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A new approach to local climate identification in the Baltic Sea's coastal area

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Abstract. One of the main tasks of this work is to investigate a different and new approach to coastal climate identification in the Baltic Sea's coastal areas. A different approach of spatial correlation between solar net shortwave radiation flux and air temperature data helps to distinguish and derive areas which receive the same amount of energy but have a different average air temperature than the surrounding territories. Most of the successful climate classifications consist of three climatic variables (temperature, precipitation and temperature range). This work establishes that bivariate correlation maps of solar net shortwave radiation flux and air temperature can also be successfully used to identify local coastal climate around the Baltic Sea. The data used is the WorldClim global climate dataset and NOAH025_2.0 model output. Model data is used for calculating the correlation maps and is later compared to long-term air temperature range maps of the Baltic Sea's coastal area. The study shows that in combination with standard classification methods, the research results can later be applied for classification of local coastal climates. Thus, the method proposed opens new potential to study coastal climate with a higher degree of accuracy. However, further studies are required to characterize the behaviour of this method for other than temperate climates.

Keywords: *Baltic Sea; coastal climate; solar radiation; air temperature change; climate classification*

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INTRODUCTION

Applications of climate classifications are often used to study climate and climate change. The incoming solar radiation to the Earth's surface and its atmosphere is the main source of energy for the planet, which is quite often underrated in classifying local and regional climate. In the past, a barrier for accurate studies might have been a coarse network of meteorological stations that do actinometric measurements. Recent development of software and high-resolution meteorological satellites provide the ability to qualitatively investigate solar radiation by utilizing research results to investigate regional climates and create topographic maps of climate parameters (Pettazzi, Salson 2012). Coastal areas are one of the most densely populated in the world. Around 40% of the total population of the world (2.4 billion people) live at 100 km distance from the coast (UN factsheet 2017). The coastal areas within the 100 km distance and 100 m elevation are considered one of the most vulnerable to climate change and over 10 percent (600 million) people live in the coastal areas that are less than 10 meters above the sea level.

The climate classification methodologies are used to identify and map climate types and their geographical extents. This is done by discretizing a number of local climates into a more easily manageable amount of climate types. This simplifies the complex spatial variability into a form that is easier to understand and operate. Classifications of climates are also used to visualize global climate datasets (Fraedrich *et al.*

2001; Diaz, Eischeid 2007; Zhang, Yan 2014; Chen, Chen 2013; Spinoni *et al.* 2015) in order to map and visualize climate change in terms of shifting geographical boundaries of major climate types. Climate classifications are often applied to historical data and model predictions and even interpret and simulate paleoclimates (Guetter, Kutzbach 1990). Similar studies are done to simulate distribution of climate types in the future as predicted by climate models (Beck *et al.* 2005; Gallardo *et al.* 2013; Hanf *et al.* 2012; Mahlstein *et al.* 2013).

The most popular and used climate classification in the world is the Köppen-Geiger classification scheme (Köppen 1936) and especially its modern implementations (Kottek *et al.* 2006; Peel *et al.* 2007; Spinoni *et al.* 2015). This became a standard in mapping climatic data collected from world's meteorological networks. Despite that, the Köppen-Geiger classification scheme (Köppen 1936) has shortcomings, with the largest one being the core methodology itself. The Köppen-Geiger classification scheme is based on the assumption that delineation of climate types can be derived from different plant regions (Thornthwaite 1943) by expressing their boundaries in terms of temperature and precipitation. It is classified by a hierarchy of predicate statements (Spinoni *et al.* 2015) that assigns a class to a local climate on the basis of the values of long-term monthly means of temperature and precipitation. The system lacks the notion of similarity between local climates, making it impossible to assess natively the uniformity of climates within a climate type. It also lacks the notion of similarity between climate types apart from organizing them into a hierarchy (Netzel*,* Stepinski 2016*)*. This becomes an issue when using global climate classifications in mapping climate change, since the climate types permanently set applying such classifications to results of climate models that are mapping future climatic zones (Netzel*,* Stepinski 2016) do not account for the possibility of emergence of new climate types.

Climate change changes the landscapes and local climates around the globe, which prompts many studies on climate zone shifting for the 21st century which are often based on the Köppen-Geiger classification scheme (Beck *et al.* 2005; Gallardo *et al.* 2013; Hanf *et al.* 2012). However, many landscapes have different change uniformity and coastal areas are exceptionally sensitive to the climate change because they are affected by warming seas and atmospheric-sea-land interactions. Naturally, more detailed studies are required to research climate change in the more sensitive territories such as coastal areas. The Baltic Sea is one of the areas that are most sensitive to climate change in the world. The Baltic Sea is a marine area with one of the highest recorded surface air temperature increases during the past century (Rutgersson *et al.* 2014; Rukšenienė *et al.* 2017), and specific warming started from the last decades of the 20th century (Lehmann *et al*. 2011; Dailidiene *et al.* 2012; BACC II Author Team 2015). Climatic fluctuations in the Baltic Sea region are associated with large-scale changes in atmospheric circulation over the North Atlantic (Lehmann *et al.* 2011). The complexity of physics of the Baltic Sea extends far beyond the typical features of many other water bodies of comparable size (BACC I Author Team) and often exhibits substantially different climatic changes in its different parts (Soomere *et al.* 2015), whereas spatial scales of changes with different signs are sometimes just a few tens of kilometres (BACC II Author Team, 2015; Rukšenienė *et al.* 2017). The waters of the Baltic Sea are generally cold and tend to freeze in the northern areas every winter, while in southern and central parts the surface waters are always free of ice. These gradients of sea surface temperature (SST) and air temperature in the Baltic Sea's region cause large differences in climate and ecological conditions along the sea in different regions and especially in coastal areas. Recent studies confirm that the effects of climate warming will first be observed in parameters related to the heat balance, such as air temperature, sun radiation, and sea water temperature (BACC I Author Team, 2008; BACC II Author Team, 2015; Omstedt *et al.* 2014). It should be noted that in the context of climate change, the mechanism of atmospheric-sea-land interaction has changed (Rukšenienė *et al.* 2017).

Naturally, most of the climate classifications consist of three climatic variables indicators, like air temperature, precipitation and temperature range. However, this work establishes that bivariate correlation maps of solar net shortwave radiation flux and air temperature can also be successfully used to identify local coastal climate and climate change around the Baltic Sea.

MATERIALS AND METHODS

In this paper we focus on a different approach to local climate identification and mapping within the Baltic Sea's coastal areas during the period from 1951 till 2000. The study area (˚W5.2734, ˚S52.2246, ˚E31.5527, ˚N68.3965) is slightly larger than the Baltic Sea alone and is represented by the coordinates dispersed in a square around the Baltic Sea region (Fig. 1). The Baltic Sea stretches from 53°N to 66°N latitude and from 10°E to 30°E longitude and is over 1600 km in length and on average 193 km in width, yet in the Köppen-Geiger classification it encloses only two climate types (temperate and subarctic). The coastline of the Baltic Sea stretches for over 8000 km, which may include more than a few local coastal climates within the two climate types derived by the Köppen-Geiger classification.

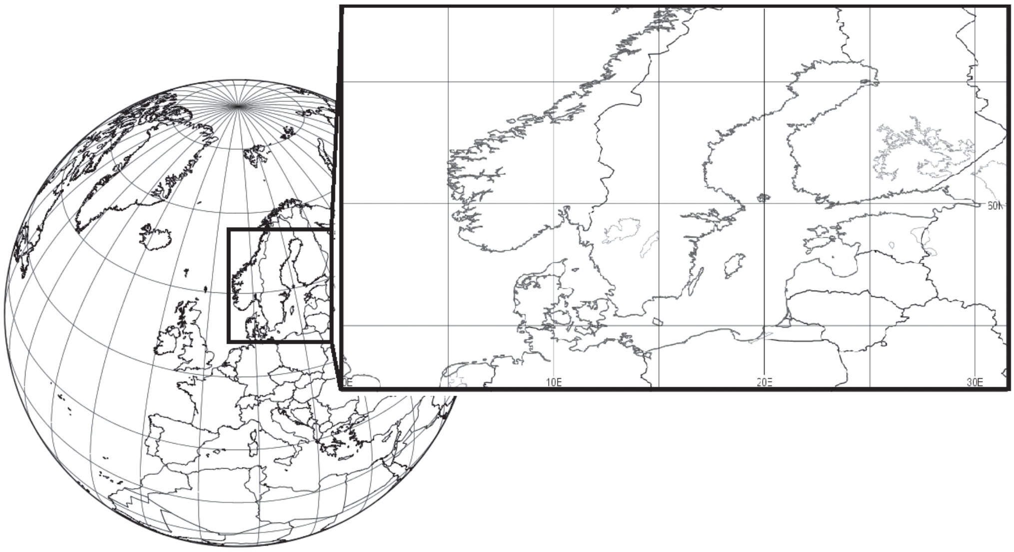

Fig. 1 Research area around the Baltic Sea ˚W5.2734, ˚S52.2246, ˚E31.5527, ˚N68.3965

Since the research area is quite large and high-resolution products require much more computing power the resolution of the data has to be selected accordingly to fit into computationally acceptable time. Hence the data used was the output of the NOAH025_2.0 model (Li *et al.* 2018; Rodell *et al.* 2004) which consists of 0.25 × 0.25 degrees resolution monthly means data, which was used for calculating correlation between solar net shortwave radiation flux and air temperature. The data was chosen for the years 1950 to 2000 to be more homogenous to WorldClim data. The resolution of 0.25 degrees was chosen for the calculations because of its lower, relatively coarse grid for computational considerations as mentioned before. Considering the goal of this paper to suggest a different approach for mapping local coastal climate around the Baltic Sea this resolution is sufficient. The NOAH025_2.0 model data consists of monthly mean values and daily mean values, but the monthly mean data was selected for the research because of homogeneity reasons with WorldClim data. More information about the NOAH025_2.0 model can be accessed in the model website. WorldClim global dataset (Hijmans 2004; Hijmans *et al.* 2005) is given on a 30-arc-s (~1 km^2 or 0.93 × 0.93 = 0.86 km^2 at the equator) grid and has the spatial extent of 90°N–60°S over all longitudes. WorldClim data is widely used in climate change studies because of its rather high resolution, which is dense enough for regional and local climate studies. The grid cells contain mean-monthly climatic variables interpolated from a meteorological time series measured from a worldwide network of meteorological stations between 1950 and 2000. The WordClim data and about the dataset can be accessed on the information WorldClim website, and a more detailed perspective is provided in the publication on the dataset (Fick, Hijmans 2017).

The WorldClim datasets consist of two versions, the 1.4 and second version 2.0. The 2.0 version of WorldClim dataset was selected because of its higher quality of the data over the 1.4 version but that limited the selection of data period from 1950–2000 to a period of 1970–2000. From the WorldClim dataset 2.0 the monthly minimum and maximum temperature data of the 30-year period (1970–2000) was selected to calculate and map the mean air temperature range map (for the 1970–2000 period) $D = T_{max} - T_{min}$, which is a measure of variability of the climatic thermal condition. The terms T_{min} and T_{max} are mean monthly values of minimum and maximum temperature. At first the monthly temperature range values were calculated by selecting each month's highest and lowest temperatures and later averaged to a 30-year period mean air temperature range values map.

Local daily maximum temperatures are largely dependent on incoming solar radiation; therefore, the more solar radiation gets the specific area, the higher the value of daily maximum temperature. Considering the high heat capacity of water 1 calorie/gram °C = 4.186 joule/gram °C, which is higher than any other common substance, the minimum and maximum temperatures near coasts are regulated by air-sea interaction. The water acts as a heatsink, absorbing the heat during the day and the warmer periods of the year and releasing the heat in a form of longwave radiation during the night or colder periods of the year. Hence, the effect of the Baltic Sea to its coastal air temperatures is indicated by lower correlation coefficient levels between solar shortwave net radiation flux and air temperature.

Spatial correlation maps are calculated using matching resolution data, based on simple linear regression equations, in which the correlation coefficient **r** is (x, y) in grids:

$$r = \frac{\sum_n (P1 - \overline{P1})(P2 - \overline{P2})}{\sqrt{\sum_n (P1 - \overline{P1})^2 \sum_n (P2 - \overline{P2})^2}}, \quad [1]$$

$$\overline{P1} = \frac{1}{n}\sum_n P1, \quad [2]$$

$$\overline{P2} = \frac{1}{n}\sum_n P2. \quad [3]$$

The sample data are represented by **P1** and **P2** from both parameters – net short-wave solar radiation flux and air temperature, **n** is the effective sample size of each member. If the effective sample size **n** is less than 2, the calculations are not performed, and the default value **r** is set to r = 0.

After all calculations have been made on all levels, a source data file with correlation coefficient (**r**) and effective sample member (**n**) at each point of the grid (**x, y**) is created, then the source data is transferred to the two dimension map for further processing and visualization. Spatial correlation values between solar net shortwave radiation flux and air temperature then have been plotted on the map. GIS platforms are used for the mapping and interpretation of these correlation maps which can later be applied to derive areas over which air temperature is influenced by the Baltic Sea.

The NOAH025_2.0 monthly mean data was divided into three periods (1951–1980; 1961–1990; 1971–2000) respectively to produce standard 30-year periods as suggested by the WMO (*World Meteorological Organization*) guidelines. These timelines were selected because in most of scientific publications it is found that the largest changes in air and sea temperature rise began in the late 1980s and 1990s (Houghton *et al.* 2001). Considering that the data ranges only for a 50-year period, the three different 30-year periods were selected to provide better comparison of climate variability. However, a period of 30 years may not be sufficient to capture the full potential range of variation of an element; therefore, additional whole 50-year data calculation was made to better represent the long-term conditions of the Baltic Sea's effect on its costal air temperatures. In order to plot the changes in the correlation coefficient maps between the three 30-year periods of 1951–1980, 1961–1990 and 1971–2000, data of each period map was subtracted arithmetically from the previous period. The basis of producing a difference map is simple: Grid C = Grid A – Grid B, Grid A and Grid B are the periods compared as Grid C is the resulting difference map. In these maps, positive changes represent the decrease of the Baltic Sea's influence over the coastal air temperatures, and negative vice versa. The mean monthly temperature data from the NOAH025_2.0 model was used to calculate the average temperature of the entire research area for each individual month for the whole three 30-year periods. The visualization of this data can help to determine the average temperature changes for each month of the year when comparing the three 30-year periods.

RESULTS

This work investigates a different approach to coastal climate identification in the Baltic Sea's coastal areas. Research results indicated a different approach of spatial correlation between solar net shortwave radiation flux and air temperature data helps to distinguish and derive areas which receive the same amount of energy but have different average air temperature than the surrounding territories.

Despite the small changes during the three 30-year periods (Fig. 2) all of the maps display same areas as affected by the Baltic Sea or the Atlantic Ocean. For example, a strong influence of Scandinavian Mountains (Scandes) is seen in the Scandinavian Peninsula that blocks the expansion of humid temperate marine climate towards inland. However, the Danish straits with a lower altitude terrain lets the humid marine temperate air masses to pass further inland, the lower the correlation between air temperature and shortwave net incoming solar radiation flux, the higher the oceanic influence on air temperatures over the area. The influence of the higher terrain is evident throughout the research area by blocking the passage of the coastal and marine climates towards inland. The small patches of lower correlation surround the north-western part of the Bothnian, where again the further expansion of coastal climates towards the Scandinavian Peninsula is outweighed by quickly rising terrain gradient moving inland. The lower lands in the Scandinavian Peninsula surrounding Stockholm and Uppsala and Vattern and Vanern lakes allow larger areas for marine and coastal climates expansion. The lowlands in southern Denmark and northern coasts of Germany and Poland have the lowest correlation rating, suggesting that the influence of the Baltic Sea and Atlantic Ocean is the highest in the whole research area. This low correlation zone expands to the conclave of Kaliningrad, where it can be blocked by the higher altitude terrain near Gdansk. The influence of the Baltic Sea to Lithuanian coastal air temperatures seems to expand up to the highs of Samogitia also covering nearly the whole western part of Latvia. At the southern coast of the Gulf of Finland, the lower correlation area expands eastward until it reaches a higher terrain; however, in the north-western part of the gulf the lower correlation zone stretches far north of the coast of Bothnian Bay.

For a better visualization of the changes of the Baltic Sea's effect on its coastal temperatures and considering the research being bound by NOAH 2.0

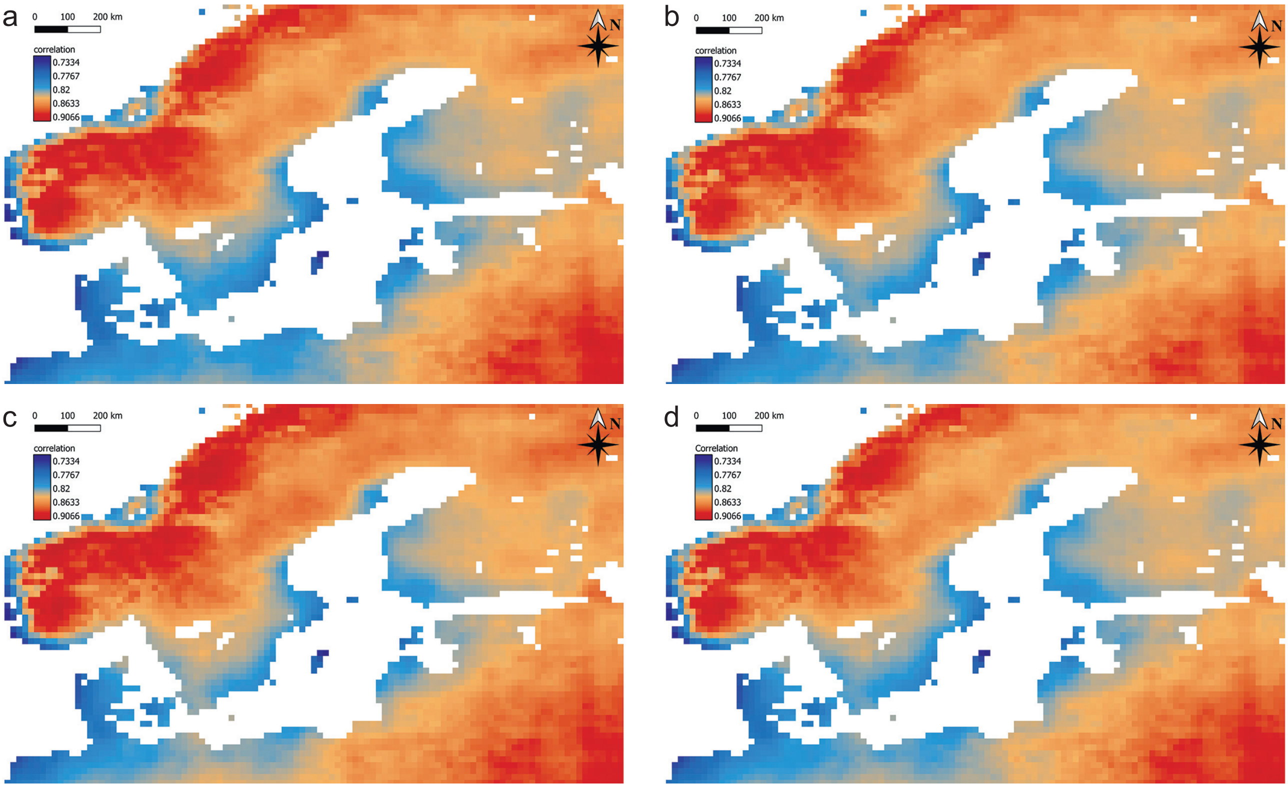

Fig. 2 Maps of linear correlation between monthly mean values of solar incoming net shortwave radiation and surface air temperature in 30-year periods: (a) 1951–1980, (b) 1961–1990, (c) 1971–2000, and (d) in the whole study period of 1951–2000

model's data range (from years of 1950 to 2000), data was divided into three 30-year periods: 1951–1980 (Fig. 2 (a)), 1961–1990 (Fig. 2 (b)) and 1971–2000 (Fig. 2 (c)), with Fig. 2 (d) representing the whole 50-year period. The monthly mean temperatures graph for the entire study area and for each 30-year period (Fig. 3) shows that the largest temperature increase is in the winter months (December, January and February) with a slighter increase during the months of March and early April. Comparing the 30-year periods, an increase in the temperature is also evident in months of July and August. The higher temperatures during summer months show a positive feedback with warming sea water temperatures which play an important role in local energy balance. As the water temperature change (warming and cooling) usually lags behind the air temperature change; therefore, it is able to influence the coastal air temperatures.

Together, the heat transfer between air and water, water and water, water heat conductivity and heat capacity affect air temperatures near water bodies such as the Baltic Sea which are well represented in the 30-year period's (1970–2000) monthly average air temperature amplitude map (Fig. 4), where the surface air temperatures amplitude close to the Baltic Sea is substantially lower than further inland. Considering a high resolution of 1 arc-sec, the coastal areas and influence of altitude on the terrain can be distinguished clearly by lower and higher temperature ranges in the research area.

The research results help identifying Baltic Sea coastal areas where the marine effect is reduced or enhanced on the coastal areas according to long-term air temperatures change in the period from 1951 till 2000. Changes of the Baltic Sea's influence on its coastal temperatures are shown in Fig. 5 (X), (Y), (Z) and are represented by maps of the difference between the periods of 1951–1970, 1961–1990 and 1971–2000. Negative values (red colour) show an increase, and positive values (blue colour) show a decrease in coastal air temperature regulated by the Baltic Sea.

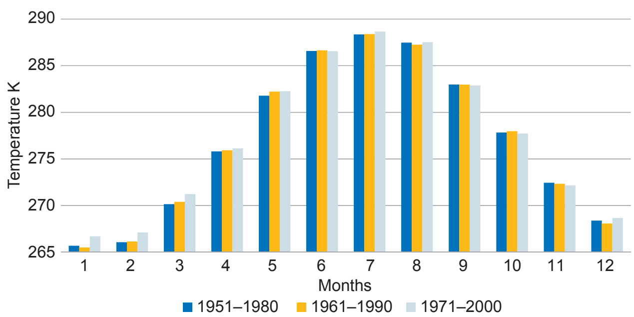

Fig. 3 The seasonal cycle of the average mean monthly surface air temperature for three different 30-year periods in the research area

The equal variances two-tailed t-test was performed to find out if the differences between equal periods of thirty years (from 1951 till 2000) bear any statistical significance. With the selected significance level of $\alpha = 0.05$ the calculations uncovered no statistical significance between periods 1951–1980 and 1961–1990 (Fig. 5 a, b) at p-value = 0.0046. However, the difference between periods 1951–1980 and 1971–2000 was found to be statistically significant with p-value = 2.76, difference in air temperature change between periods 1961–1990 and 1971–2000 was found to be statistically significant and the biggest ($p = 6.72$). The largest changes when comparing two periods of 1951–1980 and 1971–2000 are seen in south Baltic coasts and southern coast of the Scandinavian Peninsula. The negative values in the difference map (Fig. 5) indicate that the correlation value in those pixels increased. Increase in correlation value means that the general influence of the Baltic Sea on its coastal surface air temperatures in those pixels decreased.

DISCUSSION AND CONCLUSIONS

This work investigates coastal climate identification in the Baltic Sea's coastal areas. The research results indicate that the correlation between solar net shortwave radiation and surface air temperature can be used in determining the coastal climate of the Baltic Sea together with air temperature amplitude differences and range.

The extent to which the Baltic Sea influences air temperature in its coastal areas is an important factor for determining local coastal climates in the Baltic region. The surface air temperature amplitude and correlation maps can be used to determine the influence of the Baltic Sea on its local coastal climate air temperatures and even breeze circulation. However, such authors as Netzel and Stepinski (2016) suggest that even when such large regions as the Baltic Sea include only two climate types (according to the Köp-

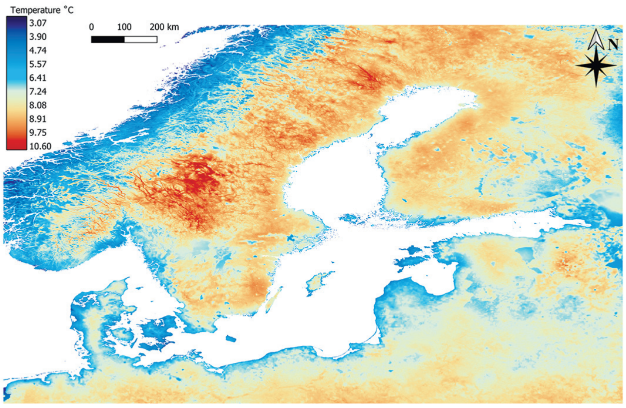

Fig. 4 Surface air temperature's mean monthly amplitude map of 1970–2000 period

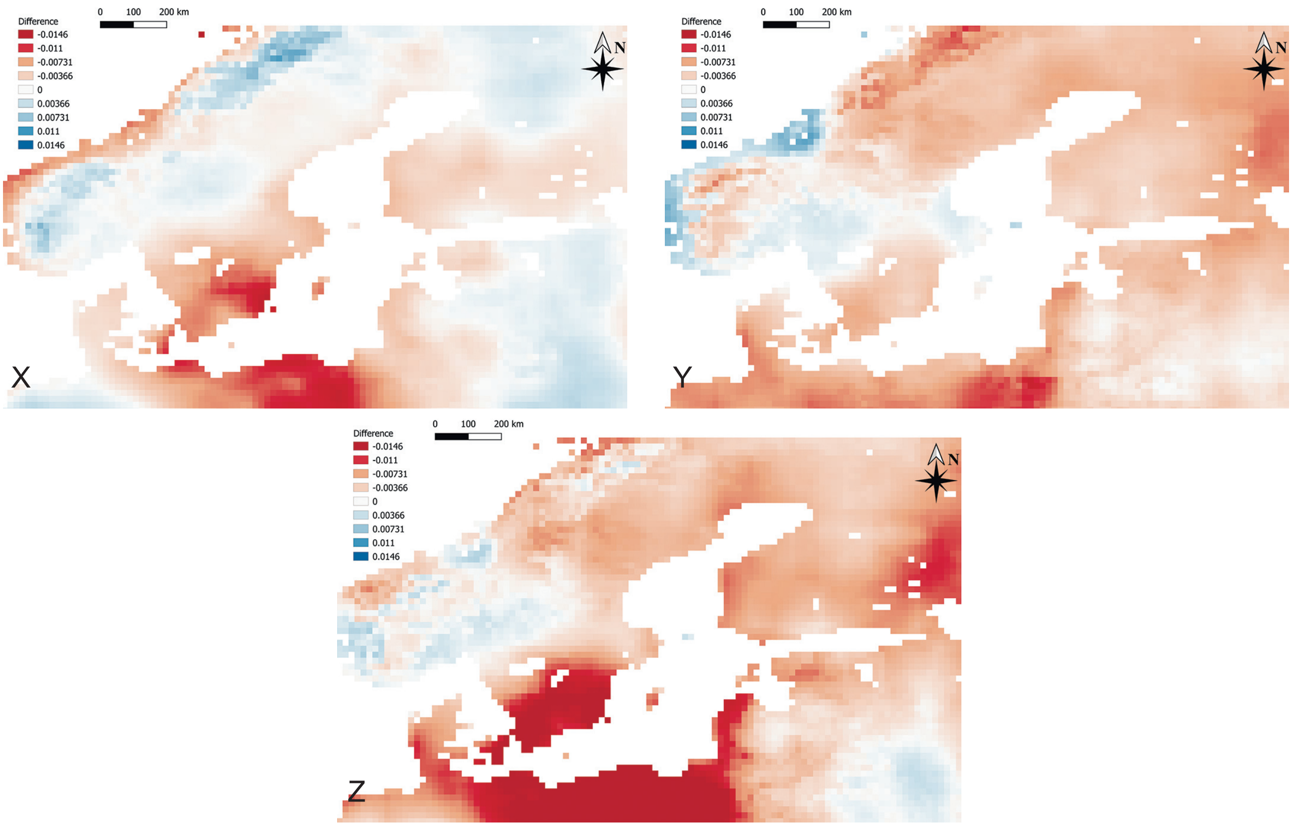

Fig. 5 Comparison of correlation maps between surface air temperature and incoming net shortwave radiation. X = period (a) – period (b), Y = period (b) – period (c), and Z = period (a) – period (c). Period (a) – 1951–1980, period (b) – 1961–1990, period (c) – 1971–2000

pen-Geiger classification), it may contain more diverse local climates. Therefore, such clustering methods as K-means clustering approach could be used to map the local climates in a large climate type – by differentiating the Baltic Sea region mathematically to a number of averages and assigning the remaining values of meteorological variables to each average group. In addition, the Köppen-Geiger classification scheme has the appealing quality of being presentable in the form of a decision tree (Spinoni *et al.* 2015). On the other hand, the clustering approach has its advantages, including a capability to delineate custom classifications and the ability to assess the uniformity of climates within a single climate type as well as diversity between different climate types. Regardless of local climate definition, as we demonstrated on this paper, climate changes continuously across the land surface. Thus, it means that boundaries between different local climates and climate types may easily shift in time or even when different classification methods are applied for the same area.

The geographical location of the Baltic Sea leads to different expansion of local climatic zones. The contrasts of coastal climate and more continental climate illustrate a distinguishable effect of the Baltic Sea on its coastal areas air temperature. It must be considered that temperature range represents the influence of the Baltic Sea on the coastal temperatures during all seasons of the year as the correlation maps between incoming net shortwave solar radiation and air temperature better represent the effect of the Baltic Sea during the summer period. Also, an important factor is the dominant westerly winds and in general a higher and steeper terrain of the Scandinavian Peninsula. The very same mountains act as a barrier for westerly winds and may in combination with a higher terrain of the Scandinavian Peninsula bind the lower temperature range closer to the coasts unlike on the opposite eastern side of the Baltic coasts.

The rising global temperatures impact the Baltic Sea's region, especially on the rising warm seasons and decreasing periods of wintertime. Further studies are required to analyze the impact of climate change on the coastal climate of the Baltic Sea. In this research we noticed some coastal areas changes between the first two periods of 1951–1980 and 1961–1990, but they remain insignificant. The largest changes when comparing two periods of 1951–1980 and 1971–2000 of the impact on the coastal climate are seen in south Baltic coasts and southern coast of the Scandinavian Peninsula. The increasing rise in air and water temperatures since the late 20th century in the Baltic Sea region (Houghton *et al.* 2001; BACC II, 2015) may have contributed to these larger differences.

In general, the changes in correlations are negative in the whole study area during all the analysed periods, which indicates that the air temperatures in the Baltic Sea area are rising as the incoming shortwave radiation remains unchanged.

For future research, breeze and atmospheric circulation variation should be considered while studying coastal climate of the Baltic Sea. As the climate changes, the breeze circulation plays an important role on creating milder temperature ranges in the coastal areas during the warm periods of the year. Sea breeze that forms because of temperature and pressure differences between land and the sea is one of the major components that indicates coastal climates (Simpson 1994).

Previous research on correlation between air temperature and incoming net shortwave solar radiation suggested the level of correlation depends on distance from the sea and altitude (Prieto *et al*. 2009). The study suggests that the produced correlation maps between incoming net shortwave radiation and air temperature may aid in determining the effect of the sea on its coastal temperatures; consequently, the research results could be applied for classification of the Baltic Sea's coastal climates.

To date, the Baltic Sea's coastal climate and its change still lack scientific studies and research. However, in this paper, a new approach to coastal climate research is suggested. Using high resolution models to account for quite a sparse meteorological stations network helps to resolve problems with data interpolation between meteorological stations providing good enough data point density for local and regional climate research. From a methodological point of view, the contribution of this paper is related to the proposal of a more accessible solution to coastal climate research without relying only on in-situ data. The produced correlation maps between incoming net shortwave radiation and air temperature may aid in determining the effect of the sea on its coastal temperatures; consequently, the research results could be applied for classification of the Baltic Sea's coastal climates.

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