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Solar Radiation and Wind as Agents of the Formation of the Radiation Regime in Water Bodies

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Declaration:

Hereby I declare that this doctoral dissertation, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

/Kai Rosin/

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Päikesekiirgus ja tuul kui kiirgusvälja kujunemise mõjurid veekogudes

KAI ROSIN

TTÜ KIRJASTUS

CONTENTS

List of original publications

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals.

I. Keevallik, S., Loitjärv, K. 2010. Solar radiation at the surface in the Baltic Proper. Oceanologia, 52(4), 583-597.

II. Rosin, K., Keevallik, S. 2012. Regional variations in hourly and daily totals of global radiation recorded at automatic weather stations in Estonia. Estonian Journal of Engineering, 18(1), 76-86.

III. Erm, A., Alari, V., Buschmann, F., Kõuts, T., Raudsepp, U., Loitjärv, K. 2010. Near bottom velocity and turbidity measurements in coastal waters of NW Estonia. In: IEEE-Inst Electrical Electronics Engineers Inc, 2010: 4th IEES/OES Baltic Symposium, Riga, Latvia, August 25-27, 2010, 1-8.

In Appendix A, copies of the papers are included.

Author's contribution

I. The author was responsible for data processing and analysis, contributed to the writing of the manuscript and presented the results at an international conference.

II. The author was responsible for data analysis and writing of the manuscript and presented the results at an international conference.

III. The author was responsible for the surface wind data analysis.

Approbations of the results

The results have been presented in the following international conferences:

1. 4th IEES/OES Baltic Symposium, Riga, Latvia, 25-27 August 2010: oral presentation – Near bottom velocity and turbidity measurements in coastal waters of NW Estonia (in cooperation with A. Erm, V. Alari, F. Buschmann, T. Kõuts, U. Raudsepp).

2. EMS Annual Meeting & European Conference on Applied Climatology (ECAC), Zürich, Switzerland, 12-17 September 2010: poster presentation – Solar radiation at the surface around the Baltic Proper (in cooperation with S. Keevallik).

3. The 8th Baltic Sea Science Congress, St. Petersburg, Russia, 22-26 August 2011: oral presentation – Evaluation of solar radiation in the coastal area of the Baltic Proper (in cooperation with E. Juust).

4. The 8th Baltic Sea Science Congress, St. Petersburg, Russia, 22-26 August 2011: oral presentation – Near bottom dynamics measurements in coastal waters of NW Estonia (in cooperation with A. Erm, F. Buschmann, V. Alari, J. Rebane, M. Listak).

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1. INTRODUCTION

According to the World Meteorological Organization (WMO, 2008) the various fluxes of radiation to and from the Earth's surface are among the most important variables in the heat economy of the Earth. The climate system converts solar radiation into heat, water vapor and the circulations of the atmosphere and ocean. The atmospheric circulation redistributes the water vapor and converts some of it into clouds and precipitation. The solar forcing varies strongly on both daily and seasonal timescales. To understand how the radiative fluxes are affected by variations in the atmospheric water vapor and clouds and how these variations interact with the atmospheric and oceanic circulations, it is important to assess the radiative flux variations on scales from diurnal and mesoscale to interannual and planetary scale (Zhang, 2004).

Solar radiation data are not only of particular importance for the assessment of the radiative forcing of the climate system, but also necessary as the input parameter for agricultural, hydrological, biophysical, environmental and oceanographic models and applications. Reliable solar radiation data has become essential for architectural design as the utilization of solar energy technologies such as photovoltaic and solar thermal power plants, passive solar heating/cooling systems and daylighting systems in buildings is increased (Journée, 2012). In this case the availability of solar radiation data, its variability and the uncertainty of the monthly means of the global radiation should be taken into account to evaluate the cost efficiency of the system (e.g. Colle, 2001).

Solar radiation is crucial to the formation of the marine environment. Besides the heating of waters it supplies the energy that drives their stratification and movement, their evaporation, the warming of the atmosphere and the photo-oxidation of marine pollutants (Dera and Woźniak, 2010).

1.1. Underwater radiation field

The underwater solar radiation field is of interest in investigating radiative, thermal, biological and dynamic processes in water bodies. Solar radiation penetrating water diminishes with depth due to a change in the energy spectrum as a result of absorption and scattering caused by water and its various components. Light provides the energy that steers the growth of phytoplankton and other species and organisms in the water column.

When passing through the atmosphere the spectrum of solar radiation is modified by absorption and scattering. At water surfaces only a small amount (about 10% in case of a smooth water surface) of the incoming sunlight is reflected back and the rest penetrates into the water. Within the water body the radiation is again absorbed and scattered, the processes depend strongly on the wavelength based on the properties of the water itself and optically active substances in there. Part of the backscattering radiation penetrates the water surface from below back to the atmosphere. The radiation reflected from the water surface and backscattered from the water column and the atmosphere is of practical significance in the satellite, air- or shipborne monitoring of the sea (Arst, 2003; Dera and Woźniak, 2010). The underwater solar radiation field and the spectral composition of light are also the indicators of water pollution (Herlevi, 2002; Arst 2003).

The spectral range of solar radiation from 400 to 700 nm to which human eye is sensitive is called light. A similar waveband corresponds with the solar energy which drives photosynthesis by phytoplankton and is called photosynthetically active radiation (PAR). The supply of PAR for growth of phytoplankton and therefore primary production in water bodies depends on the input of solar radiation at the surface and its reduction by optically active compounds through absorption and scattering. The intensity and spectral quality of the light in a water body vary markedly with depth. Within the underwater environment light availability is of major importance in determining the quantity and species of plants growing there (Kirk, 1994).

The underwater light field is determined by the incident light, the state of the water body, the bottom conditions and the optical properties of the water itself and its constituents. According to Mobley (1994) the large-scale optical properties of water can be divided into two classes: inherent and apparent. The inherent optical properties depend only upon the water and its constituents (the type concentrations of optically active substances) and not on the ambient light field. The fundamental inherent optical properties are the absorption coefficient, the scattering coefficient and the volume scattering function. The apparent optical properties depend both on the medium (the inherent optical properties) and on the directional structure of the ambient light field, these are the irradiance reflectance, the average cosines, and the various diffuse attenuation coefficients.

The water properties of the open ocean vary mainly due to the phytoplankton concentration in the water. In coastal waters, marginal seas, lakes and rivers other optically active constituents, such as suspended matter, colored dissolved organic matter, also known as the yellow substance, influence the water properties as well (Arst, 2003; Sipelgas *et al.*, 2004).

Eutrophication and pollution of the water may significantly change the amount and spectral composition of solar radiation penetrating the water body. The color and transparency of coastal and inland waters may be affected by mineral particles originated from land and transported by rivers and wind or resuspended particles from the bottom. The bottom sediment resuspension is strongly influenced by wave-current motion. Both wind- and ship-generated waves cause changes of the optical properties of the sea water and the underwater light regime in coastal areas (Erm *et al.*, 2011). Long surface waves enable light to penetrate deeper into water which is favorable for phytoplankton and biogeochemical processes. It is shown that even gravity waves and swell influence the light availability both at shallow and high waters (Hieronymi and Macke, 2010).

The underwater light field and its fluctuations depend on the sun's position, the wavelength of light, cloud conditions, scattering properties of water and dissolved matter as well as the water depth. The shape of the water surface determines the light intensity distribution in the water column. The driving force of fluctuations in underwater light field is the focusing-defocusing effect by surface waves. Besides wind sea waves all superposed single waves (capillary as well as swell waves) cause specific spatio-temporal fluctuations of the light regime.

For a short time period the focusing effect of larger wind sea waves makes it possible that light can penetrate deeper and with concentrated intensity into the water body. Strongest variations in radiation field take place in shallow clear waters under clear skies and moderate wind conditions (with wind speeds between 1 m/s and 5 m/s) (Gernez and Antoine, 2009; Hieronymi and Macke, 2010).

On the other hand, optically active compounds transported by wind waves are the factors that cause turbidity in shallow waters. Inland and coastal waters may also be affected by anthropogenic influences (e.g. eutrophication, soil erosion, dredging operations, shipping) (Erm *et al.*, 2008). Increases in turbidity produced by these activities can damage ecosystem climates (Arst, 2011).

Continuous monitoring of the underwater radiation field is necessary as the episodic radiation measurements are often not sufficient for investigating variability of the light regime and bio-optical processes in water. Satellites provide measurement data with high spatial and temporal resolution but this data is not suitable for a detailed description of the underwater light regime. Besides remote sensing techniques other methods can be used to monitor the underwater light regime (Arst *et al.*, 1997; Arst, 2003). The spatio-temporal and spectral variations of the underwater solar radiation can be measured *in situ* using shipborne devices (Sipelgas *et al.*, 2004), by means of sampling stations (Kauer *et al.*, 2010; Paavel *et al.*, 2011) or buoy stations using sensors installed at various depths in the water body (Devlin *et al.*, 2009).

The underwater radiation field can also be calculated using data for incident solar radiation and optical properties of the water body (Arst *et al.*, 1997; Arst, 2003). For this purpose, at least two external forcings should be known – solar radiation on the sea surface and turbidity of the water. The latter is considerably affected by the wind field.

1.2. Estimation of the off-shore radiation field

To assess the amount of radiation energy penetrating the water, one has to know its amount at the surface of the water body. This depends on astronomical factors and the ones that are related to the local atmospheric conditions. Necessary information to determine the off-shore radiation field relies on observational data from ground and ocean stations. Occasionally the shipborne measurements are performed in the open see.

Despite of the importance of solar radiation measurements, the information is not easily available due to cost, maintenance, and strict calibration requirements of the measuring equipment. In case of shipborne measurements the impact of ship oscillations on the accuracy of radiation flux measurements has to be taken into consideration (Sinitzyn, 2009). Since the measurements are often sparse at many locations, the availability of observed solar radiation data is spatially and temporally inadequate for many applications.

Several empirical models have been developed to estimate off-shore solar radiation based on other, more commonly observed meteorological and astronomical variables. The most widely used parameter for estimating global solar radiation is sunshine duration. The predictive efficiencies of various sunshine-based regression models have been evaluated by Bakirci (2009). Improved model with multiple variables embedded has been presented by Belcher and DeGaetano (2006). A semi-empirical model for computing the radiation characteristics at the surface of the Baltic Proper is described by Rozwadowska and Isemer (1998). A more detailed model for solar energy input at the sea surface has been suggested by Krezel (1997). Several short-wave downwelling radiative flux parameterizations for the Baltic Sea region are given by Niemelä *et al.* (2001). However, comparison of modeled values of solar radiation with *in situ* measurements obtained from meteorological land stations (Krezel, 1997; Niemelä *et al.*, 2001; Belcher and DeGaetano, 2007; Bakirci, 2009) or those made on board of ships (Rozwadowska and Isemer, 1998) shows that for short time periods the modeled totals can significantly differ from the real values. Cloudiness is the main factor responsible for these uncertainties. The main limitation on utilization of empirical models is the site-dependence of model parameters.

To achieve better spatial coverage of estimated surface solar radiation fluxes outputs of high-resolution mesoscale and local scale numerical weather prediction (NWP) models can be used. Once again the accuracy of the model results should be checked for surface level measurements. The errors of model predicted solar radiation are often associated with the cloudiness and presence of aerosols (Prabha and Hoogenboom, 2010).

For climate monitoring and climate analysis tasks the data from re-analysis (based on general circulation model output) is valuable as well (Walsh *et al.*, 2008; Träger-Chatterjee *et al.*, 2010).

Satellite data allow the retrieval of the surface radiation budget with high spatial and temporal resolution as well as a large areal coverage. They offer an alternative to ground based measurements, especially in regions with sparse measurement points (e.g. ocean). One of the components produced from satellite images is the surface solar or horizontal global irradiance.

The most variable parameter that disturbs determination of surface solar radiation fluxes from satellite data is cloud cover. The problem has been actual for at least two decades (Berger, 1995; Keevallik and Kärner, 1999; Karlsson, 2001). Development of satellite technique enables one step by step to enhance also the cloud detection and classification techniques (Berger, 2001, Dybbroe *et al*., 2005). Adding land surface properties to cloud classification enables one to calculate surface radiant flux densities for all flux components (Berger, 2002). On the other hand, satellite derivations are rather site-specific and require careful evaluation by means of ground truth data.

Journée and Bertrand (2010) have demonstrated the benefit of merging ground-measured and satellite derived solar radiation data over a mid-latitude region with rather flat orography. Dürr and Zelenka (2009) presented an upgraded algorithm of surface global irradiance retrieval scheme for satellite data in mountainous regions. The sensitivity analysis shows that higher temporal resolution of satellite data improves the accuracy of daily surface solar irradiance estimates (Journée *et al*., 2012; Dürr *et al.,* 2010). Several authors have used measurement data from Baseline Surface Radiation Network (BSRN) to validate the radiation products of satellites. The comparison of data from two satellite generations (and channels) with data from 10 BSRN stations located in different sites has performed by Posselt *et al*. (2011). Müller et al. (2009) have compared the satellite based radiation fluxes with data from the BSRN over Europe and Africa, Ineichen *et al.* (2009) with data from BSRN and the International Daylight Measurement Programme (IDMP) covering Europe. Similar comparisons based on ship observations over ocean areas have been performed by Behr *et al.* (2009) and Macke *et al.* (2010).

A rough overview of the average radiation field over the water body is obtainable by extrapolation the coastal actinometric measurements offshore. Long-term average surface global radiation for the Baltic Sea Basin has been estimated on the basis of three inland actinometric stations located in Finland, Estonia and Germany (BACC, 2008). The monograph also shows long-term monthly averages based on parameterizations applied to meteorological observations made on board voluntary observing ships during 1980–1992 (Rozwadowska and Isemer, 1998). It is shown that the average annual course of the global radiation obtained from this parameterization differs significantly from actinometric measurements at coastal stations. The main factors that cause such difference are astronomic conditions and variations in cloud cover, which during spring and summer is consistently less under open-sea conditions (Isemer and Rozwadowska, 1999, Leppäranta and Myrberg, 2009). According to BACC (2008) the difference between actinometric measurements at Tartu-Tõravere and the offshore parameterization is the least in comparison with the measurements at Lindenberg (Germany) and Sodankylä (Finland). Tartu-Tõravere represents the longest, most complete and thoroughly analyzed dataset of surface radiation measurements in Estonia. It is also one of the BSRN stations (Russak and Kallis, 2003; Eerme *et al.,* 2010).

1.3. Estimation of the off-shore wind field

The water turbidity is mainly affected by waves. It is generally assumed that the wave activity is concentrated in the vicinity of the coastlines and does not affect deeper parts of the sea. Studies indicate that waves of different origin create sediment resuspension (and thus also transport) in quite deep parts of the coastal zone. This transport may play an important role in the overall pattern of coastal processes and water transparency. To model real sediment transport, the knowledge on different types of parameters is needed: the form and morphology of the sea bed, the properties of moving sediments (size and shape, density and distribution by these parameters) and dominating waves and wakes (depending on the winds and also on the ship traffic in some regions).

Waves are tightly related to the wind field. To estimate wind parameters valid in various spatial scales and precise enough for different applications, it is necessary to exclude as much as possible the influence of local sheltering obstacles, land surface roughness, orography of the surrounding area etc. For this purpose, special computer programs and statistical methods have been elaborated (Troen and Petersen, 1989; Kull, 1999).

In case we would like to use the wind data measured at coastal stations in certain local conditions in order to characterize winds at the open sea, comparisons of on- and offshore data should be made that in some cases enable us to get regression formulae describing the relationships (Launiainen and Saarinen, 1982; Niros *et al.*, 2002; Keevallik, 2003a).

The WMO has elaborated a general system of coefficients to transfer the results of the coastal wind speed measurements to open-sea ones (WMO, 2001). However, no correction is proposed within this system for the directional wind distribution that may lead to serious discrepancies. Earlier comparisons and studies have shown that the wind roses based on measurements at Tallinn-Harku aerological station (Estonia) do not represent adequately the open-sea wind situation over the Tallinn Bay (Keevallik, 2003b).

It has also been established that the wind data from the southern coast of the Gulf of Finland poorly represent the factual wind regime at open sea (Soomere and Keevallik, 2003). Therefore, the question of description of the basic properties of open sea winds remains open for many practical applications including water transparency.

According to the WMO guidelines (WMO, 2008), a standard height of 10 m above open terrain is specified for the exposure of wind instruments. The first requirement cannot always be achieved in marine environment. The differences in wind speed data stemming from different measurement heights can be minimized by means of the boundary layer theory (Launiainen and Laurila, 1984; Barthelmie, 1999; Barthelmie *et al.*, 2007) or by simply assuming a logarithmic profile (Mass *et al.*, 2002). An extensive investigation on wind speed correction has been undertaken in the Finnish Meteorological Institute (Heiskanen and Frisk, 2002) that gives algorithms for height, meteorological stability and mechanical obstacles correction to wind speed and applies them to all Finnish stations.

Estonian weather service has 11 meteorological stations along the coastline and in West-Estonian archipelago. Pilot tests have shown (Soomere and Keevallik, 2003; Gretškosi *et al*., 2004) that their ability to represent marine winds is different. An inventory of the stations (history, changes in location, changes in measurement equipment and routine, openness to different directions, data quality, etc) was carried out in the frames of the Master's thesis of Veera Žukova (2009).

Field experiments may be accompanied by simultaneous wind measurements, but sometimes realistic wind data over a larger area are needed. This can be obtained by means of numerical weather prediction models in case the model output really describes the current wind parameters (Pirazzini *et al*., 2002; Savijärvi *et al*., 2005; Tisler *et al*., 2007). A pilot attempt to estimate HIRLAM possibilities at simulating local wind field at some sites (coastal stations and lighthouses) in the Baltic Sea has been made by Ansper and Fortelius (2003). This study was followed by systematic comparison of HIRLAM 6.4.0 outputs with measurements at nine coastal sites during one year (Keevallik *et al*., 2010). It was shown that HIRLAM overestimates wind speed and describes the angular distribution of moderate and strong winds better than that of weak winds. Next comparison was carried out for the Gulf of Finland where ground-based measurements were performed at two lighthouses – Tallinnamadal near the Estonian coast and Kalbådagrund near the Finnish coast (Keevallik and Soomere, 2011). It was shown that the HIRLAM model captures well the wind direction at Tallinnamadal whereas at Kalbådagrund the modeled wind direction is turned by >20° counter-clockwise from the measured direction. The HIRLAM output matches well wind speed at Kalbådagrund, but underestimates it at Tallinnamadal by more than 1 m/s.

Winds near the sea surface can be obtained also from satellite measurements. It has been shown that ASCAT (Advanced Scatterometer) wind data in the Baltic Sea region correlate well with HIRLAM predictions (Služenikina and Männik, 2011). On the other hand, this is not enough to say that satellite products describe the real situation.

The main objective of the thesis is to get information on the climatology of two main types of external forcing of the radiation regime in the Baltic Sea: solar radiation and wind. Solar radiation field is analyzed during 1966-2000 over the Baltic Proper and during 2005-2010 near the Estonian coast. Wind field is described near the entrance of the Gulf of Finland.

2. MEASUREMENT TECHNIQUES

Near surface solar radiation and wind characteristics are observed by means of networks of observing stations. World Meteorological Organization has elaborated number of manuals and guides to ensure reliability of observations by standardization. The Guide to Meteorological Instruments and Methods of Observation describes most instruments, systems and techniques in regular use. The guide contains recommended practices written primarily for National Meteorological Services but many other organizations, research and educational institutions taking meteorological observations have recognized the usefulness of such specifications. Moreover, many instrument manufacturers keep in mind the recommendations of the guide at the development and production of instruments and systems.

2.1. Measurement of surface solar radiation

The solar radiation incident on the top of the Earth's atmosphere is called extraterrestrial solar radiation. About 97 per cent of the radiation covers the spectral range 290 to 3000 nm and is referred to as solar radiation or shortwave radiation (WMO, 2008). Part of the extraterrestrial solar radiation penetrates through the atmosphere to the Earth’s surface, part of it is scattered and absorbed by the gas molecules, aerosol particles, cloud droplets and cloud crystals in the atmosphere. The total amount of solar radiation falling on a horizontal surface is referred to as global radiation, meaning that it is the sum of direct shortwave radiation from the sun and diffuse sky radiation from all upward angles. Due to differences in the position of the sun the local intensity of solar radiation differs during the day, at various latitudes and in different seasons. For a cloudless day the surface solar radiation is roughly 75 per cent of extraterrestrial radiation. In case of dense cloud cover the radiation is scattered in the atmosphere but even then about 25 per cent of the extraterrestrial radiation may still reach the Earth's surface mainly as diffuse sky radiation.

The instruments for measuring solar radiation are generally called radiometers. To measure different wavelength bands special categories of radiometers are designed.

Pyrheliometers are used to measure direct solar radiation from the sun and its marginal periphery. For regular measurement of direct solar radiation its receiving surface must be arranged to be normal to the solar direction, thus the instrument is usually mounted on a sun tracking device.

Pyranometers are used to measure global solar radiation, that is the solar radiation received from a solid angle of 2π sr on a plane surface. The sensor of a pyranometer has a horizontal radiation sensing surface that absorbs solar radiation energy and transforms this energy into heat. Global radiation can be determined by measuring this heat energy. The sensor is usually protected by a glass dome that should be regularly wiped clean. It has to be ensured that inside the dome natural ventilation still occurs and is sufficient to maintain the instrument body at ambient temperature. Sometimes the exposed dome of the pyranometer is ventilated by a blower to avoid or minimize deposits in cold weather, and to cool the dome in calm weather situations.

Pyranometers may also be used to measure solar radiation on surfaces inclined in the horizontal and in the inverted position to measure reflected global radiation. When measuring the diffuse sky component of solar radiation, the direct solar component is screened from the sensor by a shading device. Then the pyranometer is usually shaded either by a small metal disc held in the sun's beam by a sun tracker, or by a shadow band mounted on a polar axis.

For radiation measurements, it is particularly important to ascertain and make available information about the circumstances of the observations. This includes the type of the instrument, its calibration history, its location in space and time, spatial exposure and maintenance records.

The site selected for radiation measurements should be free from any obstruction above the plane of the sensors and, at the same time, should be readily accessible. Special care should be taken when installing radiation measurement equipment on such diverse platforms as ships, buoys, towers and aircraft. The exposure of pyranometers on these platforms is very difficult and the instrument is often affected by at least one significant obstruction (e.g. a tower). It is recommended that radiation sensors mounted on ships should be provided with gimbals because of the motion and vibration of the platform. The sensors should be mounted at a suitable height above the water surface on ships, buoys and towers, in order to keep the effects of water spray to a minimum.

There are several methods for calibrating radiation measurement equipment using either the sun or laboratory sources (WMO, 2008). Usually comparison with a standard pyrheliometer or pyranometer is performed in a national center. For example in Estonia for a long time the Yanishevski pyrheliometer was used as a secondary standard for regular assurance of the calibration. Now it is replaced with the absolute radiometer PMO-6 (Eerme *et al.*, 2010). The World Radiation Center (WRC) is responsible for maintaining the basic reference instruments (a group of absolute cavity radiometers) and every five years international comparisons are organized to compare the national standards with the world ones.

Instruments produced by Kipp and Zonen are widely used for solar radiation measurements (Kipp and Zonen, 2012). Pyranometers of the company are also approved by the solar radiation monitoring networks such as the BSRN and WMO.

Information on radiation equipment used in the Baltic Sea region is given in Chapter 3.2, Table 3.2.

2.2. Measurement of near surface wind

In meteorology near surface wind is considered as a two-dimensional vector quantity specified by two numbers representing direction and speed. Single fluctuations of wind are called gusts and the extent of wind characterized by rapid fluctuations is referred to as gustiness.

Wind speed should be reported to a resolution of 0.5 m/s to the nearest unit, wind direction in degrees to the nearest 10°, using a 01-36 code. Wind direction is defined as the direction from which the wind blows and is measured clockwise from geographical north, also called true north (WMO, 2008).

Wind direction near the surface is usually measured by a wind vane, wind speed by cup or propeller anemometer. In case of temporary interruptions in the operation of instruments or when the instruments are not provided, it is recommended to estimate the direction and force of the wind subjectively. Estimates are based on the effect of the wind on movable objects, Beaufort scale of wind force is most commonly used for this purpose.

Most users of wind data require the averaged horizontal wind (e.g. for synoptic reports averages of wind speed over 10 minutes and direction over 2 minutes are required). Many applications also need gustiness data. Therefore a wind-measuring system should contain a sensor together with a processing and recording system. The processing system is responsible for the averaging and the computation of standard deviations and extremes.

The most difficult aspect of wind measurement is the exposure of the anemometer since finding a location where the wind speed is representative of a large area is hardly practicable. Wind speed increases considerably with height, particularly over rough surface. For this reason, the standard exposure of wind instruments over level, open terrain is 10 m above the ground. Open terrain is defined as an area where the distance between the anemometer and any obstruction is at least 10 times the height of the obstruction. An optimum wind observation location is considered to be representative of the wind over an area of at least a few kilometers.

The wind measurement sensors should also be kept away from local obstructions. For example when the measurements are taken on the side of masts or towers the instruments should be placed on booms with a length of at least three mast or tower widths. All the obstacles in the station surroundings should be mapped (at least within a radius of 2 km) and the changes in the surroundings recorded in station log-books.

Special precautions must be taken to keep the wind sensors free from sleet and ice accumulations in freezing weather conditions. In some localities artificial heating for the exposed parts of the sensor is used, a few types of the instruments are equipped with sleet and ice shields.

New problems arise with application of automatic weather stations where wind is recorded continuously. A preliminary analysis of the compatibility of wind properties obtained from continuous high-resolution recordings at automatic stations and traditional wind data (obtained by means of averaging the wind speed over a 10-minute interval and the wind direction over a 2-minute interval once in every 3 hours) has been carried out by Keevallik *et al.* (2007). It is shown that the difference of estimates of the average wind speed is negligible for time scales of several weeks or longer. The scale parameter of the Weibull distribution for wind speeds is found to depend on the threshold for calm situations; it is close to 2 when wind speeds under 0.5 m/s are treated as calm. This choice also leads to a reasonable match of the corresponding wind roses.

Estonian weather service uses automatic weather stations MILOS 520 that are equipped by Vaisala wind instruments WAV151 (Vaisala, 2002a) and WAA151 (Vaisala, 2002b). Manual observations were replaced by automatic recordings step by step starting from 2003. Earlier measurements were carried out by anemorhumbometers of soviet origin.

When the instrumental measurements of wind are performed over the sea there comes up a problem with the standard exposure height of 10 m specified for land. The recommendation cannot always be accomplished in a marine environment because of the state of the sea and tidal height variation. Thus on moored buoys, the anemometer should be mounted 10 m above the waterline of the buoy. On fixed platforms and ships the wind sensors should be exposed sufficiently high above the platform and its superstructure to avoid the influence of the platform on the local wind structure. In general, at sea, good exposure should have higher priority in obtaining accurate and useful measurements than standardization of the measurements at 10 m.

The *in situ* measurement of near surface winds in a marine environment can be supplemented by remote sensing from surface- and space-based systems.

3. SURFACE SOLAR RADIATION IN THE BALTIC SEA BASIN

The spatio-temporal variation of solar radiation in the Baltic Sea Basin is considerably large. For example, in midsummer in the southern part of the basin the sun is over horizon for almost 16 hours per day. In the northern parts, which are located north of the Arctic Circle, the polar day exists in this time. In winter the length of the day is about 8 hours at the southern part, while in north the solar disk remains below the horizon for weeks (BACC, 2008).

The data coverage of radiation measurements is rather poor over the Baltic Sea Basin, moreover the open sea conditions may only be approximated from the data of station Visby, located on the Gotland Island. Long-term climatological data are available for a small number of locations, often only the global radiation and sunshine duration are observed (Bergström *et al.*, 2001; BACC, 2008; Leppäranta and Myrberg, 2009). Bergström *et al.* used data from Swedish coastal stations Luleå (65°37´N, 22°08´E, 1962-1993) and Visby (57°38´N, 18°20´E, 1957-1993) to describe the long-term variation and seasonal distribution of the global radiation in the northern part of the Baltic Sea region. They also show the variability in the annual cycle of global radiation using data from Luleå and Visby for the period 1961–1990. The example of Visby is once again presented by Leppäranta and Myrberg (2009). The authors state that the monthly mean solar radiation (flux density) in the Baltic Sea region peaks to around 200-250 W/m^2 (about 518-648 MJ/m^2) in June but disappears almost completely in December.

The BACC (2008) monograph shows average annual cycles of global radiation flux densities for the Baltic Sea Basin estimated on the basis of three inland actinometric stations – at Sodankylä (northern Finland, 1971–2000), Tartu (Estonia, 1981–2000) and Lindenberg (eastern Germany, 1981–2000). According to the estimations in December the monthly mean surface global radiation varies between less than 15 MJ/m^2 in the northern part of the basin to more than 90 MJ/m^2 in the southern part. In June the extent of mean regional variation is 550-750 MJ/m^2.

The overall conclusion is that the variations in global radiation is mainly determined by solar elevation, which causes yearly and daily cycles, and by differences in cloud cover. There is a significant difference in cloudiness between the open sea and land areas. Totals of global radiation in the coastal areas are higher during spring and summer as the formation and development of convective clouds are less intensive there. In winter the cloudiness is more extensive above the sea. The amount of radiation reaching the surface is also influenced by water vapor, other greenhouse gases and aerosols. In the cold half of the year high albedo, due to the presence of ice and snow, may considerably increase monthly totals of global radiation (BACC, 2008; Leppäranta and Myrberg, 2009).

3.1. BALTEX Data Centre

There are several institutions that provide high quality datasets from surface observation sites with directly measured radiant flux densities. Among others the Global Energy Balance Archive (GEBA) (Gilgen and Ohmura, 1999), the Baseline Surface Radiation Network (BSRN) (Ohmura *et al*., 1998) or World Radiation Data Center (WRDC) can be mentioned. The centers gather data from numerous stations all over the world but only a few of the stations are located in the vicinity of the Baltic Sea.

In 1993 the Baltic Sea Experiment (BALTEX), an international environmental research network for the Baltic Sea and its hydrological drainage basin, was launched. BALTEX was one of the first Regional Hydroclimate Projects (RHP) within the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Programme (WCRP). Three research disciplines – meteorological, hydrological and oceanographic investigations, are integrated there (BMDC, 2002).

The activity of BALTEX is divided into two phases. The research focus of BALTEX Phase I (1993-2002) was to explore and model the hydrological cycle and the exchange of energy between the atmosphere and the Earth's surface. The collection of *in situ* and remote sensing data played important role in achieving this.

BALTEX Phase II (2003-2012) concentrates on the research of regional climate variability and change, water management issues, and biogeochemical cycles under anthropogenic influence. One important goal is to impart the knowledge to policy makers, as well as to foster communication and education (Reckermann *et al*., 2011).

BALTEX study area is divided between the hydrological Baltic Sea Catchment Area (BACAR), defined as the region which the rivers run to the Baltic Sea, and the BALTEX Model Area (BAMAR) that covers great parts of Europe (BMDC, 2002).

Within the BALTEX Phase I four BALTEX Data Centers for meteorology, hydrology, oceanography and radar data were installed. The BALTEX Meteorological Data Center (BMDC) was operated by German Meteorological Service and it collected routinely observed meteorological data until 2002. Precipitation, snow and radiation are considered to be the most important parameters for BALTEX research. BMDC has been gathering atmospheric radiation data since 1986 (BMDC, 2002).

During 1996–2001 global radiation was measured at more than 50 actinometric stations within the Baltic Sea catchment area. Surprisingly, the data has not been extensively used up to now. Therefore radiation data from 12 sites around the central part of the Baltic Sea during 1996–2000 were drawn from the BALTEX meteorological data archives (paper I). The study of the spatio-temporal variability of daily global radiation totals was carried out.

3.2. Radiation data from BACAR archive

The data in BALTEX (BACAR) archive are stored in the original formats of the suppliers (the most frequently requested data types also in fixed BALTEX format). The data pass through minimum quality check for completeness of meta information of the data and station identification as well as number and order of observations.

The historical data set from the BACAR archive for 1996–2000 is rather heterogeneous with regard to the available types of radiation and resolution. At most stations the downwelling global radiation is recorded, but only a few stations give direct and diffuse radiation separately.

The analysis of spatio-temporal variability of surface global radiation was performed using data from 12 coastal or inland actinometric stations from six countries around the Baltic Sea. The location of the stations is given in Figure 3.1, station coordinates in Table 3.1.

As the measuring methods differ from country to country, there was a great diversity of original formats of the data. Table 3.2 gives an overview of the equipment for radiation measurements used at the stations. During the period 1996–2000 Finland, Sweden and Estonia all used a Kipp & Zonen CM-11 pyranometer, but the radiation parameters were expressed in different units – hourly and daily totals of global radiation in Estonia (MJ/m^2), hourly and daily mean values of global radiation in Finland (W/m^2) and hourly mean values in Sweden (W/m^2). In Latvia and Lithuania the global radiation was calculated as the sum of direct and diffuse radiation (measured with separate apparatus) on a horizontal surface, whereas the unit for expressing global radiation was MJ/m^2 multiplied by 100. In Poland a Moll-Gorczynski pyranometer (Kipp & Zonen) was used to register the radiation data. Daily totals of global radiation were expressed in J/cm^2.

Table 3.1. Station coordinates (BACAR archive)

Station name	Latitude	Longitude
Jokioinen	60.82°N	23.50°E
Helsinki-Vantaa	60.32°N	24.97°E
Tartu-Tõravere	58.27°N	26.47°E
Zīlāni	56.52°N	25.92°E
Šilutė	55.35°N	21.47°E
Gdynia	54.52°N	18.55°E
Kołobrzeg	54.18°N	15.58°E
Lund	55.72°N	13.22°E
Växjö	56.93°N	14.73°E
Visby	57.67°N	18.35°E
Norrköping	58.58°N	16.15°E
Stockholm	59.35°N	18.07°E

The whole dataset was recalculated to daily totals of global radiation and is given in MJ/m^2. Only the Estonian, Polish, Finnish and Swedish station Norrköping data sets for the period 1996–2000 had no gaps. The December 1998 data set from Latvian station Zīlāni was omitted from the analysis as it was incomplete and partly erroneous. Since numerous data were missing (paper I, Table 2), analysis of monthly totals was excluded.

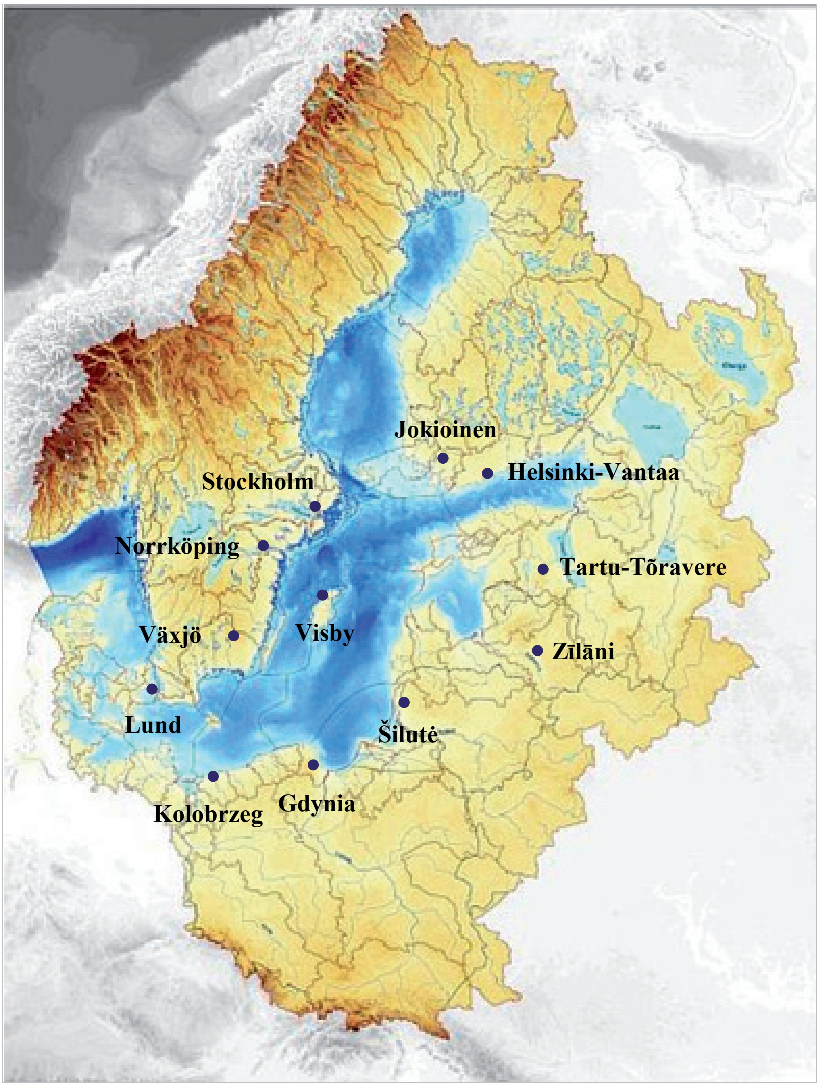

Figure 3.1. Location of radiation measurement stations around the Baltic Sea

Table 3.2. Information on radiation gauges in 1996–2000 (BMDC, 2002)

Radiation type/Country	Finland	Estonia	Latvia and Lithuania	Poland	Sweden
Global (Q)	Kipp & Zonen CM-11 pyranometer	Kipp & Zonen CM-11 pyranometer	$Q = S + D$	Kipp & Zonen pyranometer (Moll-Gorczynski)	Kipp & Zonen CM-11 pyranometer
Diffuse (D)			pyranometer PP-1		
Direct solar radiation on a horizontal surface (S)			actinometer AT-50		

3.3. Regional variability in global radiation

Analysis of the annual average of daily totals over the whole region shows noticeable variation in global radiation between stations (Figure 3.2). The annual average calculated from the data of twelve actinometric stations is 9.44 MJ/m^2.

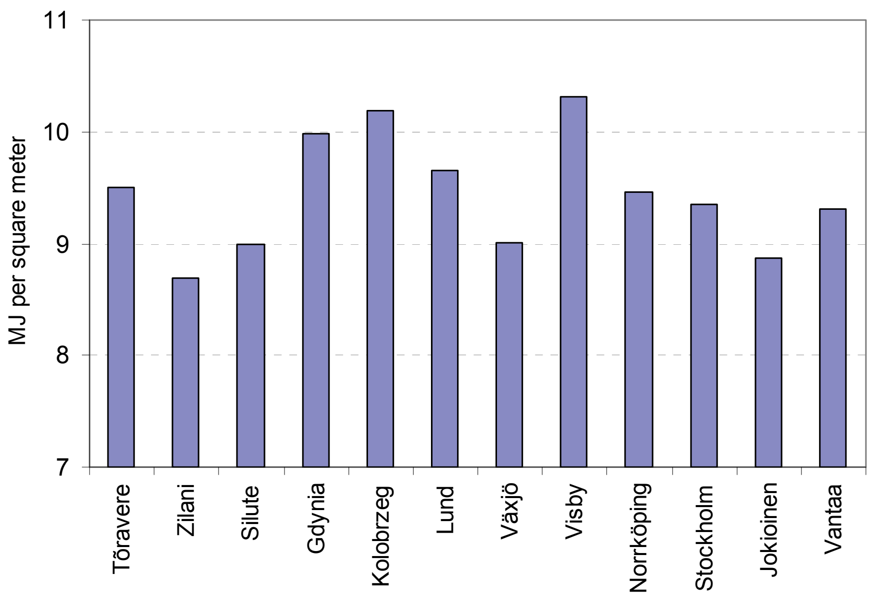

Figure 3.2. Annual average daily global radiation totals at different sites during 1996-2000

Although Visby is not the southernmost station in this area, the amount of solar energy is the largest there (10.32 MJ/m^2), which can be explained by the low average cloudiness in the vicinity (Bergström *et al.*, 2001). Radiation fluxes are also above average on the Polish coast, reaching 10.19 MJ/m^2 at Kołobrzeg and 9.99 MJ/m^2 at Gdynia. The average daily total is the smallest at Zīlāni (8.68 MJ/m^2). As the amount of solar radiation in winter is uniformly small, the differences in summer values influence the general distribution. It can be seen from the Figure 3.3 that in June the average daily total is 20.9 MJ/m^2 at Visby, but only 16.0 MJ/m^2 at Šilutė. Zīlāni, Šilutė, Växjö and Jokioinen, where the annual average daily sum is <9.0 MJ/m^2, are all inland stations where the cloud cover in summer is more extensive than over the coastal regions (Mietus, 1998). Somewhat different is the situation at inland station Tartu-Tõravere (also referred to as Tõravere) where the annual average daily sum is 9.5 MJ/m^2 and average daily total in June peaks to 19.7 MJ/m^2. The atmospheric conditions seem to be more favorable for solar radiation there.

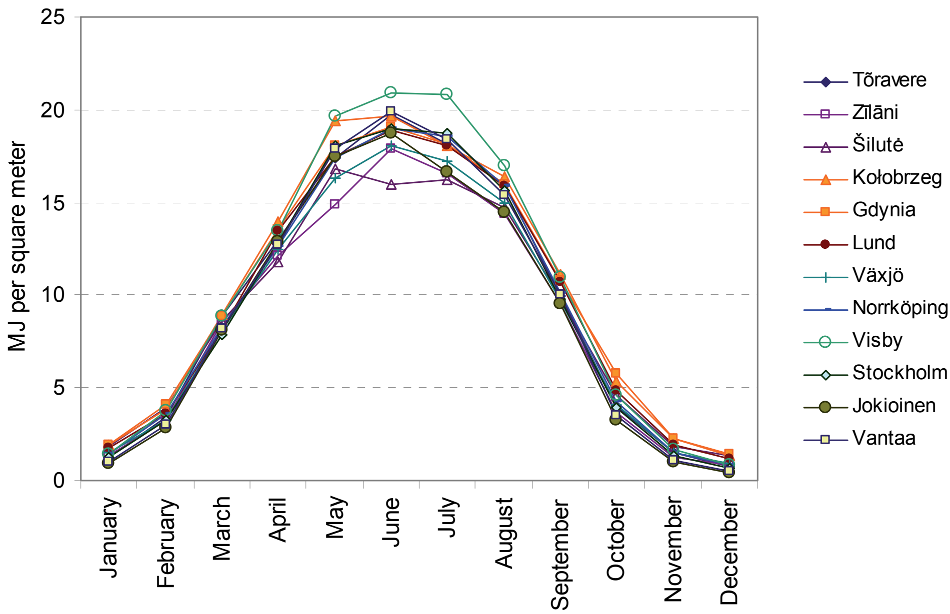

Figure 3.3. Monthly average daily global radiation totals at different sites during 1996-2000

The spatial variability of solar radiation is mostly caused by astronomical factors. In summer the impact of the northward increase in the length of daylight compensates for the influence of the decrease in solar elevation on daily global radiation totals, but in winter both factors work in the same direction, so that there are large differences in the daily totals at the top of the atmosphere (TOA) between the northernmost and southernmost sites of the region under consideration. In June the average TOA daily total at Jokioinen is 42.3 MJ/m^2, at Kołobrzeg 42.6 MJ/m^2, in December the values are 1.9 MJ/m^2 and 5.2 MJ/m^2 respectively.

Another factor which contributes to the spatial variability of solar radiation is atmospheric transmittance. To separate the meteorological factors from the astronomical ones, the recorded daily totals of global radiation were expressed as fractions of the respective daily totals at the TOA. The average fractions (see paper I, Table 4) of the TOA daily totals for different months show the smallest quantities in November and December. To estimate the spatial variability at the monthly time scale, the following procedure was applied. First the standard deviation of the fractions of TOA daily totals at 12 stations was calculated for each day. Next the standard deviations of the days were averaged over each month. According to the standard deviations the variability was the least in August.

3.4. Temporal variability in global radiation

In spring and autumn the difference of measured daily totals at the TOA between the beginning and the end of the months may cause additional variability into the estimated quantities. Thus, the astronomical factors should also be taken into account in the analysis of temporal variability.

To describe the annual cycle of the variability in the fractions of the TOA daily totals of global radiation, coefficients of variation are used. The coefficient of variation measures variability in relation to the average and allows one to compare degree of variation from one data series to another. In the present case the coefficient of variation of the fractions of the TOA daily totals actually describes the variability in atmospheric transmittance (with regard to the daily totals). The annual cycle of the variability at different measurement sites is presented in Figure 3.4. As the shorter time series normally show larger variability, only the stations where there are no gaps in the data sets are presented in the figure. As seen in Figure 3.4, the coefficient of variation is the largest from November to January, when the overall atmospheric transparency is low and variations in the amount of incoming energy due to atmospheric disturbances are comparable with the average flux. On the other hand, the variability of atmospheric transmittance is minimal not in June, when the incoming energy is maximal, but in August. Thus, the influence of atmospheric disturbances in this month is the weakest.

In late winter and early spring the temporal variability in the western part (Lund and Kołobrzeg) of the region under consideration is somewhat larger than in other parts of the Baltic Proper. In October the atmospheric transmittance on the Polish coast varies less than at the other measurement sites. At most stations (with the exception of Lund) the coefficient of variation in December is smaller than in November and January, which can be explained by the uniform cloud cover that is typical of this month in the Baltic Sea region.

To detect the sites where the fractions of the TOA daily totals co-vary, correlation coefficients were calculated between the different stations. The spatial correlation of the fraction of TOA daily totals is the best between neighboring stations Jokioinen and Vantaa, where the correlation coefficient is 0.92 in January and February and not less than 0.81, the June value (paper I, Table 5). Evidently these sites are governed by similar cloud cover systems – stratiform cloudiness in winter and cumulus clouds in summer. The correlation is also good between Norrköping and Stockholm, where during most of the year the correlation coefficient is over 0.8. The fractions of the TOA daily totals of global radiation show the strongest correlation over the whole region in April, when the temporal variability of the atmospheric transmittance is similar in all stations (as seen in Figure 3.4).

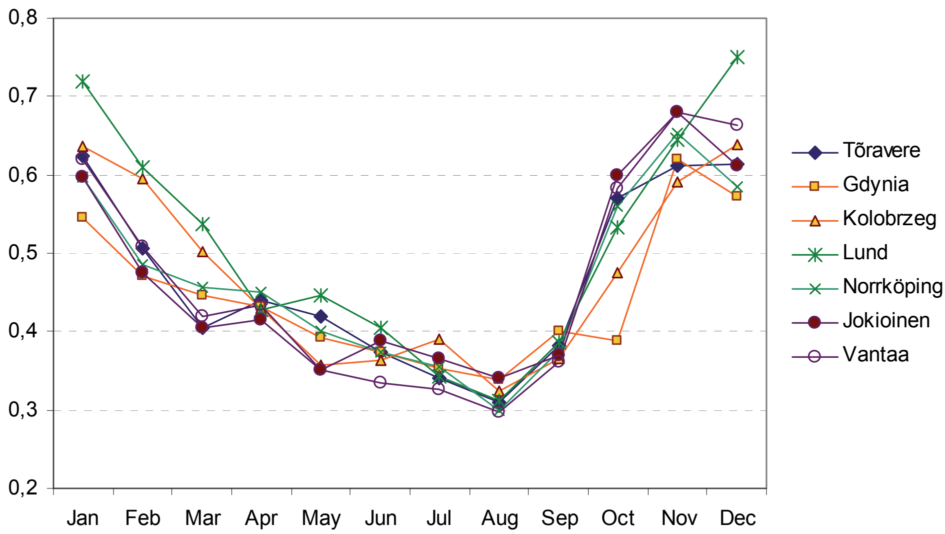

Figure 3.4. Coefficient of variation of the fraction of the TOA daily global radiation totals at different sites during 1996–2000

3.5. Coastal measurements *versus* parameterization

The average daily totals of global radiation obtained from the coastal measurements were compared with average data based on parameterizations applied to meteorological observations made on board voluntary observing ships during 1980–1992 (Rozwadowska and Isemer, 1998). The comparison reveals that the average annual course of the global radiation obtained from this parameterization is rather different from actinometric measurements at coastal stations (paper I, Figure 5). The meteorological parameters constituting the input to the parameterization model are cloud cover, humidity and air temperature. Ship observations were carried out in different parts of the Baltic Proper and the number of observations during 1980–1992 was large, but distributed unevenly in time and space. As the estimates from coastal measurements were obtained during 1996–2000, the time periods do not coincide. Therefore, a rough estimate of the possible differences between these periods based on Tartu-Tõravere data (Russak and Kallis, 2003) is presented (paper I, Figure 6). Although the annual total for the later period is larger by only 2%, the monthly totals are smaller by 18% in December, by 12% in January and by 13% in February. They are larger by 7% in March, by 15% in August and by 22% in September.

The difference between the coastal measurements averaged over the whole region during 1996–2000 and the parameterization estimates during 1980–1992 is the largest in May, when the parameterization shows an average daily sum of 20.0 MJ/m^2 and coastal measurements of 17.6 MJ/m^2. On the other hand, coastal measurements show somewhat (0.27... 0.72 MJ/m^2) larger values in March, August and September which, according to Tartu-Tõravere data, can be attributed to some extent to differences between the various periods.

The match is the best between the parameterization model outputs and the measurements at Visby, i.e. the site where the amount of the solar radiation is the largest. From this comparison, one can regard measurements of global radiation at Visby as representative of the average global radiation over the whole Baltic Proper.

Isemer and Rozwadowska (1999) have given average daily totals for three parts of the Baltic Proper. We came to the conclusion that Visby data can be used to describe the solar radiation fluxes over the Baltic Proper between 57ºN and 60ºN (paper I, Table 6). The Kołobrzeg data give a good approximation for the region west of 15ºE. The relative difference in both cases is maximal in March and September but does not exceed 20%. At least part of this difference as well as the difference in August can be ascribed to the differences between the two time periods. To describe the radiation field in the region south of 57ºN and east of 15ºE, Visby and Kołobrzeg give the best approximation, but both show rather large relative differences in winter. The Kołobrzeg measurements display larger values and the Visby measurements smaller values than those obtained by the parameterization of ship measurements. Very probably, this can be explained, at least partly, by astronomical factors.

4. SURFACE SOLAR RADIATION FIELD OVER ESTONIA

The main features of the Estonian solar radiation climate are described in the *Handbook of Estonian Solar Radiation Climate* (Russak and Kallis, 2003). According to the book the longest datasets of surface global radiation have been collected at Tartu-Tõravere (since 1955) and Tiirikoja (since 1975) meteorological stations. The book also gives approximate information on the mean distribution of annual totals of global radiation over the territory of Estonia that is gained by calculations on the basis of mean cloudiness and albedo values at 31 meteorological stations.

Tartu-Tõravere Meteorological Station presents the most complete dataset of surface solar radiation in Estonia. From the start, the radiation measurements at the station have been under scientific control of the present Tartu Observatory, since 1999 the station belongs to the BSRN (Eerme *et al.*, 2010). Because the quality of data from the station is guaranteed, the data have been used in different studies, including the validation of satellite measurements of surface solar radiation (Ineichen *et al*., 2009; Posselt *et al*., 2011).

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 or measurements at coastal stations could be applied for this purpose, especially in cloudy conditions.

Knowledge on heat fluxes at the sea surface is also important in modeling of the development of vertical stratification in an estuary (Burchard and Hofmeister, 2008). The long-term changes, e.g., in the sea surface temperature, are usually correlated with the radiation or sun hours data from coastal stations (Van Aken, 2010). 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 (Lips and Lips, 2008). Although Tõravere is situated approximately 200 km from the Estonian coastline, it was the best site in Estonia where all components of the radiation budget are recorded.

4.1. Measurement network

Since 2003 Estonian Meteorological and Hydrological Institute (EMHI) 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. Belcher and DeGaetano, 2007). On the other hand, many stations have been complemented with actinometric equipment that measure solar radiation directly. For example 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.

In the network of EMHI there are eight meteorological stations where global radiation is measured. The location of the stations is given in Figure 4.1. Table 4.1 introduces the station positions and openness of the horizon. At some stations the observation period is shorter than at others - at Pakri the radiation measurement were terminated in 2009, at Haapsalu and Roomassaare the automatic stations were installed somewhat later than others, in 2007 and 2008, respectively.

Figure 4.1. Location of the meteorological stations where solar radiation is measured.

Table 4.1. 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				
Tallinn-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
Tartu-Tõravere	58°15’51’’	26°27’40’’	70	3	5	2	2

At Estonian stations Kipp & Zonen pyranometers CM11 and CM21 are used to measure the downward and upward fluxes of solar radiation. 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. Among other parameters hourly mean global radiation data is stored in data archives at EMHI.

To investigate relationships between global radiation at the coastal stations and Tartu-Tõravere, data from six stations during 2005-2010 were used (paper II), stations with shorter observation period were left out. The goal of the study was to draw attention to the problems of radiation measurements at the automatic weather stations and discuss the possibilities of reconstruction coastal global radiation from Tartu-Tõravere data in case no measurements are carried out at the site of interest. The stress is put on daily totals and hourly fluxes. As the observation period was short (2005-2010) and there were number of gaps in data series, only a rough estimate of the spatio-temporal distribution of the solar radiation characteristics is available.

The maintenance of receivers of radiation measurements is quite strict. They need open horizon (especially in winter when the sun is low), periodic calibration of pyranometers, regular control of the conditions of the receivers, etc.

The measurements of the openness of the horizon were carried out at all stations in 2001 (Russak and Kallis, 2003). Since then the forest around Tiirikoja has grown and shades the instruments even more. The estimates for Pärnu meteorological station are not available, as the station was relocated in 2003. It is now situated at the airport and according to visual estimates the horizon is not shaded considerably. From Table 4.1 it can be concluded that winter data from Tiirikoja and Narva-Jõesuu may be underestimated.

The radiation equipment is calibrated regularly at Tartu-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 Tartu-Tõravere, Tallinn-Harku (also referred to as Harku) and Pärnu. Thermal offset corrections are applied in measurements at Tartu-Tõravere. To avoid the situations that pyranometer is covered with snow or ice, special instructions are given to the personnel of meteorological stations to check the condition of the receivers (McArthur, 2004).

The data of Tartu-Tõravere passes strict quality control before it is transmitted to the archives of EMHI, BSRN and WRDC. Datasets from other stations are not checked so thoroughly – only these values are removed that are obviously erroneous.

4.2. Missing and erroneous data

The dataset from Tartu-Tõravere was the only one without gaps. Data from all the other stations for period 2005-2010 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 (or thermal) offset of the sensor. Usually the zero offset is present when the inner dome of the pyranometer has a different temperature from the cold junctions of the sensor. Practically this happens under the clear sky conditions. The negative zero offset is also present on a clear day, however, hidden in the solar radiation signal (Kipp and Zonen, 2011). The offset is a widely recognized problem of pyranometers that may lead to discrepancies between modeled and measured solar radiation (Philipona, 2002). As mentioned above, the thermal offset corrections are applied only at Tartu-Tõravere station.

The greatest number of missing values was presented in the data set of Tallinn-Harku station. The reason here was elimination of negative values, caused by the zero offset, during the data transmission from automatic station to the archive. Mostly data were missing during night when there is no solar radiation, but some missing data were shown also for daytime hours, especially for morning and evening. At Tallinn-Harku the zero and missing data were distinguished by means of sunset and sunrise times and records with missing data were left out.

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

To estimate differences between radiation regime at Tartu-Tõravere and coastal stations, on the basis of daily totals of global radiation, the data sets had to be "cleaned". "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 when sensor problems were detected was left out.

At Pärnu two periods (February 20, 2008 to November 2, 2008 and January, 30 to September 14, 2009) when solar radiation was systematically shown at night were left out. 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 the coastal stations there exist several cases when in winter the recorded daily total was 0. As the absolute minimum during the period under consideration at Tartu-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 (e.g., pyranometers not cleaned from snow).

4.3. Regional distribution of daily radiation totals

Due to the “cleaning” of the data sets different periods were left out at different stations and the comparison of radiation regime at different stations could be carried out for shorter periods that are common to all (or at least most of the) stations. As seen from Figure 4.2 for different months these periods were different. For October the common period for all stations was less than two months. Therefore only four stations are considered where the common period was longer. At the analysis of January data Tiirikoja and Narva-Jõesuu were left out due to the restricted openness of the horizon that might introduce systematic errors.

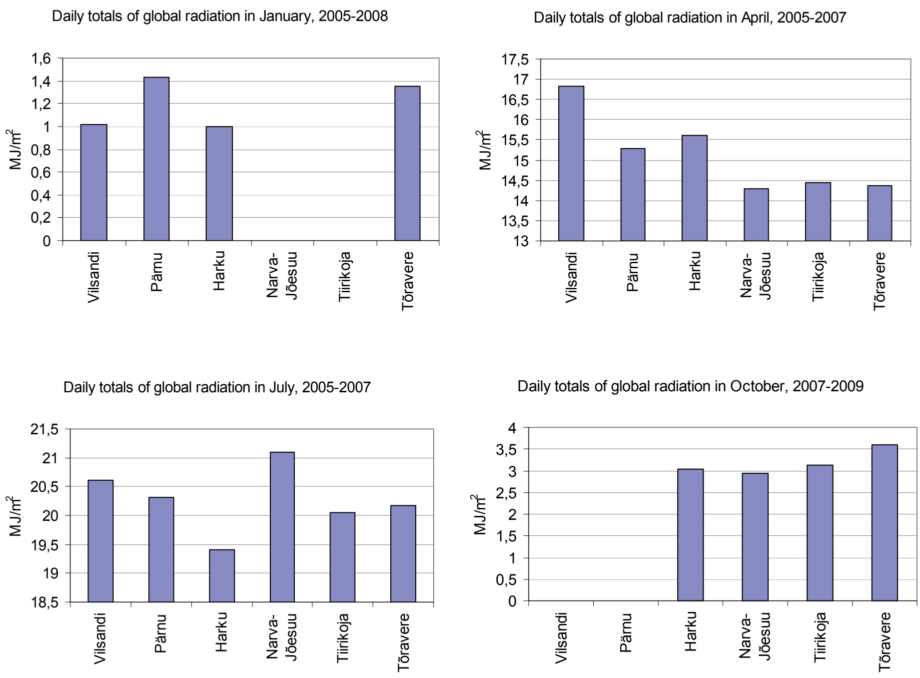

Figure 4.2. Monthly average daily totals of global radiation

Figure 4.2 shows that 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; in October the radiation conditions in North-Estonia and East-Estonia are similar, most probably due to extensive homogeneous cloud cover.

An interesting feature can be noted concerning two sites on the northern coast: There is more sunshine at Tallinn-Harku in April and at Narva-Jõesuu in July.

On the annual basis, there is more sunshine on the West-Estonian islands and coast and less on the North-Estonian coast and inland (see paper II, Figure 3). This can partly be explained with astronomical factors. In January the TOA radiation on the northern coast forms approximately 86% of that above Tartu-Tõravere. In October this percentage is around 94.

4.4. Diurnal cycle of hourly radiation totals

The data from common period of 2005-2007 (with missing data from October 2005 to March 2006, and august 2007) were used to calculate daily cycles of global radiation.

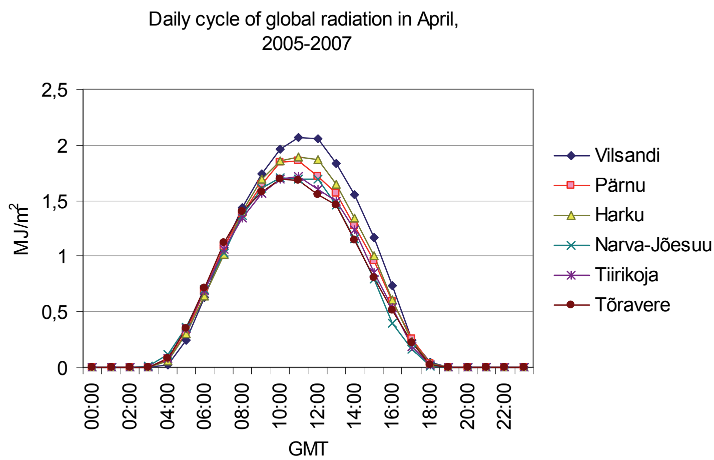

Figure 4.3. Daily cycle of global radiation in April

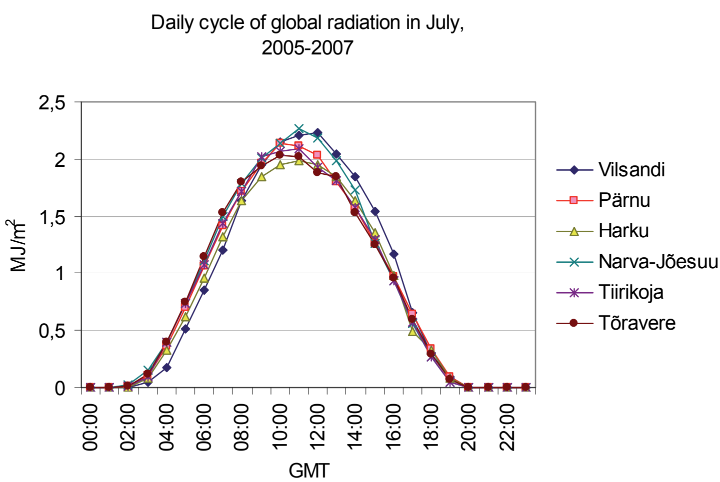

Figure 4.4. Daily cycle of global radiation in July

Figures 4.3 and 4.4 show results for April and July when a common three-year period could be found for all stations. According to Figures 4.3 and 4.4 the differences between radiation conditions at different stations are larger in spring than in summer.

At Tartu-Tõravere the maximum of the solar radiation is measured around local noon (10:00 GMT denotes the hour from 9:00-10:00 GMT or 11:00-12:00 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 may be due to meteorological conditions. On the other hand, if data at the meteorological stations were archived with a shorter time step, this shift at Vilsandi could be smaller or even disappear.

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.

4.5. Correlation between global radiation at the coastal stations and Tartu-Tõravere

To estimate global radiation at the coastal stations from Tartu-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 sky was overcast at both stations. Cloudiness is recorded with 3-hour intervals. Therefore, the afternoon hour of 11:00-12:00 GMT (13:00-14:00 East European Time) was chosen for comparison.

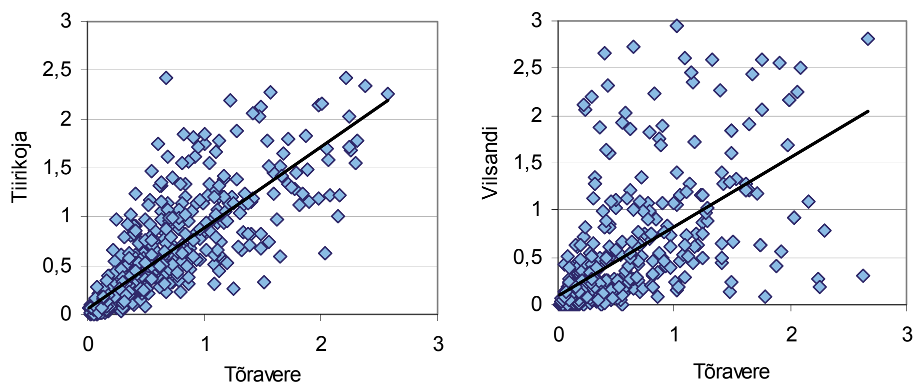

Figure 4.5. Regression lines between afternoon (11:00-12:00 GMT) hourly totals (MJ/m^2) at two coastal stations and Tõravere in overcast conditions

The regression shows that hourly fluxes at Tiirikoja and Pärnu can be restored from the Tartu-Tõravere data rather well (paper II, Table 2). 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 fluxes of global radiation at these sites is determined by the variability of the fluxes at Tartu-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 4.5 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 tenth), correlation is perfect as expected (paper II, Figure 6).

5. WIND, WAVES, CURRENTS AND WATER TURBIDITY

It is widely acknowledged that waves and currents have certain impact on the marine environment. In shallow waters, waves create significant changes in the optical parameters of sea water creating near-bottom orbital velocities that lead to resuspension of sediments. At the turn of the century, extensive investigation of the impact of fast ferry traffic in the Tallinn Bay on sediment resuspension and underwater optics was carried out (Erm and Soomere, 2004; 2006). It was shown that in the Tallinn Bay at the depths about 2-5 m wake waves bring about significant changes in the optical parameters in the near-bottom layer with a thickness of about 1 m whereas the suspended material remains in the water column for about 5 minutes. Therefore the effect of the fast ferry wakes is not negligible in coastal areas that are open seawards even in case the natural waves are frequently much higher than the wakes.

Recently the Marine Systems Institute carried out complex field measurements with acoustic Doppler velocymeter, integrated turbidity meter, pressure wave gauge and portable or near-by weather stations. During campaigns in summer and winter, the influence of wind-generated waves on the water turbidity was investigated near the southern coast of the Gulf of Finland.

5.1. Wind regime at the entrance of the Gulf of Finland

The wind regime of the Gulf of Finland is very specific. It combines southwest and north winds dominating over the Baltic Proper with local winds blowing along the axis of the gulf. As a result, directional distributions of wind properties contain numerous maxima and minima (Soomere *et al.,* 2008). In most of the gulf area, southwest winds are the most frequent but not necessarily the strongest. West and east winds also occur frequently. As different from the wind patterns in the Baltic Proper, east winds at the entrance of the gulf may be nearly as strong as southwest winds (Soomere and Keevallik, 2003), but their frequency and intensity decrease in the eastern direction. Southeast winds are infrequent and weak.

In most practical tasks, statistical properties of wind field over marine and coastal areas are of greater importance than average wind regime. Variability of wind field may become important in terms of anisotropy of different wind-induced phenomena, such as for the anisotropy of wave fields (Soomere, 2003) that may play a decisive role in the planning of harbors and coastal engineering structures (Elken *et al*., 2001), problems connected with the estimation of the wind and wave energy potential (Waters *et al*., 2009; Holt nad Palutikof, 2003) and, last but not least, resuspension that affects water turbidity (Erm and Soomere, 2006).

Long-term, seasonal, and diurnal variations of the wind speed at the entrance of the Gulf of Finland can be estimated from the data set of 1969-1992 recorded at Pakri, Naissaar and Hanko (Figure 5.1) every 3 hours according to the traditional routine of WMO.

Figure 5.1. Location of the measurement sites

5.1.1. Interannual variability

Variability of monthly mean wind speed during the 34-year period at all stations is the largest in winter and the smallest in summer. According to Table 5.1 the variability of the wind speed is similar on both coasts of the gulf.

Table 5.1. Standard deviation (m/s) of monthly mean wind speed from the long-term monthly average

	Hanko	Naissaar	Pakri
January	1.08	1.05	1.03
July	0.58	0.48	0.57

5.1.2. Seasonal variability

Monthly mean wind speed in the region under consideration is the largest in November-December and the smallest in July (Figure 5.2). Winds are stronger on the northern coast of the gulf – most probably due to the fact that there are no obstacles to reduce the speed of the general air-flow from southwest.

It can be noticed that annual cycle is developed best at Hanko that is characteristic of the marine wind regime (Achberger *et al*., 2006). The amplitude of the annual cycle (average wind speed in November minus that in July) reaches from 2.1 m/s at Pakri to 3.1 m/s at Hanko, i.e. annual monthly mean wind speed variability exceeds inter-annual variability by 2…3 times.

Variability of single measurements around the annual average cycle is the largest in December where standard deviation reaches 4.2 m/s at Naissaar and 3.6-3.7 m/s at Pakri and Hanko. The variability is the smallest in July (2.7 m/s at Naissaar, 2.5 m/s at Pakri and 2.2 m/s at Hanko).

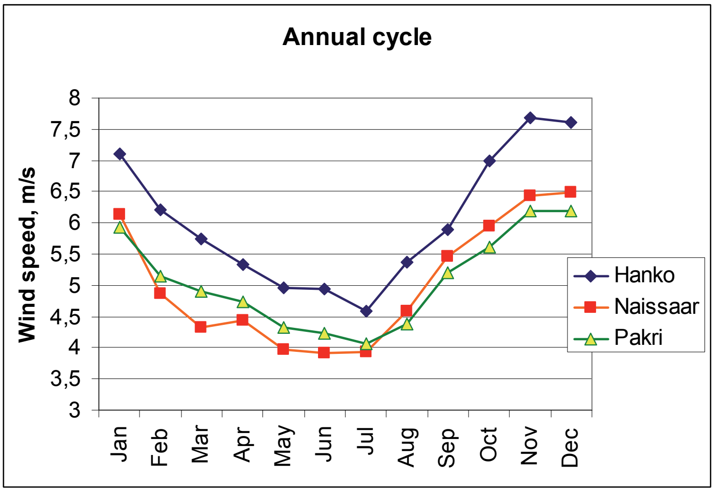

Figure 5.2. Annual cycle of the monthly average wind speed at different measurement sites

5.1.3. Daily cycle

Long-term daily wind speed amplitudes (maximal value minus minimal value) were calculated for all months at all stations together with long-term ratio of daily amplitude to the daily average wind speed (Table 5.2).

Table 5.2. Daily wind speed cycle at different stations

	Daily wind speed amplitude (m/s)			Ratio of daily amplitude to daily average wind speed (%)		
	Hanko	Naissaar	Pakri	Hanko	Naissaar	Pakri
January	0.18	0.24	0.21	2	4	4
July	0.61	0.67	1.39	13	17	34

It can be seen that the daily cycle of the wind speed is negligible in winter, but well developed in summer at Pakri. This refers to a strong influence of the mainland on the wind regime at this site (Soomere and Keevallik, 2003).

Table 5.2 shows that daily wind speed variations are of the same order of magnitude as inter-annual variations.

5.1.4. Wind speed frequency distributions

Wind speed frequency distributions for Pakri, Naissaar and Hanko in January, April, July and October for the period of November 1969 – October 1992 are published by Keevallik and Soomere (2009) together with the probabilities of wind speed over 10 m/s at the sites under consideration. In Table 5.3 these data are complemented by the probabilities of wind speed over 15 m/s.

Table 5.3. Probabilities of some wind speed gradations for different measurement sites

	Wind speed > 10 m/s, %			Wind speed > 15 m/s, %		
	Pakri	Naissaar	Hanko	Pakri	Naissaar	Hanko
January	8.7	13.4	16.8	1.2	2.0	1.5
April	3.8	3.9	4.9	0.7	0.5	0.2
July	1.4	2.0	1.2	0.1	0.1	0.1
October	5.3	11.2	12.2	0.5	1.7	1.1

5.2. Experiments at the southern coast of the Gulf of Finland

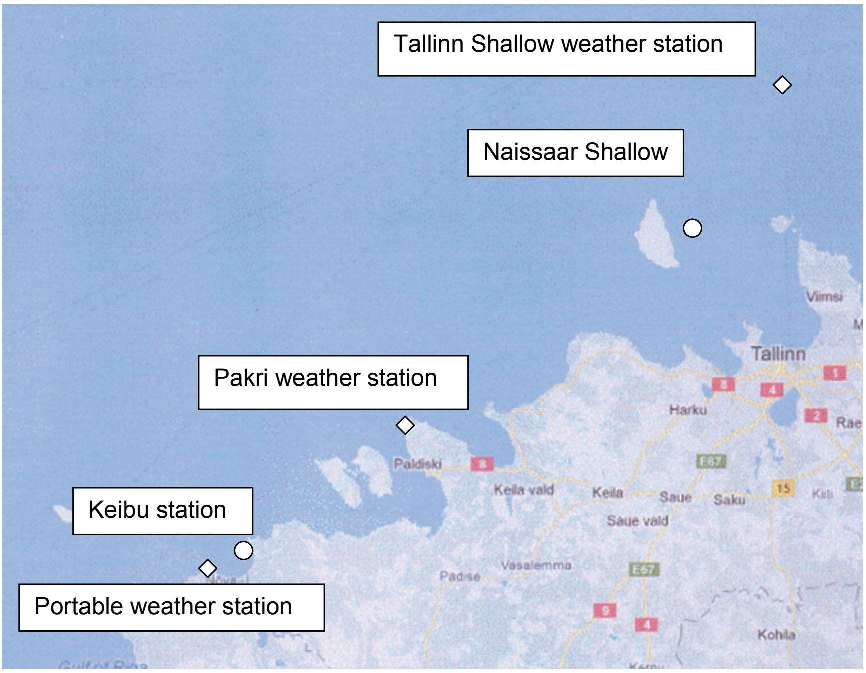

Figure 5.3. Measurement sites at Keibu Bay and Naissaar Shallow together with weather stations

Simultaneous measurements of wind, near-bottom currents, waves and turbidity were performed at two sites near the southern coast of the Gulf of Finland: at Keibu Bay from 3 to 29 June 2010 and at Naissaar Shallow from 22 December 2009 to 12 January 2010 (Figure 5.3). At Keibu the wind was recorded by means of a nearby portable weather station, but for Naissaar shallow the measurements at Tallinn Shallow were used (paper III). The latter data were recorded at the height of 32 m. Therefore the wind speed is somewhat larger than at the traditional height of 10 m: According to Launiainen and Laurila (1984), in conditions of neutral stratification the wind at 10 m forms 91% of that at 32 m. The depth of the measurement site at Keibu Bay was 7 m and at Naissaar Shallow 20 m.

5.2.1. Keibu Bay

Wind was recorded near the measurement site on the cape Toomanina by means of AIRMAR PB200 every 5 minutes. From these data wind roses for different wind speed gradations were composed (Figure 5.4). The wind roses show that west winds dominated during the measurement period whereas the frequency distribution of the strong winds (over 15 m/s) is highly anisotropic. This is characteristic of the Gulf of Finland where the angular structure of strong winds typically does not match the structure of all winds (Soomere and Keevallik, 2003).

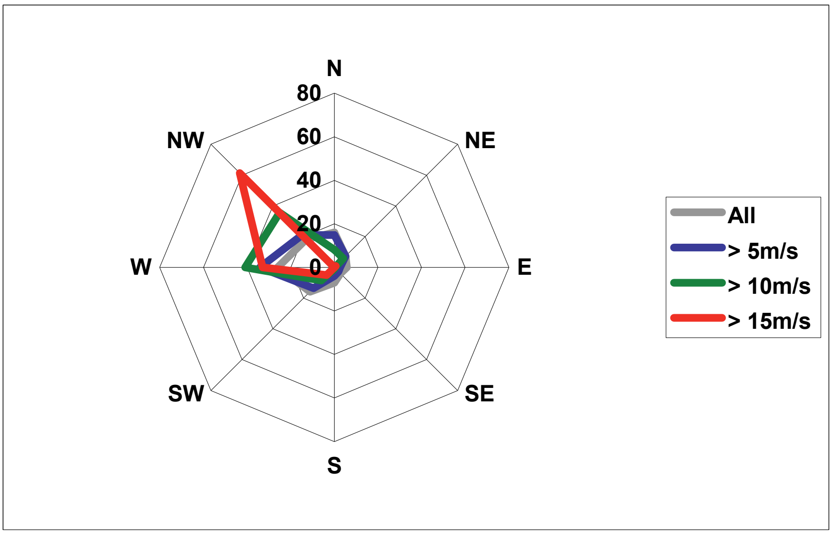

Figure 5.4. The wind roses for Keibu Bay in June 2010 for different wind speed gradations. Frequency is given in per cents

Figure 5.5 shows angular distributions of the discretized fluxes of wind and near-bottom current vector fields got by summing the respective speeds within the principal rhumbs. Here one must keep in mind that the wind vector shows the direction where the wind is blowing from and the current vector shows where the current is directed to. It can be seen that on the average the directions of the wind and near-bottom current are opposite. This can be followed also in Figure 5.6 where progressive vector diagram for near-bottom current is shown.

During June 2010, 222 cases of 6730 were recorded when the wind speed reached 15 m/s or more. Mostly these winds were blowing from the west, but on the 8 June also a short period of strong east winds were recorded. Near-bottom currents reached 10 cm/s only during five strong wind events (Figure 5.7).

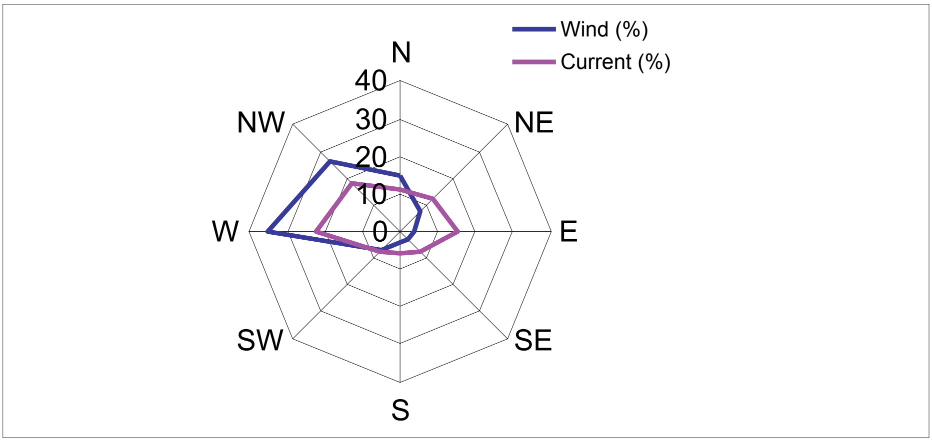

Figure 5.5. Fluxes of wind and near-bottom current vector fields discretized over the principal rhumbs in Keibu Bay in June 2010

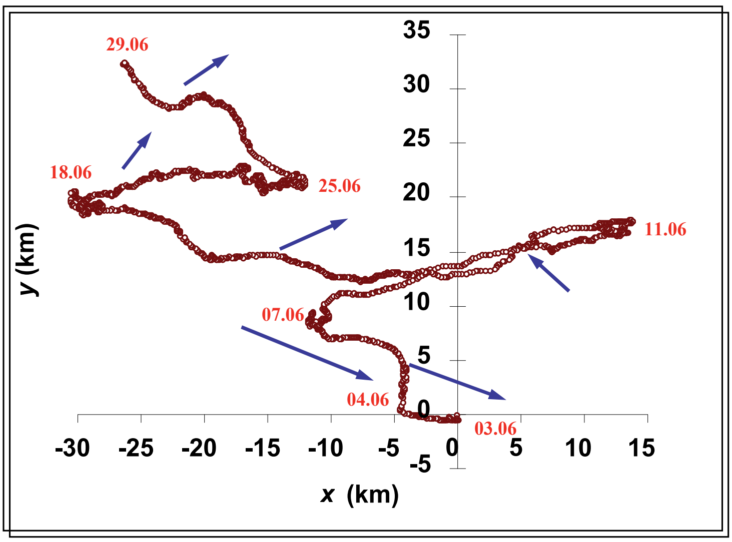

Figure 5.6. Progressive vector diagram for near-bottom current in Keibu Bay in June 2010. The arrows show wind at different moments

On the other hand, during these strong wind events wave orbital velocities showed values up to 45 cm/s exceeding thus near-bottom currents and generating bottom resuspension (Figure 5.7).

During June 2010 the probability of strong winds (over 15 m/s) was 3%. Table 5.3 shows that long-term estimate for this percentage in July at Pakri is only 0.1%. This leads to the conclusion that climatological estimates at a near-by coastal station may not represent the situation at the definite measurement site.

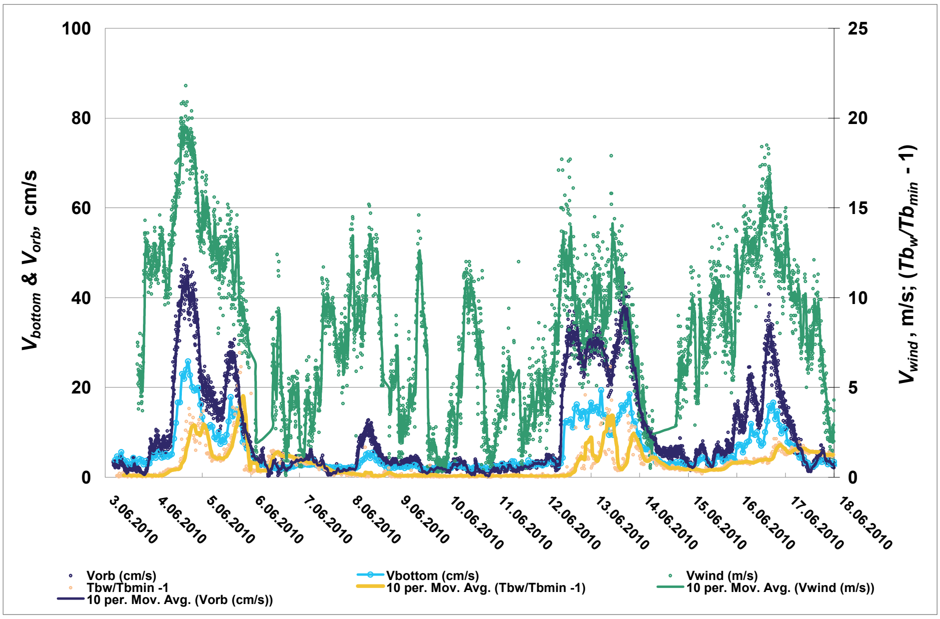

Figure 5.7. Wind speed (green line), turbidity (yellow), bottom speed (light blue) and wave orbital velocity (dark blue) in Keibu Bay in June 2010

5.2.2. Naissaar Shallow

Winds during the field campaign at Naissaar Shallow were drawn from automatic measurements at Tallinn Shallow. These wind speeds are evidently overestimated by 10-20%, as they are recorded at the height of 32 m and Naissaar Shallow is sheltered by the near-by island in the west. On the other hand, wind roses of Tallinn Shallow show that during the measurement campaign eastern winds prevailed (Figure 5.8). During the period of December 22 to January 12, 760 cases of 7248 were recorded when the wind speed reached 15 m/s or more. Mostly these winds were blowing from the east and northeast. Strong west winds over 15 m/s were registered only during the night of December 24.

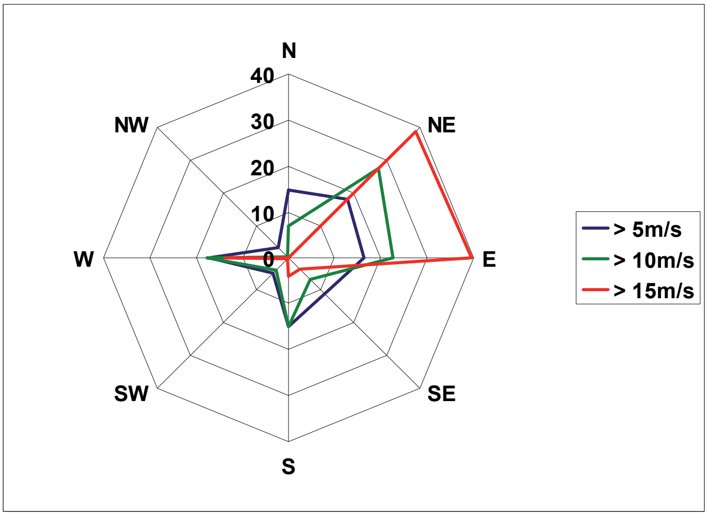

Figure 5.8. The wind roses for Tallinn Shallow in December 2009 and January 2010 for different wind speed gradations. Frequency is given in per cents

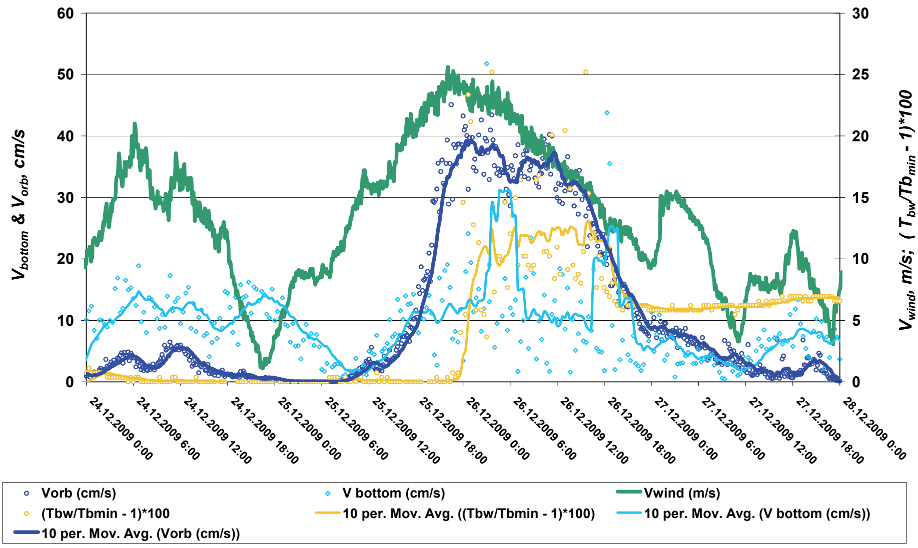

Figure 5.9. Wind speed (green line), turbidity (yellow), near-bottom current speed (light blue) and wave orbital velocity (dark blue) in Naissaar Shallow

The measurement site at Naissaar Shallow is deeper than that in Keibu Bay. Therefore the turbidity dependence on the wind, current and wave intensity was recorded only during a storm on December 25-27 when the wind speed reached nearly 26 m/s (Figure 5.9). A weak increase in the turbidity between 28 December and 2 January was most probably caused by sand mining in the vicinity of the measurement site. Strong winds on December 24 are blowing from the west and do not have enough fetch to induce waves.

Wind forced currents near Naissaar were observed in late autumn 2008 by Lilover *et al.* (2011). These measurements were not directed towards resuspension estimates. Nevertheless, the results show relationships between current systems at the measurement site and winds measured at Tallinn Shallow. Besides, the decrease of the low-frequency current velocities toward the bottom was estimated.

5.2.3 Reduction of the underwater irradiation due to the turbidity

Erm *et al*. (2008) have shown that the resuspension height of particles due to the waves is between 0.5 and 1.0 m. Keeping in mind exponential extinction of the radiation in the water, the following formula can be deduced to calculate how many times the bottom irradiation is reduced in conditions of resuspension:

$$n = \exp\left(K\left(\frac{T_{bw}}{T_{b\min}} - 1 \right) x \right)$$

where x is the thickness of the bottom layer where sediments are resuspended, K is extinction coefficient in the undisturbed water, T_{bw} is wave-induced turbidity in the bottom layer and T_{bmin} is turbidity in the calm conditions.

At Keibu on June 5 the turbidity is approximately 7 times higher than in normal conditions. The bottom of the bay is muddy and the extinction coefficient of undisturbed water could be estimated to be 0.7 m^{-1}. Taking for the sediment resuspension height the value of 0.75 m, calculations show that the bottom irradiation was reduced by 23 times.

The sea at Naissaar shallow is deeper, the bottom is sandy and the extinction coefficient in December was 0.21 m^{-1}. Here wind-induced movements of the water change turbidity less. According to the rough estimate, during the storm of December 25 the bottom irradiation was reduced by 1.5 times.

CONCLUSIONS

Solar radiation at the sea surface is the main agent of the formation of the underwater radiation field. The variability of the global radiation is caused by two factors: astronomical differences in the TOA (Top Of the Atmosphere) radiation (different latitudes) and atmospheric properties to influence the transmittance (cloudiness, aerosols).

Spatio-temporal variability of global radiation around the central part of the Baltic Sea during 1996-2000 on a monthly basis is described by means of the BALTEX (Baltic Sea Experiment) data archives.

- The annual average daily total varies from 10 MJ/m^2 at Visby (Gotland) and Kołobrzeg (Poland) to less than 9 MJ/m^2 at inland stations.
- The monthly average daily total of the global radiation over the whole region extends from 0.93 MJ/m^2 in December to 19.0 MJ/m^2 in June.
- Fractions of the TOA daily totals of global radiation show that the spatial and temporal variability in the atmospheric transmittance over the Baltic Proper is the least in August.
- There exist differences between the western part of the Baltic Proper and other parts of the region: In the western part in winter and early spring the temporal variability of the fraction of the TOA daily totals is larger and in October smaller.
- The spatial correlation of the fraction of TOA daily totals is the best in April, being especially good between the neighboring stations in Finland and Sweden.
- To approximate the western part of the Baltic Proper, the measurements at the Polish station Kołobrzeg can be used whereas the measurements at Visby describe the other parts of the region best.
- Description of the off-shore radiation field by means of the measurements at coastal stations is possible in case the phenomena of monthly or seasonal scales are studied.

Spatio-temporal variability of global radiation in Estonia during 2005-2010 on daily and hourly basis is described by means of the measurements at Estonian automatic weather stations.

- In April there is more sunshine in West-Estonia than in East-Estonia. In July the sunniest places are seaside resorts of Pärnu and Narva-Jõesuu and the westernmost island of Vilsandi. In October the radiation conditions on the western and northern coast are similar.
- Application of Tartu-Tõravere (Baseline Surface Radiation Network station) radiation data at marine investigations is recommended in

case the site under consideration is in the waters of the Pärnu Bay or Lake Peipsi and regression relationships are considered.

- The quality of global radiation data from automatic weather stations should be carefully checked as there are many factors that might contaminate the measurements.

Near-surface wind is one of the contributing agents of the formation of the underwater radiation field. The wind field variability was investigated at the entrance of the Gulf of Finland for 1969-1992 on the basis of data from Hanko, Naissaar and Pakri.

- Standard deviation of monthly mean wind speed from the long-term monthly average is around 1 m/s in January and 0.5-0.6 m/s in July.
- Average annual amplitude of the monthly mean wind speed reaches from 2.1 m/s at Pakri (southern coast of the Gulf) to 3.1 m/s at Hanko (northern coast).
- Standard deviation of wind speed is about 50% of the monthly average on the northern coast and 60-70% on the southern coast of the Gulf being larger in winter and smaller in summer.
- Probability of wind speed over 15 m/s is around 2% in winter and 0.1% in summer.

Simultaneous measurements of wind, wave, current and turbidity near the southern coast of the Gulf of Finland give information on the processes on the sea bed that lead to resuspension.

- Only strong wind events generate bottom currents with speeds exceeding 10 cm/s that are able to resuspend sediments.
- Resuspension is caused rather by the wave orbital velocities than by near-bottom currents.
- The influence of wind induced turbidity on the bottom irradiation is large in shallow waters with muddy bottom and small in deep waters with sandy bottom.

ABSTRACT

The main aim of the thesis is to get information on the spatio-temporal variability of two main types of external forcing of the radiation regime in the Baltic Sea: solar radiation and wind.

Solar radiation is essential for many applications, at the sea surface it is the main agent of the formation of the underwater radiation field. At the same time the near-surface wind contributes to the formation of the underwater radiation field through causing the waves and moving sediments.

In order to describe the variability of global radiation around the central part of the Baltic Sea during 1996-2000, analysis on a monthly basis is carried out. Radiation data were drawn from the BALTEX (Baltic Sea Experiment) meteorological data archives. The variability is analyzed on the basis of the fractions of the daily totals at the top of the atmosphere. The analysis reveals that solar surface radiation varies considerably around the Baltic Proper. There exist differences between the southwestern part of the region (which could be described by measurements at the Polish station Kołobrzeg) and other parts of the region (which could be described by measurements at Visby). In general the description of the off-shore radiation field by means of the measurements at coastal stations is possible in case the phenomena of monthly or seasonal scales are studied, for short-term phenomena some other method should be used.

Further, the variability of global radiation in Estonia during 2005-2010 on daily and hourly basis is described by means of the measurements at Estonian automatic weather stations. The relationship between global radiation at the coastal stations and Tartu-Tõravere (Baseline Surface Radiation Network station) is investigated. It can be said that application of Tartu-Tõravere radiation data at marine investigations is not recommended, as the radiation regimes differ significantly when the site under consideration is in the waters of West-Estonian archipelago or near the northern coast. On the other hand, in case there are no measurements carried out at the seaside, it should be possible to reconstruct global radiation in coastal sites using linear regression. The results are better when the area under consideration is Lake Peipsi or the Pärnu Bay. Using the global radiation data from automatic weather stations, one has to bear in mind that the data quality should be carefully checked as there are many factors that might contaminate the measurements.

Wind field is described near the entrance of the Gulf of Finland using long-term data sets from 1969-1992 and data from experimental measurements at Keibu Bay and Naissaar Shallow. It can be said that simultaneous measurements of wind, wave, current and turbidity give useful information on the processes on the sea bed that lead to resuspension. It is shown that only currents and waves that induce bottom velocities over 10 cm/s are able to resuspend sediments and cause water turbidity.

RESÜMEE

Käesoleva uurimistöö peamiseks eesmärgiks on analüüsida kahe põhilise veekogu kiirgusrežiimi mõjutava välisjõu – päikesekiirguse ja tuule ajalis-ruumilist muutlikkust Läänemere piirkonnas.

Päikesekiirgus mängib olulist rolli paljudes valdkondades, merepinnale langenud kiirgus on üheks põhiliseks teguriks veealuse kiirgusvälja kujunemisel. Pinnalähedane tuul omakorda aitab veealuse kiirgusvälja kujunemisele kaasa laineid tekitades ja setteid kergitades.

Et kirjeldada summaarse päikesekiirguse muutlikkust Läänemere keskosa kohal ajavahemikul 1996-2000, analüüsiti andmeid kuu tasandil. Kasutatud andmed pärinevad BALTEXi (Baltic Sea Experiment) meteoroloogilisest arhiivist. Kiirguse muutlikkust analüüsitakse aluspinnani jõudnud ja atmosfääri ülapiirile langenud kiirgusvoogude suhte abil. Analüüsi tulemused näitavad, et kiirgushulkade erinevus Läänemere eri piirkondades on märgatav. Selgelt väljendub erinevus regiooni edelapoolse osa (mida sobivad kirjeldama Poola jaama Kołobrzeg andmed) ja teiste osade (mida sobivad kirjeldama Visby andmed) vahel. Rannikujaamades mõõdetud andmed sobivad üldiselt avamere kiirgusrežiimi kirjeldamiseks juhul, kui uuritakse kuuajalise või sesoonse ulatusega nähtusi, lühiajaliste nähtuste puhul tuleks ülevaate saamiseks mõnda muud meetodit rakendada.

Teiseks kirjeldatakse antud uurimistöös summaarse kiirguse muutlikkust Eesti kohal ajavahemikul 2005-2010. Kirjeldamiseks kasutatakse automaatilmajaamades mõõdetud andmete põhjal arvutatud päeva- ja tunnisummasid. Lisaks võrreldakse rannikujaamades mõõdetud andmeid Tartu-Tõravere kui rahvusvahelise BSRN (Baseline Surface Radiation Network) võrgu jaama andmetega. Võib väita, et Tartu-Tõravere kiirguse andmete rakendamine mereuuringutes ei ole soovitav kiirgusrežiimide erinevuse tõttu, iseäranis kui uuritav koht asub Lääne-Eesti saarestikus või põhjaranniku lähistel. Teisest küljest, kui rannaäärses piirkonnas mõõtmisi ei teostada, võib summaarse kiirguse väärtused rannikul tuletada Tartu-Tõravere andmetest lineaarse regressiooni abil, mis toimib paremini kiirgusvälja kirjeldamiseks Peipsil või Pärnu lahel. Automaatjaamade andmete esmane analüüs näitas, et andmetesse tuleb suhtuda kriitiliselt ja mõõtmistingimusi jaamades on vaja parandada.

Tuulevälja kirjeldamiseks Soome lahe suudmealal kasutatakse pikaajalist andmerida ajavahemikul 1969-1992 ning andmeid testmõõtmistelt Keibu lahes ja Naissaare madalal. Kõige enam infot merepõhjas toimuvate setteid kergitavate protsesside kohta on võimalik saada kombineeritud tuule, lainete, hoovuste ja hägususe mõõtmistest. Mõõtmistulemused näitavad, et vaid need hoovused ja lained, mis tekitavad põhjakiirusi üle 10 cm/s, on võimelised setteid kergitama ja seeläbi vett hägustama.

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WMO Guide to Meteorological Instruments and Methods of Observation. 2008. WMO-No. 8. Geneva.

ELULOOKIRJELDUS

1. Isikuandmed

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2. Kontaktandmed

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3. Hariduskäik

Õppeasutus	Aasta	Haridus (eriala/kraad)
Tallinna Ülikool	2001	Hüdrometeoroloogia ja loodushoid/bakalaureusekraad
Eesti Mereakadeemia	1998	Hüdrometeoroloogia ja loodushoid/rakenduskõrgharidus
Rapla Ühisgümnaasium	1994	Keskharidus

4. Keelteoskus

Keel	Tase
Eesti keel	Emakeel
Inglise keel	Kõrgtase
Vene keel	Kesktase
Saksa keel	Algtase

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2010-...	Eesti Meteoroloogia ja Hüdroloogia Instituut	Nõuniku kt
2009-...	TTÜ Meresüsteemide Instituut	Insener
2007-2010	Eesti Meteoroloogia ja Hüdroloogia Instituut	Andmekogude osakonna juhataja
2006-2009	Eesti Mereakadeemia	Lektor

2004-2007	Eesti Meteoroloogia ja Hüdroloogia Instituut	Peaspetsialist
2003-2006	Eesti Mereakadeemia	Assistent
2003-2004	Eesti Meteoroloogia ja Hüdroloogia Instituut	Spetsialist
1999-2000	Eesti Mereakadeemia	Õppejõud
1998-2002	Eesti Meteoroloogia ja Hüdroloogia Instituut	Meteoroloog

6. Publikatsioonid Eesti Teadusinfosüsteemi klassifikaatori järgi

1.1.

Rosin, A., Rosin, K., Auväärt, A., Strzelecki, R. 2012. Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices. Przeglad Elektrotechniczny, 88(4b), 294 - 299.

Keevallik, S., Loitjärv, K. 2010. Solar radiation at the surface in the Baltic Proper. Oceanologia, 52(4), 583 - 597.

1.2.

Rosin, K., Keevallik, S. 2012. Regional variations in hourly and daily totals of global radiation recorded at automatic weather stations in Estonia. Estonian Journal of Engineering, 18(1), 76 - 86.

3.1.

Erm, A., Alari, V., Buschmann, F., Kõuts, T., Raudsepp, U., Loitjärv, K. 2010. Near bottom velocity and turbidity measurements in coastal waters of NW Estonia. In: IEEE-Inst Electrical Electronics Engineers Inc, 2010: 4th IEES/OES Baltic Symposium, Riga, Latvia, August 25-27, 2010, 1 - 8.

3.2.

Keevallik, S., Loitjärv, K., Rajasalu, R.., Russak, V. 2001. Meteorological Regime of Lake Peipsi. Lake Peipsi. [3.] Meteorology, hydrology, hydrochemistry (18 - 37). Tartu: Sulemees Publishers.

Keevallik, S., Loitjärv, K. 1999. Euroopa ilmamustrid ja sünoptiline situatsioon Eestis. Jaagus, J. (Toim.). Publicationes Instituti Geographici Universitatis Tartuensis (123 - 133). Tartu Ülikooli geograafia instituut.

5.2.

Rosin, K. 2011. Evaluation of solar radiation in the coastal area of the Baltic Proper. In: Book of Abstract: 8th Baltic Sea Science Congress [BSSC]: 22-26, August 2011, St.Petersburg, Russia. St. Petersburg: RSHU, 2011, 104.

Erm, A., Buschmann, F., Alari, V., Rosin, K., Rebane, J., Listak, M. 2011. Near bottom dynamics measurements in coastal waters of NW Estonia. In: Book of Abstract: : RSHU, 2011, 317: 8th Baltic Sea Science Congress [BSSC]: 22-26, August 2011, St.Petersburg, Russia. St. Petersburg: RSHU, 2011, 82.

7. Kaitstud lõputööd

Euroopa ilmamustrid ja sünoptiline situatsioon Eestis, Bakalaureusetöö Tallinna Ülikoolis, 2001.

Euroopa ilmamustrid ja sünoptiline olukord Läänemere basseinis. Diplomitöö Eesti Mereakadeemias, 1998.

8. Teadustöö põhisuunad

Meteoroloogilised mõõtmised, andmed ja andmetöötlus; päikesekiirguse ja meteoelementide ajalis-ruumiline muutlikkus.

9. Uurimisprojektid Eesti Teadusinfosüsteemi järgi

Eesti Teadusfondi grant

Lainetusest tingitud põhjasetete transport rannikumeres, 2012-2015.

CURRICULUM VITAE

1. Personal data

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Citizenship: Estonia

2. Contact information

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3. Education

Institution	Year	Education (field of study/degree)
Tallinn University	2001	Hydrometeorology and Environmental Protection / bachelor's degree
Estonian Maritime Academy	1998	Hydrometeorology and Environmental Protection/professional higher education
Rapla Gymnasium	1994	Secondary education

4. Language competence/skills

Language	Level
Estonian	Native language
English	Fluent
Russian	Average
German	Basic skills

5. Professional Employment

Period	Organisation	Position
2010-...	Estonian Meteorological and Hydrological Institute	Adviser
2009-...	Marine Systems Institute at Tallinn University of Technology	Engineer
2007-2010	Estonian Meteorological and Hydrological Institute	Head of Databases Department

2006-2009	Estonian Maritime Academy	Lecturer
2004-2007	Estonian Meteorological and Hydrological Institute	Head specialist
2003-2006	Estonian Maritime Academy	Assistant
2003-2004	Estonian Meteorological and Hydrological Institute	Specialist
1999-2000	Estonian Maritime Academy	Lecturer
1998-2002	Estonian Meteorological and Hydrological Institute	Meteorologist

6. Publications according to the Estonian Research Information System

1.1.

Rosin, A., Rosin, K., Auväärt, A., Strzelecki, R. 2012. Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices. Przeglad Elektrotechniczny, 88(4b), 294 - 299.

Keevallik, S., Loitjärv, K. 2010. Solar radiation at the surface in the Baltic Proper. Oceanologia, 52(4), 583 - 597.

1.2.

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3.1.

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7. Defended theses

European circulation patterns and synoptic situation in Estonia. Bachelor's thesis in Tallinn University, 2001.

European circulation patterns and synoptic situation in the Baltic Sea Basin. Diploma work in Estonian Maritime Academy, 1998.

8. Main areas of scientific work

Meteorological observations, data and data analysis; spatio-temporal variability of the solar radiation and meteoelements.

9. Research projects

Estonian Science Foundation grant

Wave induced transport of bottom sediment in the coastal sea, 2012-2015.

APPENDIX A: PAPERS

Paper I

Keevallik, S., **Loitjärv, K**. 2010. Solar radiation at the surface in the Baltic Proper. Oceanologia, 52(4), 583-597.

Papers

Solar radiation at the surface in the Baltic Proper*

OCEANOLOGIA, 52 (4), 2010.
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KEYWORDS
Solar radiation
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Actinometric measurements
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Abstract

Radiation data recorded at 12 sites around the central part of the Baltic Sea during 1996–2000 drawn from the BALTEX (Baltic Sea Experiment) meteorological data archives are used to study the spatio-temporal variability of daily global radiation totals. The annual average daily global radiation total varies from about 10 MJ m^{-2} at Visby (on Gotland) and Kołobrzeg (on the coast of Poland) to less than 9 MJ m^{-2} at Zīlāni (inland Latvia), Šilutė (Lithuania) and Jokioinen (Finland). The monthly average daily global radiation total over the whole region extends from 0.93 in December to 19.0 in June. The variability in global radiation is analysed on the basis of the fraction of the daily total at the top of the atmosphere. The spatial and temporal variability is the least in August – this shows that the variation in the cloud cover and atmospheric properties at this time of year is the smallest. The spatial correlation is the strongest between the two Finnish stations

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– Vantaa and Jokioinen. It is also high between Stockholm and Norrköping, on the east coast of Sweden. The correlation coefficients are the largest over the whole area in April. Radiation data from coastal stations are compared with an earlier parameterization based on ship observations (Rozwadowska & Isemer 1998, Isemer & Rozwadowska 1999). It is concluded that in climatological research, actinometric data from Visby can be used to characterize the radiation field over the northern part of the Baltic Proper and those from Kołobrzeg to characterize the radiation field over the southern part of this sea.

1. Introduction

Solar radiation at the water surface is one of the driving agents of marine dynamics and an important factor in marine biology. Solar radiation contributes to the thermal regime of the water layers as well as to photosynthesis, primary production and phytoplankton blooms.

Solar surface irradiance depends first of all on astronomical factors, but is greatly modified by cloudiness, atmospheric transparency and snow cover. The latter factors show significant spatial and temporal variability, which is reflected in the variability of solar fluxes.

There are three ways of estimating radiation fluxes over a water body. First, radiation fluxes can be calculated by applying an empirical model to marine meteorological observations. Second, outputs of some numerical weather prediction models can be used. Third, coastal actinometric measurements can be extrapolated offshore.

The first possibility relies on the meteorological properties over a water body to parameterize surface solar radiation. This field has been investigated widely, but the parameterization is closely dependent on the climate zone: the relationships established elsewhere may not necessarily be directly applicable to the Baltic Sea. A semi-empirical model for computing the climatological characteristics of the solar radiation flux at the surface of the Baltic Proper is briefly described by Rozwadowska & Isemer (1998). They applied their model to meteorological observations made on board ships during 1980–1992 and described the monthly averages of the incident solar radiation fluxes in three parts of the Baltic Proper.

A detailed model of solar energy input to the sea surface has been presented by Krężel (1997). Taking into account as many parameters as possible, the model is expected to describe the radiation field in any time scale. However, comparison with actinometric data shows that for short time periods the modelled totals of solar energy at the sea surface can differ significantly from the real values. The main factor responsible for these discrepancies is cloudiness.

Niemelä et al. (2001) give an overview of several short-wave downwelling radiative flux parameterizations suitable for the Baltic Sea region. The calculated fluxes were compared with hourly sums observed at Jokioinen and Sodankylä, both inland stations in Finland. The clear-sky fluxes were estimated rather well, but the cloudy-sky schemes showed a large scatter.

Surface radiative flux parameterizations are used to build radiative codes in numerical weather prediction (NWP) models (e.g. Morcrette 1991, Ritter & Geleyn 1992). Over the Baltic Sea region the HIRLAM NWP system is mostly used. For this system, the radiation codes were elaborated by Savijärvi (1990) and Sass et al. (1994).

The second means of estimating surface solar radiation uses operational NWP outputs. This has at least two advantages: one is that the spatial coverage of the open sea is not restricted, and the other is that the situation in the radiation field can be estimated nearly instantaneously, with the temporal frequency of the forecast scheme. However, the accuracy of this possibility should be checked for specific site and climatic conditions.

The third possibility relies on measurements at coastal actinometric stations and gives a rough overview of the average radiation field around the water body. This knowledge may be sufficient for climate studies but is rather sparse for the Baltic Sea. Long-term average surface global (direct plus diffuse) radiation for the Baltic Sea Basin has been estimated on the basis of three inland actinometric stations – at Sodankylä (120 km north of the Arctic Circle in northern Finland, 1971–2000), Tartu (Estonia, 1981–2000) and Lindenberg (lat. $52^{\circ}13'$N, eastern Germany, 1981–2000) (BACC 2008). Figure A.12 in the BACC (2008) monograph also shows long-term monthly averages based on parameterizations applied to meteorological observations made on board voluntary observing ships during 1980–1992 (Rozwadowska & Isemer 1998). As shown in BACC (2008), the average annual course of the global radiation obtained from this parameterization differs significantly from actinometric measurements at coastal stations. The difference is due mainly to differences in astronomic conditions, but also to differences in cloud cover, which during spring and summer is consistently less under open-sea conditions (Isemer & Rozwadowska 1999, Leppäranta & Myrberg 2009). The latitude of Tartu corresponds best to that of the Baltic Proper; therefore the difference between actinometric measurements and the offshore parameterization there is the least.

Leppäranta & Myrberg (2009) state that the monthly mean solar radiation (flux density) in the region of the Baltic Sea peaks to around 200–250 W m^{-2} in June but disappears almost completely in December. They also demonstrate the variability in the annual cycle of global radiation using the example of Visby (Gotland, 1961–1990).

One of the reasons for the foundation of BALTEX (The Baltic Sea Experiment) in the early 1990s was the necessity to collect oceanographic, meteorological and hydrological data from the Baltic Sea catchment area and to create an archive for modellers and other investigators (BALTEX 1995). The BALTEX Meteorological Data Centre (BMDC) collected synoptic and climate data until 2002, and has been gathering atmospheric radiation data since 1986 (BMDC 2002). During 1996–2001 global radiation was measured at more than 50 actinometric stations within the Baltic Sea catchment area.

The aim of the current paper is to refine the spatial and temporal distribution of the surface solar radiation in the region of the Baltic Proper. For this purpose, measurements at 12 actinometric stations during 1996–2000 are used. This time series is short for climatological analysis, but the results of the present study can be complemented by a detailed analysis of the radiation climate at Tartu-Tõravere during 1955–2000 (Russak & Kallis (eds.) 2003).

2. Radiation data

Global (direct plus diffuse) radiation data from the following coastal or inland actinometric stations are used in the present study (Figure 1): Jokioinen (60.82°N 23.50°E), Helsinki-Vantaa (60.32°N 24.97°E), Tartu-Tõravere (58.27°N 26.47°E), Zīlāni (56.52°N 25.92°E), Šilutė (55.35°N 21.47°E), Gdynia (54.52°N 18.55°E), Kołobrzeg (54.18°N 15.58°E), Lund (55.72°N 13.22°E), Växjö (56.93°N 14.73°E), Visby (57.67°N 18.35°E), Norrköping (58.58°N 16.15°E) and Stockholm (59.35°N 18.07°E).

The historical data set from the BALTEX (BACAR) archive for 1996–2000 is rather heterogeneous with regard to the available types of radiation and resolution. At most stations the downwelling global radiation is recorded, but only a few stations give direct and diffuse radiation separately. The measuring methods differ from country to country. Table 1 gives an overview of the equipment for radiation measurements.

The data in the BALTEX archive for the period 1996–2000 needed unification, as they exist in various forms. Finland, Sweden and Estonia all used a CM-11 pyranometer (Kipp & Zonen), but the radiation parameters were expressed in different units – hourly and daily totals of global radiation in Estonia (MJ m^{-2}), hourly and daily mean values of global radiation in Finland (W m^{-2}) and hourly mean values in Sweden (W m^{-2}). In Latvia and Lithuania the global radiation was calculated as the sum of direct and diffuse radiation on a horizontal surface, whereas the unit for expressing global radiation was MJ m^{-2} multiplied by 100. In Poland a Moll-Gorczynski pyranometer (Kipp & Zonen) was used to register the radiation data. Daily totals of global radiation were expressed in J cm^{-2}.

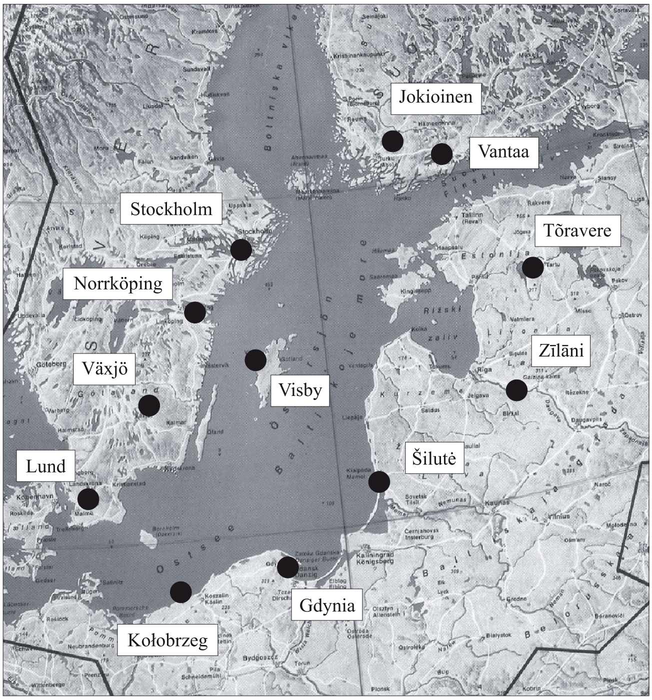

Figure 1. Actinometric stations around the Baltic Sea

Table 1. Information on radiation gauges in 1996–2000 (BMDC 2002)

Radiation type/Country	Finland	Estonia	Latvia and Lithuania	Poland	Sweden
global (Q)	Kipp & Zonen CM-11 pyranometer	Kipp & Zonen CM-11 pyranometer	$Q = S + D$	Kipp & Zonen pyranometer (Moll-Gorczynski)	Kipp & Zonen CM-11 pyranometer
diffuse (D)			pyranometer PP-1		
direct solar radiation on a horizontal surface (S)			actinometer AT-50		

To analyse the spatial distribution of the surface solar radiation, all measurement results were recalculated to daily totals and given in MJ m^{-2}. Since numerous data were missing, analysis of monthly totals was not possible.

In the BALTEX radiation data archive for 1996–2000 only the Estonian, Polish, Finnish and Norrköping global radiation data sets have no gaps. The missing data for the other stations are shown in Table 2.

Table 2. Number of days for which global radiation data are missing

Year	Zīlāni	Šilutė	Stockholm	Visby	Växjö
1996		30 (June) 2 (Dec.)		29 (Feb.) 31 (Mar.) 30 (April)	30 (Sept.)
1997		1 (Jan.) 16 (June) 21 (July) 16 (Oct.) 9 (Nov.) 19 (Dec.)			
1998	21 (Dec.)	3 (July) 16 (Aug.) 1 (Nov.)	30 (July)		
1999		9 (Dec.)			
2000		11 (Jan.) 15 (Feb) 2 (June) 7 (Sept.)	31 (Aug.)		

The December 1998 data set from Zīlāni was omitted from the analysis, as it showed random gaps, as well as two values of daily sums exceeding 11 MJ m^{-2} that were apparently erroneous.

3. Regional differences in the global radiation in 1996–2000

The annual average of daily totals over the whole region calculated from the data of the twelve actinometric stations is 9.44 MJ m^{-2}, but there are noticeable differences between different stations (Figure 2).

The amount of solar energy is the largest at Visby (10.32 MJ m^{-2}), even though it is not the southernmost station in this area. Fluxes are also above average on the Polish coast, reaching 10.19 MJ m^{-2} at Kołobrzeg and 9.99 MJ m^{-2} at Gdynia. The average daily total is the smallest at Zīlāni (8.68 MJ m^{-2}). These differences are due mostly to differences in summer,

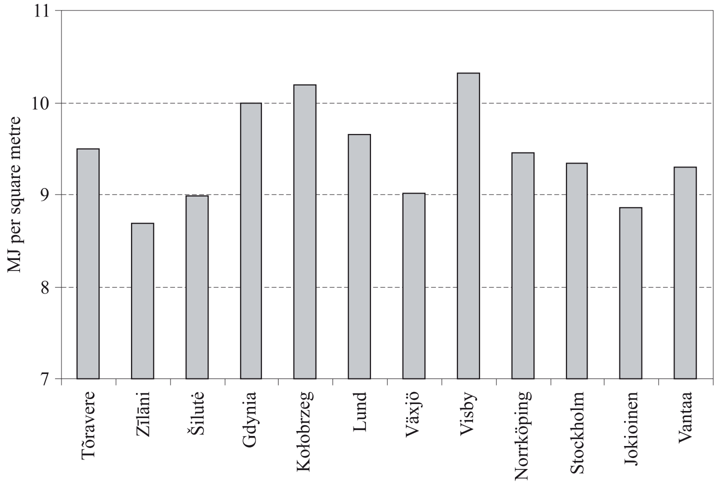

Figure 2. Regional differences in the annual average daily global radiation totals during 1996–2000

as the amount of solar radiation in winter is uniformly small. Figure 3 shows that in June the average daily total is 20.9 MJ m^{-2} at Visby, but only 16.0 MJ m^{-2} at Šilutė. Zīlāni, Šilutė, Växjö and Jokioinen, where the

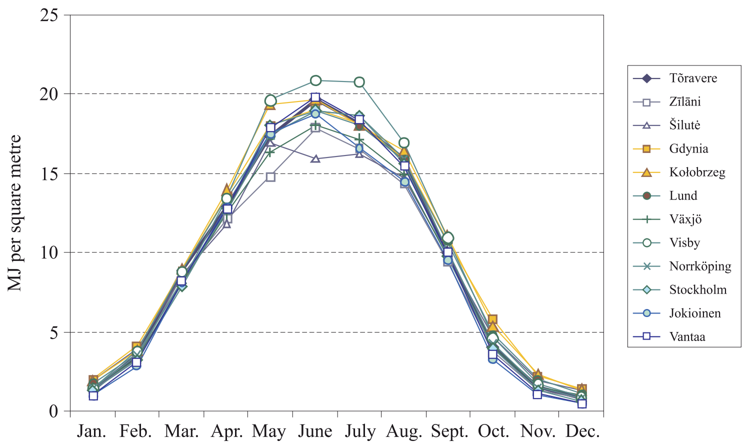

Figure 3. Monthly average daily global radiation totals at different sites during 1996–2000

annual average daily sum is < 9.0 MJ m^{-2}, are all inland stations where the cloud cover in summer is more extensive than over the coastal regions (Mietus 1998). Interestingly, Tõravere is also an inland station, but the atmospheric conditions seem to be more favourable for solar radiation here.

Spatial variability is due largely to astronomical factors. In summer the impact of the northward increase in the length of daylight compensates for the influence of the decrease in solar elevation on daily global radiation totals, but in winter both factors work in the same direction, so that there are large differences in the daily totals at the top of the atmosphere (TOA) between the northernmost and southernmost sites of the region under consideration (Table 3).

Table 3. Average TOA daily totals (MJ m^{-2}) at the northernmost and southernmost stations of the study region

Station	June	December
Jokioinen	42.3	1.9
Kołobrzeg	42.6	5.2

Spatial variability is also caused by differences in atmospheric transmittance. To separate the meteorological factors from the astronomical ones, the recorded daily totals were expressed as fractions of the respective daily totals at the TOA. These fractions still contain some astronomical influence, as the atmospheric transmittance depends on the solar zenith angle. Fortunately, this influence is much less than that of the atmospheric

Table 4. Monthly averages and standard deviations of the fraction of the TOA daily total over the whole region (12 stations)

Month	Average	Standard deviation
January	0.30	0.14
February	0.35	0.14
March	0.45	0.15
April	0.44	0.13
May	0.46	0.14
June	0.45	0.12
July	0.44	0.12
August	0.47	0.11
September	0.44	0.13
October	0.32	0.14
November	0.24	0.12
December	0.26	0.12

variability. Table 4 shows the average fractions of the TOA daily totals for different months. As expected, these quantities are the smallest in November and December. The standard deviations of the fractions of TOA daily totals over all 12 stations were calculated for every day and then averaged over the respective months. Table 4 shows that spatial variability was the least in August.

4. Temporal variability in global radiation

Astronomical factors should also be taken into account in the analysis of temporal variability, as the measured daily totals at the TOA may differ considerably at the beginning and at the end of several months (mostly in spring and autumn) and introduce additional variability into the estimated quantities. The annual cycle of the variability in the fractions of the TOA daily totals of global radiation at different measurement sites is presented in Figure 4. As the shorter time series normally show larger variability, Figure 4 shows only those stations where there are no gaps in the data sets.

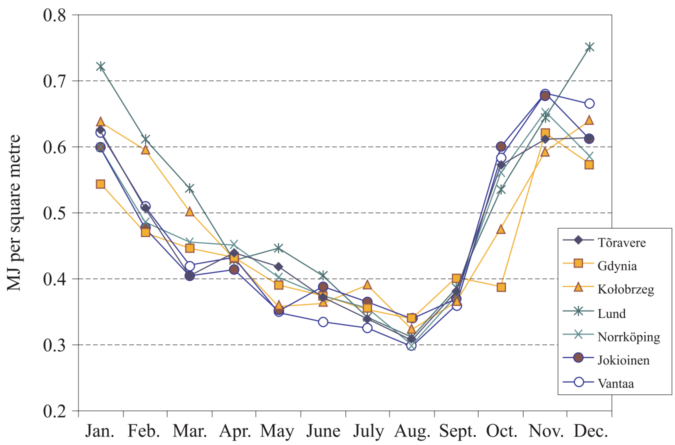

Figure 4. Coefficient of variation of the fraction of the TOA daily global radiation totals at different sites during 1996–2000

The coefficient of variation of the fractions of the TOA daily totals actually describes the variability in atmospheric transmittance (with regard to the daily totals). As is to be expected, the coefficient of variation is the largest from November to January, when the overall atmospheric transparency is low and variations in the amount of incoming energy due to atmospheric disturbances (clouds, aerosols, etc.) are comparable with the average flux. On the other hand, the variability of atmospheric transmittance is minimal not in June, when the incoming energy is maximal, but in August. Thus, the influence of atmospheric disturbances in this month is the weakest.

Figure 4 shows that in late winter and early spring the variability in the fraction of the TOA daily totals at Lund and Kołobrzeg is larger than at the other stations. In October the atmospheric transmittance on the Polish coast varies less than at the other measurement sites.

At most stations (with the exception of Lund) the coefficient of variation in December is smaller than in November and January. This fact can be explained by the uniform cloud cover that is typical of this month in the Baltic Sea region.

To detect the sites where the fractions of the TOA daily totals co-vary, correlation coefficients were calculated between the different stations. As one might expect, the fractions of the TOA daily totals are best correlated for the measurement sites that are situated close to each other. This is the case for Vantaa and Jokioinen, where the correlation coefficient is 0.92 in January and February and not less than 0.81, the June value. Evidently these sites are governed by similar cloud cover systems – stratiform cloudiness in winter and cumulus clouds in summer. The fractions of the TOA daily totals are also well correlated at Norrköping and Stockholm, where during most of the year the correlation coefficient is over 0.8; only in August, September, November and December is it between 0.75 and 0.8. Comparison of the correlation matrices for different months leads to the

Table 5. Correlation coefficients between the fractions of the TOA daily global radiation totals at different stations in April

Station	Tõravere	Zīlāni	Šilutė	Gdynia	Kołobrzeg	Lund	Väjö	Visby	Norrköping	Stockholm	Jokioinen
Zīlāni	0.72										
Šilutė	0.45	0.71									
Gdynia	0.28	0.46	0.64								
Kołobrzeg	0.20	0.33	0.49	0.75							
Lund	0.22	0.30	0.43	0.52	0.66						
Väjö	0.34	0.37	0.47	0.46	0.54	0.80					
Visby	0.39	0.33	0.41	0.43	0.49	0.45	0.65				
Norrköping	0.38	0.34	0.40	0.37	0.43	0.64	0.83	0.71			
Stockholm	0.48	0.39	0.44	0.39	0.41	0.51	0.67	0.70	0.81		
Jokioinen	0.49	0.31	0.18	0.09	0.17	0.21	0.33	0.29	0.37	0.57	
Vantaa	0.62	0.32	0.19	0.14	0.20	0.26	0.37	0.41	0.39	0.54	0.84

finding that the fractions of the daily totals of global radiation show the strongest correlation over the whole region in April (Table 5). This feature is also supported by Figure 4: the temporal variability of the atmospheric transmittance is similar all over the region under consideration.

5. Coastal measurements and parameterization from offshore meteorological observations

Comparison of our results with those obtained by Rozwadowska & Isemer (1998) shows that the average daily totals over the whole region (all data from 12 stations) differ somewhat from the daily totals obtained by the parameterization of ship-based observations (Figure 5). The meteorological parameters constituting the input to the parameterization model are cloud cover, humidity and air temperature. The number of observations during 1980–1992 was large, but they were distributed unevenly in time and space. As our estimates from coastal measurements were obtained during 1996–2000, the time periods do not coincide. Therefore, a rough estimate of the possible differences between these periods based on Tartu-Tõravere data (Russak & Kallis (eds.) 2003) is shown in Figure 6. Although the annual total for the later period is larger by only 2%, the monthly totals are smaller by 18% in December, by 12% in January and by 13% in February. They are larger by 7% in March, by 15% in August and by 22% in September.

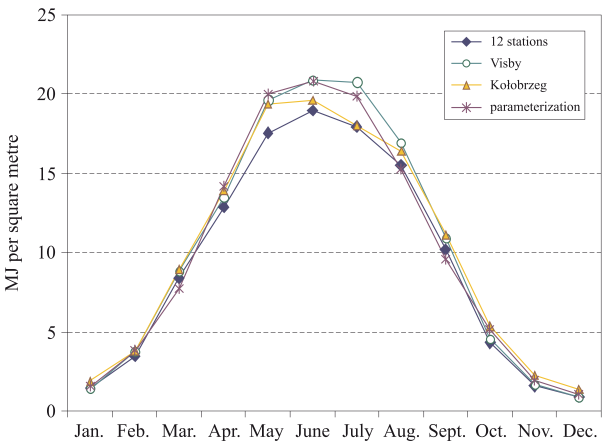

Figure 5. Annual cycle of the average daily global radiation total according to several sources: parameterization from ship measurements (1980–1992) (Rozwadowska & Isemer 1998), average over 12 coastal stations and at two measurement sites (1996–2000)

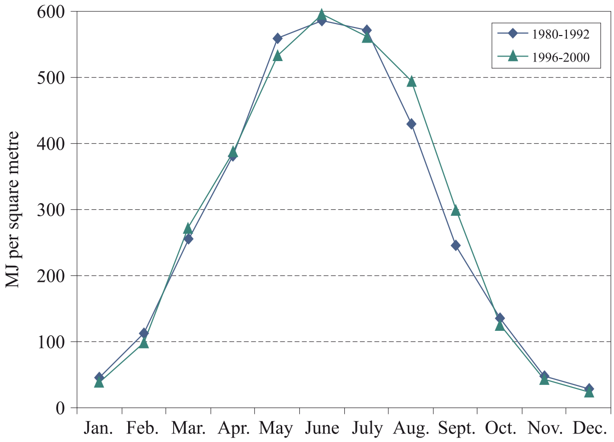

Figure 6. Monthly global radiation totals at Tartu-Tõravere for different time periods

The difference between the coastal measurements averaged over the whole region during 1996–2000 and the parameterization estimates during 1996–2000 is the largest in May, when the parameterization shows an average daily sum of 20.0 MJ m^{-2} and coastal measurements of 17.6 MJ m^{-2} (Figure 5). On the other hand, coastal measurements show somewhat (0.27…0.72 MJ m^{-2}) larger values in March, August and September. According to Figure 6, this can be attributed to some extent to differences between the various periods.

Figure 5 shows that the match is the best between the parameterization model outputs and the measurements at Visby, i.e. the site where the amount of the solar radiation is the largest. Figure 5 also shows the annual cycle at Kołobrzeg (second best according to the annual average), but this differs from the parameterization estimates to a greater extent than that at Visby. From this comparison, one can regard measurements of global radiation at Visby as representative of the average global radiation over the whole Baltic Proper.

A similar analysis for three parts of the Baltic Proper (Isemer & Rozwadowska 1999) shows that Visby data can be used to describe the solar radiation fluxes over the Baltic Proper between 57°N and 60°N. In Table 6 this region is denoted by N. The Kołobrzeg data give a good approximation for the region west of 15°E (denoted by W). The relative difference in both cases is maximal in March and September but does not exceed 20%. At least part of this difference as well as the difference in August can be ascribed to

Table 6. Average daily totals (in MJ m^{-2}) for different parts of the Baltic Proper from offshore parameterization and coastal actinometry

Month	Isemer & Rozwadowska 1999			Visby	Kołobrzeg
	Region N	Region S	Region W		
January	1.3	1.7	1.7	1.4	1.9
February	3.7	3.7	3.9	3.8	3.8
March	7.5	7.9	7.7	8.8	9.0
April	14.1	14.4	14.1	13.5	13.9
May	20.0	20.2	19.2	19.7	19.4
June	21.5	20.7	19.3	20.9	19.6
July	20.5	19.8	18.4	20.8	18.1
August	15.4	15.4	14.5	17.0	16.4
September	9.4	9.7	9.7	11.0	11.2
October	4.8	5.4	5.5	4.6	5.4
November	1.6	2.0	2.2	1.7	2.3
December	0.8	1.1	1.3	0.9	1.4

the differences between the time periods (Figure 6): in March the relative difference between the monthly totals at Tõravere is 7%, in August 15% and in September 22%. To describe the radiation field in the region south of 57°N and east of 15°E (the region denoted by S), Visby and Kołobrzeg give the best approximation, but both show rather large relative differences in winter. The Kołobrzeg measurements display larger values and the Visby measurements smaller values than those obtained by the parameterization of ship measurements. Very probably, this can be explained, at least partly, by astronomical factors.

6. Conclusions

Solar surface radiation varies considerably around the Baltic Proper. This variability is caused not only by astronomical factors, but also by spatial and temporal variability in atmospheric properties (cloudiness, aerosols).

The spatial and temporal variability in the fraction of the TOA daily totals of global radiation (practically atmospheric transmittance) is the least in August. In late winter and early spring, the temporal variability in the western part of the region under consideration is somewhat larger than in other parts of the Baltic Proper. In October it is smaller at Gdynia and Kołobrzeg than at other stations.

The spatial correlation of the fraction of TOA daily totals is the best between Jokioinen and Vantaa, but it is also good between Norrköping and Stockholm. All over the region these values are correlated best in April.

Comparison of coastal radiation data with those obtained by parameterization based on measured offshore meteorological parameters shows that the monthly average global radiation at Visby is a good approximation for the whole Baltic Proper region and especially for its northern part. For the south-western Baltic Sea, the measurements at Kołobrzeg describe the radiation field best.

Radiation measurements at Visby and Kołobrzeg can be used to characterize the radiation field over the sea if climatological problems or the phenomena of monthly and seasonal scales are studied. For short-term (daily) phenomena, some other method, e.g. in situ measurement or a numerical weather prediction model output, has to be used.

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Paper II

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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

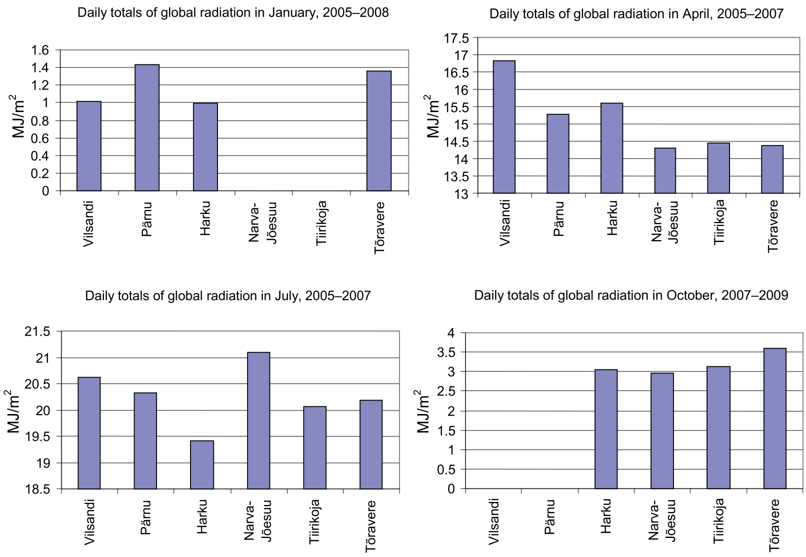

Fig. 2. Monthly average daily totals of global radiation.

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).

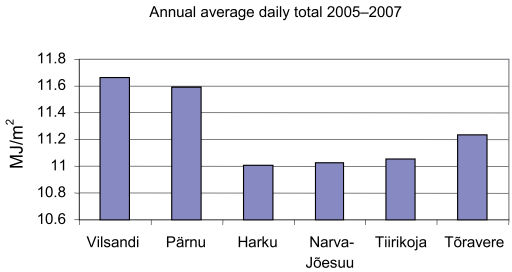

Fig. 3. Annual average daily totals of global radiation.

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.

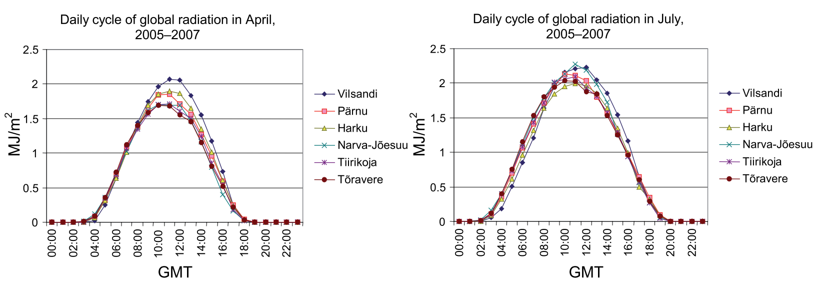

Fig. 4. Daily cycles of global radiation in April and July.

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

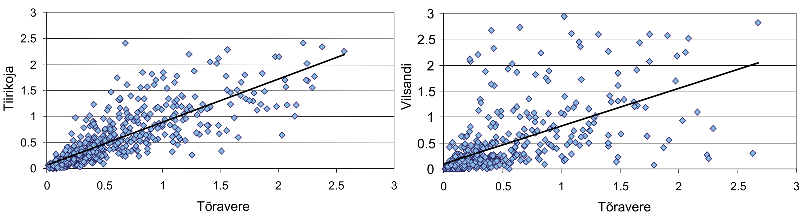

Fig. 5. Regression lines between afternoon (11:00–12:00 GMT) hourly totals (MJ/m^2) at two coastal stations and Tõravere in overcast conditions.

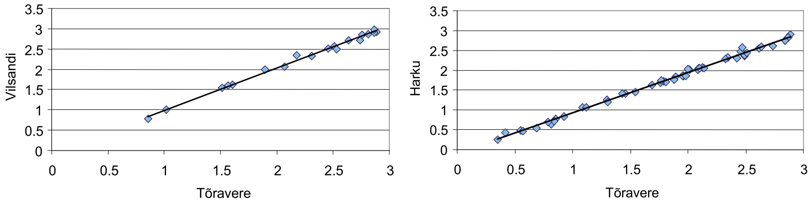

Fig. 6. Regression lines between afternoon (11:00–12:00 GMT) hourly totals (MJ/m^2) at two coastal stations and Tõravere in clear conditions.

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.

ACKNOWLEDGEMENTS

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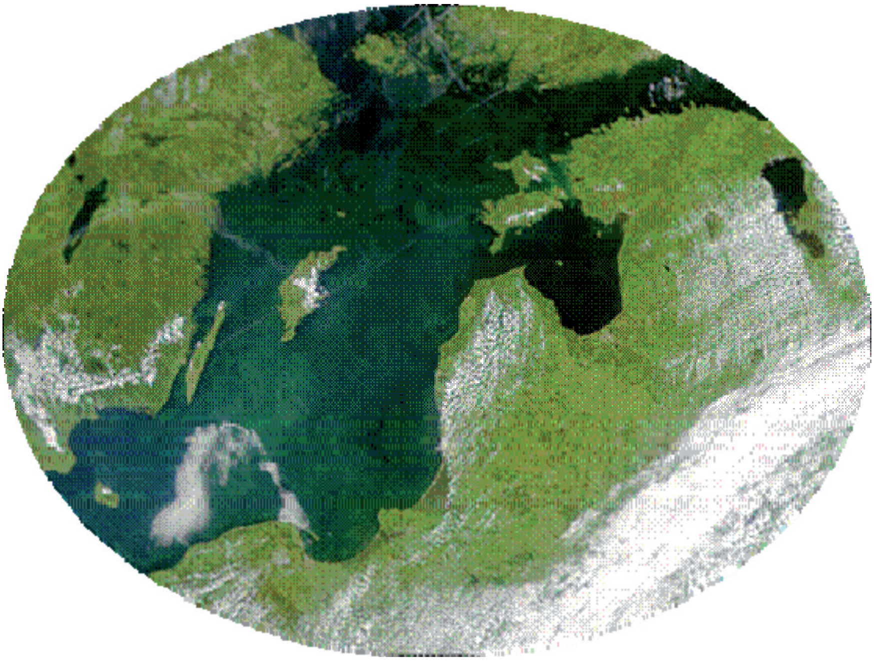
Eesti automaatsetes ilmajaamades mõõdetud summaarse kiirguse tunni- ja päevasummade regionaalne jaotus

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.

Paper III

Erm, A., Alari, V., Buschmann, F., Kõuts, T., Raudsepp, U., **Loitjärv, K**. 2010. Near bottom velocity and turbidity measurements in coastal waters of NW Estonia. In: IEEE-Inst Electrical Electronics Engineers Inc, 2010: 4th IEES/OES Baltic Symposium, Riga, Latvia, August 25-27, 2010, 1-8.



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Near bottom velocity and turbidity measurements in coastal waters of NW Estonia

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Abstract - **Dependence of near bottom currents and turbidity on wind and wave parameters is analyzed. Measurements campaigns with an acoustic Doppler velocymeter (ADV Field/Hydra, SonTek/YSI) were curried out in two bays in north western Estonia – the first one on Naissaar Shallow in Tallinn Bay (22.12.2009 -12.01.2010, water depth 9 m, 37 cm from the bottom) and the second one in Keibu Bay (03.06.2010 – 26.06.2010, water depth 7m, 27 cm). Near bottom velocities were recorded with frequencies 2 Hz (currents) and 0.2 Hz (wave induced orbital motion). Additionally the water turbidity at the same level as flow measurements was performed using an integrated turbidity meter OBS 3+ (YSI). Wave parameters were recorded using a pressure wave gauge (PTR Group, Tallinn).**

The ADV measured flows consist of wind induced currents, wave induced orbital motions and turbulence. Maximum of wind induced currents reached meanly 10 - 15 cm/s at both measurement locations, while the maximum near bed orbital motions peaked over 40 cm/s. Measurements showed that the near bottom velocities in Keibu Bay were in correlation with wind speed, but turbidity values showed a significant increase only in some special weather conditions. From the comparison of ADV, turbidity meter and wave gauge characteristics it followed that turbidity was clearly depending on the wave energy. It means only quite long and high waves inducing bottom orbital velocities (calculated from the wave gauge data) over 20 cm/s were able to resuspend bottom sediments.

I. Introduction

The resource of Estonian wind energy (both/ onshore and offshore) is comparable to (the capacity of) Denmark. There was produced around 72,3 kW electricity per 1 km^2 in 2004 (43,094 km^2, 3117 MW), but only 1,28 kW in 2006 in Estonia (45,277 km^2, 58,1 MW), hence, considering the fact that the population density in Denmark is around five times higher than in Estonia, the relative potential of Estonia is multiply higher.

It is well known, that maritime facilities require environmental impact assessment, which presume various information about physical, chemical and biological processes that take place in seawater, also facts about sea life, bottom flora and the geological structure of the sea bottom. Besides, the human activities - ship lanes, fishing, boating and tourism – could be taken into consideration.

On the base of available geological database, long time wind measurement data and existing electricity network these areas were selected as the most favourable sites to build on the wind farms [1-3] and brought into more thorough environmental investigation. The both polygons are locating near the north-west coast of Estonia, where a third of Estonian population is leaving. The first place (~20 km^2) is locating in Tallinn Bay about 13 km away from the capital of Estonia Tallinn. There is possible to put up about 100 turbines (3MW, 80 – 105m high). The second region locates nearby the SW coast of Suur-Pakri Island about 50 km to the west from Tallinn. Available territory for wind farm here (the coastline incl.) is 15-16 km^2, what enables to put up 60-90 turbines (200-300 MW). Both the areas are with sandy bottom, open to the prevailing winds, and have a good developed infrastructure on the coast.

The underwater light field, currents and wave parameters in these areas were also measured in October 2008 [1]. It was concluded that the water of the Naissaar Shallow study area was twice clearer as the water of Pakri study area, and that in case of superposition of many components the current velocity during favourable winds reached up to 45 cm/s. In Pakri Bay the wave regime was more stable as at the Naissaar Shallow, the maximum significant velocities reached 6 cm/s, and the mean current velocity was in correlation with the wind activity. It was followed from the study that the currents' induced transport of bottom sediments must be taken under the attention. Currents were also profiled in November 2006 near Aegna Island east from the Naissaar Shallow [4. During a calm weather (SW wind 2.5-5 m/s) two water layers were clearly differentiated, the upper one 3m from the surface moving with the velocity 0.4 m/s in direction 315°, and the lower layer from 4 m and deeper with the velocity ~0.1 m/s 10 -30 deg. to the left.

Long-term, seasonal, and diurnal variations of the winds measured in meteorological station on Pakri Peninsula in 1969–1992 are analyzed by Keevallik and Soomere [3]. A strong diurnal cycle in the wind speed observed may be a sign that the station does not represent offshore winds well and special observations should be undertaken to check if the daily cycle of wind speed is closer to Pakri measurements or to Naissaar and Hanko observations, where a neglible diurnal cycle appears.

The wind regime over Tallinn Bay is analyzed by Keevallik [5]. It was shown that the most probable wind direction in Tallinn Bay is SW, moderate and strong winds have a secondary maximum in NE, and winds from SE and south are mostly weak.

II. Methods and measurements

Measurements were carried out from 22 Dec. 2010 to 12 Jan. 2010 on Naissaar Shallow in Tallinn Bay and from 3 to 26 June 2010 in Keibu Bay (Fig.1). Near bottom currents and turbidity were logged with a set consisting of acoustic Doppler velocymeter and turbidity meter OBS 3+ (ADV Field/Hydra, SonTek/YSI). This set was submerged to the sea bottom (20 m on the Naissaar Shallow and 7 m in the Keibu Bay), and currents and turbidity (at the level 19 and 27 cm from the bottom respectively) were logged by burst regime. The ADV measured flows consisted of wind induced currents, wave induced orbital motions and turbulence. The low frequency data (sampling rate 0.2 Hz, burst interval 20 min, sample time 120 s, 24 samples per burst) are analyzed in this issue. Turbidity was measured in the same regime.

Simultaneously the wave parameters were recorded using a pressure wave gauge (PTR Group, Tallinn), and in Keibu Bay the bottom current measurements were supported by current measurements at 3.5 m from the sea bed using a second current meter (RDI WH Sentinel, 300 kHz)).

Wind data originate from an online available weather station on Tallinn Shallow and from a portable weather station on the Cape Toomanina (Fig.1) south-west coast of Keibu Bay mounted specially for the measuring campaign.

Fig.1. Measuring sites Keibu station and Naissaar Shallow, weather stations near Keibu Bay and on the Tallinn Shallow. . Pakri 2008 – station were in autumn 2008 the current measurements were carried out.

III. Results and discussion

A. *Keibu Bay*

We start the analysis from Keibu data, because the wind conditions there were more variable than in Tallinn Bay. At least five periods with wind speed over15 m/s could be identified within the logging cycle (Fig.2). Mostly these strong winds were blowing from westward. Near bottom currents commonly remained under 5 cm/s, and only in few cases by winds exceeding 15 m/s achieved values over 10 cm/s for a short time.

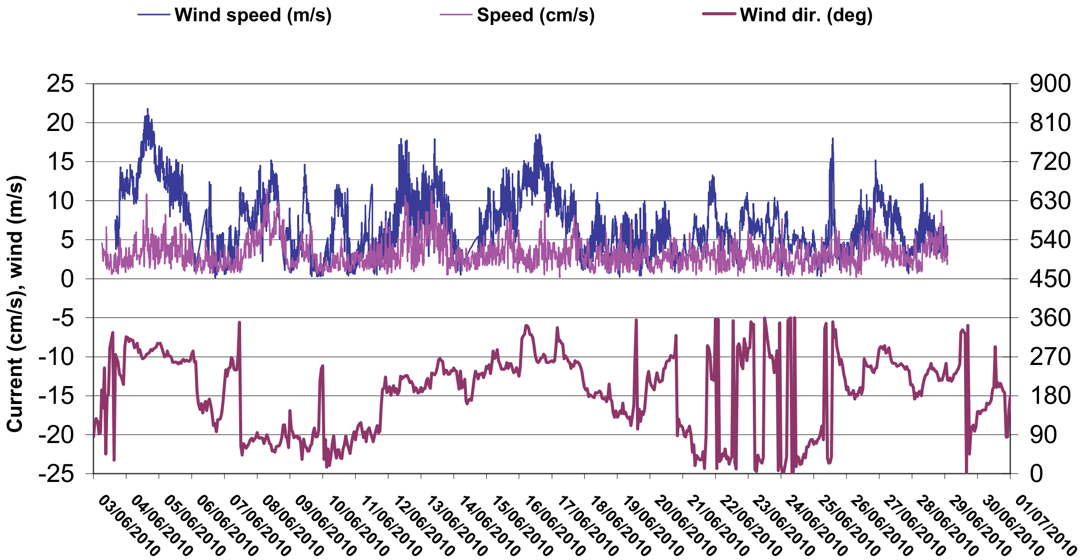

Fig. 2.Parameters of wind (speed and direction) and near bottom current speed

Currents in the subsurface layer (3.5 m from the bed) showed the same speed range as near bottom currents (up to 13 cm/s) and principally the same time dependence also – water was moved to the NW with about the same mean velocity at the both elevations (Fig. 3). A rapid upwelling simultaneous to a rapid (2h) wind change (4 m/s, 350 deg – 10 m/s, 45 deg) was registered in the noon of 10 June (Fig. 3c).

Progressive vector diagram show that at least five distinctive subperiods disgregated by steep turns of current up to 180 deg could be identified inside the all measurement cycle (Fig. 4a). As long shore as well currents out of the bay were observed in the progressive vector run. The currents were meanly opposite of E and W winds and perpendicular (turned to the left) to NW and SSW wind. Subsurface currents showed almost the same behavior (Fig. 4b).

Originating from the wind frequency diagram (Fig. 5a) W and NW winds were dominating in Keibu Bay. One can see in Fig. 4a that the total wind force was aggregated into a little angular - practically all winds over 5 m/s were blowing to the sector from N to W, winds over 10 m/s to the W and NW, and over 15 m to the NW and W rhumbs (222 samples only).

Turbidity values (Fig. 6) show a dependence on the bottom current values only if current speed exceeded 15 cm/s, i.e. on 4–6, 12–14 and 16–17 June. In other time there was no correlation between current and turbidity. As we have measured simultaneously also wave parameters, near bottom orbital velocities of waves could be calculated. These values amount to 45 cm/s, and even if directional current is below 10 cm/s the orbital velocities are sometimes 15–20 cm/s and could generate the bottom resuspension. So, turbidity is an indicator of wave orbital velocities rather than directional bottom currents.

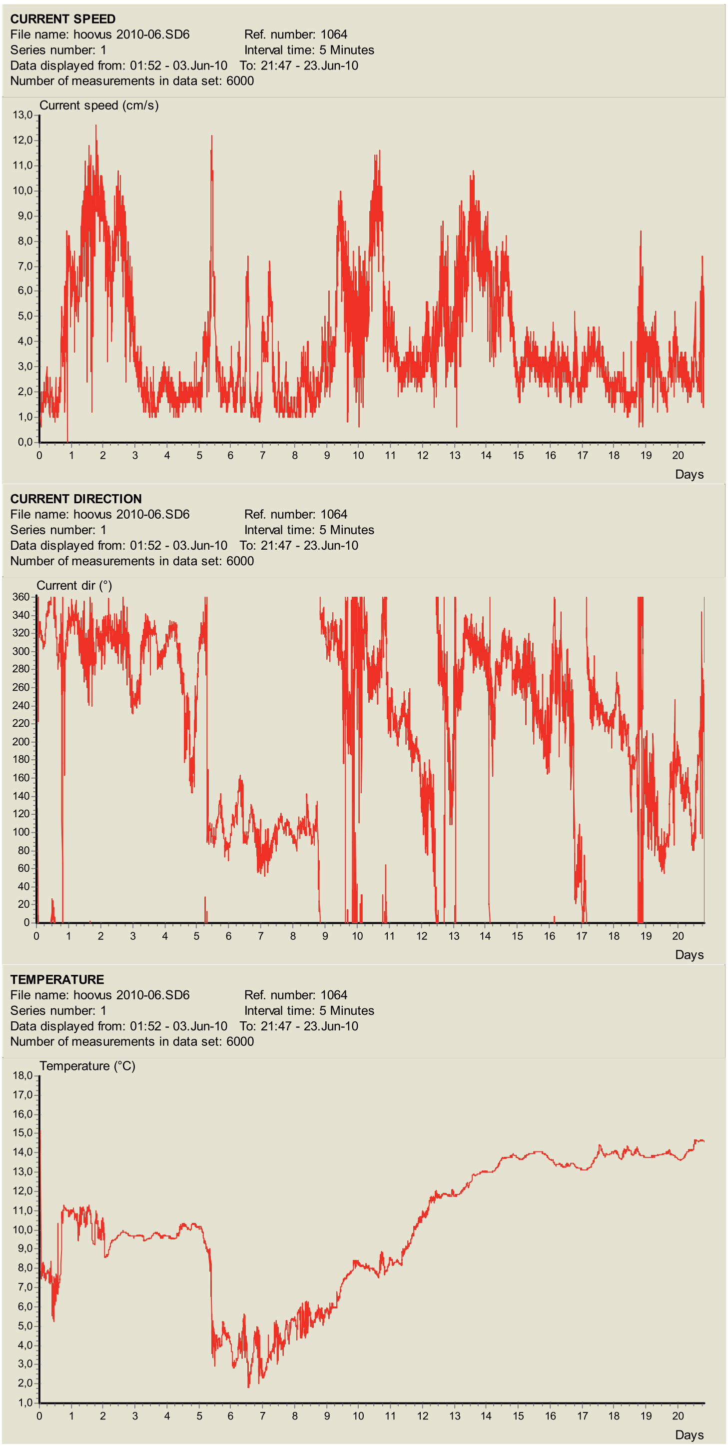

Fig. 3. Parameters off subsurface layer – current speed (a), direction (b) and water temperature (c).

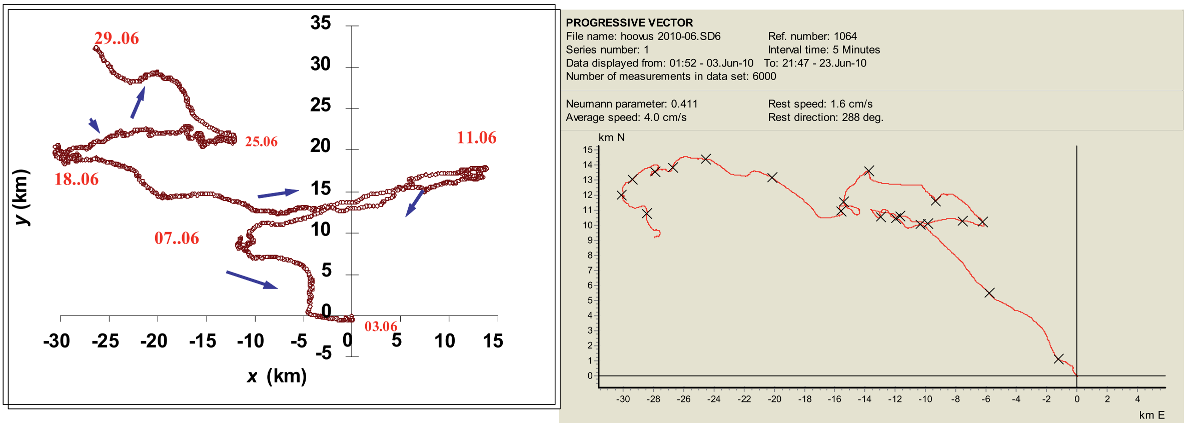

Fig. 4. Current progressive vectors of near bottom layer (a) and subsurface layer (b).

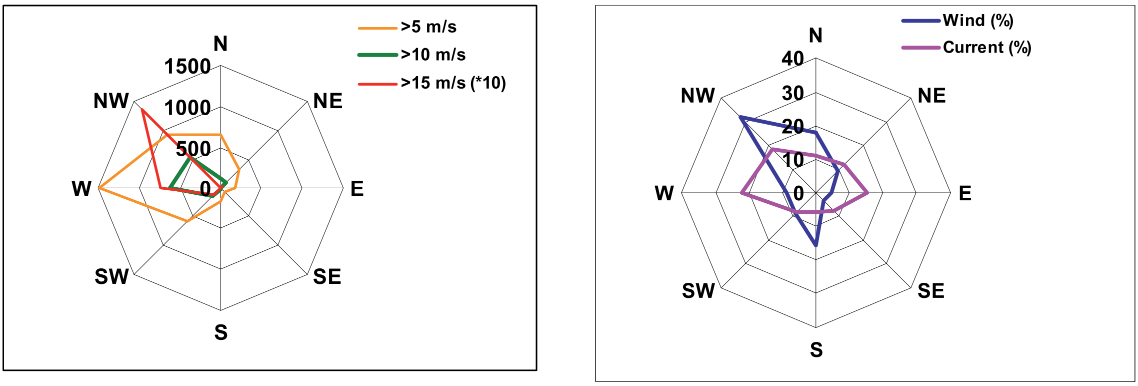

Fig.5. Wind frequency diagram (a) and distribution of wind
and near bottom current vectors (b) in Keibu Bay in June 2010.

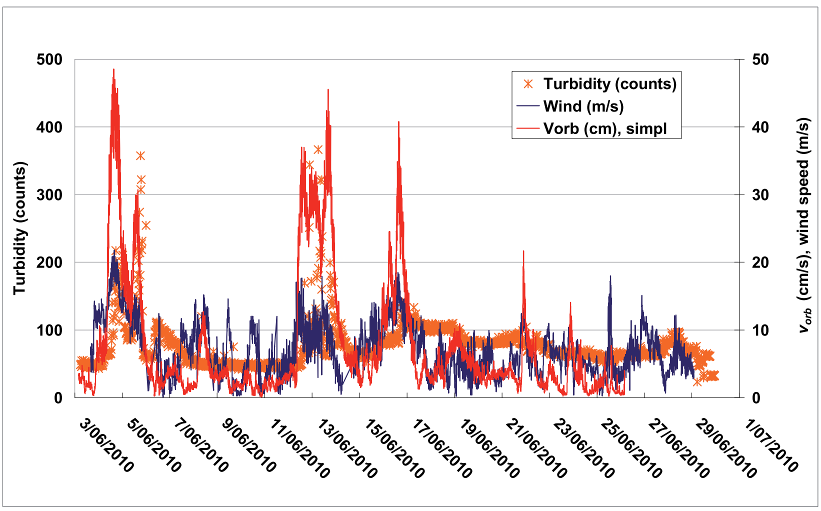

Fig. 6. Bottom current, turbidity and waves' orbital velocity in the Keibu Bay.

B. Naissaar Shallow.

On the Naissaar Shallow, where the measurements were made in a deeper area (20 m) as in the Keibu Bay, eventful near bottom currents (~10 cm/s) were registered only at the beginning of logging - from 22 to 27 December 2009. Variable wind up to 15-25 m/s was blowing in this period (Fig. 7a). The most active time interval was 25-26 December, when the east wind passed through a maximum of 25 m/s. It should be mentioned here, that the real winds in the measuring site probably were 10-20% weaker, because the shallow is somewhat restricted by islands and coast here.

Run of the currents was more unstable as the wind run. In many cases (on 25.12, 28.12, 01.01, 04.01 and 06.01) the current direction passed through the north while wind was rising, and stand at a more stable level between S and SE after that (Fig 5a). Dependence of turbidity on the wind, current and wave intensity was identified only during a storm on 25-27 Dec. (Fig5b). In periods, even by quite strong winds (10-15 m), there was no detectable effect. A week increase between 28 Dec. and 02 Jan. could be caused on sand mining works in the vicinity of the measuring site. Measurements on the Naissaar Shallow show clearly, that in the depths of 20 m and more, winds over 20 m/s are needed to generate waves able to move bottom sediments.

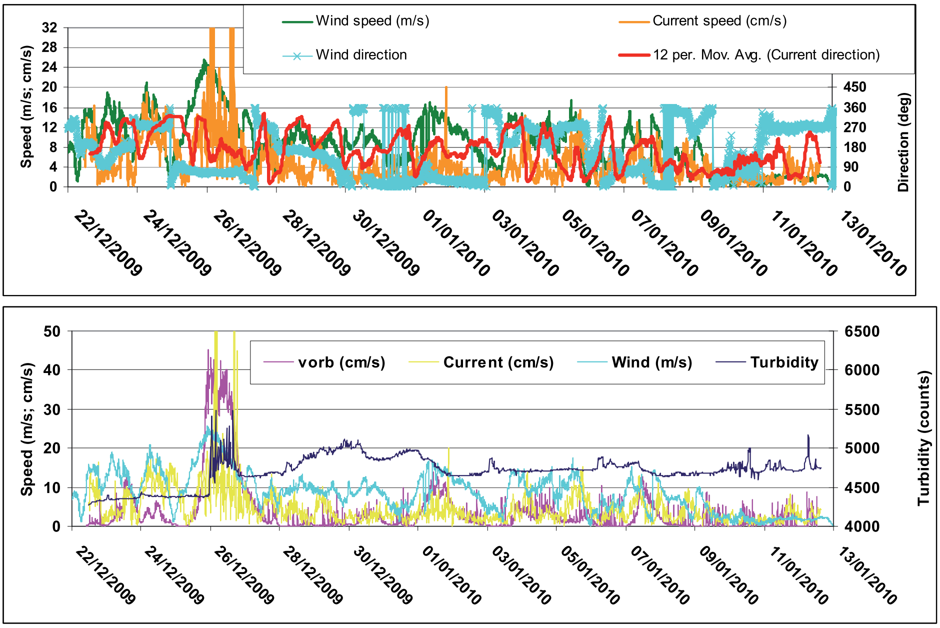

Fig. 7. Wind and bottom current parameters (a) and turbidity and waves' orbital velocity (b) in the Keibu Bay.

III. Conclusions

Combining of current, wave and turbidity measurements give very useful information about processes on the sea bed, about critical weather conditions when resuspension starts.

Originating from wind and current distribution diagrams W and NW winds were dominating in the Keibu Bay, inducing E and W near bottom currents, i.e. mostly opposite to the wind force, and out of the bay as expected by these winds. The currents were meanly opposite of E and W winds and perpendicular (turned to the left) to NW and SSW wind. Subsurface currents at 3.5 m from the sea bed and sea level also showed the same behavior. A rapid upwelling simultaneous to a wind change (4 m/s, 350 deg – 10 m/s, 45 deg) only in two hours was registered in the noon of 10 June.

In the depths at least up to 7 meters wave generated resuspension dominates over that induced by directional near bottom currents. In the depths 20 m and more winds over 20 m/s are needed to resuspend bottom sediments.

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