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# Regional variations in hourly and daily totals of global radiation recorded at automatic weather stations in Estonia

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**Abstract.** Daily cycles and totals of global radiation, recorded at the automatic weather stations on the coast of Estonia, were compared with those at Tartu-Tõravere where the quality of data is guaranteed, as this station belongs to the BSRN (Baseline Surface Radiation Network). The time period for comparison was 2005–2010, but due to the extensive gaps (mostly due to low quality) in the data sets, local differences in the radiation regime were estimated on the basis of shorter time periods. On the annual basis, there is more sunshine on the West-Estonian islands and coast and less on the North-Estonian coast. On the monthly basis, an interesting feature may be noticed concerning two sites on the northern coast: in April the daily totals at Harku are larger than at Narva-Jõesuu and in July *vice versa*. The possibilities of reconstruction of the global radiation in coastal sites from Tõravere data are analysed. Linear regression has been checked for afternoon data for two states of cloudiness: clear and overcast. Regression gives good results everywhere when both sites are cloud-free – coefficient of correlation is practically 1.0. In overcast conditions the correlation is over 0.8 for Tiirikoja and Pärnu, over 0.7 for Harku and less for the most distant sites Vilsandi and Narva-Jõesuu. This might help marine scientists to derive estimates of solar radiation at the seaside from Tõravere data. The first analysis of new data from automatic weather stations shows that the quality of data needs attention and situation in the stations needs improvement.

**Key words:** solar radiation, global radiation, daily totals, hourly fluxes, automatic weather stations.

## 1. INTRODUCTION

It is well known that diurnal variation of the surface solar radiation fluxes causes diurnal variation in the sea surface temperature and upper layer vertical stratification [1]. The related deepening/shoaling of the upper mixed layer on the daily scale will also affect the biological and material circulation processes. Marine Systems Institute performs high resolution measurements of temperature, salinity and chlorophyll *a* fluorescence in the Gulf of Finland. Two transects are recorded per day between Tallinn and Helsinki by means of the Ferrybox system [2]. An autonomous buoy profiler, deployed off the Tallinn Bay, records vertical profiles every third hour [3]. To explain the observed diurnal cycles in the surface layer temperature, vertical stratification and chlorophyll *a* fluorescence distribution, estimation of surface solar radiation fluxes (including diurnal cycle) should be available. It has not been verified yet whether the estimates, based on model outputs, could be applied for this purpose, especially in cloudy conditions.

Estimates of the surface solar radiation fluxes over the sea are important for oceanographic applications in both long-term (from a month to a season) and short-term (diurnal) scales. Modelling of the development of vertical stratification in an estuary needs (among other parameters) knowledge on heat fluxes at the sea surface [4]. The long-term changes, e.g., in the sea surface temperature, are usually correlated with the radiation or sun hours data from coastal stations [5]. A similar approach was applied in a study of inter-annual variation of the late-summer cyanobacteria blooms in the Gulf of Finland, where the radiation data recorded at Tartu-Tõravere meteorology station were used to link the observed bloom intensities to the changes in photosynthetically active radiation [6]. Tõravere is situated approximately 200 km from the Estonian coastline, but up to recent times it was the best site in Estonia, where all components of the radiation budget are recorded. The other site was Tiirikoja that is situated somewhat closer to the Gulf of Finland, but Tartu-Tõravere was preferred as it is a BSRN station where the quality of data is guaranteed [7].

Since 2003, Estonia has step by step replaced traditional measurement routine at the meteorological stations by automatic equipment. Automatic weather stations offer new possibilities to estimate solar radiation parameters by means of certain models that use meteorological information (e.g. [8]). On the other hand, many stations have been complemented with actinometric equipment that measure directly solar radiation. In Estonia, pyranometers have been installed at several coastal meteorological stations that should offer a possibility to get better input to oceanographic models that need radiation data.

It is widely known that conditions for radiation measurements are extremely strict. They need open horizon (especially in winter when the sun is low), periodic calibration of pyranometers, regular control of the condition of the receivers, etc.). Unfortunately these requirements are in many cases not met at Estonian meteorological stations (except Tõravere).

The goal of the present paper is to investigate relationships between global radiation at the coastal stations and Tõravere. First, this draws attention to the problems of radiation measurements at the automatic weather stations and, second, this might lead to the possibilities of reconstruction coastal global radiation from Tõravere data in case no measurements are carried out at the site of interest. The stress is put on daily and hourly totals. Due to the short observation period (2005–2010) and gaps in data series, it was not possible to derive direct climatological estimates. On the other hand, it was still possible to find common periods of 2–3 years when data were available for all or several observation sites. This gave us a possibility to give a rough estimate of the spatio-temporal distribution of the solar radiation characteristics.

Approximate information on the mean distribution of annual totals of global radiation over the territory of Estonia is presented in the Handbook of Estonian Solar Radiation Climate [9], where the long-term average distribution is calculated on the basis of mean cloudiness and albedo values at 31 meteorological stations. Later we compare our estimates with those described in [9].

## 2. MEASUREMENT SITES AND EQUIPMENT

In the network of Estonian Weather Service there are eight meteorological stations, where global radiation is measured (Fig. 1, Table 1). Radiation measurements at Pakri were terminated in 2009. At Haapsalu and Roomassaare the automatic stations were installed somewhat later than others, in 2007 and 2008, respectively. In the present study, radiation data from six stations during 2005–2010 were used, stations with shorter observation period were left out.

To measure the downward and upward fluxes of solar radiation, Kipp & Zonen pyranometers CM11 and CM21 are used. All stations with the exception of Tartu-Tõravere provide hourly mean radiation flux densities (W/m$^2$). At Tartu-Tõravere one minute mean values are gathered and processed.

The measurements of the openness of the horizon were carried out at all stations in 2001 [9]. Since then the forest around Tiirikoja has grown and shades the instruments even more. The estimates for Pärnu meteorological station are


**Fig. 1.** Location of the meteorological stations where solar radiation is measured.

**Table 1.** Station positions and openness of the horizon

| Station | Latitude | Longitude | Altitude, m | Approximate elevation of objects above the horizon, degrees | | | |
|---|---|---|---|---|---|---|---|
| | | | | N | E | S | W |
| Vilsandi | 58°22′58″ | 21°48′51″ | 6 | 0 | 1 | 1 | 6 |
| Pärnu | 58°25′11″ | 24°28′11″ | 12 | | | | |
| Harku | 59°23′53″ | 24°36′10″ | 33 | 3 | 4 | 2 | 3 |
| Narva-Jõesuu | 59°27′47″ | 28°02′44″ | 6 | 0 | 10 | 12 | 10 |
| Tiirikoja | 58°51′55″ | 26°57′08″ | 32 | 10 | 4 | 5 | 10 |
| Tõravere | 58°15′51″ | 26°27′40″ | 70 | 3 | 5 | 2 | 2 |

not available, as the station was relocated in 2003. It is situated at the airport and according to visual estimates the horizon is not shaded considerably. From Table 1 it can be concluded that winter data from Tiirikoja and Narva-Jõesuu may be underestimated.

The radiation equipment is calibrated regularly at Tõravere. At Tiirikoja one calibration was carried out, on 28 May 2008. No changes in sensibility were detected. The pyranometers at other stations are not calibrated during the period under consideration.

The pyranometers are ventilated to prevent dew and frost at Tõravere, Harku and Pärnu. Thermal offset corrections are applied in measurements at Tõravere. Special instructions are given to the personnel of meteorological stations to check the condition of the receivers [10]. This should avoid the situations when the pyranometer is covered with snow or ice, etc.

The data of Tõravere passes strict quality control before it is transmitted to the archives of EMHI (Estonian Meteorological and Hydrological Institute), BSRN and WRDC (World Radiation Data Centre). Datasets from other stations are not checked so thoroughly – before sending to the archives, only these values are removed that are obviously erroneous.

## 3. DATA

The whole dataset (except data from Tartu-Tõravere) contained a number of missing values. Major causes of missing values at daytime were changes in the sensor configuration and temporary interruptions of the automatic stations work.

Nighttime values contained several types of anomalies – there were missing, negative and small positive values. Negative and small positive values are related to the zero offset of the sensor [11]. This is a widely recognized problem of pyranometers that may lead to discrepancies between modelled and measured solar radiation [12]. Thermal offset corrections are applied at the Tõravere BSRN station.

The initial data from Harku station contained the greatest number of missing values. The reason here was elimination of negative values during the data transmission from automatic station to the archive. Mostly data were missing during nighttime when there is no solar radiation, but often missing data were shown also for daytime hours, especially for morning and evening.

At Vilsandi, the data from 30 July 2008 to 30 June 2010 were obviously erroneous. Due to incorrect sensor installation at the station, radiation values never exceeded 640 W/m$^2$ during the period.

## 4. REGIONAL DISTRIBUTION OF DAILY TOTALS

To estimate differences between radiation regime at Tõravere and coastal stations, daily totals were calculated from “cleaned” data sets. “Cleaning” was carried out separately for every coastal station depending on the detected problems. At all stations the days were left out when at least one hourly measurement was missing. At Vilsandi the period from 30 July 2008 to 30 June 2010 (when sensor problems were detected) was left out.

At Pärnu, two periods when solar radiation was systematically shown at night were left out (20 February to 2 November 2008 and 30 January to 14 September 2009). Additional analysis showed that nighttime recordings formed only 0.2% of the long-term average daily total, but it could be suspected that the sensor or recording regime was also biased. At Harku the zero and missing data were distinguished by means of sunset and sunrise times and records with missing data were left out.

At the coastal stations there exist several cases when in winter the recorded daily total was 0. Keeping in mind that the absolute minimum of the daily total during the period under consideration at Tõravere was 0.13 MJ/m$^2$, these cases were checked by means of historical atmospheric phenomena records that showed fog, rain or snowfall. Therefore, these results should be considered realistic and not be attributed to some mistake in the measurement routine.

As seen from the above, different periods were left out at different stations. This means that the comparison of the radiation regime at different stations could be carried out for shorter periods that are common to all (or at least to most of the) stations. For different months these periods were different (Fig. 2). In October, the common period for all stations was less than two months. Therefore only four stations are considered where the common period was longer. In January, Tiirikoja and Narva-Jõesuu were left out due to the restricted openness of the horizon that might introduce systematic errors.

The following (approximate) features of the spatio-temporal distribution of solar radiation can be seen.

– In April there is more sunshine in West-Estonia than in East-Estonia.
– In July the sunniest places are seaside resorts Pärnu and Narva-Jõesuu as well as the westernmost island of Vilsandi. Harku meteorological station is

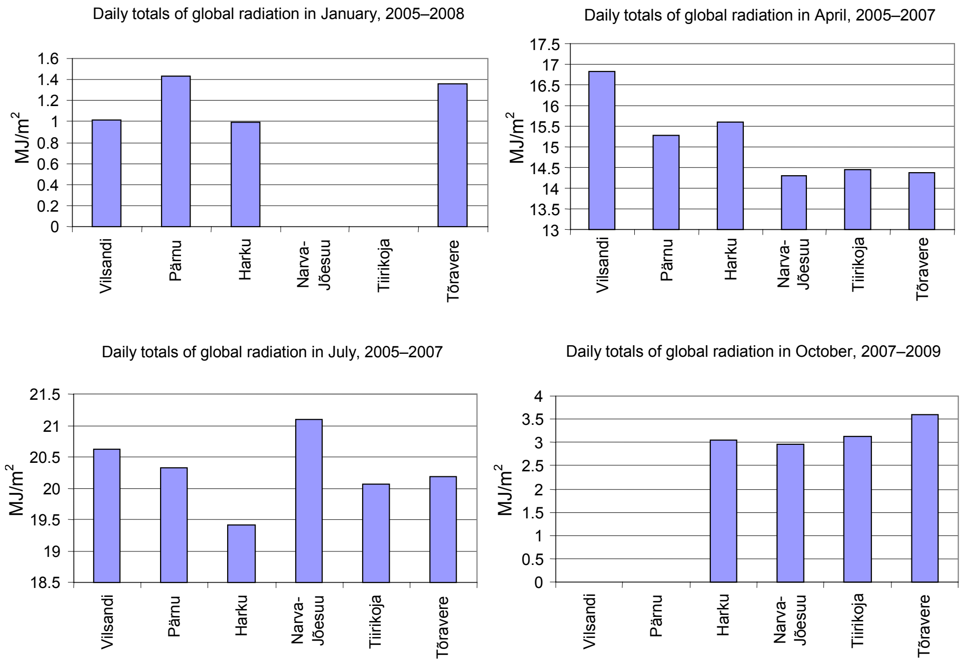


**Fig. 2.** Monthly average daily totals of global radiation.

situated at least 5 km from the sea on a cliff. Here complicated orography and the neighbourhood of a large city Tallinn affect the meteorological regime.

- An interesting feature can be noted concerning two sites on the northern coast: there is more sunshine at Harku in April and at Narva-Jõesuu in July.
- In October the radiation conditions in North-Estonia and East-Estonia are similar, most probably due to extensive homogeneous cloud cover.

To get an overview on the distribution of solar radiation over the Estonian territory, a common period of 2005–2007 (with missing data from October 2005 to March 2006, and August 2007) could be found for which annual average daily totals were calculated. Figure 3 shows that the amount of solar radiation at Pärnu and Vilsandi exceeds distinctly that on the northern coast and inland. This is partly due to astronomical factors: in January the TOA (Top of the Atmosphere) radiation on the northern coast forms approximately 86% of that above Tõravere. In October this percentage is around 94. The annual averages at Tiirikoja and Narva-Jõesuu might be underestimated, as winter data are included in annual average calculations. On the other hand, in case only the period from March to November is considered, Harku, Tiirikoja and Narva-Jõesuu show similar values (not shown in the present paper).

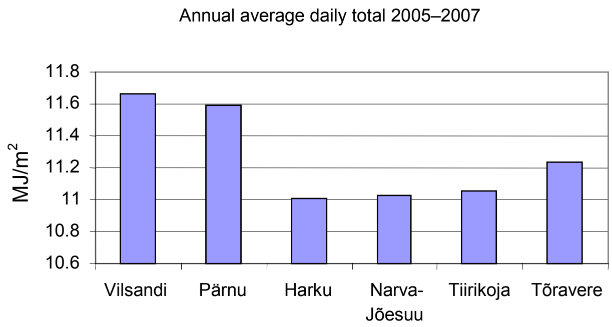


**Fig. 3.** Annual average daily totals of global radiation.

## 5. DIURNAL CYCLE OF HOURLY TOTALS

The same data from common time periods were used to calculate daily cycles of global radiation. Figure 4 shows results for April and July when a common three-year period could be found for all stations. Figure 4 also shows that differences between radiation conditions at different stations are larger in spring than in summer.

At Tõravere, the maximum of the solar radiation is measured around local noon (10:00 GMT denotes the hour from 9:00 to 10:00 GMT or from 11:00 to 12:00 winter EET) whereas solar radiation maximum at Vilsandi is about an hour later. The solar time difference between these stations is approximately 19 min. Therefore, this time lag must be due to meteorological conditions.

In July the differences between stations are the largest around 12:00 GMT, i.e., during the afternoon hours. Most probably these differences stem from the cloudiness that is more extensive at the inland sites.

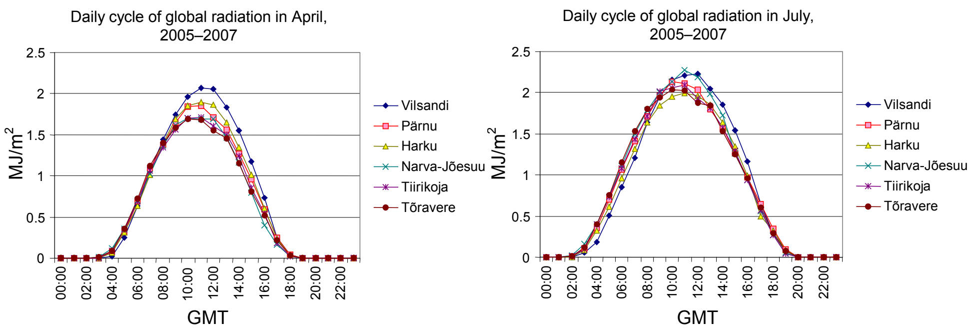


**Fig. 4.** Daily cycles of global radiation in April and July.

## 6. CORRELATION BETWEEN GLOBAL RADIATION AT THE COASTAL STATIONS AND TÕRAVERE

To estimate global radiation at the coastal stations from Tõravere data, respective regression equations can be calculated for each station. For this purpose, additional data on cloud cover was used and cases were chosen when the cloudiness conditions were similar at both stations. Cloudiness is recorded with 3-h intervals. Therefore, we chose for comparison the afternoon hour of 11:00–12:00 GMT (13:00–14:00 EET). Unfortunately, since the 1st of May 2009, clouds are recorded at Narva-Jõesuu and Tiirikoja only at 06:00 and 18:00 GMT.

Table 2 shows that hourly totals at Tiirikoja and Pärnu can be restored from the Tõravere data rather well. The square of the correlation coefficient (coefficient of determination) is 0.68 for Tiirikoja and 0.65 for Pärnu. This means that 65%–68% of the variability of the hourly totals of global radiation at these sites is determined by the variability of the fluxes at Tõravere. Correlation is low for Vilsandi and Narva-Jõesuu, showing that approximately 40% of the variability can be ascribed to the variability at Tõravere. Figure 5 presents two examples of such regression, demonstrating the best and the worst correlation.

In case only clear conditions were chosen (actually coverage up to 1/10), correlation is perfect as expected. Figure 6 shows that even for Vilsandi, where the coefficient of correlation in overcast conditions was the lowest, global radiation can be well derived from Tõravere data.

**Table 2.** Correlation and regression coefficients for reconstruction of afternoon (11:00–12:00 GMT) hourly totals at coastal stations from Tõravere data for overcast conditions

| | Coefficient of correlation | Intercept, MJ/m$^2$ | Slope |
|---|---|---|---|
| Vilsandi | 0.61 | 0.094 | 0.73 |
| Pärnu | 0.81 | 0.037 | 0.81 |
| Harku | 0.74 | 0.055 | 0.70 |
| Narva-Jõesuu | 0.65 | 0.158 | 0.65 |
| Tiirikoja | 0.82 | 0.061 | 0.83 |

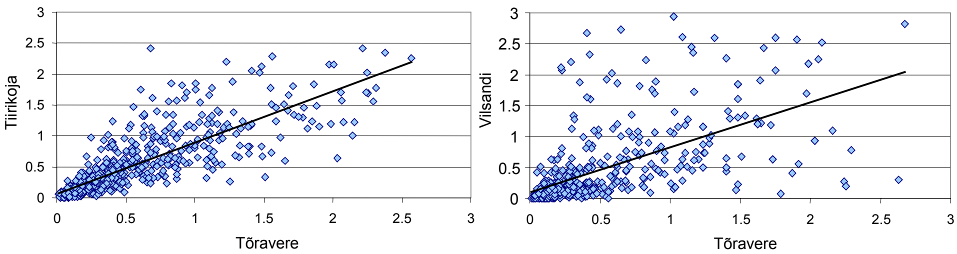


**Fig. 5.** Regression lines between afternoon (11:00–12:00 GMT) hourly totals (MJ/m$^2$) at two coastal stations and Tõravere in overcast conditions.

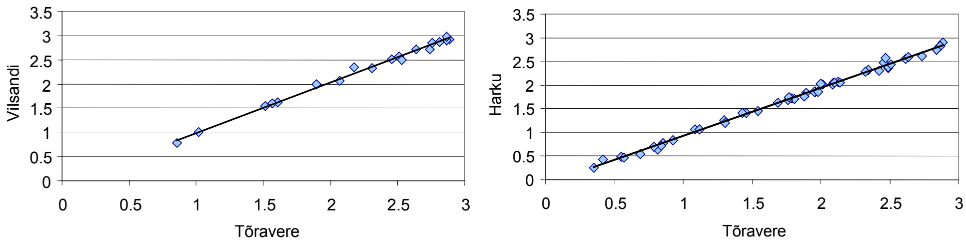


**Fig. 6.** Regression lines between afternoon (11:00–12:00 GMT) hourly totals ($MJ/m^2$) at two coastal stations and Tõravere in clear conditions.

## 7. CONCLUSIONS

The results of the present paper can be divided into two groups.

First, comparison of the simultaneous radiation measurements at coastal stations and Tõravere enables one to estimate the approximate solar radiation regime in different regions. Another approximate description of the radiation climatology is shown in [9], where global radiation is estimated on the basis of mean cloudiness and albedo values using the formula of Averkiev [13]. The authors of [9] confirm that annual totals, got by such indirect method, describe the radiation climate roughly. Our estimates are based on direct measurements. Although there are problems with the openness of the horizon and a lot of data were labelled as not reliable, the general features of the radiation regime are similar on the annual basis: there is more sunshine on the West-Estonian islands and West-Estonian coast and less on the North-Estonian coast. Although Tõravere is an inland station, it seems to be a favorable site for solar radiation [14]. Handbook [9] gives also a possibility to compare calculated and measured radiation: at Kuusiku direct measurements were carried out during 1954–1963 and at Tooma 1956–1963. It seems that calculated annual totals of global radiation are underestimated by 1% at Kuusiku and 4% at Tooma.

In the present paper also seasonal differences of global radiation are described. Here an interesting feature may be noticed concerning two sites on the northern coast: in April the daily totals at Harku are larger than at Narva-Jõesuu, and in July *vice versa*. This phenomenon is worth further analysis, as the comparison is carried out on a 3-month basis only.

As a result, in case the measurement conditions at the coastal stations are improved, direct measurements give the possibility to describe the spatio-temporal distribution of solar radiation more precisely.

Second, application of Tõravere radiation data by marine investigations is discussed. It can be said that direct transfer of inland data to marine conditions is not recommended, as the radiation regimes differ significantly. On the other hand, in case there are no measurements carried out at the seaside, it should be possible to reconstruct global radiation at coastal sites using linear regression. This has been checked for afternoon for two states of cloudiness: clear and overcast. Regression gives good results everywhere when both sites are cloud-free – coefficient of correlation is practically 1.0. In overcast conditions the correlation is over 0.8 for Tiirikoja and Pärnu, over 0.7 for Harku and less for the most distant sites Vilsandi and Narva-Jõesuu.

And last, but not least: the quality of global radiation data from automatic weather stations should be carefully checked as there are many factors that might contaminate the measurements. From the above it follows that periodical checking of all sensors is necessary and attention should be drawn to the maintenance of the equipment. If possible, also the quality control of data should be introduced.


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## Eesti automaatsetes ilmajaamades mõõdetud summaarse kiirguse tunni- ja päevasummade regionaalne jaotus

Kai Rosin ja Sirje Keevallik

Eesti rannikul asuvates automaatsetes ilmajaamades mõõdetud summaarse kiirguse päevast käiku ja päevasummasid on võrreldud mõõtmistega Tartu-Tõravere ilmajaamas, kus andmete kvaliteet on garanteeritud, sest jaam kuulub rahvusvahelisse BSRN-i võrku. Ajaperiood oli 2005–2010, ent paljude (enamasti kahtlase kvaliteedi pärast) eemaldatud andmete tõttu on erinevusi eri paikade vahel hinnatud lühemate ajavahemike alusel. Aasta lõikes on päikesekiirguse päevasummad suuremad Lääne-Eesti saartel ja rannikul ning väiksemad Põhja-Eestis. Kuude lõikes võib täheldada huvitavat olukorda põhjarannikul: aprillis on päikesekiirgust Harkus rohkem kui Narva-Jõesuus, juulis aga vastupidi. Hinnati võimalust tuletada rannaäärse summaarse kiirguse väärtused Tõravere andmetest. Selleks leiti lineaarsed regressioonid pärastlõunase tunni (13.00–14.00, Ida-Euroopa aeg) summade vahel. Selge taeva puhul korreleeruvad tulemused ideaalselt. Lauspilvisuse puhul on regressiooni korrelatsioonikordaja Tiirikoja ja Pärnu jaoks 0,8, Harku jaoks üle 0,7, ent Vilsandi ning Narva-Jõesuu jaoks ligikaudu 0,4. Regressioonide parameetrid võimaldavad mereuuringute tarbeks vajalikke kiirgusandmeid tuletada Tõravere mõõtmistest. Automaatjaamade andmete esmane analüüs näitas, et andmetesse tuleb suhtuda kriitiliselt ja mõõtmistingimusi jaamades on vaja parandada.