

The future climate regions in Estonia

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Abstract. It can be assumed that future climate changes may have diverse impact on different parts of Estonia. For the regionalization of climate change impacts we used outputs of the EURO-CORDEX climate model ensemble and added its relative changes for temperature and precipitation to the values of the model's reference period 1971–2000. In order to reduce the ambiguity of spatially detailed outputs, the clusters of future climate variables for seasons were produced. We conclude that three climatic regions – the mainland, the coast and the western Estonian islands – will most likely persist in the future climate. Major regional changes may occur at the end of the 21st century according to the pessimistic scenario of Representative Concentration Pathways RCP8.5. In the rest of the cases, although the boundaries of regions may shift, the warming as well as the increase in precipitation will mainly occur within the regions. Partially this will result in the growth of contrasts between regions.

Key words: climate change, climate modelling outputs, Estonia, climate regions, greenhouse gas emission scenarios.

INTRODUCTION

The long coastline and position of Estonia in the transition zone between continental and maritime climates cause quite significant climatic differences within the country. In the eastern and especially the northeastern parts characteristics of continental climate are clearly observable, resulting in relatively warmer summers and colder winters. The western parts, the Estonian archipelago and coastal lowlands are under the influence of maritime climate with its thermal inertia: seasonal differences are not that sharp there as in the hinterland. As a consequence of the regional contrasts climatologic spring starts in the south and southeast for nearly two weeks earlier than in northern and northeastern Estonia (Jaagus & Ahas 2000; Jaagus 2001; Jaagus & Truu 2004; Tarand et al. 2013).

There is a considerable body of research on how the ongoing climate change is reflected in the seasonal climate variables in the whole of Estonia and its different regions. For example, the climatological winter has drastically shortened during last decades and thus also the number of days with ice and snow has reduced (Jaagus 1997, 2006; Jaagus & Ahas 2000; Jevrejeva 2000; Sooäär & Jaagus 2007). In regional terms, more detailed analysis has been done for climate change effects in the coastal areas: for the ice conditions (Jevrejeva 2000; Jevrejeva & Leppäranta 2002), increase

in winter storm frequencies as well as intensification of coastal processes (Orviku et al. 2003; Suursaar & Kullas 2006; Kont et al. 2007; Jaagus et al. 2008; Tõnissson et al. 2011).

The first attempts to regionalize Estonian climate were made by Kurrik (1924) and Kirde (1943). Other outstanding works which should be mentioned here are those by Raik (1967), where the index of continentality was used and Karing (1992), where the sum of active temperatures was applied. Several attempts have also been made to define microclimatic regions, which for historical reasons, were driven mainly by agricultural needs (Int & Karing 1974; Jõgi et al. 1976; Karing 2014). The work of Jaagus & Truu (2004) should be mentioned as well since, at a certain level, their article was the basis for the present study. To sum up the works mentioned above, three main macroclimatic regions are traditionally distinguished in Estonia: the islands, the mainland and the coastal sub-region.

As noted above, the climatic differences between regions are quite substantial and thus we can assume that future climate changes may have different impact on separate parts of Estonia. Not many studies analyse climate changes in Estonia in the future. We could mention climate change impact projects conducted in the 1990s (Punning 1996; Kallaste & Kuldna 1998; Tarand & Kallaste 1998) and the work by Saue & Kadaja (2011), which examines various greenhouse gas (GHG)

emission scenarios in relation to weather impact on potato yield. Jaagus & Mändla (2014) analysed outputs of different climate models in order to find out the one that provides the best description of today's climate; the study also made projections for temperature and precipitation for the period 2070–2099 based on different GHG emission scenarios.

The most detailed and comprehensive climate projection for Estonia was undertaken by the Estonian Environment Agency (in Estonian *Keskkonnaagentuur*, abbreviation KAUR) in 2015 (Luhamaa et al. 2015). The final report of the project was published only in Estonian and is, therefore, not available to international scientific community. However, as the work we are presenting in this article is based on the outcomes of the modelling efforts of KAUR, the methodology used in it is briefly reviewed in the next section. The same projections were used as input to four parallel projects for the development of the Estonian Adaptation Strategy to climate change. The work presented in this article is related to one of the adaptation projects that dealt with urban planning, land use, human health and rescue management (abbreviation of the project – KATI).

The implementation of KATI and other projects of the Estonian Adaptation Strategy in the interpretation of climate projections faced some difficulties. The main problem was that meteorological variables of such predictions were the averages of the modelling domain and thus do not represent all regional variability of climate variables. Another difficulty was that all introduced meteorological variables were presented as differences from the averages of the reference climate period. In practice, the question arose as to what these differences mean in absolute terms.

Therefore, for practical needs, we used model outcomes (Luhamaa et al. 2015) to visualize the spatial distribution of the predicted air temperature and precipitation changes. Then we examined how these changes manifest themselves in different parts of the country, i.e. in three main macroclimatic regions of Estonia, trying to answer the question: is it possible to say that in some region climate changes will be more significant than in the others?

DATA AND METHODS

As mentioned above, the present study is based on outputs of the future climate projection made by KAUR (Luhamaa et al. 2015). They used as an input the EURO-CORDEX (Jacob et al. 2014) ensemble of climate simulations based on an ensemble of downscaled climate models developed mainly in the Nordic countries. The ensemble, used by KAUR (here and after the KAUR

ensemble), contained three models: RCA4 (developed by The Swedish Meteorological and Hydrological Institute, boundary conditions CNRM), DIM-HIRHAM5 (Danish Meteorological Institute, EC-EARTH) and KNMI-RACMO22 (The Royal Netherlands Meteorological Institute, EC-EARTH). The resolution of the used models was 12 km × 12 km (Fig. 1).

Two greenhouse gas emission scenarios, i.e. Representative Concentration Pathways (RCP) from the fifth IPCC (2014) assessment report were chosen to simulate future climate. The basic scenario for the project was RCP4.5, which can also be considered as an optimistic scenario according to which mankind is capable of agreeing on the GHG emission quantities and of gradually reducing them. An additional scenario used is RCP8.5, known as pessimistic. According to this scenario, the agreement will not be reached and the growth of GHG emissions will accelerate (IPCC 2014; Luhamaa et al. 2015). The reference period, with respect to which the changes were calculated, was 1971–2000 (Luhamaa et al. 2015).

The outcomes of the simulations were changes in air temperature, precipitation and some other meteorological variables for the periods 2041–2070 and 2071–2100. The changes were produced with respect to variables of the reference period calculated by the same ensemble of models. The future changes of variables were calculated by calendar months and seasons. The domain extent and position are *a priori* predefined by technical parameters of models, thus covering a large area of sea and including part of southwestern Finland.

The outcome of the KAUR ensemble was a raster-map (Fig. 1, grey dots), where in the cell of the 12 km × 12 km matrix each climate variable has its specific value. For the convenience of the KATI project the initial matrix was recalculated by means of the geographic information system (GIS) into raster with a resolution of 10 km and extent more focused on the Estonian territory (Fig. 1, black dots). We used ArcGIS 10.2 software for all GIS calculations and cartographic applications.

After the transformation described above the extent and, as a result, the number of cells participating in the calculation of the averages reduced. In order to evaluate the decrease in the 'sea influence', new averages were calculated. The averages of the new extent appeared to differ from those of the model domain by less than 10%.

Next, the issue of absolute values was addressed. In other words, we tried to find out the possible future absolute values of the air temperature and precipitation resulting from the projected climate changes. As the first step here, we used meteorological observations – temperature and precipitation – from the reference period (1971–2000) for the following stations: Heltermaa,

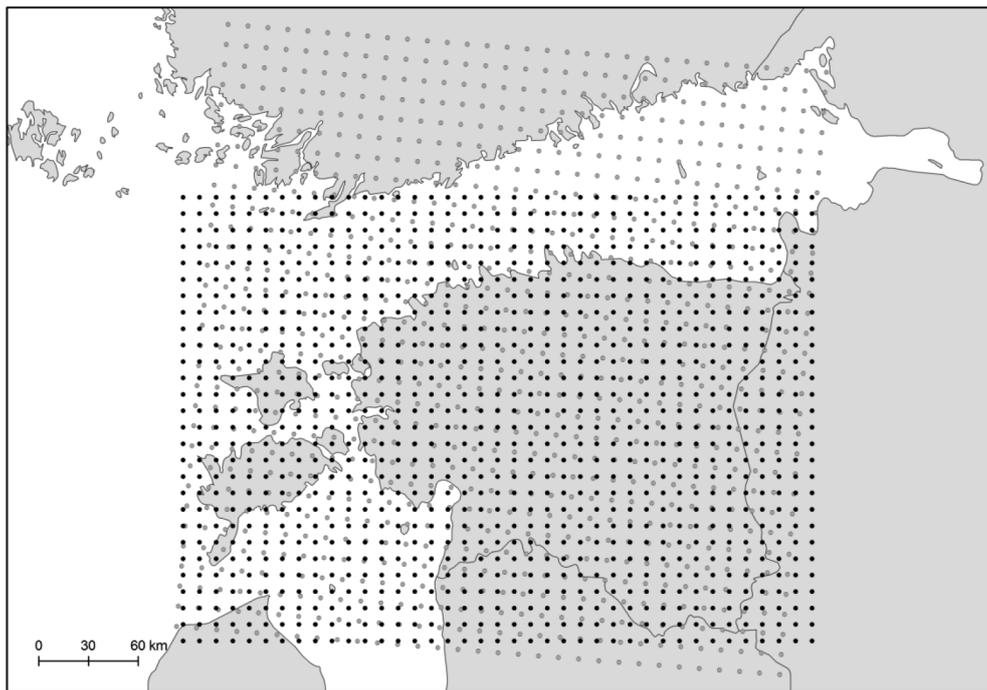


Fig. 1. The extent and resolution of the KAUR ensemble domain (grey dots) and recalculated map used for the KATI project with a new extent (black dots).

Jõgeva, Jõhvi, Kihnu, Kunda, Kuressaare (Roomassaare harbour, 1971–1999), Kuusiku, Narva, Lääne-Nigula, Pakri, Pärnu, Ristna, Ruhnu, Sõrve, Tallinn, Tartu-Ülenurme (Roela, 1971–1996), Tartu-Tõravere, Tiirikoja, Tooma, Türi, Valga, Viljandi, Vilsandi, Virtsu, Võru and Väike-Maarja. Data were obtained from the Estonian Weather Service and interpolated into a 10 km grid for a new extent (Fig. 2A). The second step was to add the value of variable change to each interpolated value of

the reference period at the same cell from the KAUR ensemble outputs.

Naturally, outputs of the KAUR ensemble, presented spatially in the resulting maps of meteorological parameters (Fig. 2B), are more detailed than just averaged numbers over the domain. However, the level of detail in this case represents certain weakness. A 10 km grid is so detailed that it seems that we can predict climate at the level of individual municipalities. Nevertheless, the

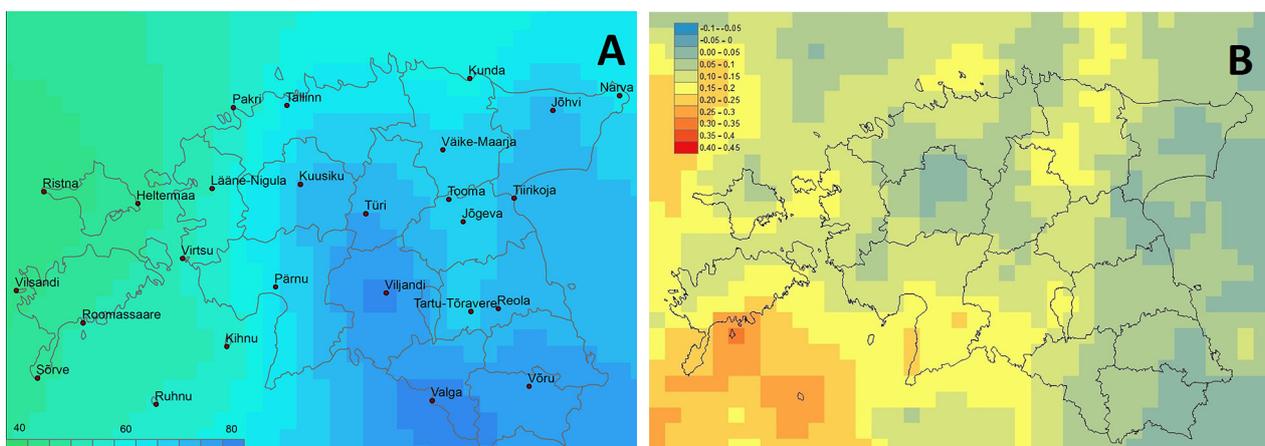


Fig. 2. Average precipitation (mm) of July for the reference period 1971–2000 (A) and changes from the KAUR model ensemble according to the scenario RCP8.5 for the period 2071–2100 (B); -0.1 refers to 10% reduction in the precipitation compared to the reference period.

mosaic of discrete pixels (Fig. 2B) does not have any climatological sense, especially in the case of precipitation where the actual spatial distribution is highly variable and full of randomness.

To avoid false conclusions, the results should be generalized by a geographical or/and time step. One possibility here is to move from monthly averages to seasonal ones, as it has been done in Luhamaa et al. (2015). Data averaging reduces a large part of random anomalies. In addition to averaging through seasons, we aggregated projected meteorological variables into clusters in order to define and describe areas of similar climatic patterns. Numerous different classification methods are currently used for the delineation of clusters, which are described in the scientific literature. After a thorough consideration we found that ArcGIS 10.2 *IsoCluster Unsupervised Classification* tool was the optimal choice for our purposes.

The *IsoCluster* algorithm determines the characteristics of natural groupings of cells in the multi-dimensional attribute space (in other words, several raster-maps) and stores the results in an output ASCII signature file where each cluster is defined by its statistics. The resulting signature file can be used as the input for a classification function, such as *Maximum Likelihood Classification*, which produces an unsupervised classification raster-map, where cells belong to one of the cluster classes and therefore the geographical extent of each cluster can be visualized. The minimum valid number of clusters is two and the algorithm does not limit the maximum number of clusters. However, to provide sufficient statistics necessary for generating a signature file for a classification, each cluster should contain enough cells to be accurately represented (Ball & Hall 1965). In our case, when we have only 39 columns and 28 rows in our 10 km × 10 km raster map, it is not wise to try to specify more than five clusters. On the other hand, the number of classes should allow for explaining the most important regional differences, but must be just enough to maintain a reasonable balance between the level of varieties and generalization (Linoff & Berry 2011). Based on several tries, we limited the number of clusters to three. We proceeded from the assumption that the resulting spatial structure of the regions should broadly conform to Jaagus & Truu (2004) where three climatic regions were distinguished.

RESULTS

In principle, the pattern of regional climate will remain in the future as it was defined by Jaagus & Truu (2004): the sea–coast–hinterland gradient will persist both in the case of air temperature and precipitation. In general, the

warmest and the rainiest region will gradually expand in the future, usually at the expense of the coastal area. The major changes will materialize in case of the pessimistic scenario RCP8.5 in the period 2071–2100.

In the following we describe the future regional change in seasonal temperature and rainfall patterns. We present two figures for each season – the reference climate and RCP8.5 regions for the period 2071–2100. The patterns of these periods differ the most. All patterns of the optimistic scenario and the pessimistic scenario for the period 2041–2070 are more like the reference climate.

Air temperature

As mentioned above, the climatologic spring arrives earlier in southern and southeastern Estonia. These parts warm up quicker than northern Estonia, islands and sea. The temperature contrast between the south and the islands is relatively sharp (Fig. 3A). This spatial distribution is maintained equally in all scenarios and time periods, although at the end of the 21st century according to RCP8.5 the average air temperature of March, April and May (MAM) in all regions will be twice higher than in the reference period (Fig. 3B).

The summer (JJA) of the reference period is characterized by the northern and southern Estonia temperature contrast – the inland region is on average 0.6 °C warmer than northern and central Estonia, and marine areas. The temperature difference between maritime and northern regions is virtually non-existent (Fig. 4A). In the future, the regional boundaries and content (air temperature or precipitation) will transform significantly. The temperature differences of the Estonian mainland will level out, and will differ only in very warm southeastern Estonia. On the other hand, the Gulf of Finland and the area of islands will become even warmer than the mainland (Fig. 4B). Why the sea turns warmer than the average of the mainland needs separate in-depth analysis. It may be a peculiarity of climate models or a forecasting error. However, it is also possible that high pressure will dominate during summers and result in a clear and sunny weather. If this is the case, during day both land and sea heat up, but at night land cools faster than thermally inert sea. Statistically, sea inertness produces higher average temperature.

Autumn begins earlier in the eastern and northeastern part of Estonia. The temperature contrast between the marine and inland areas deepens because of the thermal inertia of the sea and for a long time the sea is relatively warmer than the inland (Fig. 5A). This distribution will remain in the future according to all scenarios. The temperature gradient between the west and east will remain slightly over 2 °C (Fig. 5B).

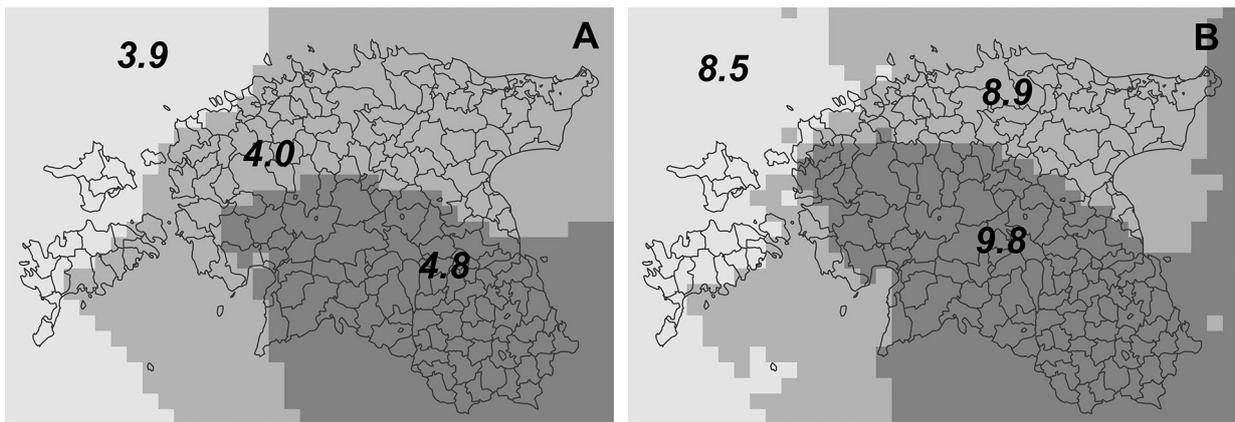


Fig. 3. Spring (MAM) air temperature (°C) regions and their average air temperature during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

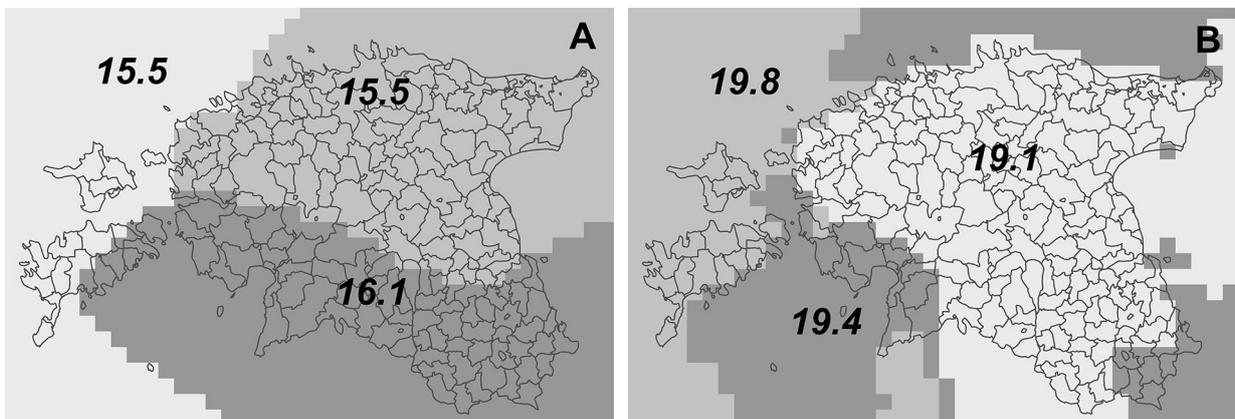


Fig. 4. Summer (JJA) air temperature (°C) regions and their average air temperature during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

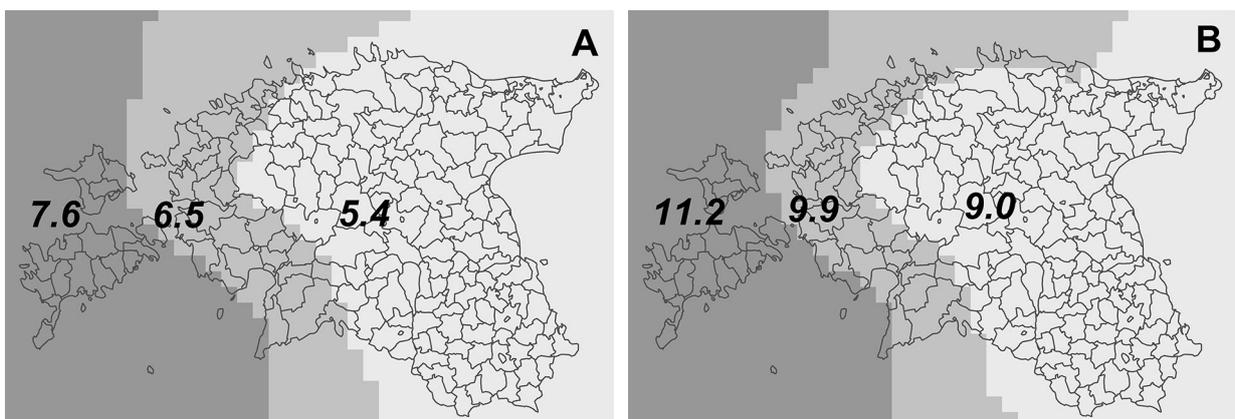


Fig. 5. Autumn (SON) air temperature (°C) regions and their average air temperature during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

The temperature distribution during winter (DJF) is similar to that of autumn. This means that the farther from the sea, the lower the temperature (Fig. 6A). Also, eastern and northeastern Estonia will be relatively cooler in the future than western Estonia, and especially the islands. However, if the reference period of the averages of all three clusters is below 0 °C, according to the

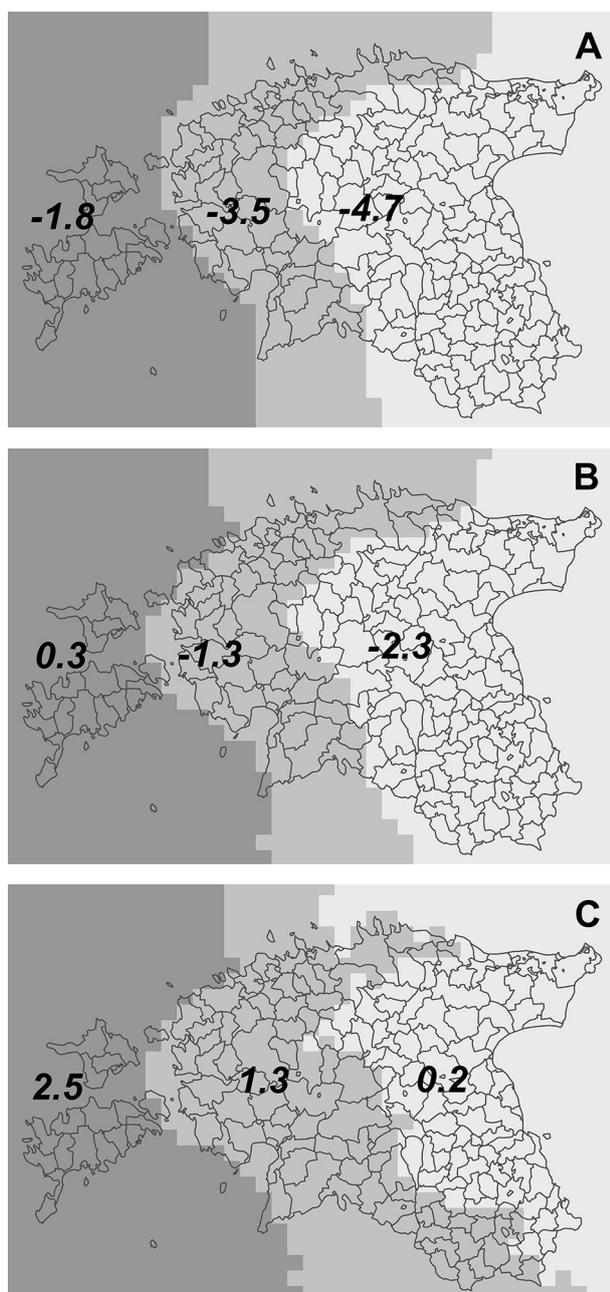


Fig. 6. Winter (DJF) air temperature (°C) regions and their average air temperature during the reference period 1971–2000 (A), according to RCP4.5 for the period 2071–2100 (B) and according to RCP8.5 for the period 2071–2100 (C).

RCP4.5 scenario, even a relatively small change means winter temperatures average above 0 °C for islands (Fig. 6B). The result of the warming according to RCP8.5 will be the sprawl of the coastal region (but not maritime) towards the hinterland (Fig. 6C). The contrast in the weather between the west and east will increase – the winter in the coastal areas may be relatively warm and snowless, but snowy weather and minus temperatures will still be common in the east.

Precipitation

Since during spring the sea is much cooler than the rapidly warming mainland, the distribution of precipitation follows the same pattern – it rains more on the mainland than on the western Estonian islands and along the coastline (Fig. 7A). This pattern will persist in the future. Precipitation will increase in all three regions, but more steeply in eastern Estonia that will be the most rainfall-rich region (Fig. 7B). One could say that the contrast in precipitation between the islands and mainland will grow, but compared to the reference climate, it will rain a lot on the islands and much more on the mainland.

The summer distribution as well is largely similar to the spring pattern – it rains less on the coast and islands. However, the coastal region of relatively poorer rainfall is much narrower than in spring (Fig. 8A). This narrow belt will shrink in the future. A significant change may take place at the end of the 21st century, when according to both RCP4.5 and RCP8.5 scenarios, the contrast between the islands and mainland becomes so strong that we can speak about only two precipitation regions. However, the mainland may become subdivided into the southern and northern sub-regions. Once again, we should not make the conclusion that the islands will suffer from water shortage: more rain will be on the islands in the future and much more on the continent.

The geography of precipitation turns to contrary in autumn. It rains more on the coast and islands than in East Estonia. The rainfall ridge in the western part of the mainland parallel to the coastal line, i.e. so-called western Estonian rainfall ridge (Tarand et al. 2013), is clearly prominent (Fig. 9A). This division remains in the future, though the ridge of rainfall in western Estonia will probably be even sharper (Fig. 9B).

The current winter rainfall pattern is similar to the one of autumn; the abovementioned precipitation ridge in the western part of Estonian mainland is even more prominent. Rains are relatively fewer in northeastern Estonia and alongside the Gulf of Riga (Fig. 10A). Most likely the contrast between the northeast and the rest of the country will increase in the future (Fig. 10B). Presumably, it will snow more often in the northeast than elsewhere at the end of the 21st century.

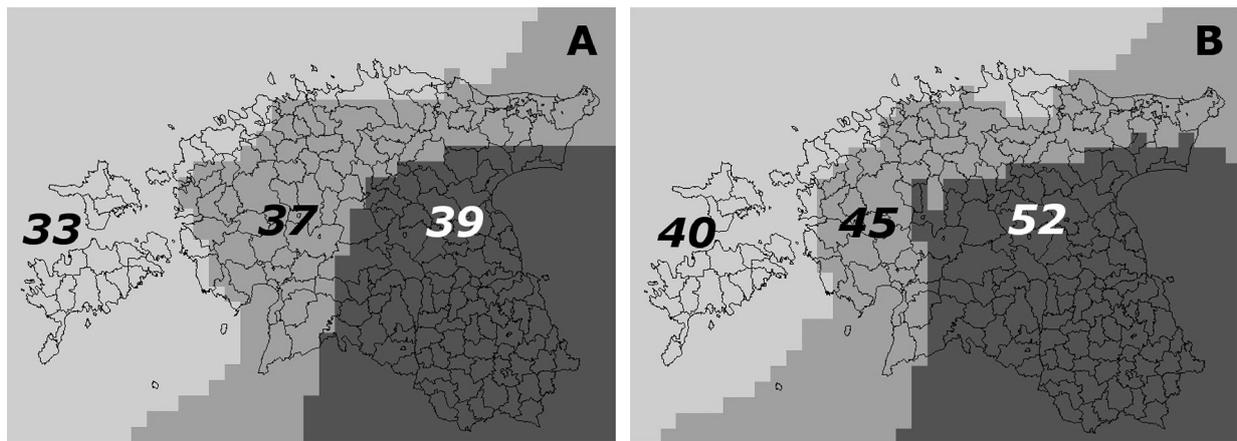


Fig. 7. Spring (MAM) precipitation sum (mm) and regions during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

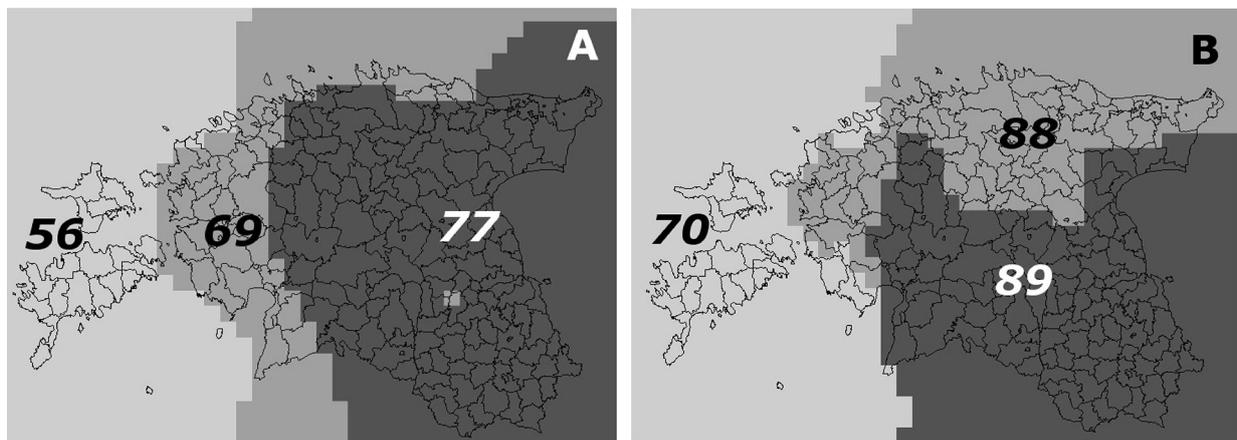


Fig. 8. Summer (JJA) precipitation sum (mm) and regions during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

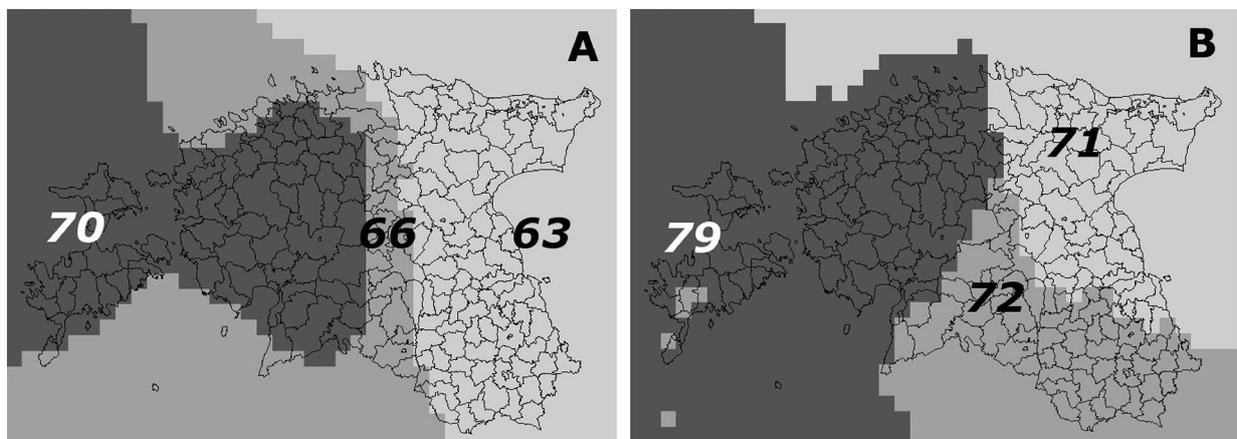


Fig. 9. Autumn (SON) precipitation sum (mm) and regions during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

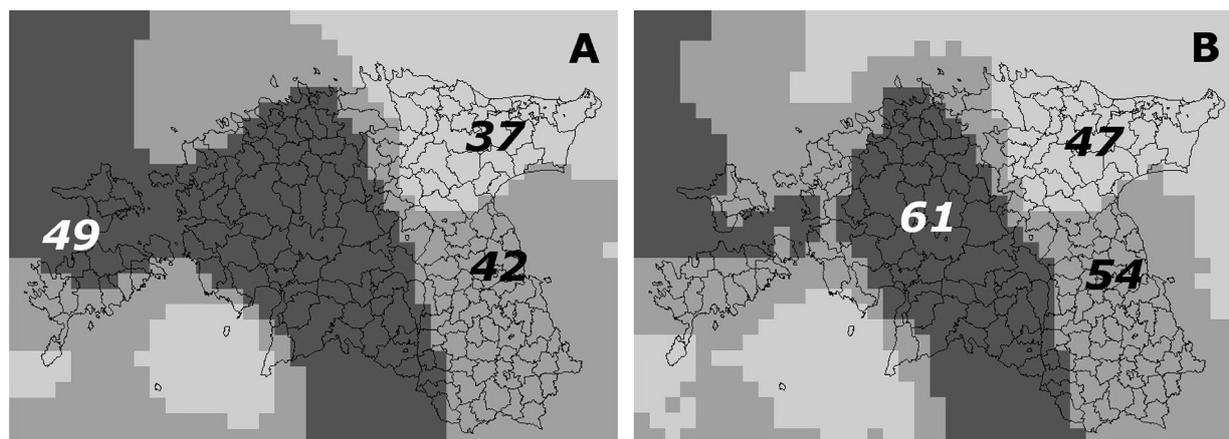


Fig. 10. Winter (DJF) precipitation sum (mm) and regions during the reference period 1971–2000 (A) and according to RCP8.5 for the period 2071–2100 (B).

CONCLUSIONS

Spatially detailed outputs of climate models give us better opportunities to assess the future effects of climate change in different regions of Estonia. However, the paradox of climate projections should be kept in mind: going into more detail in time and space will result in greater randomness and uncertainty. In a small country like Estonia, the 10 km × 10 km grid of meteorological parameters leads to the temptation to make the monthly climatological conclusions for each pixel. In the Estonian context, every pixel means actually a quite specific municipality. This, however, can lead to an absurd conclusion *à la* in June, in this municipality it rains more than in the neighbouring one and in July, the situation will reverse. Therefore, the present work suggests that only the seasonal and regional averages should be used when dealing with future climate changes.

Three main climatic regions are clearly distinguishable in Estonia: the Estonian mainland, the coastal areas and the western Estonian islands. For precipitation the rainfall ridge in the western part of the mainland is clearly prominent. Unfortunately, the outputs of the climate models and the observation data of the reference period did not permit the evaluation of more detailed climate variations caused for example by the Pandivere and the South Estonian uplands.

Three climatic regions – the mainland, the coast and the islands – will broadly persist in the future climate. According to the pessimistic scenario of RCP8.5, major regional changes may take place at the end of the 21st century. In the rest of the cases, although the boundaries of regions will shift, the climate warming as well as the increase in precipitation will mainly occur within the

regions. Partially this will result in the growth of contrasts between regions. The most significant change may occur in the winter air temperature – the deepening of regional disparities between the islands and eastern Estonia. Most likely the winter average temperature on the Estonian islands will turn to be persistently above 0 °C in the coming decades, while in eastern and especially in northeastern Estonia it may happen only in the last quarter of the century. The contrast in precipitation between the mainland and the islands will increase as well. In this case it means, in comparison with the reference period climate, a critical change in the upper range of the scale: ‘a lot’ versus ‘much more’. According to RCP8.5, it will rain on Saaremaa (the biggest Estonian island) one-fifth more at the end of the century than during the reference period.

A separate analysis is required to estimate how the deepening of regional contrasts will affect other components of nature. Based on winter changes in the air temperature and precipitation regime, one can assume that for example spring flood threats will remain in northeastern Estonia, but in the west high water will be a rare event already in the near future.

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Eesti tulevikukliima regioonid

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Võib eeldada, et kliimamuutustel tulevikus on Eesti eri piirkondades ka erinev mõju. Kliimamuutuste regionaalsete mõjude uurimiseks kasutasime algandmetena EURO-CORDEX-i kliimamudelite ansambli õhutemperatuuri ja sademete väljundeid mudelite normaalkliima perioodil 1971–2000. Mudelarvutuste väljundid üldistasime kolmeks kliimaregiooniks: Mandri-Eesti, rannikuvöönd ja Lääne-Eesti saarestik.

Analüüs näitas, et tulevikus need kolm kliimaregiooni säilivad, kuid suuremad nihked regioonidevahelistes piirides ilmnevad 21. sajandi lõpul, kui realiseerub kliimamuutuste pessimistlik stsenaarium RCP8.5. Prognoositavad kliima soojenemine ja sademete hulga tõus suurendavad Eesti-siseseid kliimaerinevusi. Näiteks võib lähikümnenditel muutuda tavaliseks, et Kirde-Eestis on talved lumised, kuid saartel on õhutemperatuur üle 0 °C.