ATMOSPHERIC CIRCULATION INFLUENCE ON THE WINTER THERMAL CONDITIONS IN POLAND IN 2021-2050 BASED ON THE RACMO2 MODEL

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Abstract. Thermal conditions are largely determined by atmospheric circulation. Therefore, projection of future temperature changes should be considered in relation to changes in circulation patterns. This paper assess to what extent changes in circulation correspond to spatial variability of the winter temperature increase in Poland in 2021-2050 period based on the RACMO2 model. The daily data of the mean temperature and sea level pressure (SLP) from selected regional climate model and observations were used. SLP data were used to determine the advection types and circulation character. Firstly, changes in frequency of circulation types between 2021-2050 and 1971-2000 periods were examined. Then changes in air temperature for specific circulation type in relation to reference period were studied. Finally, the influence of atmospheric circulation on spatial temperature variation was discussed. Considerably high increase in cyclonic situation of more than 18%, especially from the west and south-west direction, and decrease in anticyclonic situation mainly from the west and northwest in winter was noticed. Changes in frequency of circulation types result in temperature growth. For some types it is predicted that warming can reach even 3-4°C. The cyclonic (Ec, SEc, Sc) and anticylonic (SEa, Sa, Ea) types are likely to foster the highest warming in the scenario period.

Keywords:.circulation patterns, RACMO2, temperature change, A1B scenario

Introduction

According to IPCC report and many other studies the most remarkable temperature change is projected for winter (Kjellström 2004). Regional climate model data for A1B scenario presents higher warming in eastern and northeastern Poland up to 25th percentile and in its southern and western part above 50th percentile (Jędruszkiewicz 2012). Significant variety in spatial temperature increase underlines the necessity of further studies. Kjellström (2003) and Räisänen et al. (2003) indicate snow cover reduction as a main factor of strong temperature increase in wintertime in eastern Europe. It in turn is associated with feedback processes involving lower albedo and more intensive shortwave radiation absorption in the ground. It might be a reason for the highest increase of the lowest temperature in northeastern Poland in order to the longest snow deposition in this area. However it does not explain warming in the southern part of the country.

Slonosky et al. (2001) suggest that there is a certain amount of internal variability generated within the climate system by the relationship between atmospheric circulation and temperature anomalies on different time-scales. Changes in the atmospheric circulation can affect the heat advection into a region. Van Loon and Rogers (1978) concluded that regional trends of mean winter temperature on timescales of years to decades were so closely related to changes in atmospheric circulation that it was unlikely that regional temperature trends were caused directly by variations in aerosol concentration, insolation or radiative changes.

During majority of winter in Poland the western circulation determine the thermal conditions and seasonal average temperature decreases from the west (over 1°C) to the east (below -3°C) (Woś 2010). The meridional isotherm distribution is the result of heating ocean influence of the west and cooling continental effect of the east.

The aim of this paper is to study the influence of circulation patterns on spatial distribution of warming in Poland in 2021-2050. Changes in frequency of different directions of air masses inflow and the way they affect temperature increase in future scenario in analyzed area (Räisänen & Ruokolainen 2009; IDDRI 2010) have been considered. Furthermore, temperature change for specific circulation type between 2021-2050 and 1971-2000 periods in Poland have been analyzed.

Data and methods

Daily mean 2-meter temperature and mean see level pressure data have been obtained from the Regional Atmospheric Climate Model (*RACMO2*) created by the

Royal Netherlands Meteorological Institute for A1B scenario 2021-2050 and reference 1971-2000 periods which was a part of ENSEMBLES project. That data are available for download from *http://ensemblesrt3.dmi.dk/*. RACMO2 have been selected because temperature simulated by this model fits better to observations than seven other regional climate models (RegCM3 - *International Centre for Theoretical Physics*, HadRM3 - *Met Office Hadley Centre for Climate Change*, RCA - *Swedish Meteorological and Hydrological Institute*, CLM - *Max-Planck Institut für Meteorologie*, HIRHAM - *Norwegian Meteorological Institute*, HIRHAM5 - *Danish Meteorological Institute*, WRF - *National Center for Atmospheric Research, National Centers for Environmental Prediction, Department of Meteorology and Climatology in Lodz*). The verification based on Kolomogorov-Smirnov test was performed for 6 synoptic stations selected as to present different Polish climate conditions. The test for mean temperature was significant at 95% confidence level for all stations only in case of the RACMO2 model. Data from 40 station from Poland for 1971-2000 period have been collected from the Institute of Meteorology and Water Management, National Research Institute.

Before any analysis was set out, the simulation temperature data for 2021-2050 had been corrected. The correction was based on quantile mapping method. It is so called "distribution-based" bias correction described in more details by Déqué (2007) and Piani et al. (2010).

Atmospheric circulation conditions were determined on the ground of automatic method developed by Jenkinson and Collison (1977). This method allows to set following indices: geostrophic flow and shear vorticity. Geostrophic flow index determines the direction of air masses flow and shear vorticity defines the character of circulation. The indices based on the automatic classification used for Poland study area were calculated from following equations:

- Geostrophic flow

$$V = (S^2 + W^2)^{1/2}, \qquad (1)$$

where geostrophic wind components can be found from:

$$W = 0.25 \cdot (p_{23} + p_{24} + p_{25} + p_{26}) - 0.25 \cdot (p_7 + p_8 + p_9 + p_{10}), \qquad (2)$$

$$S = 1.62 \cdot [0{,}125 \cdot (p_{10} + (2 \cdot p_{18}) + p_{26} + p_9 + (2 \cdot p_{17}) + p_{25}) - 0.125 \cdot (p_7 + (2 \cdot p_{15}) + p_{23} + p_8 + (2 \cdot p_{16}) + p_{24})], \qquad (3)$$

- Total shear vorticity

$$\xi = \xi_u + \xi_v, \qquad (4)$$

where shear vorticity components can be found from:

$$\xi_u = 1.06 \cdot [0.25 \cdot (p_{29} + p_{30} + p_{31} + p_{32}) - 0.25 \cdot (p_{15} + p_{16} + p_{17} + p_{18})] - 0.95 \cdot [0.25 \cdot (p_{15} + p_{16} + p_{17} + p_{18}) - 0.25 \cdot (p_1 + p_2 + p_3 + p_4)] \qquad (5)$$

$$\xi_v = 1.32 \cdot [0.125 \cdot (p_{12} + (2 \cdot p_{20}) + p_{28} + p_{11} + (2 \cdot p_{19}) + p_{27}) - 0.125 \cdot (p_{10} + (2 \cdot p_{18}) + p_{26} + p_9 + (2 \cdot p_{17}) + p_{25})] - 1.32 \cdot [0.125 \cdot (p_8 + (2 \cdot p_{16}) + p_{24} + p_7 + (2 \cdot p_{15}) + p_{23}) - 0.125 \cdot (p_6 + (2 \cdot p_{14}) + p_{22} + p_5 + (2 \cdot p_{13}) + p_{21})] \qquad (6)$$

The constants (1.62, 1.06, 0.95, 1.32) in the equations 3, 5 and 6 reflect the relative differences between the grid-point spacing in the east-west and north-south directions. P_1 to p_{32} are daily mean sea level pressure values at grid points shown in Figure 1. The W, S, V assign respectively, the westerly (zonal) flow, the southerly (meridional) flow and the resultant flow, while ξ_u, ξ_v, ξ assign respectively, the westerly shear vorticity, the southerly shear vorticity and the total shear vorticity. Total shear vorticity enables the determination of the circulation character – ξ is positive for cyclonic types and negative for anticyclonic types. The direction of flow is given by $\tan^{-1}$ (W/S), $180°$ being added if W or S is positive.

Basing on this scheme 16 atmospheric circulation types were distinguished. The designations of types refer to the direction of geostrophic wind and the character of circulation (e.g. the respective letters of designation NWa signify that the direction of geostrophic wind is north-westerly – letters NW, the character of circulation is anticyclonic – letter a).
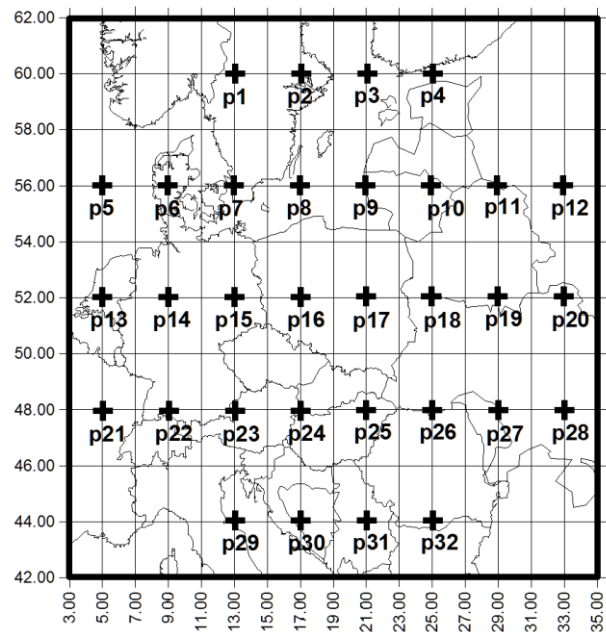
Fig. 1. The grid points used in atmospheric circulation indices calculations (symbols of grid points are used in equations 2-3 and 5-6)

Change in daily mean temperature according to particular circulation pattern have been calculated for six grid points situated in different parts of the country which

represent diversity of Polish climate (Table 1). The aim was to distinguish circulation types, during which the highest temperature changes are expected.

Except local factors, the thermal conditions are affected not only by particular air mass advection but also by the distance to the baric centers. Therefore thermal condition diversification has been studied separately for each grid point. In the next part of the paper some examples of spatial variety in mean temperature for specific geostrophic wind directions and the circulation character have been presented.

Table 1. Temperature grid point coordinates

Grid number	Longitude	Latitude
1	16.0°E	54.0°N
2	22.0°E	54.0°N
3	16.0°E	51.6°N
4	20.0°E	52.0°N
5	22.0°E	50.6°N
6	20.0°E	50.0°N

In the refrence period 1971-2000 in winter the prevalence of the western circulation was observed quite similar to Piotrowski's (2009) results for 1959-2005.
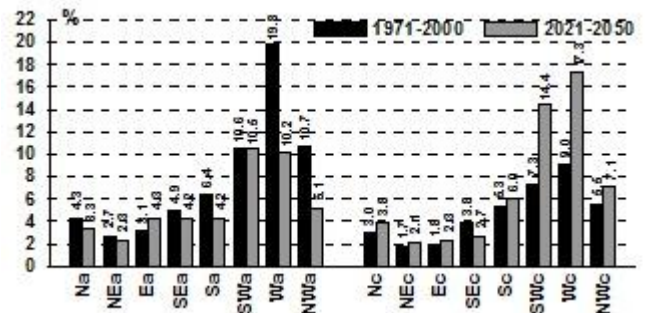
Fig. 2. Relative frequency of atmospheric circulation types in winter for observation (1971-2000) and RACMO2 simulation (2021-2050)

Results
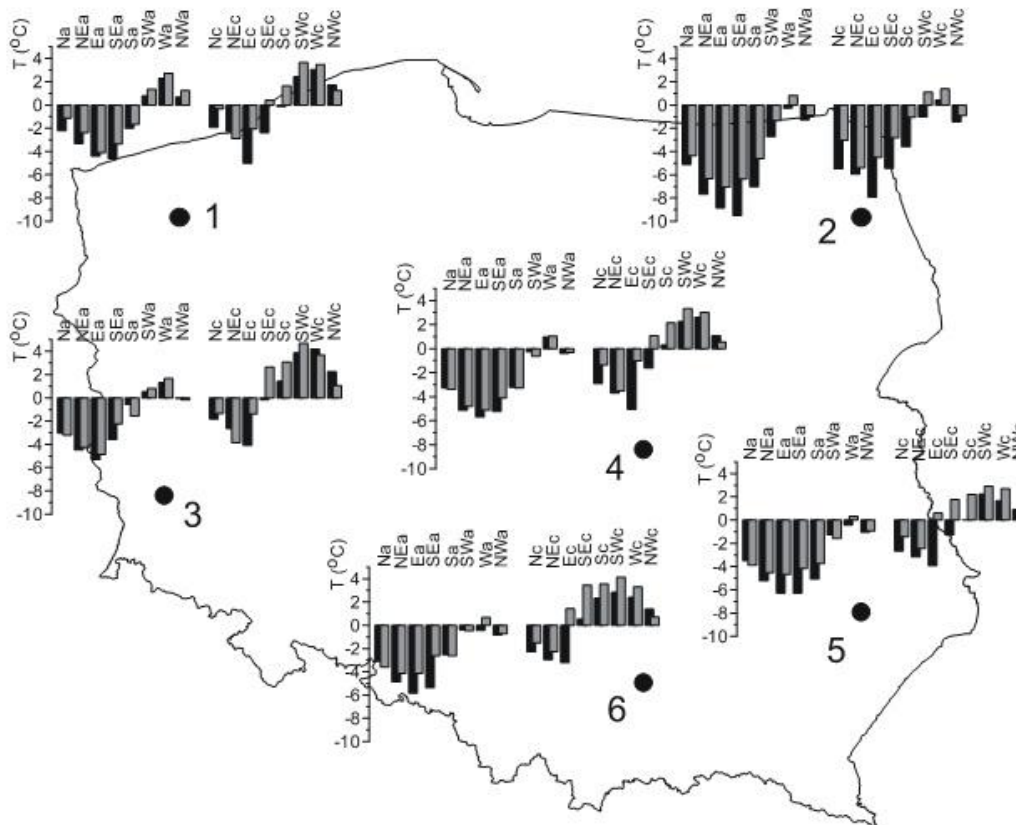
Fig. 3. Winter temperature in particular atmospheric circulation types for observation 1971-2000 (black) and RACMO2 simulation 2021-2050 (grey) in 6 grid point listed in Table 1

During winter in 1971-2000 for Poland Wc (9.0%), SWc (7.3%), NWc (5.5%) were the most frequent cyclonic types and Wa (19.8%), NWa (10.7%) and SWa (10.6%) were the most frequent anticyclonic types (Fig. 2). The western circulation occurred in almost 63% of all cases.

Generally calculations based on RACMO2 simulations for 2021-2050 period indicate considerably increase of cyclonic circulation frequency of more than 18%. This

rise mainly relates to Wc and SWc circulation types, but for all cyclonic types (except SEc) an increase was observed. Frequency of the west and south-west cyclonic circulation is predicted to rise up to 14.4 and 17.3% respectively.

Moreover the frequency of the west and north-west anticyclonic circulation will decrease considerably of over 9 and 5% respectively. In other anticyclonic situations (except Ea) the decrease will not be higher than 2.2%. The further enhancement of western cyclonic situation might have a great influence on future temperature change.

The lowest temperature in 1971-2000 period have been observed mainly during eastern anticyclonic situations as Ea, NEa, SEa from approximately -4° to -6°C in the west and from about -7° to -10°C in the northeastern part of Poland, which will determine 10.7% of all circulation types. Low temperature have also been noticed during the occurrence of northeastern cyclonic types (Ec, NEc, Nc) from -2° to -5°C in the west and from -6 to -8°C in the north-east, that will be 6.3% of all circulation types. That results from the inflow of cold air masses from the east and north that develops in the presence of high pressure system in eastern Europe during the winter. Whereas the highest temperature was observed during western circulation types especially cyclonic: SWc, Wc and Sc and reached up to 3° and 4°C in western and southern Poland, that determined 21.6% of all circulation types. This was related to the inflow of relatively warmer Atlantic air masses. Furthermore, dense cloud cover associated with low pressure system could protect the surface from heat losses due to irradiation during the nighttime.

In 2021-2050 significant changes in circulation type that determine the coldest weather are not predicted. In the majority of the Polish area the slight shift from the southeastern to the northeastern cyclonic circulation types, which coresspond to the coldest weather, might be expected from reference to scenario periods (Fig. 3). Moreover in the reference period the coldest area situated in north-eastern part of Poland for each circulation type (except Wc) were characterized by mean temperature below 0°C. In future predictions this area will be represented by the highest temperature growth. During Wa, SWc and Wc types the average temperature will be positive, raising up to 1°C, which might considerably influence climate condition. It will probably be caused by an increase of western cyclonic circulation frequency.

Changes of temperature between scenario and reference periods in Poland, depending on the type of circulation, are provided in Figure 3. For six grid points the air temperature change for different types of atmospheric circulation was examined.
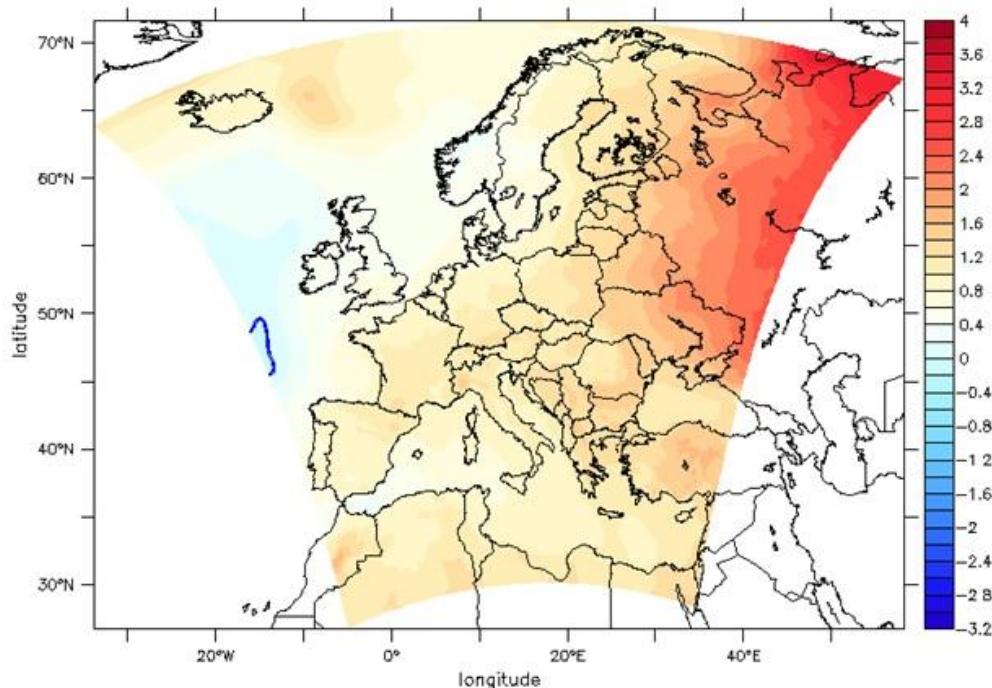
Fig. 4. Temperature change between scenario (2021-2050) and reference (1971-2000) period for winter according to RACMO2 model. The blue line indicate isotherm 0°C

For majority of circulation types the warming is evident in each grid point. Going into details, the highest temperature growth from 2° to even 4°C is predicted for types: SEc, Ec, SEa and Nc. In the case of the SEa type the warming will be considerably higher in eastern and south-eastern Poland and for the Nc type it will be higher in central and northern Poland. Looking more carefully into temperature change for every grid point the most significant warming is predicted for eastern and south-eastern part of Poland. This area of Poland is under the influence of continental air masses which were developed over Asian mainland.

On the other hand for some circulation types the temperature decrease is predicted as well. Data from all of analyzed grid points indicate the decrease of about 1°C for the NWc circulation type. Furthermore for points located in central and south-eastern Poland the temperature during SWa and Na types will slightly decline of approximately 0.5-0.7°C. Additionally in both grid points located on the west, the decrease of 0.5-1°C during NEc circulation will appear. In southwestern Poland colder conditions are expected during the largest number of circulation types. For the anticyclonic types: Sa, NWa and cyclonic types: NEc, Wc, NWc the predicted temperature will be lower up to 1°C in comparison to reference period.

Case study

The aim of this chapter is to show spatial distribution of temperature in Poland during selected circulation patterns. For this purpose the differences between scenario and observation have been examined. Figures 5 and 6 present maps of six cyclonic (Ec, SEc, Sc, SWc, Nc, NWc) and two anticyclonic (SEa, Ea) circulation types. This types have been chosen because of the most significant changes in thermal conditions as was shown in Figure 3.

Ec circulation type. Ec type does not contribute significantly to Polish climate conditions and will occur with a frequency of 2.3%. The increase of temperature in the majority of Polish area is predicted except the northwestern outskirts of the Great Poland Lakeland. The higher warming, of above 2°C, is shown in Żuławy Wiślane and southern and western Poland (Fig. 5a). Warmer weather during advection from the east might be caused by milder winters predicted also over the Asian continent (Fig. 4).

SEc circulation type. Despite slightly less attendance of SEc circulation type in scenario period, considerably higher temperature increase of 2-4°C is predicted (Fig. 5b). The farther west the greater warming the RACMO2 model predicts. Spatial distribution of temperature change in Poland relates to low pressure system location, which control circulation from the south-east. Low is usually located on the south or south-west of Poland. This location contributes to higher cloudiness in western Poland. Whereas during this condition the eastern part of the country is a feature of less cloudiness, which in turn en-

courages heat transfer from the ground to the atmosphere and results in lower warming near the surface. The reason of significant warming is common for both Ec and SEc circulation types.

Sc circulation type. During Sc type Poland is mainly affected by low pressure system located in the northwestern Europe. In majority of the analyzed territory the temperature will increase of 1-3°C. Only in the southeastern edge of the country the temperature below 0°C might be expected (Fig. 5c).

SWc circulation type. The spatial temperature change in SWc type is quite similar to this during the Sc type, but the temperature increase is slightly less in majority of Polish area. In Figure 5d the SWc type presents warming of up to 2°. During this type, only the northern area is influenced by the low pressure system where the warming is the greatest. It is worth mentioning that SWc type in the scenario period is predicted to occur twice as frequent as in the reference one.
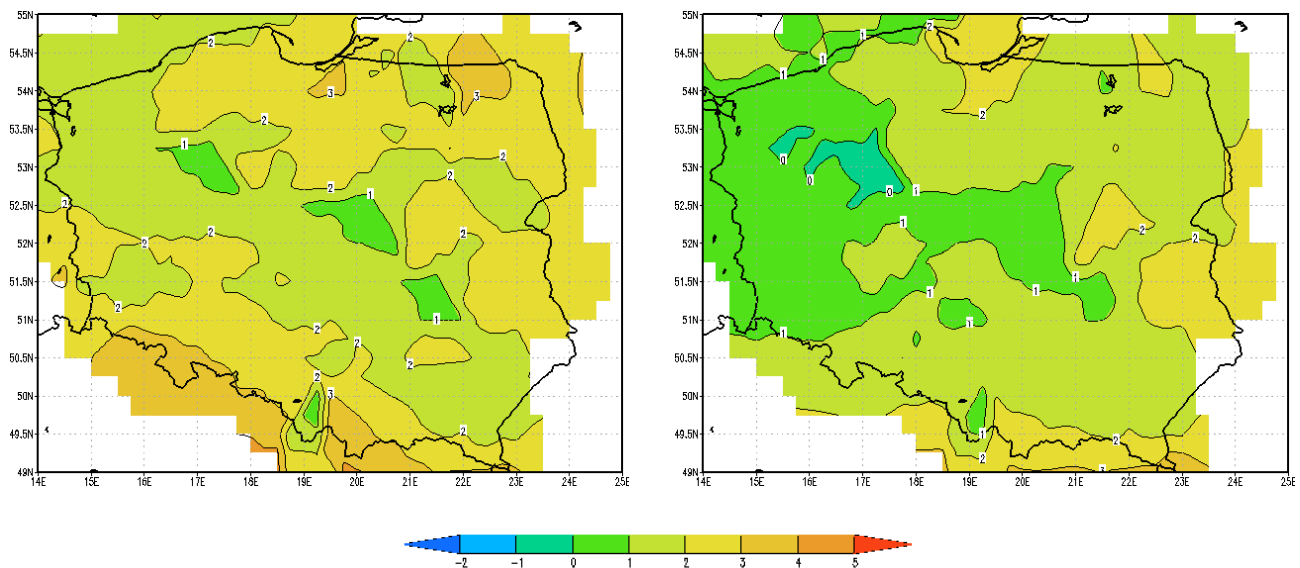
Nc circulation type. North cyclonic situations will occur more often, from 3 to 3.8%, and it will be associated with the temperature increase from the south-west (1°C) to the north and north-east (2°C) Poland (Fig. 5e). During this type, the low pressure system is situated on the east of Poland and in the future will cause the warmer masses inflow (in relation to 1971-2000) from area situated on the north-east of Poland.

NWc circulation type. Generally during the northwestern circulation the cooling is predicted in Poland (Fig. 5f). In the western part the temperature will decrease of more than 1°C in some places as Warta and Odra Valley or upland area in the south. Furthermore, that effect might be reinforced by greater inflow of cold arctic masses instead of the polar ones. Only the Lakeland areas in the north and northeastern Poland will probably be characterized by the slight (less than 1°C) temperature growth.

SEa and Ea circulation type. During these circulation types the pressure system foster the warmer, transformed air masses inflow from western and south-western Asia. In both cases the highest temperature increase for 2021-2050 is predicted for the Gdansk Gulf, Elk Lakeland and the Carpathians reaching above 3°C for SEa and above 2°C for Ea circulation type (Fig. 6). Moreover in the case of SEa type the warming of 3°C is also shown for the Sudety. For Mazovian Plain and "Polesie Lubelskie" the RACMO2 model predicts also quite high warming reaching 2°C. The area of the lower temperature increase, approximately 1°C, stretches from the north-west, along Notec and Vistula River up to uplands in the south. During the Ea type the slight temperature decrease near Notec Valley is even predicted. Moreover the lower warming can be expected for Ea and the higher for SEa type. The causes of predicted warming are similar to these in cyclonic circulation for the same inflow directions.
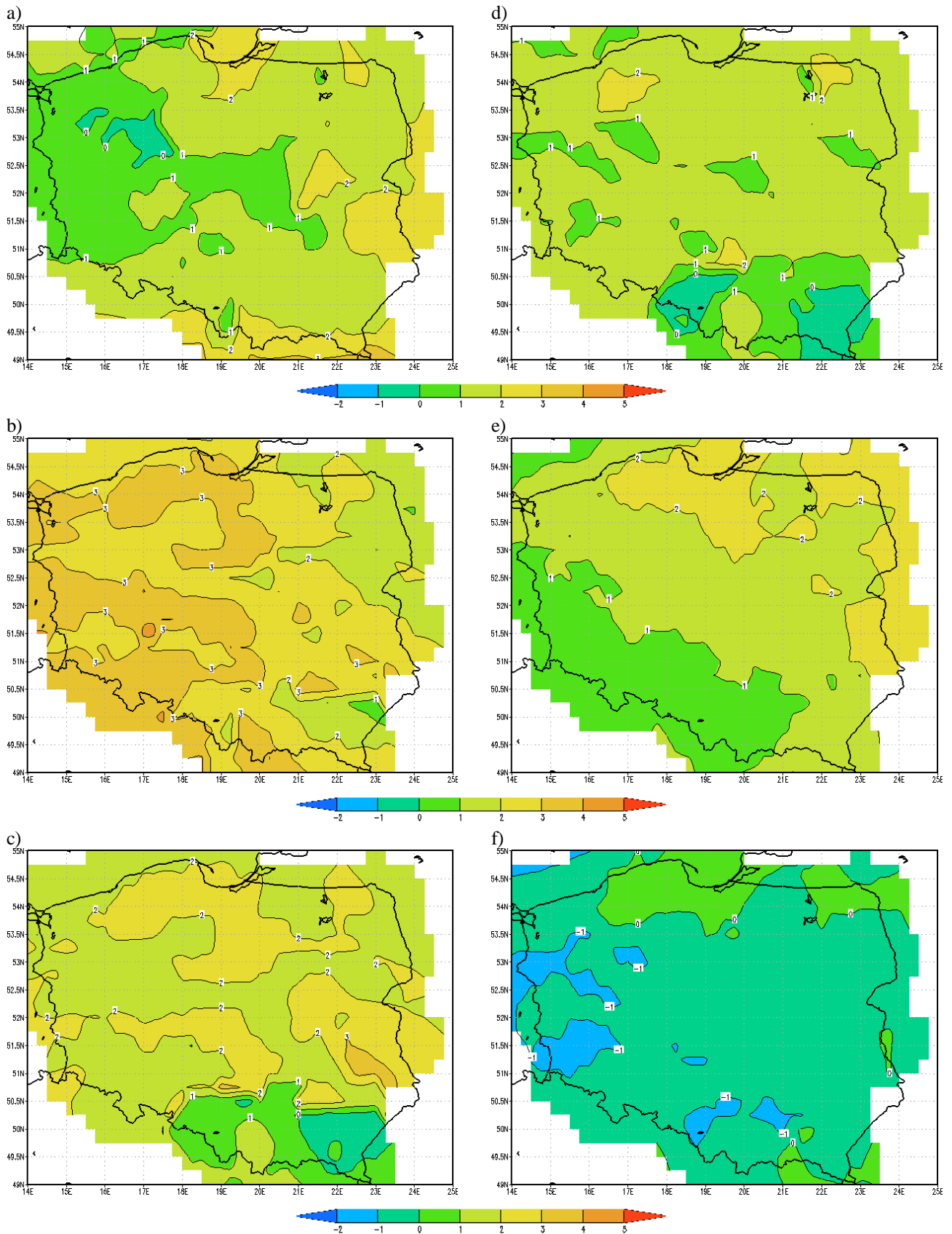
Fig. 5. Temperature change between 2021-2050 and 1971-2000 period according to particular cyclonic circulation pattern a) Ec b) SEc c) Sc d) SWc e) Nc f) NWc

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Fig. 6. Temperature change between 2021-2050 and 1971-2000 period according to particular anticyclonic circulation pattern: SEa (left), Ea (right

Conclusion

Generally, future projections show far more frequent cyclonic situation of above 18%. This increase mostly relates to the inflow from the west and south-west. On the other hand the frequent reduction of anticyclonic circulation largely refers to Wa and NWa types. This might led to more frequent and longer occurrence of positive NAO phase and less frequent "blocking situation" with well-developed high pressure system. The Ec and SEc circulation types foster the greater warming of 3-4°C, in the studied area. Anticyclonic circulation from the same directions will also cause the temperature increase in 2021-2050 period. It can be related to future warming that is predicted for eastern Europe and Asia.

Furthermore, for majority of circulation types the temperature increase is predicted. The most considerably warming is shown for north-eastern Poland, which might relate to lower continental cooling on the east and advection of relative warmer air masses during winter time. Only during NWc type in all analyzed grid points a temperature decrease is expected. During the Na and SWa types temperature will decrease in southern and during the Sa type in western Poland.

Detailed analyze of particular circulation patterns has revealed the most considerably cooling during NWc type, especially in western and south-western Poland of above 1°C. It might be caused by quite fresh arctic air masses inflow from the north-west instead of the polar ones. The southeastern cyclonic and anticyclonic advection may induce the high warming in Poland, up to 3-4°C.

This study has confirmed high relation between temperature and atmospheric circulation. Spatial distribution of temperature changes varies significantly depending on the circulation type. Generally the cyclonic types Ec, SEc, Sc and anticylonic types SEa, Sa, Ea will probably foster the highest warming in the 2021-2050 period.

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Abstrakt

Polska charakteryzuje się znacznym zróżnicowaniem przestrzennym w rozkładzie temperatury powietrza w porze zimowej. W sezonie zimowym przeważa południkowy układ izoterm co świadczy o silnym oddziaływaniu z jednej strony ciepłych, wilgotnych mas powietrza napływających znad Atlantyku, a z drugiej chłodniejszych i bardziej suchych znad kontynentu azjatyckiego. Regionalne modele klimatu opracowane dla obszaru Europy wskazują jednoznacznie na wzrost temperatury w okresie zimy na obszarze całego kontynentu, szczególnie a wschodzie i północnym-wschodzie kontynentu, nawet o 3°C. Projekcje te są oparte są m.in. o prognozy występowania krótszych zim oraz cieńszej i krócej zalegającej pokrywie śnieżnej wpływającej w znacznym stopniu na albedo i ilość ciepła zatrzymywanego przez grunt.

Jedną z ważniejszych przyczyn zmienności temperatury powietrza jest cyrkulacja powietrza. Pomimo licznych badań dotyczących powiązań cyrkulacyjno-termicznych w XX wieku prowadzonych przez polskich badaczy, brakuje opracowań dotyczących wpływu cyrkulacji atmosferycznej na prognozowane zmiany temperatury w XXI wieku. Celem opracowania jest zbadanie tych relacji dla zimy z okresu 2021-2050 w porównaniu z obserwacjami z lat 1971-2000. W pracy posłużono się danymi średniej dobowej temperatury powietrza oraz ciśnienia atmosferycznego na poziomie morza z regionalnego modelu RACMO2 opracowanego w ramach projektu ENSEMBLES. Symulowane wartości temperatury z modelu zostały poddane korekcji za pomocą metody kwantylowej.

Wyniki modelu jednoznacznie wskazują na wzrost cyrkulacji cyklonalnej o ponad 18% miedzy latami 2021-2050 a 1971-2000. Szczególnie wysoki wzrost częstości cyrkulacji cyklonalnej oczekiwany jest z kierunków południowo-zachodniego i zachodniego o 7 i 8%. Z drugiej strony prognozowany jest wyraźny spadek częstości występowania cyrkulacji antycyklonalnej z kierunków zachodniego i północno-zachodniego o ok. 9 i 5%. Największy wzrost temperatury powinien towarzyszyć występowaniu cyrkulacji SEc od 2 na wschodzie do 4°C na zachodzie kraju. Istotne ochłodzenie prognozowane jest z kierunku NW podczas cyrkulacji cyklonalnej miejscami nawet poniżej 1°C w zachodniej i południowej Polsce. W omawianym 30-leciu prawdopodobnie coraz rzadziej będzie występować sytuacja blokadowa, natomiast coraz częściej pozytywna faza NAO.

Słowa kluczowe: cyrkulacja atmosferyczna, RACMO2, zmiany temperatury, scenariusz A1B