Chyhareva, A., & Krakovska, S. (2022). Climate projections over the Antarctic Peninsula region to the end of the 21st century. Part III: clouds and extreme precipitation. *Ukrainian Antarctic Journal*, *20*(2), 188–202.
https://doi.org/10.33275/1727-7485.2.2022.699

Гідрометеорологічні та океанографічні дослідження

Hydro-Meteorological and Oceanographic Research

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Climate projections over the Antarctic Peninsula region to the end of the 21st century. Part III: clouds and extreme precipitation

Abstract. This paper focuses on the parameters that represent the characteristics of clouds and extreme precipitation events over the Antarctic Peninsula region, where clouds and precipitation play a crucial role in regional climate warming, particularly when a higher fraction of precipitation becomes liquid. In this work, we assess cloud and precipitation properties under climate change over the Antarctic Peninsula region under the Representative Concentrations Pathways (RCP) scenarios using model outputs of the Coordinated Regional Downscaling Experiment for polar regions (Polar CORDEX) for the 21st century. A similar approach was previously applied by authors for estimating projected changes in the temperature regime (Part I) and wet/dry indices (Part II) for the Antarctic Peninsula. We evaluated changes in cloud ice and condensed water contents, spatial distributions of both rain fraction and 95th percentile of total precipitation for the future periods, 2041–2060 and 2081–2100, for RCP4.5, RCP8.5 comparing them to the historical period of 1986–2005.We found that changes in studied parameters have similar tendencies and patterns under both scenarios, with more remarkable changes for the RCP8.5 scenario through the end of the 21st century. Analysis of obtained projections shows that all cloud amounts, liquid content in clouds, the annual fraction of rain in precipitation events, and frequency of extreme precipitation events will increase over the Antarctic Peninsula by the end of the 21st century under both RCP scenarios. The most significant changes are expected for the west coast and over the ocean to the west of the Antarctic Peninsula region, while the lowest changes are projected for the ridge of the Antarctic Peninsula mountains. However, the rates of expected changes vary within the broad Antarctic Peninsula region. While extreme event intensities will increase over the whole area, the changes will be most remarkable over the northwestern slopes of the Antarctic Peninsula, where Akademik Vernadsky station is located.

Keywords: climate change, condensed water path, ice water path, polar clouds, precipitation, Polar CORDEX, Representative Concentrations Pathways

1 Introduction

The Antarctic Peninsula (AP) region has experienced the highest warming rate on the Antarctic continent since the 1950s (Gutiérrez et al., 2021). This region, therefore, requires special attention in climate studies, and the assessments of projections in precipitation and cloud properties are particularly important in this context. It is well known that atmospheric processes over the AP region differ from the continental Antarctic and marine Arctic regions (Bromwich et al., 2012). At the same time, the AP region has unique terrestrial and marine ecosystems that could be dramatically impacted by further warming because of air and marine heat waves, seawater acidification, melt water share increase, and ice shelves and glaciers retreat due to climate change (Smith et al., 1999; Trivelpiece et al., 2011; Siegert et al., 2019; Pörtner et al., 2019).

Warm moist intrusions from the mid-latitudes could break the thermal isolation of the continent that formed during the planet's evolution (Li, 2022). They could also cause strong fohn winds with abrupt essential warming over the AP slopes, particularly Larsen Ice Shelves (Turton et al., 2018). Moist intrusions with extreme precipitations and temperature increases enhance the glaciers' calving process in the region (Wille et al., 2022).

Clouds could impact the AP region indirectly through scattered radiation and directly through precipitation formation (Bennartz et al., 2013). Precipitation could cause ice mass changes and melting effects by interacting with surface layers. It is shown that combining clouds with liquid precipitation could enhance melting events by hindering freezing processes (Van Tricht et al., 2016). On the other hand, phase transition of precipitation on the ground is still a big challenge for predicting and needs more focused research with simulation and measurements as were recently studied with ERA5 reanalysis product downscaled by Polar-WRF model and additional measurements at Akademik Vernadsky (hereinafter Vernadsky) and Escudero stations (Chyhareva et al., 2021).

Nowadays, the parameterization of clouds is still an issue for atmospheric forecast and climate models that causes many uncertainties (Bony et al., 2015). Over Antarctica and the Southern Ocean particularly, it is challenging to simulate absorbed radiation, ice nucleating particles, cloud condensation nuclei distribution, and aerosol-cloud interaction in general. Four collaborative projects organized by different funding agencies in the United States and Australia were focused on improving the understanding of clouds, aerosols, precipitation, and their interactions in the Southern Ocean: the Clouds Aerosols Precipitation Radiation and atmospheric Composition Over the Southern Ocean (CAPRICORN), Measurements of Aerosols, Radiation and Clouds over the Southern Ocean (MARCUS), Macquarie Island Cloud Radiation Experiment (MICRE), and Southern Ocean Cloud Radiation and Aerosol Transport Experimental Study (SOCRATES) (McFarquhar et al., 2021).

There were a few field campaigns recently aimed at improving our understanding of clouds in continental Antarctica, such as the airborne field campaign in the region of the Rothera station (Lachlan-Cope et al., 2016), the ARM West Antarctic Radiation Experiment (AWARE) field campaign at the McMurdo station (Lubin et al., 2017), and Year of Polar Prediction in Southern Hemisphere (Bromwich et al., 2020) over the whole Antarctic continent. Also, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite-based lidar data were used to assess supercooled water-containing clouds' geographical, vertical, and temporal distribution in comparison to total cloud fraction and to all-ice clouds (Winker et al., 2010; Listowski et al., 2019). This research found that supercooled liquid-clouds fraction varies approximately from 50% in summer to 20% in winter over all of Antarctica; the average total cloud fraction is around 70% with minor interannual variability. The largest monthly variability is observed on Antarctic Plateau and the lowest over the West Antarctic Ice Shield.

Data sets from CALIPSO and the Moderate Resolution Imaging Spectroradiometer (MODIS) were compared to the CMIP5 projections for the cloud water paths and surface downwelling radiation components (Lenaerts et al., 2017). It was shown that depending on the model in the CMIP5 there could be observed great stable biases that cause underestimation or overestimation of snowfall amount.

Cloud yearly fraction has large variability on short time scales and no distinct pattern in Antarctica. However, research based on micropulse lidar data shows that the annual mean cloud fraction over the McMurdo station, which represents West Antarctic Coast, is of 67%, while over the Syowa station, which represents East Antarctic Coast, is of 74%, and over the South Pole is of 40% (Shiobara et al., 2003; Mahesh et al., 2005; Silber et al., 2018).

The assessment of cloud and precipitation characteristics in the future, according to scenarios of Representative Concentration Pathways (RCPs) and based on climate models, remains an important scientific task for a better understanding of future challenges in polar regions (Bennartz et al., 2013; Pörtner et al., 2019; Gutiérrez et al., 2021).

Although the AP region is the most studied part of the whole Antarctica, climatic projections of clouds are not estimated there, while only total precipitation in connection to surface mass balance and temperature is assessed in Gutiérrez et al. (2021). That is why evaluating the changes in clouds, liquid precipitation fraction, and extreme precipitation, according to RCP scenarios by Regional Climate Models (RCMs), is the ultimate goal of this study. We assess changes in cloud and precipitation properties, through the projected changes in the ice water path (IWP), condensed water path (CWP), and extremity of precipitation, through the total precipitation change and change in a number of days with precipitation higher than 95 percentiles of the historical period. IWP and CWP are essential for estimating cloud absorption, optical depth, albedo, and emissivity from a climatic perspective (Stephens, 1980; Platt & Harshvardhan, 1988; Platt, 1997; Heymsfield et al., 2003).

In turn, characteristics of precipitation regime change will help to understand the process of surface-atmosphere interaction and possible melt events enhanced with extreme precipitation (Wille et al., 2022).

2 Methodology

Simulations data from the Coordinated Regional Downscaling Experiment – Arctic and Antarctic Domains (Polar CORDEX) remain one of the best tools that allow scientists to assess long-term variations in the Antarctica climate. We use the same initial data from Polar CORDEX, methodological approach, and periods as in Parts I and II of the research (Chyhareva et al., 2019a; 2019b). Note that clouds and precipitation considered in the presented study could connect our understanding between temperature and wet/dry regimes analyzed in the previous parts of the study.

The study used two regional climate models (KNMI-RACMO21P and DMI-HIRHAM5) from the Antarctic-CORDEX initiative. They were forced by two global driving models (MOHC-HadGEM2-ES and ICHEC-EC-EARTH), both from Coupled Model Intercomparison Project 5th Phase (CMIP5) and formed an ensemble of three datasets in total in the same way as in the previous parts of the study.

The spatial resolution of a grid used was 0.44° over the Antarctic Peninsula region (lon1 = –85, lon2 = = –50, lat1 = –75, lat2 = –60). In our assessment of climate evolution, we used IWP, CWP, precipitation, and near-surface air temperature during two future periods (2041–2060, 2081–2100), with respect to the historical period 1981–2005 according to representative concentration pathway scenarios RCP 4.5 and RCP 8.5. Data were processed with CDO (Climate data operators) and Python 3 software. This paper analyses the relative rate of chosen parameter changes as the best way to represent the projected climate dynamic in the region.

In this research, definitions of IWP and CWP are used regarding the Climate and Forecast models Metadata Conventions (Hassel et al., 2017). IWP is the integral from the surface to the top of the atmosphere of the ice water content per unit area. CWP is the integral from the surface to the top of the atmosphere of the liquid and ice phase of cloud water content per unit area. Liquid cloud water is cloud drops with an upper diameter limit of 0.2 mm. For the IWP and CWP, multi-year mean yearly sums based on yearly sums for each period and model were calculated. For each model, a change for future periods was assessed. These changes were calculated as differences between the future and historical period multi-year mean of yearly sums.

We define amounts of liquid precipitation and their change over time, assuming that liquid precipitation appears when the near-surface air temperature is over 0 °C. For this task, chosen days with positive temperatures for daily data for each period created an appropriate mask and applied it to daily data of total precipitation. Obtained liquid precipitation was summed for each year and averaged over chosen periods. The same algorithm was applied to ERA5 reanalysis data to verify the rain share in the total precipitation and rain multi-year sum retrieved from the Polar CORDEX ensemble mean for the historical period 1986–2005.

 ISSN 1727-7485. Ukrainian Antarctic Journal, 20(2), 2022, https://doi.org/10.33275/1727-7485.2.2022.699

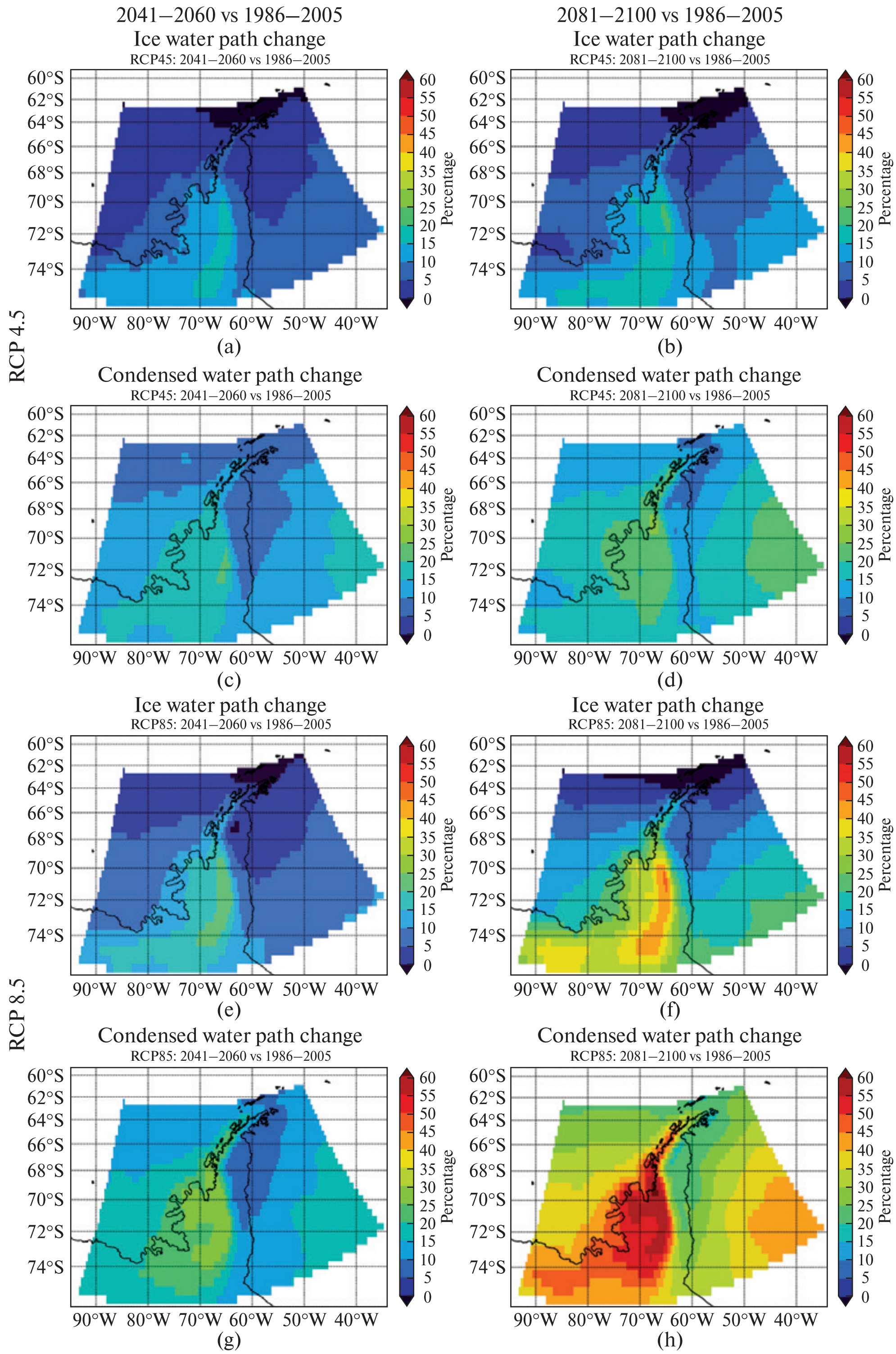

Figure 1. Ensemble multi-year mean change (%) over 1986–2005 of atmosphere cloud ice content (a, b, e, f) and condensed water content (c, d, g, h) for 2041–2060 (a, c, e, g) and 2081–2100 (b, d, f, g) according to RCP 4.5 (a–c) and RCP 8.5 (e–h)

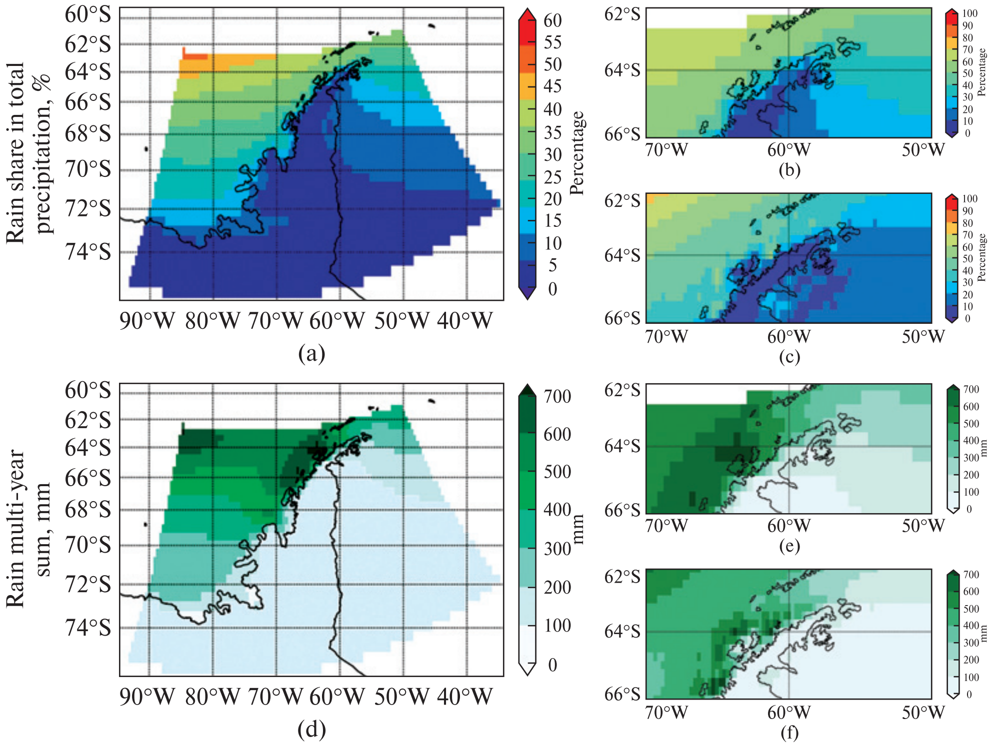

Figure 2. Share of rain fraction in the total precipitation yearly amount (a, b, c) and rain multi-year sum (d, e, f) for 1986–2005 for Antarctic Peninsula (a, d) and the Northern Tip of AP (b, c, e, f), according to CORDEX historical period (a, b, d, e) and ERA5 (c, f)

Based on daily precipitation sums, the percentage of wet days with total precipitation higher than 95 percentile of the reference period for future periods and values of 95 percentile for all chosen periods were calculated. Algorithms of calculation can be found in the Climate Data Operator (CDO) software description (CDO, https://code.mpimet.mpg.de/projects/cdo/embedded/index.html).

3 Results

3.1 Cloud condensed water and ice paths

According to projections based on RCP 4.5 and RCP 8.5, IWP and CWP (Fig. 1) will increase over the studied region during the century. However, projected changes of CWP are much greater than IWP, meaning that the relative part of the liquid phase of water in clouds will increase. The most significant changes for both parameters are over Palmer Land, and the lowest changes are over the Antarctic Peninsula's northern tip.

Noticeably, IWP did not change much during the century according to both scenarios for the AP northern tip. At the same time, CWP is projected to change by 10%, according to RCP 4.5, and from 10% to 30%, according to RCP 8.5, during the century, which again demonstrates the increase of liquid phase share in clouds.

For Palmer Land, CWP increased by 20–25% and 20–50% according to both scenarios, respectively, during the century (Fig. 1c, d, g, h). Also, a change of IWP of over 40% is projected according to the RCP 8.5 scenario during the end of the century for Ellsworth Land (Fig. 1f). CWP is projected to increase by 20–30% (Fig. 1c, d) according to RCP 4.5 and by 25–55% according to RCP 8.5 (Fig. 1g, h) over the Palmer Land.

Changes in IWP over the South Pacific Ocean have zonal distribution and increase up to 15% during the middle of the century according to both scenarios

 ISSN 1727-7485. Ukrainian Antarctic Journal, 20(2), 2022, https://doi.org/10.33275/1727-7485.2.2022.699

(Fig. 1a, e). Over the Weddell Sea, changes are more remarkable than over the Bellingshausen Sea and reach up to 25% until the end of the century, according to the RCP 8.5 scenario (Fig. 1f). Over the South Pacific Ocean and the Weddell Sea, the cloud condensed water path will increase by 10—25% according to RCP 4.5 and 15—50% according to RCP 8.5 during the century (Fig. 1d, h). Changes are similar to IWP zonally distributed over the South Pacific Ocean and mainly parallel to the AP over the Weddell Sea.

Based on the analysis of the results, we can assume that not only the total cloud fraction will increase over the studied region but also liquid to total cloud fraction according to changes in the ratio of IWP to CWP.

3.2 Rain fraction of precipitation

Total precipitation and other wet/dry indices have been analyzed in Chyhareva et al. (2019b). Since we found that water clouds will increase and expected more liquid phase precipitation with further warming even in Antarctica (Vignon et al., 2021), we calculated the rain share of total precipitation for the considered domain. First, we analyzed historical values for 1986—2005 for the share of rain in total precipitation and in multi-year annual sums (Fig. 2).

The liquid fraction of total precipitation is about fifty per cent on the northern and northwestern windward side of the AP (Fig. 2b). It is lower for the southwestern windward side of the AP — up to 30% over the western slopes of Alexander Island (Fig. 2a). Rain fraction is about 10% over the AP mountains, Palmer Land and south of the Weddell Sea. The precipitation fraction is comparatively low to the east of the AP over the Weddell Sea (Fig. 2a). It is about 40% for the northern tip of AP, where Esperanza and Petrel stations are situated, and about 20% for the James Ross Island, where Mendel station is situated (Fig. 2b).

The highest amount of multi-year liquid precipitation was found in the region where Vernadsky and Rothera stations are located, between islands Anvers and Adelaide on the northwest of AP (Fig. 2d, e). There is higher than 600 mm of annual liquid precipitation, with a maximum over Anvers Island of more than 700 mm for the historical period (Fig. 2e). At the same time, the share of rain in total precipitation is evenly distributed with a gradual decrease to the southeast over the studied region. Such distribution confirms that the region between islands Anvers and Adelaide has the highest amount of precipitation during the historical period. Such a precipitation distribution could be explained by a combination of the orographic effect and prevailing atmospheric flow from the ocean with high moisture content. At the same time, the northern tip of AP has lower mountains, which are more parallel to the moist atmospheric flows that smooth the orographic effect. The frequency of heavy precipitation events could be lower to the south of AP.

Rain share and multi-year liquid precipitation sums for the CORDEX historical experiment (Fig. 2b, e) were verified by ERA5 reanalysis data (Fig. 2c, f) for the northern part of the studied domain where a maximum rain yearly amount was found. Overall both characteristics in the CORDEX historical experiment are higher over ERA5 reanalysis data.

It should be noted that ERA5 has a higher grid resolution of $0.25° \times 0.25°$ and better represents regional features of liquid precipitation distribution. It shows the almost absent liquid precipitation over the Northern tip Mountains and leeward slopes.

Projected results of the CORDEX ensemble show that the liquid precipitation fraction will increase all over the studied region according to both scenarios during the 21st century compared to the current historical period (Fig. 3). The greatest changes are over the oceans, and the lowest — are over the continent further south of the 65 parallel. Changes, projected by scenarios RCP 4.5 and RCP 8.5, are similar in pattern and magnitude for the middle of the century: 10—15% over the South Pacific Ocean and windward slopes of the AP, up to 5% over the vast majority of the AP and 5—15% over the Weddell Sea (Fig. 3a, c) and differ significantly for the end of the century (Fig. 3b, d). Three regions can be distinguished for liquid precipitation fraction changes: South Pacific Ocean, the AP, and the Weddell Sea.

Over the South Pacific Ocean, rain share will increase to 15—20% according to RCP 4.5 (Fig. 3a, b) and up to 35% between 65° and 72° parallels according to

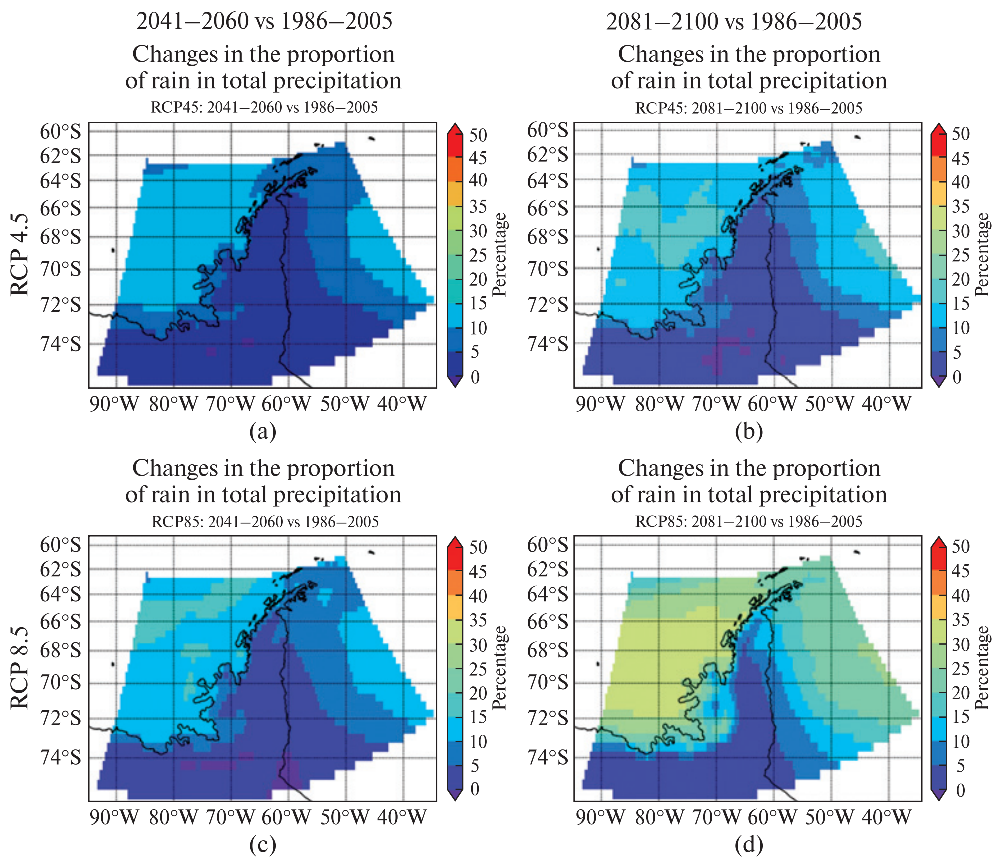

Figure 3. Change of rain fraction in the total precipitation yearly amount for 2041–2060 (a, c) and 2081–2100 (b, d) over 1986–2005 according to RCP 4.5 (a, b) and RCP 8.5 (c, d)

RCP 8.5 (Fig. 3c, d) scenarios during the century. Similar precipitation ratio changes are projected for the northern tip and northern windward side of the AP.

Projected rain changes to total precipitation ratio are lower over the Weddell Sea compared to the South Pacific Ocean. They vary from 5% to 15% for the middle of the century according to both scenarios and from 5% to 30% to the end of the century according to the RCP 8.5 scenario (Fig. 3d).

The lowest liquid precipitation changes are about 5%, projected for the AP mountains, Palmer Land, Ellsworth Land, and part of the Weddell Sea. It is expected that the west part of the Weddell Sea and the leeward coast of the Antarctic Peninsula will undergo lower changes because of the lowest yearly total precipitation amount in the studied region (see Chyhareva et al., 2019b).

The papers (Chyhareva et al., 2019a; 2019b) proposed zoning of the Antarctic Peninsula based on studied changes in temperature and precipitation regime. To continue the previous study, we choose five points of interest. Based on their detailed analysis, we could quantitatively summarize projected changes in liquid precipitations over the AP region in five Points of Interest (POI). They are: Vernadsky station which represents windward slopes of mountain ridges (POI-1); the point over the former Larsen B Ice Shelf is for the leeward slopes of mountain ridges (POI-5); point 70°S, 65°W represents the condition over the Antarctic Peninsula ridge (POI-3); and two points 70°S, 80°W (POI-2) and 70°S, 60°W (POI-4) are for Bellingshausen and Weddell seas, respectively. The distribution of annual liquid precipitation amounts and their share in total precipitation are shown in Figure 4a and 4b, with those five POIs from left to right.

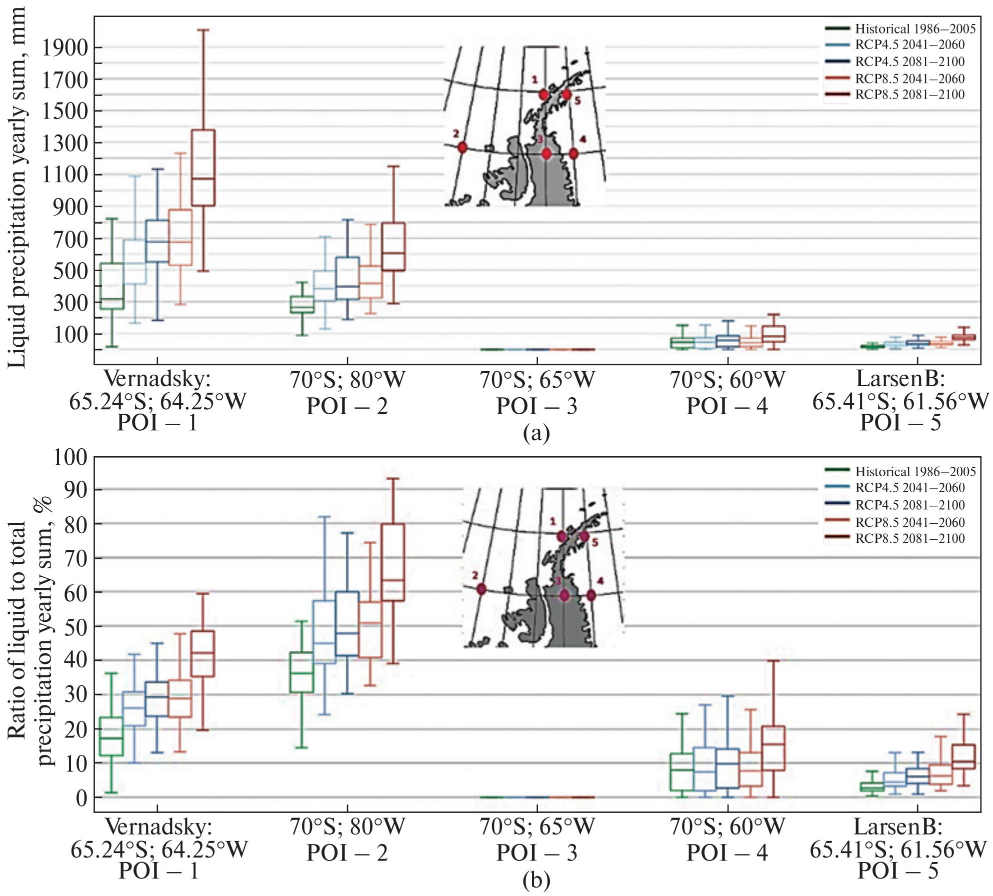

Figure 4. Distribution of liquid precipitation yearly sum (a) and their share in total precipitation yearly sum (b) over the Antarctic Peninsula region according to 3 RCMs' ensemble for RCP 4.5 and RCP 8.5 scenarios in 5 Points of Interests (POI) to the end of the century

Precipitation characteristics vary a lot across the AP region. Higher liquid precipitation yearly amounts and their share in total precipitation are to the west, and lower is to the east of the AP. The lowest values are projected for the mountain region (Figs. 2–4).

The largest yearly liquid precipitation is over the Vernadsky station region (POI-1). It is about 310 mm for the 1986–2005 period (Fig. 2d), increasing to 700 mm and 1100 mm by the end of the century, according to RCP 4.5 and RCP 8.5, respectively (Fig. 4a). For the historical period, rain fraction is about 17% in total precipitation (Fig. 2b). It is projected that this share will increase up to 30% based on the RCP 4.5 scenario and up to 42% based on the RCP 8.5 scenario (Fig. 4b).

The point that indicates the Bellingshausen Sea (POI-2) shows a lower yearly liquid precipitation amount compared to the Vernadsky station region. Rain yearly amounts are about 250 mm for 1986–2005, 400 mm and 600 mm for RCP 4.5 and RCP 8.5, respectively, by the end of the century (Fig. 4a). However, the fraction of liquid precipitation over the Bellingshausen Sea is much higher than over the Vernadsky station region. It consists of 35% for the historical region, 45–49% according to RCP 4.5, and 51–64% according to RCP 8.5 during the 21st century (Fig. 4b).

Over the Weddell Sea (POI-4) and Larsen B region (POI-5), projected yearly rain amounts will mostly stay the same. Gain values vary from 50 mm during the historical period to 95 mm until the end of the century, based on the RCP 8.5 scenario for the Weddell Sea region (Fig. 4a). This will consist of rain fraction

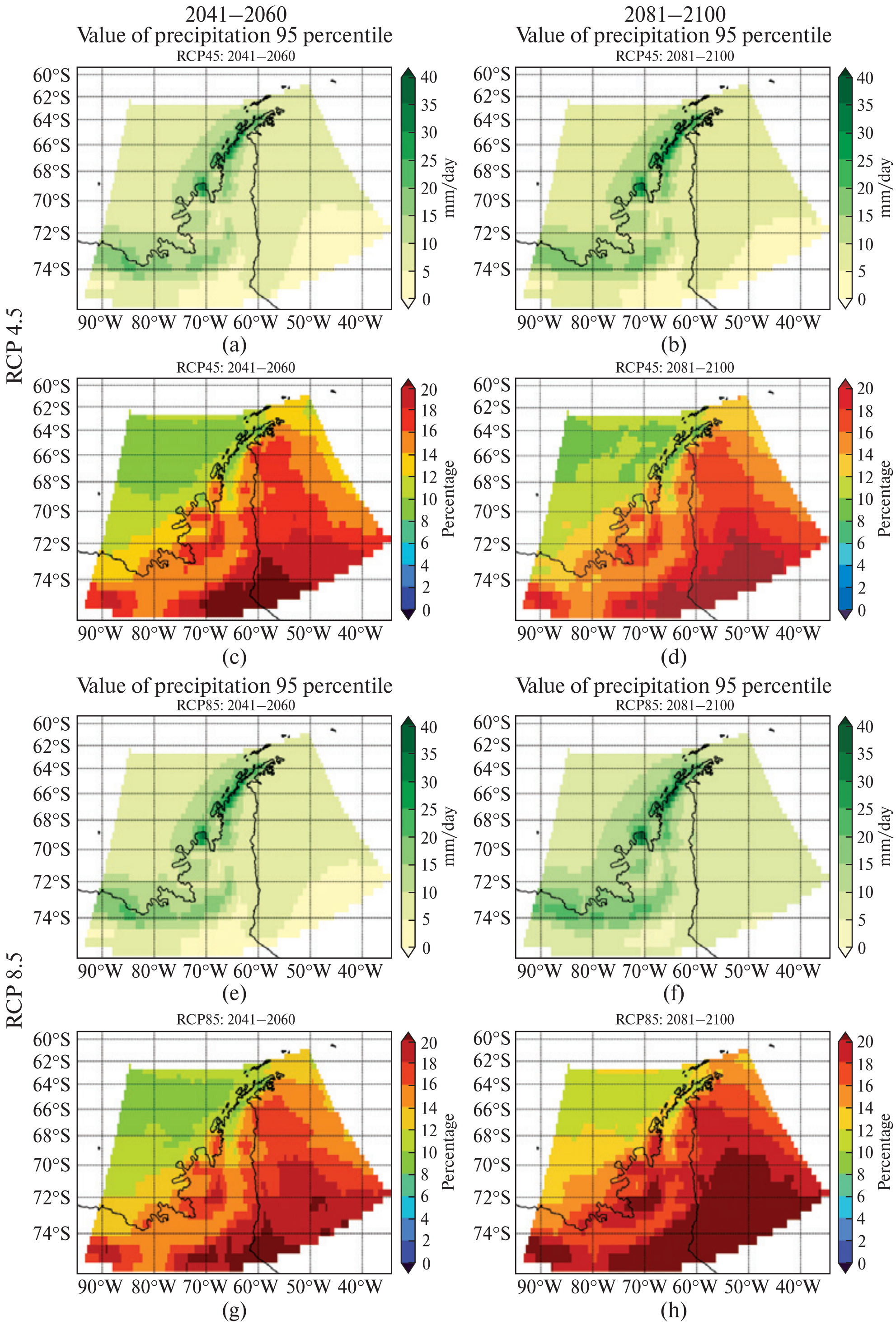

Figure 5. Value of multi-year daily precipitation 95 percentile (a, b, e, f) and percent of time per wet days (when daily sum at least 1 mm/day) where daily precipitation amount of a wet day is above a reference historical value (c, d, g, h). Results presented for 2041–2060 (a, c, e, g) and 2081–2100 (b, d, f, h) according to RCP 4.5 (a–d) and RCP 8.5 (e–h)

change from 8% to 17% (Fig. 4b). The Larsen B region's projected yearly amount of rain would increase from 10 to 70 mm (or from 3 to 10% of rain share), according to historical and RCP 8.5 scenarios, respectively.

According to the results, there was not much rain over the mountain region (POI-3) during the historical period, and it will not increase by the end of the century (Fig. 4).

3.3 Extreme precipitation of 95 percentiles

We calculated future values of the 95 percentile of daily precipitation distributions and their changes against historical ones as an indicator of the heavy precipitation regime during the 21st century by two scenarios (Fig. 5a, b, e, f).

The 95 percentile for precipitation varies much around the AP region. Higher values are obtained over the west windward side of the AP comparatively to the east leeward side of the Peninsula and the Weddell Sea, which demonstrates the effect of the enhancement of precipitation orographically due to the AP mountain ridge. The highest values of 95 percentile, 20–40 mm per day, are obtained over the west coast of the Antarctic Peninsula from 64°S to 70°S, Palmer and Ellsworth Lands around 72°–74°S. The lowest precipitation values for the 95 percentile, up to 15 mm per day are over the ocean. The distribution of high precipitation amounts of the 95 percentile does not change much until the end of the century.

The reference value of extreme precipitation increases during future periods versus the historical period was assessed (Fig. 5c, d, g, h). The most significant change is obtained over the Weddell Sea and leeward slopes of the Antarctic Peninsula. In this region, the percentage of days with precipitation higher than the 95 percentile during the historical period will increase by 12–20%. For the end of the century, according to the RCP 8.5 scenario, these changes will be more significant than 20% of the Weddell Sea and North Ronne Ice Shelf (Fig. 5g, h).

The lowest increase of days with extreme precipitation is over the Pacific Sector of the Southern Ocean and the northern tip of the Antarctic Peninsula. Nevertheless, they are 10–12% during both periods until the end of the century. However, changes over the Bellingshausen Sea will be more significant, namely 10–16% according to RCP 4.5 (Fig. 5c, d) and 10–18% according to RCP 8.5 (Fig. 5g, h).

The percentage of days with precipitation higher than values of the historical 95 percentile varies a lot over the Antarctic Peninsula, where two zones could be distinguished: 64°S–70°S with an increase of 8–14% and 70°S–76°S with an increase from 14% to more than 20%.

The amount of extreme precipitation will increase over the whole studied area until the end of the century according to both scenarios compared to the historic period.

4 Discussion and conclusion

Assessment of projected changes in polar clouds and precipitation regime is an important part of understanding the climate system and future challenges associated with climate change. Atmosphere processes over Antarctica remain understudied due to the lack of direct measurements and difficulty with remote sensors' data processing over Antarctica.

In the presented research, we offered an extension of the previous assessment of temperature and precipitation projections; based on the considered variables, we can describe possible changes in clouds' phase state, liquid precipitation share, and extreme precipitation in the AP region. This can be the basis for further study of the surface energy budget and surface mass balance, both highly impacted by macrophysical and microphysical processes in polar clouds.

Previous studies of climate change suggested that future warming will result in higher rates of evaporation from the ocean with higher amounts of clouds in polar regions (Pörtner et al., 2019). Our estimation of condensed and ice water paths has shown that not only the total cloud fraction will increase over the studied region but also liquid to total cloud fraction according to changes in the ratio of IWP to CWP. Qualitatively, IWP is projected to increase mostly zonally, with the biggest changes over the Palmer Land between 70°S and 75°S to the south of the studied region. CWP changes more meridionally with the greatest changes over the Palmer Land and Alexander I Island, comparatively lower changes to the east of the Weddell Seas, and the minimum is over the eastward slopes of AP. Our quantitative estimations of IWP and CWP should be considered with caution since we did not verify model results against any measurements in the historical period. The global model HadGEM2 from CMIP5 initiatives (used as driving for RCM KNMI-RACMO21P in this study) underestimates the liquid water path over the Antarctic ice sheet and Southern Ocean (Figure S4 in Lenaerts et al., 2017). Nonetheless, in our analysis in Figures 1 and 2, we used the ratio (change in %) of projected vs. past values, which means we excluded most of the possible systematic biases in estimating both cloud characteristics.

We have found that in the historical period, liquid precipitation in CORDEX RCMs overestimated values obtained in ERA5 (Fig. 2). It is in line with the results of Palerme et al. (2017) where from Figure 3, almost all CMIP5 models, which are driving the analyzed here CORDEX RCMs, overestimated historical precipitation in comparison to the previous version of reanalysis ERA-Interim for all considered in the paper domains. At the same time, for the AP region, the higher end of the standard deviation of the mean annual precipitation of the ensemble of all CMIP5 models corresponded to the Cloud Sat satellite data. It was around 700 mm — the same value we obtained in Chyhareva et al. (2019b) for historical total precipitation. In our view, the conclusions of Palerme et al. (2017) and our previous estimations allow us to have high confidence in our obtained results based on CORDEX RCMs driven by CMIP5, notwithstanding we analyzed only the liquid share of total precipitation. There was an increase of such liquid precipitation in the AP region in previous warm events (e. g., Chyhareva et al., 2021; Wille et al., 2022) and expected with future warming based on an ensemble of the next-generation CMIP6 models (Vignon et al., 2021).

Nonetheless, Roussel et al. (2020) concluded that there was no clear overall improvement in the representation of Antarctic precipitation in the CMIP6 ensemble over the CMIP5 ensemble against Cloud Sat and ERA5, particularly with degradation for the AP region. Downscaling with RCMs provided a more detailed and generally improved representation of physical processes in the atmosphere, particularly in the highly heterogeneous AP region with mountains and fjords. Therefore, the next generation of RCMs, e.g., COSMO-CLM2 (Souverijns et al., 2019), and/or results of further international projects, e.g., PolarRES (Lee et al., 2022), would improve our understanding of Antarctic precipitation formation including liquid phase taking into account other drivers, e.g., stratospheric ozone recovery, the Southern Annular Mode (SAM) and the El Niño—Southern Oscillation (ENSO) climate modes and others that definitely have influence but are out of the scope of this study. What is clear at the moment from the estimation of the possible change in Antarctic climate based on the next generation of RCP scenarios — Shared Socio-economic Pathways realized in CMIP6 ensembles, projected changes over coastal Antarctica do not scale linearly with global warming (Bracegirdle et al., 2020).

Our results confirm previous findings that the precipitation amount and their liquid share will increase during the 21st century (Pörtner et al., 2019; Gutiérrez et al., 2021; Vignon et al., 2021). The greatest changes in annual liquid precipitation sums are west of the Antarctic Peninsula. Lower precipitation increases are projected for the Weddell Sea and the east slopes of the Antarctic Peninsula. Over the mountains of the Antarctic Peninsula, no significant liquid precipitation increase is projected.

The frequency of extreme precipitation (with a daily amount of precipitation higher than the precipitation's value for the 95 percentile during the historical period) will increase over the whole region. However, relative changes are more significant southeast of the AP, where there were fewer such events in the historical period.

Overall changes for all considered parameters at the end of the century, according to scenario RCP 4.5, are similar to changes during the middle of the century, according to scenario RCP 8.5.

We can further highlight for the regions distinguished previously in the Part I and Part II of this study (Chyhareva et al., 2019a; 2019b):

• The windward side of the northern Antarctic Peninsula between Vernadsky and Rothera stations has the highest yearly liquid precipitation in the studied region. This will persist until the end of the century. There are the lowest changes in IWP and CWP over the region.

• The Palmer Land, Alexander I Island: lowest amount of precipitation and liquid fraction, no significant changes in precipitation regime projected. There is the highest increase in IWP and CWP over the studied region.

• The Weddell Sea: has a parallel to the AP distribution of IWP changes. The greatest changes are expected in the south of the sea. CWP changes vary from the maximum on the southeast to the minimum on the northeast of a sea. The value of the 95 percentile is 5—10 mm per day until the end of the century for both periods over the Weddell Sea, with the lowest values to the south of the region. However, the south of the Weddell Sea is expected to have the biggest changes in the number of days with daily precipitation amount higher than the mean 95 percentile value in the historical period with much fewer wet days than in other parts of AP region.

• The South Pacific Ocean: has a hight liquid yearly precipitation sum and the highest share of rain in total precipitation. Also, there is the highest increase in liquid precipitation fraction compared to the historical period over this region.

Our results complement and extend previous research on precipitation regime change in the AP region under future climate change. The novelty is particularly in more detailed estimations of liquid precipitation formation processes in clouds and changes in heavy rain- and snowfalls in projected warmer conditions. In particular, the change in clouds' phase highly impacts surface energy balance while rain fraction in total precipitation — surface mass balance in the highly vulnerable to warming AP region.

There are a few possible ways for future research based on the results: to use the same methods for other RCM data from Antarctica CORDEX (e.g., Souverijns et al., 2019) and to obtain more robust estimations of analyzed characteristics; to estimate projections of other important processes, e.g., radiation fluxes in the region for the same set of RCMs for consistency with previous parts of the study; do the same set of characteristics with the next generation of models and scenarios, e.g., from PolarRES project (Lee et al., 2022).

Author contributions. Idea, conceptualization: A. C., S. K. Data collection and preparation: A. C. Research: A. C, S. K. Visualization: A. C. Summary: A. C, S. K. Initial draft: A. C. Writing: A. C., S. K. Reviewing, editing: S. K.

Acknowledgments. The work has been financially supported by the Ukrainian State Special-Purpose Research Program in Antarctica for 2011—2023, research direction: Hydrometeorology, and by the European Commission H2020 project Polar Regions in the Earth System (PolarRES; Grant 101003590).

We are thankful to the Polar-CORDEX community for providing openly simulation data. We thank two anonymous reviewers for the insightful and valuable comments and suggestions that help us to improve our paper.

Authors are grateful to the Army Forces, Territorial Defense Forces, volunteers, and all the Ukrainian defenders. Without their courage, this research and paper would be impossible to finalize.

Conflict of Interest. The authors declare no conflict of interest.

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Received: 29 November 2022
Accepted: 9 February 2023

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**Кліматичні проекції в районі Антарктичного півострова до кінця XXI століття.
Частина III: хмарність та екстремальні опади**

Реферат. Потепління, що спостерігається в районі Антарктичного півострова, може серйозно вплинути на екосистеми регіону та за його межами. У свою чергу, хмарність і режим опадів відіграють вирішальну роль у регіональній зміні клімату, особливо збільшення частки рідких опадів та зростання кількості випадків затоку вологого теплого повітря з субтропічних широт. У цьому дослідженні були розглянуті характеристики хмар та опадів в умовах зміни клімату впродовж 21 століття за двома сценаріями Representative Concentrations Pathways RCP 4.5 та RCP 8.5 на основі даних проекту Polar CORDEX. Подібний підхід раніше застосовувався для оцінки зміни температурного режиму (Частина I) та індексів режиму зволоження і посушливості (Частина II) в районі Антарктичного півострова. Проаналізовано інтегральний вміст льоду та сконденсованої води в атмосфері, просторовий розподіл рідких опадів та 95-ї процентилі сумарних опадів. Зміни розглянутих параметрів оцінено для майбутніх періодів, 2041–2060 та 2081–2100, у порівнянні з історичним періодом, 1986–2005. Найбільш значущі зміни прогнозуються для західного узбережжя Антарктичного півострова, тоді як майже не очікується змін в горах Антарктичного півострова. Очікується, що зросте частота випадків екстремальних опадів. Значення 95-ї процентилі добових опадів в межах північно-західного району півострова становитиме близько 30 мм на день до кінця 21-го століття, що складатиме зміни приблизно на 10–12% відносно історичного періоду. Отримані результати свідчать про зростання загальної кількості хмар, їх водності, річної суми рідких опадів та повторюваності випадків екстремальних опадів у районі Антарктичного півострова до кінця 21-го століття за розглянутими сценаріями RCP. Зміни неоднакові для різних областей досліджуваного регіону. Не дивлячись на те, що збільшення випадків екстремальних опадів зростатиме у всьому регіоні, найбільші зміни очікуються в районі північно-західного схилу Антарктичного півострова, де розташована станція «Академік Вернадський».

Ключові слова: Polar CORDEX, Representative Concentrations Pathways, зміна клімату, інтегральний вміст води в атмосфері, інтегральний вміст льоду в атмосфері, полярні хмари та опади