Theor. Appl. Climatol. 81, 1–10 (2005)
DOI 10.1007/s00704-004-0088-x

Theoretical and Applied Climatology
Printed in Austria

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Recent warming in a small region with semi-oceanic climate, 1949–1998: what is the ground truth?

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With 8 Figures

Received December 19, 2003; revised July 8, 2004; accepted August 14, 2004

Summary

Trends of monthly air temperature extremes were investigated in five meteorological stations of the Grand-Duchy of Luxembourg during the period 1949–1998. The application of an innovative homogenization method based on the concept of relative homogeneity to climatic time series allows identifying multiple break points, as well as correcting data series in an objective and robust statistical way. The rise of maximum temperature (*Tmax*) has occurred at a rate of 1.5 times that of the minimum temperature (*Tmin*) in winter (+1.4 °C versus +0.9 °C) and summer (+1.4 °C versus +0.8 °C). No trend in temperature extremes was found in autumn, while spring was affected by a small warming (+0.3 °C) of *Tmin* and no change in *Tmax* resulting in a decrease of the diurnal temperature range (DTR) (−0.3 °C). In spring, a strong positive linear relationship between *Tmin* warming and local terrain slope could be found. Comparison to new-gridded large-scale climatologies indicates generally close agreement to temperature trends during the 1949–1998 period, while a lower local warming was observed in summer during the post-1975 period following the changing-point year of atmospheric circulation over North-western Europe. This study shows that the question of data homogeneity is not trivial and should receive careful attention before quantifying historical temperature trends and identifying their spatial patterns at regional scale.

1. Introduction

Our environment is subject to a global change abundantly documented by scientific papers during the last decades. The most evident signature of this global change is a global climate warming initiated since the mid nineteenth century, partly due to unprecedented emissions of anthropogenic greenhouse gases resulting in a positive radiative forcing of the low terrestrial atmosphere. After more than a century of ground measurements, the premonition of Arrhenius (1896) is verified and the global warming magnitude is estimated to be near +0.6 °C ± 0.2 °C for a 99% confidence interval since 1860, according to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001). Different synoptic climatologies of recent air temperature evolution indicate the following trends for the last 150 years (e.g. IPCC, 2001; Hansen et al., 2001; Jones and Moberg, 2003):

- The climate warming was more pronounced over land masses than over oceans.
- The diurnal temperature range was generally decreasing.
- The temperature increase was more pronounced in winter at least in the Northern Hemisphere.
- Two warming periods could be identified: one during the 1910–1945 period centered in the Northern Atlantic and a second one during the 1976–2000 period especially prominent at

the middle and high latitudes in the Northern Hemisphere in winter and spring, excepted in the North-Western part of the Atlantic Ocean.

On a regional scale, different geographical factors are likely to influence the magnitude of hemispheric temperature trends: heat island effect (Hansen et al., 2001), distance from the sea coast (Moisselin et al., 2002), climate station elevations (Beniston and Rebetez, 1996; Weber et al., 1997). Moreover, different non natural sources may hamper the detection and estimation of surface air temperature trends: changes in measurement sites, changes in thermometer screens (Parker, 1994), changes in mean air temperature calculation, changes in instruments, recording practices, urbanization, etc.

This paper aims at estimating the magnitude of change in monthly mean air temperature extreme (*Tmax* and *Tmin*) records since World War II in five climatic stations of the Grand Duchy of Luxembourg (2586 km^2), under a semi-oceanic climate. A rigorous statistical procedure developed thanks to a synergy between meteorologists and statisticians (Mestre, 1999, 2000; Caussinus and Mestre, 2004) was applied to time series in order to detect multiple change-points in time series and remove their effect for constructing homogeneous 'natural' time series. The ultimate goal is to document patterns of local recent warming versus continental climatic assessment recently published by Tank et al. (2002), Jones and Moberg (2003) and secondly, to provide a basis for the validation of Regional Climate Model outputs of typical resolution of 50 km $\times$ 50 km (2500 km^2) against local climate variability.

2. Data set and quality control

2.1 Air temperature records

Monthly means of daily *Tmax* and *Tmin* values were drawn from the archives of the Administration des Services Techniques de l'Agriculture (ASTA, Ministry of Agriculture) of the Grand Duchy for the 1949–1998 period. Records from five climatic stations (four manual and one synoptic stations) distributed throughout the country were selected (Fig. 1). These are located at low to middle altitudes (188 to 465 m.a.s.l.) and are generally surrounded by rural or suburban environment (Fig. 1). Record length extend from 1949 to 1998, except for the Clervaux station, extending from 1949 to 1995. Metadata (name of the observer, type of sensor, station relocation, etc.), unfortunately rarely explicitly mentioned in the ASTA meteorological bulletins, were also systematically recorded in order to validate, at least partly, results from the multiple change-point method. Time series were generally complete and for the few missing data, a reconstruction was made with the algorithm presented below.

2.2 Procedure of time series homogenization

Most of the statistical techniques used in climatic studies are not able to detect multiple change-points and outliers in time series and correct them in a single statistical framework. For example, the test of Alexandersson (1986), widely used for its simplicity and correction possibility that it offers, cannot identify more than one break point. Recently extended to the case of multiple breaks (Alexandersson and Moberg, 1997), the detection method remains somewhat empirical and visual. Moreover, it postulates the existence of a reference or regional series, which is free of inhomogeneity (a strong assumption over thirty years) used both for non-stationarity detection and correction. Lanzante (1996) proposed to introduce a powerful non-parametric technique for the objective identification of discontinuities in the mean but without dealing with a statistical model correction, which could be applied to time series. The method used here to detect outliers, to remove discontinuities and homogenize the air temperature data set is the double step procedure presented in detail in Caussinus and Mestre (2004) and applied for example in the EC-project ALPCLIM (e.g. Boehm et al., 2001). It is based on the concept of relative homogeneity introduced by Conrad and Pollack (1962) and postulates two major assertions:

- First, the Caussinus-Lyazrhi rule (Caussinus and Lyazrhi, 1997) gives an objective method to detect an unknown and multiple number of break points in a gaussian sample.

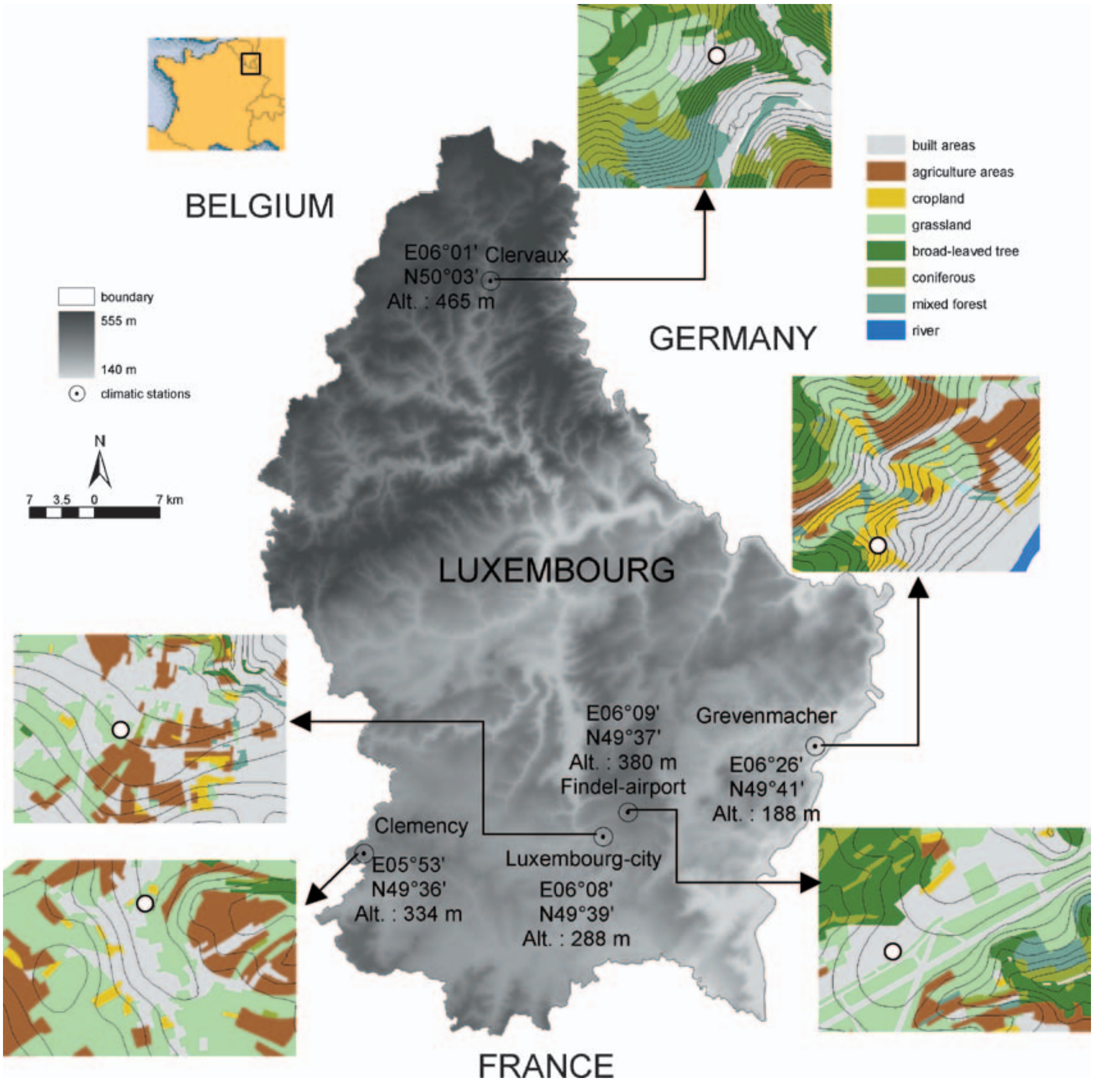

Fig. 1. Study area and macro to micro-location of climatic stations

- Secondly, all time series of the same climatic area are compared individually. If one candidate time series presents a break point at the same date as it appears in all residual series, then this date can be assigned to it. This approach was already carried out by e.g. Rhoades and Sallinger (1993) but the detection method was always subjective.

Performance of the Caussinus-Mestre method was evaluated on French long-term climate series well documented with metadata. Results show that the level of detection with this approach was more efficient in comparison to station metadata and expert knowledge than the Alexandersson test (Mestre, 2000). As the Caussinus-Mestre method is sensitive to the ratio between the magnitude of the discontinuity and the standard deviation determined on the residual series, it was applied on the annual mean value of daily extremes. Once discontinuities are detected, a least squares linear model correction, which used all available local (i.e. having the same climate signal) time series is applied to raw monthly and annual data. Correction coefficients are calculated according to the last homogeneous sequence of the measurement period and supposing that all time series have the same climatic signal, an assumption acceptable for air temperature in the small-considered region.

An example of the Caussinus-Mestre procedure implementation is given hereafter for the *Tmin*

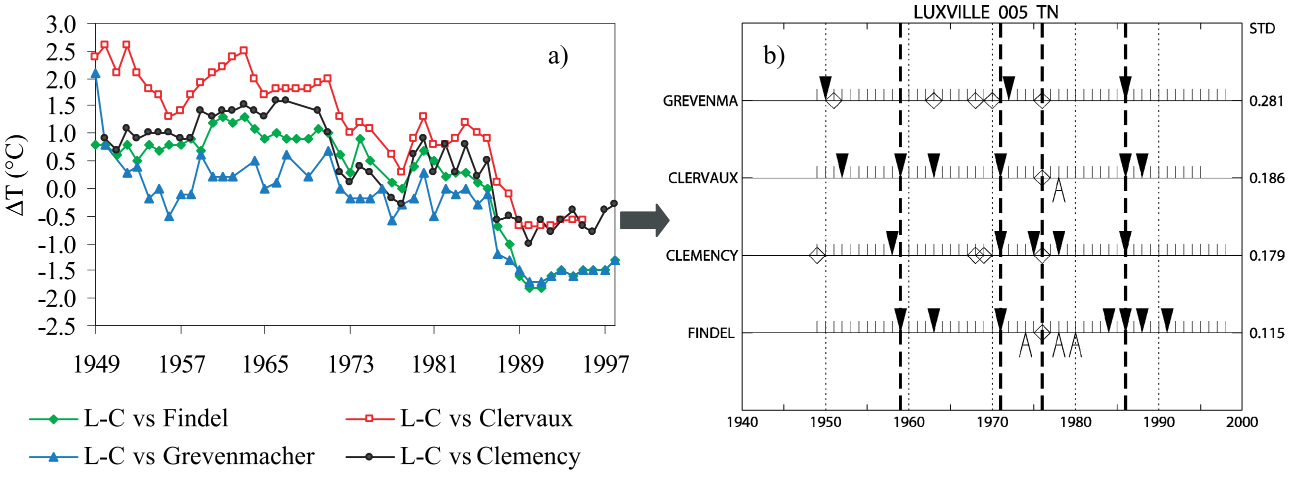

Fig. 2. Detection of change point years in the *Tmin* time series of the Luxembourg-city (L-C) station with the Caussinus-Mestre procedure: residual series of raw annual *Tmin* values (**a**), distribution of break points (**b**). A triangle indicates a break point between the L-C station and a neighboring station. The alignment of triangles indicates a constant break point in the considered time series. Vertical dash lines are break points validated by expert knowledge. Lozenges correspond to years with missing monthly data and symbol ∧ to outliers. STD corresponds to the standard deviation of residual series in °C

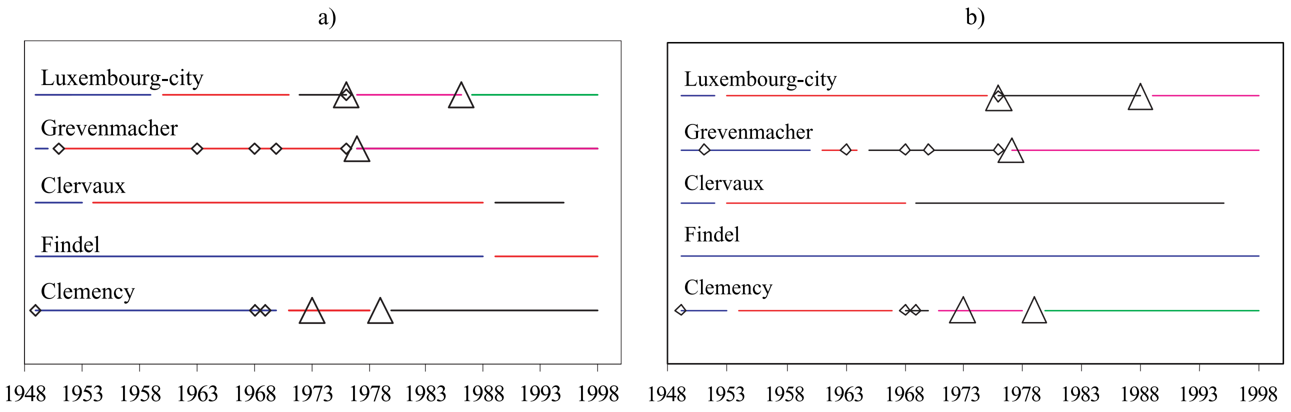

Fig. 3. Homogeneous periods (color lines) identified with the Caussinus-Mestre procedure for mean annual *Tmin* and *Tmax* values. Triangles correspond to site changes regarding the ASTA archives. Lozenges correspond to years with missing monthly data. **a**) *Tmin* – **b**) *Tmax*

data series of the Luxembourg-city (L-C) station (see Fig. 1 for location). Residual series between L-C annual *Tmin* values and other stations were first calculated (Fig. 2a). After verification of the normality of residual series of raw mean annual air temperature records between neighboring stations, the automatic detection procedure allows identifying four common dates of residual series showing potential break points in 1959, 1971, 1976 and 1986 (Fig. 2b). Two of the four inhomogeneities detected were confirmed by the metadata of the station indicating change sites in 1976 and 1986 (ASTA, 1976 and 1986).

An overview of results from the multiple change point procedure application is presented in Fig. 3 for *Tmin* and *Tmax* mean annual values. Break points are more frequent for *Tmin* (Fig. 3a) than for *Tmax* (Fig. 3b), which seem to be less sensitive to site changes. Only a few identified break points could be validated with changes in measurement sites according to the ASTA bulletins. Note that the displacement of a climatic station does not always coincide with break points. Correction coefficients were determined for each station and added to each monthly raw time series to produce the homogeneous monthly extreme temperature series. The example of the L-C station is again considered here. In Fig. 4a are represented the distributions of monthly correction coefficients to be added to homogeneous sequences to correct them according to the last homogeneous sequence. In Fig. 4b are represented the corresponding

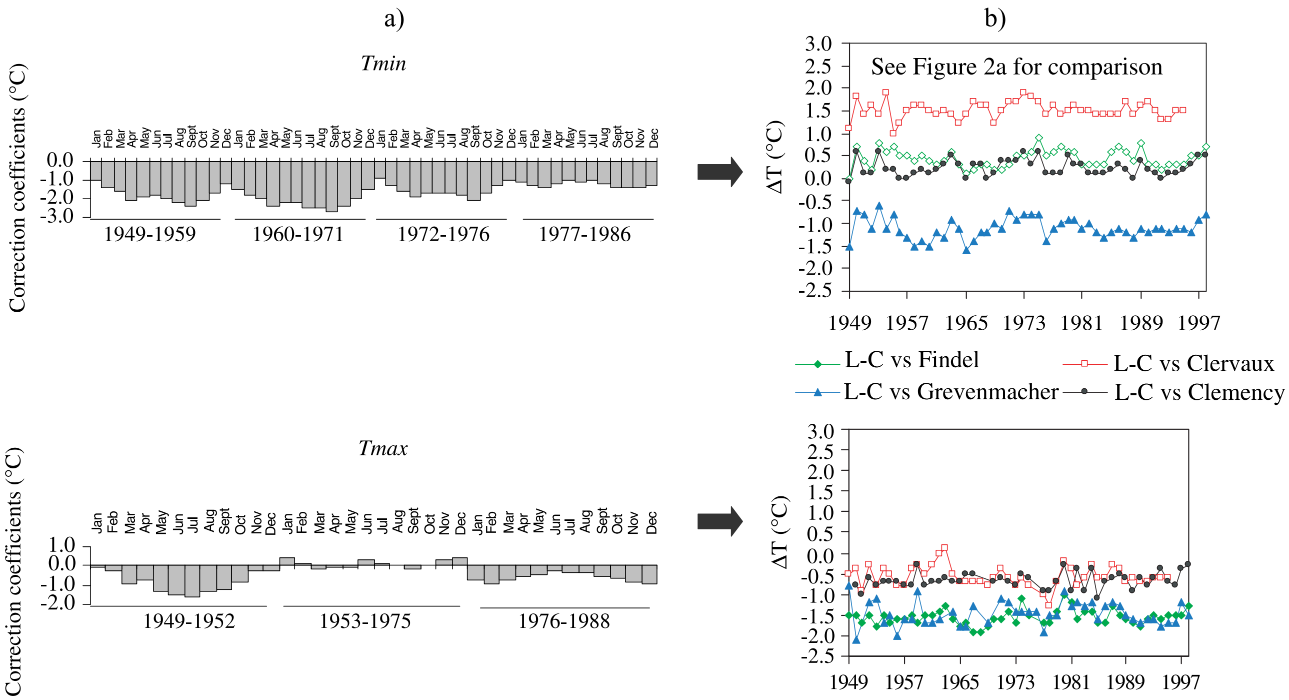

Fig. 4. a) Monthly correction coefficients (in °C) applied to raw data of each homogeneous sequence according to the last homogeneous sequence of the *Tmin* (1987–1998) and the *Tmax* (1988–1998) series of the Luxembourg-city station. **b**) Resulting corrected residual time series

Table 1. Magnitude in °C per LR (length of record) of the linear trend fitted to seasonal mean monthly *Tmin*, *Tmax* as well as DTR (Diurnal Temperature Range). LC = Luxembourg-city. In brackets: associated error to linear regression slope

Stations	DJF	MAM	JJA	SON	Year
Tmin					
Clemency	+0.9 (±0.77)	+0.2 (±0.41)	+0.8 (±0.35)	−0.1 (±0.42)	+0.3 (±0.28)
Clervaux	+1.1 (±0.83)	+0.5 (±0.44)	+0.9 (±0.39)	+0.1 (±0.49)	+0.6 (±0.32)
Findel-airport	+0.8 (±0.75)	+0.2 (±0.41)	+0.8 (±0.41)	0.0 (±0.41)	+0.3 (±0.28)
Grevenmacher	+0.9 (±0.81)	+0.4 (±0.40)	+0.7 (±0.38)	+0.1 (±0.45)	+0.5 (±0.30)
L-C	+0.9 (±0.76)	+0.3 (±0.43)	+0.7 (±0.38)	−0.1 (±0.46)	+0.5 (±0.29)
Tmax					
Clemency	+1.4 (±0.77)	0.0 (±0.60)	+1.5 (±0.68)	0.0 (±0.49)	+0.7 (±0.39)
Clervaux	+1.4 (±0.71)	−0.1 (±0.59)	+1.3 (±0.73)	0.0 (±0.53)	+0.6 (±0.33)
Findel-airport	+1.4 (±0.80)	+0.1 (±0.60)	+1.5 (±0.71)	−0.1 (±0.52)	+0.7 (±0.41)
Grevenmacher	+1.4 (±0.78)	+0.1 (±0.59)	+1.5 (±0.70)	0.0 (±0.53)	+0.7 (±0.40)
L-C	+1.4 (±0.75)	0.0 (±0.61)	+1.4 (±0.70)	0.0 (±0.52)	+0.7 (±0.39)
DTR					
Clemency	+0.5 (±0.33)	−0.2 (±0.48)	+0.8 (±0.55)	0.0 (±0.50)	+0.3 (±0.77)
Clervaux	+0.2 (±0.37)	−0.6 (±0.42)	+0.4 (±0.51)	0.0 (±0.51)	0.0 (±0.28)
Findel-airport	+0.6 (±0.24)	−0.1 (±0.39)	+0.6 (±0.43)	−0.1 (±0.41)	+0.4 (±0.24)
Grevenmacher	+0.5 (±0.33)	−0.3 (±0.50)	+0.8 (±0.59)	0.0 (±0.60)	+0.2 (±0.30)
L-C	+0.5 (±0.31)	−0.3 (±0.46)	+0.7 (±0.49)	0.0 (±0.51)	+0.3 (±0.27)

residual time series calculated on homogenized time series.

3. Trend analysis

Magnitude and statistical significance of monotonic trends in monthly-homogenized temperature extremes were estimated through least square linear regression analysis and the widely used nonparametric Mann-Kendall test (Yue et al., 2002). Results of trends summarized in Table 1 indicate that annual *Tmax* increases more rapidly than *Tmin* since the World War II. During winter (DJF), *Tmax* has uniformly risen by about +1.4 °C and quicker than *Tmin* warming. As a result, DTR (Diurnal Temperature Range) increases in greater proportion in the south of the country than in the north. In spring (MAM), magnitude of change was more important for *Tmin* than for *Tmax*, the latter having remained almost stationary during the measurement period. Spring is the only season affected by a DTR damping (between −0.1 °C and −0.6 °C). The same qualitative and quantitative trends than wintertime characterize summer (JJA) temperature extremes. Note that no heat island effect could be detected for the station located in Luxembourg-city. In autumn (SON), trends in *Tmax* and *Tmin* values were almost null. Monthly distributions of the Mann-Kendall tau's values, show that trends in *Tmax* and DTR values were only significant in August at a 0.05 probability level (Fig. 5b). If Mann-Kendall tau's values are usually close

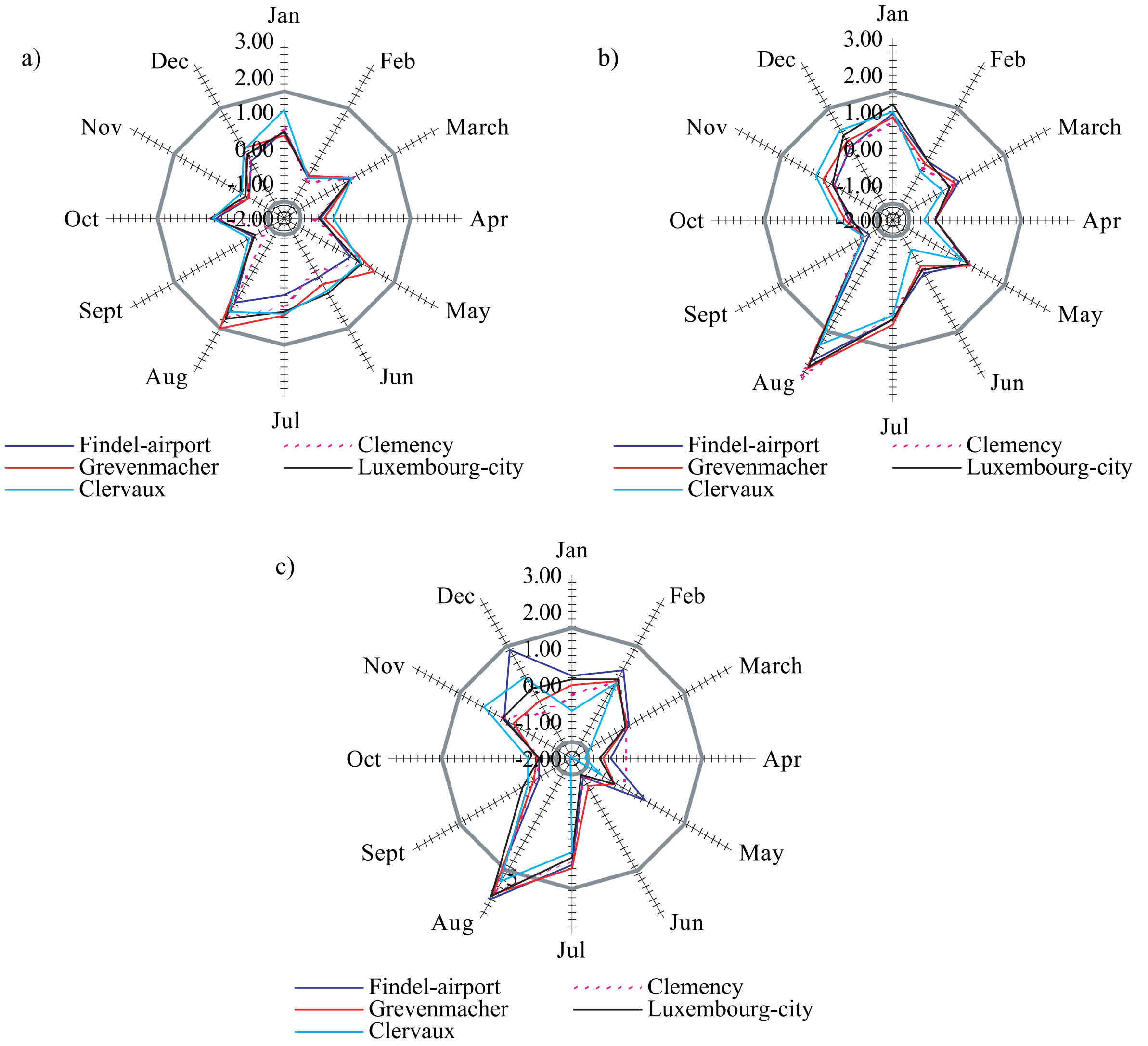

Fig. 5. Statistical significance of temperature trends for the period 1949–1998: **a**) *Tmin*, **b**) *Tmax*, **c**) DTR. Grey lines indicate positive (1.56) and negative (−1.56) Kendall's tau values for the 5% probability level

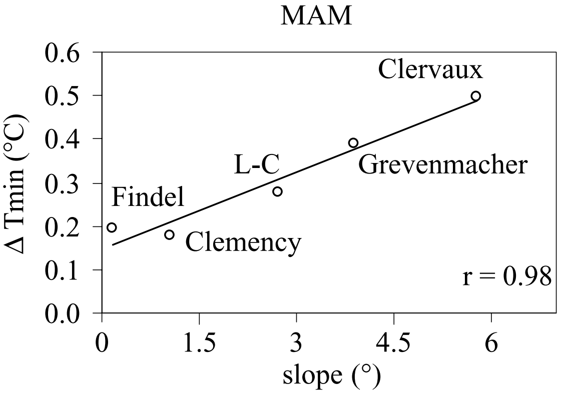

Fig. 6. Scatter plot and significant Pearson correlation coefficients ($r_\alpha \approx 0.81$ at 5% significance level) between station slope and the magnitude of linear trend fitted to *Tmin* spring (MAM)

between climatic stations, those of DTR were more variable in space, especially in April and June with a significant decrease for the Clervaux station where *Tmax* values were affected by a slight cooling.

Microclimatic conditions and site effects can explain the variability of the temperature trends, especially for *Tmin* which is more prone to topoclimatic influences in a low-contrasted relief region than *Tmax*, essentially depending on diurnal radiative budget distribution. Hence, the relationship between seasonal magnitude of *Tmax*, *Tmin* changes and station characteristics (altitude, slope, aspect, geographical coordinates and maximum height between altitude station and minimum elevation in a 225 × 225 m grid-box around the station) was investigated with a 75 × 75 m DEM. A significant correlation and robust linear relationship for *Tmin* spring increase versus local terrain slope could only be found (Fig. 6). While this relationship should be carefully considered due to the reduced number of available climatic stations, this finding indicates that *Tmin* warming was lower during the 1949–1998 period for stations in low-lying flat areas (see Fig. 1) exposed to poor cool air drainage, as well as temperature inversions associated to clear nights in spring.

4. Discussion and conclusion

Karl et al. (1995) concluded to an increase of +0.28 °C for the annual *Tmax* and of +0.84 °C for the annual *Tmin* over the 1951–1990 period for the 50% (10%) of the Northern (Southern) Hemisphere land masses. The authors state that most regions were affected by a DTR attenuation, but some regions in Western USA, Europe, Meridional India and Oceania were concerned by an increase of the DTR. Studying daily climate extremes, Tank et al. (2002) recently found that DTR has decreased in the Grand Duchy of Luxembourg as a result of a quick rising of *Tmin*, our findings being somewhat different. Raw annual *Tmin* data of the synoptic Luxembourg-airport station (Fig. 7a) indeed indicate a strong warming after 1988, but this year showed to be a non-natural abrupt change from a statistical point of view (Fig. 3a). The natural warming after

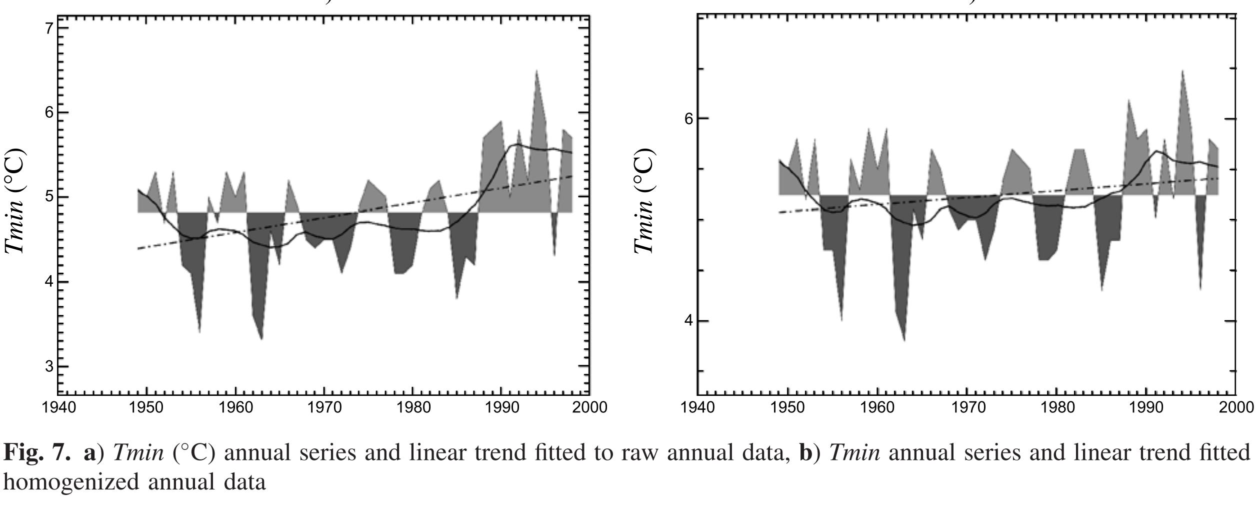

Fig. 7. **a**) *Tmin* (°C) annual series and linear trend fitted to raw annual data, **b**) *Tmin* annual series and linear trend fitted to homogenized annual data

Table 2. Mean seasonal and annual temperature change explained by the linear trend for the Grand Duchy of Luxembourg (E06°10′ – N49°45′) for two sub-periods separated by the NAO (North Atlantic Oscillation) change point year. Trends are expressed in °C per decade

Period	DJF	MAM	JJA	SON	Year
1949–1976	+0.330	−0.240	+0.331	−0.080	+0.067
1977–1998	+0.702	+0.709	+0.732	+0.038	+0.613

homogenization is clearly lower according to the Caussinus-Mestre double step homogenization procedure (Fig. 7b), ultimately leading to an increase of the DTR.

In order to compare our trend results to the recent Jones and Moberg (2003) large-scale surface air temperature variation, the change of the mean temperature, derived as the half sum of *Tmin* and *Tmax* values, was computed (Table 2) for two sub-periods separated by the NAO (North Atlantic Oscillation) change point year. In North-western Europe, post-1975 period was characterized by stronger westerlies in winter and longer anticyclonic residence times in summer (Gerstengarbe and Werner, 1999).

Sign and magnitude of annual change in pre-1976 mean temperatures of the Grand Duchy of Luxembourg (Table 2) is slightly different to what Jones and Moberg (2003) found for land-only temperature for Europe (−0.029 °C). Cooling trend was similar to northern land-only temperature of Jones and Moberg (2003) in spring and autumn, while warming rather than cooling was found for the winter and summer on our dataset. Post-1977 mean temperature warming for the Grand Duchy of Luxembourg (Table 2) is stronger than European temperature change found by Jones and Moberg (2003), similar results being found in all seasons except autumn for the northern hemisphere.

Jones and Moberg (2003) also provide a gridbox dataset of 5° × 5° temperature anomalies according to the 1961–1990 normal. Therefore the gridbox including the Grand Duchy of Luxembourg (45–50° N–05–10° E) was extracted from the CRUTEM2 dataset (http://www.cru.uea.ac.uk/cru/data/temperature/) and temperature anomalies of large scale compared to the mean local temperature anomalies calculated from the five selected climatic stations series. According to the CRUTEM2 dataset, on average, 13 climatic stations were used to compute the temperature anomalies of the grid box 45–50° N–05–10° E over the 1949–2003 period. Figure 8 demonstrates that the large-scale temperature anomalies of Jones and Moberg climatology were able to provide good agreement to the local temperature anomalies for most seasons without systematic bias. Correlation coefficients between large scale and local anomalies were always above 0.9

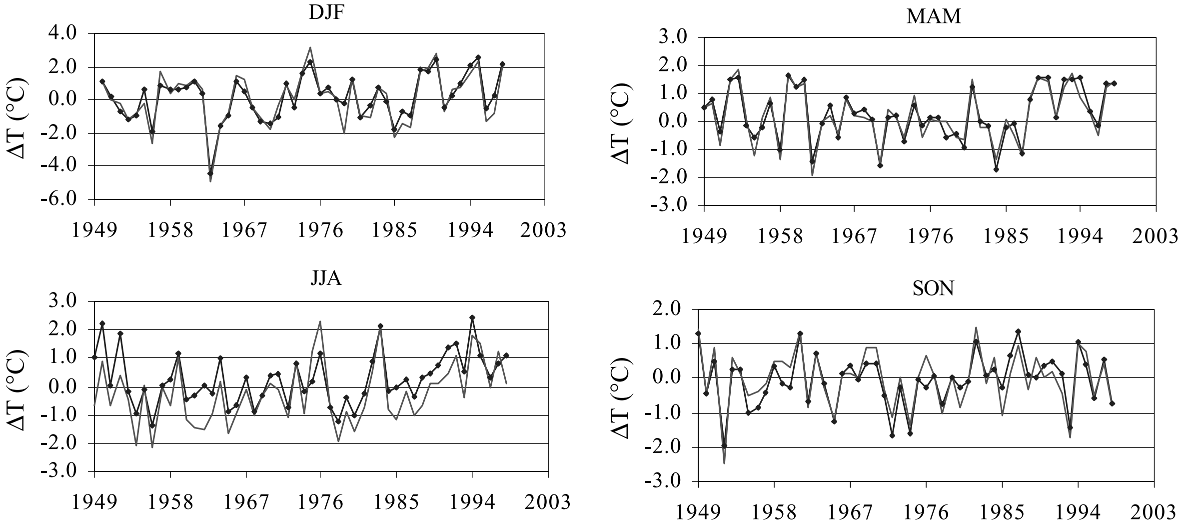

Fig. 8. Seasonal comparison of temperature anomalies (departures from the 1961–1990 mean) between Jones and Moberg (2003) gridbox (bold line) and average from five climatic stations of the Grand Duchy of Luxembourg over the period 1949–1998 (grey line)

except for summer (0.84) for which CRUTEM2 anomalies were frequently warmer than those prevailing for the local investigated semi-oceanic climate.

Therefore, the trend analysis applied to homogenized monthly temperature series show a certain divergence with previous publications on climate warming at European continental scale since the World War II based on similar raw *in situ* data. One can also conclude that the gridded climatology of Jones and Moberg (2003) gives good fitting of mean seasonal air temperature variations since 1949 for a semi-oceanic climate, in comparison to *in situ* temperature signal of a local-scale set of low altitudes and rural climatic stations.

This study shows, however, that estimating precisely the nature and magnitude of air surface temperature trend is not a trivial task and should receive close attention. Especially large regional datasets with high temporal resolution should systematically subject, at least on mean monthly and annual values, to robust statistical procedures able i) to detect an unknown number of multiple change-point years and ii) to remove their effect through a model correction applied to raw long term data series. In future works, findings about local warming in Luxembourg should be extended to a larger regional temperature dataset and linked to other climate variables (sunshine duration, synoptic situations), as well as to the topographic position of climatic stations, in order to explain more precisely surface air temperature variations and particularly the asymmetric trend of *Tmax* regarding *Tmin* during winter.

Acknowledgments

This study was partially funded by the Luxembourg Ministry of Culture, Higher Education and Research. The authors wish to thank the Administration des Services Techniques de l'Agriculture (ASTA) as well as the Meteorological Service of the Luxembourg Airport for providing some of the data required for this study.

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