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Variability of extreme precipitation in West Antarctica and its response to the Amundsen Sea Low changes

Abstract. Changes in precipitation extremes over West Antarctica and the Antarctic Peninsula belong to the observed consequences of current climate change. We discuss the spatio-temporal patterns of extreme precipitation and their relationships with the Amundsen Sea Low (ASL) parameters. Based on the ERA5 reanalysis data, the 95th percentile of daily precipitation totals was estimated and linked to the ASL parameters over the main glacier basins in the region. The 95th percentile of precipitation varied from 5 mm to over 40 mm over the region, showing higher values along the coastline and reaching the maximum over the west coast of the Antarctic Peninsula. The tendencies of extreme precipitation vary from −3 to 4 mm per decade and enhance the observed spatial distribution differences. On average, extreme precipitation events covered 4.7—4.9% of the basins' area. All dependencies had a well-detected seasonality. Both total and extreme precipitation varied under the ASL fluctuations, showing significant average-to-strong correlations. The ASL shifts to the west caused a decrease in precipitation over the Amundsen Sea and an increase over the Antarctic Peninsula. The ASL deepening (lower atmospheric pressure of the system) resulted in a precipitation decrease over the Getz Ice Shelf and a precipitation increase over the western part of the Antarctic Peninsula. There are two regions with opposite responses of precipitation to the ASL changes: the western part over the Getz Ice Shelf with nearby marine areas, and the eastern part covering the Antarctic Peninsula, Pine Island glaciers, the Abbot Ice Shelf, and the Bellingshausen Sea. The obtained results are crucial for our understanding of extreme precipitation occurrences over West Antarctica in recent decades under climate change.

Keywords: atmospheric pressure, glacier basin, ice shelf, precipitation, 95th percentile of precipitation

1 Introduction

Climate change has caused the shrinkage of ice sheets and glaciers and, consequently, the rise of sea levels (IPCC, 2022). Their outcome can redistribute radiation and energy balances through surface albedo modifications that can amplify the existing warming again (Liang et al., 2023). West Antarctica, which is covered by the West Antarctic Ice Sheet (WAIS), has one of the sharpest trends in warming (Schneider et al., 2012; Bromwich et al., 2013; Gymez-Valdivia et al., 2023). Thus, WAIS melting significantly contributes to sea level rise in this region. Precipitation, especially extreme precipitation events, is another factor that impacts the whole Antarctic ice sheet, including WAIS, contributing the most to the mass balance. Some extreme precipitation daily totals could reach 40—60% of the annual amount (Turner et al., 2019; Wille et al., 2021).

Turner et al. (2005) applied observational and ERA-40 data for the last several decades over the western Antarctic Peninsula and showed precipitation to increase in duration during summer and

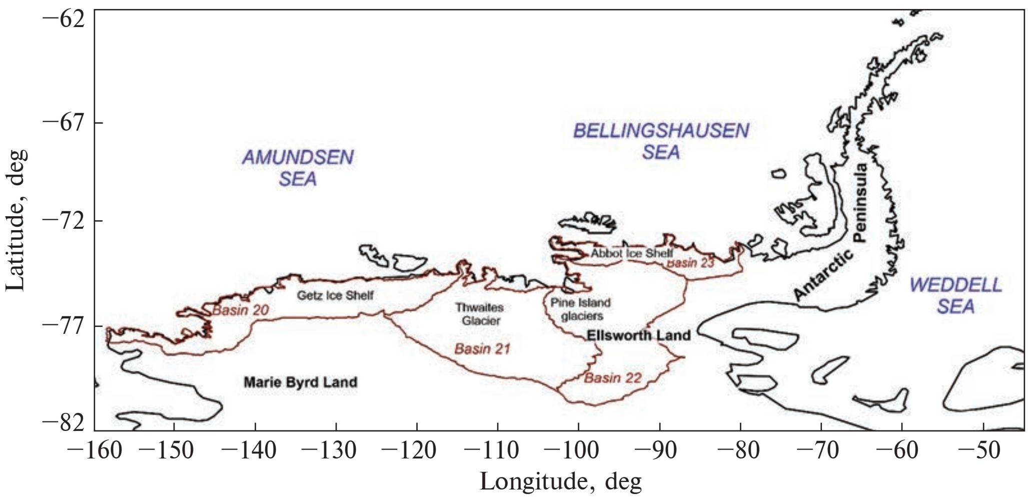

Figure 1. The studied domain of West Antarctica

autumn. It developes on the background of the general temperature rise, according to the Coupled Model Intercomparison Project Phase 5 (CMIP5) model data (Nicola et al., 2023). Although in 1990—2000, there was a tendency toward decreasing precipitation totals, starting in the 2010s, the tendency has changed to increasing precipitation sums and extremes for some stations on the Antarctic Peninsula (Carrasco & Cordero, 2020; IPCC, 2022; IPCC, 2023). Between the mid-1990s and mid-2010s, the fraction of snow rose while the fraction of rainfall decreased during the austral summer season. However, in recent years the growth of extreme rainfall events has been observed in the austral summer (Carrasco & Cordero, 2020; Wang et al., 2022). Precipitation totals' fraction over the 95th percentile is projected to increase till the end of the 21st century for the region of the Antarctic Peninsula based on the estimations for the Representative concentration pathways (RCP 4.5 and RCP 8.5) (Chyhareva & Krakovska, 2022). Changes in precipitation and their fluctuations are related to variability phases in climate drivers of the Southern Annular Mode (SAM), the Amundsen Sea Low (ASL) (Zheng et al., 2013; Turner et al., 2019; Carrasco & Cordero, 2020; Wille et al., 2021), and El Nico—Southern Oscillation (ENSO) (Raphael et al., 2016; IPCC, 2022). These big climate drivers shape and define weather and climate conditions in West Antarctica and can provoke "moisture intrusions" with precipitation extremes.

In this paper, we will focus on the climatological ASL pattern that is located near the coast of West Antarctica in the southern sector of the Pacific Ocean and the western of the Southern Ocean (Fig. 1). It is very changeable during seasons and years (Hosking & National Center for Atmospheric Research, 2020; Raphael et al., 2016; Hosking et al., 2016). It was found that the positive phase of SAM intensifies or deepens ASL (Carrasco & Cordero, 2020; Wille et al., 2021) while the negative one with an ASL-blocking activity can cause summer warming over West Antarctica and, as a consequence, snow melting (Scott et al., 2019). These phenomena of climate drivers have been affected by an increase in man-made greenhouse gas concentrations (IPCC, 2022) and have caused shifts and alterations in the phases of climate drivers and Southern Westerly Winds and changes in meridional winds (Turner et al., 2009; Raphael et al., 2016; Hosking et al., 2016). Particularly, ASL has a significant impact on the weather and climate conditions in West Antarctica, which is the focus of this study.

In recent decades, the ASL circulation pattern has deepened due to increased cyclonic activity in response to growth in greenhouse gas concentrations and a decrease in stratospheric ozone since the 1960s. ASL intensification has mostly been observed during the summer (England et al., 2016). In the future, it could be challenging to forecast because of uncertainties and regional aspects. However, ASL is expected to deepen according to the reanalysis dataset ERA-Interim and CMIP 5 models' data and RCP scenarios in response to the increase of greenhouse gases emissions. It could migrate in the future poleward during the summer and autumn seasons while eastward during winter (Turner et al., 2009; Zheng et al., 2013; Raphael et al., 2016; Hosking et al., 2016). Thus, ASL deepening can intensify hazards such as extreme precipitation, specifically above defined thresholds of percentiles that define very wet days and precipitation totals. The intensification of ASL in the spring of 2021 was the deepest since the 1950s and accelerated southern winds. Also, it has been found that during the summer of 2022 (February), ASL was one of the main factors of sea ice extent (Wang et al., 2023). This trend is expected to continue, according to climate projections, leading to stronger winds.

Consequently, there will be a spatio-temporal redistribution of extreme precipitation within different timescales. It tends to increase the frequency of hazards, especially along the coastline, and they can affect water flow, polar ecosystems, etc. Previous research also covered extreme precipitation records for 1979—2017 via applying reanalysis ERA5 and the RACMO2 regional climate model (Gonzalez-Herrero et al., 2023) and studied a connection among geopotential height anomalies of ASL, ASL-lon index, blocking high and seasonal distribution of extreme precipitation events (Deb et al., 2018; Chitella et al., 2022).

The study aims to analyze the tendency of the spatio-temporal patterns of precipitation variability and its extreme values during the last decades till 2021 within West Antarctica and deepen the research in response to the ASL shifts. At first, we need to check if the general approach for detecting precipitation extremes based on 95th percentiles is representative of a wide range of local climate zones and includes responses to atmospheric circulation. Then, search for tendencies over separate glacier basins in west Antarctica that have been affected by strong elevation decreases in recent decades. Finally, estimate the multiplicative dependencies between ASL characteristics and precipitation over West Antarctica to determine the most significant indicators of regional circulation related to the distribution of extreme precipitation.

2 Data and methods

The study is based on the historical European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis (Hersbach et al., 2020) data for hourly accumulated precipitation with a horizontal resolution of 0.25° × 0.25° for the polygon of West Antarctica (62...82 °S, 45...160 °W) for the last decades from 1991 to 2021. Data were retrieved from the Climate Data Store (CDS) https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset. This reanalysis has replaced the ERA-Interim (Hersbach et al., 2019; Bell et al., 2021) and was already used for the Southern Antarctic Peninsula—Ellsworth Land Region (Tetzner et al., 2019). It should be noted that *in-situ* observations scarcely cover the investigated area and have a point-like character. Consequently, models have some uncertainties in representing atmospheric-ocean-land processes.

The latest satellite studies showed decreased glacier elevation along the Western Antarctica coast (Otosaka et al., 2023). Although many factors can cause these changes, our study focuses specifically on the redistribution of precipitation in the context of changes in atmospheric circulation. To provide a physically valid statistical generalization within natural zones, we selected four areas along the coast corresponding to glacial basins according to (Zwally et al., 2012). Basins 20, 21, 22, and 23 correspond mainly to the Getz Ice Shelf, Thwaites Glacier, Pine Island glaciers, and Abbot Ice Shelf (see Fig. 1). The Antarctic Peninsula was omitted because of its highly heterogeneous environment.

Several indices of the Amundsen Sea depression were used to characterize the atmospheric circulation in this region (https://climatedataguide.ucar.edu/climate-data/amundsen-sea-low-indices), including the average pressure field in the West Antarctic sector, the central pressure, longitude and latitude coordinates of the pressure field, and the relative pressure at the center, calculated as the difference between the central pressure and the averaged pressure field (Hosking et al., 2013; Hosking et al., 2016; Hoskin & National Center for Atmospheric Research, 2020; The ASL Climate Index https://scotthosking.com/asl_index).

We added one more ASL characteristic — the distance to the ASL center (d [km]) — to check whether there is any dependency between precipitation in the grid cell and the location of the ASL center. The distance was approximated using the haversine formula (1):

$$d = 2 \cdot R \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{\varphi_{grid} - \varphi_{ASL}}{2}\right) + \cos\varphi_{ASL} \cdot \cos\varphi_{grid} \cdot \sin^2\left(\frac{\lambda_{grid} - \lambda_{ASL}}{2}\right)}\right)$$

where R is the average radius of the Earth; φ_{ASL} — the latitude of the ASL center; φ_{grid} — the latitude of the grid cell center; λ_{ASL} — the longitude of the ASL center; λ_{grid} — the longitude of the grid cell center.

These characteristics were calculated as a monthly average inside a typical climate period of 30 years (from 1991 to 2021). The data processing utilized the Climate Data Operators (CDO) software package and author-developed programming algorithms.

Initial hourly accumulated precipitation data were sequentially summed to daily totals and then to monthly totals. Daily totals were used to estimate extreme precipitation (precipitation exceeding the 95th percentile value (in mm)). The 95th percentiles were calculated separately for each austral season — summer (December to February), autumn (March to May), winter (June to August), and spring (September to November) — using the "seaspctl" operator in CDO. With this operator, we aimed to receive a time series of the 95th percentiles as a boundary for extreme precipitation to estimate the temporal changes of extremity and dependence on atmospheric circulation. A similar approach was implemented for other regions (Ehmele et al., 2020; Reed et al., 2022).

Relationships between precipitation (daily totals and 95th percentile) and ASL characteristics were assessed using Spearman rank correlation coefficients in each grid cell of the studied domain. In our study, we did not provide additional field significance testing, as, for example, presented for precipitation in Lavers et al. (2013) and Ivanov et al. (2018), because the conclusions about the processes were made only for the highest correlation values of the most significant results at $\alpha = 0.05$. Trends were calculated using the least-squares method. Mapping was performed in the Panoply data viewer (https://www.giss.nasa.gov/tools/panoply/) using standard coastline overlays and in Python using the Basemap package.

3 Results

3.1 Spatio-temporal distribution of extreme precipitation

West Antarctica is rather unusual regarding global precipitation distribution as it includes quite dry and comparatively wet regions. With increasing distance from marine to inland areas, daily total precipitation rarely exceeded 5 mm, making the 95th percentile very low. At the same time, extreme precipitation events with huge coverage, with daily totals over 40 mm, can penetrate deeper into the continent. However, the frequency of such events was very low. As a result, precipitation over 5 mm per day for deep continental areas was observed in less than 5% of days (Fig. 2).

For all seasons, the coastline in Basins 20—23 had a higher 95th percentile value of about 15 mm compared to marine areas with a value of up to 12 mm. In these basins, local spots with values

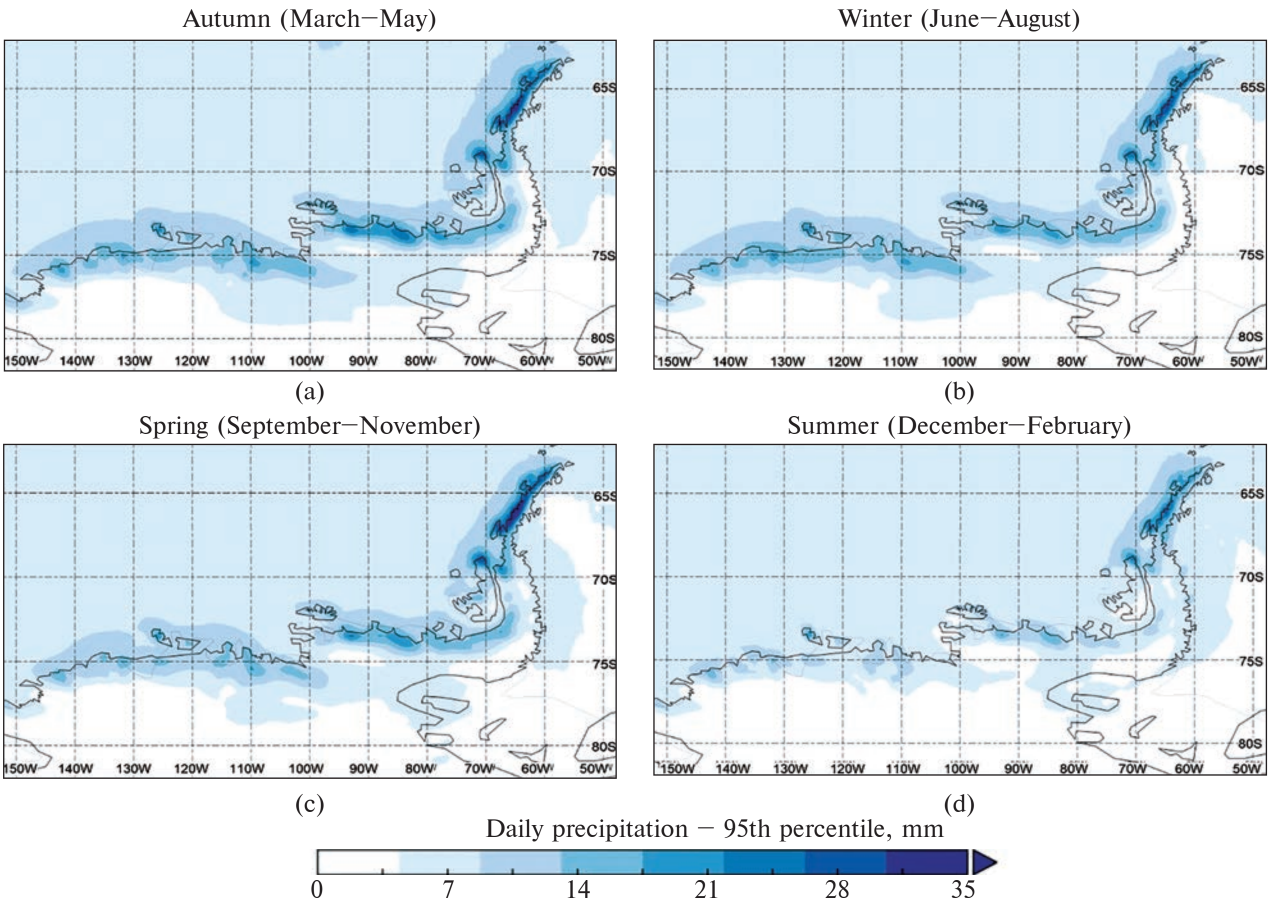

Figure 2. The 95th percentile of daily total precipitation for different seasons 1991–2021

over 20 mm appeared, resulting from orographic impacts and spatial orientation. In the studied domain, the Antarctic Peninsula has the highest precipitation amount and frequency. The 95th percentile exceeded 35 mm (Fig. 2), especially on its west coast, oriented towards prevailing marine air mass transport.

The highest values of the 95th percentile were observed during the autumn and spring (Fig. 2), reaching ca. 40 mm over the Antarctic Peninsula. The lowest values are typical for the summer, with values lower than 25 mm in Basins 20–23. However, the difference between seasonal values of the extreme threshold is inconsequential.

During the last 30 years, the observed distribution has intensified its features in general. More humid regions in West Antarctica that can be found in Figure 2 are receiving more precipitation (Fig. 3), and *vice versa* – the dry region has become drier. The coastline of Basins 20 and 21 that correspond to the Getz Ice Shelf and Thwaites Glacier showed the tendency for the 95th percentile to decrease by 0.2 mm per year (2 mm per decade), especially in autumn and spring. One of the highest trends was observed over the Abbot Ice Shelf (Basin 23) in autumn, with an increase of 0.4 mm per year (4 mm per decade). Less intense (but with a larger coverage) positive tendencies in the region were observed during winter (Fig. 3). The Antarctic Peninsula was characterized by positive trends in the 95th percentile during autumn and spring (up to 0.3 mm per year (3 mm per decade)) and negative trends during winter (up to –0.2 mm per year (–2 mm per dec-

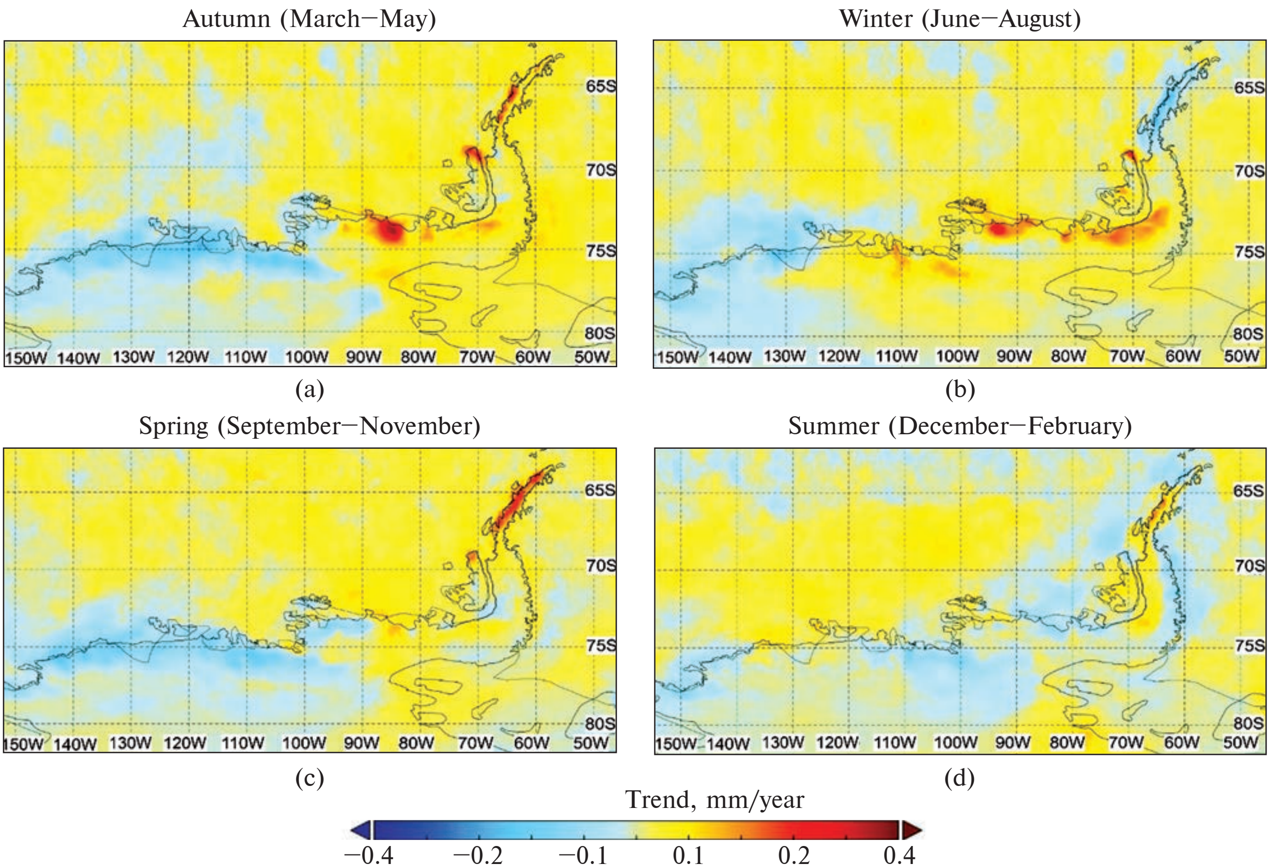

Figure 3. Trends of the 95th percentile of total precipitation for different seasons 1991–2021

ade)). Thus, here obtained the most vivid changes between seasonal shifts in extreme precipitation thresholds. Summer was the only season with no intense changes in the 95th percentile distribution.

3.2 Changes in coverage by extreme precipitation

Extreme precipitation events covered approximately 4.7–4.9% of basin areas, which equals ca. 9500 km^2 for Basin 20, ca. 10600 km^2 for Basin 21, ca. 10300 km^2 for Basin 22, and ca. 3600 km^2 for Basin 23. During 1991–2021, more than 80% of days with extreme precipitation covered up to 5% of the basins' territory (see Table). The most frequent extreme precipitation that covered less than 5% of the basins was observed in autumn, reaching 89.8% in Basin 20, 86.9% in Basin 21, and 87% in Basin 22.

The Getz Ice Shelf (Basin 20) was not fully covered by extreme precipitation during winter and summer. However, up to 0.1% of days in spring and up to 0.4% of days in autumn, extreme precipitation covered the entire region, exceeding the area of 90% of the basin (Table). Thwaites Glacier (Basin 21) was more frequently fully covered by extreme precipitation events that were observed in 0.6% for all seasons. Among all the basins researched in the study, Thwaites Glacier more frequently faced the largest extreme precipitation events over West Antarctica. The frequency of days with extreme precipitation and coverage in the regions of Pine Island glaciers (Basin 22) and Abbot Ice Shelf (Basin 23) had similar features – the highest frequency in autumn (0.9% and 0.6%, respectively) and the lowest in winter (0.1% and 0.2%, respectively).

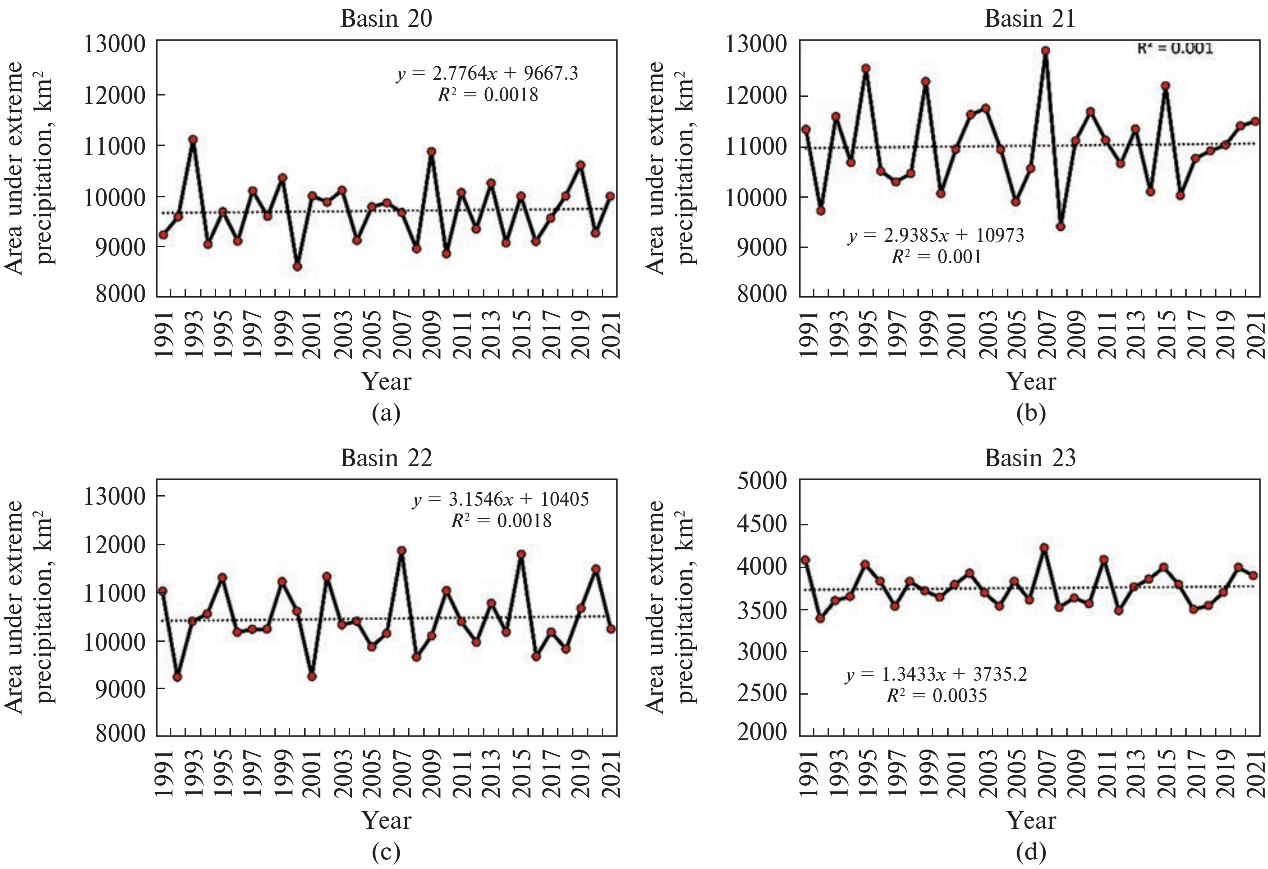

Figure 4. Interannual variability of areas under extreme precipitation (the y-axis for Basin 23 differs for better visibility)

Table. Frequency of days with extreme precipitation over basins in 1991–2021

Coverage area, %	Basin 20				Basin 21				Basin 22				Basin 23			
	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.	Win.	Spr.	Sum.	Aut.
0–5	83.3	83.2	81.3	89.8	82.8	86.1	84.8	86.9	83.9	84.8	84.0	87.0	84.5	85.5	84.6	85.0
5–10	3.5	3.5	4.3	2.0	2.4	2.7	3.6	1.9	3.5	3.2	3.5	1.7	3.8	2.4	3.1	2.9
10–20	3.9	4.0	5.1	1.7	2.9	2.8	3.9	2.6	4.0	3.3	4.2	3.1	3.3	3.2	4.1	3.1
20–30	2.7	2.9	3.4	1.0	5.8	1.9	2.1	2.0	2.5	2.4	2.5	2.1	2.5	2.5	1.8	2.1
30–40	2.1	2.0	2.5	1.3	1.5	1.6	1.3	1.3	1.5	1.9	1.5	1.5	1.2	1.7	1.9	1.6
40–50	1.7	1.6	1.3	1.0	0.8	1.5	1.1	1.0	1.3	1.0	1.5	1.1	1.3	1.3	1.0	1.3
50–60	1.2	1.2	0.8	1.0	1.2	0.9	0.7	0.9	0.9	0.8	0.5	0.6	0.9	0.9	1.0	1.1
60–70	1.0	0.6	0.8	0.6	0.8	0.9	0.6	1.0	0.7	0.9	0.7	0.8	1.0	0.9	1.1	0.8
70–80	0.5	0.6	0.4	0.6	0.8	0.6	0.7	0.7	0.9	0.8	0.6	0.8	0.7	0.8	0.5	1.0
80–90	0.2	0.4	0.1	0.6	0.4	0.4	0.6	1.0	0.7	0.6	0.6	0.5	0.7	0.4	0.6	0.5
90–100	0.0	0.1	0.1	0.4	0.6	0.6	0.6	0.6	0.1	0.2	0.5	0.9	0.2	0.4	0.3	0.6

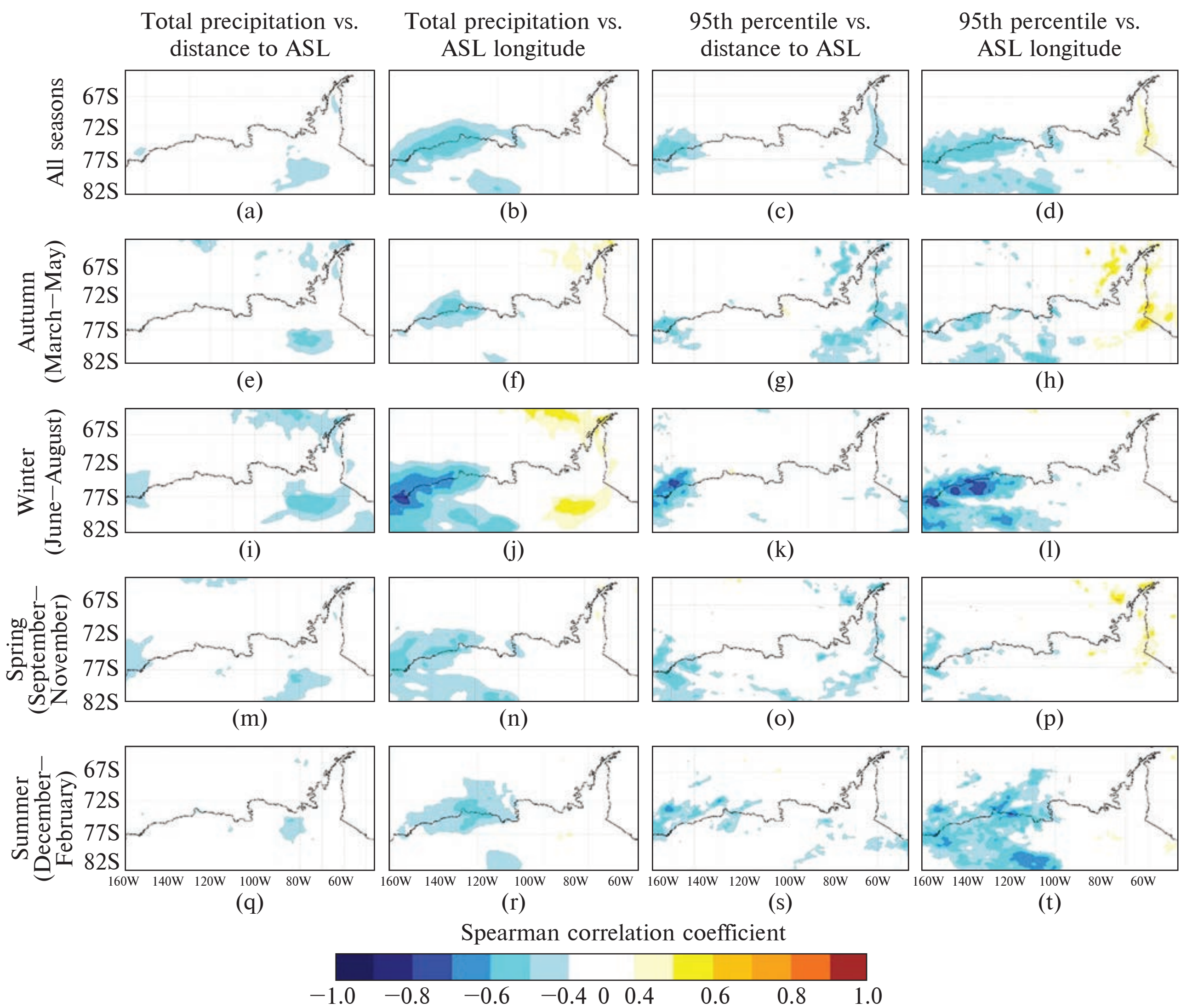

Figure 5. Spatial distribution of the Spearman correlation coefficient ($\alpha = 0.05$) between precipitation and ASL characteristics (distance to ASL and ASL longitude), 1991–2021

Interannual variability of areas under extreme precipitation had well-detected fluctuations with an amplitude of 20–27% of maxima. The average annual area covered by extreme precipitation varied from 8600 km^2 to 11100 km^2 in the Getz Ice Shelf (Basin 20), with especially high values in 1992 and 2009 and a minimum in 2000 (Fig. 4 a).

The variance of the coverage by extreme precipitation was the highest in Thwaites (Basin 21), from minimum values of about 9400 km^2 in 2008 to over 12500 km^2 in 1995, 1999, and 2007 (Fig. 4 b). In Pine Island glaciers (Basin 22), the lowest average coverage was observed in 1992 and 2001 at about 9200 km^2, while the largest area under extreme precipitation events occurred in 2007 and 2015, reaching 11800 km^2. In the Abbot Ice Shelf (Basin 23), the coverage varied from 3400 km^2 in 1992 to 4200 km^2 in 2007 (Fig. 4 c, d). We observe some opposite variations in the Getz Ice Shelf (Basin 20) compared to other basins, which are explained by the different ASL influences described in Section 3.3.

Another feature of the obtained results is the absence of any tendencies: the area under extreme precipitation neither increased nor decreased over decades' timescale.

3.3 Relationship between precipitation and ASL characteristics

The variability of ASL location determines the pressure field over West Antarctica. Hence, total precipitation patterns and the probability of their extremities might vary in response to changes in ASL location. Two ASL characteristics that describe its location (distance to the ASL center (Fig. 5 a, c, e, g, i, k, m, o, q, s) and ASL center longitude (Fig. 5 b, d, f, h, j, l, n, p, r, t)) were used to define the dependence's main features.

Despite the distance of the grid to the ASL location being a more accurate parameter, ASL longitude correlated better with precipitation. It means that the meridional position of ASL impacts weather and precipitation over the region much more than changes in latitudinal distance to the coast. The correlation between total precipitation and distance to the ASL center varied only from −0.4 to 0.4 (Fig. 5 a, e, i, m, q), showing moderate correlations during autumn – spring partially on the Antarctic Peninsula and the coast of Ellsworth Land (Pine Island glaciers and Abbot Ice Shelf – Basins 22–23) (Fig. 5 e, i, m). At the same time, dependence on the ASL longitude was more vivid: negative correlations up to −0.6 appeared on the coast of the Amundsen Sea (Getz Ice Shelf – Basin 20) and positive correlations up to 0.6 over the Antarctic Peninsula for the general period (Fig. 5 b). These processes intensified during winter, with the most significant correlations up to ±0.8 (Fig. 5 j). It means that ASL movement towards the west caused a decrease in precipitation near the Amundsen Sea and an increase over the Antarctic Peninsula, especially during winter.

Extreme precipitation was more sensitive to the changes in ASL location than total precipitation (Fig. 5 c, d). With the increase in distance to the ASL center, extreme precipitation intensified over marine areas of the Bellingshausen Sea and the Amundsen Sea during summer and spring (Fig. 5 o, s), shifting towards coastal regions during winter and autumn (Fig. 5 g, k). Extreme precipitation responded stronger to the ASL longitude changes (correlation up to ±0.8 depending on the season and area). The longitudinal shift of the ASL center to the west caused extreme precipitation to decrease over Marie Byrd Land (Getz Ice Shelf – Basin 20) during winter (Fig. 5 l). During spring and autumn, extreme precipitation increased over the eastern coast of the Antarctic Peninsula and marine areas to the west of it (Fig. 5 h, p).

Regarding atmospheric air pressure, ASL can be described by the pressure in the center of the pattern (Fig. 6 b, d, f, h, j, l, n, p, r, t) and the sector pressure of the entire system (Fig. 6 a, c, e, g, i, k, m, o, q, s). Both total precipitation and its extremity correlate better with ASL pressure than with ASL location. In general, the ASL deepening (atmospheric air pressure decrease) resulted in a total precipitation decrease over Marie Byrd Land (Getz Ice Shelf – Basin 20) and an increase over the western part of the Antarctic Peninsula. For the general period, correlations remain moderate up to 0.6 (see Fig. 6 a, b). However, stronger relationships and drier conditions under deeper ASL were observed during autumn (Fig. 6 e, f), reaching 0.7–0.8. More precipitation over the Bellingshausen Sea was typical during winter-spring (Fig. 6 i, j, m, n). In winter, it depends more on ASL sector pressure, whereas especially low center pressure has a greater impact on total precipitation increases during spring.

Extreme precipitation responded to ASL pressure changes the same way as total precipitation but with a more heterogeneous spatial distribution. Compared to total precipitation, the differences between the impact of the ASL sector and center pressure were absent for the 95th percentile. Less extreme precipitation over Marie Byrd Land is typical not only for autumn but also for spring – winter – autumn seasons (see Fig. 6 g, h, k, l, o, p). The extremity of precipitation increased with lower ASL pressure along the west coast of the Antarctic Peninsula, covering less

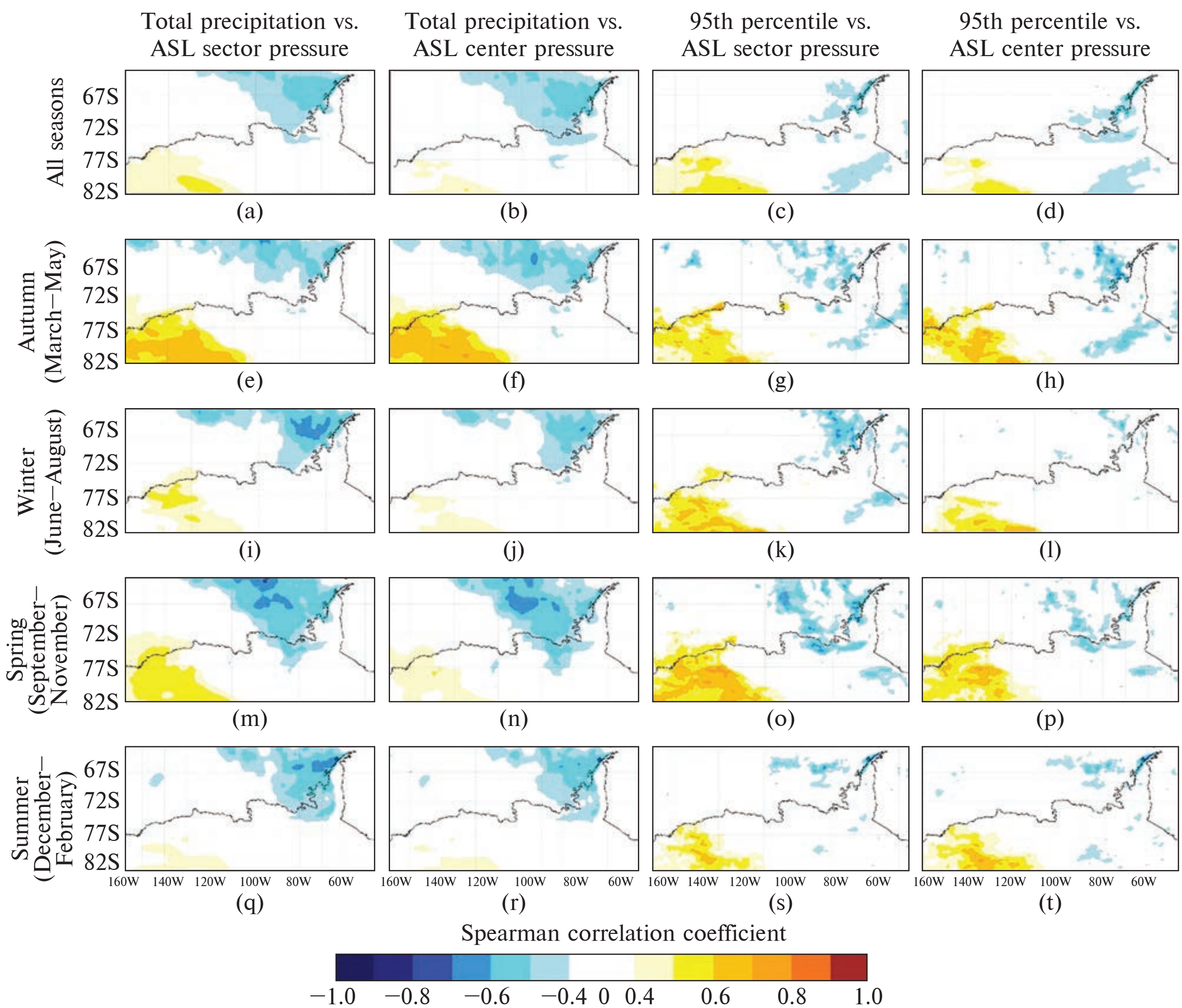

Figure 6. Spatial distribution of Spearman correlation coefficient ($\alpha = 0.05$) between precipitation and ASL characteristics (ASL sector and center pressure), 1991–2021

area and being more concentrated along the coastal part.

Despite the availability of different responses of total precipitation to sector and center pressure, we did not find any significant dependencies between precipitation and pressure differences in ASL.

Overall, West Antarctica can be divided into two regions with opposite responses to ASL changes: (1) the western part covering Marie Byrd Land (Getz Ice Shelf – Basin 20) with nearby marine areas, and (2) the eastern part covering the Antarctic Peninsula, Ellsworth Land (Pine Island glaciers and Abbot Ice Shelf – Basins 22–23), and the Bellingshausen Sea. Total and extreme precipitation increased over the western part of the studied domain when ASL moved to the east and became less deep. In contrast, precipitation increased over the eastern part of the domain when ASL moved to the west and became deeper than usual. Extreme precipitation over the continent shows a stable correlation distribution, while total precipitation has some seasonal variability, with the strongest relationship in autumn.

4 Discussion

Changes in spatiotemporal extreme precipitation during the last decades over West Antarctica are the consequences of climate change (England et al., 2016; Hosking et al., 2016; Carrasco & Cordero, 2020; Chown, et al., 2022; Chyhareva & Krakovska, 2022; Wang et al., 2023). The previous papers have represented the cases of extreme precipitation during 1970—2019 (Carrasco & Cordero, 2020). The frequency, coverage, and duration of extreme precipitation play a significant role in climate and impact surface mass balance in Antarctica. The intensity of extreme precipitation events is so large that it can determine general accumulation trends over the region. These dependencies were detected over the Antarctic Peninsula (Carrasco & Cordero, 2020), showing the crucial role of extremes in climatology. Previous studies emphasized the availability of positive trends in precipitation (Carrasco & Cordero, 2020; Chyhareva & Krakovska, 2022), which we also found. The fact that this happens in spring/autumn is very important for consideration and future prediction of the mass balance of the glaciers, surface runoff, flora and fauna development, and other processes. Chyhareva and Krakovska (2022) estimated that the 95th percentile will reach 30 mm at the end of the century; however, these changes might be stronger, considering the trends and average values we obtained. At the same time, the other part of West Antarctica — continental areas of Marie Byrd Land — faced the opposite changes. Despite being much drier, the decrease in precipitation and its extremes continues. The observed spatial differences in precipitation tendencies could further enhance spatial gradients in meteorological fields.

Special attention should be paid to the interannual variability of the area of extreme precipitation, which fluctuates at 20—27% of the maximum values. The variability suggests that it is a highly sensitive indicator of some atmospheric processes occurring in the summertime over Antarctica.

Extreme precipitation in West Antarctica is mainly associated with the ASL and the Southern Annular Mode (Deb et al., 2018; Chitella et al., 2022). The ASL is considered the major driver of West Antarctic climate variability (Hosking et al., 2016). This pressure system has become deeper in recent decades (Raphael et al., 2016) and can cause changes in air mass advection, impact precipitation, and ice loss. The deepening of the ASL and the changes in the observed precipitation variability are consistent. We obtained especially strong correlations between corresponding parameters in autumn and spring.

The observed precipitation changes and strong relationships with the ASL in two areas cause a large concern: the continental territories of Marie Byrd Land and the coastal line in the eastern part of West Antarctica, with significant opposite effects. Based on the obtained results, the impacts of extreme precipitation will redistribute, possibly affecting ocean-land-atmosphere interaction and heat fluxes.

5 Conclusions

The presented study analyzes spatio-temporal patterns of extreme precipitation within West Antarctica and their relationships with the ASL parameters. Overall, the highest values of the 95th percentile of about 35 mm were typical for the western coast of the Antarctic Peninsula, decreasing to 15 mm over the rest of the coastline in West Antarctica and to 5 mm over continental areas. Extreme precipitation had well-detected seasonality, with maximum precipitation totals during the austral autumn/spring seasons. Over the last 30 years, the tendencies of extreme precipitation intensified the observed spatial differences: the 95th percentile increased over more humid areas with a trend of 4 mm/decade and decreased in continental regions by 2 mm/decade. Despite the differences in areas of basins, the relative coverage of extreme precipitation remained almost equal to 4.7—4.9% of the basins' area. Interannual variability of areas under extreme precipitation had well-detected fluctuations of 20—27%. These fluctuations can be a sensitive indicator of atmospheric processes in the Antarctic atmosphere.

The meridional position of ASL impacts weather and precipitation over the region much more than changes in its latitudinal remoteness to the coast. The correlation between ASL location and precipitation reached up to ±0.8. The ASL movement towards the west caused decreased precipitation near the Amundsen Sea and increased over the Antarctic Peninsula. Extreme precipitation was more sensitive to changes in ASL location than total precipitation, enhancing the observed dependencies. Both total precipitation and its extremity correlate better with ASL pressure parmeters. The ASL deepening decreased precipitation over the Getz Ice Shelf and increased precipitation over the western part of the Antarctic Peninsula, which was especially visible during autumn. Two regions with opposite responses of precipitation to the ASL changes can be identified: the western part covering the Getz Ice Shelf with nearby marine areas, and the eastern part covering the Antarctic Peninsula, Pine Island glaciers, the Abbot Ice Shelf, and the Bellingshausen Sea.

The results showed the extreme precipitation redistribution over West Antarctica in recent decades and helped to identify some features in their occurrence in response to the ASL changes and with regards to their influence on the regional surface mass balance of the ice sheet. Estimated dependencies partly explain the link between atmospheric circulation and precipitation distribution; therefore, they are relevant for more reliable climate change diagnostics based, for example, on forecast datasets of climate models.

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Data availability. The data used for the study were derived from publicly open datasets, including the ASL Climate Index (Retrieved September 20, 2023, from https://scotthosking.com/asl_index) and the ECMWF ERA5 reanalysis (Retrieved September 20, 2023, from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview).

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Варіативність екстремальних опадів у Західній Антарктиді та їх відгук на зміни поля низького тиску моря Амундсена

Реферат. Зміни екстремальних опадів над Західною Антарктидою та Антарктичним півостровом стали одними із спостережуваних наслідків поточної зміни клімату. У цьому дослідженні обговорюються просторово-часові закономірності екстремальних опадів та їхні зв'язки з параметрами поля низького тиску моря Амундсена (the Amundsen Sea Low, ASL). На основі даних реаналізу ERA5 було оцінено 95-й процентиль загальної добової кількості опадів та їх зв'язки з параметрами ASL над основними басейнами льодовиків у регіоні. Встановлено, що 95-й процентиль опадів змінювався від 5 мм до понад 40 мм над регіоном, демонструючи вищі значення вздовж берегової лінії та досягаючи максимуму над західним узбережжям Антарктичного півострова. Тенденції екстремальних опадів варіюють від −3 до 4 мм за декаду і посилюють типові просторові відмінності. У середньому екстремальні опади охопили 4.7−4.9% площі басейнів. Встановлено, що усі залежності мали добре виявлену сезонність. Як загальна, так і екстремальна кількість опадів змінювалися залежно від коливань ASL, демонструючи значні кореляції від середнього до сильного зв'язків. Зміщення ASL на захід спричинили зменшення кількості опадів над морем Амундсена та водночас збільшення над Антарктичним півостровом. Поглиблення ASL (найнижчий атмосферний тиск у системі чи центрі дії атмосфери) призвело до зменшення кількості опадів над шельфовим льодовиком Гетц і зростання кількості опадів над західною частиною Антарктичного півострова. Є два регіони з протилежною реакцією опадів на зміни ASL: західна частина над шельфовим льодовиком Гетц з прилеглими морськими районами та східна частина, що охоплює Антарктичний півострів, льодовики острова Пайн, шельфовий льодовик Еббота та море Беллінсгаузена. Отримані результати мають важливе значення для нашого розуміння випадків екстремальних опадів над Західною Антарктидою в останні десятиліття в умовах зміни клімату.

Ключові слова: атмосферний тиск, басейн льодовика, шельфовий льодовик, опади, 95-ий процентиль