Diurnal cycle of precipitation in Estonia

Regina Alber[a], Jaak Jaagus[a] and Peeter Oja[b]

[a] Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia; regina.alber@ut.ee, jaak.jaagus@ut.ee
[b] Institute of Mathematics, University of Tartu, J. Liivi 2, 50409 Tartu, Estonia; peeter.oja@ut.ee

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Abstract. The diurnal cycle of precipitation in Estonia during the warm period (from April to October) is analysed separately at continental and coastal stations. The results were obtained using hourly data from the automated gauges at 13 stations in 2003–2013 as well as from the pluviographic records at 10 stations in 1991–2003. The diurnal cycle is approximated using the second-order trigonometric polynomial. A clear diurnal cycle of precipitation with the maximum in the afternoon and evening (13–19 EET – East European Time), and the minimum at night and in the morning (22–11 EET) was revealed at the continental stations of Estonia. The daily amplitude was the highest in summer and much lower in spring and autumn. The highest monthly mean daily amplitudes up to 7 mm were observed in June and July. The diurnal cycle of precipitation was much weaker at the coastal stations without clear maxima and minima and with lower amplitudes. In autumn, the coastal stations showed clearer and bimodal maxima in the early morning and in the evening. The diurnal distribution of precipitation is quite stable, which is confirmed by the high similarity of the curves characterizing these two periods.

Key words: hourly precipitation, diurnal cycle, continental stations, coastal stations, Estonia.

INTRODUCTION

Precipitation is one of the most important climatic variables having a direct effect on many kinds of human activity. The precipitation regime affects water management, agriculture, water transport and also humans' everyday life. Precipitation extremes, i.e., excessive rainfall and snowfall as well as droughts can cause the severest natural damages in Estonia. A climatological analysis by Tammets & Jaagus (2013) has revealed a significant increase in the frequency of precipitation extremes at 51 stations over the territory of Estonia during 1957–2009.

Precipitation is a climatic variable, which can be characterized by a very high spatial and temporal variability. Therefore, a dense network of measurements is required for the representation of an adequate precipitation pattern. Problems concerning the accuracy of precipitation measurements are currently increasing due to the growing popularity of scientific and practical issues related to the extreme events such as storms and floods (Lanza & Stagi 2009).

The diurnal variability of precipitation is one of the pronounced climatic cycles. It is closely related to many other climatic cycles, such as temperature and air pressure variations. The knowledge about the mean diurnal precipitation cycle has a high scientific and practical importance. This topic has not been earlier studied in Estonia.

Instruments and methods of precipitation measurements have changed over the time. From 1950 onwards traditional manual measurements of precipitation were made two or four times per day using the Tretyakov gauges. In comparison with the earlier instruments, the Tretyakov gauges are able to reliably register solid precipitation. In parallel, pluviographs were used at many stations in Estonia to record precipitation on a more detailed time scale (Tammets & Jakovleva 2001). On pluviograph tapes, the rainfall amount was recorded in the time interval of 10 min.

Automatic weather stations were installed in Estonia starting from September 2003. Precipitation records were taken hourly from the automated gauges. There are two main types of automated precipitation gauges. Tipping-bucket rain gauges are the most popular ones used for providing highly accurate measurements of low to intermediate intensity rainfalls (Saidi et al. 2014), i.e., they measure only liquid precipitation. However, they usually underestimate intense rainfall due to the loss of rainwater during the movement of the bucket (Vasvári 2005). The second type of automated precipitation gauges is the weighing-type precipitation gauge. This type of gauge has some advantages over the tipping-bucket gauges. It does not underestimate intense rain and can measure all forms of precipitation, including rain, hail and snow.

Globally, the most pronounced diurnal precipitation amplitudes have been recorded in summer (Dai 2001). Drizzle and non-showery precipitation most frequently fell over land areas in the morning, but over oceanic areas, at night. On the contrary, over land areas showery precipitation tended to occur more often in the late afternoon but over the oceans preferably at night or in the morning (Dai 2001). Satellite data enabled of the conclusion that, in summer, over the land areas of low- and mid-latitudes, the precipitation amounts tended to peak in the afternoon to evening, but over the oceans from midnight to the early morning (Janowiak et al. 2005; Dai et al. 2007; Biasutti et al. 2012).

Kikuchi & Wang (2008) have identified three tropical diurnal precipitation cycle regimes using the satellite data – oceanic, continental and coastal. The oceanic regime is characterized by moderate amplitude and an early morning peak at 6–9 Local Solar Time (LST). The continental regime is described by large amplitude and an afternoon peak at 15–18 LST. The coastal regime by offshore phase propagation peaks at 21–12 LST, whereas the landside coastal regime has a maximum at 12–21 LST (Kikuchi & Wang 2008).

A pronounced late afternoon to early evening precipitation maximum was revealed in the interior regions of India and South Africa (Sen Roy & Balling 2007; Rouault et al. 2013). Sen Roy & Balling (2007) observed a midnight to early morning maximum in the coastal regions of India during the summer monsoon season from June to September. Similarly, in South Africa, Rouault et al. (2013) registered the time of maximum precipitation from midnight to the early morning along the Agulhas Current. The analysis of the diurnal cycle in winter (January, February) also demonstrated obvious spatial differences over India. Most of the study area experienced the time of maximum precipitation during the latter half of the day close to midnight (Sen Roy 2009).

In a detailed study for China, Yin et al. (2009) detected different types of the diurnal variation in precipitation in the summer 1954–2001. The nocturnal maximum is characteristic of the Tibetan Plateau, southwestern and southeastern China. It is related to vertical circulation, mountain-valley winds and the night-time cooling of cloud tops. The precipitation maximum in the daytime in the eastern part of China could be attributed to the moist convection connected with solar heating. The morning maxima at coastal stations have been attributed to the local land–sea breeze (Yin et al. 2009).

Zhuo et al. (2014) detected the early morning and afternoon maxima of precipitation in Shandong province of eastern China. Similar bimodal distribution characterized the intensity of heavy precipitation in case of cyclonic weather type in Eskdalemuir parish in Scotland (Svensson & Jakob 2002). In Japan, intense precipitation increased in the early morning but decreased in the afternoon during summer and spring in 1898–2003 (Fujibe et al. 2006). Secondary maxima of precipitation have also been registered in many oceanic and continental regions in the tropics (Yang et al. 2008). According to Twardosz (2007), maritime polar air masses caused the morning maximum, whereas homogeneous continental or maritime polar air masses and zones of cold fronts determined the afternoon maximum of precipitation in Krakow. Cold fronts were more related to afternoon precipitation, warm fronts to evening and night precipitation.

In Europe, the daily maximum period over the land areas during the warm season is usually detected in the afternoon and evening in Switzerland (Wüest et al. 2010), Austria (Yaqub et al. 2011), the entire Alpine region (Mandapaka et al. 2013) and Sweden (Jeong et al. 2011; Walther et al. 2013). A similar diurnal cycle has also been revealed in the conterminous USA (Matsui et al. 2010). This can be explained by the maximum of convective precipitation corresponding to the daily maximum of air temperature, which is most typical for the summer season.

Nearly all these studies deal with the diurnal cycle of precipitation in regions located at much lower latitudes than Estonia, mostly in the tropics. Sweden is the only country lying at the same latitude, and here analogous research has been done. Detailed investigations of the diurnal cycle of precipitation in Sweden using hourly ground observations at 93 automated stations in 1996–2008 provided the general characteristics of the phase and amplitude, both in the amount and frequency (Jeong et al. 2011; Walther et al. 2013). During the warm season (April–September), the afternoon (14–16 LST) maxima prevailed over inland, while late night to early morning (04–06 LST) peaks with a relatively weak amplitude occurred at the western coast of the Baltic Sea. The diurnal variation was almost negligible during the cold season (Jeong et al. 2011). In Helsinki, Kilpeläinen et al. (2008) detected almost equal morning and late afternoon maxima in August, four precipitation maxima in July and only one late-afternoon maximum in June.

The main objective of this study is to analyse the diurnal cycle of precipitation in different regions of Estonia by means of hourly precipitation. Special attention is paid to differences in the diurnal cycle between continental and coastal stations. The diurnal cycle of precipitation is approximated using second-order trigonometric polynomials.

DATA AND METHODS

The precipitation data used in this study were obtained from the Estonian Weather Service. The diurnal cycle of precipitation was described by the use of hourly precipitation from 13 automated weather stations (Fig. 1) during the warm half-year from April to October in 2003–2013. For comparison, the diurnal distribution of hourly precipitation was analysed using the pluviographic records at 10 stations during the warm half-year of the previous period 1991–2003 (Fig. 1).

The RG13H-type automated precipitation gauges were taken into use in Estonia starting from September 2003. They use a tipping-bucket mechanism to produce a contact closure every time it receives a predetermined small quantity of rainfall (0.2 mm), but are not able to measure solid precipitation in winter. Therefore, only the warm period from April to October was studied. The RG13H gauges were later replaced by the VRG-type automated gauges, which can measure solid winter precipitation as well. The weighing-type precipitation gauge VRG consists of a storage bin which is weighed to record the mass. This instrument change was made at different stations from September to November 2010. The only exception was the Tallinn station where the VRG recorder was installed already in February 2006. Comparison of parallel measurements of precipitation using manual and automated gauges of 13 stations revealed a much higher quality of the VRG-type automated gauges.

The diurnal cycle of precipitation from April to October was analysed using hourly data of automated gauges from 13 stations from September 2003 to October 2013. The diurnal cycle was described by mean annual amounts of hourly precipitation and mean diurnal amplitudes of hourly precipitation. Monthly mean daily precipitation amplitudes were calculated as differences between monthly mean maximum and minimum hourly precipitations. The diurnal cycles are illustrated on graphs where the local East European Time (EET = UTC + 2 h) was used (UTC, Coordinated Universal Time, is the World's Time Standard). The official summer time (UTC + 3 h) is used in Estonia from the last weekend in March until the last weekend in October.

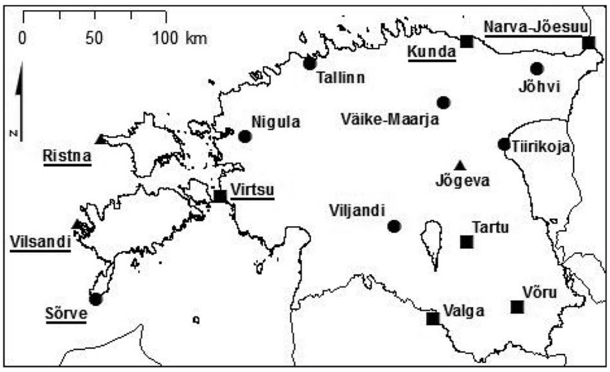

Fig. 1. Locations of meteorological stations in Estonia used in this study: triangles – only pluviographic records, squares – only automated records, circles – both pluviographic and automated records. Names of the coastal stations are underlined.

Local Solar Time is usually used in the studies of the diurnal cycle of precipitation. We did not recalculate the time from EET to LST because of the small territory of Estonia. The temporal differences between the easternmost and the westernmost stations in LST are about 25 min. The 12 LST is equal to 12 EET at the Narva-Jõesuu and to 12:25 EET at the Vilsandi station.

Continental and coastal stations were studied separately, indicating monthly and seasonal distributions. A station was considered to be coastal if it was listed as a coastal station by the Estonian Weather Service. Coastal stations are located on the coast of the Baltic Sea where also hydrological measurements of sea have been made. Other stations were categorized as continental stations. Seasons were defined as usual. Spring includes data from April and May, summer from June, July and August, and autumn from September and October. As pluviographic data involved only one month of spring (May), this season was left out in studying seasons of pluviographic data.

The diurnal cycle of precipitation calculated for 2003–2013 was compared with the pluviographic records from May to October in 1991–2003. Precipitation was recorded with the time resolution of 10 min. In this study we used the hourly precipitation sums from the pluviographic records for the analysis of the diurnal cycle of precipitation.

For generalization mean diurnal cycles of precipitation are usually approximated using the harmonic analysis (Dai 2001; Sen Roy & Balling 2007; Sen Roy 2009; Yin et al. 2009; Rouault et al. 2013). The sinusoidal curve is considered to be the most adequate for expressing diurnal variations. In this study we used the second-order trigonometric polynomial

$$F(x) = c_0 + c_1 \sin k_1 x + c_2 \sin k_2 x + c_3 \cos k_1 x + c_4 \cos k_2 x,$$

where $F(x)$ is hourly precipitation in the diurnal precipitation cycle at the time moment x in the interval [0,24]; $k_1 = 2\pi/24$ and $k_2 = 4\pi/24$ are fixed coefficients of trigonometrical expansion which guarantees the 24 h periodicity of the function F. The parameters $c_0, \ldots, c_4$ are found by the least squares method minimizing the expression $\sum_{i=1}^{24} (F(x_i) - y_i)^2$, where $x_i = i - 1/2$ and y_i means hourly precipitation.

RESULTS

Mean diurnal distribution of hourly precipitation, averaged by all 13 stations in Estonia during the period from May to October (Fig. 2A), demonstrates a clear afternoon to evening maximum at 13–20 EET. The peak of the hourly precipitation was at 14–16 EET, which is 15–17 according to the local summer time. The maximum period showed a sharper increase in precipitation amounts up to the peak compared to the decrease after the maximum. A flat minimum period was detected in the night and morning time between 23 and 11 EET, with the lowest values at 24–02 EET.

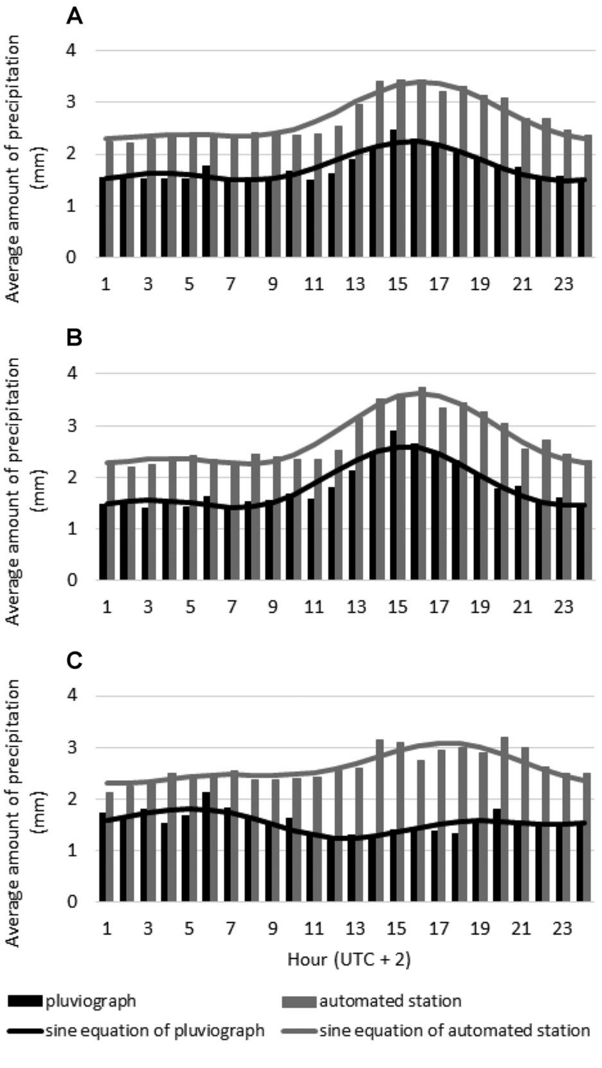

Fig. 2. Annual mean distribution of hourly precipitation amounts (mm) from May to October at all stations of Estonia (**A**), and separately at the continental (**B**) and coastal stations (**C**) according to the pluviographic data from 1991–2003 (black columns) and automated weather station data from 2003–2013 (grey columns). Thick lines present the approximating diurnal curves of precipitation.

The continental stations revealed a well-distinguished diurnal cycle of precipitation (Fig. 2B), while the coastal stations had no clear cycles (Fig. 2C). The pluviographic data had slightly higher values early in the morning, while the data from the automated gauges showed comparatively higher precipitation in the afternoon. This weak maximum occurred later than at the continental stations, extending up to 21 EET.

The results in Fig. 2 indicate that the pluviographs measured significantly less precipitation than the automated weather stations. The reason can be that the period 1991–2003 had generally less precipitation than the period 2003–2013.

Pronounced diurnal cycles of hourly precipitation were characteristic of summer and spring (Fig. 3). There were no well-distinguished maximum or minimum periods in autumn. In spring, the maximum precipitation was measured at 14–20 EET, having a peak at 15–17 EET. The maximum period in summer was a bit earlier – at 12–19 EET, being the highest at 14–16 EET. The minimum period was observed since midnight to late morning. In autumn, a slight maximum period can be detected during 13–20 EET, with a maximum at 19–20 EET according to automated measurements. The pluviographs showed a weak maximum in the early morning. The daily minimum precipitation in autumn was close to midnight (22–3 EET).

Diurnal cycles of hourly precipitation were more distinctive at the continental than at the coastal stations during spring and summer (Fig. 4). At the continental stations, maximum precipitation was recorded between 14 and 19 EET in spring and between 12 and 19 EET in summer with peaks at 14–17 EET and 13–16 EET, respectively. It shows that the highest precipitation in summer occurs clearly earlier than in spring. At the continental stations, the precipitation minimum was revealed at 22–11 EET.

The coastal stations were characterized by a flat and weak maximum period in summer from 13 to 21 EET according to automated measurements. It was interesting that two maxima were revealed in the diurnal cycle of precipitation in autumn, at night and in the morning time (2–7 EET), and in the evening (18–22 EET). Daily precipitation amplitudes were much lower at the coastal stations than at the continental ones.

Monthly analysis of the diurnal distribution of hourly precipitation indicated that the most pronounced afternoon-to-evening maximum periods existed during the warmest period from May to August (Fig. 5). In August, two maxima were revealed: in the afternoon and at night according to records of the automated

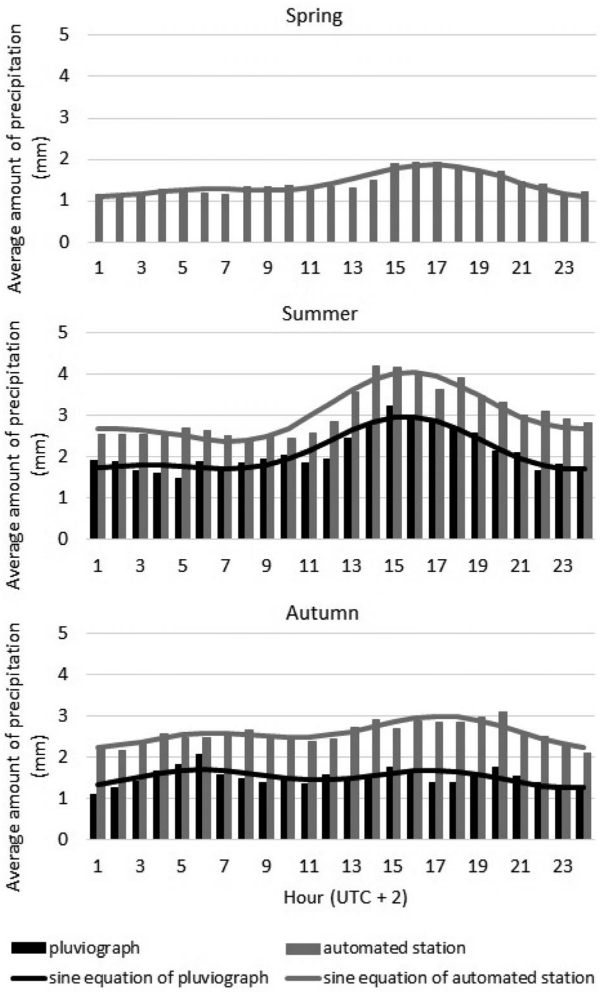

Fig. 3. Mean diurnal distribution of hourly precipitation amounts (mm) in Estonia by seasons in 2003–2013, calculated from the pluviographic records in 1991–2003 (black columns) and from the automated precipitation gauges in 2003–2013 (grey columns). Thick lines present the approximating diurnal curves of precipitation.

stations. In September a weaker maximum period occurred in the evening. In April and October the graph was rather flat.

In some cases, obvious differences in the diurnal cycles exist between the pluviographic records in 1991–2003 and the automated precipitation records in 2003–2013. The timing of maximum precipitation varied: in June the respective times were 14–19 EET and 12–15 EET, in July 14–15 EET and 13–14 EET, in August 13–15 EET and 14–16 EET and in September 14–15 EET and 18–20 EET (Fig. 5). The differences in the diurnal cycle of precipitation between these two periods are likely caused by the different lists of recording stations. At the same time, in most cases, the approximating curves to data from two periods are very similar, in particular, they have almost coinciding places of maxima and minima.

Monthly mean daily precipitation amplitudes, i.e., differences between the highest and the lowest mean hourly precipitation in the diurnal cycle, are presented in Table 1. They were the highest mostly in summer, especially in June and July. At some stations, substantial precipitation amplitudes of more than 3 mm were observed also in May and September. The amplitudes were negligible in April and October. Higher mean daily precipitation amplitudes tend to occur in June in northeastern, in July in southern and in August in western Estonia.

DISCUSSION

In summer, the diurnal cycle of precipitation in Estonia showed a clear afternoon-to-evening maximum period similar to other places in Europe, for example in Sweden (Devasthale & Norin 2014), Switzerland (Wüest et al. 2010), Krakow in southern Poland (Twardosz 2007) or Eskdalemuir in Scotland (Svensson & Jakob 2002). Especially pronounced amplitudes were characteristic of the continental stations in Estonia, as found also in former studies for Sweden (Jeong et al. 2011) and the Global Tropics (Kikuchi & Wang 2008).

The diurnal distribution of precipitation is rather flat at the coastal stations of Estonia. A similar pattern was also determined on the western coast of South Africa (Rouault et al. 2013). The minimum period of precipitation, revealed in Estonia in the morning hours in summer, was similar to that in Switzerland (Wüest et al. 2010). As the number of continental stations was much higher than the number of coastal stations, the properties of the continental stations dominated for the whole of Estonia.

The diurnal distribution of precipitation at the coastal stations differed from that at the continental stations presumably because of the influence of the Baltic Sea. The sea surface having a larger heat capacity than the land surface is generally cooler in spring and during the first half of summer. It is not a favourable environment for convection. At the same time, convective rainfall is usual in the continental areas. A large proportion of precipitation in the Baltic countries is caused by convective spells (Jaagus et al. 2010). Jeong et al. (2011) demonstrated that the clear peak in the diurnal curve of precipitation in the afternoon in Sweden is influenced by convective rainfalls. Convective rainfalls can be quite intense and produce large amounts of precipitation.

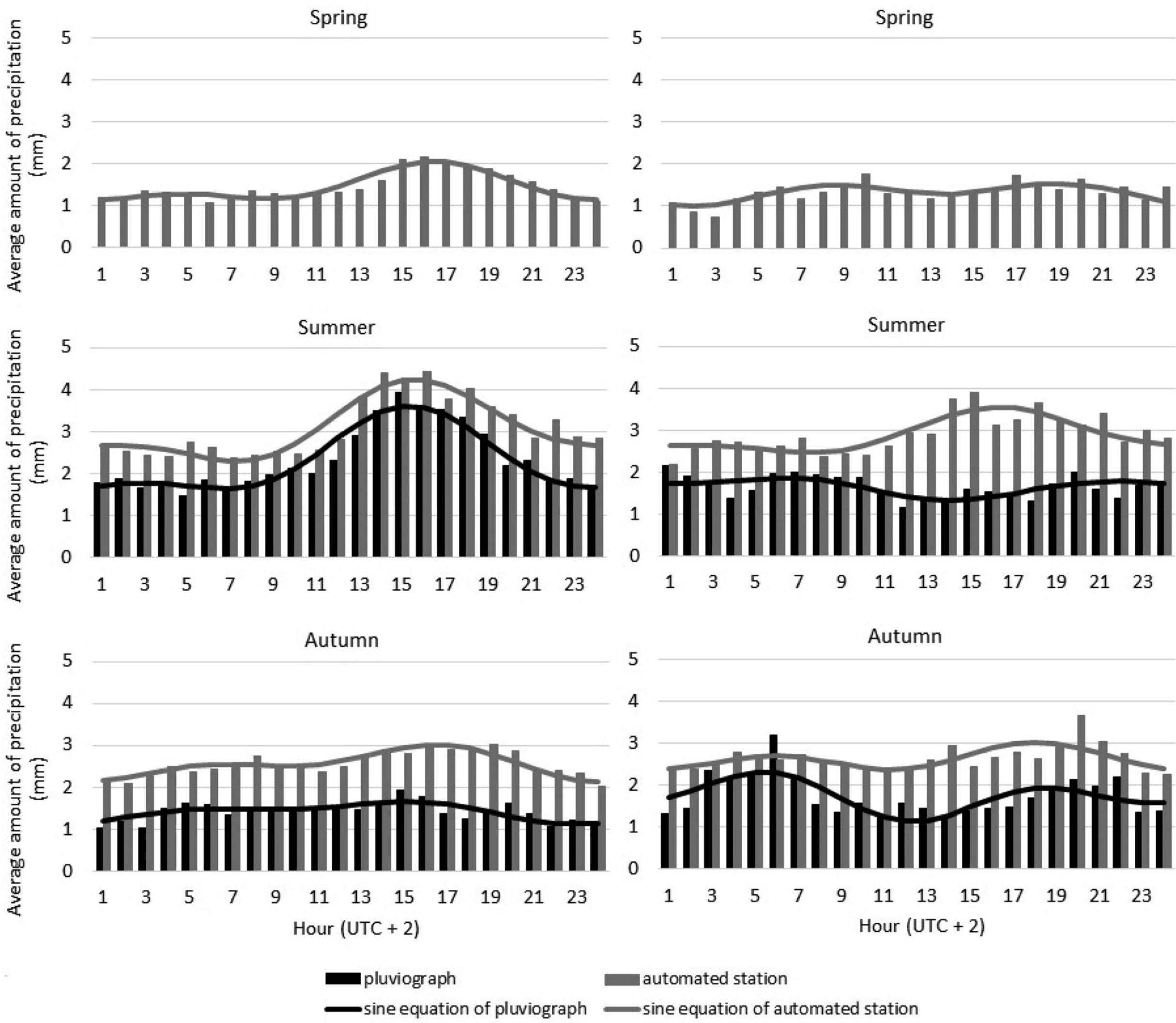

Fig. 4. Mean diurnal distribution of hourly precipitation amounts (mm) in Estonia by seasons at the continental (left panel) and coastal stations (right panel), calculated from the pluviographic records in 1991–2003 (black columns) and from the automated precipitation gauges in 2003–2013 (grey columns). Thick lines present the approximating diurnal curves of precipitation.

The diurnal maxima, especially in the continental stations in spring and summer, were observed in the late afternoon to evening, following the diurnal cycle of air temperature. Convection is weak in April and in October and therefore there are no differences in the daily distribution of precipitation. Two precipitation maxima occur in August: a slightly higher afternoon maximum caused by thermal convection and the secondary maximum at night or in the early morning hours. It is presumably caused by a decrease in the proportion of convective rainfalls and by a cooling effect during the night when the developed lower clouds can also produce precipitation. A similar secondary maximum in the morning hours was registered in Eskdalemuir (Svensson & Jakob 2002) and Krakow (Twardosz 2007).

Diurnal amplitudes of hourly precipitation were higher in spring and summer than in autumn apparently due to the higher position of the sun during a day, which allowed an intense warming of the land surface inducing convective rainfall. In autumn there is too little energy for the formation of many and powerful convective clouds. In spring and autumn, the coastal stations have no clear maximum or minimum, whereas in summer precipitation was slightly higher in the afternoon.

Generally, diurnal amplitudes of hourly precipitation in Estonia were lower at the coastal stations. This has also been mentioned with regard to the tropics

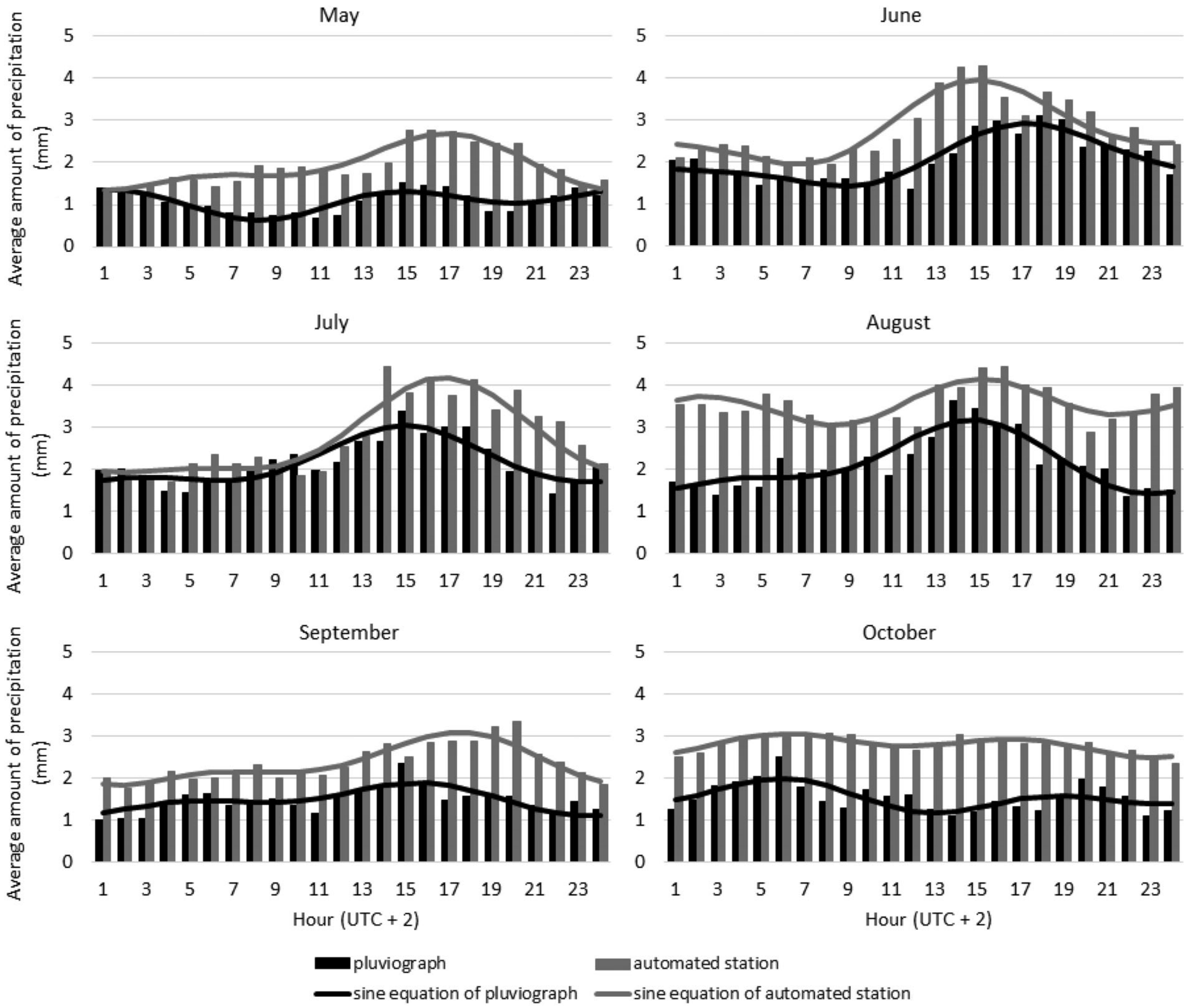

Fig. 5. Mean diurnal distribution of hourly precipitation amounts (mm) in Estonia by months from May to October, calculated from the pluviographic records in 1991–2003 (black columns) and from the automated precipitation gauges in 2003–2013 (grey columns). Thick lines present the approximating diurnal curves of precipitation.

Table 1. Monthly mean daily precipitation amplitudes at the stations during 2003–2013

Station	April	May	June	July	August	September	October
Tallinn	1.0	2.6	3.7	6.3	5.7	2.3	2.2
Jõhvi	1.2	4.3	5.3	4.5	3.6	2.7	2.1
Kunda	1.3	2.7	5.3	4.4	3.1	3.6	2.0
Nigula	0.7	3.2	2.7	4.5	5.2	3.4	2.8
Narva-Jõesuu	1.1	2.7	7.3	4.6	3.8	3.8	2.7
Sõrve	1.3	4.6	4.0	3.5	5.3	1.8	3.2
Tiirikoja	1.0	2.0	6.2	6.1	4.3	3.0	1.9
Tartu	0.9	4.8	5.1	5.8	4.7	2.6	1.4
Valga	1.2	3.5	4.5	6.3	4.1	2.3	2.1
Viljandi	1.2	4.1	3.3	6.2	4.5	3.6	1.7
Virtsu	1.0	3.6	3.1	3.2	3.6	2.6	1.9
Võru	1.2	3.6	5.0	7.1	4.5	2.2	1.7
Väike-Maarja	1.0	4.7	4.4	3.7	5.1	2.7	2.0

(Kikuchi & Wang 2008) and the global extent (Dai 2001). Higher amplitudes tended to occur in southern Estonia in spring, but at the coastal stations in autumn. Southern Estonia warms up earlier in spring but the coastal area is longer warm in autumn due to the influence of the warmer sea. The lowest precipitation amplitudes were typical for April and October. The maximum amplitudes in Estonia can, on average, be found in July when precipitation amounts are the highest and the land surface is the warmest.

CONCLUSIONS

The diurnal distribution of precipitation was different at the continental and coastal stations in Estonia. A clear daily cycle with the maximum in the afternoon and evening (13–19 EET), and minimum in the night and morning time (22–11 EET) was revealed in the continental stations. The maximum corresponds to the maximum intensity of convection rainfall. The precipitation peak is earlier in summer than in spring. The daily distribution of hourly precipitation at the coastal stations is more even and without clear maxima and minima. The daily curve of precipitation is most clearly expressed in summer and also in spring but not in autumn. The diurnal precipitation amplitudes are the highest in midsummer, 4–6 mm. The largest precipitation amplitudes are characteristic of the continental stations during the first part of summer and of the coastal stations in autumn. The spatial distribution of precipitation amplitudes is in consistence with the warming of the sea and land surface. Despite the high randomness of such a phenomenon as precipitation, the diurnal distribution of precipitation is quite stable, which is illustrated by the similarity of the curves in most cases corresponding to the two periods of 1991–2003 and 2003–2013.

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Sademete ööpäevane jaotus Eestis

Regina Alber, Jaak Jaagus ja Peeter Oja

Eesti sisemaa- ja rannikujaamade sademete ööpäevast jaotust uuriti soojal perioodil (aprillist oktoobrini) nii kuude kui ka aastaaegade kaupa. Andmed saadi Riigi Ilmateenistusest. Uuringuperiood jaotati kaheks vastavalt kasutuses olnud sadememõõtjate tüüpidele. Aastate 1991–2003 andmete analüüsiks kasutati 10 jaama pluviograafide ja aastate 2003–2013 uurimiseks 13 automaatjaama tunniandmeid. Sademete ööpäevane käik kirjeldati aastate keskmiste sademete tunnisummadega. Lähendatavateks kõverateks olid teist järku trigonomeetrilised polünoomid, mis leiti vähimruutude meetodil.

Sisemaa- ja rannikujaamade sademete ööpäevased jaotused olid erinevad. Sisemaajaamades esines selge pärastlõunane kuni õhtune maksimum kell 13–19 EET (Eesti kohalik talveaeg) ja öine kuni hommikune miinimum kell 22–11 EET. Suurimad sademete ööpäevased amplituudid (4–6 mm) esinesid kesksuvel. Rannikujaamade sademete ööpäevane käik oli tagasihoidlik: selge maksimumita ja väikeste amplituudidega. Sügisel esines rannikujaamadel siiski kaks eristuvat maksimumi: varahommikul ja õhtul. Sademete ööpäevane jaotumine oli kahel perioodil (1991–2003 ja 2003–2013) mõnel juhul erinev, mis on seletatav sademeid fikseerivate jaamade erineva koosseisuga rannikujaamade korral. Enamikul juhtudel olid aga kahe perioodi andmeid lähendavad kõverad täiesti sarnased, vaatamata asjaolule, et sademed on juhusliku iseloomuga nähtus.