Detailed temperature mapping - warming characterizes archipelago zones

L. Veneranta[a*], J. Vanhatalo[b] & L. Urho[c]

[a] Natural Resources Institute Finland, Quark, Korsholmanpuistikko 16, 65320 Vaasa, Finland
[b] Department of Environmental Sciences, University of Helsinki, P.O. Box 65, FIN-00014, University of Helsinki, Finland
[c] Natural Resources Institute Finland, P.O. Box 2, FI-00791 Helsinki, Finland
**Corresponding author email lari.veneranta@luke.fi, tel. +358 295 327 203*

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Abstract

Rapidly warming shallow archipelago areas have the best energetic options for high ecological production. We analyzed and visualized the spring and summer temperature development in the coastal areas of the Northern Baltic Sea. Typical for the Baltic is a high annual periodicity and variability in water temperatures. The maximum difference between a single day average temperatures across the study area was 28.3 °C. During wintertime the littoral water temperature can decrease below zero in outer archipelago or open water areas when the protective ice cover is not present and the lowest observed value was -0.5 °C. The depth and exposition are the most important variables explaining the coastal temperature gradients from the innermost to the outermost areas in springtime when water is heated by increasing solar radiation. Temperature differs more within coastal area than between the basins. Water temperature sum was highest in innermost areas, lowest in open water areas and the variation in daily averages was highest in the middle region. At the end of the warming period, the difference in surface water temperatures between the innermost and outermost areas had diminished at the time when the cooling began in August-September. These clear temperature gradients enabled us use the cumulative water temperature to classify the coastal zones in a biologically sensible manner into five regions. Our study shows a novel approach to study detailed spatial variations in water temperatures. The results can further be used, for example, to model and predict the spatial distribution of aquatic biota and to determine appropriate spatio-temporal designs for aquatic biota surveys. The new spatial knowledge of temperature regions will also help the evaluation of possible causes of larger scale climatological changes in a biological context including productivity.

Keywords: temperature, Baltic Sea, data logger, gradient, coastal zone, production prerequisites

1. Introduction

Water temperature in coastal areas is of critical ecological importance for many species. It reflects atmospheric and climatological forcing and it is also a driver of regional weather and climate (Oesch et al. 2005; Neumann 2010). The cycle of the water temperature affects limnological and biological processes, including actions from ice cover break-up (Anderson et al. 1996) to species distribution (Magnuson et al. 1979) and the growth, timing and success of reproduction and survival of several aquatic organisms (Jackson, Peres-Neto & Olden 2001; Casselman, 2002; Staehr & Sand-Jensen 2006; Chezik et al. 2014). Water temperature has been recognized as one of key factors, for example, in spatial mapping of species distribution in the coastal areas (Sundblad et al. 2009; Veneranta et al. 2011; Kallasvuo et al. submitted).

In the Baltic Sea, coastal zone classifications have been based on depth zones that are often natural boundaries for fast ice (Leppäranta 1981), vegetation on dry land (Häyrén 1900), or topographic complexity and zonation of biota. Often classifications include three classes, inner, middle and outer archipelago (Hänninen & Vuorinen 2001; O'Brien et al. 2003; Perus & Bonsdorff 2004). These approaches are limited to small areas, partly since vegetation changes with latitude. Defining ecologically meaningful coastal zones in large geographic scale is a complicated task, since there are not clear topographic features that would be directly linked to biota.

Water temperature depends on the heat energy absorbed by water mass and the volume of water, which is dependent on water depth and coastal morphology (Edmundson & Mazumder 2002; Kettle et al. 2004). Latitude has been used as a simple proxy for air temperature which is related to ice break-up (Palecki & Barry 1986; Assel & Herche 2000; Weyhenmeyer et al. 2004) as well as water temperature in coastal areas (Kjelman et al. 2003). In addition, freshwater and occasional marine water inflows affect the water temperature. In inshore areas, the freshwater input from rivers alters the sea water temperature directly through the temperature difference between the freshwater and sea water as well as indirectly through enhanced solar radiation absorption by murky river waters (Edmundson & Mazumder 2002). In general, heat exchange between inshore and offshore waters is mostly driven by winds and pressure changes by weather fronts (Imberger 1994; Finlay et al. 2001; Lehmann & Myrberg 2008). There are no notable tides in the Baltic Sea, but water-level can fluctuate occasionally over 1.5 m due to internal waves and air pressure changes (Jerling 1999) which causes strong currents and mixing. The spatial variation in water temperature is highest in April and July in the Baltic Sea since in spring near shore shallow waters warm up faster than deeper areas and in contrast, the wind driven upwelling can significantly decrease water temperature locally in certain areas in summer (Kozlov et al. 2014). Upwelling has also a direct impact on coastal ecosystems (Raid 1989; Haapala 1994; Szymelfenig 2005). The upwellings are based on the existence of seasonal thermocline at depth of 15-30 m, where the warm surface water faces the colder water, often with a temperature drop of as much as 10 °C over a distance of few meters (Leppäranta & Myrberg 2009). The impact of upwellings and sudden temperature changes on different coastal areas from most sheltered archipelago to edge of open water in a high spatial resolution is, however, not well documented due to lack of detailed temperature data.

Currently, there is no continuous follow-up of water temperature with high resolution network of monitoring stations or buoys in the Baltic Sea. The gap in available temperature records is especially apparent in shallow and structurally complex coastal areas, like the archipelagos of the Baltic Sea. Previously the water temperature in near shore areas has for example been modelled by using nearby air temperature stations (Kjellman et al. 2003; Pekcan-Hekim et al. 2011) or by using temperature recorders in small scale (Ljungren et al. 2010). In open water areas, this gap in measurements has been filled with sea surface temperature (SST) data available on satellite images (Gidhagen 1984; Kahru et al. 1995; Kozlov et al. 2011). Also large scale meteorological data (Omstedt & Axell 2003) have been used to study spatial variation in water temperature. The spatial and temporal resolution achieved by satellites has been enough for studies focusing on temperature patterns or phenomena in open water areas (Siegel et al. 2006; Lehmann et al. 2011). However, due to its coarse resolution, the SST interpretation from satellite imagery or weather grids is not well suited for coastal areas where the mosaic of islands and water is highly fragmented. Moreover, missing data due to occasional cloud cover can obscure the use of satellite data in spatial comparisons in monthly or even in annual temporal resolution. Satellite measurements for SST seem also to consistently overestimate the actual in-situ measured SST in spring and summer time (Smale et al. 2009; Smit et al. 2013). Coastal features like bays, river mouths and archipelago areas are often smaller than the highest resolution of most available SST data on the Baltic Sea.

Recent development in low-cost temperature data loggers has made it possible to collect high resolution time series data. In this paper, we present a novel method to study coastal temperatures and areal warming, which produces detailed knowledge on temperature dynamics. We utilize records from spatial set-up of temperature measurements to investigate and visualize the spring and summer temperature sum in the near shore coastal areas of the Northern Baltic Sea. We present also a novel classification for coastal zones based on the cumulative water temperature along the entire Finnish coast. Our results can further be used, for example, to model and predict the spatial distribution of aquatic biota and to determine appropriate spatio-temporal designs for aquatic biota surveys. The modelled, spatial knowledge of temperature regions will also help forecast the effect of large scale climatological changes in aquatic ecosystem.

2. Study area

The brackish water Baltic Sea consists of large gulfs and areas with varying water quality properties. The Finnish coastal area of the Baltic Sea has exposed shores and sheltered archipelago areas with high structural variability. The length of the coastal mainland area is approximately 1100 km. The area is divided into seven sub basins (Fig 1). The Gulf of Bothnia (GoB) is the northest part with two major basins, the Bothnian Sea (BS) and the Bothnian Bay (BB), separated by the Quark, a shallow sill with complex archipelago in its east coast. Åland Sea (ÅS) is a deep strait separated from mainland by Archipelago Sea (AS). In the Archipelago Sea, there are narrow, more than 100 m deep, basins between the islands that are connected to straits. Compared to the AS, the Quark is very shallow and erratic area. The Northern Baltic Proper separates the AS from the eastern basin, the Gulf of Finland (GoF), which is an elongated estuarine basin with varying topography and coastline. Especially the easternmost part of GoF is characterized by dense archipelago. Both, the GoB and the GoF have large freshwater river input. Due to the differences in water volume and retention time (Håkansson et al. 1996, Myrberg & Andrejev 2006), salinity ranges from limnic waters (<1 psu) in the innermost reaches in the north and in the estuaries to 6−7 psu in the south (Voipio 1981; Håkansson et al. 1996; HELCOM 2002). Overall the salinity in the area is lower than in the open Baltic.

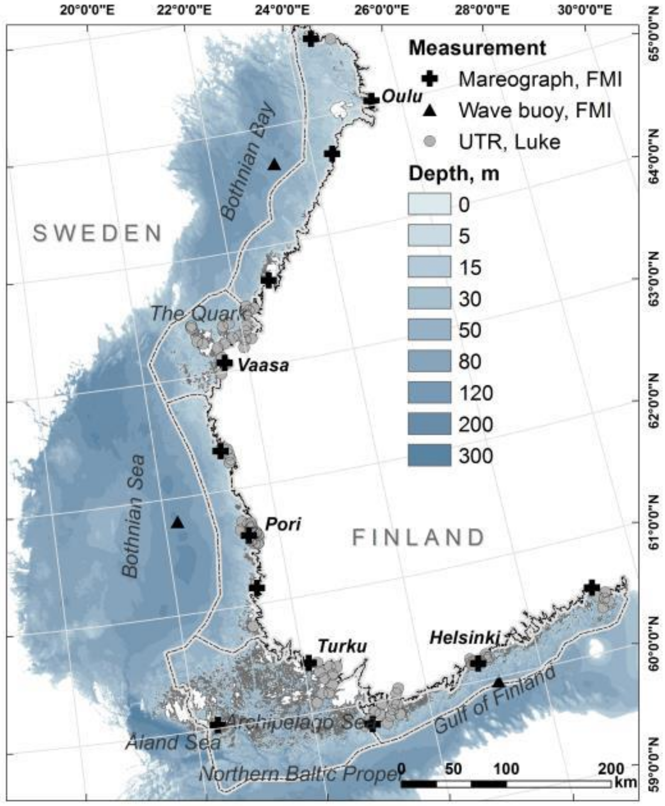

Fig. 1. Map of the study area in northernmost Baltic Sea with bathymetry and marked locations of temperature recorders (UTRs), wave buoys and mareographs. Sea-areas are marked with gray line. The legend indicates the depth of water and responsible institutions for data collection.

The Finnish territorial waters are shallow. The average depth of the GoF is only 38 m and the GoB (including AS, BS and BB) 60 m respectively. In Finnish territorial waters the areas shallower than 10 m cover 21 % of the surface area, shallower than 20 m 42 %, and shallower than 30 m 63 % of the total area. Sea ice occurs every year in the Baltic Sea. During mild winters, ice covers only the BB and the easternmost GoF, but in cold winters nearly the entire Baltic Sea may freeze. In normal winters about 45% of the Baltic Sea is covered by ice. The ice covers the coastal areas of the GoB and GoF from October-December to April-May, and breaks up from south to north in approximately 1 month.

3. Temperature data collection and analyses

We studied SST of the coastal areas during the spring warming period in years 2012-2014, using three sources of thermometer data. The stratification of sampling sites is shown in the supplement A.1. The data collection with temperature loggers was started in autumn 2012 with annually increasing number of sampling stations (2012 n=62; 2013 n=59; 2014 n=98). The spring period 2014 was selected to this study as most representative both in number of samplings and areal coverage. Data from water temperature recorders located to mareograph stations in the vicinity of harbours (n=13) and wave buoys (n=3) in pelagic areas of BB, BS and GoF were obtained from Finnish Meteorological Institute (FMI). Temperature data at mareograph stations and wave buoy data are collected regularly with temporal resolution of one hour. Due to wintertime ice conditions, the wave buoys were set to measurement positions in spring after ice break-up. In 2014, the stations in the BB started measuring May 23rd, in BS April 6th and in the GoF first of April. Temperature recorders on mareographs work on annual basis.

Underwater temperature recorders (UTR, Onset Hobo models UA-001-64, UA002-64 and UA-001-8; given accuracy 0.57 °C and resolution 0.01 °C; response time < 10 min) were set to record temperature readings at two hour intervals to littoral zone at approximately 2 m depth . They were fastened on a 3 kg cement blocks with a small underwater float mark or a weighted thin rope to the shore. The distance between bottom and UTRs was 0.2 - 0.3 m. The location of UTRs was recorded with handheld GPS -device and they were underwater over winter until autumn 2014. Out of 99 UTRs set up in 2014 82 were recovered. Wave buoys located in the open water areas measure temperature at 1.0 m depth and nearshore mareographs at 2-3 m depth in the vicinity of bottom.

After retrieving UTRs, we tested their calibration in laboratory conditions. The precision of the data loggers was on average 0.15°C, with maximum deviation of 0.31 °C on single device. Hence, no corrections on data were done. Moreover, all data were visually inspected for visible errors and outlying values removed.

3.1 Variables in Geographical Information system (GIS)

The environmental variables used in the model are summarized in supplement A.2. The basic data were obtained from FMI, FEI and Metsähallitus and constructed for this study by the authors. For the modeling, all variables were converted to a grid with a resolution of 50 m. The depth data was improved by 1) attaching 2 m depth value estimate to estuaries with no depth data and 1 m estimate to small bays shown in "Lagoons" data from Metsähallitus and 2) if available, depth data in shallow areas collected by Luke with echosounder was also used to complete areas with no data in original layer. Closed estuaries (freshwater reservoirs) with no available depth data were excluded from spatial analyses. Shoreline density per area was calculated based on vector data of basic maps (scale 1:5000-10000, National Land Survey of Finland). The developed predictor variables were constructed to describe the coastal zones, using distance to 10 m and 30 m depth curves, wind and wave exposure (SWM), distance to river mouths (weighted with annual average flow) as well as average depth in 3 km and 5 km circles as basic data. All GIS analyses were performed using the ESRI ArcGIS (ArcMap 10.2 and Spatial Analyst extension).

3.2 Modeling the cumulative water temperature

We calculated the cumulative water temperature from the day when SST reached 3 °C for the first time in spring 2014 until July 15th. The limit of 3 °C was used, since water at that temperature was completely iceless and it is the temperature of maximum density (T_m 1.5 °C - 3 °C). When the temperature rises above T_m, the surface water becomes lighter than water masses below, starting to form the thermocline (Leppäranta & Myrberg 2009). We modeled the cumulative water temperature, y_i (rescaled to have standard deviation of 1), at location i with a regression model

$$y_i = \alpha + x_i^T \beta + f(x_i) + \phi(s_i) + \varepsilon_i,$$

where α is an intercept, x_i a k × 1 vector of environmental variables, β a vector of weights of linear regression model, $f(x_i)$ a non-linear function of the environmental variables, $\phi(s_i)$ a spatially correlated random effect, which is a function of the location s_i, and ε_i an independently and identically distributed error terms. We followed the Bayesian approach in inference and gave priors for the parameters of the model. We gave a zero mean Gaussian prior for the intercept and weights so that $\alpha \sim N(0,10)$ and $\beta_k \sim N(0,10)$. The error terms were given a zero mean Gaussian prior, $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and the variance of the observation error was given a half Student-t priors.

The non-linear function was modeled by giving it a zero mean Gaussian process (GP) prior, $f(x) \sim GP(0, k(x, x'))$. GP is a stochastic process that defines probability distribution over functions (Rasmussen and Williams, 2006). A GP is defined by both a mean function (here zero) and covariance function $k(x_i, x_j) = Cov(f(x_i), f(x_j))$ which determine the properties of the process, such as the smoothness and variability. GP allows non-linear responses along environmental variables and interactions between them. For the non-linear part of the model, we used squared exponential covariance function parameterized as $k_{\mathrm{se}}(x_i, x_j) = \sigma_{\mathrm{se}}^2 e^{-\sum_{d=1}^{k}(x_{i,d}-x_{j,d})^2 \lambda_d^2}$, where λ_d^2 is the inverse of a length-scale (Rasmussen and Williams, 2006), which governs the smoothness of the process, and σ_{se}^2 the magnitude governing the variability of the process. The inverse of the length-scale was given a Laplace prior which promotes small values of λ_d^2 that correspond to rigid (near linear) response along environmental variable x_d. The spatial random effect was given a GP prior with exponential covariance function, $k_\phi(s_i, s_j) = \sigma_\phi^2 e^{\sqrt{-\sum_{h=1}^{2}(s_{i,h}-s_{j,h})^2 / l_h^2 l_h}}$, where l_h is the length-scale and σ_ϕ^2 the magnitude (Finkenstädt et al 2007). The length-scale l_h and the magnitude parameters were given a half-Student-*t* prior (Gelman, 2006). The model was implemented with Matlab using GPstuff package (Vanhatalo et al., 2013).

The inference for the model was conducted as follows. We set the parameters of the covariance functions and the variance of the observation error to their maximum a posterior estimate (MAP) (Gelman et al., 2013), denoted by $\hat{\theta}$ which was found by gradient based optimization. Conditional to these MAP estimates the posterior of the rest of the linear and nonlinear functions can be solved analytically. Since the full set of covariates (*k*=25) is large compared to the size of data (*n*=99) and many of the variables are similar, for example the three DEPMD variables, we removed unnecessary covariates from the model. This was done by choosing a set of covariates which maximized the leave-one-out cross validation (LOO-CV) log predictive density of the model (Vehtari & Ojanen, 2012).
Going through all combinations of the parameters was infeasible we chose the set of parameters with forward-backward selection scheme. In the forward selection scheme, we added covariates into the model iteratively so that at each iteration we added the covariate that increased the LOO-CV log predictive density the most. We stopped adding parameters when the LOO-CV log predictive density stopped increasing. Since the model includes interactions between covariates, the relative explanatory power of covariates included in the early stage of the forward selection may decrease due to the interactions between other covariates included in the later stage of the iteration. For this reason, after the forward selection, we conducted a backward selection where we removed all of the chosen covariates whose removal did not decrease the LOO-CV log predictive density.

The predictive function, $h(x) = x^T\beta + f(x)$, includes interactions between covariates the shape of its response along individual covariate as well as its expected value vary across locations. Hence, in order to study the effect of covariates to cumulative water temperature, we visualize the mean, zero centered, response and variation in it over the training data locations.

3.3 Coastal area classification based on cumulative water temperature

For cumulative water temperature classification we defined five coastal regions with class boundaries based on the 75, 50, 25 and 5 % quantiles of increasing measured cumulative water temperature so that they represent, respectively, coastal zones from innermost archipelago to open sea:

1) innermost region, highest temperatures and rapid response to average air temperature
2) inner region, high temperatures, fast response to average air temperature
3) middle region, high variation in temperatures
4) outer, slowly upwarming area in the outer limit of archipelago areas, prone to upwelling.
5) open water areas, coldest area with high variation between stations due to latitude

The above mentioned class boundaries are justified since the locations of measurement stations, except from the most open areas (class 5) which corresponds to 5 % quantile, were stratified so that, *a priori*, they should be approximately uniformly spaced over the spectrum of cumulative water temperature.

4. Results

4.1 Coastal warming

Winter temperatures mostly stay between 0 to 3°C with lowest extremes at - 0.5 °C, but for example in 2013 higher temperatures, such as 4 to 6 °C, were measured just before the end of the year. The warming also started earlier in 2014 than the year before.

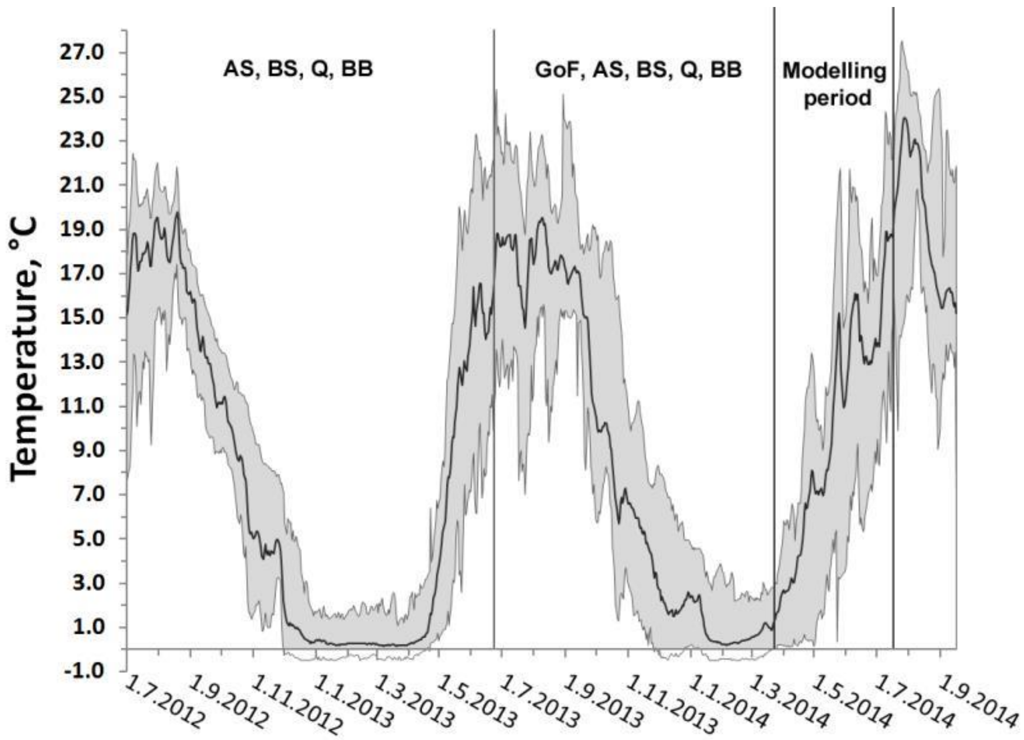

Fig. 2. Daily average temperature in the Finnish coastal area in 2012-2014.The black line indicates the average temperature of all measurements and gray area the range of minimum and maximum values. The number of data loggers was increased and areal coverage extended to Gulf of Finland in June 2013. GoF = Gulf of Finland, AS = Archipelago Sea, BS = Bothnian Sea,Q = Quark and BB = Bothnian Bay.

Winter 2013-2014 was exceptional in the lack of ice; the average air temperature of winter months (Dec-May) was 2-4 °C higher than long term average (FMI annual statistics). Fast ice was observed only in the northernmost BB. In temperature measurements, the first observation of temperature > 3 °C was registered in 23rd March. The date of first observation of > 3°C per observation stations did not follow any trends with latitudes, except in the BB area. The early warming sites were recorded in the inner areas of the GoF, BS and Quark (Fig 3 and table 1). All areas had nearly identical start in rise of temperatures within one week. In the BB the range of start days was highest.

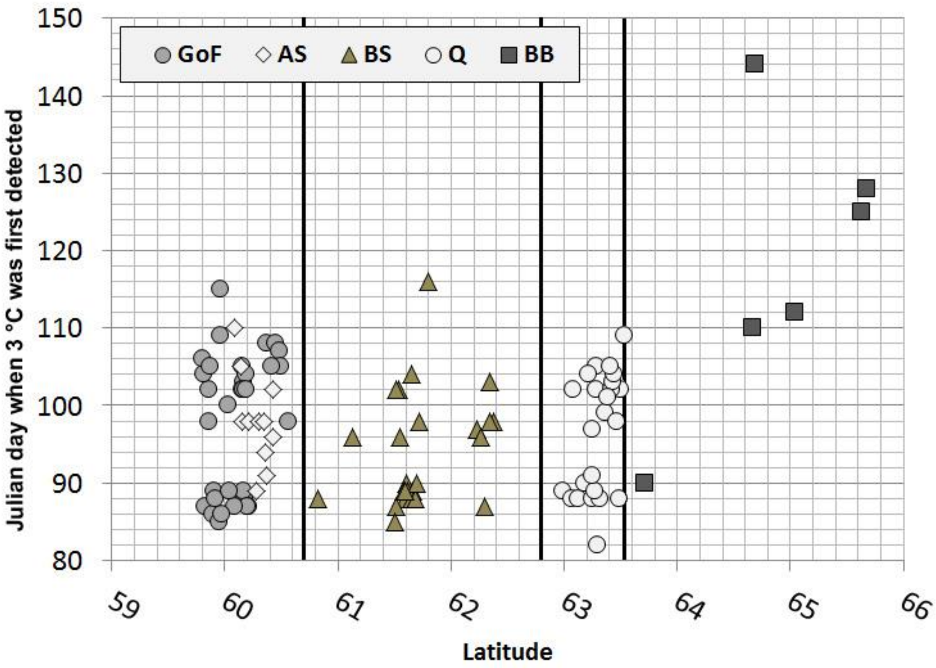

Fig. 3. Latitude in relation to Julian day when the temperature reached the 3° C threshold value. The black lines represent sea-areas.

Table 1. The day of start of cumulative water temperature measurements in different sea areas. The number of observation stations per sea area is denoted by n. The date of the first observation of temperature over 3 °C across observation stations is given in the third column (Start). The fourth (Range days) and the fifth (Average) column summarize the time between the date of the earliest and latest first observation of temperature over 3 °C and the average date of the first observation of temperature over 3 °C across observation stations.

Coastal area	n	Start	Range days	Average
GoF	32	26.3.2014	30	8.4.2014
AS	10	30.3.2014	21	8.4.2014
BS	27	26.3.2014	31	4.4.2014
Quark	24	23.3.2014	27	6.4.2014
BB	6	31.3.2014	54	28.4.2014

The warming was slower in the outermost stations, where the water volume is the highest. Fig 4 shows an example from three representative measurement locations in the Quark in spring 2014. The outer offshore island (A) was the coldest location (average temperature 10.0 ℃ and variance 1.0 ℃ during weeks 14-31) while sheltered bay (B) and estuary area (C) had nearly identical temperature development in spring and summertime (sheltered bay, average temperature 14.7 ℃, variance 3.4 ℃ and estuary average 15.9 ℃, variance 1.0 ℃). However, the daily variance and range of temperature can be high both in sheltered bay (max range 6.4℃, variance 5.4) and outer island (max range 7.3℃, variance 4.7), while in estuary the diurnal temperature is more stable (max range 5.3℃ and variance 4.0). The graph on Fig 4 indicates that water temperature in these shallow areas follows the air temperature measured in nearby outer coastal measurement station. The water warming continues until middle of July when the water temperature reaches similar maximum values in estuary, sheltered bay and outer archipelago. In hot summers like 2014, the surface waters temporary warmed up to 25-27.8°C in daily average values. The highest temperatures are observed in sheltered and shallow places in all sea areas of the northern Baltic, although the May-August mean temperatures are about ten degrees lower (Table 3). In respect to annual temperature development, the results indicate that variation between inner-outer archipelago is higher than between sea-areas (Tables 2 and 3).

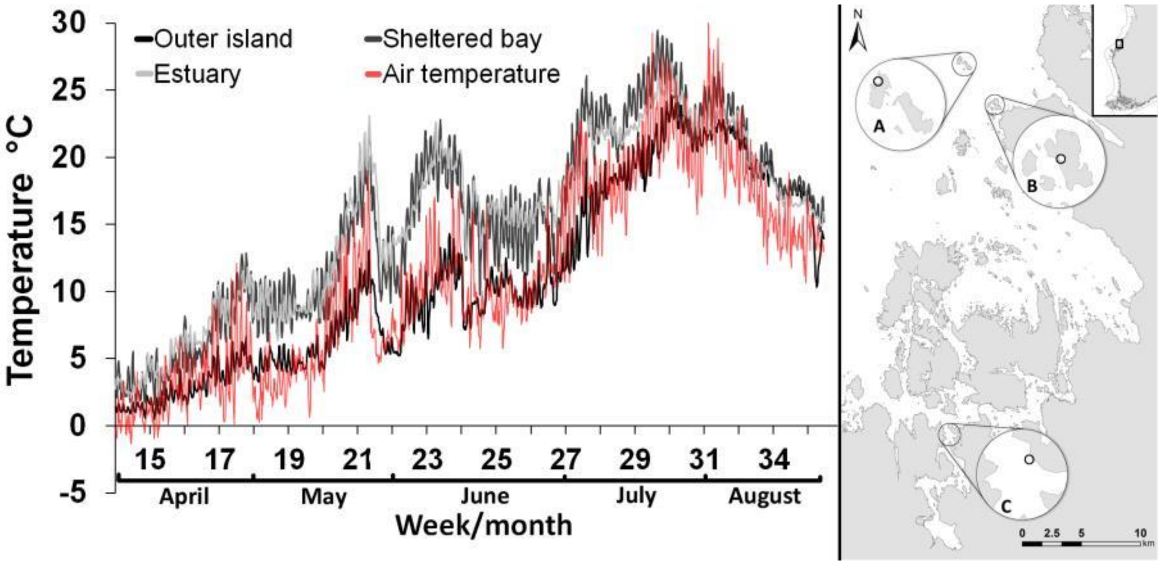

Fig. 4. Temperature in spring 2014 measured in outer island (A), sheltered bay (B), river estuary (C) and air temperature station (50 km to west). Measurement interval 2h. X-axis indicates the week of measurement.

4.2 Regional temperature values

In summer (May-August) the BB was the coldest area with lowest mean and minimum temperature. The maximum mean summer temperatures are at the same level of magnitude in all regions. The northernmost area BB had also highest peak summer temperature. In winter (October-April), the AS and GoF are over two times as warm as areas the BS, Quark and BB (Table 3).

Table 2. Regional trends in measured temperatures. Summer = May-August, Winter = October - April.

Period	Area	N Obs	Mean	Std Dev	Minimum	Maximum
Summer	1 Bothnian Bay (BB)	1210	14.55	5.74	0.35	27.54
2014	2 Quark	2783	16.25	5.09	3.99	26.29
	3 Bothnian Sea (BS)	3267	16.13	5.18	2.46	26.51
	4 Archipelago Sea (AS)	2299	16.01	5.40	4.79	26.14
	5 Gulf of Finland (GoF)	3146	15.64	5.26	3.61	26.77
Winter	1 Bothnian Bay (BB)	1520	1.23	1.57	-0.25*	6.81
2014	2 Quark	3496	1.20	1.44	-0.49*	6.54
	3 Bothnian Sea (BS)	4104	1.76	1.88	-0.44*	7.84
	4 Archipelago Sea (AS)	2888	2.92	2.49	-0.50*	9.49
	5 Gulf of Finland (GoF)	3952	2.52	2.35	-0.50*	11.24

* The lowest minimum winter value is caused by ice formation on bottom

The prevailing winds on the Northern Baltic Sea from April to July in 2014 blew from the southwest in the GoF, south in the As, Northwest in the BS and between NE and SW in the BB (data from FMI coastal stations). The most typical wind speed was between 5-10 ms^{-1}. Due to the lack of strong northern and eastern winds strong upwellings were not observed in the modelling period.

4.3 The effect of environmental variables to the cumulative water temperature

Latitude (Y) as well as depth, wave exposure and river run-off related variables D30DSWM, RIVERDEPTMQ, DISTOO10M, LGSWM and D30DEP were the best combination of predictor variables for modeling the cumulative water temperature (Fig 5). The correlation between observed and LOO-CV predictive mean for cumulative water temperatures was 0.88 and the model explained 77 % of total variation in observations, with RMSE of 98.42 (Fig 5). Larger values of D30DSWM indicate shallow and sheltered areas while the smallest values are found in deep open sea. RIVERDEPTHMQ increases towards shallow estuaries and open water near low river discharge areas have the smallest RIVERDEPTHMQ values. The largest DISTO10M values occur in the most sheltered and shallowest archipelago areas and decrease towards deep areas. The largest values of LGSWM occur in open sea areas and the smallest values in sheltered archipelago areas or closed small bays. The large D30DEP values indicate sheltered areas and lower open sea areas.

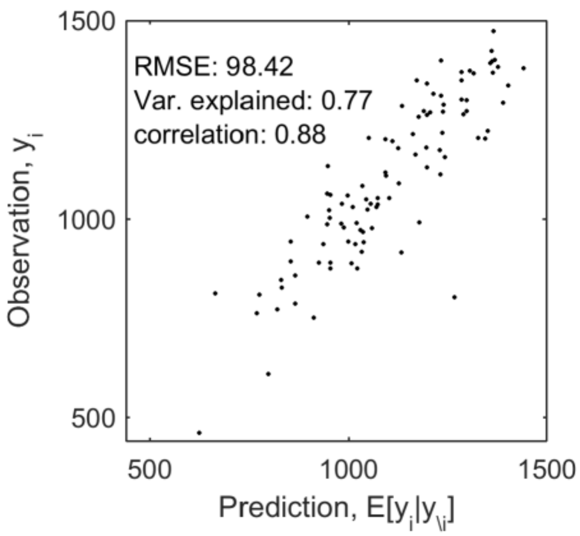

Fig. 5. A scatter plot on LOO-CV predictive mean and data.

In general, the cumulative water temperature followed the gradients in the geographical properties, wave exposure and depth (Fig. 6). The average depth and exposure increase from coast to open water and outer archipelago areas and sheltered innermost areas had the highest cumulative water temperatures. The cumulative water temperature decreases by increasing Latitude and the response was the steepest from Northern Quark (Y=450000) to BB. Other covariates had a near linear average response on the cumulative water temperature. However, there is spatial variation in the responses. The vicinity of river mouths or location at estuary areas increases the cumulative water temperature, as well as the larger surrounding shallow area in depths less than 10 m, as can be seen from RIVERDEPTH5 variable.

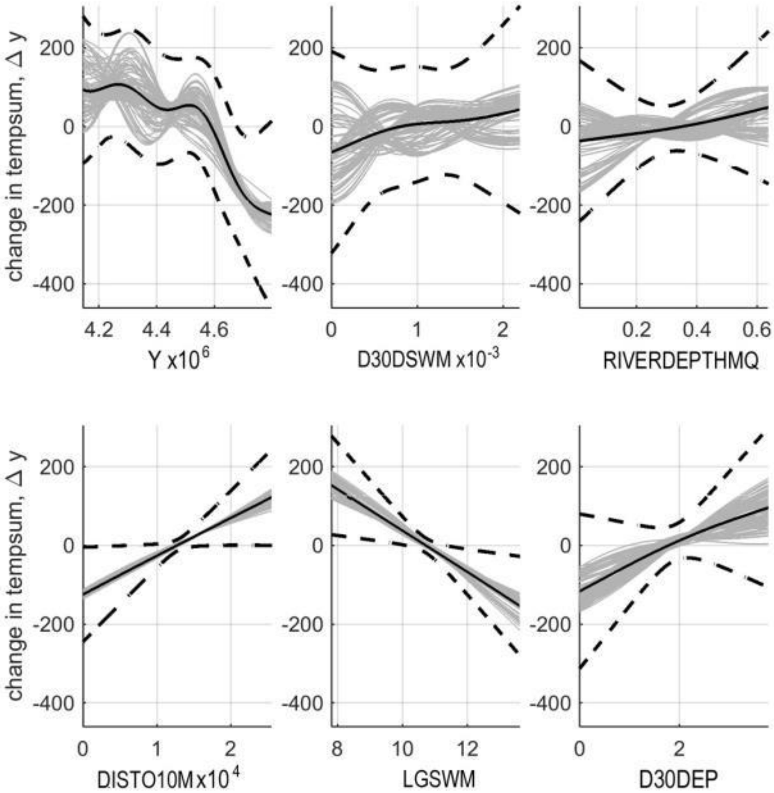

Fig. 6. The average response of water temperature sum along covariate (the black line) and the 95% credible interval of responses across the study area (dashed line). The grey lines show the expexted response along a covariate at training data locations.

4.4 Spatial temperature prediction

The highest temperature sums were predicted in estuaries and in sheltered, shallow bays and the lowest cumulative water temperatures were predicted in open sea areas (Fig. 7). The model and spatial prediction indicates that the open water areas of the BB are the coldest in the Finnish coastal areas, while in the southern latitudes the temperature sum increases. Thus, the spatial model indicates the effect of latitude on temperature sum, but indicates also the strong temperature gradients between shallow sheltered and exposed areas.

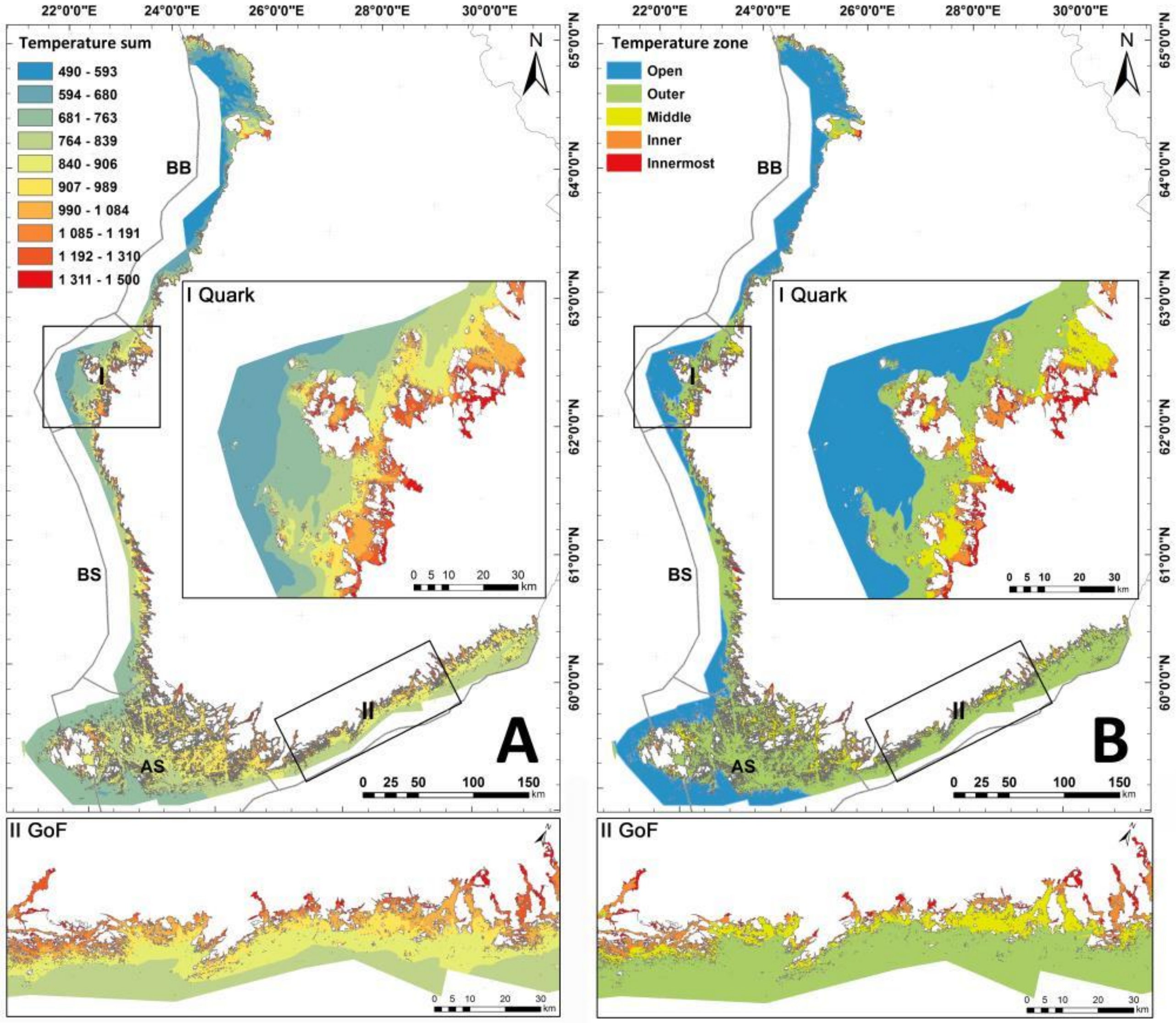

Fig. 7. Temperature sum maps (A) and coastal temperature zones (B) with sections I Quark and II Gulf of Finland.

4.5 Coastal area classification based on cumulative water temperature

In our training data the maximum difference in cumulative water temperatures were 1012 degree days. The maximum variation in daily average temperatures was observed in 26th of May (difference between minimum and maximum was 18.5 °C and variance over observations was 12.3). The difference in cumulative water temperature increases from spring to late summer, although the difference in absolute temperature values remains relatively stable from May to July, after the initial warming.

The class boundaries used in coastal area classification were 760 degree days (dd, 5% quantile), 960 dd (25% quantile), 1100 dd (50% quantile) and 1240 dd (75% quantile). The thermographs of each temperature zone have similar temperature trend, but average temperature differ between zones (Fig 8, Table 3). In the middle zone (3) the variation in daily average temperatures is highest and in the innermost (5) and outermost (1) areas smallest. In the open sea (1) the variation in early spring is caused by latitude and only three measurement stations, the northernmost measurements remain cold while the temperature in south already rises.

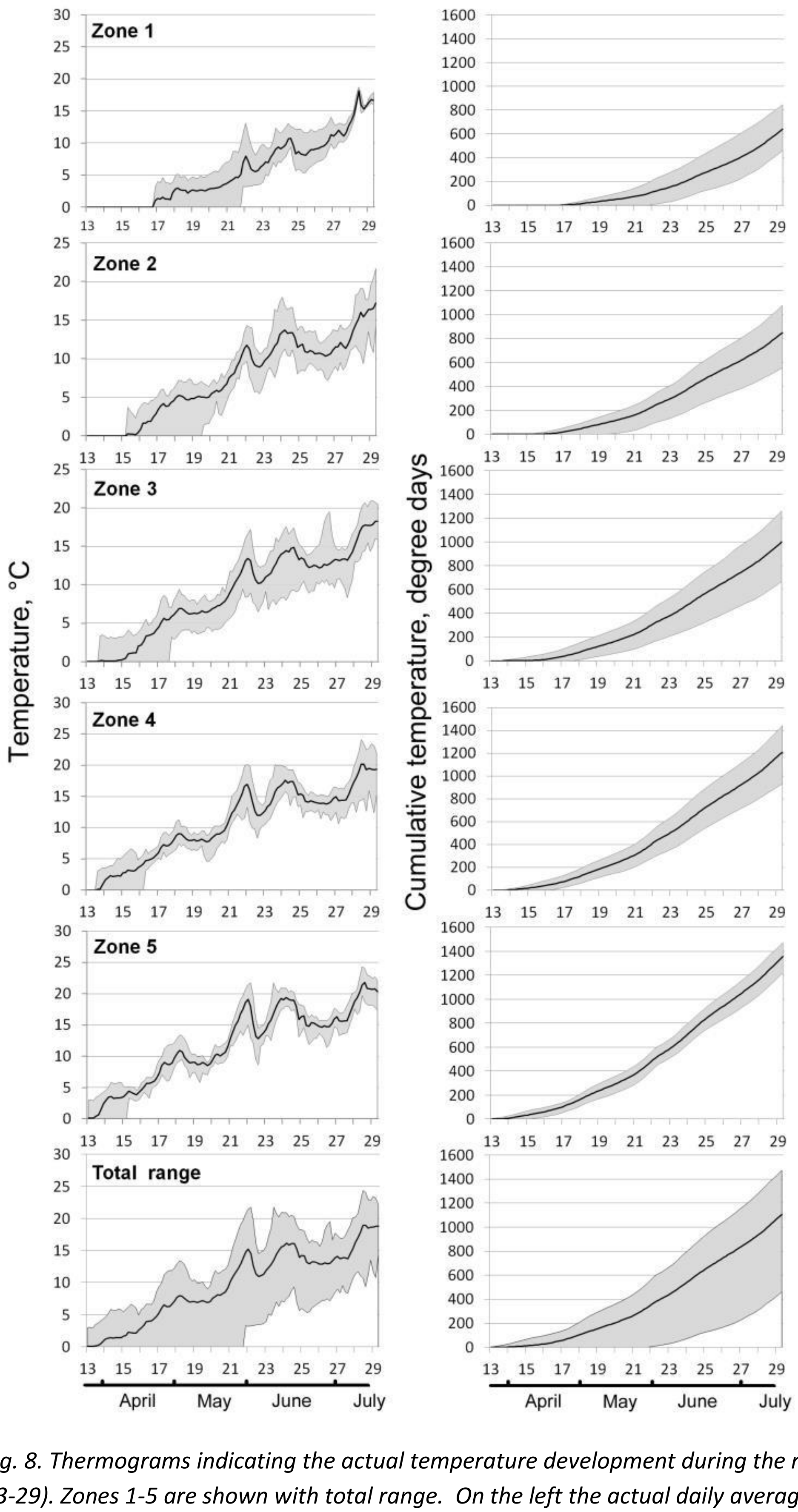

Fig. 8. Thermograms indicating the actual temperature development during the modelling period (weeks 13-29). Zones 1-5 are shown with total range. On the left the actual daily average temperature and on the right the cumulative water temperature sum over all measurement stations. The grey area indicates range of min and max values.

In 2014 the average temperature in May was nearly three times higher in innermost zone (5) compared to open water areas (1). In June the difference is twice the temperature of innermost area compared to open water. The relative difference in average temperatures of other areas are slowly balancing to same level, especially the inner and innermost area are close to each other, as well as in July. The outer areas reach the prevailing temperatures in inner areas in July. To characterize the sea-areas, the shoreline length and surface area of innermost and inner regions can be compared between sea regions and temperature zones suggested in this study (Fig 7, supplement A.3). In the gradient from innermost coastal area to open water there is a decrease in shelter from wind and waves, sediment shores, surface area of most shallow water and freshwater input. The innermost coastal areas are the most sheltered and shallow. The second coastal zone is inner region with high temperatures and relatively fast response to average air temperature. The third zone, middle region is an area between the fast heating nearshore areas and open water. The outer area limits to the outermost islands and shallows and it is greatly affected by temperature in open water areas. The Quark, BS and GoF have the highest proportion of innermost area compared to total area, the actual innermost area in BB is about half from the other areas (see A.3). In the BB, AS and GoF the shoreline density in the innermost areas resemble each other. In the BS the high proportion of inner zones is most likely influenced by high river inflow at Pori region (see Fig . 1), where the warm estuary water faces the outermost areas. In contrast, the Quark area has only a low river inflow, thus reflecting the actual warming capacity of shallow areas. The AS has the highest proportion off middle zone and only minor area of innermost coastal zone. The shorelines of the GoF lack the coldest, open water temperature zone but have a large proportion of middle zone. In the BB the proportion of open water temperature zone is highest and the proportion of shoreline lowest. The BB is also the coldest sea area in terms of small area of innermost and inner temperature zones.

#Table 3. Modelled and measured temperature sums during the warming period (> 3°C to the end of July) with monthly measured temperatures in different coastal zones 1 to 5 and their geographical properties.

MODELLED TEMP. SUM VALUES	1 Open water	2 Outer	3 Middle	4 Inner	5 Innermost
Minimum	490	773	945	1086	1272
Maximum	773	945	1086	1272	3109
Average	681	850	1002	1171	1356
MEASURED TEMP. SUM VALUES					
Minimum, modelling period	462	555	669	933	1222
Maximum, modelling period	847	1078	1262	1443	1474
Average, modelling period	640	847	1000	1209	1356
Average temperature					
- May	4.1	7.2	8.8	10.9	12.1
- June	8.2	11.5	13.0	15.0	16.4
- July	17.8	17.7	18.7	20.3	21.5
- October	9.2	8.2	9.0	8.2	7.4
- February	*	0.2	0.2	0.4	0.5
Temperature sum					
- May	126	234	273	337	377
- June	274	345	364	397	492

- July	549	560	578	629	666
- October	285	255	277	254	231
- February	*	5.8	6.7	11.7	14.5
Temperature variance					
- May	5.6	6.1	6.9	10.0	12.3
- June	5.9	3.7	2.6	2.9	3.6
- July	15.2	16.3	11.8	12.3	9.9
- October	2.9	5.4	6.3	4.2	4.6
- February	*	0.1	0.2	0.2	0.3
Daily average range, modelling period	3.27	4.20	4.61	4.16	3.46
GEOGRAPHICAL PROPERTIES					
Average exposure (m)	59319	28462	4248	1788	794
Average depth (m)	30	18	10	4	2
Area (km^2)	>9732**	>14085**	5100	2588	1579
Shoreline length (km) / % of total	1383 / 3	10655 / 24	14810 / 33	10725 / 24	7557 /17

** No measurements - the open water buoys are removed for winter*
***Limited by modelling area*

5. Discussion

5.1 Annual temperature cycle with inshore-offshore differences

Our results show that temperature of the Baltic Sea is highly variable compared to the more stable oceanic coastal areas (Miller et al. 1985). Water temperature in shallow areas can reach values below freezing point in wintertime. The freezing point of brackish water in salinity of 3-7 PSU varies between -0.24 to -0.46 °C (IPTS-68). In mild winters, like 2013-2014, the lack of permanent ice cover may enable the strong mixing of surface water by waves and wind for extended periods. Thus, in exposed shores the ice formation may start from bottom, as registered in shallows at 2 m depth where UTRs were held measuring. In exposed areas the littoral zone can be colder in mild winters than in years when fast ice covers the sea. In wintertime the water temperature decreases slowly, first in innermost areas and last in outermost areas with high volume. In 2014, the highest wintertime water temperatures were observed in AS and GoF , where average temperature was over 1 °C higher than in other coastal areas. The high early winter maximum temperature explains the higher average temperature and delays the ice formation during coldest months (Jan-Feb). The long iceless period may increase the average temperature of the coastal areas also in summertime. Austin & Colman (2007) suggest a similar heating pattern in Lake Superior in a time series that can be seen as a regional pattern between BB and AS. The lack of ice and extreme events in winter temperatures will most likely be more frequent on shallow shores if the climate change will effect as predicted (Meier et al. 2006; Meier et al. 2012, BACC-II 2015). The ecological consequences can be multifaceted; for example salmonid fish can take advantage of higher winter temperatures in growth (Kallio-Nyberg et al. 2011; 2015) or the lack of ice can start reproductive cycle of algae earlier in spring (Lewandowska & Sommer 2010). Water temperatures below zero, although sometimes only a short period, can be hazardous for species that have resting or sensitive stage on reproduction cycle on wintertime. For example, extremely cold winter temperature effects on hatching time or survival of some fish species (Jäger et al. 1981; Veneranta et al. 2013a; Veneranta et al. 2013b).

The first observation of over 3 °C water temperature was done within a period of one week in late March in all sea areas, that indicated the lack of ice cover in winter 2013-2014. In normal winters the ice-cover delays the sudden heating of small sheltered bays and river estuaries in early spring, even on southern latitudes. Interestingly in the AS, where the wintertime average temperature in 2014 was highest, the date of the first observation of over 3 °C water temperature was later than in the GoF, BS and Quark. This might be caused by higher water volume of the sea-area, even in sheltered inner archipelago. The range of dates of the first observation over 3 °C temperature was highest in the BB, probably due to partial ice cover and slow heating of outermost areas. The average date of the first observation of over 3 °C was nearly three weeks later in the BB compared to other sea areas. The readings from UTR's suggest also that in the innermost areas the winter temperature can be substantially higher than in middle or outermost areas. The higher temperature might be caused by soft bottom that has decomposing organic material producing heat or by heat accumulated on sediment (ZoBell et al. 1953, Likens & Johnson 1969, Fang & Stefan 1998). The sediment type was not followed in study sites, but generally the bottom in innermost sheltered areas is covered with sedimented fine particle matter and decomposing vegetation.

Results indicate the most sheltered shallow bays have high capacity for warming. The river estuaries and shallow bays were the warmest regions in the coastal area all year round except autumn. In springtime, the high day-night air temperature variation affects the water temperature of shallow bays due to low water volume. In the early spring and late summer at upwelling occasions the temperature differences can be high between shallow and sheltered small bays located to outer islands and nearby open water areas. The river mouths and estuaries warm up fast, since the rivers descending to Finnish coastal areas have turbid run-off water due to humic and clay particles, double the amount of Swedish coastal area (Pettersson et al. 1997). The freshwater supplied to the basins by coastal rivers induces horizontal and vertical density gradients near the coasts and alters the temperature accumulation in estuary areas. Also plankton and micro-organisms contribute to turbidity that increases the heat accumulation from solar radiation both in extremely shallow conditions as well as in open water areas (Kara et al. 2004; Paaijmans et al. 2008; Jacobs et al. 2008). In early spring the freshwater from rivers may flow in the surface layer due to weak mixing, amplifying the upwarming of estuarine waters (Leppäranta & Myrberg 2008).

During the modelling period the temperatures reached daily average values of up to 15 - 16 °C, with maximum temperatures over 23-28 °C in July. The July 2014 was in the Northern Baltic Sea the warmest of the last 25 years (Siegel & Gerth 2015). Higher temperatures improve possibilities for example alien species to be established. The summertime warming on daily basis is most stable in the outermost stations, where the water volume is highest, as seen also on lakes (Livingstone & Lotter 1998), although the variation between sea areas can be high due to latitude. The cooling starts in August-September, when also the water temperature reaches the equivalence between the innermost and outer areas. When cooling begins, temperature variation depends on local meteorological conditions. The open water areas remain warmer than shallow bays that react faster to the air temperature as noted also by Horsch & Stefan (1988), Monismith et al. (1990) and James & Barko (1999).

The upwellings occur occasionally during summer months, most often in period from June to August (Myrberg & Andrejev 2003). In areas of upwelling, the total temperature difference between upwelled region and the open sea can range from 2 to 10 °C in a period of 0.5 to 10 days (Bychkova & Victorov 1986). The data period used for modelling included no significant upwelling occasions as can be seen in relatively stable temperature accumulation from spring to summer. The two drops in temperatures in early June and early July (Fig. 3.) are a combination of decrease in air temperature and slight upwelling caused by northward wind. The wind forcing can alter the temperatures significantly in the middle, outer and open areas, especially if they are located near deeper (>20 m) water areas. Usually the severe upwellings occur due to strong northward or east-side winds forcing along the coastline (Haapala 1994; Myrberg & Andrejev 2003, 2008). In the middle archipelago, the inshore-offshore mixing slows the rate of water heating and cooling. The archipelago works as a buffer in upwelling events that is indicated by higher variation in temperature values observed in thermogram of zone 3, while in zones 1 and 5 the temperature trend at summertime remains more stable.

5.2 Factors affecting areal temperature development

In this study the spatial modelling is based on data of the last sampling year and therefore annual variation is not covered in this paper. Average water temperature and the magnitude of short-term variability vary greatly between years (Siegel & Gerth 2015). We assumed that the temperature pattern between coastal areas remains nearly stable, independent of short term variability.

The most representative spatial model included variables that all were derivatives of depth, wave exposure and river run-off. Of these variables, depth and wave exposure describe gradient from shallow innermost areas to deeper outer region. Latitude (variable Y) and RIVERDEPTH include the effect of high freshwater run-off to the GoB, especially in the BB. The latitude shows a clear change in effect from Quark to BB indicating the BB was during modelling period colder than other sea-areas. After the ice break-up and reaching the 3 °C limit, northern areas warm up fast and nearly reach the temperature of southern areas in July. In model, distance to 10 m depth curve separates shallow areas that react on air temperature and areas that are prone to effects of water circulation. Short distance to deeper water makes the area colder and long distance warmer relative to average. Log transformed wave exposure reflects the gradient from inner coastal areas to outer and most open areas, thus correlating also with water circulation patterns. Outermost archipelago or open coastlines have small sheltered bays with low exposure and water volume. The distance to 30 m deep water weighted either with average depth in 3 km circle (D30DEP) or wave exposure (D30DSWM) separates these small fast heating patches from larger scale temperature gradients. The influence of D30DSWM is not as robust, since the effect is dependent on sample location on coastal inner-outer gradient. D30DEP loses the influence of small shallow sheltered areas, but has an effect on inner coastal areas, where the 3 km circle for depth reveals the gradients in geophysical properties of the coastal area. Water depth, distance from rivers, open sea and islands are most important determinants to areal temperature development.

5.3 Characterization of coastal zones , species areal use and production guided by temperature

Temperature influences on distribution of species and their seasonal movements (Schofield et al. 2009) or even in smallest scale (meters to kilometers), temperature may drive habitat selection by individuals and schools, as seen on fishes (Urho & Hildén 1990, Urho 2002; Mackenzie et al. 2007). The modelled temperature sum can be used to classify coastal gradients to form a basis for geophysical-biological classification. The coastal classification of the Baltic Sea have previously been somehow unclear, with no exact basis for the limits of outer, middle and inner archipelago (see, for example, Häyrén 1900; Hällfors et al. 1983) and the borders have been defined more on management view than based on actual data. A classification based on expert knowledge have been also used to define ecologically relevant areas (HELCOM 2013), however this is based on salinity and location (Kangas et al. 2003).

We suggest the use of temperature sum as a basis for this coastal zone classification as it has direct link to the coastal ecology. The temperature reveals coastal zones that have presumably different responses to climatological and water circulation changes due to water volume. The temperature sum class boundaries used to define the zones are specific to our data. Biologically more justified approach to define the class boundaries would be to choose the boundaries based on the biota of the sampling stations but we did not have data on that. However, our results show that already this kind of rather crude classification provides biologically sensible coastal regions. The knowledge of the extent of different zones with warm or cold temperature is important for estimating the available areas for species that are limited to cold water areas or dependent on warm reproduction areas. These differences in coastal temperature structure may affect for example on growth rates and fish hatching times at reproduction (Kjellman et al. 2003; Ložys 2004; Sundblad et al. 2009;) and thus, suggest that the observed variability in water temperature would result in differences in the productivity of different portions of the littoral zone. In addition, rates of photosynthesis, respiration and growth generally increases with temperature, but this effect is enhanced by high nutrient availability, and is most evident on nutrient amended areas (Staehr & Sand-Jensen 2006), like river estuaries.

In coastal areas water temperature is a key determinant of ecosystem status and cause for concern under a changing climate. For example, fish are heterothermic ectotherms and habitat temperature directly influences their physiology and behavior (Hokanson 1977; Magnuson et al. 1979; Pritt et al. 2014). The reproduction of pikeperch (*Sander lucioperca*) takes place only in the innermost zone (Veneranta et al. 2011) and early survival is dependent on temperature (Peckan-Hekim et al. 2011). In addition to reproduction, for wintertime distribution of certain fish species, like perch (*Perca fluviatilis*) and pikeperch (*Sander lucioperca*), the observed temperature differences can be important. These species will be found at greatest densities in habitats within thermal niche. During this century winter fishing of perch and pikeperch in the Gulf of Finland and AS has been more intensive in the shallow inner bays and estuaries compared to previous century when fishing took place in more outer areas (Luke, unpublished data). Our measurements show that the innermost areas were the warmest in winter (Table 3) that may have attracted fish there, too. For species distribution modeling, the data forms a biologically sensible base layer, and it can be used in species distribution modelling (Kallasvuo et al. 2015, submitted). In the past there has been insufficient data describing temperature distribution from observations and the earlier data collection has focused on sparse local time series, thus making the biological use more or less scarce. Our data shows that there may be huge differences in daily and even in average monthly temperatures within a sea area when different archipelago zones are compared.

The temperature model could also be extended to other coastal areas in the Baltic Sea. The temperature sum prediction could potentially be improved by combining the in-situ data with coarser scale satellite measurements in similar manner as in, for example, statistical calibration of weather forecast systems (Berrocal et al., 2008) and downscaling of marine seasonal forecasts (Vanhatalo et al. 2016). The in-situ measurements would help in correcting biases in satellite measurements and to down-scale the information in satellite data to high resolution coastal prediction. The satellite data could also be used to extend the time series to cover larger temporal periods. This is, however, left for future.

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APPENDIX A - Sampling stratification with tables A.2 and A.3

A.1 Sampling stratification

The underwater temperature recorders were positioned based on map stratification by wind exposure (Isaeus, 2004) and depth (Finnish Environment Institute, FEI) that were a priori estimated to be the most important variables explaining the water temperature. In analyses, the resolution of original GIS layers was reduced from 25 m (fetch) and 50 m (depth) to 100 m. For the stratification, the open sea areas were defined based on wind exposure data (values 509504-1150552) by following the original openness classification of Häyren (1900), that sets limits for outer, middle and inner areas based on existence of vegetation. Then a new raster layer describing the shortest distance from open sea to shore was calculated along the water surface in cell size of 100 m, with increasing distance to shore. The depth layer did not cover all innermost coastal areas and for stratification these areas with no data were completed with depth of 2 m. In stratification we used the average depth on a circle with 2000 m radius so that the final raster layer for stratification was:

*sample stratification = √((distance to open sea * (1/average depth))*

The entire coastal area was classified to 11 strata to achieve approximately 8-9 temperature data recording sites for each class. The stratification was then done in intervals of 1/3 standard deviation of the distribution of stratification values. For practical reasons, the location of data loggers in different coastal areas was clustered. However, the data logger sites were randomized as far as logistically possible to avoid spatial autocorrelation in the data, in practice the water distance between data loggers was determined to be at least 1500 m.

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Table A.2 Variables used in the temperature model. FEI = Finnish Environmental Institute, Luke = Luonnonvarakeskus.

Variable	Description	Resolution	Value range	Unit	Source
DEPMD1500	Depth, median, calculation radius 750 m	50	1 - 274	m	FEI, Luke
DEPMD1000	Depth, median, calculation radius 500 m	50	1 - 276	m	FEI, Luke
DEPTHAV10	Average depth, radius 5000 m	50	1 - 249	m	FEI, Luke
DEPTHAV15	Average depth, radius 7500m	50	1 - 248	m	FEI, Luke
DEPTHAV5	Average depth, radius 2500 m	50	1 - 252	m	FEI, Luke
DEPTHAV3	Average depth, radius 1500 m	50	1 - 249	m	FEI, Luke
LINED15	Shoreline density, radius 7500 m	50	0 - 4.28	km/km^2	Luke
LINED10	Shoreline density, radius 5000 m	50	0 - 5.31	km/km^2	Luke
LINED5	Shoreline density, radius 2500 m	50	0 - 7.55	km/km^2	Luke
LINED3	Shoreline density, radius 1500 m	50	0 - 10.31	km/km^2	Luke
SWM	Exposure (Fetch) , fine	50	150-1150558	m	FEI, Isaeus 2004
SWMMDN	Exposure (Fetch) median, radius 150 m , fine resolution	50	150-1150483	m	FEI
SWM300M	Exposure (Fetch), coarse, original resolution 300 m	50	0 - 1169627	m	FEI, Isaeus 2004
LGSWM	Exposure, log transformed average of three cells.	50		m	FEI, Isaeus 2004
DISTO10M	Distance to 10 m depth, areas < $10km^2$ removed	50	0 - 35224	m	Luke
DISTO20M	Distance to 20 m depth, < $10km^2$ removed	50	0 - 47717	m	Luke
DISTO30M	Distance to 30 m depth, < $10km^2$ removed	50	0 - 85130	m	Luke
DISTSUM	Sum of distmin(10;20;30)	50	0 - 145956	--	Luke
RIVERDISTMQ	Distance to coastal river mouths, multiplied by MQ of each river and summed	50	0.01 - 12.58		Luke
RIVERDEPTHMQ	Index value of distance to coastal river mouths and depth: RIVERDEPTH = 1/DEPAVG5 * Exp(Sq(RIVERDISTMQ)	50	0.01 - 14.58	--	Luke
X	Longitude	50	--	ETRS 89 LAEA	-
Y	Latitude	50	--	ETRS 89 LAEA	-
D20DSWM	(D20DEP * (Log10(SWMMDN))*(1/SWMMDN))	50	0 - 0.03	--	Luke
D30DSWM	(D30DEP * (Log10(SWMMDN))*(1/SWMMDN))	50	0 - 0.12	--	Luke
D20DEP	(DIST20MA / 10000) *(1/DEPAVG3)	50	0 - 6.46	--	Luke
D30DEP	(DIST30MA / 10000) *(1/DEPAVG3)	50	0 - 16.51	--	Luke
VOL3	Water volume, radius 1500 m	50	1 - 709593	km^3	Luke
Lagoons		vector		--	Metsähallitus, Natural Heritages
Shoreline		vector		--	FEI

Table A.3 Shoreline length in relation to surface area of coastal zone in the studied sea-areas.

Sea-area	Coastal zone	Average depth (m)	Shoreline lenght (km)	Shoreline length (%) of total lenght	Zone area (km^2)	Shoreline length (m)/ area (km^2)	Zone area / total coastal area (%)	Shoreline length (km) / total area
BB	Open	12.9	710	1.6	4227	168	.	6.2
	Outer	5.8	1257	2.8	1059	1187	.	11.0
	Middle	2.6	715	1.6	277.3	2578	2.4	6.2
	Inner	2.0	789	1.7	247.6	3187	2.2	6.9
	Innermost	1.5	799	1.8	171	4674	1.5	7.0
Quark	Open	16.2	158	0.4	1624	97	.	2.6
	Outer	9.3	894	2.0	1039	860	.	14.4
	Middle	6.5	933	2.1	432	2159	7.0	15.0
	Inner	2.8	1332	3.0	327.4	4067	5.3	21.5
	Innermost	1.8	1782	3.9	330.2	5396	5.3	28.8
BS	Open	17.8	61	0.1	1317	46	.	0.7
	Outer	11.2	858	1.9	1456	589	.	9.5
	Middle	4.1	1086	2.4	425.3	2553	4.7	12.0
	Inner	2.6	1453	3.2	366.5	3966	4.1	16.1
	Innermost	1.7	1955	4.3	354.3	5517	3.9	21.6
AS	Open	33.5	454	1.0	2564	177	.	2.3
	Outer	19.5	6160	13.6	6130	1005	.	31.9
	Middle	11.9	9327	20.7	2955	3156	15.3	48.2
	Inner	5.5	4742	10.5	1063	4461	5.5	24.5
	Innermost	3.7	1558	3.5	395.2	3941	2.0	8.1
GoF	Open	.	.	.	.	.	.	.
	Outer	23.1	1487	3.3	4401	338	.	17.7
	Middle	8.8	2750	6.1	1003	2741	.	32.7
	Inner	4.3	2409	5.3	583.5	4129	6.9	28.6
	Innermost	2.2	1464	3.2	328.3	4459	3.9	17.4
SUM	Open	29.9	1383	3.1	9732	142	17.9	2.5
	Outer	17.9	10655	23.6	14085	757	25.9	19.6
	Middle	9.5	14810	32.8	5093	2908	9.3	27.2
	Inner	4.0	10725	23.8	2588	4144	4.8	19.7
	Innermost	2.2	7557	16.7	1579	4786	2.9	13.9
	All	19.9	45131	100	33076	12737	60.7	82.8