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Influence of changes in the station location and measurement routine on the homogeneity of the temperature, wind speed and precipitation time series

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Abstract. Changes in the location, instrumentation and measurement times are documented for three Estonian meteorological stations during the last century. These metadata were used to check if such changes have introduced significant discontinuities into the time series of daily and monthly mean temperature, average wind speed and daily and monthly precipitation sums. For this purpose, time periods of the length of at least ten years were separated before and after each change and average values of meteorological elements during these periods were compared by means of the *t*-test at the significance level of 0.05. On the daily basis, such changes introduced an increase in all parameters under consideration. On the monthly basis, only wind speed and precipitation sums were affected in some cases. Earlier climatological analyses have shown that in Estonia the temperature has risen and the precipitation sums have increased. Therefore, it is very difficult to separate natural trends from the artificial changes.

Key words: temperature, wind speed, precipitation, meteorological station, meteorological measurements, time series of meteorological parameters.

1. INTRODUCTION

The value of meteorological data, recorded all over the world, cannot be underestimated. Therefore very strict prescriptions are elaborated for measurement fields and routines [1]. Unfortunately, these guidelines are not always followed. Therefore even questions arise if the records are reliable and could be used at climate applications [2]. Problems also arise when measurement times are changed as most of the meteorological elements show daily cycles [3,4]. Precipitation records are sensitive to the measurement equipment and corrections for wind, wetting and evaporation [4,5]. Wind speed is affected by local orography and the openness of the measurement field. The recorded wind speed may be different for a traditional wind vane, anemorhumbometer or an automatic device [6].

Even in case when there are no changes in the measurement equipment and routine, the time series of meteorological data may be contaminated. One such widely known problem is urbanization that may contribute to the fake rise of surface air temperature [7]. Trends in cloud cover and wind are affected by growing forest: this is the case for two Estonian meteorological stations, Ristna and Tiirikoja. Cloud amount, recorded at Ristna, showed unrealistic decreasing trend because the growing forest shadowed the part of the sky near the horizon where the ground based observer could have recorded larger values of the cloud amount. That is why this station was left out of the analysis of Estonian cloud cover during 1955–1995 [8]. The Tiirikoja wind data does not serve as good input for models to get realistic wave regime on the Lake Peipsi. Most probably the questionable quality of the data can also be attributed to the growing trees around the measurement site [9].

A poor station location is rather widely analysed in the context of temperature measurements. Several attempts have been made to correct the errors with various adjustment methods [10,11]. On the basis of data from Taiwan, in [12] it is demonstrated how artificial discontinuities in the temperature time series occur due to station relocation. Such problems lead to elaboration of the methods to detect inhomogeneities in the observed data series [13–15]. To prepare homogenization of the time series, attention should be paid to the metadata [16]. An analysis of the changes in the station location, measurement instruments or observation routines is the basic step by the detection of discontinuities in the meteorological time series and their homogenization.

Tarand [17] has made an attempt to reconstruct a homogeneous time series of the air temperature in Tallinn for the period of 1756–2002 on the monthly basis. For the period of 1850–2002 (that may be called a period of modern observations), the following operations were conducted: reducing all different time observations to a 24-hour average, filling in the gaps in the data by means of the recordings at the neighbouring stations, and eliminating meso-scale impact at measurement sites by means of parallel observations. The attempts to homogenize older data were based on parallel measurements and recordings at Paldiski and St. Petersburg.

The aim of the present paper is to present metadata for three Estonian meteorological stations and to check if the changes in the location, instruments and observation schedule have introduced inhomogeneities into the time series of the principal meteorological parameters – daily and monthly mean temperature, wind speed and precipitation sums.

2. MATERIAL AND METHODS

The stations under consideration are situated in different parts of Estonia: Tallinn at the coast of the Gulf of Finland, Tartu in South Estonia and Pärnu at the coast of the Gulf of Riga (Fig. 1). For these stations all changes have been registered. The dates of the changes are labelled as possible breakpoints and the homogeneity of the time series is checked by means of a standard test. For this purpose, the time series were divided into different periods that cover the time intervals between the instants of changes. A two-sample Student's *t*-test has been applied to determine whether the averages of the meteorological parameters during different periods are equal. To decide whether or not the samples had equal variance, the *F*-test was applied. The differences were detected on the significance level of 0.05.

The analysis of the possible breakpoints was only performed for cases when only one non-climatic change occurred at the breakpoint – either a relocation of the station or a change of the equipment or a change in the observation times. The periods between the instants of changes only contained whole years in order to eliminate possible systematic differences due to the annual cycles of the meteorological parameters.

The periods when no change in the location, instrumentation or measurement routine took place, were sometimes very short. In the present paper only time intervals with the length of at least ten years were considered. A comparison of shorter time periods may reveal changes due to the natural variability of meteorological parameters that could be ascribed to the consequences of artificial changes.

It can be said that all changes in the measurement times took place at all meteorological stations simultaneously. Until 1966 all measurements were carried out according to the Local Mean Time (GMT + 2 h). On the 1st of January 1966 the Moscow Time was introduced (GMT + 3 h). In 1992 the Moscow Time was replaced by the GMT (Greenwich Mean Time), but this did not change the measurement routine as the difference between these two time systems is three hours. Such reorganization only changed the division of measurement instants between subsequent calendar days: for the sake of homogeneity, a new date starts at 21 GMT.

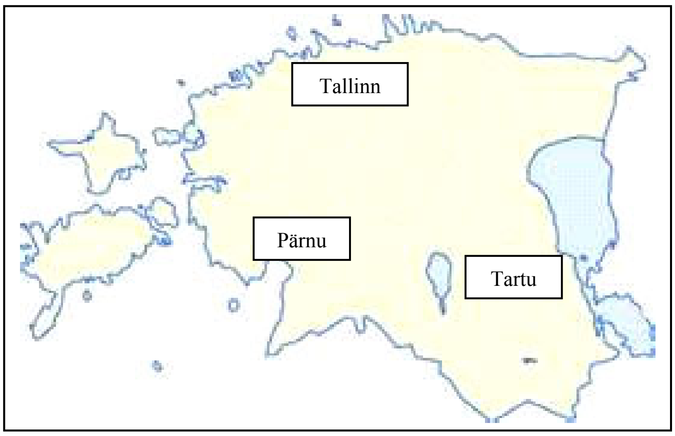

Fig. 1. Location of the meteorological stations under consideration.

To get daily average values of temperature from the existing inhomogeneous data set, special correction coefficients have been proposed [18]. These coefficients represent average differences between the mean value, calculated from the temperature of three (or four) observations a day, and the average daily temperature, calculated from the thermograph data. In the present paper no corrections have been introduced.

It is not recommended to directly compare the daily average wind speed for the periods with different observation times [4]. Therefore, wind data are analysed for a shorter period of 1966–2010 when no changes in observation times took place.

Precipitation is not measured according to the same scheme as temperature and wind. The rain gauges are checked up to 4 times per day, sometimes with unequal intervals. A change in the number of observations per day may introduce systematic errors into the daily and monthly sums in case no wetting correction is applied [19]. In Estonia, the wetting correction was introduced in 1966. When the strict homogeneity of the time series is necessary, the wetting correction should be added to all earlier measurements [4].

Traditional manual measurements were replaced by automatic weather stations at the beginning of the last decade. These stations record data continuously and special filtering is needed to simulate traditional measurements to keep the time series as homogeneous as possible [20]. Automatic weather stations in Estonia use the following Vaisala equipments: temperature sensor DTS-12A, averaging wind display unit WAD21M, anemometer WAA151, rain and precipitation sensor RG13H and weighing gauge VRG101.

3. RESULTS

3.1. Metadata for the Tallinn meteorological station

Although the instrumental observations date back to the end of the 18th century [17], the present paper describes changes for the period of 1931–2010 (tables 1 to 3). During this period the station has moved from the vicinity of the Tallinn Lower Lighthouse to Kose, later to Ülemiste and finally to Harku. Tallinn Lower Lighthouse (59°26′N, 24°48′E) is situated on the cliff above the eastern part of the city. Kose (59°28′N, 24°49′E) is located lower, not far from the cliff. Ülemiste meteorological station (59°24′N, 24°36′E) was established at the airport, near the southern border of the city. Harku (59°38′N, 24°58′E) is situated some kilometres to the west of Tallinn.

3.2. Metadata for the Tartu meteorological station

The time series of temperature starts in 1821, but in the present paper the period of 1881–2010 is considered (tables 4 to 6). During the time span of 129 years, the measurements were carried out at the Tartu Meteorological Observatory that was situated at different places inside the town (58°23′N, 26°43′E). In 1950 the station was moved out of the town, 7 km to the south to Ülenurme (58°18′N, 26°41′E). Since 1997 the station is situated 25 km to the south-west of Tartu at Tõravere (58°16′N, 26°28′E).

Table 1. Changes at the Tallinn meteorological station that may affect the temperature time series

Date of the change	Location	Instrument	Observation time
01.01.1931	Tallinn Lower Lighthouse	Mercury thermometer	07,13,21 Local Time
01.01.1941			01,07,13,19 Local Time
01.09.1941			07,13,21 Local Time
01.01.1945			01,07,13,19 Local Time
01.09.1948	Kose		
01.01.1965	Ülemiste		
01.01.1966			00,03,06,09,12,15,18,21
01.05.1980	Harku		Moscow Time/GMT
01.09.2003		Vaisala DTS-12A	

Table 2. Changes at the Tallinn meteorological station that may affect the wind speed time series

Date of the change	Location	Instrument
01.01.1966	Ülemiste	Anemorhumbometer M63-M1, height 10.7 m
01.01.1973		Anemorhumbometer M63-M1, height 10.0 m
01.05.1980	Harku	
01.01.1997		Vaisala WAD21M
01.09.2003		Vaisala WAA151

Table 3. Changes at the Tallinn meteorological station that may affect the precipitation time series

Date of the change	Location	Instrument	Observation time
01.01.1931	Tallinn Lower Lighthouse	Rain gauge with the Nifer shield	Once a day
01.01.1945			07,19 Local Time
01.09.1948	Kose		
01.09.1952		Tretyakov rain gauge	
01.01.1965	Ülemiste		
01.01.1966		Tretyakov rain gauge with wetting correction	00,06,12,18 GMT
01.05.1980	Harku		
01.04.1981			06,18 GMT
01.01.1984			03,06,15,18 GMT
01.09.2003		Vaisala RG13H + Tretyakov	
01.11.2003			06,18 GMT
11.02.2005			06,12,18 GMT
03.02.2006		Vaisala VRG101 + Tretyakov	
01.05.2009			06,18 GMT

Table 4. Changes at the Tartu meteorological station that may affect the temperature time series

Date of the change	Location	Instrument	Observation time
01.01.1881	Tartu, Tiigi 1	Mercury thermometer	07,13,21 Local Time
01.01.1893	Tartu, Tiigi 15		
01.01.1926	Tartu, Liivi 3		
01.01.1941			01,07,13,19 Local Time
01.09.1941			07,13,21 Local Time
01.01.1945			01,07,13,19 Local Time
01.01.1950	Ülenurme		
01.01.1966			00,03,06,09,12,15,18,21 Moscow Time/GMT
01.01.1997	Tõravere		
01.09.2003		Vaisala DTS-12A	

Table 5. Changes at the Tartu meteorological station that may affect the wind speed time series

Date of the change	Location	Instrument
01.01.1966	Ülenurme	Anemorhumbometer M63-M1, height 12 m
01.01.1969		UATGMS weather station, height 12 m
01.01.1986		Anemograph M-12
01.01.1997	Tõravere	Vaisala WAD21M, height 10 m
01.09.2003		Vaisala WAA151

Table 6. Changes at the Tartu meteorological station that may affect the precipitation time series

Date of the change	Location	Instrument	Observation time
01.01.1881	Tartu, Tiigi 1	Rain gauge in garden, height 1 m	Once a day
01.01.1893	Tartu, Tiigi 15	Rain gauge in garden, height 2 m	
01.01.1900		Rain gauge with the Nifer shield on the roof	
01.01.1926	Tartu, Liivi 3	Rain gauge with the Nifer shield, height 2 m	
01.01.1945			07,19 Local Time
01.01.1950	Ülenurme	Tretyakov rain gauge	
01.01.1966		Tretyakov rain gauge with wetting correction	00,06,12,18 GMT
01.04.1981			06,18 GMT
01.01.1984			03,06,15,18 GMT
01.01.1997	Tõravere		
01.09.2003		Vaisala RG13H + Tretyakov	
01.11.2003			06,18 GMT
11.02.2005			06,12,18 GMT
01.05.2009			06,18 GMT
28.10.2010		Vaisala VRG101 + Tretyakov	

3.3. Metadata for the Pärnu meteorological station

Meteorological observations started at Pärnu in 1842, but in the present study the period of 1901–2010 is considered (tables 7 to 9). During this time the station was relocated four times. Mostly this took place in the boundaries of the city, e.g. 58°23′N, 24°30′E when the observation site was in a courtyard of Nikolai Str. 21. In 2004 the station was moved out of the town to the airport (58°25′N, 24°28′E). Until the 23rd of December 2004 the measurements were carried out using the mercury thermometer, but this was placed differently during different periods. The same can be said about the older versions of rain gauge.

Table 7. Changes at the Pärnu meteorological station that may affect the temperature time series

Date of the change	Location	Instrument	Observation time
01.01.1901	At the pilot tower	Mercury thermometer, height 3.4 m	07,13,21 Local Time
01.08.1914		Mercury thermometer on the roof	
31.05.1921		Mercury thermometer, height 2 m	
01.01.1941			01,07,13,19 Local Time
01.09.1941			07,13,21 Local Time
01.01.1945			01,07,13,19 Local Time
07.11.1947	Open site on the beach, 100–150 m from the water line		
01.01.1966			00,03,06,09,12,15,18,21 Moscow Time/GMT
23.04.1971	250 m from the beach house, open to SW, W and NW		
07.09.1990	Nikolai Str. 21		
23.12.2004		Vaisala DTS-12A	

Table 8. Changes at the Pärnu meteorological station that may affect the wind speed time series

Date of the change	Location	Instrument
01.01.1966	Open site on the beach, 100–150 m from the water line	Wind vane, height 16 m
23.04.1971	250 m from the beach house, open to SW, W and NW	
01.01.1975		Anemorhumbometer M-63M-1, height 15.5 m
07.09.1990	Nikolai Str. 21	Anemorhumbometer M-63M-1 on the roof, height from the roof 4.35 m and from the ground 25 m
01.01.1997		New type of M-63M-1 on the roof, height 25 m
23.12.2004		Vaisala WAA151, height 10 m

Table 9. Changes at the Pärnu meteorological station that may affect the precipitation time series

Date of the change	Location	Instrument	Observation time
01.01.1901	At the pilot tower	Rain gauge, height 6.1 m	Once a day
01.08.1905		Rain gauge, height 9.1 m	
07.07.1907		Rain gauge, height 6.1 m	
01.01.1921		Rain gauge with the Nifer	
01.01.1945		shield	07,19 Local Time
07.11.1947	Open site on the beach,		
01.04.1952	100–150 m from the	Tretyakov rain gauge	
01.01.1966	water line	Tretyakov rain gauge with	00,06,12,18 Moscow
23.04.1971	250 m from the beach	wetting correction	Time/GMT
01.04.1981	house, open to SW,		06,18 Moscow Time/GMT
01.01.1984	W and NW		03,06,15,18 Moscow
07.09.1990	Nikolai Str. 21		Time/GMT
01.09.2003			06,18 GMT
23.12.2004	Sauga airport	GEONOR T-200B	
11.02.2005		precipitation gauge	06,12,18 GMT
01.05.2009			06,18 GMT
14.09.2010		VRG101	

3.4. Breakpoints in the time series of daily data

From Tables 1–9, only six changes were identified that provided a possibility to compare periods of the length of ten or more years where only one change took place. They are shown in Table 10 together with the changes introduced to the meteorological time series of daily data.

In both cases that could be checked (Tallinn and Pärnu) the relocation of the station introduced statistically significant inhomogeneities into the daily temperature time series. The change affected both the variance and average value. The average temperature after the breakpoint was higher and the variance was lower than before the breakpoint.

Table 10. Statistically significant differences detected at the comparison of time periods of the length of at least 10 years from daily averages of temperature and wind speed and daily precipitation sums

Station	Periods compared	Change in	Parameter	Variance	Average
Tallinn	1966–1979/	Location	Temperature	83/70 C^2	5.0/5.8 C
	1981–2002		Precipitation	13.5/17.7 mm^2	1.7/1.9 mm
Tartu	1950–1965/	Observation	Temperature	94/90 C^2	4.6/5.1 C
	1966–1996	times			
	1969–1985/	Instrument	Wind speed	3.4/2.7 m^2/s^2	3.8/4.0 m/s
	1986–1996				
Pärnu	1972–1988/	Location	Temperature	84/75 C^2	5.7/6.7 C
	1991–2003		Precipitation	15.3/18.3 mm^2	1.9/2.1 mm

Relocation of Tallinn and Pärnu stations was also accompanied by an increase in the average values of the daily precipitation sum. In these cases the variance after the change was higher than before.

The Tallinn station was moved from Ülemiste (flat landscape of the airport) to Harku (on the cliff). It is difficult to find the reason why temperature has risen and precipitation sums increased after the relocation. The Pärnu station was moved from the beach to the city centre. In this case the rise of temperature and the increase in the precipitation sums could be expected due to the urban conditions.

The change in the observation times from 01, 07, 13, 19 Local Time to 00, 03, 06, 09, 12, 15, 18, 21 GMT at Tartu-Ülenurme led to an increase in the average temperature and a decrease in the variance.

The only possibility to check the impact of the breakpoints on the wind speed data was at Tartu-Ülenurme where replacing the weather station UATGMS by anemograph M-12 led to an increase in the average wind speed from 3.8 m/s to 4.0 m/s.

3.5. Breakpoints in the time series of monthly data

For the same 10-year periods also monthly values of the meteorological parameters were tested. It turned out that these time series were considerably less affected by changes in the station location, equipment or measurement routine (Table 11).

4. DISCUSSION

Many papers by different authors address the climate change in Estonia and report increasing trends in temperature and precipitation and a decreasing trend in wind speed [[21,22]]. These findings are based on the time series, collected at different meteorological stations that may have undergone changes in the location, instruments and observation times. The discontinuities detected in the present paper may partly overlap with natural trends in the meteorological parameters, especially when the time periods under comparison are long. Long periods are traditionally believed to guarantee stable statistical estimates, a feature that is not necessarily true for shorter periods, especially if the data sets exhibit large variability. In the present analysis, in which we have used at least ten years long time periods, all changes in temperature and precipitation showed an increase. Therefore, natural and artificial changes have the same sign and it is difficult to separate them.

One might argue that differences in the average values of meteorological elements detected in the present work are totally caused by natural trends. It would be so if the behaviour of other statistical parameters was homogeneous. In the present case the changes in the average values were always accompanied by changes in the variance.

Table 11. Statistically significant differences detected at the comparison of time periods of the length of at least 10 years from monthly averages of the wind speed and monthly precipitation sums

Station	Periods compared	Change in	Parameter	Variance	Average
Tallinn	1966–1979/ 1981–2002	Location	Precipitation	974/1242 mm^2	53/59 mm
Tartu	1969–1985/ 1986–1996	Instrument	Wind speed	0.6/0.5 m^2/s^2	3.8/4.0 m/s

The method applied in the present paper assumes that there exist one or several homogeneous populations of temperature, wind speed and precipitation sums. Actually, the time series do not consist of independent random values and the entire climate system should be regarded as the concurrent array of weather patterns [23]. Therefore it is highly possible that the variability of the time series is sample-dependent.

To separate the signal of climate change from artificial influences, special procedures are recommended that are also valid for non-stationary series [24]. From this point of view, climate change should not be regarded as a change at the moments of the relevant probability distributions. One possibility is to analyse deviations from the average annual cycle and to estimate the frequency of the outliers [25]. If climate change is not defined by means of average values and variances, it may turn out that the artificial changes do not affect the signal of the changing structure of the variability of the weather (i.e. climate) even if the data is recorded by different means.

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Ilmajaama asukoha ja mõõtmistingimuste muutmiste mõju temperatuuri, tuule kiiruse ning sademete hulga aegridade homogeensusele

Sirje Keevallik ja Kairi Vint

On kirjeldatud kõiki asukoha, mõõteriistade ja vaatlusaegade muutusi, mis on toimunud kolmes Eesti ilmajaamas viimase sajandi jooksul. Kogutud meta-andmestiku alusel on välja selgitatud nimetatud muudatustest tekkinud murdepunktid ööpäeva keskmise temperatuuri ja tuule kiiruse ning sademete ööpäeva-summade aegridades. Selleks on omavahel võrreldud vähemalt kümne aasta pikkusi perioode enne ja pärast uuritavat muutust ning *t*-testi abil kindlaks tehtud, kas nendel perioodidel registreeritud meteoroloogiliste parameetrite keskväärtused erinevad olulisuse nivool 0,05. Muudatuste järel osutusid kõikide meteoroloogiliste parameetrite väärtused keskmiselt suuremateks. Eestis on enamasti täheldatud temperatuuri tõusu ja sademete suurenemist, mistõttu on nn tehislikke muutusi vaatlustingimustes väga raske klimatoloogilistest trendidest eristada.