BALTICA Volume 25 Number 2 December 2012 : 129–142
doi:10.5200/baltica.2012.25.13

Dryness dynamics of the Baltic Sea region

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Rimkus, E., Valiukas, D., Kažys, J., Gečaitė, I., Stonevičius, E., 2012. Dryness dynamics of the Baltic Sea region. *Baltica, 25 (2)*, 129-142. Vilnius. ISSN 0067-3064.

Manuscript submitted 27 July 2012 / Accepted 25 October 2012 / Published online 10 December 2012

Abstract The dynamics in dryness over the Baltic Sea region during the observation period of 1960–2009, as well as the climate prediction for the 21st century have been evaluated in this research. The dryness of the investigated area has been examined using the Standardized Precipitation Index (SPI). The precipitation amount data provided by the *Climate Research Unit* (*CRU*) at the *University* of *East Anglia* have been used in this study. Projections of future dryness changes are based on the output data of the regional CCLM model driven by A1B and B1 emission scenarios. The increase of SPI values, i.e. a decline in dryness, have been found over the last fifty years in the major part of the investigated area. However, the probability of short-term droughts remain high against the background of a general decrease in dryness. The increased dryness during the analyzed period has been found only in the southern part of the Baltic Sea region. Similar changes are also foreseen for the 21st century. The dryness is expected to increase in the south (especially in summer), while the central and northern parts of the region are likely to witness the recurrence of a drought decrease.

Keywords *• Droughts • Standardized Precipitation Index • Precipitation • CCLM • Baltic Sea region*

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INTRODUCTION

Extreme weather and climate events can produce severe impacts on our society and environment (Nicholls, Alexander 2007). One of the major extreme events is the drought, and its impacts on economy, social- and wild-life already pose many challenges (Gathara *et al.* 2006; Kundzewicz 2009). The climate change will bring even more extreme weather and climate events, including droughts in the future (IPCC 2007; van Lanen *et al.* 2007; Bordi, Sutera 2012). Though drought impact is more evident in the low latitudes of the world (Alcamo *et al.* 2007; UNISDR 2009) and Europe (Loyd-Hughes, Saunders 2002; Lehner *et al.* 2005; Bordi *et al.* 2009), but it is also an issue in the Baltic Sea region (Graham 2004; Kjellström, Ruosteenoja 2007; Barnett *et al.* 2005; Thorsteinsson, Björnsson 2011). The awareness of drought is rising and it shows in the political agenda (IPCC 2007; UNISDR 2009; EU 2010). Large research centres are already dealing with drought issues in Europe (European Drought Centre) and in the USA (National Drought Mitigation Center), moreover, a new network is on the way (Kossida *et al.* 2009).

The term ‘drought’ is used to define a temporary decrease in water availability due to, for instance, rainfall deficiency. A drought is an indistinct event of water deficiency that results from the combination of many complex factors, and neither the beginning nor the end can be precisely defined (Kossida *et al.* 2009). Drought types are defined by the impact on specific scopes and are classified into meteorological, agricultural, hydrological and socio-economic droughts (Gathara *et al.* 2006).

There are plenty of drought indices in the world (Heim 2002; Niemeyer 2008). All drought indices are based on drought as a relative concept: drought is defined as a negative departure of meteorological/water-related variables from some pre-established mean conditions (often referred to as a calibration period that according to the WMO recommendation should be at least 30 years long) (Bordi, Sutera 2012). Experts agreed on the use of a universal meteorological drought index for more effective drought monitoring and climate risk management. The agreement states that the Standardized Precipitation Index (SPI) should be used to characterize meteorological droughts by all National Meteorological and Hydrological Services around the world (WMO 2009). Most of the scientific investigations are concentrated on the spatial and temporal distribution of droughts (Hisdal *et al.* 2001; Loyd-Hughes, Saunders 2002; Kjellström *et al.* 2007) and on the impact of droughts on hydrological cycles (Bordi *et al.* 2009; Wilson *et al.* 2010; Tallaksen *et al.* 2011). Droughts are analyzed in a very wide context of scientific researches: drought impact on agro-ecosystems (Sakalauskaitė 2006; Schindler *et al.* 2007; Kalbarczyk 2010; Rad, Zandi 2012) and on forest life (Maracchi *et al.* 2005; Lindner *et al.* 2007; MacKay *et al.* 2012); interactions with water bodies (Peters *et al.* 2006; Jakimavičius, Kovalenkovienė 2010; Hänninen, Vuorinen 2011) and water quality (Sakalauskiene, Ignatavicius 2003; van Vliet, Zwolsman 2008; Zielinski *et al.* 2009). Palaeoclimatological drought conditions are discovered using sediments (Dippner, Voss 2004) and tree rings (Vitas, Erlickytė 2008; Büntgen *et al.* 2010; Drobyshev *et al.* 2011) data analysis. Projections of droughts into the past (Graham *et al.* 2009; Tomassini *et al.* 2011) and future (Lehner *et al.* 2005; Alcamo *et al.* 2007; Beniston *et al.* 2007; Fischer, Schär 2009) are modelled. Remote sensing methods (Peters *et al.* 2002; Sandholt *et al.* 2002; Bayarjargal *et al.* 2006) are more often invoked for recent drought dynamics studies.

The paper focuses on drought dynamics in the Baltic Sea region (further – BSR) (50.25°–70.25° N and 10.25°–30.25° E which includes the whole of the Baltic Sea area and surrounding countries (Fig. 1). Recent 50-year trends (1960–2009) and future projections (up to 2100) of droughts are analyzed. The high-resolution precipitation data are taken from the Climat*e* Research Unit at the University of East Anglia. For the first time in the region, the Standardized Precipitation Index (SPI) for four different periods ranging from one month (short-term conditions) to 60 months (long-term conditions) is used. The annual and summer drought dynamics are analyzed separately. SPI could be applied determining meteorological, hydrological and agricultural droughts. The region is also divided into sub-regions with variant drought dynamics using the cluster analysis. Meanwhile, for the first time in the region, the future dryness is projected using COSMO Climate Limited-area Model (CCLM) A1B and B1 scenario runs.

DATA AND METHODS

Monthly precipitation amount data from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) and Climate and Environmental Retrieval and Archive (CERA) data bases have been used in this research. KNMI database contains global high resolution (0.5° × 0.5° degree grid on land areas) precipitation data provided by the Climat*e* Research Unit at the East Anglia University (Mitchell, Jones 2005). CRU TS3.1 monthly precipitation data are based on land observation in meteorological stations. Grid point data have been interpolated from observational data. Data accuracy and homogeneity have been assessed during the data base creation.

The fifty-year period of observation from 1960 till 2009 has been covered by the present research of the dryness. Gridded data from the regular 105 grid points at 1-degree resolution in the BSR have been used. The data cover the areas 50.25°–70.25° N and 10.25°–30.25° E (Fig. 1). The dataset is based on the results of measurements on land. Therefore, the information on the precipitation amount over the Baltic Sea water surface is not provided in this dataset (Fig. 1).

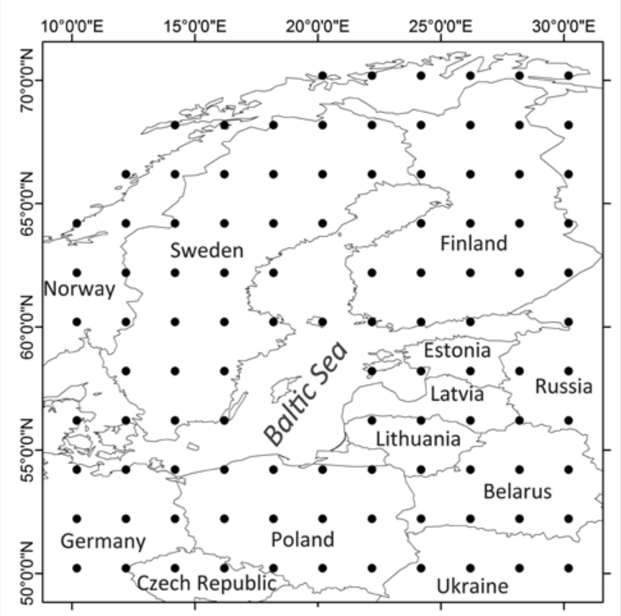

Fig. 1 The regular grid points over the BSR from the CRU precipitation dataset used in the study. Compiled by E. Stonevičius, 2012.

The first part of the research presents the comparison of the precipitation amount measured in meteorological stations and the precipitation data taken from the nearest CRU dataset grid point. For evaluation of the dataset quality, the precipitation data from Panevėžys (Lithuania) and Jyvaskyla (Finland) meteorological stations have been analyzed. The estimated average monthly precipitation amount slightly differs from the CRU data for both stations (Fig. 2). The mean absolute difference is equal to 9.37 mm in Panevėžys and 9.05 mm in Jyvaskyla. The precipitation amount in 66 percent of cases does not differ by more than 10 mm. It shows that the data from the CRU database reflect moisture conditions of the investigated area quite accurately. Some disagreement is caused by large unevenness of the precipitation field. The monthly precipitation amount observed in the meteorological station can differ significantly from the spatial average, which is reflected in a separate grid point of the CRU database. Larger differences arise when a large amount of precipitation falls. Then, the absolute unevenness of

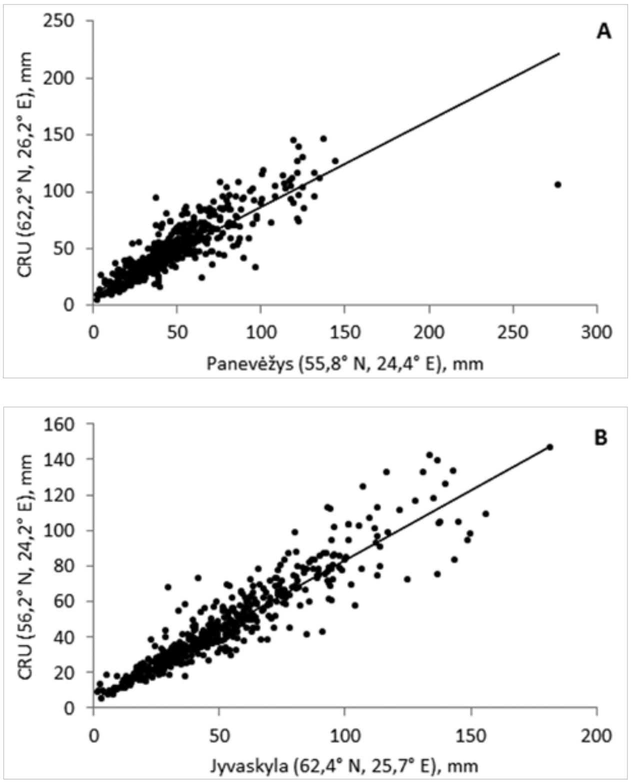

Fig. 2 Relationship between the precipitation amounts measured in Panevėžys (A), Jyvaskyla (B) and data from the nearest grid point of the CRU precipitation dataset in 1960–2009. Compiled by E. Rimkus, 2012.

the precipitation field increases. For example, in July 1998 the precipitation amount in Panevėžys reached 278 mm, while in some other meteorological stations of Lithuania the precipitation amount was more than five times less. Therefore, this value is very different from the value presented in the nearest grid point of the CRU database (102 mm). However, the size of the value in CRU database reflects well the spatial average of precipitation in grid cell at that time.

The Standardized Precipitation Index (SPI) has been calculated in this study. T. B. McKee and colleagues (1993) developed the SPI to assess the rainfall deficit in various time periods. SPI is calculated from monthly rainfall data series, first applying gamma distribution and then transforming it into a normal distribution (McKee *et al.* 1993; Edwards, McKee 1997). Positive SPI values indicate greater than average precipitation amounts and negative values indicate lower amounts. Based on the SPI value, dryness of the area can be evaluated (Table).

According to B. Loyd-Hughes and A. Saunders (2002), it is possible to identify all three (meteorological, hydrological and meteorological) drought types using different time steps of SPI. One of the main advantages of this index is its simplicity because the monthly precipitation data is the only input parameter. However, the precipitation data series must be at least 30-year long. The beginning of drought can be fixed when the SPI value falls below −1.0, and the end of the drought can be determined when the index value becomes positive. Intensity of drought should be calculated as a sum of all the SPI values during the drought period (McKee *et al.* 1993).

Table Interpretation of SPI values (McKee *et al.* 2007).

Value	Interpretation
> 2.0	Extremely wet
1.5–1.99	Very wet
1.0–1.49	Moderately wet
-0.99–0.99	Near normal
-1.0– -1.49	Moderately dry
-1.5– -1.99	Severely dry
< -2.0	Extremely dry

The SPI can be calculated for different time steps. In this research SPI1, SPI3, SPI12 and SPI60 index values have been calculated. One-month time step (SPI1) means that only one-month precipitation data are used for calculation. SPI1 distribution is very similar to a distribution of monthly precipitation sums. For the calculations of SPI3, three-month precipitation data are used, i.e. the data of the month for which SPI3 is calculated and the data of the previous two months. Hence, SPI3 shows short- and medium-term moisture conditions and provides a seasonal estimation of precipitation. This time step is quite widely used to identify agrometeorological droughts. SPI3 can describe spring and summer moisture conditions which are very important for plant vegetation, fire danger conditions etc. The calculation of SPI12 covers the month for which it is calculated and the precipitation amount of the previous 11 months. Using this SPI12 time step, not only droughts, but also long-term dry and wet periods can be distinguished. The SPI12 index values are also used to identify the hydrological droughts. The index value defines one-year moisture conditions. SPI60 reflects the overall 5-year conditions.

Cluster analysis has been used to evaluate dryness dynamics in different parts of the analyzed territory. K-method is used for clustering, and complete linkage (Euclidean distance) is employed like distance metric. Four regions with different dryness dynamics (according to SP1 index) have been distinguished. The annual and summer precipitation and SPI values are analyzed separately. The annual values allow assessing the changes of general moisture conditions in the area, while summer values characterize the growing season conditions when the intensity of drought and its damage are the largest.

The sign and magnitude of SPI values changes during the investigation period have been estimated using a Theil-Sen estimator (Helsel, Hirsh 1992). This method chooses the median slope among all lines through pairs of sample points so it is more resistant to outliers to compare with the least square method. The Theil-Sen estimator is the most popular nonparametric technique for estimating a linear trend. The Mann-Kendall test has been performed to evaluate the statistical significance ($\alpha = 0.05$) of SPI values trends

(Libiseller, Grimvall 2002). The big advantage of using this test is that the data do not need to conform to any particular distribution.

Regional climate model CCLM output data is used in this research to investigate possible changes of SPI values in the 21st century. CCLM data were taken from the CERA database. CCLM (COSMO Climate Limited-area Model) is the regional nonhydrostatic operational weather prediction model developed from the Local Model (LM) of the German Weather Service (Domms, Schättler 2002; Steppeler *et al.* 2003). This model has been also applied for climate predictions. The regional CCLM model covers almost the whole European territory with high spatial resolution (20 km – 20 km). The model is driven by the initial and boundary condition of the ECHAM5/MPI-OM global model. Dynamical downscaling has been used to get finer spatial resolution.

Modelling outputs are presented for two periods: a control run (1960–2000) and two scenario runs (2001–2100) (Böhm *et al.* 2006). The two emission scenarios (A1B and B1) have been used in model simulations, where B1 is a low emission scenario, and A1B is a relatively high emission scenario. CCLM model data outputs are taken from the CERA data base which is driven by WDCC (World Data Center for Climate).

CCLM model control run data for the grid points which correspond to the CRU database grid points differ quite a lot. CRU and CCLM precipitation data have been compared for the overlapping period 1960–2000. The determined ratio between mean monthly precipitation values has been used to make the climatic forecast. Afterwards, annual and summer precipitation sums for 21st century under two different climate scenarios (A1B and B1) have been estimated. Predicted values for the end of 21st century (2070–2100) are compared to the control period 1960–2000. These differences are calculated for each grid point.

RESULTS

Drought dynamics through the observation period of 1960–2009

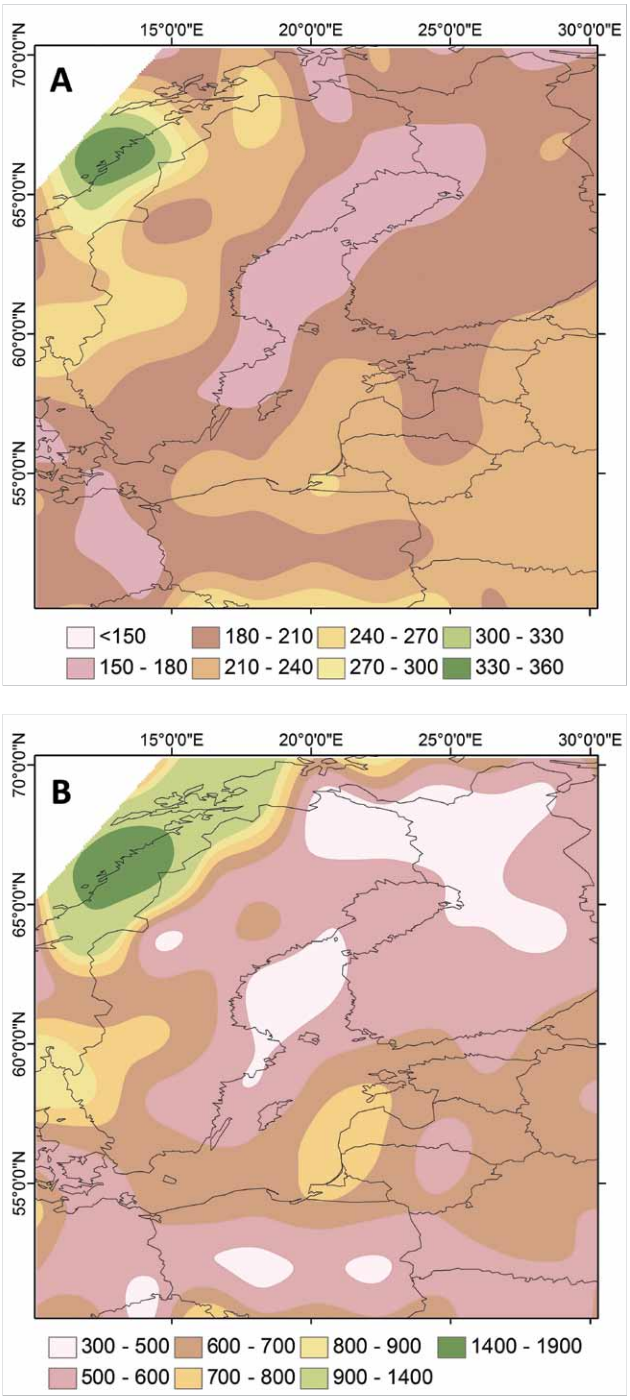

Fig. 3 The mean precipitation amount in the BSR in summer (A) and annually (B) in 1960–2000. Compiled by E. Stonevičius, 2012.

The mean annual precipitation amount for the period of 1960–2009 in the BSR is equal to 632 mm, while the summer rainfall reaches 211 mm (Fig. 3). Despite the fact that the analyzed region is large, precipitation sums are distributed quite evenly. Especially even distribution is observed for the summer rainfall amount. The coefficient of variation equals to 0.15. The precipitation sum of three summer months varies from 170 to 230 mm in the major part of the investigated area. The precipitation amount exceeds 300 mm only in the most southern and the north-western parts due to influence of orography (Fig. 3A). Because of a very large precipitation amount in the coastal area of Norway, the unevenness of the annual precipitation amount is higher (CV = 0.32). The annual precipitation sums in the northwest are 2–3 times larger than those in other parts of the BSR. This is mainly due to high precipitation amounts during the cold season, when the Gulf Stream brings warm air which cools adiabatically during orographic lifting on the slopes of the Scandinavian mountains (Førland *et al.* 2000). In the rest part of the territory the annual precipitation mostly varies from 500 to 750 mm (Fig. 3B).

The analysis of the drought dynamics in the BSR in 1961–2010 shows increased SPI values for different time steps. It can be concluded that during the investigation period the region has received the increased amount of moisture with the overall dryness declined. The most notable changes have been observed at long-term time steps (Fig. 4B). The first part of the investigation period can be described as a period with especially low SPI60 values. As mentioned above, this index assesses overall five-year moisture conditions. The positive changes of the three-month long dry periods (SPI3) are not so significant (Fig. 4A). Thus, the probability of short-term droughts remains quite high against the background of the overall decline in dryness.

According to SPI3 values, 31 cases with more than half of the analyzed area being moderately dry (SPI3 < -1) have been determined during the observation period of 1960–2009. Five cases have been found with such conditions observed in the area covering more than two-thirds of the whole region. The most extreme drought in the BSR is recorded in May 1974 with the average SPI3 value falling to -1.86, while nearly half of the territory has reached a critical level of -2 (extremely dry) (Fig. 5A). Since the beginning of 1974, due to low precipitation amount, the drought conditions have started to form in the south-eastern part. Afterward, in March–April, the drought has intensified and spread throughout the region. Although the drought has intensified in a large part of the territory and fell below a critical level in May, close to normal or even higher rainfall leads to a slight increase of SPI3 values at the southern part of the region.

From an economic point of view, however, the summer droughts are most important. During the investigated period, eight cases have been distinguished with SPI3 values being less than -1 (moderately dry) in more than half of the analyzed area. The most intense summer drought is recorded in August 1976 (Fig. 5B). The average SPI value in the BSR is equal to -1.24, and the critical level (-2) has been reached in almost one-fifth of the territory (mostly in the southwest). The drought in a large part of the BSR starts to form in April (especially in the south and south-east). Later the drought slightly intensifies and reaches maximum values in August.

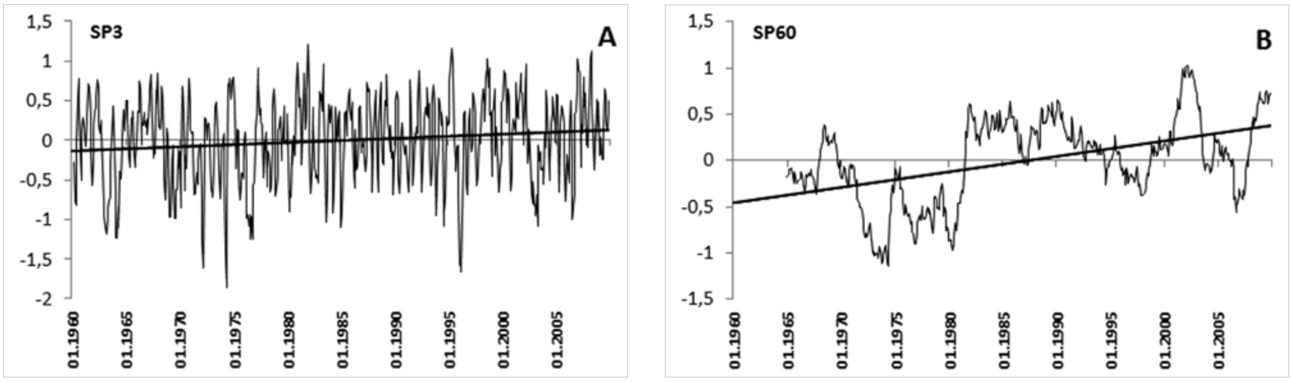

Fig. 4 Dynamics of dryness in the BSR in 1960–2009 according to SPI3 (A) and SPI60 (B). Compiled by E. Rimkus, 2012.

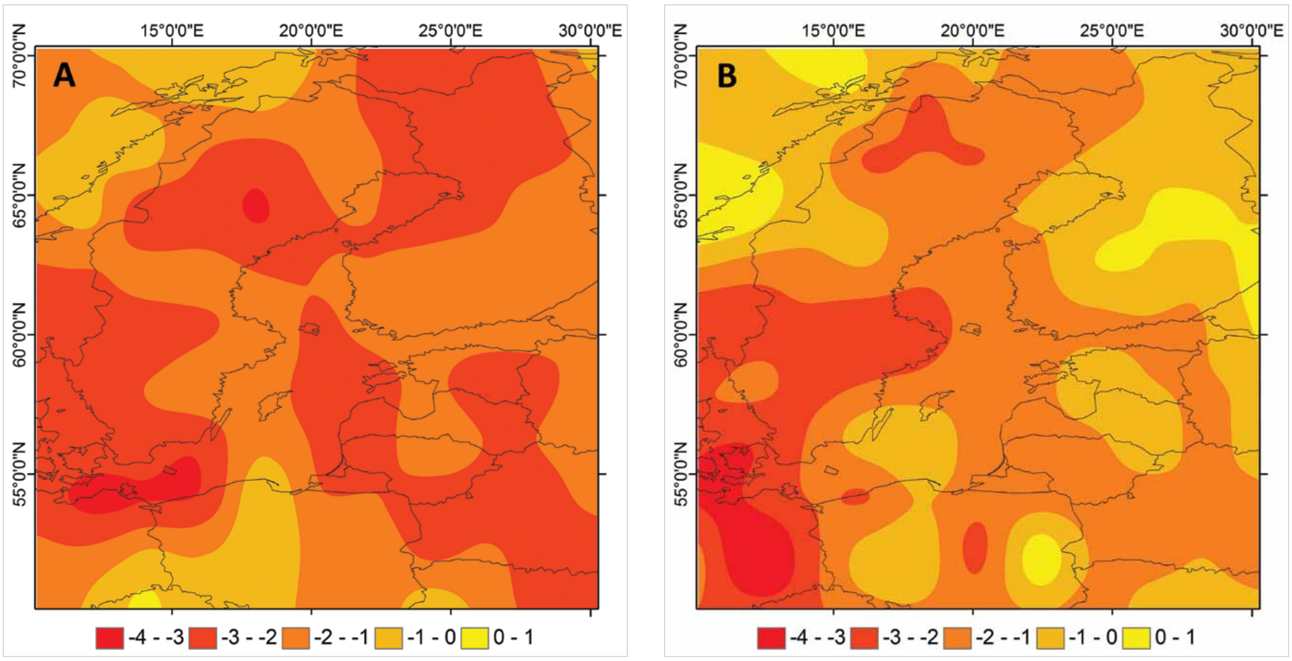

Fig. 5 Spatial distribution of SPI3 values during extreme droughts of May 1974 (A) and August 1976 (B). Compiled by E. Stonevičius, 2012.

It should be pointed that tendencies in dryness vary in different parts of the region. Figure 6 shows the sign and statistical significance of changes in summer months (according to SPI3) and annually (according to SPI12). The sign of changes in the large part of the investigated area coincides with the sign of the overall regional trend, i.e. SPI values increase. According to SPI3 values, the largest statistically significant positive changes during the summer months have been determined around the Baltic Sea at the south coast of Sweden, the Baltic Sea islands and south-western Finland (Fig. 6A). Statistically significant positive changes have been also identified in a major part of the eastern area of the BSR. Meanwhile, the negative tendencies of the index values have been observed in the southern and western part of the region, i.e. summer dryness increases. Statistically significant changes were recorded in the southern and central part of Poland. According to SPI12, positive tendencies of index have been determined in a larger part of the territory to compare with SPI3 (Fig. 6B). The changes are statistically significant in some areas (α = 0.05). Significant negative changes are observed in a major part of Poland.

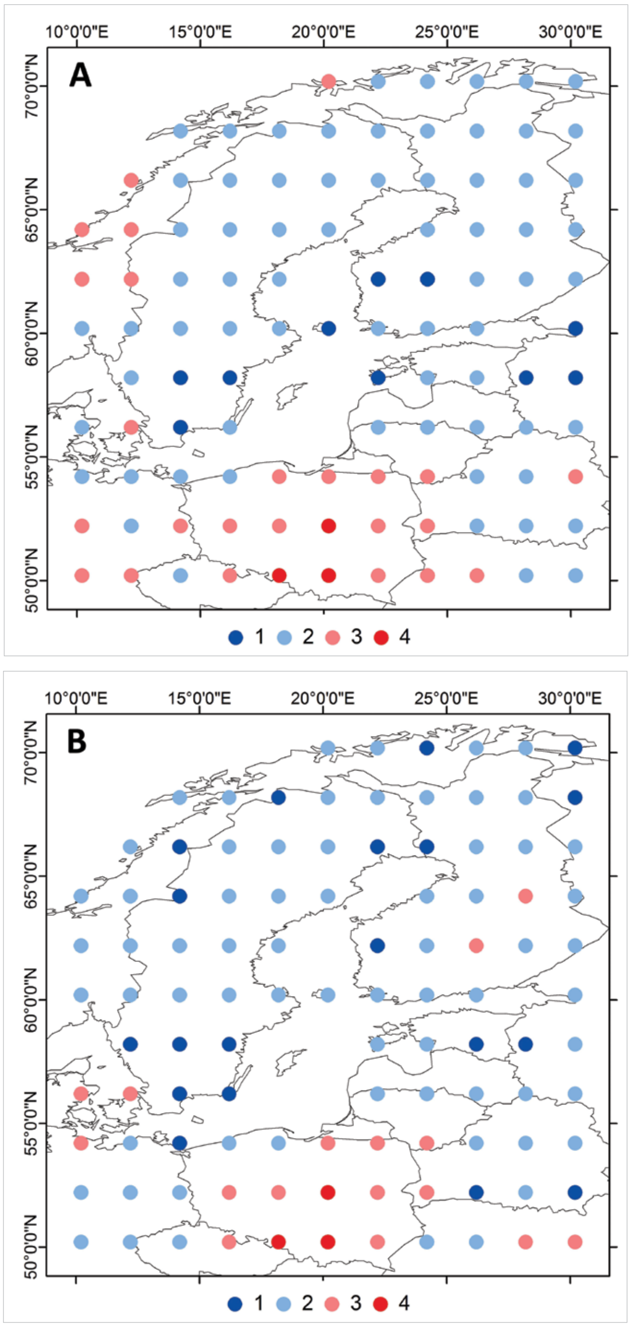

Fig. 6 The sign and statistical significance (α = 0.05) of observed SPI values tendencies in the BSR in 1960–2009 according to SPI3 in summer (A) and SPI12 annually (B). 1 – significant positive changes; 2 – insignificant positive changes; 3 – insignificant negative changes; 4 – significant negative changes. Compiled by E. Stonevičius, 2012.

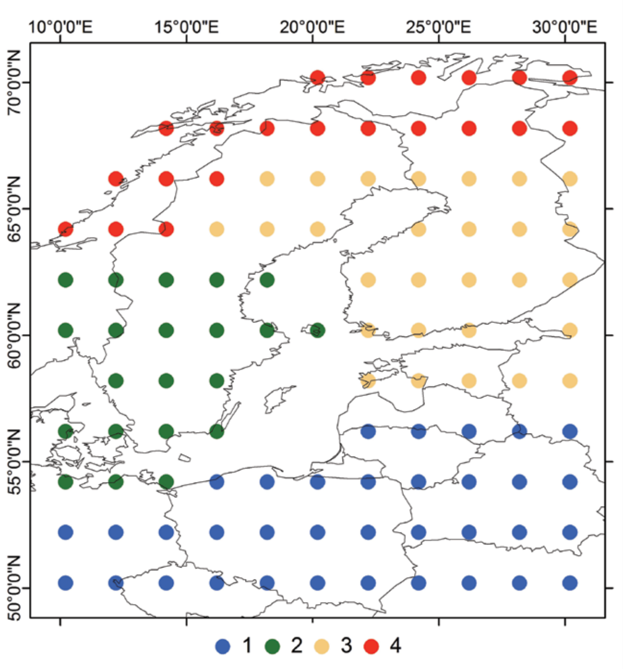

Fig. 7 The BSR's distinguished using cluster analysis according to dryness dynamics during the observation period of 1960–2009. Compiled by E. Stonevičius, 2012.

The cluster analysis has been employed for the purpose to assess the dynamics of drought duration and intensity in different parts of the investigated territory. Four regions with different precipitation and dryness regime have been distinguished (Fig. 7). The southern part of the territory is attributed to the first region. The second region covers the southern part of Sweden and Norway as well as Germany's coastline. The third region includes Estonia, a large part of Finland and Central Sweden. The fourth region is attributed to the coastal area of Norway and the most northern part of the BSR.

The drought intensity is calculated as a sum of SPI3 index values during the droughts (Fig. 8). The correlation analysis has been used to choose grid points which reflect the average characteristics of dryness dynamics of each cluster best. A slight tendency to intensification of the drought is observed in the first region (Fig. 8A). The drought intensity in the rest part of the region decreases. Such shift has been particularly strong in the north (Region 4) (Fig. 8D). The number of years when the SPI3 value did not fall below -1 has increased significantly over the past two decades in the second and fourth regions. The second region has recorded the strongest annual sum of drought intensity

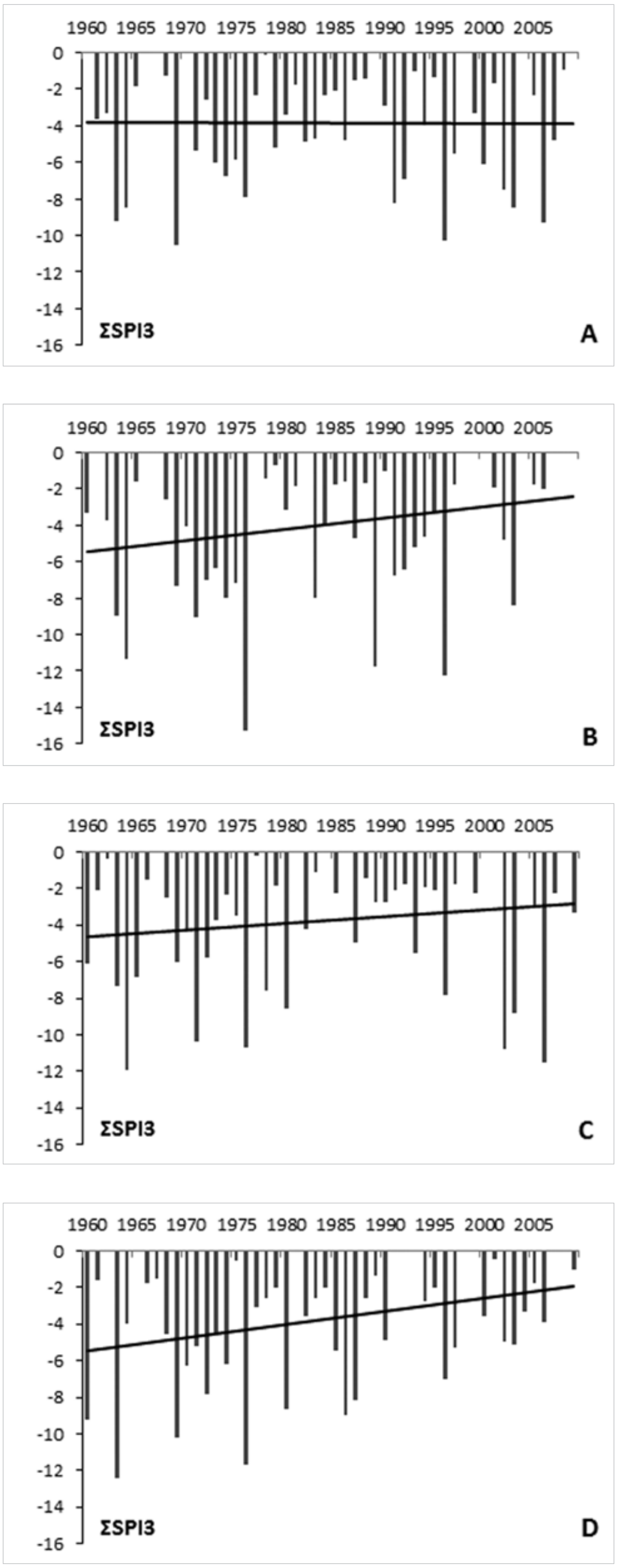

Fig. 8 Dynamics of drought intensity in different BSR's in 1960–2009 according to SPI3 (data from regular grid points of CRU database): A) region 1 (54.2° N; 24.2° E); B) region 2 (58.2° N; 14.2° E); C) region 3 (62.2° N; 24.2° E); D) region 4 (70.2° N; 24.2° E). Compiled by E. Rimkus, 2012.

(-15.3 in 1976). The driest years in other regions are observed during 1960s, when the total annual intensity of the drought has fallen below -10.

Modelling changes of dryness for the 21st century

According to the regional CCLM model outputs, the average annual precipitation amount in the BSR will increase. Under the climate scenario A1B, the precipitation will increase by 13% (Fig. 9A), while the B1 climate scenario foresees the rise by 11% (Fig. 9B). The strongest rise is expected at the beginning and the end of the 21st century. Meanwhile, at the middle of the century, rainfall will vary insignificantly. Summer rainfall under the A1B climate scenario will remain almost unchanged (Fig. 9B). According to the B1 climate scenario, the summer rainfall will slightly increase (by 6%).

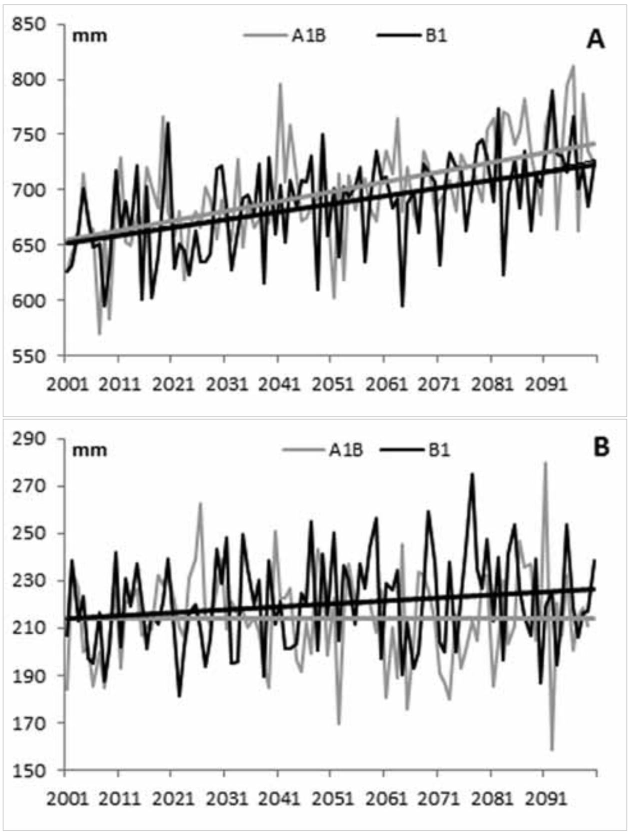

Fig. 9 Dynamics of the annual (A) and summer (B) precipitation amount in the BSR for the 21st century simulated using the CCLM model output data according to the A1B and B1 emission scenarios. Compiled by E. Rimkus, 2012.

The annual precipitation amount according to both climate scenarios will rise (Fig. 10). Only in the southwest part of the territory, according to the A1B climate scenario (Fig. 10A), and in the southern part, under the B1 climate scenario (Fig. 10B), the precipitation amount will remain almost unchanged or it will even slightly decrease. The largest positive changes are expected in the central part of the area around the Gulf of Bothnia (27%), according to the A1B scenario, and at the western part of Norway (up to 22%), under the B1 climate scenario. The general trend is very clear – further to the north, stronger positive changes will be recorded.

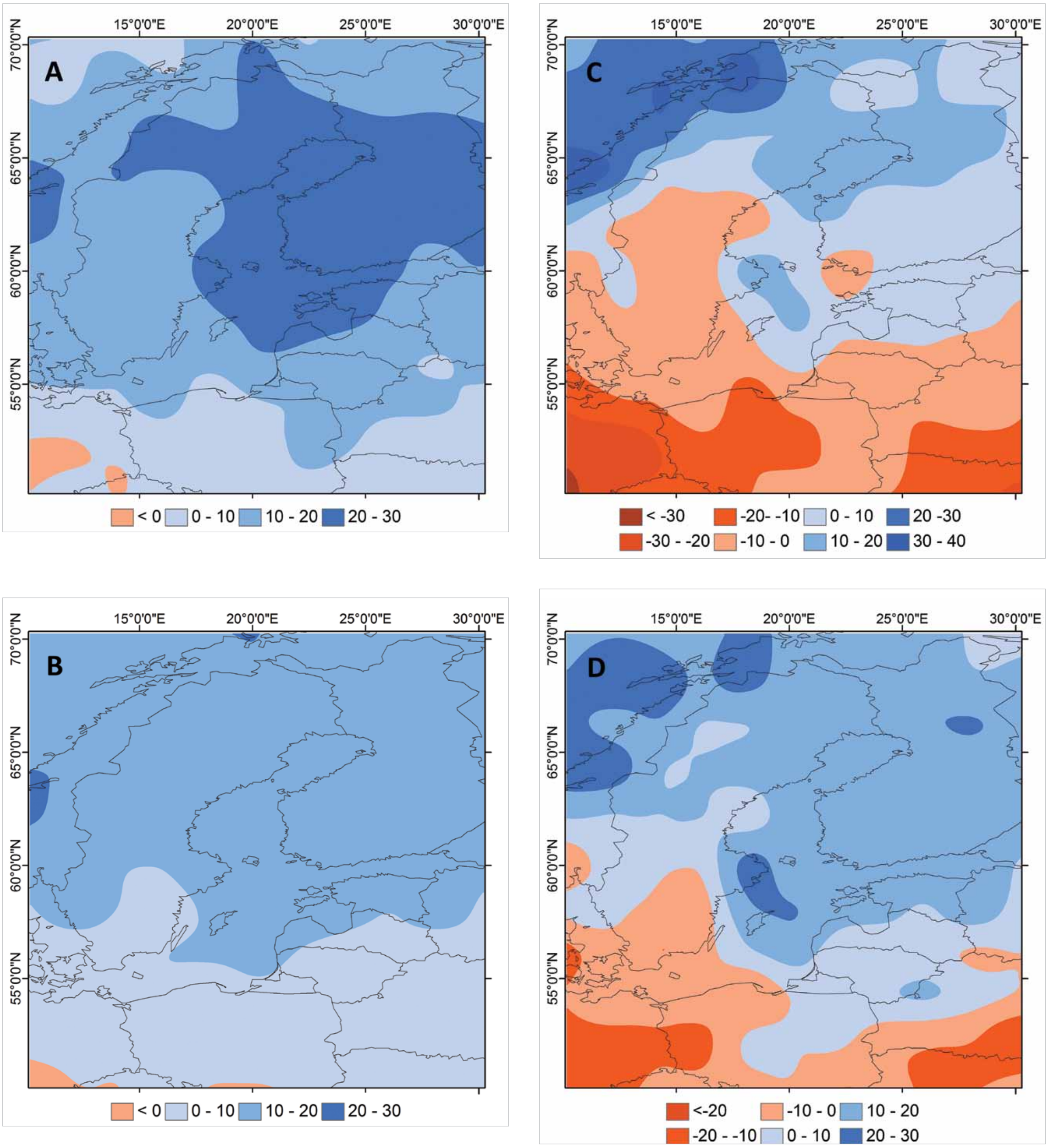

Fig. 10 The precipitation amount change (%) in 2071–2100 to compare with the control 1960–2000 period in the BSR simulated using the CCLM model output data according to the A1B and B1 emission scenarios: A) A1B annual; B) B1 annual; C) A1B summer; D) B1 summer. Compiled by E. Stonevičius, 2012.

The same tendency is expected for the summer months. However, in this case, strong negative changes are foreseen for the southern part of the BSR. Under both climate scenarios, the most significant negative changes should be observed at the southwest edge of the investigated area: up to 34% under A1B (Fig. 10C) and up to 20% according to B1 (Fig. 10D).

Such changes will strongly worsen growing conditions in the area. According to the A1B climate scenario, negative changes will be recorded in wider area and will reach Lithuania and Central Sweden. Changes will be positive under the both two scenarios in the northern part of the territory. The largest positive changes are expected on the coastal part of Norway and will reach 36% and 26% under the A1B and B1 scenarios, respectively.

Predicted drought dynamics quite accurately reflects changes in the precipitation regime (Fig. 11). Positive SPI12 tendencies will be statistically significant almost in the whole territory (Fig. 11A and

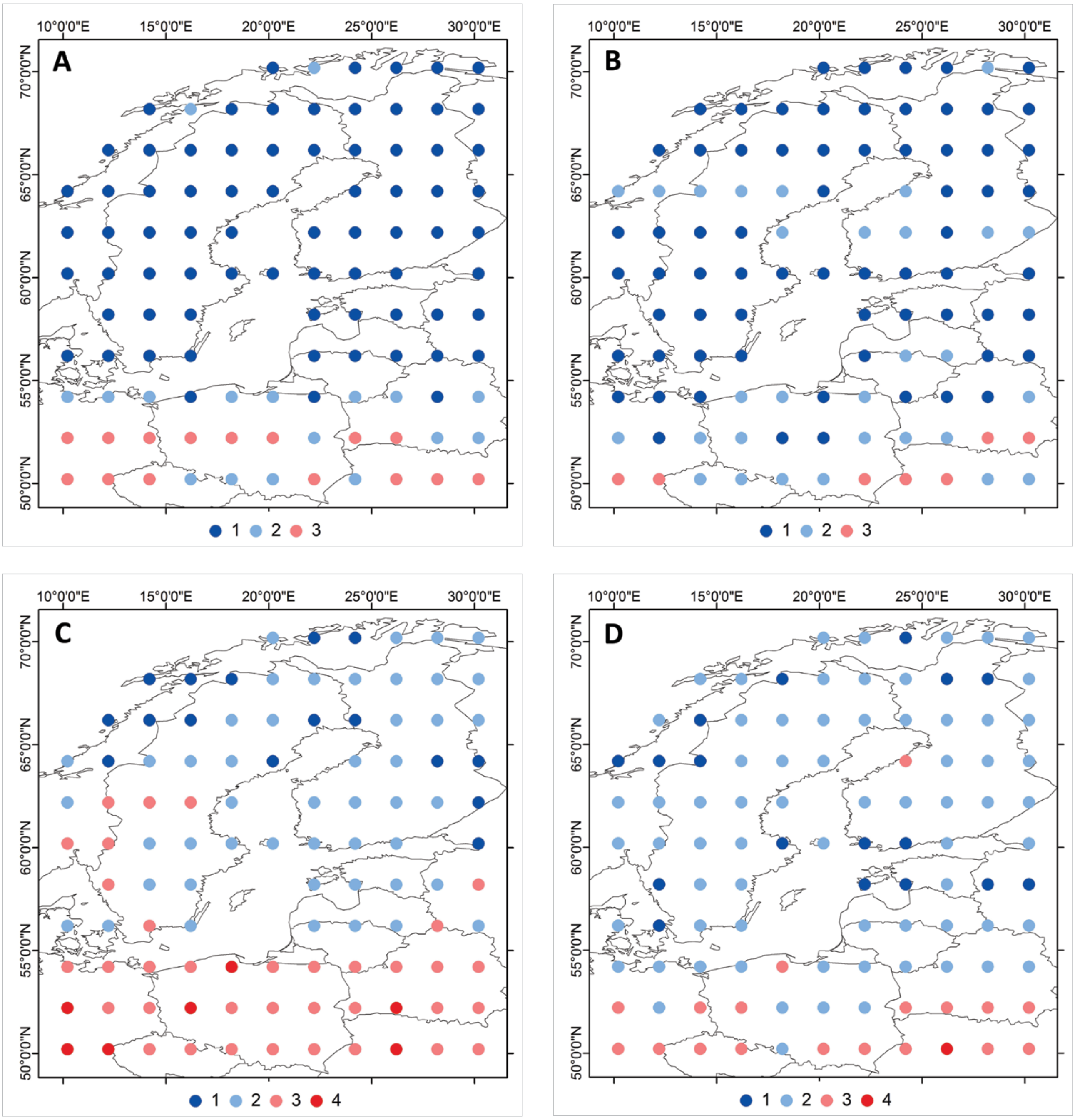

Fig. 11 The sign and statistical significance (α = 0,05) of SPI tendencies in the BSR in 21st century according to SPI12 annually and SPI3 in summer and simulated using the CCLM model output data based on the A1B and B1 emission scenarios: A) A1B annual; B) B1 annual; C) A1B summer; D) B1 summer. 1 – significant positive changes; 2 – insignificant positive changes; 3 – insignificant negative changes; 4 – significant negative changes. Compiled by E. Stonevičius, 2012.

B). Statistically insignificant negative changes are predicted only for the most southern part of the BSR. Moreover, the observed tendencies will remain or even will intensify in the future. On the other hand, the area with negative changes determined during the observation period will decrease. Meanwhile, in the summer months such area will be much larger. Especially it will be evident according to the A1B climate scenario (Fig. 11C). Negative trends will be significant in many locations.

The increase in summer dryness only in the most southern part of the BSR is expected under the B1 climate scenario (Fig. 11D). Positive and in many cases statistically significant changes of SPI3 values are foreseen in the remaining part of the territory. The largest changes have been projected for the most northern part of the region.

According to both climate scenarios, the intensity of droughts in the 21st century will likely decline almost in the whole investigated area. The most significant changes are foreseen for the north (Region 4). It should be noted that not only the decline in recurrence of extreme dry years will be observed but also the increase in number of years without droughts according to SPI3 is expected (Fig. 12A). The increase in intensity of droughts is foreseen only in the southwestern edge of the BSR. This is mainly due to the projected rainfall decrease during the summer months (Fig. 12B).

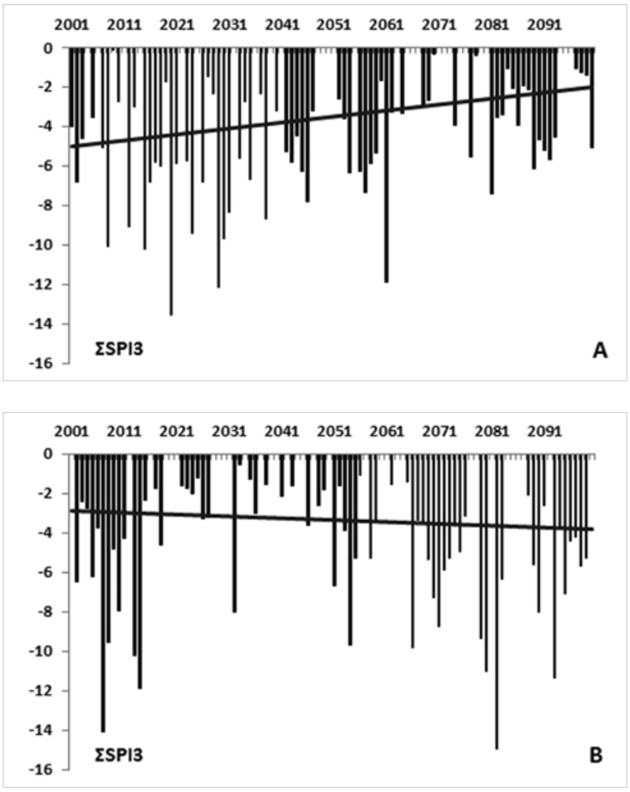

Fig. 12 Dynamics of drought intensity in 21st century (according to SPI3) in different BSR's simulated using the CCLM model output data according to the A1B emission scenario (data from regular grid points of CCLM model outputs): A) region 4 (70.2° N; 24.2° E); B) region 1 (50.2° N; 20.2° E). Compiled by E. Rimkus, 2012.

DISCUSSION

Drought dynamics through the observation period of 1960–2009

The BSR is relatively large and notable for quite different landscapes. The annual and summer dry spell length and number of dry days vary depending on the location of the stations with respect to large water bodies and mountain ranges, as well as local air temperatures (Thorsteinsson, Björnsson 2011). The analysis of trends in dry spells generally suggests that meteorological drought occurrence has either remained the same or has decreased during the 20th century, although some increasing trends have been found for sites in Denmark and in Latvia (BACC 2008). The drought recurrence in the region is decreasing in the last 50 years. However, severe droughts might still occur in every part of the region (van Lanen *et al.* 2007; Graham *et al.* 2009; Tallaksen, Stahl 2012). For example, the extreme drought of 1976 was recorded throughout the most of Northern Europe. It particularly strongly impacted the United Kingdom. As a result, the UK Government adopted "The Drought Act", which gives the power to water companies to restrict the usage (Rodda, Marsh 2011). And in the end of the analyzed period, in 2002 and in 2003, the droughts show that they are still extreme (Tallaksen *et al.* 2011).

The SPI has been developed in the USA (McKee *et al.* 1993), but it is widely used in Europe for drought determination (Loyd-Hughes, Saunders 2002; Łabędzki 2007; Bordi *et al.* 2009). Also decrease in drought recurrence is found by using other meteorological drought indexes and determination methods in different parts of the BSR (Mager *et al.* 2000; Hisdal, Tallaksen 2003; Tammets 2007; Jakimavičiūtė, Stankūnavičius 2008; Avotniece *et al.* 2010; Samaniego *et al.* 2011; Valiukas 2012). Agrometeorological drought occurrence shows negative trends (Schindler *et al.* 2007; Daugėlienė, Žekonienė 2009; Tammets 2010; Kaznowska 2011), as does the hydrological one (Hisdal *et al.* 2001; Stonevičius *et al.* 2006; Kriaučiūnienė *et al.* 2007; Kļaviņš *et al.* 2008; Wilson *et al.* 2010; Gailiušis *et al.* 2011) in the BSR.

The results discussed in this paper and their coincidence with other scientific findings show that different types of dryness periods (from short- to long term) can be revealed using different time steps of SPI (especially SPI3, SPI12 and SPI60). It proves that SPI can be successfully applicable for identification of meteorological droughts in the BSR in the future studies. Another important issue of this paper is the distinguishing of four regions according to the dynamics in dryness during the observation period of 1960–2009.

Modelling changes in dryness for the 21st century

The paper results are similar to the findings of other authors in the BSR (Räisänen *et al.* 2003; BACC 2008). The drought recurrence in the major part of the region tends to decrease throughout the 21st century. Only the most southern parts of the region seem to be characterised by the drought recurrence tending to increase in the future. These trends are similar to temperature and precipitation projections in the Central and Southern Europe (Kjellström *et al.* 2007; Fischer, Schär 2009).

Because of growth in summer air temperatures, the recurrence and intensity of droughts may increase (IPCC 2007; BACC 2008). Previous studies have shown that the number of heavy precipitation events will increase in some parts of the region (Christensen, Christensen 2004; Beniston *et al.* 2007; Kjellström, Ruosteenoja 2007; Rimkus *et al.* 2011). It should be noted that an increasing part of precipitation will fall in a form of short-term but very intensive rainfall which often will be followed by dry periods.

Meanwhile, the drought recurrence in the BSR will be relatively lower, but the drought will be more severe and could be evident in every part of the region in the 21st century (Dankers, Hiederer 2008; van der Linden, Mitchell 2009). The region was analyzed using discrete RCM models (Räisänen *et al.* 2003; Blenkinsop, Fowler 2007; Kjellström, Lind 2009) and their ensembles (Räisänen *et al.* 2004; Beniston *et al.* 2007; Kjellström, Ruosteenoja 2007) including CCLM model projections (Christensen *et al.* 2007; Rockel *et al.* 2008). In this article, for the first time in the BSR, the most probable A1B and B1 emission scenarios, using CCLM model precipitation output data, have been used to project tendencies of different term dryness periods in the 21st century according to projected SPI values.

An indirect proof of the decreasing trends of drought recurrence, but not in severity is given by the changes in temperature extremes in the region (Beniston *et al.* 2007; Fischer, Schär 2009; Kažys *et al.* 2011), as well as changes in the freshwater runoffs and in the river flow across the Baltic Sea (Graham 2004; Kriaučiūnienė *et al.* 2008; Apsīte *et al.* 2011; Hänninen, Vuorinen 2011). The uncertainties of dryness dynamics, however, are still under investigation (Lehner, Döll 2001; Rowell, Jones 2006; Graham *et al.* 2007; Kundzewicz 2009).

CONCLUSIONS

Climat*e* Research Unit monthly precipitation data (taken from KNMI) are relevant for SPI values calculations in the BSR in 1960–2009. Meanwhile, the regional CCLM model runs data (taken from CERA) are applicable detecting dryness tendencies in the region for the 21st century. The analysis of the dryness dynamics showed increased SPI values of different time steps in the BSR in 1961–2010. It can be concluded that during the investigation period the region has received an increasing amount of moisture with the overall dryness declining. SPI60 index shows most noticeable long-term positive changes, while the probability of short term dryness period stays quite high according to SPI3 index changes.

Dryness tendencies vary in different parts of the region. The largest positive changes during the summer months are at the south coast of Sweden, the Baltic Sea islands and south-western Finland. Meanwhile, the negative tendencies are observed in the southern and western part of the region, i.e. summer dryness has increased. According to SPI12, positive annual tendencies of index are determined in a major part of the territory to compare with SPI3.

According to the regional CCLM model outputs, the dryness will continue to decrease in the BSR in the 21st century. The more intense changes are modelled under climate scenario A1B, while climate scenario B1 will bring minor changes in dryness in 2071–2100. Moreover, the regional differences in dryness will be even higher – dryer southern and more humid northern part. Especially significant regional differences are projected for the summer months.

Acknowledgements

The authors are grateful to Koninklijk Nederlands Meteorologisch Instituut (KNMI) for the possibility to use high-resolution precipitation data from the Climat*e* Research Unit at the University of East Anglia and, also, to Climate and Environmental Retrieval and Archive (CERA) for the regional CCLM model runs data which were used in the paper. Valuable remarks and comments on the manuscript were made by Professor Agrita Briede (Rīga) and Dr. Laura Šukienė (Šiauliai) that enabled to improve the paper.

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