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A. Chyhareva [1,2,*], S. Krakovska [1,2], D. Pishniak [2]

[1] Ukrainian Hydrometeorological Institute, State Service of Emergencies of Ukraine and National Academy of Sciences of Ukraine, 37 Nauky Ave., Kyiv, 03028, Ukraine

[2] State Institution National Antarctic Scientific Center, Ministry of Education and Science of Ukraine, 16 Taras Shevchenko Blvd., Kyiv, 01601, Ukraine

* Corresponding author: chyhareva@ukr.net

Climate projections over the Antarctic Peninsula region to the end of the 21st century. Part II: wet/dry indices

Abstract. **Objective** of the study is an assessment of possible climate change in the region of the Antarctic Peninsula from 1986 until the end of the 21st century projected by the RCMs' ensemble. During the last decades Antarctica has undergone predominantly warming, with the highest rate of surface air temperature increase found over the Antarctic Peninsula, where the Ukrainian Antarctic Akademik Vernadsky station is located. There is a unique ecosystem in the region which is vulnerable and under the growing impact of a changing weather regime due to rapid climate changes with consequent changes in sea ice, land distribution under snow/ice, etc. Thus, an important task for the region is an estimation of climate change trends and definition of possible subregionalization. **Data and methods**. Data of two regional climate models HIRHAM5 and RACMO21P forced by two global climate models EC-EARTH and HadGEM from the Polar-CORDEX (Coordinated Regional Downscaling Experiment - Arctic and Antarctic Domains) as part of the international CORDEX initiative were used in the study. Spatial distribution of the model output is 0.44°. Set of scripting codes developed by Climate4R project (An R Framework for Climate Data Access and Postprocessing) was modified in order to extract data for the Antarctic Peninsula region from the Antarctic domain and obtain climatological characteristics for individual RCMs and their ensemble mean. Projected changes in wet/dry climate indices for scenarios RCP4.5 and RCP8.5 for two periods 2041—2060 and 2081—2100 were assessed with respect to the historical experiment 1986—2005. **Results.** An analysis of projected wet/dry climate indices for both RCP4.5 and RCP8.5 scenarios is presented in Part II of the paper. An analysis of the cold temperature indices (FD, ID) is presented in Part I of the study. In the historical experiment Larsen Ice Shelf and leeward east coast are the regions with the lowest total precipitation in wet days (PRCPTOT, 200—300 mm) and simple daily intensity index (SDII, about 5 mm/day) with under 10 days of consecutive wet days (CWD) and up to 30 days consecutive dry days (CDD). In the cross of the 21st century, duration of dry spell is projected to shorten for the whole peninsula and for Akademik Vernadsky station by about 7—10% under the scenario RCP4.5 and 10—15% under the RCP8.5. Projected SDII changes are up to +20% till the end of the century under the scenario RCP8.5 at north-west coast of the Antarctic Peninsula. **Conclusions**. Over the Antarctic Peninsula region both scenarios project an average increase in total PRCPTOT and SDII; overall the maximum length of CWD is extended while the maximum length of the CDD is reduced. In combination with decreasing number of frost (FD) and ice (ID) days, the pattern of changes differs notably across the peninsula. It is shown in the first part of the paper that over the Antarctic Peninsula region, both scenarios project an average decrease in the cold season period. The most pronounced changes of ID and FD climate indices are for the Larsen Ice Sheet area. Analyzing results presented in both parts of the paper we can distinguish a few subregions with different projected changes in climate conditions based on obtained climate indices. Obtained results can be used for studies of the climate changes impact on ecosystems in the region and for the strategic planning of future activities (scientific, touristic, fishery, etc.).

Keywords: Antarctic Peninsula, Akademik Vernadsky station, climate indices, regional climate model, Polar-CORDEX, RCP scenarios.

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INTRODUCTION

Antarctica is among the most important players in global climate. During the last decades it has undergone predominantly warming, however, over the Antarctic continent it was not homogeneous, and the highest rate of surface air temperature increasing was found over the Antarctic Peninsula based on the station data of 1966—2000 (Marshall et al., 2006, Doran et al., 2002, Steig et al., 2009).

The Antarctic Peninsula has a complex topography. Mountains are an essential part of it, including a lot of volcanoes on the nearby islands. The highest peaks in the Antarctic Peninsula mountain ridge are Mount Jackson (3 184 m) and Mount Hope (3 239 m). There are a lot of different types of glaciers in the region: from the smallest ice caps on islands to the large outlet glaciers forming ice shelves. Besides this, there is plenty of sea ice along the peninsula. All these types of ice respond differently to changes in temperature and precipitation regimes. The biggest in the region Larsen Ice Shelf has collapsed a few times driven by both atmospheric and oceanic warming according to Marshall et al. (2006). Very recent study by Wille et al. (2019) has shown that the main trigger for melting in the West Antarctica can be attributed to the atmospheric rivers, bringing from lower latitudes warm airmass with huge amount of moisture causing extreme precipitation events over ice shelves.

Many biological studies, e.g. Convey, Smith (2005), have found that increasing air and water temperatures, reducing ice and snow covers on the islands and the Mainland mainly lead to increasing and developing of biodiversity in this region. At the same time, new milder weather conditions in austral summer promote growth of touristic industry and fishery, and more smooth logistic operations for Antarctic stations and biological, oceanographic and another research. Therefore, a study of possible climate change over this region addresses some important issues: what distribution of snow/ice cover could be expected in the future and how it will influence an overall picture, biodiversity and other aspects of the region?

The main modern instruments for climate study are Global Climate Models (GCM), the most advanced one of them is the so-called Earth System Model, which includes representations and interactions between all components of the Earth's climate system: Atmosphere, Hydrosphere, Cryosphere, Biosphere and Lithosphere. GCMs can be used to study past, present and future climates, the later based on different scenarios, but they cannot describe regional climate features good enough due to low spatial resolutions and in most cases simplified physics (Connolley, O'Farrell, 1998). That is why Regional Climate Models (RCMs) forced by GCMs driving fields are used for regional climate research (IPCC, 2013). As opposed to GCMs, RCMs have higher spatial and temporal resolutions, so they are more useful, particularly for mountain regions. Also, RCMs better than GCMs describe mesoscale physics in the atmosphere.

In this paper we consider two RCMs HIRHAM5 (Christensen et al., 2007) based on a subset of the HIRLAM model (HIgh Resolution Limited Area Model) and physics from ECHAM, and RACMO21P (RegionAl Climate MOdel) (van Meijgaard et al., 2008) forced by two GCMs EC-EARTH (A European community Earth-System Model) and HadGEM (Hadley Centre Global Environmental Model). Features of HIRHAM5 in comparison to ERA-40 are examined in Dethloff et al. (2010), while RACMO 21P forced by ERA-40 (ECMWF re-analysis of the global atmosphere and surface conditions for 45 years) was explored in Rodrigo et al. (2013). van Wessem et al. (2016) use RACMO2.3 to estimate background climate conditions in snow balance research over the Antarctic Peninsula.

The main **objective** of the study was to assess a possible climate change in the region of the Antarctic Peninsula until the end of the 21st century projected by the RCMs' ensemble. The assessment was based on major cold and wet/dry climate indices proposed by World Climate Research Program WCRP (Karl et al., 1999; Peterson et al., 2001) and calculated by climate4R open framework tools (Iturbide et al., 2019).

DATA AND METHODS

Detailed description of used data and methods are presented in the first part of the paper (Chyhareva et al., 2019). Here just a brief description will be presented essential to understand the results and conclusions.

This research is based on results of Polar-CORDEX initiative (Coordinated Regional Climate Downscaling Experiment for the Polar Regions) (Giorgi, Gutowski, 2015; Koenigk et al., 2015). Driving fields for used RCMs were derived from two GCMs of the Fifth Coupled Model Intercomparing Project (CMIP5) (Taylor et al., 2011). Three runs of two regional climate models (RCMs) available at Antarctica Polar-CORDEX web-site (http://climate-cryosphere.org/activities/targeted/polar-cordex/antarctic) at the time of the study were used: RACMO21Pv1 and HIRHAM5 both forced by EC-EARTH GCM, and RACMO21 Pv2 forced by HadGEM2 (van Meijgaard et al., 2008, Christensen et al., 2007, Collins et al., 2008, http://www.ec-earth.org). Ensemble was formed by averaging of the above three runs and their mean as like as all individual RCM runs were processed in order to calculate indices and their dispersion by a software tool climate4R (Iturbide et al., 2019).

Outputs for historical runs with driving fields from ERA-Interim for the period of 1986—2005 (Granier et al., 2011) and two scenarios for Polar-CORDEX namely Representative Concentration Pathways (RCPs) for radiative forcing 4.5 W/m^2 (RCP4.5, Thomson et al., 2011) and 8.5 W/m^2 (RCP8.5, Riahi et al., 2011) are considered for two future periods: 2041—2060 and 2081—2100.

Orography of the whole RCM HIRHAM5 domain is presented in Figure 1, *a*, while a part of the West Antarctica orography from RACMO2 is at Figure 1, *b*. We focus on the Antarctic Peninsula region where narrow and high ridge of mountains is clear recognizable on the maps of both RCMs. However, the highest isolines are of 1800 m (Fig. 1, *a*) and 1500 m (Fig. 1, *b*) in Palmer Land region, while real peaks reached much over 2000 m (Mt. Jackson, Mt. Coman, and Mt. Hope) show obviously misrepresentation of the topography in the models.

Estimation of climate change in the Antarctic Peninsula region was done on the basis of six indices from the recommended by the World Climate Research Program WCRP (Karl et al., 1999; Peterson et al., 2001).

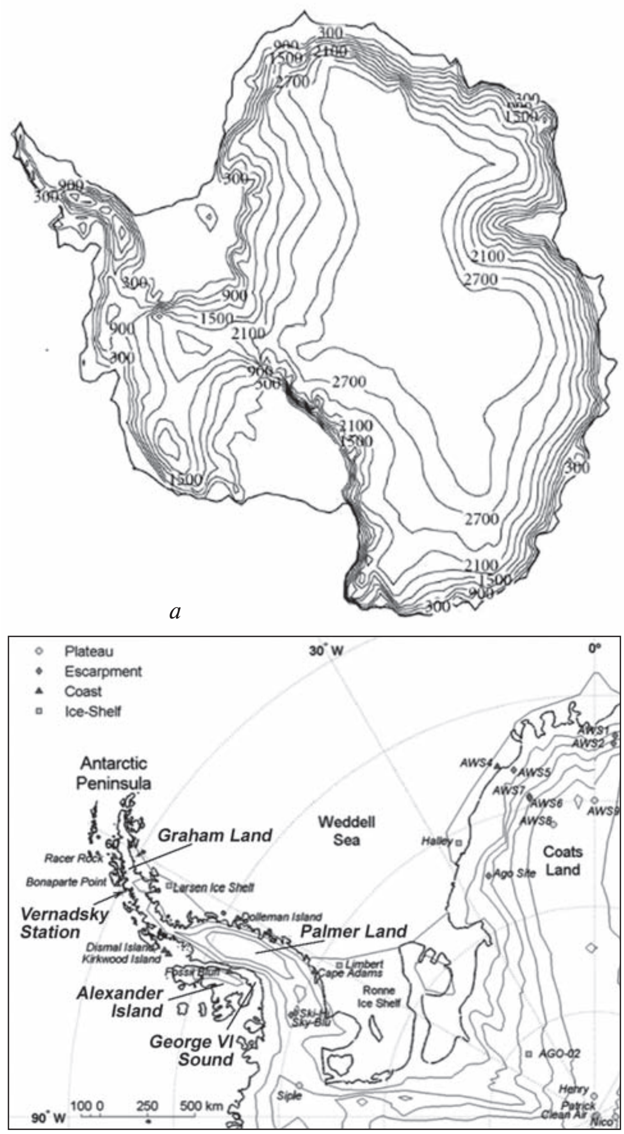

Fig. 1. *a* — modelled topography of the whole Antarctica domain by HIRHAM5 from Fig. 1 in Dethloff et al. (2010); *b* — modelled topography of part of the West Antarctica by RACMO2 adopted from Fig. 15 in Rodrigo et al. (2013)

Cold temperature indices were described in the first part of this paper (Chyhareva et al., 2019): FD — frost days, number of days per year when daily minimum temperature is less than 0°; ID-ice days, number of days per year when daily maximum temperature is less than 0°. This part is devoted to wet/dry indices, namely:

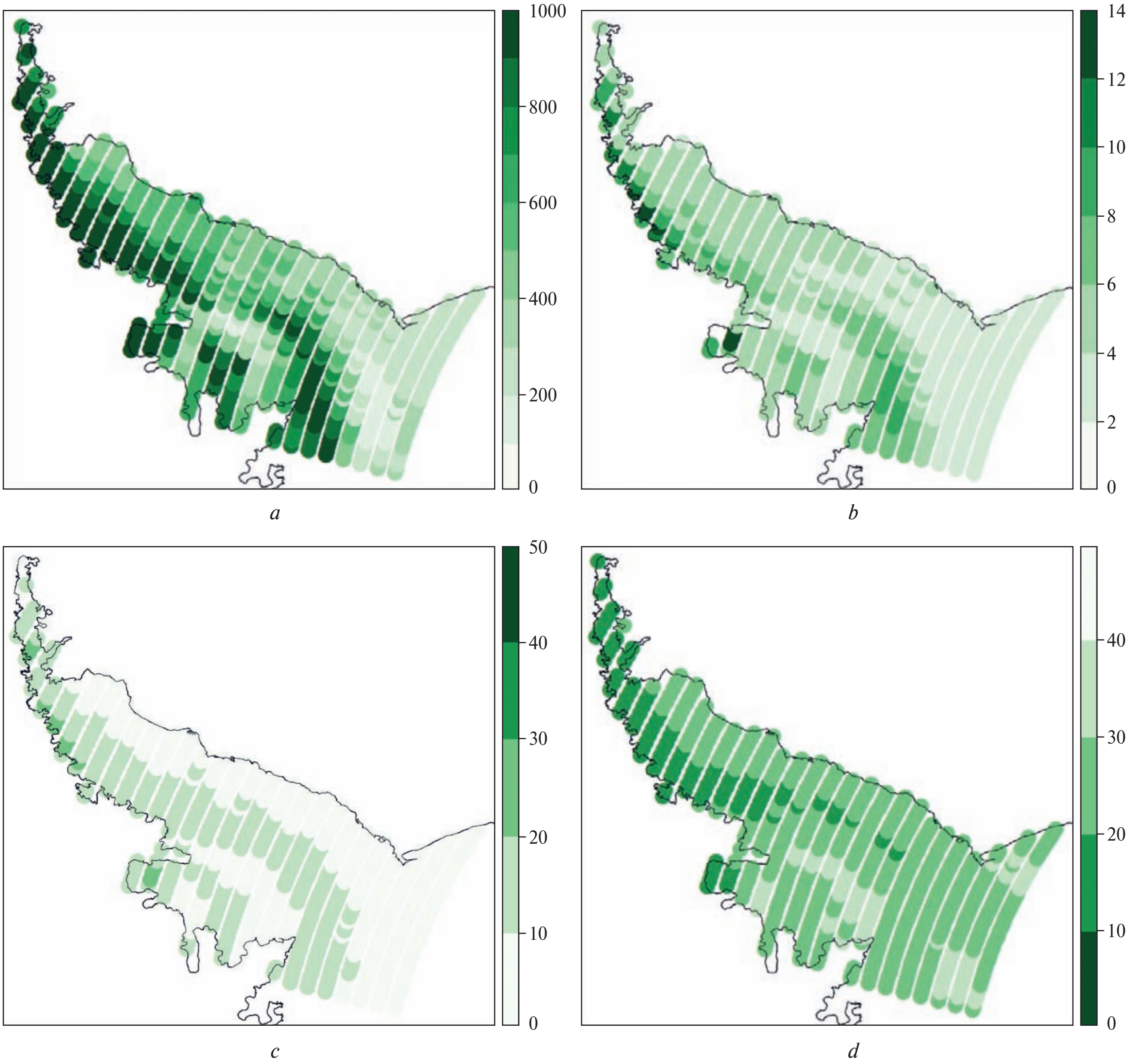

Fig. 2. Wet/dry climate indices over the Antarctic Peninsula and its ice shelves for Historical period 1986—2005: *a* — PRCPTOT (mm); *b* — SDII (mm/day); *c* — CWD (days); *d* — CDD (days)

• PRCPTOT (mm/year) as annual sum of precipitation in wet days (WD), when daily sum is over 1 mm;

• SDII (mm/day) simple daily (precipitation) intensity index calculated as PRCPTOT divided by number of WD;

• CWD (days) the longest period in year with consecutive WD;

• CDD (days) the longest period in year with consecutive dry days, when daily precipitation sum is less than 1 mm.

Although CDD index may not be representative for continental Antarctica because of naturally dry climate, but for the Antarctic Peninsula region where precipitation amount is often more than 1000 mm (van Wessem et al., 2016) it is still relevant.

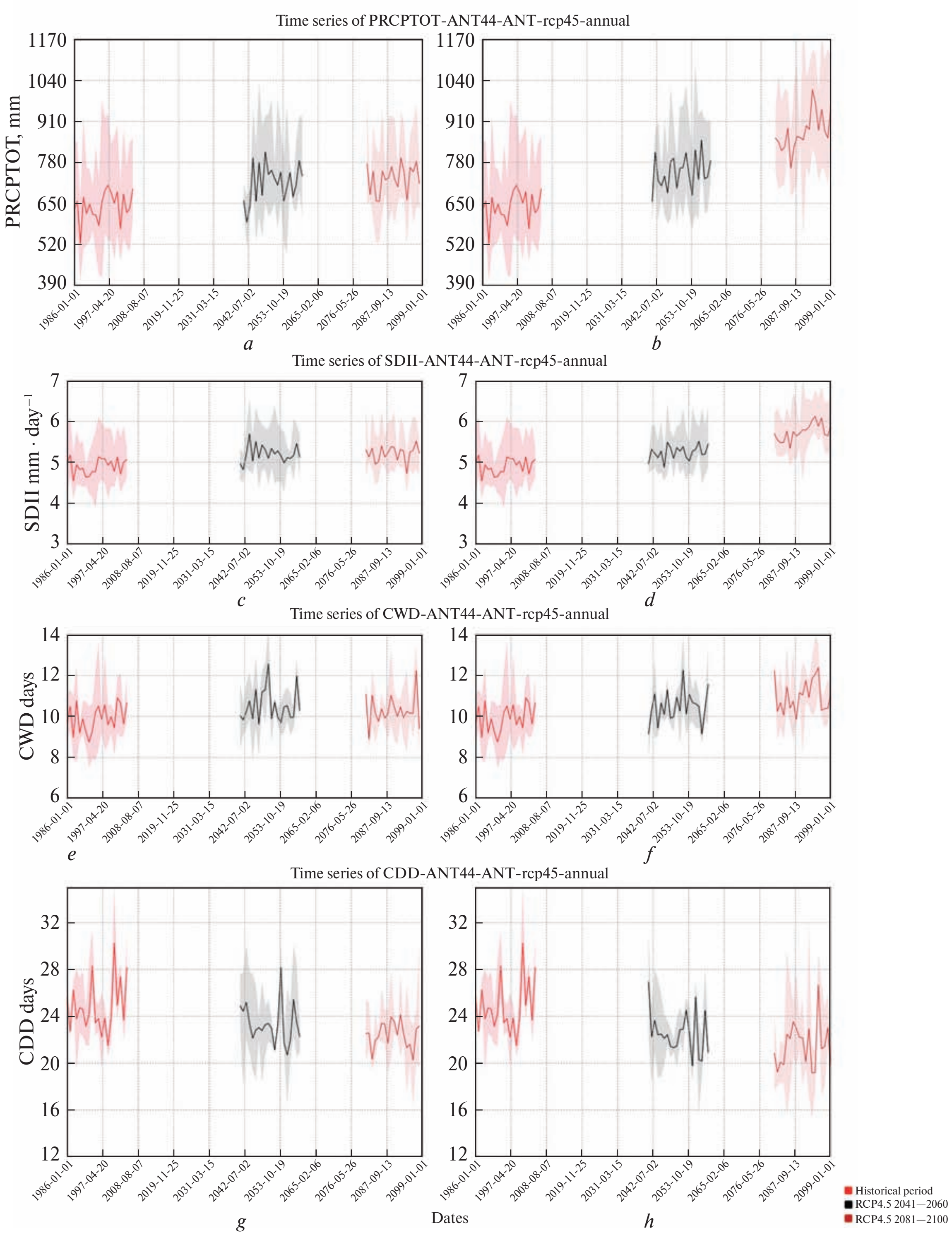

Fig. 3. Time series of climate indices PRCPTOT (*a, b*), SDII (*c, d*), CWD (*e, f*), CDD (*g, h*) for Historical (all), RCP4.5 (*a, c, e, g*) and RCP8.5 (*b, d, f, h*) scenarios for the 21st century. Solid line is RCM's ensemble means. Shaded areas on graphs are representing RCMs' ensemble range

RESULTS

In this section, obtained results for the above four climate indices are presented and discussed as the mean of used RCMs. Spatial features will be analyzed as maps for three periods and time-series of the indices for both averaged over the whole domain and a single grid point nearest to Akademik Vernadsky station. The specific obtained feature is that changes in the wet/dry indices for Akademik Vernadsky station have similar tendencies and values as averaged over the whole Antarctic Peninsula. It differs from the findings for the cold temperature indices' changes, when range of values for Akademik Vernadsky station few times exceed the range of averaged values for the whole peninsula (Chyhareva et al., 2019). Since the obtained wet/dry indices for Akademik Vernadsky station do not differ significantly from the characteristics for the whole peninsula, they are not discussed in detail and presented in the Appendix.

Analysis of the wet/dry indices over the Antarctic Peninsula for historical period

Regions with the highest precipitation amount and intensity are found on the west windward side of the Antarctic Peninsula, namely, Graham Land and Palmer Land, north-west of Alexander Island (Fig. 2, *a, b*). In the above region the longest CWD (with precipitation ≥ 1 mm) is less than 20 days with some points at the coast where this period is longer (Fig. 2, *c*), and the longest CDD (with precipitation < 1mm) is mostly over 20 days with a minimum of less than 10 days (Fig. 2, *d*). Respectively the regions with the lowest PRCPTOT values (200—300 mm) and SDII (about 5 mm/day) are Larsen Ice Shelf and leeward east coast where CWD is less than 10 days, while CDD is up to 30 days (Fig. 2).

Projections in the 21st century

Increase in the total precipitation is projected at the end of the century by both scenarios. According to the scenario RCP4.5 PRCPTOT is expected to increase by 17% in the middle of the century compared to the historical period of 1986—2005 and remain on the same level at the end of the century (Fig. 3, *a*). According to scenario RCP8.5 PRCPTOT is projected to increase from 20% in the middle to approximately 40% till the end of the 21st century (Fig. 3, *b*).

Projected changes for SDII are not so high, and they are similar to the PRCPTOTs' time series (Fig. 3, *c, d*). SDII increase for about 5% is expected from the middle to the end of the century according to the scenario RCP4.5 (Fig. 3, *c*). Under the scenario RCP8.5 projected SDII changes are from about 8% at 50th of 21st century and increasing up to 20% till the end of the century (Fig. 3, *d*). These results indicate increasing of precipitation intensity in the 21st century.

In the 21st century, the number of CWD will increase by 5—10% to the end of the century in the Antarctic Peninsula region under scenario RCP4.5 (Fig. 3, *e*) and by 7—15% under scenario RCP8.5 (Fig. 3, *f*). Higher variability is projected for Akademik Vernadsky station (Fig. 3, *a*). Here, maximum values could exceed 30% in some periods according to both scenarios; however, averaged multiyear mean changes are similar to averaged values over the whole peninsula. Variability of maximum changes is higher for CWD than for CDD.

In general, duration of maximum dry spell is projected to become shorter under both scenarios for the whole peninsula and for Akademik Vernadsky station. Changes are projected to be about 7—10% under the scenario RCP4.5 (Fig. 3, *g)* and 10—15% under the RCP8.5 (Fig. 3, *h)*.

Spatial distribution

Several regions are found for the projected changing precipitation regime. The least changes are expected on the east leeward hills of Graham Land and in the region of the Larsen Ice Shelf for the scenario RCP4.5 with increasing of precipitation total less than 10% (Fig. 4, *a, b*). Under the scenario RCP8.5 the decrease in precipitation and its intensity down to 5% is projected over the Larsen Ice Shelf in the middle and increase up to 10% at the end of the century (Fig. 4, *c, d,* Fig. 5, *c, d*). These values are the lowest over the Antarctic Peninsula for both scenarios.

In general, under RCP4.5 increases by 20—30% for PRCPTOT (Fig. 4, *a, b*) and 5—10% for SDII

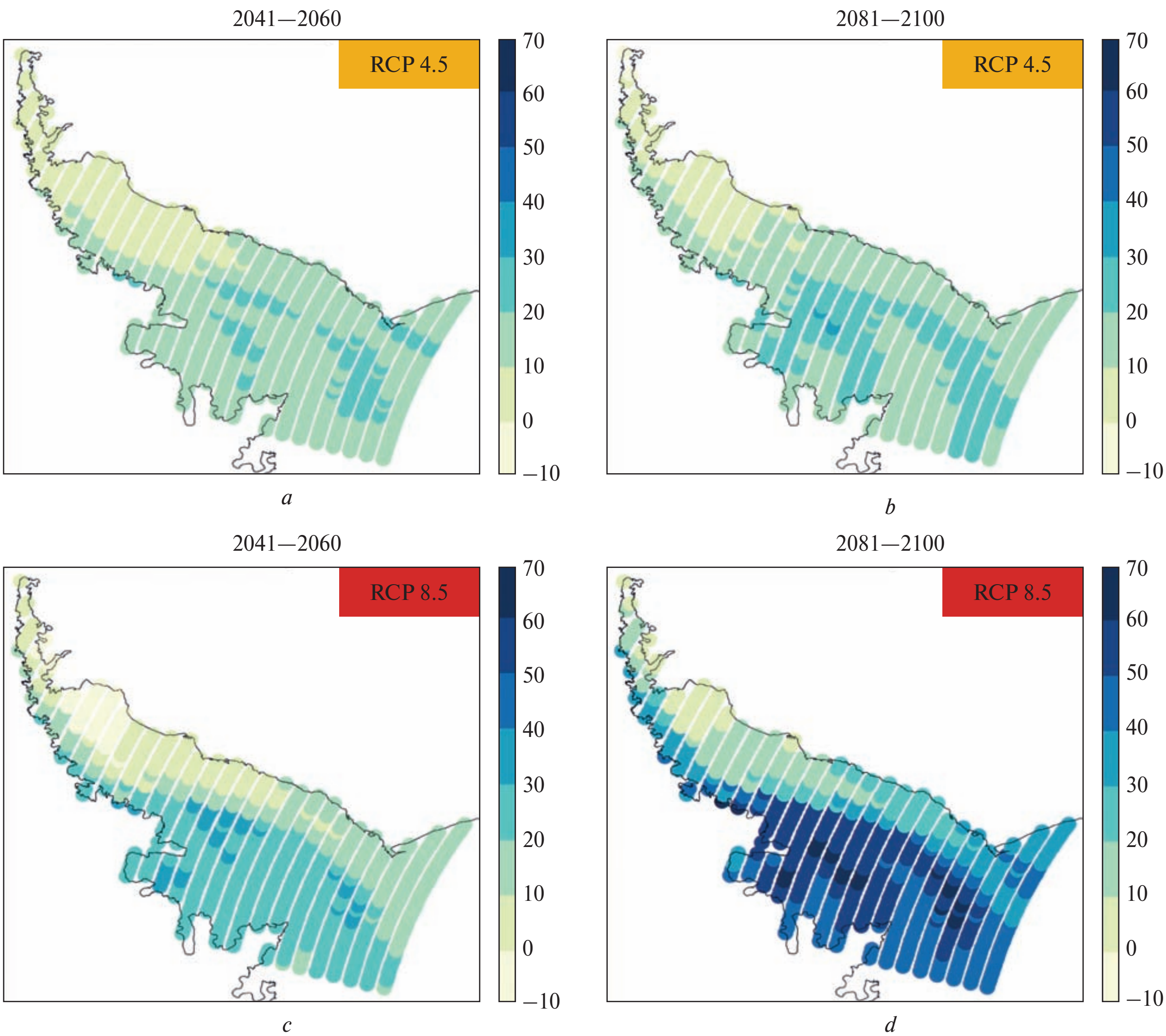

Fig. 4. Spatial distribution of PRCPTOT mean change (%) for the pointed climatic periods for scenarios RCP4.5 (*a, b*) and RCP8.5 (*c, d*)

(Fig. 5, *a, b*) are projected over the vast majority of the peninsula for both periods. Under scenario RCP8.5 on the west windward slopes of the peninsula maximum obtained values for the middle of the century are higher by 40% for PRCPTOT (Fig. 4, c) and by 15% for SDII (Fig. 5, c). The projected changes of the indices till the end of the century are over 60% for PRCPTOT in the region of Palmer Land (Fig. 4*, d*), and precipitation intensity is projected to increase by 15—25% (Fig. 5*, d*).

The spatial distribution of projected changes of consecutive wet days presented in Fig. 6 has a similar pattern as of PRCPTOT and SDII. There is decreasing in CWD for Larsen Ice Shelf and some regions of the east coast (leeward slopes at prevailing west winds) under the RCP4.5 scenario (Fig. 6*, a, b*). These changes are about –10% with maximum of about –20% till the end of the century. At the same time for the majority of the region of about 10% decreasing in CDD is also projected (Fig. 7*, a,*

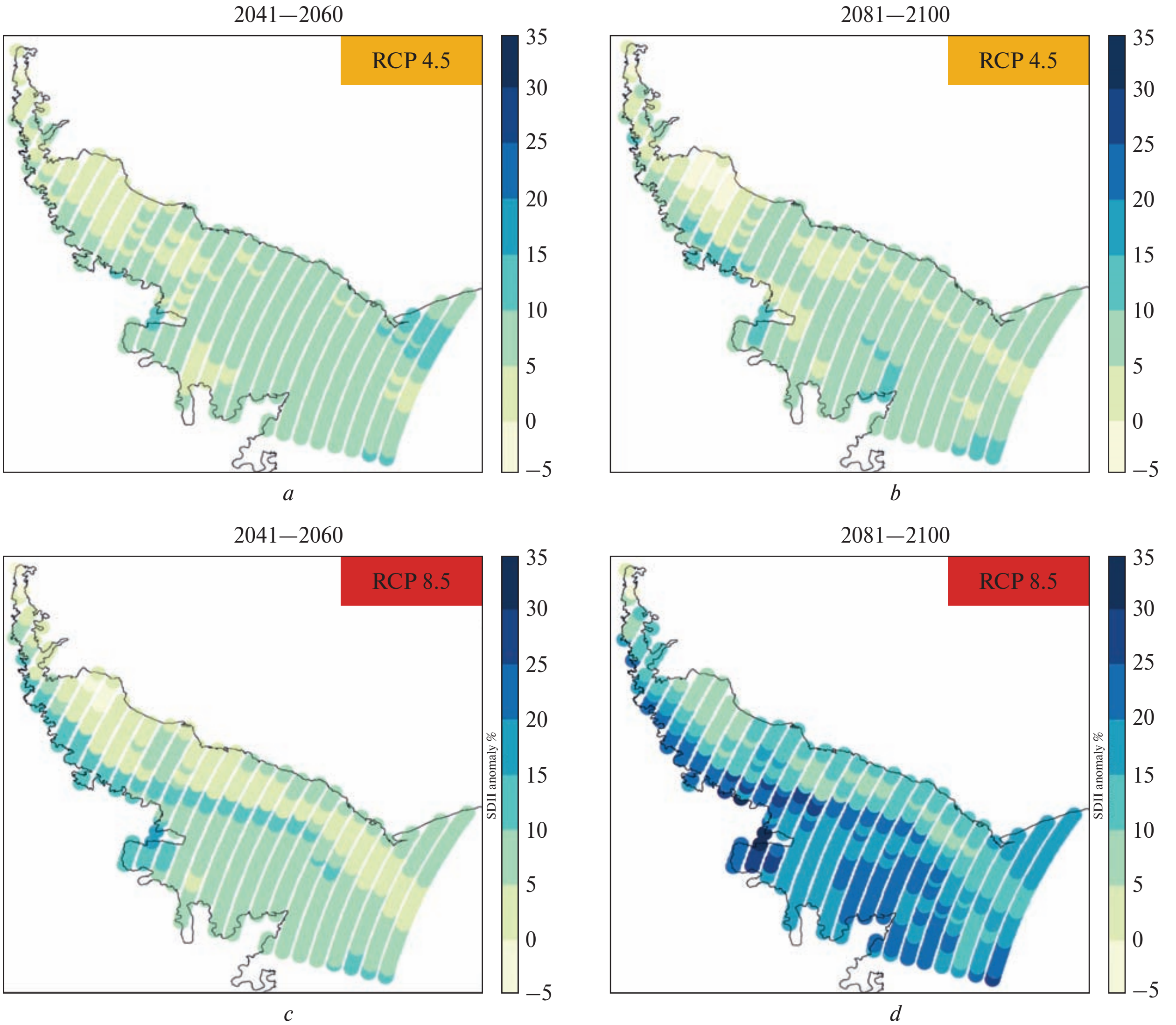

Fig. 5. Spatial distribution of SDII mean change (%) for the pointed climatic periods for scenarios RCP4.5 (*a, b*) and RCP8.5 (*c, d*)

b). For the rest of the peninsula, increasing of CWD period by 10% in general and up to 20% on some west mostly windward mountain slopes is obtained (Fig. *6, a, b*). For these regions, projected CDD changes are 10% decreasing, with maximum decreasing of about 20% in mountain regions till the end of the century (Fig. 7*, a, b*).

Projected changes for CWD under the scenario RCP8.5 have more pronounced decreasing of the index by about –10% (Fig. 6*, c*) with maxima of about –20% (Fig. 6*, d*) on the eastern leeward slopes of mountains and Larsen Ice Shelf. For the rest of the peninsula, increasing of CWD period of about 10-20% with maxima of about 30% at the middle and 20—30% with maxima up to 40% till the end of the century is projected.

At the same scenario RCP8.5 decreasing of CDD period by 10—20% is expected for almost the whole peninsula (Fig. 7*, c, d*). It is higher on windward west slopes and in mountain regions, where maximum changes could exceed 40% till the end of the century. Since CDD is projected to decrease for the majority

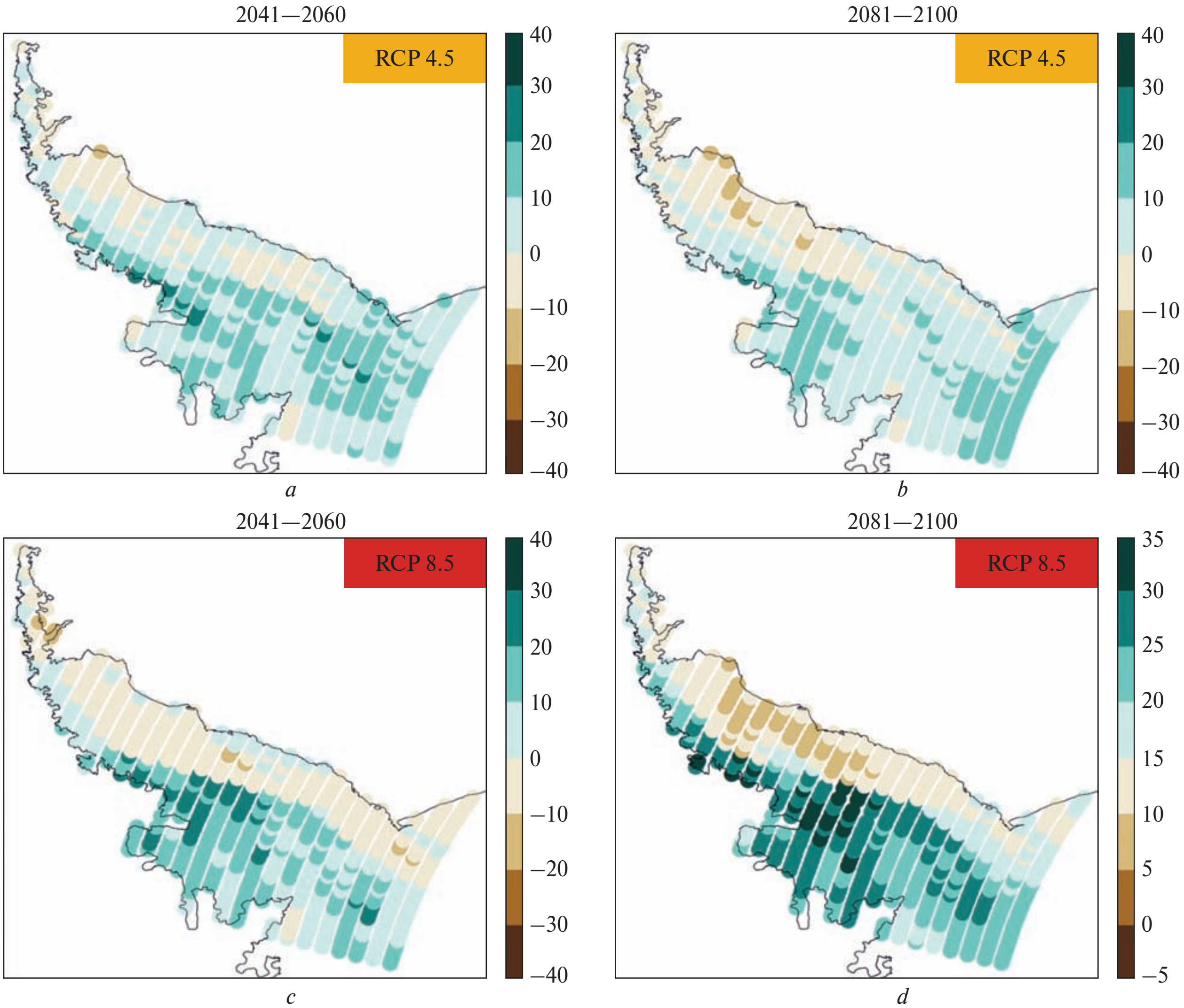

Fig. 6. Spatial distribution of CWD mean change (%) for the pointed climatic periods for scenarios RCP4.5 (*a, b*) and RCP8.5 (*c, d*)

of the peninsula, potentially there could be subregions where CWD and CDD will be decreasing simultaneously (Fig. 6*, c, d*, Fig. 7*, c, d*).

CONCLUSIONS AND DISCUSSIONS

Remarkable features of obtained PRCPTOT and SDII changes' projections over the Antarctic Peninsula are associated with its orography, namely the highest increase in precipitation amount and intensity are observed on windward slopes. Since the Antarctic Peninsula is under the influence of both warm oceanic westerlies and cold winds from the continent (Turner et al., 2005), projected warming will cause more evaporation from the ocean resulting in more precipitable water in the atmosphere of the region (Feng et al., 2019). Hence precipitation pattern triggered by Antarctic Peninsula mountains expects changes. Moreover, smoothed and underestimated terrain height can decrease the modeled precipitation in comparison with real values. This issue has been studied in many works from different parts of the world, e.g. (Cannon et al., 2017). An increase in precipitable water can probably intensify formation of

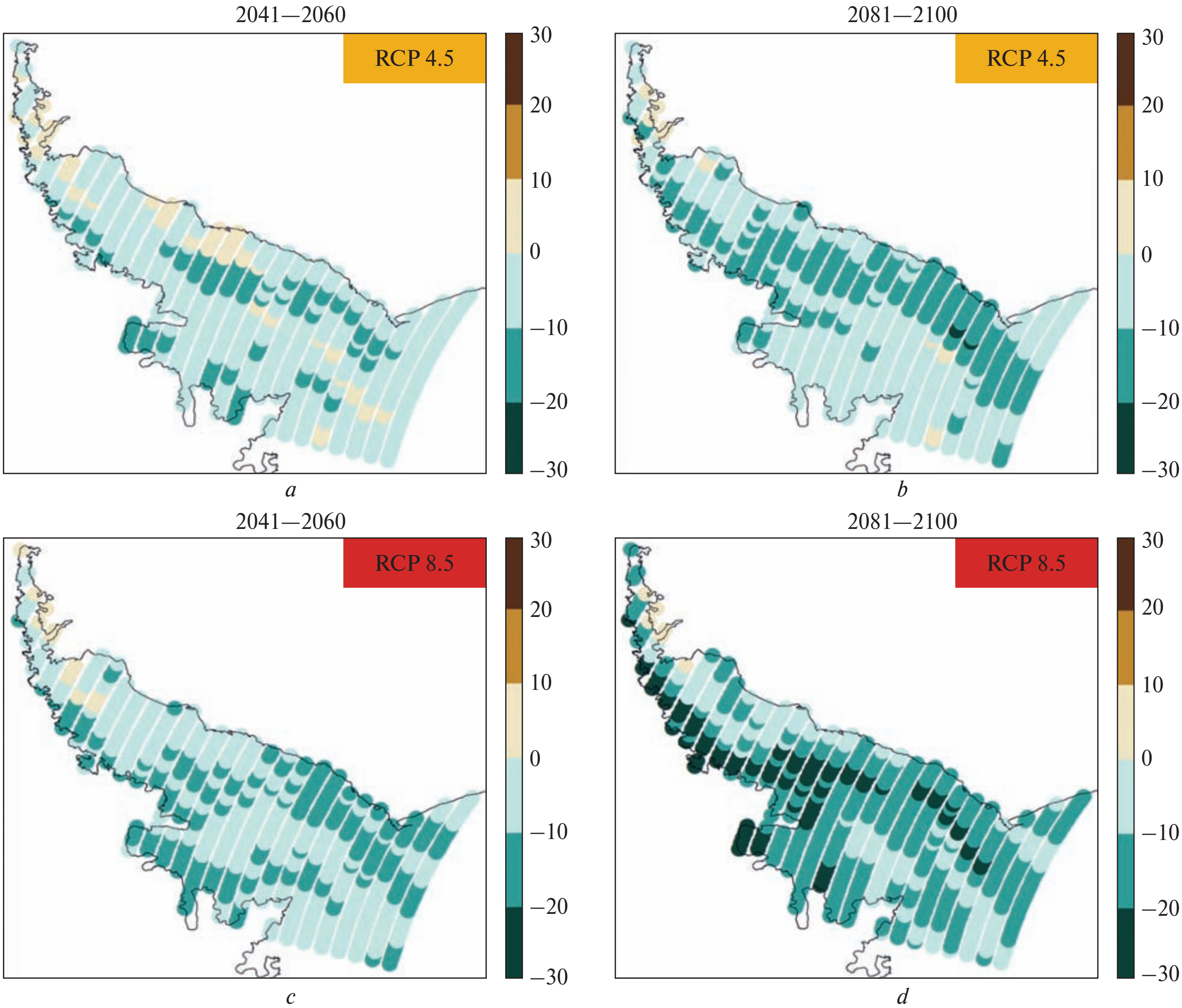

Fig. 7. Spatial distribution of CDD mean change (%) for the pointed climatic periods for scenarios RCP4.5 (*a, b*) and RCP8.5 (*c, d*)

atmospheric rivers, which have a significant and uncertain effect on the formation of snow and ice cover in Antarctica (Wille et al., 2019).

In general, the CWD period is extended while of the CDD period is reduced. CWD changes are much more influenced by the orography than CDD, where CDD increasing just for a few points on the east slopes are found.

Changes of the analyzed wet/dry indices time series in the Akademik Vernadsky station region are similar to changes over the whole Antarctic Peninsula. This is different from the tendency for cold temperature indices, for which projected changes for Akademik Vernadsky station had both much bigger variability and values than for the Antarctic Peninsula in general (Chyhareva et al., 2019).

Analyzing results presented in both parts of the research (Chyhareva et al., 2019) a few subregions with different projected changes in climate conditions based on obtained climate indices can be distinguished:

a. Leeward slopes of Graham Land and Palmer Land. A decrease in the number of frost and ice days (which indicates an extension of the warm period) and a slight increase in precipitation and their intensity in these regions are projected. Also, a decrease in CWD duration is predicted here. The highest warming and drying are projected for *Larsen Ice Shelf* according to both RCP4.5 and RCP8.5 with significant decrease of frost and ice days in combination with just 10% increase in precipitation.

b. Windward slopes of ridges, Graham Land and Palmer Land. Maximum projected increasing of precipitation and comparatively low decreasing of ice and frost days, with projected substantial reducing of CDD and extending of CWD.

c. West coast and islands, including Alexander Island and George VI Sound. Increasing of precipitation and their intensity, extending of CWD, reducing of CDD and remarkable decreasing of frost and ice days. According to both scenarios, islands in the north-west will experience the highest increase in PRCPTOT and SDII with simultaneous projected one of the highest frost and ice days decline.

It should be stressed that obtained increasing/decreasing of precipitation cannot be directly connected with ice/snow balance, because we cannot define rain/snow fraction of future precipitation from the analyzed indices. Reducing of ice/frost days can indirectly indicate on changing precipitation fraction towards rain, which could lead and intensify melting of ice sheets.

Even if there is snow precipitation, which part of it will be accumulated, is still the question, which could be answered only from extensive field experiments.

Future research on other climate indicators can add more information in order to project ice/snow balance of Antarctic Peninsula region more precisely.

Obtained results could be used for impact study on ecosystems in the region, e.g. colonization of the land, used to be under the snow/ice and developing of biodiversity (Convey et al., 2005, Sancho et al., 2007, Sancho et al., 2017).

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*А. Ю. Чигарева[1, 2, *], С. В. Краковська[1, 2], Д. В. Пішняк[2]*

[1] Український гідрометеорологічний інститут, Державна служба надзвичайних ситуацій України та Національна академія наук України, пр. Науки, 37, м. Київ, 0302, Україна

[2] Державна установа Національний антарктичний науковий центр МОН України, бульв. Тараса Шевченка, 16, м. Київ, 01016, Україна

* Автор для кореспонденції: chyhareva@ukr.net

Кліматичні проекції в районі Антарктичного півострова до кінця XXI століття. Частина II: індекси зволоження

Реферат. **Мета дослідження** — оцінка можливої зміни клімату в регіоні Антарктичного півострова до кінця 21 століття за проекціями ансамблю регіональних кліматичних моделей (РКМ). Впродовж останніх десятиліть на переважаючій території Антарктиди спостерігається потепління, воно найінтенсивніше для Антарктичного півострова, де знаходиться Українська антарктична станція «Академік Вернадський». У регіоні існує унікальна екосистема, яка є вразливою до зміни погодного режиму, що відбувається під впливом швидких змін клімату та їхніх наслідків, зокрема, зміни розподілу морського льоду та суші вкритої снігом / льодом тощо. Отже, для регіону важливим завданням є оцінка проекцій зміни клімату з визначенням окремих районів з подібними тенденціями. **Дані та методи**. В дослідженні використовувалися дані двох РКМ HIRHAM5 та RACMO21P, для регіону Антарктичного півострова, від міжнародного проекту Polar-CORDEX (Координований регіональний експеримент з динамічного масштабування для регіонів Антарктиди та Арктики) в рамках міжнародної ініціативи CORDEX. Граничні умови РКМ були взяті з глобальних кліматичних моделей EC-EARTH та HadGEM. Просторовий розподіл даних РКМ становить 0,44°. Скрипти, розроблені проектом Climate4R (Середовище R для доступу до кліматичних даних та їх обробки), було модифіковано для доступу до даних для Антарктичного півострова з домену Антарктиди та отримання кліматологічних характеристик для окремих РКМ та їх усереднення за ансамблем. Прогнозовані зміни кліматичних показників періоду з опадами більше (менше) 1мм на день за двома сценаріями RCP4.5 і RCP8.5 за два періоди 2041—2060 рр. та 2081—2100 рр. були оцінені відповідно до історичного експерименту 1986—2005 рр. **Результати**. Аналіз прогнозованих показників режиму зволоження за двома сценаріями RCP4.5 і RCP8.5 представлений в частині II статті, тоді як аналіз індексів холоду (FD, ID) був представлений у частині I дослідження. За історичним експериментом льодовик Ларсена та підвітряне східне узбережжя є регіонами з найнижчою загальною кількістю опадів у вологі дні (PRCPTOT, 200—300 мм) та спрощеним добовим індексом інтенсивності опадів (SDII, приблизно 5мм/день), при цьому тривалість днів поспіль з опадами більше 1мм (CWD) до 10 днів, а тривалість послідовних днів з опадами менше 1 мм (CDD) до 30 днів. У XXI столітті прогнозується, що CDD на всьому півострові та на антарктичній станції «Академік Вернадський» скоротиться на 7-10% за сценарієм RCP4.5 і на 10—15% за сценарієм RCP8.5. Також прогнозується зменшення SDII на 20% до кінця століття за сценарієм RCP8.5 на північно-західному узбережжі Антарктичного півострова. **Висновки**. Для регіону Антарктичного півострова обидва сценарії прогнозують в цілому збільшення загальної кількості опадів та їх інтенсивності; в цілому максимальна тривалість періоду з опадами більше 1 мм збільшується, а максимальна тривалість періоду з опадами менше 1 мм – скорочується. У поєднанні зі зменшенням кількості днів з мінімальною (FD) та максимальною (ID) температурою менше 0 °C зміни неоднорідні на півострові. У першій частині статті було показано, що для регіону Антарктичного півострова за двома сценаріями прогнозується загалом зменшення тривалості холодного періоду. Найсуттєвіші зміни кліматичних індексів ID та FD прогнозуються для льодовика Ларсена. Аналізуючи результати, представлені в обох частинах статті, ми можемо виділити кілька районів в регіоні з різними прогнозованими змінами кліматичних умов на основі отриманих кліматичних показників. Отримані результати можуть бути використані як для вивчення впливу на екосистеми в регіоні, так і для стратегічного планування майбутньої діяльності (наукової, туристичної, рибної промисловості та ін.).

Ключові слова: Антарктичний півострів, Українська антарктична станція «Академік Вернадський», кліматичні показники, регіональна модель клімату, Polar-CORDEX, сценарії RCP.

APPENDIX

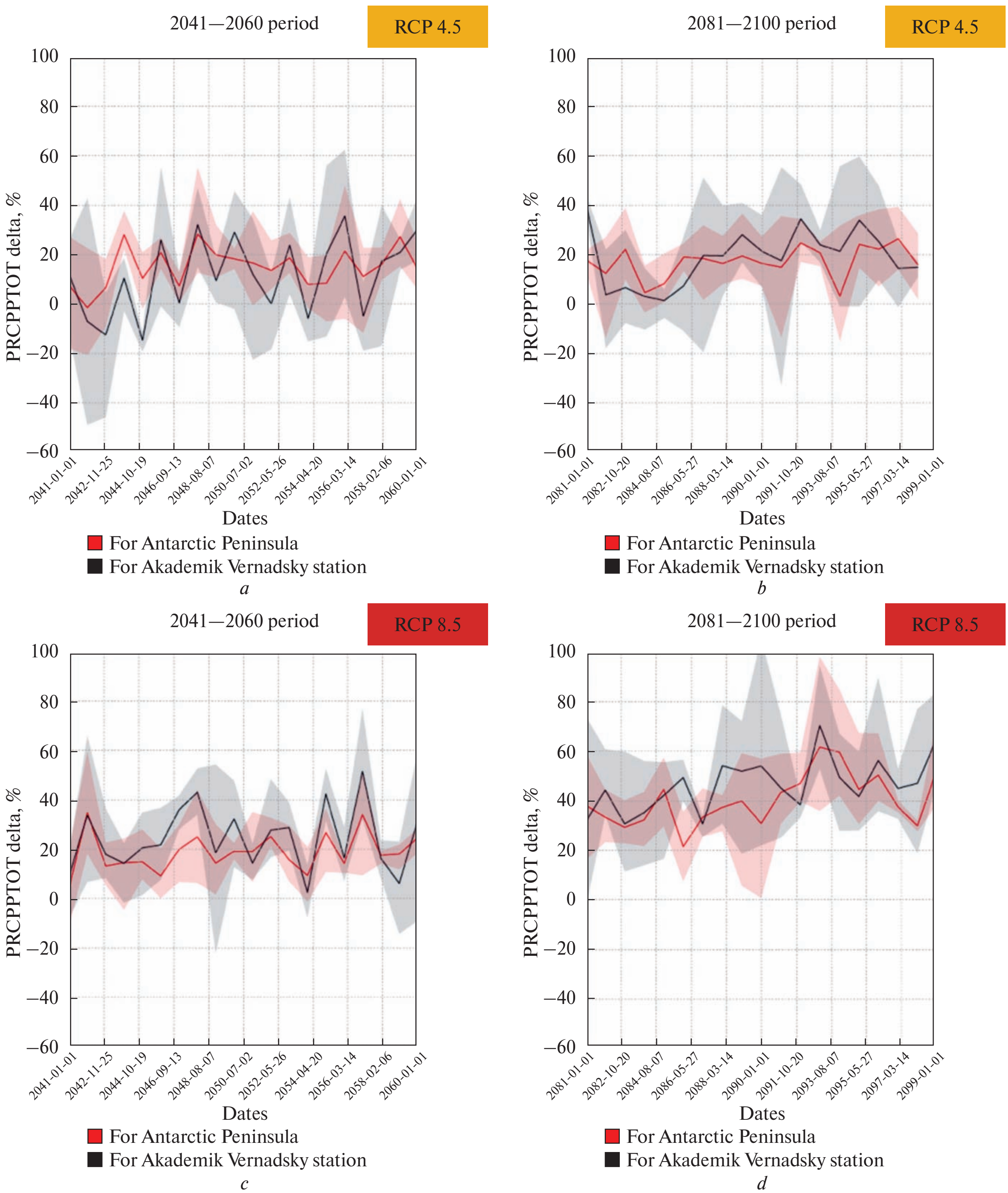

Fig. A.1. Time series of PRCPPTOT change for Antarctic Peninsula (pink) and the Akademik Vernadsky station (black)

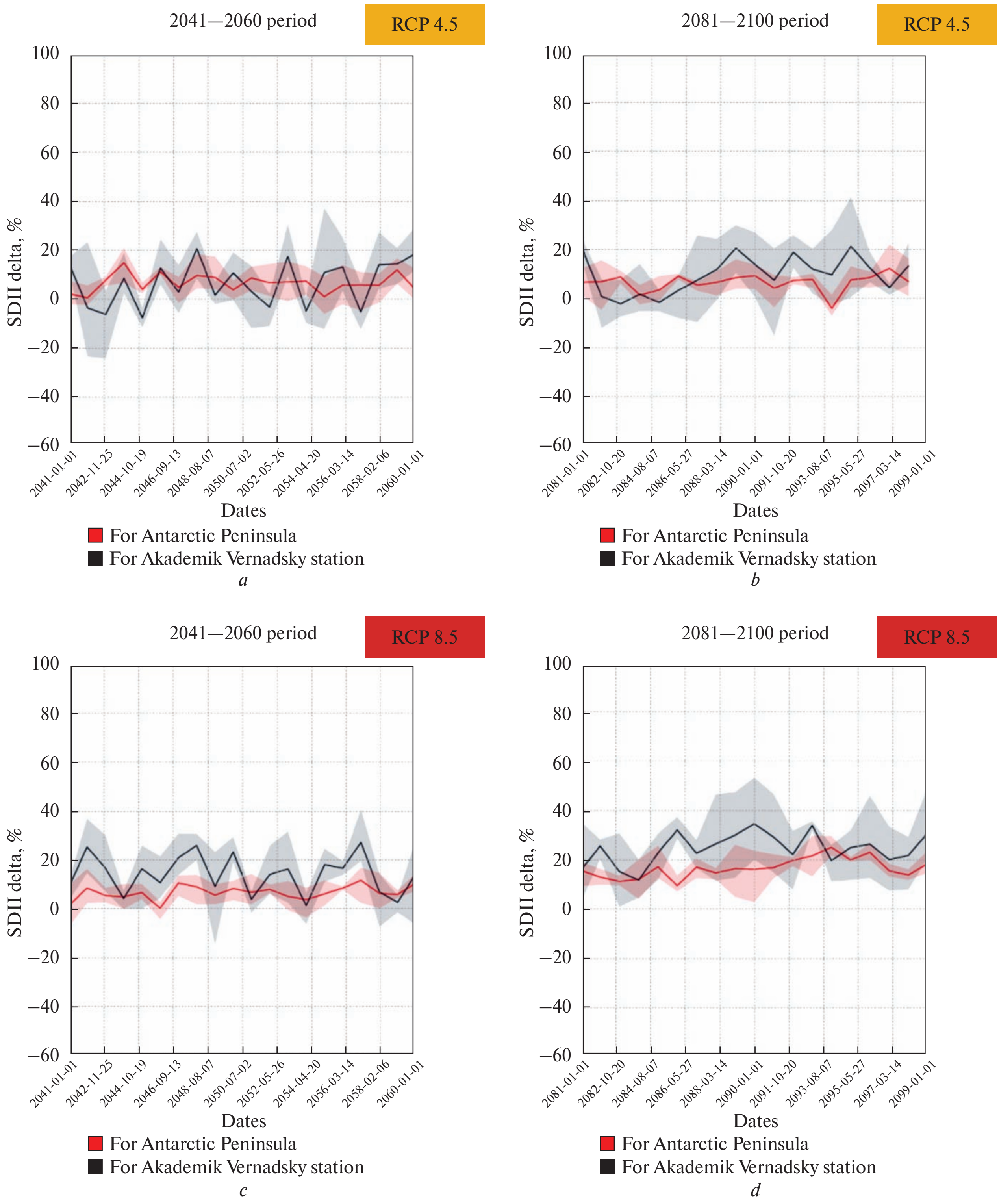

Fig. A.2. Time series of SDII change for Antarctic Peninsula (pink) and the Akademik Vernadsky station (black)

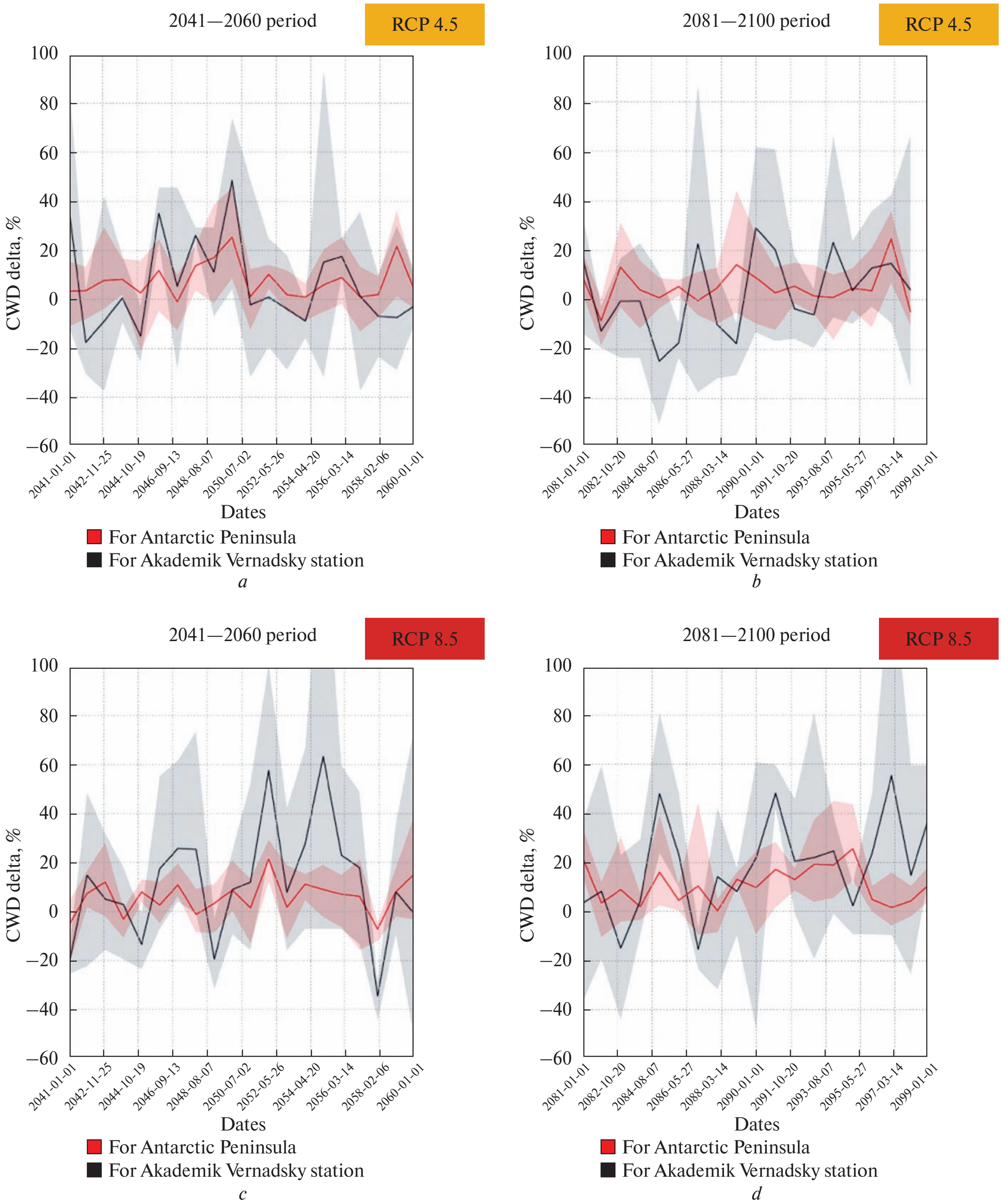

Fig. A.3. Time series of CWD change for Antarctic Peninsula (pink) and the Akademik Vernadsky station (black)

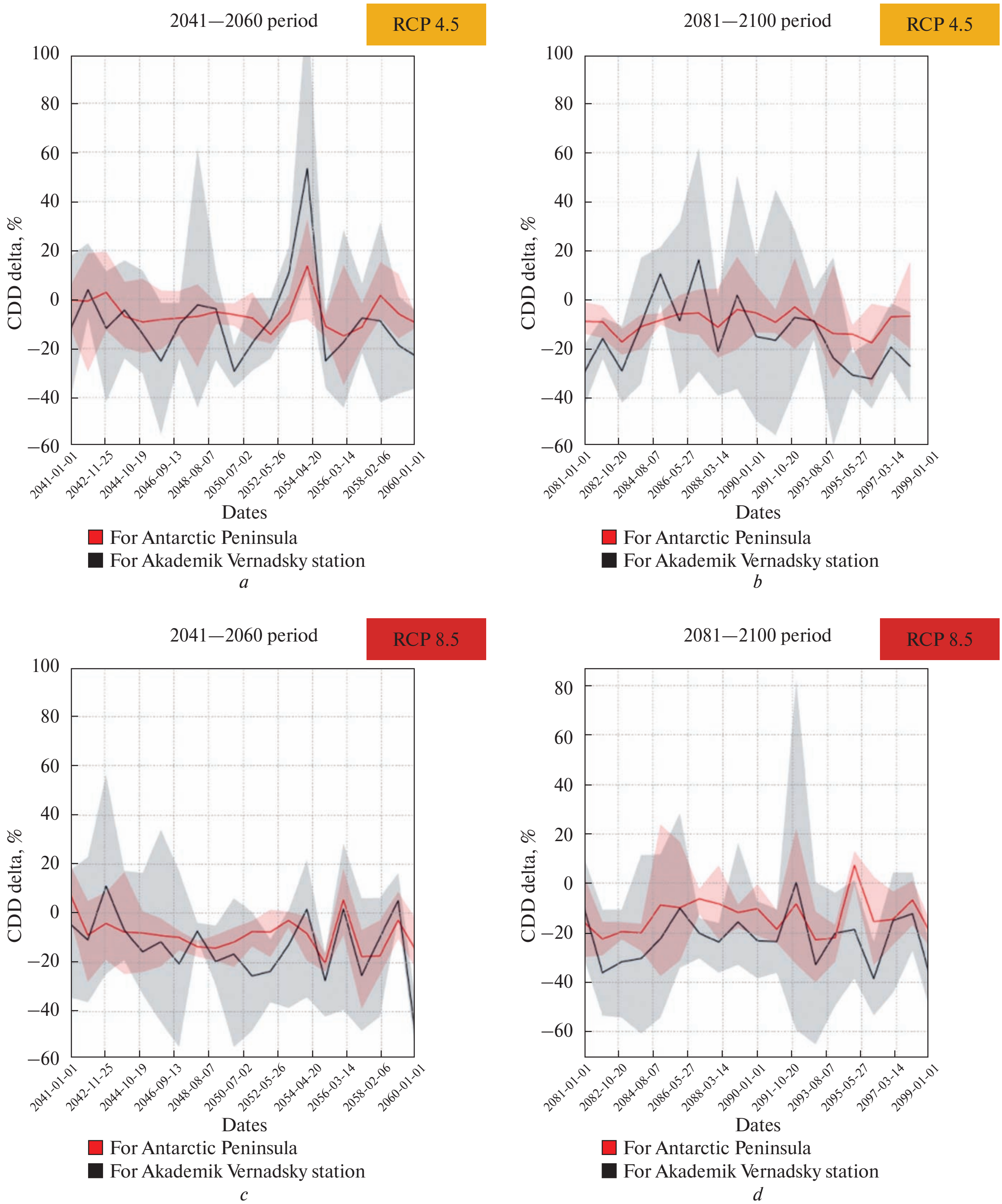

Fig. A.4. Time series of CDD change for Antarctic Peninsula (pink) and the Akademik Vernadsky station (black)