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# DEEPENING AND POLEWARD SHIFT OF THE ANTARCTIC CIRCUMPOLAR PRESSURE TROUGH FROM ERA5 REANALYSIS DATA

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The Antarctic circumpolar pressure trough (ACT) is a prominent feature of the Southern Hemisphere polar atmosphere. This band of low atmospheric pressure is formed as a net effect of individual storms emerging in, developing, and traversing the high-latitude region of the Southern Ocean. The location and depth of the trough directly influence regional weather patterns, atmospheric circulation, ocean currents, and sea ice dynamics. The north-south movement of the ACT presents a key aspect of the Southern Annular Mode (SAM). In this study we used monthly mean sea level pressure data from ERA5 atmospheric reanalysis to characterize the current properties of the ACT, its seasonal variability and trends in the last 45 years. Two major metrics of the ACT were considered, the sea level pressure and the meridional position of the ACT axis. Our analysis has shown the dominance of decreasing trends in the ACT pressure and gradual shifting of the ACT axis towards the continent. The largest changes in the ACT position and pressure occur in Western Antarctica, particularly in Weddell, Amundsen and Ross Seas. The estimated overall drop in the annually and zonally averaged pressure at the ACT axis in the last 45 years amounted to around 3 hPa in Western Antarctica and to around 1.5 hPa in Eastern Antarctica while the ACT axis in these sectors shifted poleward correspondingly by 0.45 and 0.27 degrees latitude. Deepening of the ACT and its poleward contraction were mostly due to their strong changes in the austral summer and fall seasons whereas in winter and in spring the trends were mixed and close to neutral. Trends in both the meridional position of the ACT axis and the sea level pressure were found to accelerate in the last 10–15 years.

**Keywords:** ERA5 reanalysis, Antarctic circumpolar through, sea level pressure, multiyear mean values and trends

## Introduction

Sea level atmospheric pressure is one of the main elements of weather and climate. The principal feature of the high-latitude pressure field of the Southern Hemisphere is the Antarctic Circumpolar Trough (ACT) – a wide belt of low atmospheric pressure usually located between 60°S and 70°S. The ACT belt is associated with high cyclonic activity throughout the year and is formed as a cumulative effect of quasi-stationary low-pressure systems inherent in Antarctic seas and individual storms that emerge in, develop, and traverse the high-latitude region of the Southern Ocean (Turner et al., 1998).

ACT is characterized by strong short-term (synoptic-scale), seasonal and interannual fluctuations that include both the latitudinal position of the trough and the pressure within it. Most prominent are the semi-annual oscillations in which the trough expands southward and weakens in the spring and autumn, and contracts and intensifies in the summer and winter (e.g., Tolstikov, 1969). These fluctuations are explained by peculiarities of the seasonal dynamics of incoming solar radiation and of the sea ice extent, which alter the meridional temperature gradient (van Loon, 1972). The latitudinal position and pressure of the ACT strongly determines the meridional position and strength of the belt of Antarctic westerly winds and, as a consequence, affects ocean currents, heat exchange between the ocean and atmosphere, precipitation regime, sea ice cover dynamics, and a number of other elements of the region's weather and climate (Hall and Visbeck, 2002; Eayrs et al., 2021).

Atmospheric pressure in the ACT largely determines the magnitude and variations of the pressure gradient between the middle and high latitudes of the Southern Hemisphere and hence the Southern Annular Mode (SAM) or Antarctic Oscillation (AO). The positive phase of SAM is associated with lower-than-normal pressure in the high latitudes of the Southern Hemisphere, higher-than-normal pressure in the middle latitudes, and an intensification and poleward contraction of the westerly wind zone. Conversely, the negative phase of SAM implies weakening of the meridional pressure gradient and an equatorward shift of the westerly wind zone (Marshall et al., 2006). Because of the relatively smaller variability of the sea-level pressure in the subtropical and midlatitude Southern Hemisphere on a decadal time scale, long-term changes in the state of SAM are mostly determined by the variation of the sea level pressure in the polar area and in the ACT zone in particular.

In recent decades, substantial changes have been occurring in the climate regime of the Antarctic continent and the adjacent waters of the Southern Ocean. A strong warming of the Antarctic Peninsula at the rate of up to 0.3–0.4 °C/decade since the early 1980s has been identified (Carrasco et al., 2021; Romanov and Romanova, 2023). Warming of the high latitudes of the Southern Hemisphere is the most apparent reason for a noticeable drop in the seasonal sea ice extent observed since 2016 (Raphael and Handcock, 2022). Increasing wind speeds along the Antarctic coast have been documented indicating a possible increase in the cyclonic activity (Yu et al., 2020; Romanova and Romanov, 2020; Tetzner et al., 2025). There are reports of changing precipitation amounts and, correspondingly, snow accumulation in Antarctica (Marshall et al., 2017), changing glacier dynamics (Cook et al., 2016), the ocean salinity (Menezes et al., 2017), as well as a number of other environmental parameters. (Smith et al., 2017; Amesbury et al., 2017).

The observed climate and environmental changes in Antarctica are mostly attributed to the positive phase of SAM dominating since the mid-1950s and its intensification in the post-2010 time period (Ferreira et al., 2024). Strengthening of SAM is generally associated with the decrease of the sea level pressure in the high-latitude region of the Southern Hemisphere (Turner et al., 2005) and in the ACT, in particular. In the course of the year, most pronounced negative pressure trends are seen during the summer season (Fogt et al., 2017). Location wise a stronger pressure decrease over time is observed in Western Antarctica, particularly in the area of the Amundsen Sea Low (Schmidt and Grise, 2017; Turner et al., 2013).

The specific magnitude of surface pressure trends at the ACT axis, however, remains arguable due to large spatial heterogeneity and strong seasonal fluctuations of the sea level pressure as well as due to a significant scatter in its estimates between different datasets (e.g., O'Connor et al., 2021). Although an overall poleward shift of the band of high-latitude westerlies in the last decades (e.g., Tetzner et al., 2025) suggests a similar change in the ACT position, no reliable confirmation or quantitative estimates of the rate of the corresponding southward shift of the ACT have yet been reported.

In this study, we examined sea level pressure fields in the high-latitude region of the Southern Hemisphere over the last several decades to characterize the current properties of the ACT around the Antarctic continent, and to establish and quantitatively assess their associated long-term variability and trends. We used two parameters as metrics for the state of the pressure trough: the meridional position of its axis and the sea level pressure along the axis. The study is based on ECMWF v5 (ERA5) reanalysis data, covering the period from the early 1980s to the present.

## Data and Method

Monthly mean sea level pressure data from ERA5 reanalysis over the 45-year time period from 1980 to 2024 were used to infer mean properties of the ACT, to characterize their variation in space and time and to estimate corresponding long-term trends. ERA5 incorporates the 2016 version of the ECMWF Integrated Forecast Model (IFS) with the four-dimensional variational analysis (4DVAR) for data assimilation (Hersbach et al., 2020). At 0.25° by 0.25° global grid cell size of output products, ERA5 provides the highest spatial resolution among most popular atmospheric reanalysis datasets (e.g., Malakar et al., 2020). A number of studies focused at the comparison of different reanalysis schemes and their validation concluded on a better performance of ERA5 when reproducing sea-level pressure patterns and on their best agreement to available in situ observations of the atmospheric pressure (Huang et al., 2023; Romanov and Romanova, 2021; Xu et al., 2025).

In this work ERA5 monthly mean sea level pressure data over the 1980–2024 time period were applied to establish season mean, annual mean and multiyear mean values. Focusing on the high-latitude Southern Hemisphere, the study exclusively used reanalysis data south of 50°S.

The location of the ACT axis was inferred from meridional profiles of the sea level pressure from 50°S down to the Antarctic coastline by identifying the grid cell with the minimum pressure value. If the minimum was found across multiple grid cells across the profile, the mean latitude of these grid cells was adopted as the location of the ACT.

Over the open ocean the vast majority (over 99.95 %) of examined meridional pressure profiles contained a single distinct minimum incorporating one or several adjacent grid cells and, hence, allowed for the unambiguous determination of the ACT axis position. To minimize the effect of a small number of remaining ambiguous ACT locations and to dampen small-scale zonal variations, the ACT position across the longitudes was subsequently smoothed using a 7-point running average.

Over the Antarctic Peninsula accurate delineation of the ACT is hampered by larger spatial inhomogeneity of the estimated sea level pressure. The latter is apparently due to uncertainties associated with extrapolating the estimated surface pressure to the sea level. Therefore, ACT properties over the Antarctic Peninsula and in the adjacent coastal areas were excluded from the analysis.

Trends in the sea level pressure in the ACT as well long-term trends in the latitudinal position of the ACT were calculated using a standard linear regression technique based on the least squares method. Other statistical metrics used include Pearson correlation and the standard deviation (SD). The statistical significance of trends was estimated using a standard two-tailed T-test with a p-value of less than 0.05.

## Results

Figure 1 presents the multiyear mean annual sea level pressure over the high-latitude region of the Southern Hemisphere and the corresponding position of the ACT established from ERA5 reanalysis data. The axis of the annual mean ACT closely follows the contour of the Antarctic coastline at a distance of around 2 to 7 degrees of latitude off the coast. It traverses the three major atmospheric pressure ‘lows’ in the Southern Ocean centered at the Amundsen, Riiser-Larsen and Davis Seas. For reasons specified earlier, estimates of the ACT position over the Antarctic Peninsula were excluded from the study creating a gap in the plotted ACT axis.

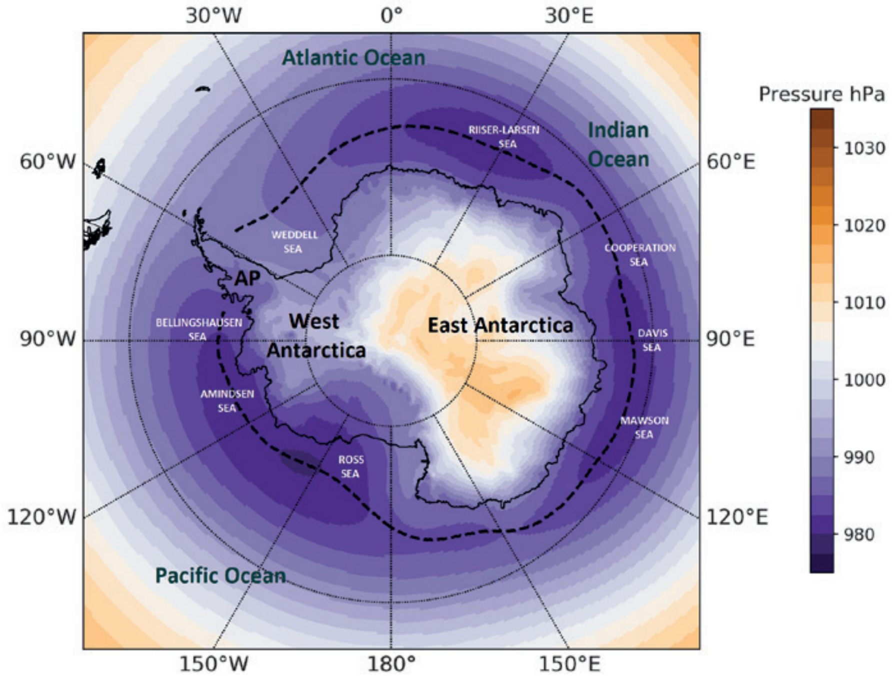

Fig. 1 – Multiyear mean annual sea level pressure for the years 1980–2024 derived from ERA5 data. Dashed line indicates the annual mean position of the Antarctic Circumpolar Trough (ACT). AP is Antarctic Peninsula

Asymmetry of the Antarctic continent with respect to the South Pole causes a similar asymmetry in the location of the ACT. The mean meridional position of the annual ACT changes from 63.7°S in the eastern sector of Antarctica, or east of the Prime Meridian, to 70°S in its western sector, averaging to 66.8°S across all longitudes (see Table 1). This asymmetry does not affect the annual mean ACT pressure which remains the same at 982.7 hPa in both hemispheres. The values of the zonal mean latitude and pressure of the perennial ACT obtained in this work are consistent with van Loon's (1972) estimates of 65.9°S and 984 hPa, respectively, from the early 1970s. The difference may be due to uncertainties in both estimates, but may also indicate deepening of the ACT and its shift toward the pole in the last several decades.

Substantial zonal and seasonal variations in the ACT position and pressure are evident from the results presented in Figure 2 and Table 1. The western sector of Antarctica is associated with a more pronounced seasonal cycle of the ACT meridional position than the eastern one. The strongest seasonal changes occur immediately to the west and east of the Antarctic Peninsula, in the Bellingshausen and Weddell Seas where the ACT axis migrates up to 3 degrees latitude north and south in the course of the year. The observed difference between the seasonal amplitude of the ACT position in the two hemispheres is generally consistent with the results of storm track analyses in the region (e.g., Hodges et al., 2011) which suggest a generally higher cyclone track density, and hence, their smaller spatial spread, in the eastern sector of the Southern Ocean.

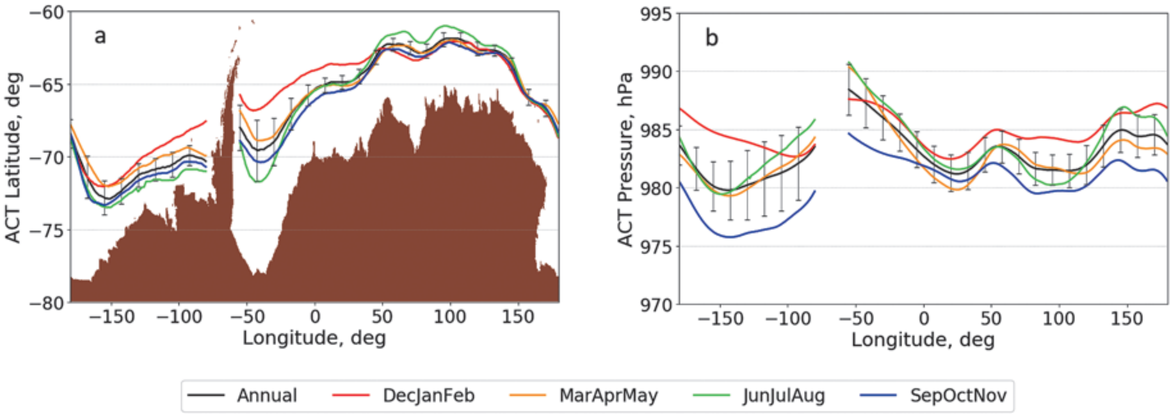

Fig. 2 – Multiyear mean position (**a**) and pressure (**b**) of the Antarctic pressure trough based on ERA5 data for 1980–2024. The continental land mask is shown in brown. Error bars for the annual mean latitude and pressure show ± one standard deviation of the value. Negative latitudes represent the Southern Hemisphere. Longitudes are negative/positive in the Western/Eastern Hemisphere

Tab. 1 – Multiyear mean ACT zonal averaged position and pressure (1980–2024) over East Antarctica (0°E to 180°E) and West Antarctica (180°W to 0°W)

| **Season** | **Latitude, deg** | | **Pressure, hPa** | |
|---|---|---|---|---|
| | **East Antarctica** | **West Antarctica** | **East Antarctica** | **West Antarctica** |
| Summer (DecJanFeb) | –63.6 | –68.5 | 984.4 | 984.6 |
| Fall (MarAprMay) | –63.8 | –69.6 | 982.2 | 982.6 |
| Winter (JunJulAug) | –63.6 | –70.7 | 982.8 | 983.4 |
| Spring (SepOctNov) | –64.0 | –70.6 | 980.8 | 979.0 |
| Annual | –63.7 | –70.0 | 982.7 | 982.7 |

Meridional profiles of the ACT multiyear mean sea level pressure (see Figure 2) feature three local minima at around 100–160°W, 10–40°E and 70–120°E corresponding to the Antarctic "lows" mentioned above and a substantial seasonal amplitude of up to 10 hPa. Along most of the ACT perimeter the lowest and the highest sea level pressure are attained correspondingly during the austral spring and summer season. As a result, the spring-summer period is associated with the fastest change in the ACT pressure in the course of the year. Worth noting is a strong interannual variability of both ACT parameters which results in the standard deviation (SD) of the ACT annual mean meridional position ranging from around 0.5 to 2 degrees latitude in the eastern and western sectors of Antarctica, respectively. Interannual variations of the ACT annual mean pressure were also larger in the Western than in the Eastern hemisphere, amounting, correspondingly, to 3 and 1.5 hPa. Similar scatter is inherent in the values of the ACT mean seasonal position and pressure (not shown in Figure 2)

Plots of multiyear mean monthly ACT meridional position and pressure (Figure 3) clearly show their semi-annual oscillations. The two ACT parameters vary in phase, reaching minimum pressure values and its most southerly position around the equinoxes in spring and autumn. The main, deeper, pressure minimum of 973–980 hPa occurs in September–October, while the secondary, weaker one of around 982 hPa falls on March–April. A similar semi-annual asymmetry is also inherent to the meridional position of the ACT with closer poleward ACT position in spring than in fall. Both ACT parameters exhibit noticeably larger yearly amplitude in the western sector of Antarctica (around 8 hPa and 2.5 degrees of latitude for the pressure and meridional position, respectively) than in the eastern sector of Antarctica where it reaches, correspondingly, 5 hPa and 1 degree of latitude. Semi-annual oscillations of the ACT pressure and meridional position are generally attributed to contrasting temperature cycles of the Antarctic continent and mid-latitude oceans (e.g., Van Loon, 1967; Eayrs et al., 2019). This difference results in a semi-annual variation of the meridional temperature gradient and a corresponding semi-annual wave of cyclonic storm activity around the continent. A deeper ACT in spring is explained by deeper cyclones occurring in the region in this season (e.g., Walland and Simmonds, 1999).

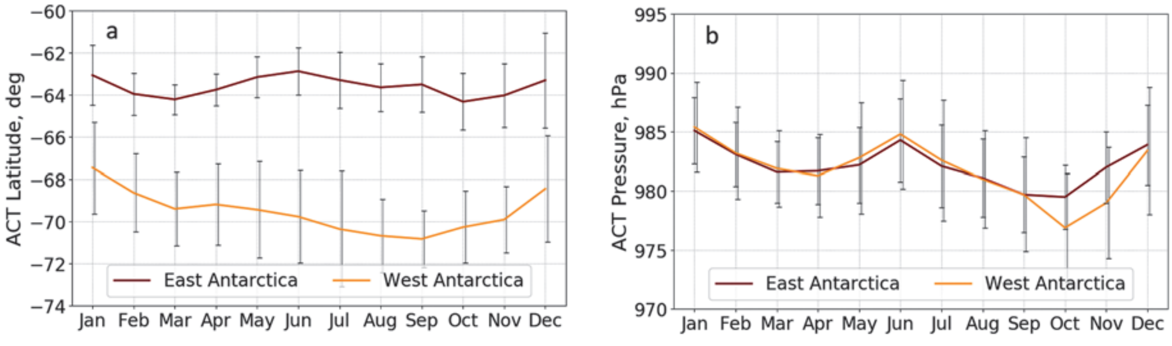

Fig. 3 – Seasonal variation of the ACT zonal mean latitude (**a**) and pressure (**b**) in the eastern and western sectors of Antarctica. Error bars show ± one standard deviation of the mean

Further analysis of the ERA5 45-year-long records of the sea level pressure was focused on the assessment of the long-term changes and trends in the ACT. Despite considerable inter-annual variability of the ACT parameters, their time series clearly show dominating trends toward a decrease in the ACT pressure and a poleward contraction of its axis. These tendencies are evident in particular from Figure 4, which presents estimates of the zonally averaged annual mean ACT position and pressure over the 1980–2024 period. As seen from the plots, ACT shifted southwards and deepened in both hemispheres, however changes in these two parameters occurred approximately twice as fast in the western sector of Antarctica than in its eastern sector. The estimated rates of zonally averaged poleward migration of the ACT of 0.1 deg/decade and 0.06 deg/decade in the western and eastern hemisphere respectively are equivalent to corresponding overall shift of the ACT axis of 0.45 degree latitude and 0.27 degree latitude over the past 45 years.

Deepening of the ACT in the western and eastern sectors occurred at the rate of 0.75 hPa/decade ($p < 0.05$) and 0.34 hPa/decade ($p < 0.05$), which converts to a total decrease in the zonally averaged sea level pressure of approximately 3 and 1.5 hPa in the two hemispheres over the entire observation period. Worth noting is a statistically significant positive correlation of both the annual mean ACT pressure and the annual mean ACT meridional position in the eastern and western sectors of Antarctica (Figure 4). This suggests that the observed year-to-year variations in the two parameters are, at least partially, due to large-scale processes rather than regional peculiarities of the atmospheric circulation or ice cover dynamics.

As evident from Figure 4, long-term changes in ACT properties during the analyzed period were not uniform: a relatively slow decrease in the sea level pressure until approximately 2010 was followed by a noticeable acceleration after that. The largest drop occurred in 2021 and 2022, when the annual mean pressure on the ACT axis in the western sector of Antarctica fell below 980 hPa and reached historical lows.

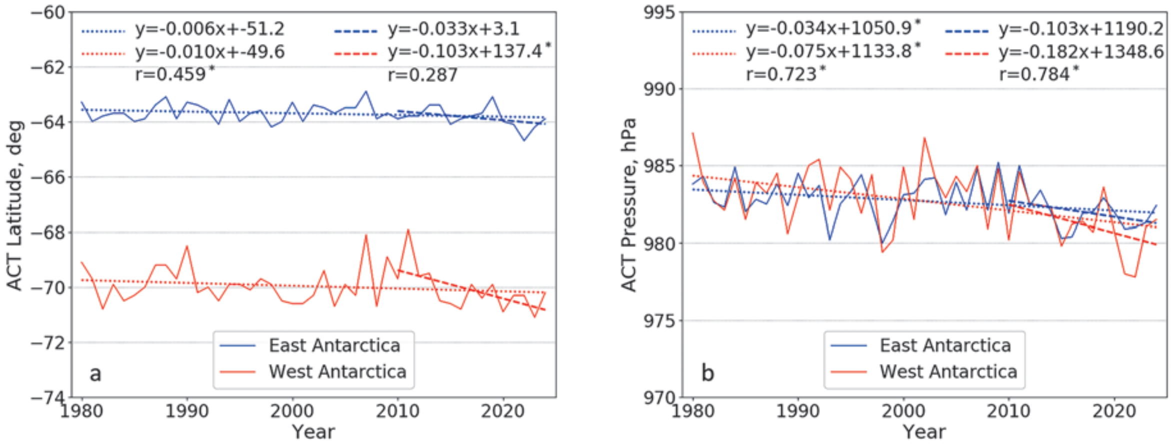

Fig. 4 – Time series and trends of the annual mean ACT latitude (**a**) and pressure (**b**) in 1980–2024 in the eastern and western sectors of Antarctica. The trend calculated for the last 15 years of the series (2010–2024) is shown by the thick dotted line. Statistically significant at $p < 0.05$ trends and correlation coefficients are marked with an asterisk

Similar to the ACT pressure, the poleward shift of the ACT axis has also accelerated since around 2010. Due to a relatively short time period since 2010 and high interannual variability, neither the negative trends in the ACT zonally averaged latitude and pressure values over the last 15 years nor the difference between the trends over the last 15 years and over the entire period of observations have reached a statistically significant level. Still, the trend increase over the 2010–2024 period was quite substantial compared to the entire 45-year period, ranging mostly between 2.5 and 5 times. In the western sector of Antarctica, the trend in the latitudinal position of the ACT in 2010–2024 grew more than 10 times. However, this result is apparently an artifact of the anomalously northern position of the ACT in 2010 and 2011.

Further details of changes in the annual mean properties of ACT over time are provided in Figure 5, where we show zonal profiles of the ACT's meridional position and pressure, averaged over four decades from 1985–1994 to 2015–2024. As evident from the plots, along most of its length, the ACT reached its minimum pressure and southernmost position in the last 10-year period (2015 to 2024). Changes in the ACT pressure over time were relatively uniform only directly west of the Antarctic Peninsula, in the Bellingshausen and Amundsen Seas region, at 70–150°W, whereas in other regions, the main pressure drop occurred in the last ten years of observations. There is a less distinct structure of decadal changes in the ACT's position in Antarctica. Nevertheless, in many cases, particularly in the eastern sector of Antarctica, the poleward shift of the ACT axis was the largest in the last decade.

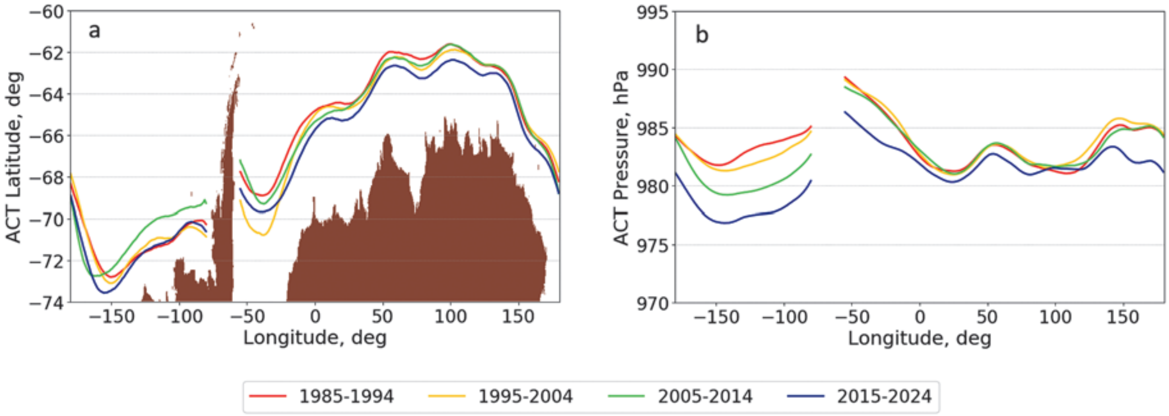

Fig. 5 – Zonal profiles of the ACT annual mean latitude (**a**) and pressure (**b**) for four decades, from 1985–1994 to 2015–2024

Estimates of trends in the ACT position and pressure over the last 45 years reveal their considerable regional and seasonal variations. In the ACT meridional position (Figure 6a), the Weddell Sea region, within 0–50°W, stands out by consistently negative, or poleward, trends in all seasons of the year. Over most of this longitude range, trends ranging from up to –0.3 degree latitude per decade in spring to up to –0.6 degree latitude per decade in summer and winter were statistically significant at the 0.05 level. Across the year, most persistent negative ACT position trends occur during the summer season with the fastest poleward ACT migration of –0.6 deg/decade immediately west of Antarctic Peninsula, at 80–100°W. A slower but still significant poleward shift ranging from –0.2 to –0.4 deg/decade is also found in a number of locations in the eastern Antarctic sector. Zonal average trends in the ACT position in summer were very close in magnitude in the eastern and western sectors of Antarctica, amounting to –0.27 deg/decade and –0.28 deg/decade, respectively (Table 2). Fairly large, –0.32 deg/decade, but not statistically significant trends in the ACT zonal average position were found in the western sector of Antarctica in fall, whereas in other seasons of the year trends were mostly mixed and small in magnitude.

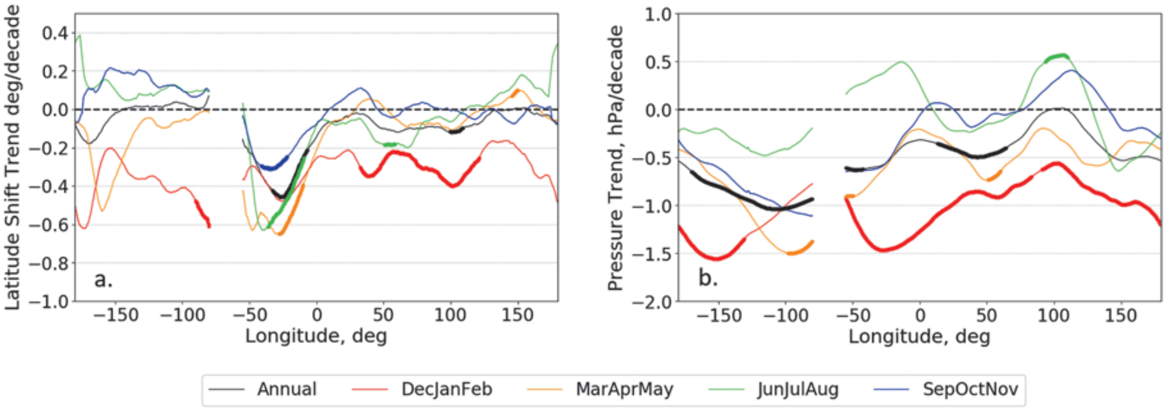

Fig. 6 – Trends in the ACT latitude (**a**) and pressure (**b**) over the 1980–2024 time period. Thick lines indicate statistically significant trends at $p < 0.05$. Negative ACT position trend values indicate its poleward shift with time

Compared with the ACT position, trends in the sea level pressure at the ACT axis more frequently reached statistically significant levels (see Figure 6b). As with the ACT position, the most distinct decrease in ACT sea level pressure over time occurred during the austral summer.

Negative pressure trends this season were statistically significant along almost the entire perimeter of the ACT, reaching peak values of –1.5 hPa/decade at 30°W in the Weddell Sea and at 150°W in the eastern Ross Sea. Zonally averaged trend values of –0.88 hPa/decade and –1.25 hPa/decade in the eastern and western sectors of Antarctica (Table 2) are equivalent to a corresponding accumulated pressure drop of around 4 and 5.5 hPa over the last 45 years. Predominant, but smaller in magnitude, negative pressure trends are also observed in the fall season. In winter and fall, negative pressure trends persist in the western sector of Antarctica but change to mixed trends in the east.

Tab. 2 – Trends in the ACT zonal mean latitude and pressure (1980–2024) over the eastern sector (0°E to 180°E) and the western sector of Antarctica(180°W to 0°W). Statistically significant trends at $p < 0.05$ are shown in bold

| **Season** | **Latitude Trend, deg/decade** | | **Pressure Trend, hPa/decade** | |
|---|---|---|---|---|
| | **East Antarctica** | **West Antarctica** | **East Antarctica** | **West Antarctica** |
| Summer (DecJanFeb) | **–0.274** | –0.281 | **–0.882** | **–1.258** |
| Fall (MarAprMay) | –0.039 | –0.318 | –0.437 | **–0.932** |
| Winter (JunJulAug) | –0.003 | 0.014 | –0.073 | –0.111 |
| Spring (SepOctNov) | 0.003 | –0.055 | 0.055 | –0.637 |
| Annual | –0.064 | –0.102 | **–0.342** | **–0.757** |

ACT trend values calculated by month of the year demonstrate a certain seasonal asymmetry (Figure 7). In the eastern sector of Antarctica, strongly negative trends in the ACT pressure and meridional position in summer months (December, January, and February) gradually weaken toward the middle of the calendar year and turn positive in late winter and spring. Despite much larger intra-annual variability, a similar pattern is also seen in the western sector of Antarctica. Negative pressure trends were statistically significant at $p < 0.05$ in January, February, and March in the Western Hemisphere and in January and February in the Eastern Hemisphere. The southward shift of the ACT axis reached statistically significant levels in January and November in the western sector of Antarctica and in January in its eastern sector.

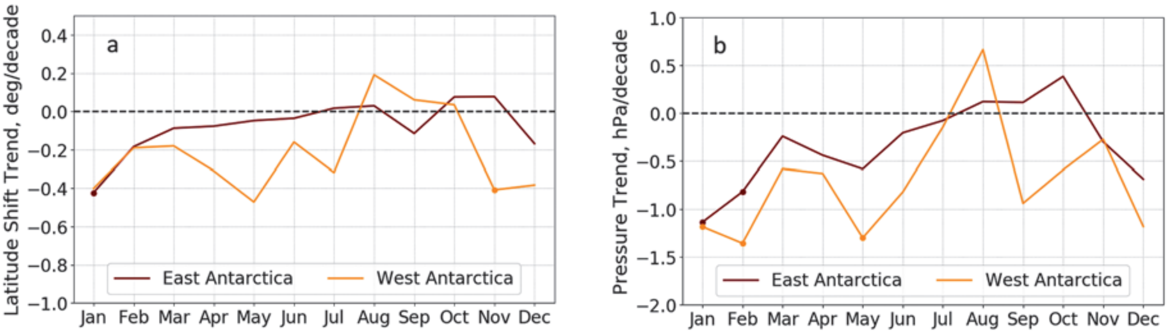

Fig. 7 – Monthly trends of the ACT zonal average latitude (**a**) and pressure (**b**) in the eastern and western sectors of Antarctica. Statistically significant trends at $p < 0.05$ are labeled with closed circles

As the ACT axis shifts northward in summer and in winter, large summertime trends in the ACT position directed towards the pole, as well as seasonal asymmetry of the trends noted above, should lead to a decrease in the annual amplitude of ACT position fluctuations. Similar considerations apply to sea level pressure: higher ACT pressure in summer and winter, negative pressure trends in summer, and their seasonal asymmetry should generally reduce seasonal variations of pressure at the ACT axis. Figure 8, presenting estimates of the ACT pressure and position averaged over two decades, 1985–1994 and 2015–2024, supports this conclusion. Indeed, over the 30-year period separating these two decades, the range of seasonal fluctuations in the zonal mean ACT pressure decreased by a factor of approximately 1.5, from 8.1 hPa in 1985–1994 to 5.9 hPa in 2015–2024. Over the same period the annual amplitude of the ACT meridional position decreased by a factor of 2.5, correspondingly from 3.1 to 1.3 degrees of latitude. The drop in the amplitude of seasonal fluctuations of the ACT parameters occurred mainly due to a drop in the ACT pressure and a shift of the ACT axis to the south in the first half of the year, from January to June.

## Discussion and Conclusions

In this study, we performed quantitative assessments of the current state of the Antarctic Circumpolar Trough (ACT), its temporal and regional variations, and associated long-term trends. The focus of the work was on two main properties of the ACT: the sea level pressure at the axis of the trough and its meridional position. ERA5 monthly reanalysis data covering the period from 1980 to 2024 were used for the study. Consequently, the obtained estimates can be considered the most up-to-date at the time of writing.

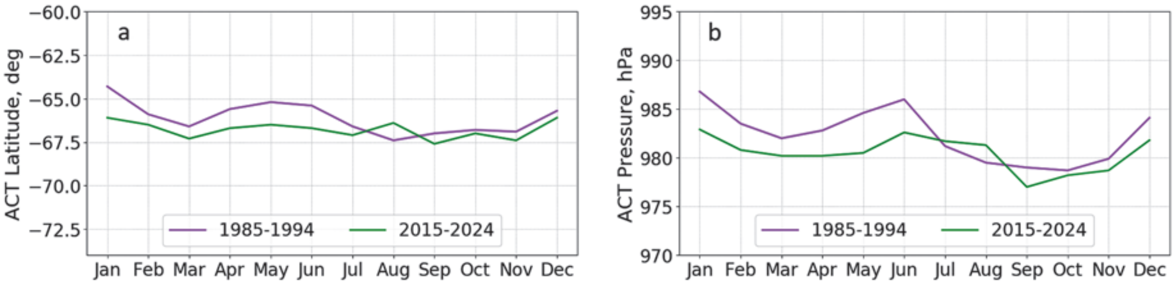

Fig. 8 – Monthly latitude (**a**) and pressure (**b**) of the zonal-average annual ACT for two decades 1985–1994 and 2015–2024

Estimates of the mean properties of the ACT obtained in this work agree well with the results of earlier studies of the sea level pressure distribution in the Antarctic region. These include, in particular, regional peculiarities of the ACT meridional position and depth as well as its semi-annual oscillations. Quantitatively, differences in the estimates of ACT parameters were quite small, amounting to less than 1.0 degree latitude in the zonal average position of the ACT and less than 2 hPa in the annual mean pressure at the ACT axis. These differences may be attributed to uncertainties associated with the estimates and to changes in the ACT properties over time.

Based on the ACT pressure trend calculations, the estimated overall drop in the annually and zonally averaged pressure at the ACT axis in the last 45 years amounted to around 3 hPa and 1.5 hPa in the western and eastern sector of Antarctica, respectively. The predominantly decreasing trends in the sea level pressure at the ACT axis established in this study are generally consistent with the increasing SAM in the last decades and with the observed broader long-term changes of the sea level pressure in the Antarctic region (e.g. Turner et al., 2005; Romanov and Romanova, 2021). Consitent with earlier studies is the conclusion of stronger ACT pressure changes in the western sector of Antarctica than in its eastern sector, and of the strongest negative pressure trends during the austral summer season.

Long-term strengthening of the SAM as well as associated deepening of the ACT in the last decades is attributed primarily to the two anthropogenic factors, the depletion of stratospheric ozone due to chlorofluorocarbons (CFCs) release and the increase of greenhouse gas emission (Morgenstern et al., 2014). As model results suggest (e.g., Shindell and Schmidt, 2004), both factors act to cool the polar stratosphere and increase the temperature gradient between the pole and mid-latitudes. The latter accelerates the stratospheric polar vortex, intensifies the lower level westerly winds and enhances the meridional pressure gradient between middle and high latitudes in the Southern Hemisphere.

The results of the study demonstrate that, in addition to the deepening of the ACT over the past decades, its axis has been shifting towards the Antarctic continent. Similar to the observed pressure trends, the ACT's poleward migration was approximately twice as fast in the western sector of Antarctica (–0.102 degrees per decade) as in its eastern sector (–0.064 degrees per decade). At this rate the total poleward shift of the ACT in the two sectors over the last 45 years amounted to 0.45 and 0.27 degrees, respectively. As with the pressure trends, the strongest and most consistent across longitudes contraction of the ACT across the year occurred in the summer. The estimated zonal-average trends ranging from –0.27 to –0.31 degree latitude per decade in this season are equivalent to an overall southward shift of the ACT axis by 1.2–1.4 degrees of latitude, or approximately 130–150 km, over the entire period of observations. The shift of the pressure trough axis towards the pole indicates a corresponding southward shift of trajectories of high-latitude storms in the Southern Ocean and of the band of the Southern Hemisphere westerlies.

An interesting consequence of the identified trends in the ACT parameters has been a decrease over time in the amplitude of their seasonal fluctuations. These changes more significantly affect the ACT's position, where the amplitude of seasonal changes has decreased by a factor of 2.5, than its pressure, where the amplitude reduction was 1.5 times since the early 1980s. An expected consequence of the decrease in the amplitude of seasonal fluctuations of ACT parameters, in conjunction with a general drop in its pressure, is a corresponding contraction of the band of westerly circumpolar winds and a decrease in the seasonal fluctuations of their strength and meridional position.

Another important finding of the work consists in a notable acceleration of deepening of the ACT and of its poleward migration over the last 10–15 years. Compared to the 1980–2024 time period, the observed negative trends in the ACT position and pressure in the last 15 years increased 2.5–5 times. This finding is coherent with a number of other studies reporting substantial changes in the Antarctic climate system since around 2015 (Hobbs et al., 2024; Roland et al., 2024). Changes have been documented in particular in the Antarctic sea ice extent, ocean salinity and air temperature (Silvano et al., 2025). The accelerated deepening and contraction of the ACT suggests corresponding trends towards increasing intensity of Antarctic low-pressure systems and storms as well as accelerated southward shift of the storm tracks. Given the recovery of the ozone layer resulting from the implementation of the Montreal protocol of 1987 (e.g., Strahan and Douglass, 2018) the direct forcing of ozone depletion on the SAM is diminishing. Consequently, the observed accelerated ACT changes indicate that greenhouse gas emissions are likely becoming the primary driver of these shifts and, hence, of the further strengthening of the SAM.

This study relied solely on ERA5 atmospheric reanalysis as the data source. The validity and accuracy of the obtained results are largely determined by the accuracy and consistency of these data. As shown in Romanov and Romanova (2021), ERA5 data reproduce long-term trends in the annual mean sea level pressure observed at Antarctic coastal ground-based stations to within 0.02 hPa/year or 0.2 hPa/decade. Trends in the monthly mean sea level pressure inferred from ERA5 and *in situ* data agreed to within 0.03 hPa/year or 0.3 hPa/decade. Since a similar level of uncertainty may be reasonably assumed for the ERA5-based trend estimates of the sea level pressure at the ACT axis, trends exceeding 0.2–0.3 hPa/decade can be considered highly reliable.

Another common practice to verify reanalysis outputs involves comparing them with other reanalysis datasets or climate model output. This approach is unlikely to be effective in this particular instance. Prior studies demonstrated advantages of ERA5 data in reproducing short-term variations as well as long-term trends of atmospheric parameters, compared to other widely used reanalysis models including MERRA2, JRA55, CFSR, NCEP (Gossart et al., 2019; Romanov and Romanova, 2023). Furthermore, the spatial resolution of these alternative models is considerably lower than that of ERA5. This difference in resolution complicates the precise determination of the ACT's latitudinal position and pressure at its axis, leading to substantial errors in assessing the seasonal dynamics and long-term trends of these parameters.

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# УГЛУБЛЕНИЕ И СМЕЩЕНИЕ К ПОЛЮСУ АНТАРКТИЧЕСКОЙ ЦИРКУМПОЛЯРНОЙ ЛОЖБИНЫ ДАВЛЕНИЯ ПО ДАННЫМ РЕАНАЛИЗА ERA5

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Антарктическая циркумполярная барическая ложбина (АЦБЛ) является важной особенностью полярной атмосферы Южного полушария. Эта полоса низкого атмосферного давления формируется как суммарный эффект отдельных циклонов, зарождающихся, развивающихся и перемещающихся в высокоширотном регионе Южного океана. Положение и глубина ложбины непосредственно влияют на региональные погодные условия, атмосферную циркуляцию, океанские течения и динамику морского льда. Движение АЦБЛ с севера на юг представляет собой ключевой аспект Южного Колебания (Southern Annular Mode, SAM). В этом исследовании мы использовали ежемесячные данные среднего давления на уровне моря атмосферного реанализа ERA5 для характеристики современного состояния АЦБЛ, ее сезонной изменчивости и трендов за последние 45 лет. Были рассмотрены два основных показателя АЦБЛ: давление на уровне моря и меридиональное положение оси АЦБЛ. Наш анализ показал преобладание отрицательных трендов давления в АЦБЛ и постепенное смещение оси АЦБЛ в сторону континента. Наибольшие изменения в положении и давлении АЦБЛ обнаружены в Западной Антарктике, особенно в морях Уэдделла, Амундсена и Росса. Оценка общего падения среднегодового и зонально усредненного давления на оси АЦБЛ за последние 45 лет составило около 3 гПа в Западной Антарктике и около 1.5 гПа в Восточной Антарктике. В то время ось АЦБЛ в этих регионах сместилась к полюсу, соответственно, на 0.27 и 0.45 градуса широты. Углубление АЦБЛ и ее приполярное сжатие были в основном вызваны сильными изменениями в летний и осенний сезоны, тогда как зимой и весной тренды были смешанными и близкими к нейтральным. Было обнаружено, что тренды как в меридиональном положении оси АЦБЛ, так и в давлении на уровне моря ускорились за последние 10–15 лет.

**Ключевые слова:** реанализ ERA5, Антарктическая циркумполярная барическая ложбина, давление на уровне моря, многолетние средние значения и тренды

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# 基于ERA5再分析资料的南极环极地低压槽加深及向极移动趋势

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南极环极地低压槽：基于ERA5再分析资料的近45年变化特征
南极环极地低压槽是南半球极地大气的重要环流特征。这一环绕南极大陆的低压带是由南大洋高纬度地区多个气旋生成、发展及移动的综合效应所形成。低压槽的位置和深度直接影响区域天气条件、大气环流、洋流及海冰动态。南极环极地低压槽的经向位移是南极涛动的核心表现之一。
本研究利用ERA5大气再分析资料的月平均海平面气压场，揭示了近45年来南极环极地低压槽的现代状态、季节变化及长期趋势。研究聚焦低压槽的两项核心指标：海平面气压及其轴线所在的经向位置。分析表明，低压槽气压总体呈下降趋势，轴线呈现向极地方向持续退缩的特征。低压槽位置与气压变化最显著的区域位于西南极，尤其是威德尔海、阿蒙森海和罗斯海。过去45年间，西南极地区低压槽轴线上年平均、纬向平均海平面气压整体下降约3百帕，东南极地区下降约1.5百帕；与此同时，两区域低压槽轴线分别向极地方向移动约0.27个纬度及0.45个纬度。低压槽的加深及向极收缩主要受夏、秋季节的显著变化驱动，而冬、春季节趋势较不显著，接近中性。研究还发现，低压槽轴线经向位移及海平面气压的变化速率在过去10至15年间呈现加速趋势。

**关键词：** ERA5再分析，南极环极地低压槽，海平面气压，多年平均与趋势

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