was estimated for the series to be converted (see fig. 3).

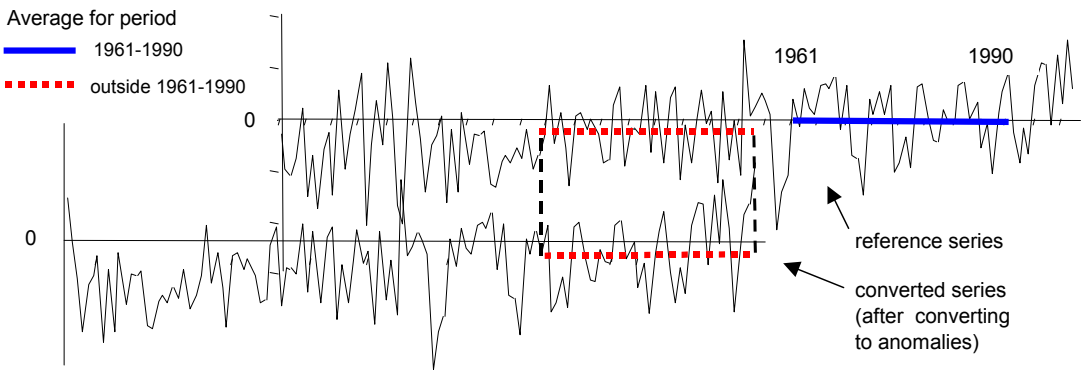


Fig. 3. Converting series to anomalies for the period 1961-1990 and outside 1961-1990

After the measurements of all stations were converted into series of anomalies (with regard to 1961-1990 period), the averaged series of the Czech Republic have been calculated and used as an unique reference series for each station (series with lengths shorter than 30 years could not be used for this averaging). It was possible to create this type of reference series because of high correlations between all the stations within the Czech Republic.

3.3.2 Reference series calculated by means of correlations

In this case, reference series were created using an average of 5 stations which had the highest correlation coefficients with respect to the candidate station series. The correlations used for selecting the stations were calculated from the first difference series of the two series. The reason is that possible inhomogeneities (steps) in the series are then manifested only by one value. The average used for the calculation was a simple average (there was no difference between simple and weighted average because of very similar correlations between stations). Stations with correlations less than 0.9 were not accepted for the calculation. Furthermore only stations with an average number of missing values not exceeding one missing value per 1.5 years were selected (because of less number of available values as well as due to fact that such series are less reliable and contain inhomogeneities very often).

3.3.3 Reference series calculated by means of distances

Reference series were created in a similar way as in the previous case (based on correlation coefficients), but the stations used for calculation were selected according to distances from a given candidate station. Reference series were calculated as weighted average from 5 nearest stations, with weights as a reciprocal value of square of distances. A limit for selecting the stations was 100 km, further stations were not accepted. Only stations with an average number of missing values not exceeding one missing value per 1.5 years were selected (for the same reason as indicated in 3.3.2). No other limits for selection, such as similar altitude etc., were added because of very high correlations between stations of the same region (in case of air temperatures of the Czech Republic).

3.4 Assessment of homogeneity of the series

As stated before, the reason for using three different types of reference series and three different homogeneity tests applied to monthly as well as seasonal and annual data, was to get a large number of test results for each station so that assessing homogeneity (inhomogeneity determination) was more precise and more reliable (see chapter 2).

The main criteria for determining the year of inhomogeneity was the probability of the given inhomogeneity, i.e. number of detections of a given year from all the testing of a given station expressed relatively to number of all theoretically possible detections. Regarding all the tests and reference series, months, seasons and year, the total number of testing results (100%) was more than 100 values (usually 123) for each tested 40-year part of the series. For deciding about the inhomogeneity, a limit of 20% of all possible detections have been used in cases where there was no information in metadata about the change, 10-15% were sufficient in cases where the inhomogeneity was in agreement with the metadata. The number of detections for groups of years were also taken into account (some inhomogeneities started during the course of a year and thus manifested in 2 years at least). In cases where there was no mention in the metadata about the detected shift (most of the cases), some other information was also used (e.g. distribution of the given year within individual months or seasons, graphs of differences with reference series and some other characteristics) for deciding whether

the undocumented inhomogeneity could be regarded as "undoubtfuly" proven and thus to be corrected.

Some series (or parts of the series) were problematic to assess for homogeneity (e.g. a great number of inhomogeneities were detected but it was not possible to find any clear pattern in the detected years). Such series (or their parts) were excluded from further processing and were marked as unreliable for further studies.

The mentioned decision limits were estimated subjectively, from a selected set of stations, so that only clear inhomogeneities were corrected (the aim was not to “over-homogenize” the series). These limits are appropriate for the air temperature series of the Czech Republic, for other elements or areas these would have to be determined according to the given purposes.

3.5 Adjustment of inhomogeneities

Adjusting of the detected inhomogeneities was done by means of reference series calculated as an average of 5 stations with the highest correlation coefficients with respect to the series being adjusted (correlations were calculated from the first difference series), stations with correlations less than 0.9 were not accepted. The amount of change was estimated as a difference between averages calculated from difference series between the candidate and reference series from a period taken 20 years before and 20 years after the year being adjusted (the period was truncated in case there was encountered another inhomogeneity within this period). The adjustment was applied to all monthly data. The start of inhomogeneity was determined to the particular month (where possible).

Inhomogeneities closer than 4 years from the end of series could not be adjusted. This happens relatively often in the recent years because of transition to automatic measurements (since 1997). The parts of series with inhomogeneities near the ends of series had to be removed from further processing.

3.6 Final remarks

The above-mentioned steps (creating reference series, homogeneity testing, assessing and adjusting possible inhomogeneities) were performed in several iterations. In each of the iteration more precise results were obtained. Reference series were recalculated after each of the iteration for every tested series (for the 40-year parts of the series, respectively). After the third iteration no further inhomogeneities were detected in the series. The final adjustments of inhomogeneities were estimated from original data, taking into account inhomogeneities detected in all the three iterations. It was necessary to use original data for the final correction (but used reference series were calculated from adjusted series in the last iteration), so that the final adjustments were estimated using periods without any inhomogeneities (a period taken for an adjustment was truncated when there was found another inhomogeneity in the series).

Filling of missing values was performed only after homogenization and adjustment of inhomogeneities in the series. The reason was that the new values were estimated from data not influenced by possible shifts in the series. Moreover, when missing data are filled before homogenization, they may influence inhomogeneity detection in a wrong way (above all when a gap is longer than one year and there is an inhomogeneity - change of mean - near the position of the missing value). Filling the gaps was done by means of linear regression between filled value series (dependent variable) and a

reference series (independent variable). The reference series was calculated as an average of 5 stations with the highest correlations with respect to the series with filled value. For the linear regression model values 20 years before and 20 after the value being filled were used.

One of the remaining open questions of homogenization is the influence of the transition to automatic measurements which was started in the stations network of the Czech Republic in 1997. It is too early for adjusting the data, but inhomogeneities caused by the transition were already detectable (even if the database ends with year 2000). Such end parts of the series had to be removed from further processing. The replacement will be accomplished within a short period (several years) and there are only a few stations with comparative measurements (manual and automatic). **The problem in the future will be then that after transition of all stations in the network to automatic measurements, not enough stations will be available for creating homogeneous reference series, i.e. there will be no way how to assess or adjust inhomogeneities caused by the transition!** Until there is an assessment of the impact of the transition on the series, it is also not possible to add new years to the end of the homogenized series (ending in 2000).

4. HOMOGENIZATION RESULTS

Before homogenization, there were almost 200 stations from the Czech Republic available in the database. During homogenization, some series had to be truncated near the ends of measurements, mainly in cases of suspicious values or when the series could not be adjusted for inhomogeneities because the break was near the end of the series (e.g. several cases with transition to automatic measurements after 1997). In several cases even whole stations had to be excluded from the database - when their data were regarded as too suspicious throughout the whole period of measurements and when it was impossible to carry out meaningful homogenization.

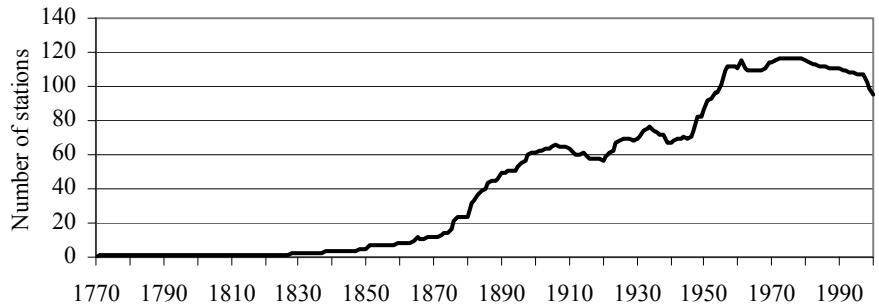


Fig. 4. Number of homogenized stations in the Czech Republic in individual years for the period of instrumental measurements.

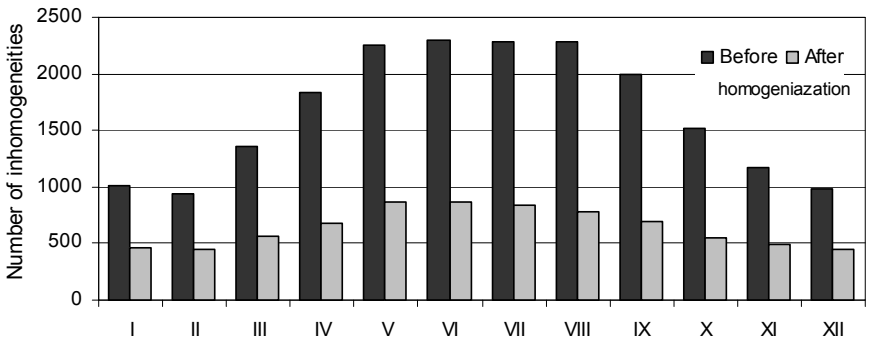
After homogenization, 174 stations are available with homogeneous air temperature measurements (monthly averages). Fig. 4. shows number of these stations available for individual years. An average length of these homogenized series is 60 years (median 50 years), an average minimal distance between stations is 13 km (the same for median). There are 41 stations with a length of 20-39 years, 80 stations with a length

40-59 years, 32 stations with a length of 60-99 years and 21 stations with a length more than 100 years.

Characteristic	Data	
	Original	Homogenized
Number of stations	192	174
Number of tested 40-year parts of the series	348	307
Number of adjusted inhomogeneities - years		231
Number of all tested series	40716	35919
Number of significant inhomogeneities (p=0.05)	32445	13802
Number of significant inhomogeneities per number of tested series	***79.7%***	***38.4%***

Table 4. Homogenization overview.

Table 1. shows the number of tested series and other characteristics pertinent to the performed homogenization. The high number of tested series is due to the fact that 40-year parts of monthly, seasonal and annual averages, using three homogeneity tests, with three reference series (see chapter 3 for details) were tested for inhomogeneities. Before homogenization, almost 80% of the series were detected as being inhomogeneous. After adjusting "undoubtful" inhomogeneities, almost 40% of the series still remain inhomogeneous. This great deal of inhomogeneities present in the series after homogenization is due partly to the random component of the series (see chapter 2 for uncertainty of correct inhomogeneity detection), and partly to the fact that some real inhomogeneities in the series still remain, however without further metadata it is not possible to correctly assess (and then to adjust) them.



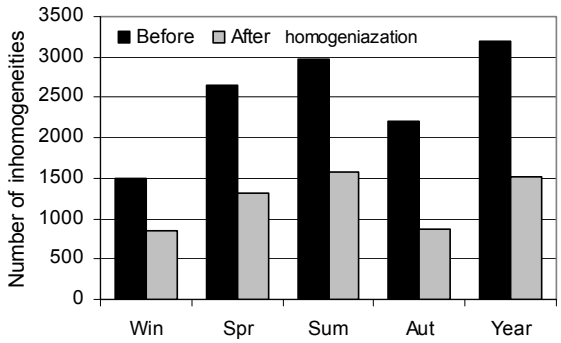


Fig. 5. The number of significant inhomogeneities (α=0.05) detected before and after homogenization for monthly, seasonal and annual averages (total number of tested series: Before almost 41000, After 36000 series).

Fig. 5. shows number of detected significant inhomogeneities (α=0.05) before and after homogenization. The inhomogeneities were detected mainly in summer (more than two times greater number than in winter months). After adjustments the number of inhomogeneities decreased mainly in summer (almost three times against two times in winter).

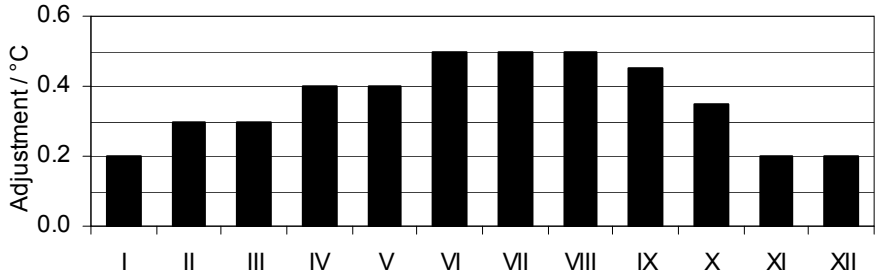


Fig. 6. Medians of the amounts of adjustments (absolute values) for homogenized series (for 231 adjusted inhomogeneous years).

Amounts of used adjustments for changes in mean are shown on fig. 6. Averages of the amounts of adjustments are about 0.1 higher then the medians in individual months. The highest adjustments were applied in summer months (average value over 0.5°C), the least in winter months (average over 0.2°C).

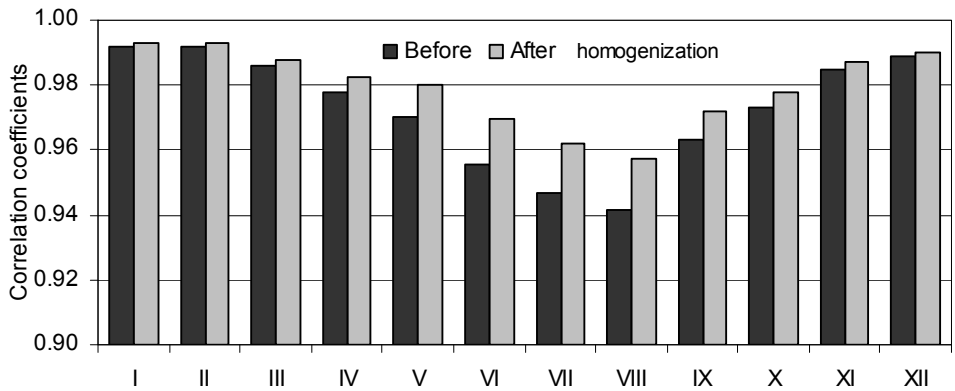


Fig. 7. Medians of correlation coefficients between candidate and reference series before and after homogenization (for 231 adjusted series).

Fig. 7 shows influence of adjustments in individual months (measured by means of correlation coefficients). We can see that the correlations increased in summer months considerably, while in winter months the effect of adjusting was relatively small (because of already high correlations and because of small amounts of changes applied in winter months - see fig. 6.).

Following the given results we can conclude that a change in measuring conditions (relocation, etc.) manifests mainly in summer while in winter the changes have a smaller influence on the series. This can be explained by the different role of active surface in summer versus winter months (in summer, the

role of active surface is increased by prevailing radiative factors, in winter it is diminished because of prevailing circulation factors).

Further details about homogenization results are given in Štěpánek (2003a).

Averaged air temperature series for the Czech Republic was calculated from homogenized series (1848-2000) using the same method as for calculation of reference series from all available stations (see chapter 3.3.1). Homogenized air temperature measurements of the Czech Republic as well as the averaged series for the Czech Republic are now prepared for further analysis in consequent studies (influence of climatological forcings etc.).

5. CONCLUSIONS

In this paper methods and results of homogenization of air temperature monthly series of the Czech Republic in a period of instrumental measurements (since 1771 up to date) were presented.

The question was to find a better way for the homogenization of series from the results of statistical tests in cases were there was no information in metadata (unfortunately most of the cases). Applying relative homogeneity testing, an important task was to guarantee homogeneity of the reference series used. In this work the reference series were calculated as an average from several selected stations, so that this condition was fulfilled without any problems. For more reliable homogenization, the reference series were calculated in three different ways for each candidate series (its 40-year long parts respectively), each pair of candidate and reference series was tested by a number of methods (three tests for relative homogeneity), and monthly, seasonal and annual averages (seasons and years have less variability so homogeneity assessment can be clearer in such series) were tested.

The advantage of such an approach is that a large number of test results for each tested series is available so that uncertainties of individual inhomogeneities detection are suppressed to a large extend. According to the probability of a given inhomogeneity (number of detected inhomogeneities per number of all theoretically possible detections for a tested series), together with graphs of differences of series and further information, it was then (relatively easily) decided whether certain inhomogeneity can be regarded as “"undoubtful", even without support in metadata.

Even after homogenization there still exists a large portion of statistically significant inhomogeneities in the series (almost 40% in homogenized series, with respect to almost 80% before homogenization), but without further metadata it is very problematic to adjust the rest of the inhomogeneities detected in the series because there is a big uncertainty in test results regarding correct inhomogeneity detection. For example, when the amount of change (step) is less than 0.5 °C, statistical tests are able to detect this inhomogeneity correctly (for a given year) in less than 50% of the cases (testing). A further task is the use or development of other homogeneity testing techniques, as long as it is possible to improve testing results with regard to the statistical properties of climatological time series (random component of the series, etc.).

Some parts or even whole series had to be excluded during the process of homogenization because of unreliable measurements. An open problem remains e.g. inhomogeneities near the ends of the series that cannot be adjusted because of a small length of the series for estimating an adjustment. Such series were truncated after such a year. These cases are relatively often in recent years due to transition to automatic

measurements. More time will be needed to assess the impacts of such innovations in the station network.

From the homogenized series an averaged series for the Czech Republic was calculated which together with the homogenized series can be used for further analysis.

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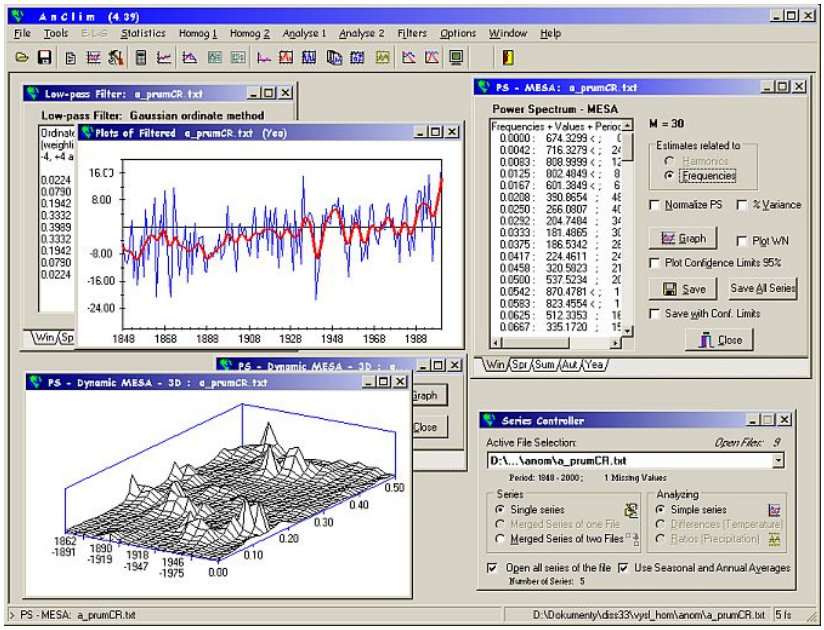
Appendix I. AnClim software description

- General characteristic
  - o A comprehensive tool for processing monthly time series (from transformations through quality control and homogenization to time series analysis)
  - o Operates under Windows 95/98/NT/ME/2000/XP
  - o User friendly: a lot of graphical components, graphs clarifying the results, etc.
  - o Continuous development 1995-2003
  - o Freeware: the latest version can be downloaded from http://www.sci.muni.cz/~pest

- Functionality
  - o Series overview:
    - ▪ basic statistical characteristics, tests of randomness, outliers detection etc.
    - ▪ normal distribution testing, histograms
    - ▪ graphs of the series
  - o Adjusting data:
    - ▪ replacing outliers, filling missing values, etc.
    - ▪ various transformations, converting series into anomalies from a mean, etc.
    - ▪ calculating differences/ratios of two series
    - ▪ switching between monthly or seasonal and annual averages
  - o Homogeneity testing:
    - ▪ absolute homogeneity tests
    - ▪ relative homogeneity tests (Alexandersson SNHT – various modifications, Bivariate test, Easterling and Peterson test, Vincent MLR, and others), creating reference series
    - ▪ adjustment of the inhomogeneities
  - o Time series analysis:
    - ▪ one series analysis (autocorrelations, power spectrum – MESA, dynamic MESA, etc.)
    - ▪ two series analysis (coherency analysis, etc.)
    - ▪ filtering the series (low-pass, band-pass, high-pass filters)



See www.sci.muni.cz/~pest/ for more details.

Appendix II. ProcData software description

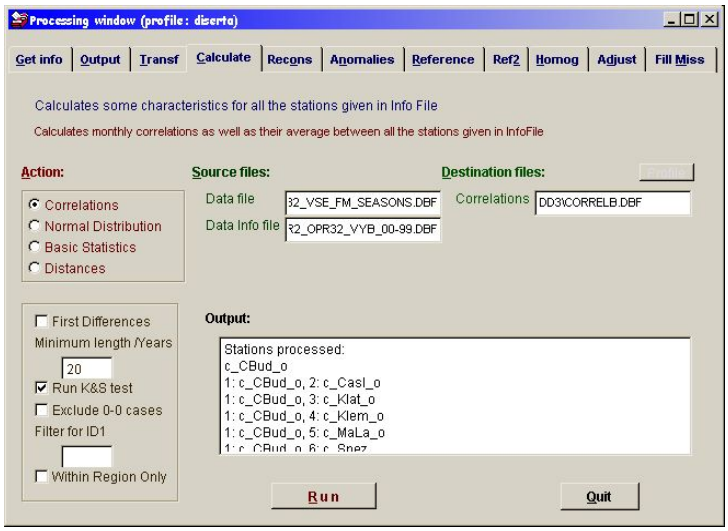
- General characteristic
  - o Database software for processing climatological datasets (supports dbf IV files)
  - o Two modes of processing: monthly or daily data
  - o Automatization of the processing (processing for a given list of stations, using all the stations in database)
  - o Full control of the processing: many parameters for each option can be set, various outputs are created
  - o Flexibility in modifying or adding new functions

- Functionality
  - o Basic statistical characteristics computation, normal distribution testing, etc.
  - o Finding outliers and extreme values
  - o Finding neighbours of a given list of stations
  - o Calculating correlation coefficients between all the pairs of a given list of stations
  - o Reference series calculated as:
    - ▪ an average from the best correlated stations
    - ▪ an average from the nearest stations
    - ▪ an average of all stations available for a given year and month

    (output: reference series, information file with sets of stations selected for creating reference series of a given candidate, etc.)
  - o Processing output from the AnClim software homogeneity testing
  - o Adjusting the series for inhomogeneities

    (output: values - adjustments for each month, t-test, comparison of change in correlations after the adjustments, etc.)
  - o Filling missing values:
    - ▪ from differences
    - ▪ using linear regression

    (output: t and F test for periods to be used for filling missing values, etc.)
  - o Calculating monthly or seasonal and annual averages, calculating differences with a given reference series, etc.
  - o Export to txt files, Excel, import from txt to dbf



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EXPERIENCE REGARDING HOMOGENISATION OF TEMPERATURE TIME SERIES IN THE CZECH REPUBLIC FOR PERIOD 1961-2000

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INTRODUCTION

Following problems are discussed:

- Experiences with homogenisation software MASH 2.0.
- Some notes about metadata.
- Method developed for creating of technical time series by combination both space interpolation and time series statistics

MASH 2.0 IN THE CZECH REPUBLIC

In the past six years we have been using different versions of the MASH method for precipitation and temperature monthly, seasonal and annual series. ([5], [6]).

In year 1999 we used version 1.06 for homogenisation of 55 precipitation time series 1961-1998. This software made it possible to solve the homogenisation problem only for groups consisting maximal of ten stations altogether. Some details were referred on the Second Homogenisation Seminar in 2000. In year 2001 we used version 2.0 for homogenisation of 100 temperature time series of monthly averages both of daily maximum and minimum. Homogenised was 54 series of monthly temperature averages, too.

Maximal and minimal temperature time series were homogenised with personally co-operation of the MASH software author T. Szentimrey.

For using of MASH method has been developed user-friendly environment for data management (input data i.e. both measured data and metadata, result output, charts) in Czech database software language WinRedap ([8]).

Results were used for projects of National Climate Program. Better knowledge of temperature series from mentioned period including detection and correction of some errors in data resulted from using of MASH method, too.

Opinions with MASH 2.0

1) The software is very good mathematics sophisticated method for homogenisation
2) Detects more breaks (shifts) in analysed series
3) The new version makes it possible to analyse 100 series altogether
4) This version makes it possible to involve metadata directly in mathematical procedures of the software, which is very useful and very important for the qualitative better estimation of breakpoints (shifts)
5) It is possible to repeat homogenisation procedures with internal automatic management of input and output files (inhomogenised series, homogenised series, files with shifts etc.)
6) There are some possibilities to draw time series both before and after homogenising in the MASH software but not user friendly
7) Some subjectivity stays except of clear inhomogenities supported by metadata (it is a problem of all homogenisation methods)
8) The MASH system has great possibilities to become qualitative more user-friendly if its input of parameters for single programs were changed. In case it would be possible relatively easy to prepare user-friendly comfortable environment (included graphics) of this mathematically very excellent method.

User-friendly software for better management of MASH in database software WinRedap has been developed. It enables more comfortable handling with MASH inputs and outputs as well as graphic charts of cumulative deviations from regional series. But removing of conversation inputs from MASH exe-files to external control files of parameters would be useful. These would be used by MASH exe-files as input parameter files together with data files. In this case parameter files could be both used and changed by above mentioned environment (WinRedap), included creating a better visualisation of homogenisation process e.g. by graphs suggested by Němec [2].

Excluding of conversation parts from MASH exe-files is a base requirement both for creating of user-friendly environment and for independence of MASH method on concrete environment. User-friendly environment would lead to far greater expanding (using) of this method in the world. We offer help with solving of problem mentioned above.

METADATA

Using of metadata in homogenisation procedure is very needed for a better result of homogenisation. But, only some metadata are known and correspond with breaks (shifts) in data series. In many cases are detected breaks, which do not correspond with known metadata. Sometimes it is a question, if these breaks should be homogenised and under which conditions.

Sometimes it is a tendency to research, if climate trends in a given region depend on an elevation. It is a question, if eventual different trends will fully remain after homogenisation process.

CREATING OF TECHNICAL TIME SERIES IN THE CZECH REPUBLIC

In introduced presentation of this seminar T. Szentimrey [7] mentioned a problem of solving a connection between space interpolation problem and time series statistics problem. A geographic software has very good-based instruments for space analysis, but it do not make possible to solve time relations. Homogenisation software is in a contrary situation.

As one from possible solutions of this problem a method for creating of technical time series by combination both space interpolation and time series statistics has been developed by V. Květoň. Method was used for purpose of solving temperature time series published in [1]. Computations were made by help own special software developed in software language WinRedap, but there are different possibilities of a technical solving of this, e.g. as follows:

- Full solving as special software in database.
- Space interpolation in GIS (geographic information system, in CHMI using ArcGIS), the other in WinRedap.
- Solving as the direct Oracle application used Clidata (input data and saving of output technical series), GIS application and special software in Oracle – may be in future. Describing of a system Clidata see e.g. ([9], [10]).

Main steps of technical series construction:

- Fictive stations creation.
- Space interpolation problem (estimating of time series without missing values).
- Time series problem.
    - Conversion space data to time series data.
    - Solving of relations between both space estimated and measured data included of corrections of estimated fictive station data by average differences between both measured and estimated data.

Fictive stations creation

- Every station is divided to parts on the base of metadata (for example position, altitude, changing of instrument etc.). Each part of a real station is accounted as a separate station now; remaining part of time period is filled by missing values.

- Every pixel (square of given size, we used 1x1 km) of the Czech Republic terrain can be accounted as a fictive station. Fictive stations in pixels without real station have initial series full of missing data.

Space Interpolation problem

Estimation of values on fictive stations was made by computing of linear regression dependence on altitude from measurement data of surrounding stations. Surrounding was chosen according to a station density and orographic condition. Residuum, i.e. difference between measured and estimated value was counted in the case of existence of measured value on the tested fictive station. Computation was made for every day and fictive station, without respect to existence of measured value on fictive station on the concrete day. By this way were constructed space representative preliminary time series without missing data.

Time series problem

1) Conversion of space data to time series data
   a) If space interpolation is providing in GIS than conversion of space data to time series data is realised by export of grids to an ASCII format. Than follows an import to database. From pixels contained fictive stations are created time series of fictive stations.
   b) In full database solving this problem is automatically over.
2) Solving of relations between both space estimated and measured data in following steps:
   a) Comparison of measured and space interpolated (estimated) data by counting of differences between them.
   b) Summarisation of differences over time period. Result is average difference between measured and estimated value for every fictive station and month.
   c) Correction of estimated fictive station data by average differences (more estimation algorithms were tested).
   d) Error of estimation values is possible to quantify.
   e) Selecting of time series with different amounts of measured values is easy.
3) If the aim is creating of climatological maps, the last step is importing of fictive stations back into GIS and creating requested maps by using GIS (see e.g. ([3], [4]).

Technical time series - some notes

Computing of statistics of differences between concurrent time series both measured and estimated values enables to create requested connection between space interpolation and time series.

Resulted fictive station time series are composed from two sorts of data: At first from a measured data, at second from an estimated data (an estimation of missing values). Remember, if e.g. time series has full measured data but a station position was once changed, this station was divided to two parts, each with one from mentioned positions. Two fictive stations are created in this case. Each of them has a part of measured data from origin station related to a given position, the remainder of this fictive time series is estimated by above described process.

It should be note, by a described way estimated time series can lost some microclimate properties, but space representative of them is increasing. By the described way all time series are roughly homogenised to changing of a station position, too. It is possible to adjust fictive series to chosen altitude (position), too. We can speak about a homogenisation regard to regional climate. May be, from a strict view of study long-term climate changes should be done some objections.

Technical time series - Some results

The method was used it for creating 280 technical temperature daily and monthly time series in 1961-2000 ([1]). Used software was based on adaptation of GIS methods to WinRedap database both for missing values estimation and for homogenisation due to changing of station position.

From tab. 1 follows, the differences between measured and estimated monthly temperature averages for stations in Czech Republic are in half of count of cases in frames ±0,3°C for average and maximal temperatures. For minimal temperature is it ±0,4°C, but rarely differences up to +8°C can be found on some stations (special microclimatic position). Checking of some big differences in origin data records is planned. Two methods of weighted averages computation were tested. The estimation accuracy of both methods is similar. Annual course of estimation errors presents tab. 2.

Prvek	Druh odhadu	N	Průměr	Min.	Max.	Percentily								
						0.1	1.0	5.0	25.0	50.0	75.0	95.0	99.0	99.9
Max. teplota	WTIL	91046	0.00	-4.30	4.60	-2.30	-1.30	-0.80	-0.30	0.00	0.30	0.90	1.60	2.50
	WTIK		-0.01	-4.10	5.00	-2.60	-1.50	-1.00	-0.40	0.00	0.40	1.00	1.70	2.70
	EXP		0.00	-4.20	4.90	-2.40	-1.40	-0.90	-0.40	0.00	0.30	1.00	1.60	2.60
Min. teplota	WTIL	90902	-0.02	-7.90	6.90	-4.00	-2.40	-1.50	-0.50	0.00	0.50	1.40	2.20	3.70
	WTIK		-0.01	-8.10	6.90	-4.20	-2.40	-1.50	-0.50	0.00	0.50	1.40	2.30	3.70
	EXP		-0.01	-7.90	6.20	-4.10	-2.40	-1.50	-0.50	0.00	0.50	1.40	2.30	3.50
Prům. teplota	WTIL	91402	-0.01	-4.70	4.20	-2.00	-1.30	-0.80	-0.30	0.00	0.30	0.80	1.20	2.20
	WTIK		-0.01	-4.70	4.20	-2.10	-1.30	-0.90	-0.30	0.00	0.30	0.90	1.40	2.20
	EXP		-0.01	-4.60	4.20	-2.10	-1.30	-0.80	-0.30	0.00	0.30	0.80	1.30	2.16

Tab. 1: Statistics of pairs differences between monthly means both measured and estimated from surrounding stations *(different estimation methods)*.(307 stations in the Czech Republic in 1961-2000 (WTIL is estimation from surrounding stations with weight of residua 1/distance, WTIK with weight 1/distance2. EXP is expected value of linear regression with altitude, N is number of cases).

Měsíc	Maximální teplota					Minimální teplota					Průměrná teplota				
	N	Min.	5%	95%	Max.	N	Min.	5%	95%	Max.	N	Min.	5%	95%	Max.
I	7564	-3.8	-0.9	1.0	4.6	7549	-7.9	-1.4	1.3	6.7	7601	-4.7	-0.8	0.8	3.8
II	7567	-3.4	-0.9	0.9	3.7	7553	-6.4	-1.5	1.3	6.4	7594	-3.8	-0.8	0.8	3.1
III	7584	-3.9	-0.8	0.9	4.3	7564	-5.2	-1.3	1.2	3.7	7608	-2.9	-0.8	0.7	2.1
IV	7603	-3.0	-0.8	0.9	3.2	7594	-6.1	-1.5	1.3	5.1	7634	-3.6	-0.9	0.8	3.2
V	7616	-3.0	-0.9	0.9	3.4	7606	-6.4	-1.6	1.5	5.5	7645	-2.6	-0.8	0.8	4.2
VI	7608	-3.0	-0.8	0.9	4.3	7589	-6.9	-1.5	1.5	4.9	7629	-2.3	-0.8	0.7	3.2
VII	7595	-3.1	-0.9	1.0	3.1	7585	-7.6	-1.6	1.6	6.9	7623	-2.6	-0.8	0.8	3.6
VIII	7581	-4.3	-0.8	0.9	3.5	7572	-6.1	-1.7	1.6	5.3	7609	-3.0	-0.9	0.9	3.0
IX	7593	-2.6	-0.8	0.9	3.6	7576	-7.2	-1.6	1.5	5.7	7616	-3.9	-0.9	0.8	4.1
X	7584	-3.1	-0.8	0.9	4.6	7571	-7.2	-1.5	1.3	6.2	7614	-4.1	-0.8	0.8	3.2
XI	7575	-2.5	-0.8	0.9	3.8	7575	-5.0	-1.1	1.0	5.3	7618	-3.3	-0.6	0.6	3.2
XII	7576	-2.3	-0.8	0.9	3.3	7568	-5.7	-1.2	1.1	6.4	7611	-3.9	-0.7	0.7	3.9

Tab. 2: Extreme differences and interval obtaining 90 % of all differences between really measured monthly means of air temperature (°C) and values estimated from surrounding stations by the WTIL method for 307 stations in ČR in 1961-2000. 2000 (WTIL is estimation from surrounding stations with weight of residua 1/distance, N is number of cases)

On fig. 1 are compared three times series form the station of Ústí nad Orlicí, 1961 – 2000. In this period the station have been changed positions. Altitudes of them are as follows: 557 m msl in 1961-1970, 399 m msl in 1971-1989 and 402 in 1990-2000. Green is original series, red is homogenised by homogenisation tests (part from 1971 is the same with original). Blue line is the technical time series constructed by method described in this paper.

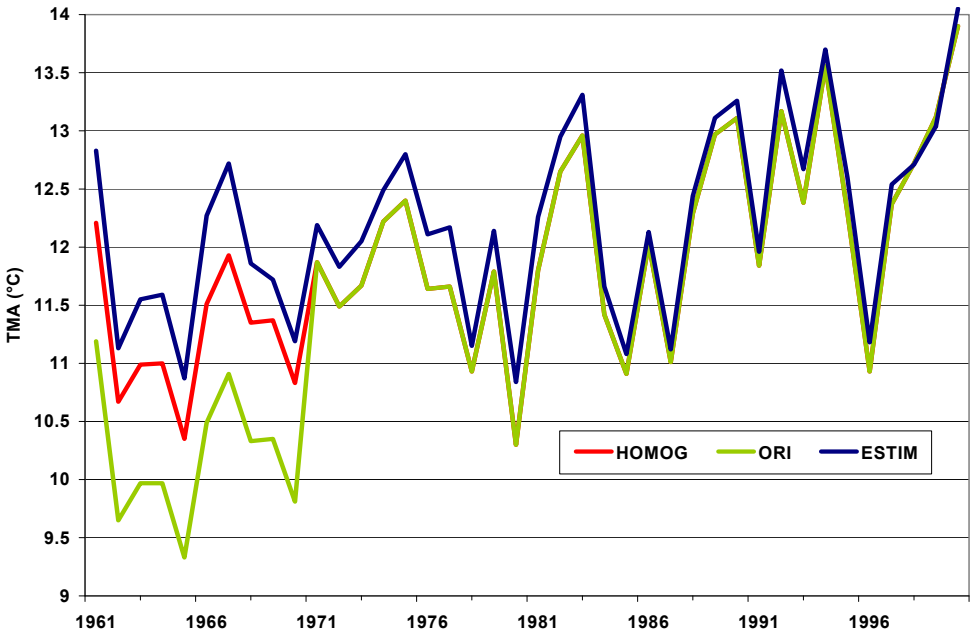

Fig. 1: Monthly averages of daily maximal temperature. Ústi n Orlicí, the Czech Republic

CONCLUSION

Described construction of technical time series is one from possibilities of integrated solving of problem conversion of space interpolation problem to time series problem. The method makes possible a data quality control. Some results during process can be used for both an error data and data quality detection. Method does not any special mathematical presumptions. Further development of the method in future is planned.

ABSTRACT

At first, some experiences with practical using and interpretations of homogenisation software MASH 2.0 are presented. At second, construction method of 280 technical temperature time series for the period 1961-2000 is presented (both an estimation of missing values and an adjustment data to unique station position).

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Homogeneity of daily "European Climate Assessment and Dataset" series

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INTRODUCTION

We developed a procedure to assess the homogeneity of daily temperature and precipitation series. This homogeneity procedure was applied to the series of the European Climate Assessment and Dataset (ECA&D) project (Klein Tank et al, 2002). This is of great importance because exploiting daily datasets, like in ECA&D, requires a monitoring of their quality with a well-defined methodology to support the credibility of the conclusions gained from them.
Several methods are in use to test homogeneity in annual and monthly series. However, for daily series well-established methods are lacking. So we developed a method which compiles from the daily series annual resolution testing variables, which represent important characteristics of the variation at the daily scale. Subsequently, these annual series are tested with respect to homogeneity.

METHOD

To assess the homogeneity of the series we followed a two–step approach. First four homogeneity tests are applied to the series. Second, the results are grouped in an overall classification to express the reliability of the series.

The four test methods selected to test the departure of homogeneity in the time series are: the Standard Normal Homogeneity Test for a single break (SNHT test) (Alexandersson, 1986), the Buishand Range test (Buishand, 1982), the Pettitt test (Pettitt, 1979), and the Von Neumann Ratio test (Von Neumann, 1941). In general, it is recommended (e.g. Peterson et al., 1998) to apply homogeneity tests relatively, that is testing with respect to a neighbouring station that is supposedly homogeneous. However, for datasets with a sparse spatial density, like the ECA&D dataset, relative testing is not appropriate. Therefore, we restrict the homogeneity analysis to absolute tests, having the additional advantage of being able to deal with simultaneous changes in observational routines.

The second step in the homogeneity assessment of the daily dataset is an overall evaluation of the four tests. The outcomes of the four tests for each temperature and precipitation series are grouped together. A classification is made depending on the number of tests rejecting the null hypothesis. The following categories are distinguished:

- Class 1: “useful” – 1 or 0 tests reject the null hypothesis at the 1% level
- Class 2: “doubtful” – 2 tests reject the null hypothesis at the 1% level
- Class 3: “suspect” – 3 or 4 tests reject the null hypothesis at the 1% level

For temperature, where two variables (*mDTR* and *vDTR*, see below) are tested, the two categories are calculated separately for each variable. If the results are different, the highest of the two category values (hence the least favourable) is assigned to the temperature series of the station.

Series labelled class 3 “suspect” should not be used in the analysis of trend and variability analysis without full scrutiny. Only in exceptional cases, where it is plausible that a real climatic signal rather than an artificial break triggered the test results, the original station series can be used in further analysis.

The period of analysis is the period 1901-1999 and results are also presented for the sub-period 1946-1999. Three annual testing variables with daily characteristics are used. For temperature, the testing variables are two features of the diurnal temperature range (DTR): its annual mean (*mDTR*) and its annual mean of the absolute day-to-day differences (*vDTR*). For precipitation, the annual number of wet days (threshold 1 mm) is considered. The choice of these variables is discussed in more detail in Wijngaard et al. (2003).

RESULTS

To illustrate the capacity of the homogeneity tests for temperature series, the results of the four tests applied to the ECA&D station series of Eelde (The Netherlands) are discussed. Figure 1 shows the annual mean temperature and *mDTR* at station Eelde. Three well-documented changes in observational routine contaminate the homogeneity of this station series during the last century: the introduction of a ventilated observation hut in 1948, a station relocation from the city to the nearby airport in 1951, and a change in sensor height from 2.2 m to 1.5 m in 1959. The Figure shows that the contaminations are hardly visible in the annual mean temperature series, whereas they lead to a 1-degree increase of the *mDTR* in the 1950-ies.

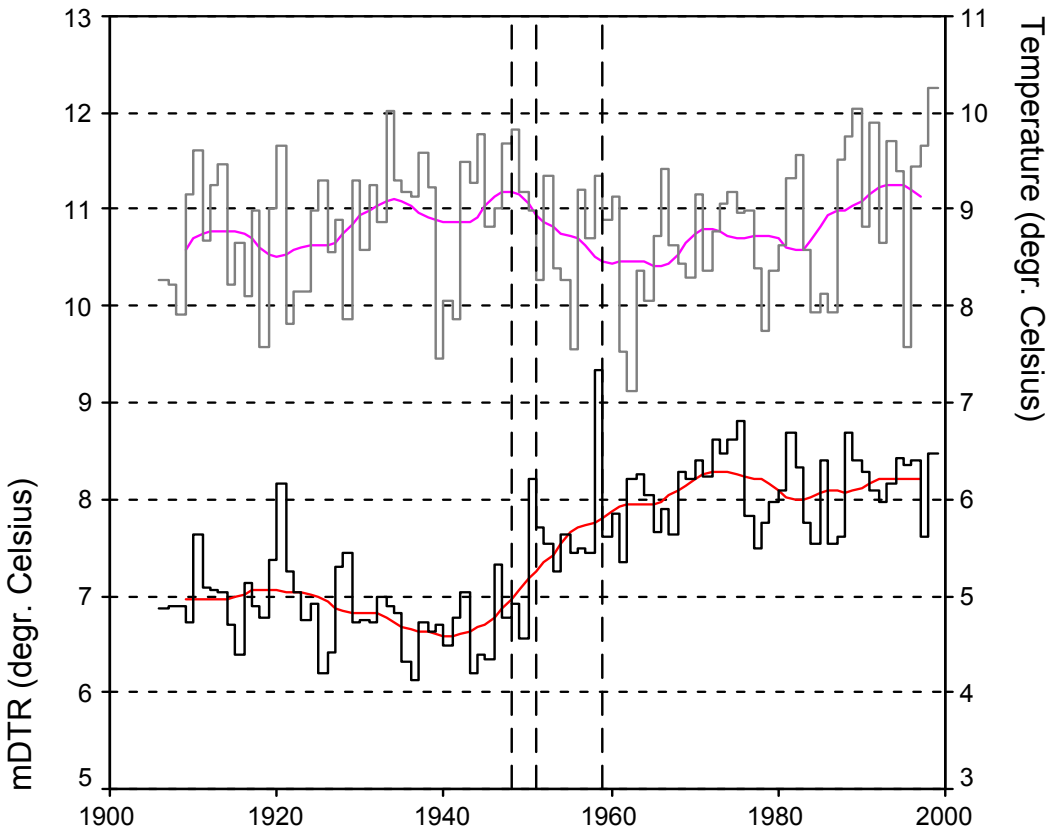

Figure 1: Black: Annual mean of the diurnal temperature range (*mDTR*) at station Eelde (The Netherlands). Grey: Annual mean temperature of the station. The smoothed curves are calculated using the Loess smoother (Cleveland, 1979) with a time span of 15 years. Station changes that are documented in the station history are indicated by the vertical dashed lines.

In Figure 2 the results of the SNHT applied to the *mDTR* and mean temperature of Eelde are shown. The test statistic of the SNHT passes an extreme in 1950 in the *mDTR* series, indicative of a break around that year (significant at 1%). As the three other tests also clearly indicate an inhomogeneity at the 1% level, the temperature series of Eelde is assigned to class 3 “suspect”. The right part of the figure shows the results of the SNHT test applied to the annual mean series of Eelde. Contrary to the *mDTR*, there are hardly indications for a break around 1950. Despite of the fact that the mean temperature passes successfully the tests in this period, the failure of *mDTR* to pass the tests reminds one to remain suspicious even with respect to the homogeneity of the daily mean temperatures. This is of particular importance if trends in daily extremes are studied. A second feature presented in Figure 2 is the SNHT test indicating a homogeneity break in the mean temperature series around 1987, which is not apparent from the *mDTR*. This break lacks documentation from the station history and is likely to be unrelated with changes in observational routines. This result, combined with the fact that the homogeneity tests of other Dutch stations show the same feature, indicates that a climate variation rather than homogeneity break triggered the tests.

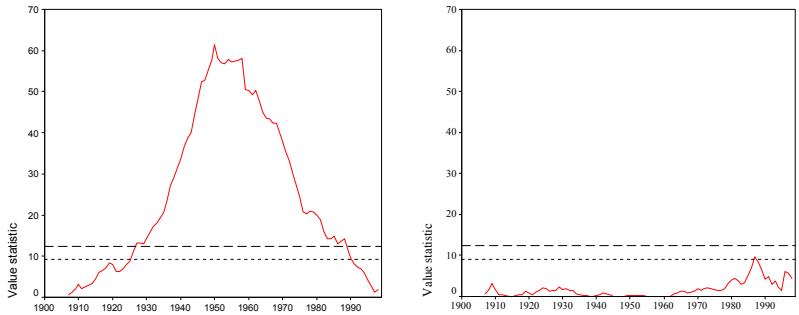

Figure 2: Test results of the SNHT applied to the *mDTR (left)* and the annual mean temperature (right). Dashed lines give 1% critical values, dotted lines 5% critical values.

Figure 3 shows, separately for the *mDTR* and the *vDTR* testing variables, for each station the number of tests that rejected the null-hypothesis at the 1% level for the period 1901-1999 and its sub-period 1946-1999. The figure shows that the breaks in *mDTR* (left) are not always accompanied by breaks in *vDTR* (right) or vice versa. Table 1 summarises the statistical results according to the classification system, in which *mDTR* and *vDTR* results are merged. The full 1901-1999 period shows a very high percentage "suspect" station series, but for the 1946-1999 sub-period the situation improves. Agreement exists on the year of the break for the three location-specific tests. For 73% of the "suspect" series the year of the detected break is within three years. Figure 4 and Table 2 show that the majority of precipitation series are labelled "useful", only in Eastern Europe a considerable part of the station series suffers from significant breaks. Consistent with the higher year-to-year variability of the precipitation testing variable, the percentage of stations labelled "suspect" is much smaller for precipitation than for temperature. For 59% of the precipitation series, the year of the break detected by the tests used agrees within three years.

Temperature				
	Class 1 "useful"	Class 2 "doubtful"	Class 3 "suspect"	Total number of station series
1901-1999	4 (7%)	1 (1%)	55 (92%)	60 (100%)
1946-1999	61 (39%)	12 (7%)	85 (54%)	158 (100%)

Table 1: Number of temperature series (percentage) in the ECA set in each category according to the classification pointed out in the method section.

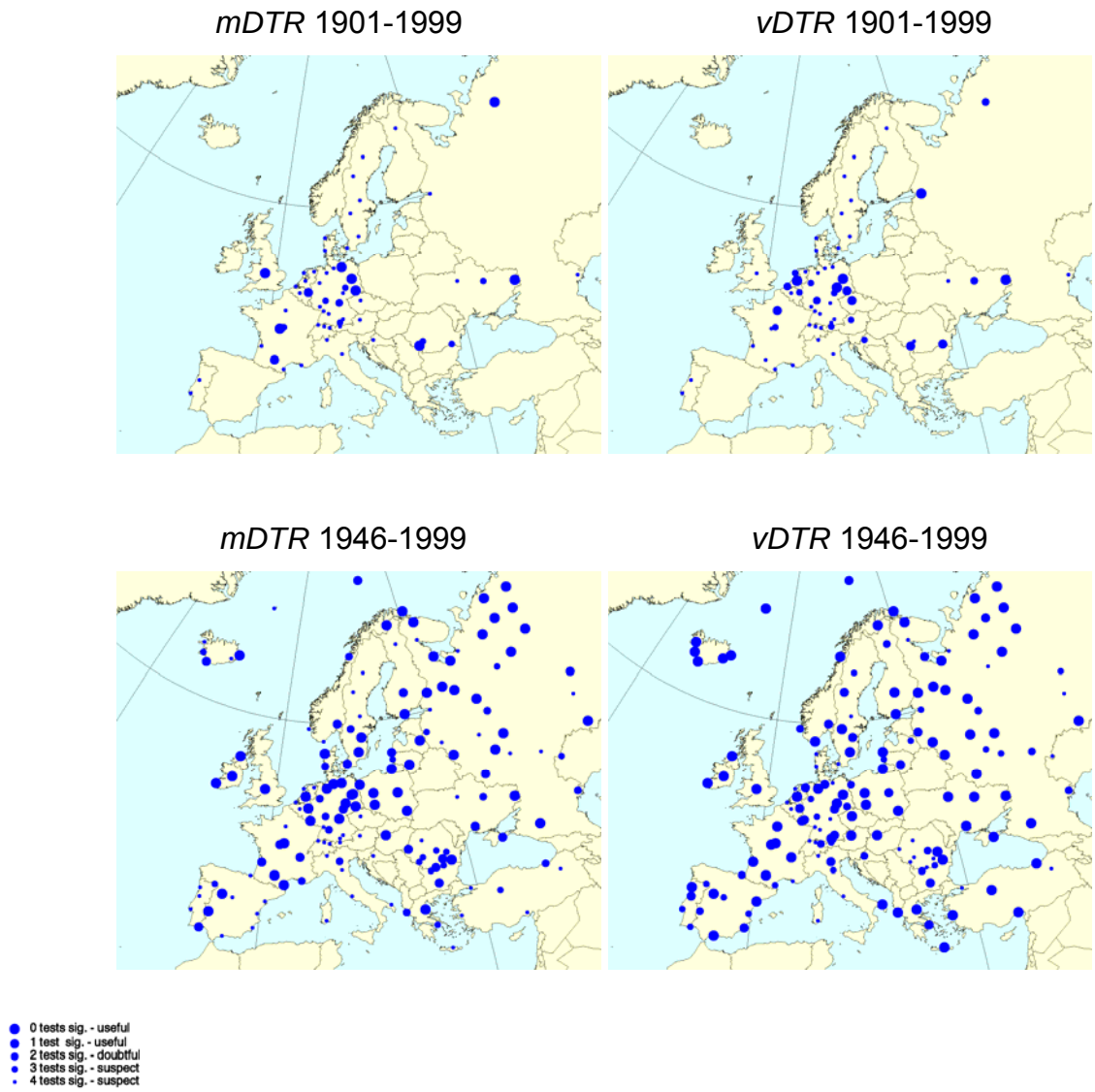

Figure 3: Test results for the ECA temperature series. Station dots are scaled with the number of tests that detected breaks in temperature series at the 1% significance level. The four tests applied to the *mDTR* series (left) and the *vDTR* (right) are: the SNHT, the Buishand Range, the Pettitt, and the Von Neumann Ratio test. The classification is indicated in the legend. Top: 1901-1999 (stations with at least 79 observation years). Bottom: 1946-1999 (stations with at least 43 observation years).

wet day count 1901-1999 wet day count 1946-1999

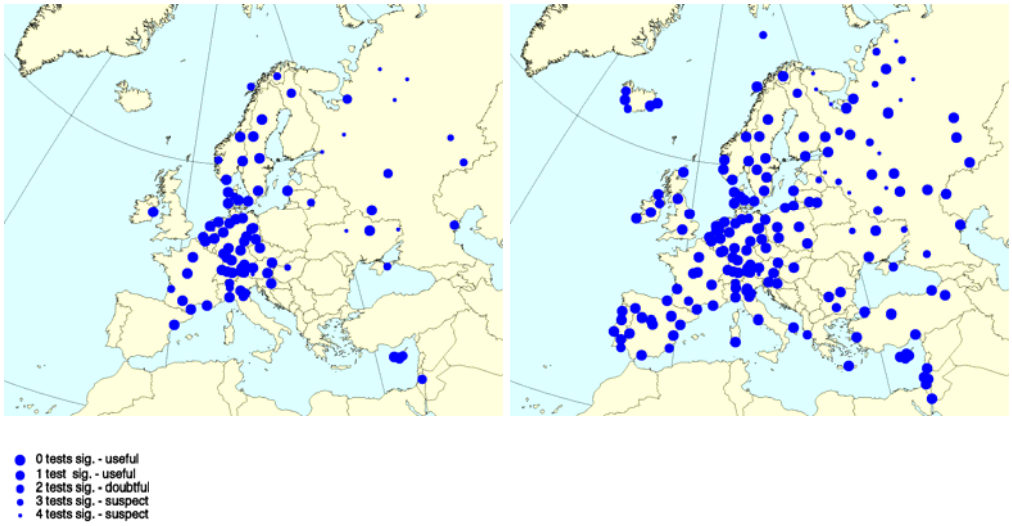

Figure 4: As in Figure 3, but now the test results for the ECA precipitation series. The testing variable is the wet day count.

Precipitation				
	Class 1 "useful"	Class 2 "doubtful"	Class 3 "suspect"	Total number of station series
1901-1999	66 (75%)	10 (11%)	12 (14%)	88 (100%)
1946-1999	156 (87%)	7 (4%)	17 (9%)	180 (100%)

Table 2: Number of precipitation series (percentage) in the ECA set in each category according to the classification pointed out in the method section.

The study of metadata of temperature measurements shows that about 65% of the detected breaks in station series labelled "doubtful" or "suspect" in the period 1946-1999 can be traced back. About 15% of the breaks appear to be related to known climate variations, whereas the remaining 20% of the breaks could not be explained from metadata or climate variations. For precipitation, about 90% of the detected breaks in station series labelled "doubtful" or "suspect" in the period 1946-1999 can be traced back from historic information. For the remaining 10% no explanation could be found. The most frequent cause of breaks turns out to be station relocation, although changes in observing practice and measuring technique do occur as well.

FINAL REMARKS

The classification system as presented is a good base to select daily series for trend and variability analyses. We were able to detect inhomogeneities in the ECA&D daily

temperature and precipitation series effectively by testing series of two DTR variables and of the number of wet days. For precipitation with its higher variability, fewer breaks can be detected compared to temperature. In trend studies this shortcoming is compensated by the fact that possibilities for trend detection in these series are also reduced.

An extensive review of this study is published in Wijngaard et al. (2003).
Further information about the project at: *www.knmi.nl/samenw/eca*

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SOURCES OF METEOROLOGICAL DATA FOR THE CANADIAN ARCTIC AND ALASKA FROM 1819 TO 1859 AND THEIR USEFULNESS FOR CLIMATE STUDIES[1]

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INTRODUCTION

The key role of polar regions in shaping the global climate is now very well known. Awareness of this fact has prompted many scientists to undertake detailed climatic studies in this area and, as a result, variations of the Arctic climate in the 20th century are quite well understood (though with the exception of climatic variations in the central Greenland and central Arctic regions). For more details of these variations, see for example, Vowinckel and Orvig (1970) or Przybylak (2002, 2003), and the references therein. One of the main aims of the contemporary climatology is to describe the range of natural climate changes in the last few centuries and to identify the reasons for these changes. In the case of the Arctic, proxy data have mainly been used for this purpose (e.g. Koerner 1977, 1992; Bradley 1990; Koerner et al. 1990; Mosley-Thompson et al. 1993; Overpeck et al. 1997; Gajewski, Atkinson, 2003). On the other hand, existing meteorological data obtained during ships' expeditions to the Arctic in the 19th century have very seldom been examined. For the Canadian Arctic Archipelago only three papers using these sources of data (Kay 1995; Przybylak 2000; Wood and Overland 2003) have been published in recent decades. Significantly more such papers exist for the continental Canadian Arctic (Catchpole and Ball 1981; Wilson 1982, 1983a, b, 1985, 1988, 1992; Ball 1983, 1992; Catchpole and Faurer 1983, 1985; Hopper 1985; Catchpole and Hanuta 1989) based on data gathered mainly in posts kept by the Hudson Buy Company. Both of these kinds of early instrumental data, although containing some biases and errors, are definitively better sources of information about climate in the Canadian Arctic than the best existing records of proxy data.

The present paper provides a review of the available sources of meteorological data and the preliminary results of investigations based on data obtained during nautical expeditions to the Canadian Arctic and Alaska from 1819 to 1859.

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SOURCES OF DATA AND THEIR QUALITY

A search for meteorological data for the study area showed that there are quite a number of valuable series ranging between one and three years in length (for details see Table 1). They were gathered mainly during the wintering of vessels which were sent to the Canadian Arctic by the Royal Navy to find and transit the Northwest Passage. As can easily be seen from Table 1, a majority of the expeditions were sent after 1845 in order to search for the lost expedition under the command of Sir John Franklin. Useful meteorological observations may be noted from the period when vessels, due to severe winter conditions, were frozen up. Usually, wintering lasts from September to July and the meteorological measurements, according to the high standards of the Royal Navy, were mostly carried out hourly, two-hourly, four-hourly, or six-hourly a day (Table 2). The following meteorological elements were registered: air temperature, air pressure, wind direction and force, as well as the general state of the weather. All results of these observations were written in the ships' log books (mainly in the Meteorological Registers). The majority are available in different archives located in the UK (the Scott Polar Research Institute in Cambridge, the Meteorological Office (hereafter Met Office in Bracknell which will move to Exeter in 2004), and the Royal Geographical Society, Royal Society and Public Record Office in London). Unfortunately, some ships' log books, such as that from H.M.S. Enterprise (location: Walker Bay and Cambridge Bay) were given back by the Meteorological Office to the Captain of the ship and there is no information as to whether they still exist. Luckily, Mr R. Strachan who worked in the Met Office in the second half of the 19th century had the access to the majority of the ships' log books (including those which are now missing) and made a careful examination of the correctness and quality of the data. When sufficient information was available about the thermometers used and their calibration, he introduced appropriate corrections to eliminate instrumental errors (see Table 2). He then calculated average monthly and annual air temperatures for fixed hours and these he published in a work entitled *Contribution to our knowledge of the meteorology of the Arctic Regions, Part I (1879), II (1880), III (1882), IV (1885) and V (1888).* Here meteorological data are published for 36 different historical locations. Also particularly useful is the commentary written by Strachan, especially those passages which present information gathered from different sources that are helpful in estimating the quality of measurements obtained during the expeditions.

Table 1. A list of expeditions to the Canadian Arctic and Alaska from 1819 to 1859 which carried out the meteorological observations

Location	j	l	Ships/station	Captain/Observer	Years	Months
Winter Harbour, Melville Island	74°47'N	110°48'W	H.M.S. "Hecla"	Sir W.E. Parry	1819-20	12
Winter Harbour, Melville Island	74°47'N	110°48'W	H.M.S. "Griper"	Sir W.E. Parry	1819-20	12
Fort Enterprise	64°28'N	113°06'W	Station	J. Franklin	1820-21	9
Winter Island	66°11'N	83°10'W	H.M. Ships "Hecla" and "Fury"	Sir W.E. Parry	1821-22	12
Igloolik	69°21'N	81°53'W	H.M. Ships "Hecla" and "Fury"	Sir W.E. Parry	1822-23	12
Port Bowen	73°13'N	88°55'W	H.M. Ships "Hecla" and "Fury"	Sir W.E. Parry	1824-25	12
Fort Franklin	65°12'N	123°13'W	Station	Sir W.E. Parry	1825-26	11
Felix Harbour, Gulf of Boothia	69°59'N	92°06'W	"Victory"	Sir J. Ross	1829-30	12
Victoria Harbour, Gulf of Boothia	70°08'N	91°35'W	"Victory"	Sir J. Ross	1830-31	12
Mundy Harbour, Gulf of Boothia	70°18'N	91°40'W	"Victory"	Sir J. Ross	1831-32	7
Fort Reliance	62°43'N	109°10'W	Station	W. Back	1833-35	19
Hudson Strait	drift		H.M.S. "Terror"	Sir J. Back	1836-37	12
York Factory	57°00'N	92°26'W	Station	J. Rae	1845-46	6
Fort Hope, Repulse Bay	66°32'N	86°56'W	Station	J. Rae	1846-47	11
Port Leopold	73°50'N	90°12'W	H.M.S. "Investigator"	Sir J.C. Ross	1848-49	12
Wolstenholm Sound	76°34'N	68°45'W	H.M.S. "North Star"	J. Saunders	1848-49	12
Port Providence	64°26'N	173°00'W	H.M.S. "Plover"	T.E.L. Moore	1848-49	9
Chamiso Island	66°13'N	161°46'W	H.M.S. "Plover"	T.E.L. Moore	1849-50	12
Fort Simpson	62°07'N	121°33'W	Station	J.W.S. Pullen	1849-51	17
Port Clarence	65°05'N	165°30'W	H.M.S. "Plover"	T.E.L. Moore	1850-51	11
Assistance Bay	74°40'N	94°16'W	"Sophia"	W. Penny	1850-51	12
Assistance Bay	74°40'N	94°16'W	"Lady Franklin"	A. Stewart	1850-51	4
Griffith Island	74°34'N	95°20'W	H.M.S. "Resolute"	Sir H.T. Austin	1850-51	12
Batty Bay	73°12'N	91°10'W	"Prince Albert"	W. Kennedy	1850-51	8
Wellington Chanel to Baffin Bay	drift		"Advance"	E. De Haven	1850-51	9
Fort Confidence	66°40'N	119°00'W	Station	J. Rae	1850-51	9
Princess Royal Islands	72°47'N	117°35'W	H.M.S. "Investigator"	Sir R.J. McClure	1850-51	12
Port Clarence	65°05'N	165°30'W	H.M.S. "Plover"	T.E.L. Moore	1851-52	11
Walker Bay	71°35'N	117°39'W	H.M.S. "Enterprise"	Sir R. Collinson	1851-52	12
Mercy Bay	74°06'N	117°55'W	H.M.S. "Investigator"	Sir R.J. McClure	1851-53	20
Dealy Island	74°56'N	108°49'W	H.M.S. "Resolute"	H. Kellett	1852-53	12
Dealy Island	74°56'N	108°49'W	H.M.S. "Intrepid"	H. Kellett	1852-53	10
Northumberland Sound	76°52'N	97°00'W	H.M.S. "Assistance"	Sir E. Belcher	1852-53	12
Northumberland Sound	76°52'N	97°00'W	H.M.S. "Pioneer"	Sir E. Belcher	1852-53	12*
Cambridge Bay	69°03'N	105°12'W	H.M.S. "Enterprise"	Sir R. Collinson	1852-53	12
Beechey Island	74°43'N	91°54'W	H.M.S. "North Star"	J.W.S. Pullen	1852-54	13
Point Barrow	71°21'N	156°17'W	H.M.S. "Plover"	R. Maguire	1852-54	22
Port Clarence	65°05'N	165°30'W	H.M.S. "Rattlesnake"	H. Trollope	1853-54	11
Wellington Channel	75°31'N	92°10'W	H.M.S. "Assistance"	Sir E. Belcher	1853-54	12
Wellington Channel	75°31'N	92°10'W	H.M.S. "Pioneer"	Sir E. Belcher	1853-54	12*
Melville Sound	74°42'N	101°22'W	H.M.S. "Resolute"	H. Kellett	1853-54	8
Melville Sound	74°42'N	101°22'W	H.M.S. "Intrepid"	H. Kellett	1853-54	8
Camden Bay	70°08'N	145°29'W	H.M.S. "Enterprise"	Sir R. Collinson	1853-54	11
Fort Hope, Repulse Bay	66°32'N	86°56'W	Station	J. Rae	1853-54	11
Baffin Bay	drift		"Fox"	F.L. McClintock	1857-58	13
Port Kennedy	72°01'N	94°14'W	"Fox"	F.L. McClintock	1858-59	12

* - only wind and weather notations

Table 2. Characteristics of air temperature observations and instrument used during expeditions to Canadian Arctic and Alaska, 1819-1859

Location	Place of measurements			Type of thermometer			Instrumental errors		Frequency of observations
	on the board	on the ice	on the land	spirit	mercurial	un-known	intro-duced	not intro-duced	
Winter Harbour, Melville Island	+			+	+			+	two-hourly
Fort Enterprise			+			+		+	at least 3 daily
Winter Island	+			+	+			+	two-hourly
Igloolik	+			+	+			+	two-hourly
Port Bowen	+					+		+	two-hourly
Fort Franklin	+			+	+				hourly (7 to 24)
Felix Harbour, Gulf of Boothia		+		+	+		+?		hourly
Victoria Harbour, Gulf of Boothia		+		+	+		+?		hourly
Mundy Harbour, Gulf of Boothia		+		+	+		+?		hourly
Fort Reliance	+			+				+	two-hourly (6 to 24)
Hudson Strait	+	+		+			+		two-hourly
York Factory			+			+	+		two-hourly
Fort Hope, Repulse Bay, 1846-47			+		+		+		3 daily (7, 13, 19)
Fort Hope, Repulse Bay, 1853-54			+		+		+		3 daily (8, 14, 20)
Port Leopold	+					+	+		two-hourly
Wolstenholm Sound	+	+				+	+		four-hourly
Port Providence	+					+		+	hourly
Chamiso Island	+					+		+	hourly
Fort Simpson, 1849-50			+	+			+		two-hourly (8 to 20)
Fort Simpson, 1850-51			+	+			+		three-hourly (9 to 21)
Port Clarence, 1850-51	+					+		+	hourly
Assistance Bay		+		+				+	three-hourly
Griffith Island		+		+	+			+	two-hourly
Batty Bay	+					+		+	4 daily (8, 12, 16, 20)
Wellington Chanel to Baffin Bay	+	+		+				+	two-hourly
Fort Confidence			+			+	+?		3 daily (9, 13, 21)
Princess Royal Islands	+					+		+	two-hourly
Port Clarence, 1851-52	+					+		+	hourly
Walker Bay	+	+	+			+	+		four-hourly
Mercy Bay	+					+		+	two-hourly
Dealy Island, "Resolute"	+			+	+			+	six-hourly
Dealy Island, "Intrepid"	+			+	+			+	two-hourly
Northumberland Sound	+		+	+				+	two-hourly
Cambridge Bay	+	+	+			+			four-hourly
Beechey Island	+					+		+	two-hourly
Point Barrow	+			+			+		hourly
Port Clarence, 1853-54	+					+		+	three-hourly
Wellington Channel	+	+		+				+	two-hourly
Melville Sound, "Resolute"	+			+	+			+	six-hourly
Melville Sound, "Intrepid"	+			+	+			+	two-hourly
Camden Bay	+					+	+		four-hourly (8 to 24)
Baffin Bay	+			+			+		two- or four-hourly
Port Kennedy	+			+			+		two- or four-hourly

+? - probably introduced

For some locations for which raw data were collected within our project, we checked the correctness of the calculations of monthly and annual means presented by Strachan. We obtained almost identical results, and thus we can conclude that the data from this publication are reliable and may be used for climate studies. However, in comparison with the present-day climate, we must be aware of the fact that these data still include a variety of errors and biases which should be taken into account when such analyses are conducted. For example, some sources of errors result from different locations of historical and present-day observation points, different types of instruments used and their exposures, along with varied recording schedules. The problem is that it is impossible to estimate some of these errors due to the lack of any information. In Table 2 some important information is given which is helpful in estimating the quality of air temperature measurements.

It is possible to use contemporary data to eliminate those differences in air temperature results which are the result of the use of different geographical locations for the taking of measurements. On the other hand, we encounter more problems when we try to eliminate the influence of the detailed localisation of the meteorological observation points on the results. From Table 2 it can be seen that, during majority of the expeditions, meteorological observations were carried out on board the ships - rarely on the ice or on land. Those observations which were carried out on land, were made mainly during land expeditions which wintered in one place (e.g. Fort Franklin, Fort Reliance). For the purposes of comparison with the present climate (mainly land-based) the data from the land are better than those obtained from the other two localisations. This is connected with the fact that the air temperature on the ice is colder than on land in the summer and warmer in the wintertime due to heat diffusion from water under the sea ice (and this is especially clear in the first part of the winter) (Kay 1995). In turn, the air temperatures taken on board are warmer than on the land because of the fires which were kept up on the ships. This influence with different intensities was present probably only during wintertime (from September to May). In summer, the cooling effect of the cold seawater should decrease, to some degree, the air temperature in comparison to the warmer land (greater solar radiation effect). Synchronous measurements made on board and on the ice (about 300 m from the ship) during winter in Wolstenholm Sound (H.M.S. “North Star”) showed that air temperature on the ice in February and March was from 0.5^{o}C to 2.0^{o}C warmer than on board the ship.

Another source of biases and errors is connected with the type of thermometer used, especially when there is no information available about thermometers’ calibration. As can be seen from Table 2, such cases are quite numerous. However, this does not rule out the possibility that the corrections were introduced by the observers. Only rarely were corrections not needed due to very small instrumental errors. Usually, a variety of thermometers (all using the Fahrenheit scale), both spirit and mercurial, were taken on the expeditions. As follows from the Table 2, it was most often spirit thermometers which were used, although it seems that for temperatures higher than -38.8^{o}C (the freezing point of mercury) it was mercurial thermometers which were used as the main (standard) thermometers for which data were registered in the ships’ log books.

A possible source of bias is also connected with different methods of calculating daily means and monthly means in historical temporal terms (means

from different number of fixed hours) and in modern temporal terms (using an average from maximum and minimum temperatures). For the elimination of this kind of error, hourly data are needed for the Canadian Arctic. At present, such data are not available to us. However, comparison of monthly averages using different formulas has recently been made for climate conditions in Poland (Filipiuk 2000/2001). He found that the average estimation errors (in comparison to averages calculated from 24-hourly data) of monthly average temperatures calculated using a formula based on extreme air temperatures are very small for winter months (0.0°C to 0.15°C). Slightly greater errors occurred for summer months (0.1°C to 0.25°C) and the highest were for transitional months (up to 0.4°C). Based on these findings one can conclude that in the Canadian Arctic, where winter conditions prevail over almost 9 months and transitional seasons are short, such biases are probably less important than those mentioned earlier.

Also important are those sources of meteorological data prepared by meteorological observers (usually the captains or officers of the ships), arranged most often in the form of tables (called Meteorological Abstracts) and placed at the end (or sometimes in the main body of the text) of journals published after each expedition (e.g. Ross and Ross 1835; Belcher 1855). Here corrections due to instrumental errors were introduced rather rarely and the data are presented mainly in the form of monthly and annual averages for fixed hours. These sources of data should be used if - and only if - the meteorological data from the given expedition are not present in the publication *Contribution to our knowledge....* On the other hand, the journals give much useful information about the weather during the time of the expedition and are a rich source of information helpful in estimating the quality of meteorological measurements.

AIR TEMPERATURE IN THE CANADIAN ARCTIC FROM 1846 TO 1859 AND ITS COMPARISON WITH MODERN DATA

Area, Data, and Methods

The change of air temperature from the mid-19th century (1846 to 1859) to the present time (1961-1990) is illustrated, based on data taken from some of the expeditions listed in Table 1. They were chosen for three different regions, two of which represent the northern subregion (IVb) and one the southern subregion (IVa) of the Canadian Arctic (Fig. 1). Meteorological data from stations located very close to the historical observation points have been chosen for purposes of comparison with the present-day climate.

Table 2. Characteristics of air temperature observations and instrument used during expeditions to Canadian Arctic and Alaska, 1819-1859

Location	Place of measurements			Type of thermometer			Instrumental errors		Frequency of observations
	on the board	on the ice	on the land	spirit	mercurial	un-known	intro-duced	not intro-duced	
Winter Harbour, Melville Island	+			+	+			+	two-hourly
Fort Enterprise			+			+		+	at least 3 daily
Winter Island	+			+	+			+	two-hourly
Igloolik	+			+	+			+	two-hourly
Port Bowen	+					+		+	two-hourly
Fort Franklin	+			+	+				hourly (7 to 24)
Felix Harbour, Gulf of Boothia		+		+	+		+?		hourly
Victoria Harbour, Gulf of Boothia		+		+	+		+?		hourly
Mundy Harbour, Gulf of Boothia		+		+	+		+?		hourly
Fort Reliance	+			+				+	two-hourly (6 to 24)
Hudson Strait	+	+		+			+		two-hourly
York Factory			+			+	+		two-hourly
Fort Hope, Repulse Bay, 1846-47			+		+		+		3 daily (7, 13, 19)
Fort Hope, Repulse Bay, 1853-54			+		+		+		3 daily (8, 14, 20)
Port Leopold	+					+	+		two-hourly
Wolstenholm Sound	+	+				+	+		four-hourly
Port Providence	+					+		+	hourly
Chamiso Island	+					+		+	hourly
Fort Simpson, 1849-50			+	+			+		two-hourly (8 to 20)
Fort Simpson, 1850-51			+	+			+		three-hourly (9 to 21)
Port Clarence, 1850-51	+					+		+	hourly
Assistance Bay		+		+				+	three-hourly
Griffith Island		+		+	+			+	two-hourly
Batty Bay	+					+		+	4 daily (8, 12, 16, 20)
Wellington Chanel to Baffin Bay	+	+		+				+	two-hourly
Fort Confidence			+			+	+?		3 daily (9, 13, 21)
Princess Royal Islands	+					+		+	two-hourly
Port Clarence, 1851-52	+					+		+	hourly
Walker Bay	+	+	+			+	+		four-hourly
Mercy Bay	+					+		+	two-hourly
Dealy Island, "Resolute"	+			+	+			+	six-hourly
Dealy Island, "Intrepid"	+			+	+			+	two-hourly
Northumberland Sound	+		+	+				+	two-hourly
Cambridge Bay	+	+	+			+			four-hourly
Beechey Island	+					+		+	two-hourly
Point Barrow	+			+			+		hourly
Port Clarence, 1853-54	+					+		+	three-hourly
Wellington Channel	+	+		+				+	two-hourly
Melville Sound, "Resolute"	+			+	+			+	six-hourly
Melville Sound, "Intrepid"	+			+	+			+	two-hourly
Camden Bay	+					+	+		four-hourly (8 to 24)
Baffin Bay	+			+			+		two- or four-hourly
Port Kennedy	+			+			+		two- or four-hourly

+? - probably introduced

Fig. 1. Locations of historical observation points and comparison stations with modern data

Key: A – historical observational points; B – comparison stations with modern data; C – Arctic border; D – borders of climatic regions; E – borders of climatic sub-regions; V, VI, VII – climatic regions; Ia, IVa, IVb, VIIb – climatic subregions, 1. Repulse Bay.; 2. Chesterfield Inlet A; 3. Coral Harbour A; 4. Mercy Bay; 5. Mould Bay CS; 6. Sachs Harbour A; 7. Resolute ARS; 8. Port Kennedy; 9. Port Leopold; 10. Griffith Island; 11. Beechey Island; 12. Assistance Bay; 13. Northumberland Sound;

The monthly means of air temperature for the mid-19th century were taken from Strachan's *Contribution to our knowledge…*For purposes of comparison with modern data, we decided to use the long-term means from the period 1961-1990, a period which, in our opinion, very reliably represents climate conditions in the second half of the 20th century (as it includes both cold and warm spells) and for which the data availability is the greatest. At present, the most reliable data for this part of the world are available from the *Historical Adjusted Climate Database for Canada*, version December 2002 (Vincent and Gullett 1999, (updated)).

For the analysis, simple standard methods used in climatology have been utilised. Corrections to the analysed series of data were also introduced, where necessary.

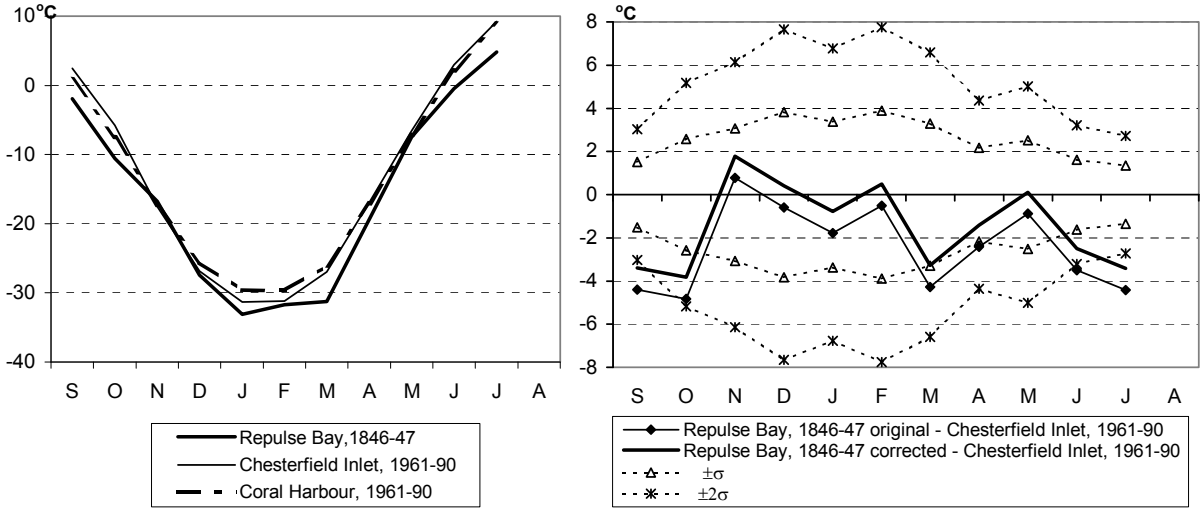
Results

For the southern Canadian Arctic the series of air temperature data from Fort Hope located on the north shore of the Repulse Bay (see Fig. 1) have been chosen. Observations were made here three times a day by Dr. John Rae during two winterings in 1846/47 and in 1853/54. The historical meteorological station was located about 1-2 m above sea level. Dr. Rae was a very experienced scientist and consequently the quality of measurements, and thus of the statistical air temperature characteristics, is good.

From Fig. 2 it can be seen that the autumn/winter period was clearly colder in 1853/54 than in 1846/47. In November, this difference was exceptionally large and reached 11.2^{o}C. In 1854, from March onwards the air temperature was warmer by 2-3°C than in 1847. The coldest month was January (1847) or February (1854), and the warmest month was July in both years.

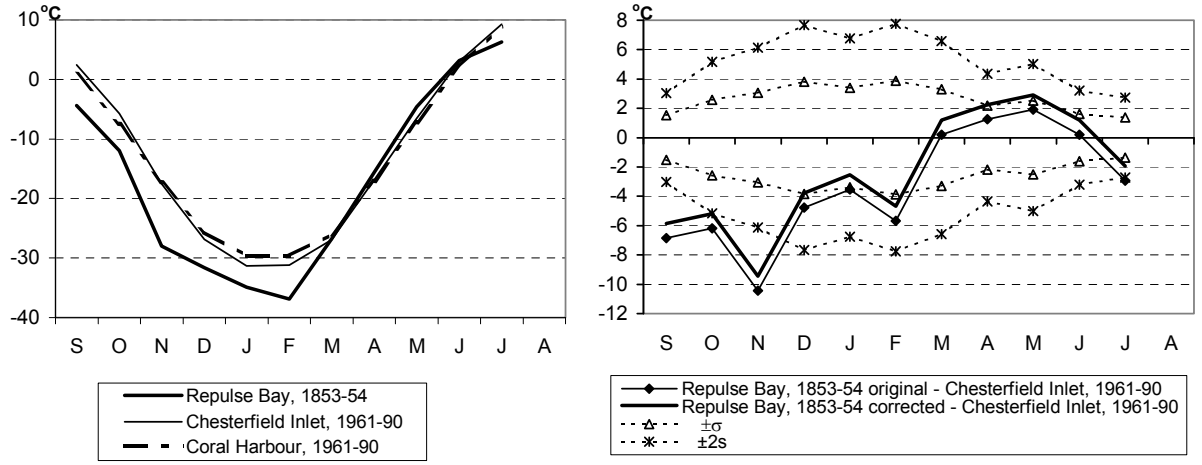
For comparison with modern climate conditions, the two nearest stations (Coral Harbour and Chesterfield Inlet) have been chosen (see Fig. 1). Annual air temperature courses in both stations are very similar (Fig. 2) and therefore the only data used for further analysis was from the latter station (with temperatures closer to those occurring at present in the region where the historical station was located). Based on the spatial mean air temperature distribution for January and July (*Atlas Arktiki* 1985), it was estimated that Chesterfield Inlet is about 1°C colder than the region of Repulse Bay. This correction was introduced to the data and the results are presented in Fig. 2. The mean annual air temperatures for the years 1846/47 and 1853/54 were 1.4^{o}C and 2.4^{o}C colder than the present-day temperature, respectively. In 1846/47 all months were colder or slightly warmer (excluding November) than today (Fig. 2a). Very cold conditions were observed mainly in the following months: September, October, March, June, and July. The wintering of 1853/54 was very difficult due to anomalously cold conditions lasting from September 1853 to February 1854 (the monthly means were colder by 3°C to 9°C than present). As has already been mentioned, November in particular was very cold, with severe conditions also being noted in other parts of the Canadian Arctic (e.g. in Melville Sound and on Beechey Island). On the other hand, the period from March to June was warmer by 1-3°C than today, with the maximum occurring in April. However, monthly mean temperatures only sporadically exceed the distance of two standard deviations from the modern mean (see Fig. 2).

a)



Locations	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Year
RepB-ChesInl original	**-4.4**	**-4.8**	0.8	**-0.6**	**-1.8**	**-0.5**	**-4.3**	**-2.4**	**-0.9**	**-3.5**	**-4.4**		**-2.4**
RepB-ChesInl corrected	**-3.4**	**-3.8**	1.8	0.4	**-0.8**	0.5	**-3.3**	**-1.4**	0.1	**-2.5**	**-3.4**		**-1.4**

b)

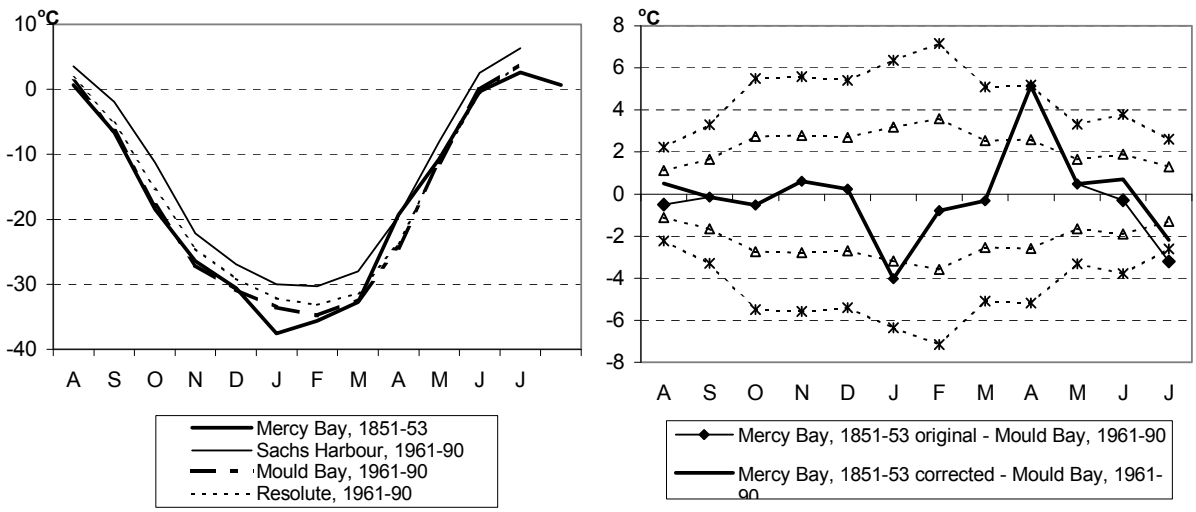


Locations	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Year
RepB-ChesInl original	**-6.9**	**-6.2**	**-10.4**	**-4.8**	**-3.5**	**-5.7**	0.2	1.2	1.9	0.2	**-2.9**		**-3.4**
RepB-ChesInl corrected	**-5.9**	**-5.2**	**-9.4**	**-3.8**	**-2.5**	**-4.7**	1.2	2.2	2.9	1.2	**-1.9**		**-2.4**

Fig 2. Annual courses of historical and modern air temperatures (left panel) and differences between them (right panel and tables) in the Repulse Bay region

For the northern part of the Canadian Arctic there is significantly more meteorological data available for the 19th century. For this reason, the results for two regions located in the north-western and northern parts are presented (see Fig. 1). For the first region, an analysis was conducted based on temperature data measured on board the H.M.S. "Investigator", which wintered twice in the Mercy Bay region from September 1851 to May 1853. In his commentary to this expedition Strachan wrote that "No satisfactory check on the correctness of the thermometers used had been discovered". However, it is known that thermometers were tested before the beginning of the expedition.

For purposes of comparison with the present-day climate, the three nearest meteorological stations have been chosen (Fig. 3). From this figure and the maps presenting the spatial distribution of mean air temperature in January and July (*Atlas Arktiki* 1985) it may be concluded that the air temperature differences are lowest between the Mould Bay and Mercy Bay regions. Only in summer is Mould Bay about 1°C colder in comparison with Mercy Bay. Therefore, the appropriate corrections were only introduced for this season for the modern series.

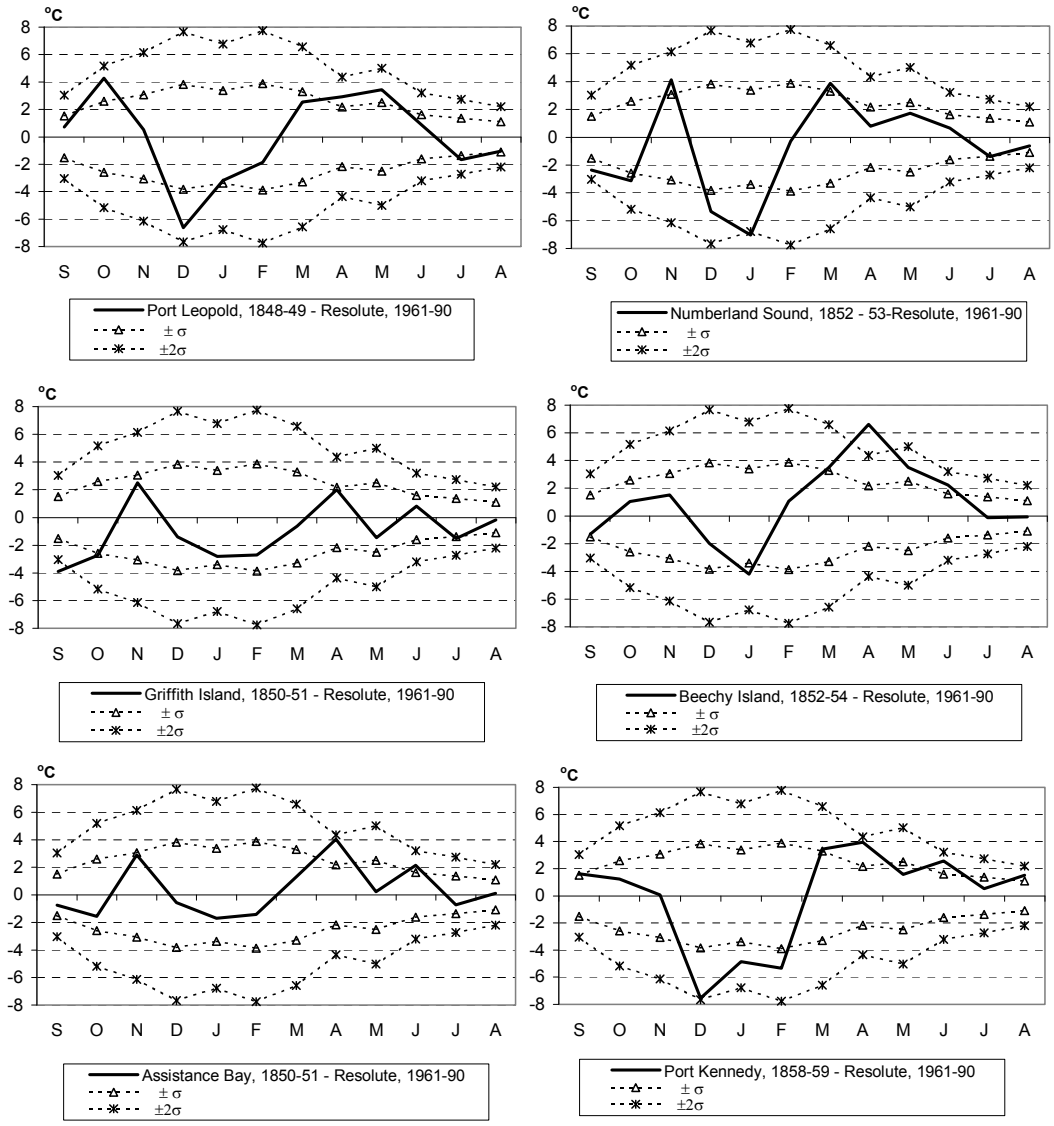


Locations	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Year
MerB-MouldB original	**-0.5**	**-0.1**	**-0.5**	0.6	0.2	**-4.0**	**-0.8**	**-0.3**	5.1	0.5	**-0.3**	**-3.2**	**-0.3**
MerB-MouldB corrected	0.5	**-0.1**	**-0.5**	0.6	0.2	**-4.0**	**-0.8**	**-0.3**	5.1	0.5	0.7	**-2.2**	0.0

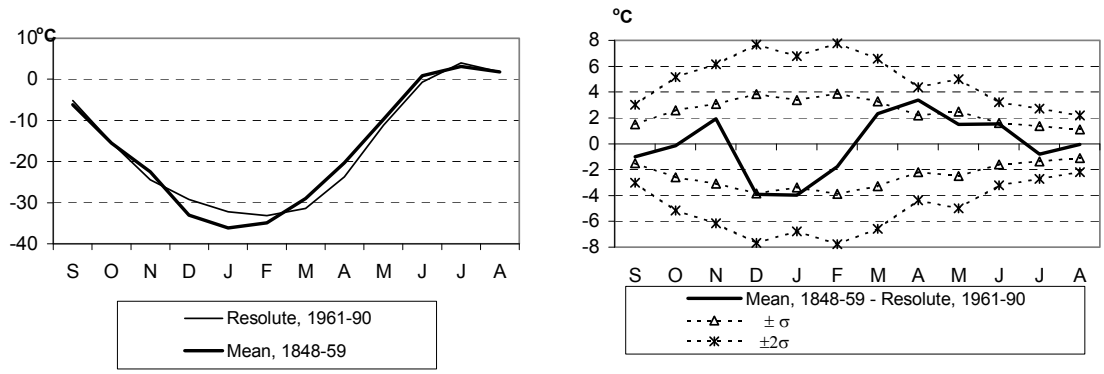
Fig 3. Annual courses of historical and modern air temperatures (left panel) and differences between them (right panel and tables) in the Mercy Bay region

The warmest mean monthly air temperature occurred in January (-37.5°C) and the highest was in July (2.6°C). January 1853 was anomalously cold (-42.1°C) while April 1852 was exceptionally warm. However, in both these cases the mean monthly temperatures lie within two standard deviations, while the majority of the other values do not exceed even one standard deviation from the modern mean (see Fig. 3). On average, the mean annual air temperatures for the historical and corrected modern series are identical.

a)



b)



Locations	Sep	Oct	Nov	Dec	Jan	Febr	Mar	Apr	May	Jun	Jul	Aug	Year
PKenn-Res	1.6	1.2	0.1	**-7.5**	**-4.8**	**-5.3**	3.4	3.9	1.6	2.6	0.5	1.5	**-0.1**
PLeop-Res	0.7	4.3	0.5	**-6.6**	**-3.2**	**-1.9**	2.5	2.9	3.4	0.9	**-1.7**	**-1.1**	0.1
GriffIsl-Res	**-3.9**	**-2.7**	2.5	**-1.4**	**-2.8**	**-2.7**	**-0.6**	2.0	**-1.4**	0.8	**-1.5**	**-0.2**	**-1.0**
ABay-Res	**-0.7**	**-1.6**	2.9	**-0.6**	**-1.7**	**-1.4**	1.3	4.1	0.2	2.2	**-0.7**	0.1	0.3
BeechIsl-Res	**-1.3**	1.0	1.5	**-2.0**	**-4.2**	1.1	3.5	6.6	3.5	2.2	**-0.1**	**-0.1**	1.0
NumS-Res	**-2.4**	**-3.1**	4.1	**-5.3**	**-7.0**	**-0.3**	3.9	0.8	1.7	0.7	**-1.4**	**-0.6**	**-0.7**
Mean, 1848-1859	**-1.0**	**-0.1**	1.9	**-3.9**	**-4.0**	**-1.8**	2.3	3.4	1.5	1.5	**-0.8**	0.0	**-0.1**

Fig 4. Annual courses of historical and modern air temperatures (left panel) and differences between them (right panel and tables) in the Resolute region

A large concentration of wintering ships in the mid-19th century was noted near (up to 150 km) the present location of the Resolute Meteorological Station (Cornwallis Island). Six temperature records (see Fig. 4) have been chosen for the analysis. In particular, two of them (from Griffith Island and Assistance Bay) are of great importance for purposes of comparison because they come from areas close to the present-day location of the Resolute Meteorological Station. However, another four records can also be successfully compared with modern data due to the significant spatial temperature uniformity in the analysed region (see *Atlas Arktiki* 1985). For this reason, no correction of data is needed because of different geographical locations.

Fig. 4a presents the annual courses of air temperature differences between historical and modern data. In the case of each site, the same features in the annual cycle can be distinguished, i.e. very cold winters and, on the other hand, very warm springs (April, in particular). However, again as in previous cases, almost all mean monthly temperatures lie within two standard deviations from the modern mean.

The great uniformity of spatial temperature in the region of Resolute (mentioned earlier) allows us to calculate areally averaged air temperatures based on all six historical series. The mean annual course of such a constructed historical series was compared with the long-term (1961-1990) modern series (Fig. 4). The results confirm previous findings that, in the mid-19th century, winters/springs were markedly colder/warmer than present-day temperatures. The greatest negative differences (-4°C and –3°C) occurred in January and December, respectively. On the other hand, large positive differences were noted in April (3.4°C) and in March (2.3°C). Annually averaged air temperature was only slightly colder (0.1°C) in comparison with modern data. These results are in good agreement with those presented by Przybylak (2000) and Wood and Overland (2003).

CONCLUDING REMARKS

A search for the sources of early instrumental meteorological records for the Canadian Arctic for the study period indicates that they are numerous. Thanks to the detailed work conducted at the Met Office (by Strachan in particular) in the second half of the 19th century, the monthly means calculated for the fixed hours are probably available for all expeditions working in the Canadian Arctic from 1819 to 1859. On the other hand, the raw data are available only in ships' log books, which are dispersed between different archives in Great Britain or in private collections; thus access is sometimes limited. The quality of meteorological data is good for the majority of series because meteorological observations were carried out by training officers, according to the high standards of the Royal Navy. Thus, these data are very valuable and useful for climate and climate change studies.

Analysis of data allows the following conclusions to be drawn:

i) The annual mean air temperature in the mid-19th century in the southern part of the Canadian Arctic was colder than today by about 2°C or more, while in the northern part no change was noted. However, when we subtract a possible warm bias from the historical data connected with the fires kept on the ships, then we must state that the whole Canadian Arctic was colder than today,

ii) The most typical features in the annual courses of air temperature in the study period were very cold winter moths (December to March) and warm springs (March to May) - April in particular (from 2°C to 5°C depending on the region),

iii) The results showed that air temperatures in the mid-19th century were not exceptionally cold, as some analyses of proxy data suggest (Koerner 1977; Overpeck et. al. 1997). This conclusion is confirmed by the fact that majority of the mean monthly air temperatures lie within one standard deviation and only in a few cases do they exceed the level of two standard deviations from the modern mean.

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