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Southward migration of the zero-degree isotherm latitude over the Southern Ocean and the Antarctic Peninsula: Cryospheric, biotic and societal implications

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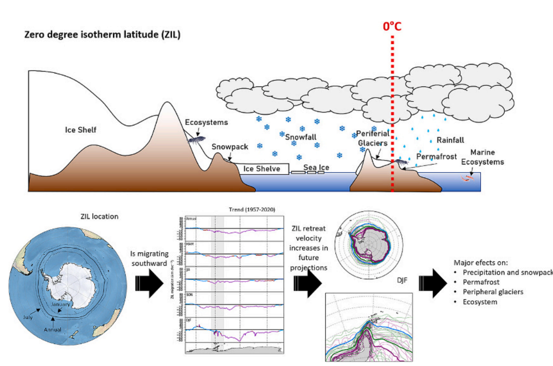
HIGHLIGHTS

- The zero-degree isotherm latitude (ZIL) drives major changes in cryospheric and biological processes in maritime Antarctica
- We explore near-surface ZIL spatio-temporal variations in Antarctica
- The ZIL has migrated poleward faster than the global mean velocity of temperature change
- It is expected that the ZIL migration velocity will increase under both SSP2-4.5 and SSP5-8.5 scenarios
- We expect major impacts on the precipitation phase, snow accumulation and peripheral glaciers

GRAPHICAL ABSTRACT



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ABSTRACT

The seasonal movement of the zero-degree isotherm across the Southern Ocean and Antarctic Peninsula drives major changes in the physical and biological processes around maritime Antarctica. These include spatial and temporal shifts in precipitation phase, snow accumulation and melt, thawing and freezing of the active layer of the permafrost, glacier mass balance variations, sea ice mass balance and changes in physiological processes of biodiversity. Here, we characterize the historical seasonal southward movement of the monthly near-surface zero-degree isotherm latitude (ZIL), and quantify the velocity of migration in the context of climate change using climate reanalyses and projections. From 1957 to 2020, the ZIL exhibited a significant southward shift of 16.8 km decade^{-1} around Antarctica and of 23.8 km decade^{-1} in the Antarctic Peninsula, substantially faster than the global mean velocity of temperature change of 4.2 km decade^{-1}, with only a small fraction being

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attributed to the Southern Annular Mode (SAM). CMIP6 models reproduce the trends observed from 1957 to 2014 and predict a further southward migration around Antarctica of 24 ± 12 km decade^{-1} and 50 ± 19 km decade^{-1} under the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The southward migration of the ZIL is expected to have major impacts on the cryosphere, especially on the precipitation phase, snow accumulation and in peripheral glaciers of the Antarctic Peninsula, with more uncertain changes on permafrost, ice sheets and shelves, and sea ice. Longer periods of temperatures above 0 °C threshold will extend active biological periods in terrestrial ecosystems and will reduce the extent of oceanic ice cover, changing phenologies as well as areas of productivity in marine ecosystems, especially those located on the sea ice edge.

1. Introduction

The Southern Ocean and the Antarctic Peninsula (AP) are the mildest areas of the southern polar region and have undergone profound changes during recent decades (Auger et al., 2021; Mulvaney et al., 2012). The AP has experienced a marked long-term warming trend for the last 60 years (Carrasco, 2013; Gonzalez and Fortuny, 2018; Jones et al., 2019; Steig et al., 2009), among the greatest in Antarctica together with central West Antarctica (Bromwich et al., 2013, 2014; Vaughan et al., 2003). Part of this regional warming has been attributed to dynamical changes, with the increase of westerly zonal winds associated with the positive phase trend of the Southern Annular Mode (SAM) in response to stratospheric ozone depletion and the increase of greenhouse gas concentrations (Lubin et al., 2008; Marshall, 2007; Thompson and Solomon, 2002). However, there is recent evidence that anthropogenic climate warming has also thermodynamically contributed to temperature increases in the region (González-Herrero et al., 2022; Gorodetskaya et al., 2023; Jones et al., 2019; Thompson and Solomon, 2002). The regional long-term warming has not been restricted to terrestrial environments, but the adjacent Bellingshausen and Weddell seas have also experienced an increasing sea surface temperature trend (Meredith and King, 2005), accompanied by a reduction in seasonal sea-ice extent (Porter et al., 2016). Over recent decades, there have been shorter periods of alternating cooling/warming trends (Gonzalez and Fortuny, 2018) embedded into the long-term warming, including the recent 1998–2016 cooling phase (Oliva et al., 2017; Turner et al., 2016) that seems to be now coming to an end (Carrasco et al., 2021) as evidenced by the minimum Antarctic sea ice extents recorded in February 2022, and February 2023.

In areas dominated by snow, frozen ground and freshwater, the onset and withdrawal of the zero-degree isotherm drives major changes and adjustments in the environment, responding to changes in both the physical and the biological processes occurring in the region (Bonsal and Prowse, 2003; Łupikasza and Szypuła, 2019). These processes include rain-snow phase transition (Dai, 2008), snowpack accumulation and melt (Medley and Thomas, 2018), thawing and freezing of the permafrost active layer (Bockheim et al., 2013; Oliva and Ruiz-Fernández, 2015; Vieira et al., 2010), glacier surface melt and runoff (Costi et al., 2018; Jonsell et al., 2012), glacier mass balance variations including changes in the equilibrium-line altitude (Navarro et al., 2013; Recio Blitz, 2019) and in the physiological processes of biodiversity (Chown and Nicolson, 2004). Whereas in mid-latitude mountain regions these processes are controlled by seasonal oscillations of the altitude of the zero-isotherm, and therefore the surface temperature lapse rate (Ibañez et al., 2021), in the polar regions the near-surface zero-isotherm latitude (ZIL) controls a key aspect of environmental dynamics with a large effect on the intensity and extent of cryospheric processes (Bonsal and Prowse, 2003). According to future forecasted scenarios that anticipate a significant warming in the Southern Ocean and the AP (Bracegirdle et al., 2020), the ZIL is also expected to undergo pronounced changes in the forthcoming decades, although their timing and magnitude are yet to be explored.

The aim of this study is to quantify how the ZIL is changing around Antarctica and draw inferences on the consequences that might result from these changes. To do this, we first characterize the spatio-temporal oscillations of the ZIL around the Antarctic continent, with a focus on the AP, which is crossed by the monthly mean zero-isotherm in summer. Then, we calculate the latitudinal changes of the ZIL that have occurred since the mid-20th century in order to frame climatic and environmental changes recorded in the AP region over the last 70 years. Then, we analyse the projections of the expected future changes in the ZIL by the end of the 21st century and its impacts on the cryosphere and the biosphere. Trends in ZIL might be established as an index of the velocity of climate change in the southern polar region.

2. Data and methods

2.1. Area of study

This study examines data from the maritime Antarctic, including the entire Southern Ocean. We focus on the AP and neighbouring islands, as well as the more distant South Shetland and South Orkney Islands, in addition to the adjacent Southern Ocean, including the Drake Passage and parts of the Bellingshausen and Weddell seas (50–75°S, 40–85°W, Fig. S1a, b). The AP is a mountainous region that stretches from S to N with its portion north of 62°S orientated from SW to NE (Fig. S1c, d). The AP shows a rough relief, with many areas, especially in its central spine, exceeding 1500 m in altitude. Consequently, the western/eastern sides of the northern AP belong to two different biogeographical regions: North-east Antarctic Peninsula/North-west Antarctic Peninsula, with the South Orkney Islands being a separate region (Terauds and Lee, 2016). Together with local topography, climate determines the total glacierized surface, type of glaciers (cold/warm-based, polythermal) and the environmental dynamics in ice-free areas (Barry and Gan, 2011; Ruiz-Fernández et al., 2019). The South Shetland and South Orkney islands are located, respectively, N and NE of the AP as part of the Scotia Arc. At a continental scale, we study the Southern Ocean, characterized by cold waters with seasonal sea ice that extends from about 3 million km^2 at the end of summer to up to 18 million km^2 at the end of winter (Cavalieri and Parkinson, 2008). The Bellingshausen Sea to the west of the AP is ice-free in austral summers, whereas the east side of the AP in the Weddell Sea is ice bound all year round (Cavalieri and Parkinson, 2008).

2.2. Datasets

2.2.1. Reanalysis

We have used monthly-averaged surface air temperature from ERA5 (Hersbach et al., 2020) to characterize the position of the ZIL. ERA5 is the 5th-generation global climate reanalysis of the ECMWF based on the IFS Cycle 41r2 of the ECMWF. It has a horizontal resolution of 31 km on 137 hybrid levels to 0.01 hPa covering all the globe. The field data are available at hourly intervals from 1957 to 2020. It has improved model physics, core dynamics and data assimilation with respect to previous generations (Hersbach et al., 2020) and it is the state-of-the-art reanalysis product that best represents the seasonal cycle of near-surface temperature in Antarctica (Gossart et al., 2019). Recent comparisons indicate that ERA5 improves its predecessor in the AP (Hillebrand et al., 2020; Tetzner et al., 2019), which can be seen in the reduction of the amplified warm trend detected in ERA-Interim at the leeward side of the AP (Bozkurt et al., 2020). ERA5 also reproduces well the climate patterns previous to the satellite era (Marshall et al., 2022), but not before the first observations over the AP (González-Herrero et al., 2022).

2.2.2. CMIP6 simulations

Different climate models from phase 6 of the Coupled Model Intercomparison Project (CMIP6) of the World Climate Research Programme are used to assess future changes in ZIL. We used monthly data of near surface temperature of the variant r1i1p1f1. The climate models assessed are listed in Table S1. The historical run is used to assess the performance of the CMIP6 simulations compared with ERA5. To assess future changes in the ZIL we used projections based on scenarios SSP2-4.8 and SSP5-8.5 that present medium and high radiative forcings, respectively (O'Neill et al., 2016).

2.2.3. Station temperature datasets

Monthly mean surface air temperature data from six stations (Bellingshausen, Orcadas, O'Higgins, Esperanza, Faraday/Vernadsky - henceforth Vernadsky - and Rothera) were used to compare the melting season in the AP (Fig. 1a). The stations were selected based on their geographical location and the length and quality of their records. Station-based data were collected from the quality-controlled Reference Antarctic Data for Environmental Research (READER) project (Turner et al., 2004) (https://legacy.bas.ac.uk/met/READER/). Only months with >90 % of data availability were used in the analysis. Annual and seasonal temperatures for each station were calculated averaging monthly means using the meteorological seasons (DJF for summer, MAM for autumn, JJA for winter and SON for spring). All the stations are located near sea level.

2.3. Methodology

2.3.1. Melting season

In this study, we define the melting season as the period of the year when monthly mean surface air temperature at the site is above 0 °C. To calculate the day when the change of season takes place, the mean

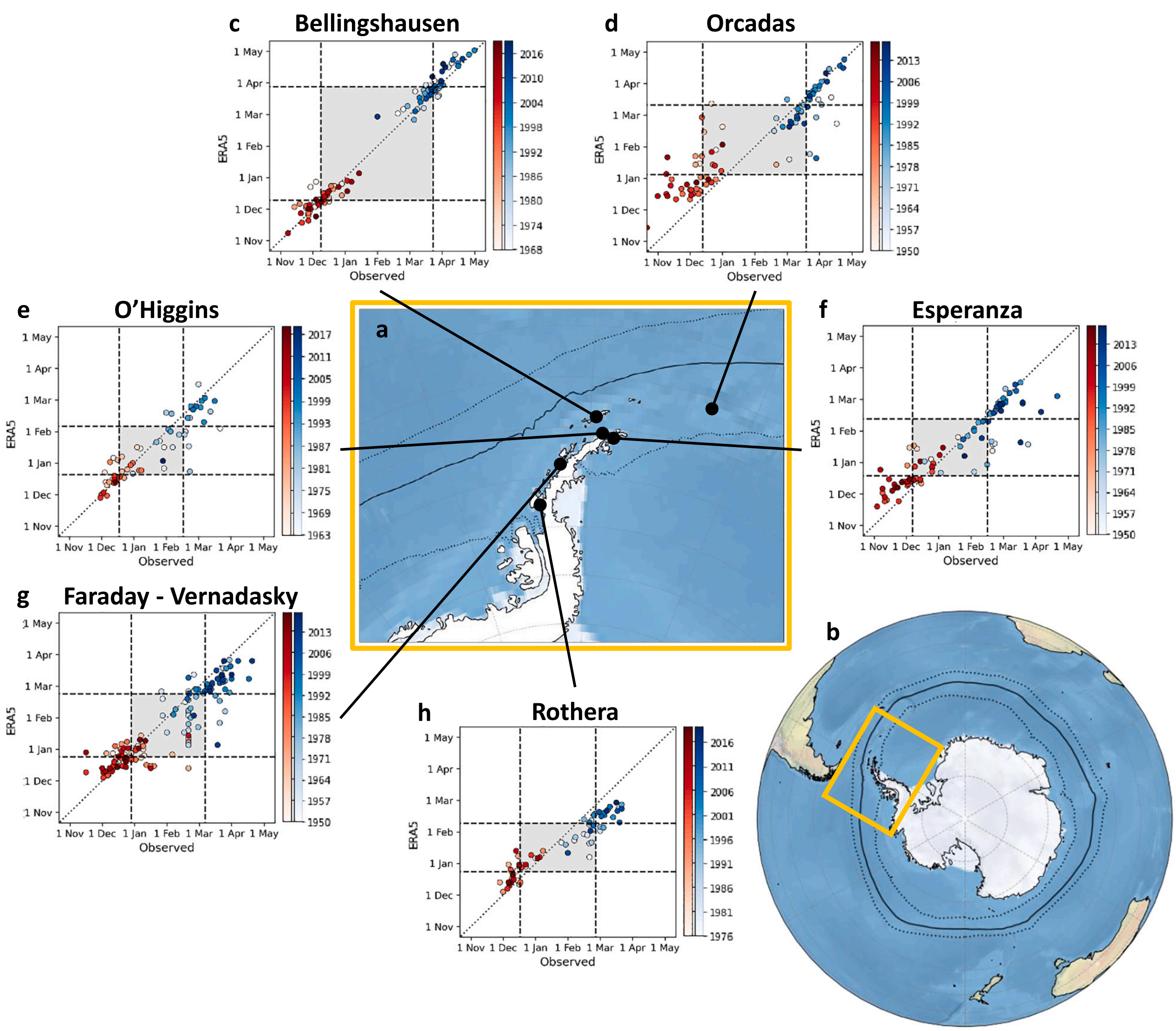

Fig. 1. Beginning and ending dates of the melting season for six different stations of the Antarctic Peninsula. (a, b) Position of the stations with the mean annual position of the ZIL (black line) and mean January and July position of the ZIL (black dotted lines). (c, d, e, f, g) Observed (x axis) vs. simulated by ERA5 (y axis) date of the beginning (red dots) and ending (blue dots) dates of the melting season. Dotted diagonal line indicates the coincidence of dates. Black dashed lines indicate the average date of the beginning and end of the melting season and the grey area indicates the mean duration of the melting season. Scales are not conserved in this projection.

temperature of the month is set on the 15th day of the month and the date is obtained by linear interpolation with the neighbouring months with the duration of every month set at 30 days (see Fig. S2). We used the monthly mean temperature to establish a clear beginning of the melting season, instead of daily temperatures that record frequent oscillations around the 0 °C threshold during the summer. This process was conducted for station-based datasets and comparisons between stations are given for the common period 1980–2019. To compare with the ERA5 reanalysis, we used the longest period available and linear interpolation with respect to the adjacent grid points adjusting the height in the reanalysis using a lapse rate of 0.0065 $^{\circ}C\ m^{-1}$.

2.3.2. ZIL calculation and trends

The latitude of the surface air zero-isotherm determines the ZIL. To calculate the position on the ERA5 grid, a linear interpolation was performed for each longitude. At the northern tip of the AP in summer, where the zero-isotherm intersects at different latitudes for each longitude, the highest latitude was selected. The mean 30-year period 1950–79 was compared against the period 1990–2020, as well as the averaged decades. The ZIL migration velocity was calculated using least-square linear trends between 1957 and 2019. Statistical significance of the trends was calculated using the Wald test with t-distribution (Wasserman, 2004) with the zero slope as the null hypothesis.

2.3.3. SAM congruence

To determine the SAM contribution to the ZIL trends a congruence analysis was performed (Thompson and Solomon, 2002). This analysis has been previously used to determine the widespread background warming in Antarctica after removing the SAM-congruent trends (Jones et al., 2019) and to attribute polar warming to human influence (Gillett et al., 2008; González-Herrero et al., 2022). To determine the SAM-congruent trend, we linearly regressed the detrended SAM index and ZIL series for each longitude. The migration of the ZIL caused by the SAM was obtained after multiplying the regression coefficient by the SAM trend at each longitude. Finally, to obtain a background ZIL trend linearly independent of the SAM, the SAM-congruent trend was removed from the original ZIL trend. Computational procedures and software environment are described in Section 2 of the supplementary information.

3. Results

3.1. Characterization of the zero-degree isotherm over the Antarctic Peninsula

3.1.1. Melting season

The annual evolution of the duration of the melting season and its start and end dates at the six stations of our observed temperature datasets are presented in Fig. S3 and Table 1 with their mean values over the period 1980–2019. Bellingshausen and Orcadas stations, located in the South Shetland and South Orkney Islands respectively, record the longest melting season with 106 ± 47 and 107 ± 61 days, respectively. The average season starts in early December and ends in mid-to-late March. However, the melting season at both sites exhibits remarkable variability, with start dates between 6 November and 11 January and end dates between 28 Jan and 28 April in Bellingshausen. The longest season occurred in 1999–2000 with a duration of 145 days and the shortest season took place in the anomalously cold summer of 2013–14, with only 17 days.

Despite their similar proximity (ca. 50 km) to the northernmost tip of the AP, O'Higgins and Esperanza stations present very different melting seasons with 65 ± 47 and 84 ± 61 days, respectively. The average melting season in Esperanza starts on 28 November, substantially earlier than in Bellingshausen and Orcadas, and ends on 21 February. By contrast, the average melting season in O'Higgins starts on 14 December and ends on 17 February. The longest season in Esperanza happened in 2016–17 with 165 days, while the shortest season occurred, as in Bellingshausen, in 2013–14 with 21 days.

In the two southernmost stations, Vernadsky (65.4°S) and Rothera (67.5°S), the melting season duration extends over 86 ± 47 and 73 ± 43 days, respectively. It starts in mid-December in both stations and ends in mid-March at Vernadsky and in late February at Rothera. Interestingly, Vernadsky presents one year without a melting season in 1999–2000, precisely when Bellingshausen recorded the longest season. It is also noticeable that the melting season length is not controlled solely by latitude (O'Higgins at 63.3°S records a shorter melting season than Rothera at 67.5°S).

We analysed how ERA5 reproduces the melting season at different AP stations to evaluate ZIL uncertainties. Fig. 1 shows the comparison between ERA5 and observations of the starting and ending of the melting season at different stations. Table 1 also presents the mean absolute error (MAE) and the bias. ERA5 replicates very well the beginning and the end of the melting season at Bellingshausen station, with MAEs of 6.5 and 4.7 days, respectively. The other stations present a range of MAEs ranging from 4.2 to 26.8 days with the smallest and largest error in the beginning of the season at O'Higgins and Orcadas, respectively. Generally small MAE values suggest that ERA5 accurately characterizes the onset and the withdrawal of the near-surface zero-degree isotherm.

3.1.2. Mean annual position and yearly advance and withdrawal of the ZIL

Fig. 2 and Video S1 show the annual and seasonal mean ZIL and the monthly ZIL evolution around Antarctica and over the AP. The annual mean ZIL ranges between a maximum latitude of 65°S around the

Table 1
Melting season at six different stations of the Antarctic Peninsula with the extent of the melting season, beginning and ending dates. Mean Absolute Error (MAE) and BIAS for performance comparison of ERA5 with respect to the stations on the Antarctic Peninsula during the period 1980–2019.

	Bellingshausen	Orcadas	O'Higgins	Esperanza	Vernadsky	Rothera
Location	62.2S 58.9W	60.7S 44.7W	63.3S 57.9W	63.4S 57.0W	65.4S 64.4W	67.5S 68.1W
Altitude	16 m	6 m	10 m	13 m	11 m	32 m
Max season	145 d	167 d	106 d	165 d	127 d	107 d
Mean season	106 ± 24 d	107 ± 31 d	65 ± 22 d	84 ± 31 d	86 ± 24 d	73 ± 22 d
Min season	17 d	26 d	0 d	21 d	0 d	21 d
Day Beg Min	6 Nov	20 Oct	25 Nov	3 Oct	14 Nov	24 Nov
Day Beg Mean	6 Dec	2 Dec	14 Dec	28 Nov	16 Dec	13 Dec
Day Beg Max	11 Jan	25 Jan	5 Jan	5 Jan	13 Jan	6 Jan
Day End Min	28 Jan	20 Feb	19 Jan	16 Jan	3 Feb	22 Jan
Day End Mean	22 Mar	19 Mar	17 Feb	21 Feb	12 Mar	24 Feb
Day End Max	28 Apr	21 Apr	14 Mar	18 Apr	17 Apr	20 Mar
ERA5 MAE Beg	5.0 d	26.8 d	4.2 d	14.3 d	8.3 d	9.2 d
ERA5 MAE End	5.1 d	8.4 d	12.3 d	9.6 d	15.1 d	18.5 d
ERA5 BIAS Beg	−0.4 d	−26.8 d	+0.1 d	−14.2 d	−1.9 d	−8.6 d
ERA5 BIAS End	−4.0 d	+6.7 d	+9.1 d	+9.3 d	+14.0 d	18.5 d

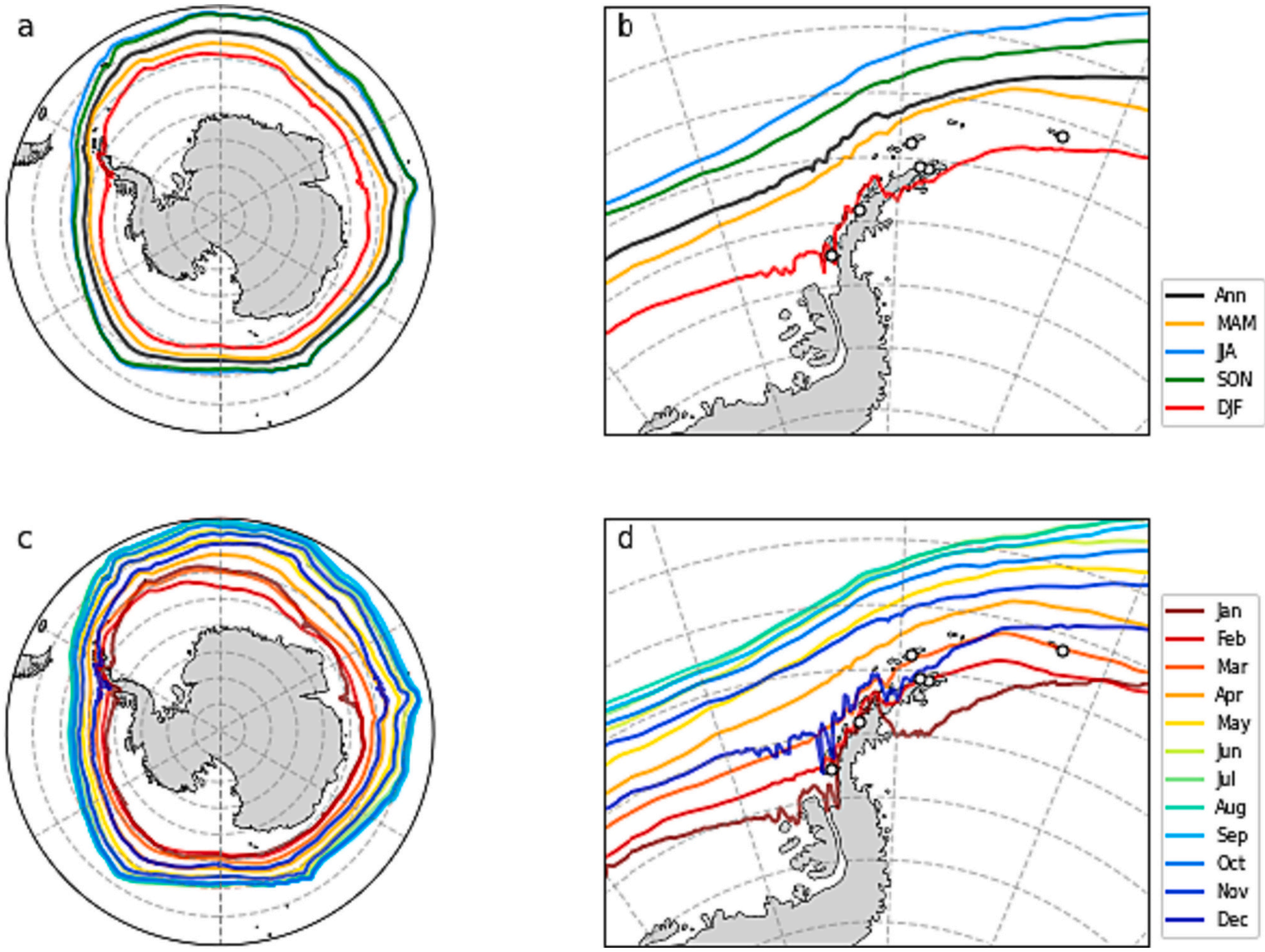

Fig. 2. Mean Annual and seasonal mean (a and b), and monthly mean (c and d) positions of the zero isotherm over Antarctica (a and c) and the AP (b and d) from ERA5 for the period 1950–2019. White dots in b and d show the position of the stations analysed. Scales are not conserved in this projection.

African Sector of the Southern Ocean, and a minimum latitude of 55°S in the Bellingshausen Sea (Fig. 2a). The monthly extremes are 50°S in July and 70°S in January (Fig. 2c) at the mentioned locations. The greatest latitudinal gradient of the ZIL occurs around the AP, where the zero-isotherm stretches from SW to NE, almost parallel to the coast of the northern tip of the AP (Fig. 2b). That is, the ZIL southern limit decreases towards the east, being at higher latitudes over the Bellingshausen Sea and at lower latitudes over the Weddell Sea. The mean annual ZIL southern limit decreases towards the east at a rate of about 1.5–2° for each 10° of longitude. The interannual variability of the mean annual ZIL is about 3° in latitude (ca. 300 km) with only small variations with longitude (Fig. S4).

The mean annual oscillation of the ZIL varies from 6° (ca. 700 km) in the Ross Sea to almost 13° (ca. 1400 km) in the African sector (Fig. 2c). Over the AP, the mean annual oscillation is about 8° of latitude (ca. 900 km) except for some parts of the region where it is about 6° (ca. 700 km) (Fig. 2d). Over the AP, the ZIL is located further north in winter, specifically from June to September, reaching its northernmost position in July and August. The southern movement of the ZIL in early spring is gradual: from September to November, it progresses at a rate of $<1°$ latitude month^{-1}. In late spring and early summer, ZIL progression accelerates, moving south at 2–3° latitude month^{-1}, except in the AP sector where the steep terrain lessens its speed. The southernmost position of the ZIL occurs in January and February. Spring is characterized by a slow northward advance of the ZIL at a rate of 1–2° latitude month^{-1} returning to its northernmost position in early winter. The interannual variability of the ZIL in all seasons lies within 3–4° at nearly all longitudes, except in summer when it exceeds 5° in the Atlantic and East Pacific Sectors (Fig. S4 and Video S2).

3.2. *Migration of the ZIL*

3.2.1. *Recent trends (1950–2019) of the ZIL from ERA5*

We examined ZIL variations from 1957 to 2020 from ERA5 data. Fig. S5 illustrates these changes by comparing the position of the ZIL between the 30-yr periods from 1961 to 1990 and from 1991 to 2020. A pronounced southward migration is observed in some regions such as the Weddell Sea, almost no variations are detected in the Indian sector, and an advance is also seen in some seasons in the Pacific sector (Fig. S5a). Over the AP (Fig. S5b), a clear shift of the ZIL of about 1° (ca. 100 km) is observed throughout the region between both periods, except for the summer on the western side of the Peninsula, where ZIL migration is obstructed by the mountains defining the spine of the AP. In this zone, a lift of the zero-isotherm with elevation (due to the steep relief) probably counterbalances its southward movement. The evolution of the annual mean ZIL (Fig. 3) shows a clear southward shift from 1957 to the 1980s and a subsequent stabilization or advance (Vaughan et al., 2003; Gonzalez and Fortuny, 2018; Oliva et al., 2017; Turner et al., 2016).

We examined the 64-year linear trends of the annual and seasonal ZIL from 1957 to 2020 at each longitude in Fig. 4a and Table 2. The annual position of the ZIL shows a significant southward migration of about 20–40 km decade^{-1} in the Atlantic sector of the Southern Ocean, and around 20 km decade^{-1} in the Indian sector. In the Pacific sector, trends are not statistically significant. Averaged over the entire

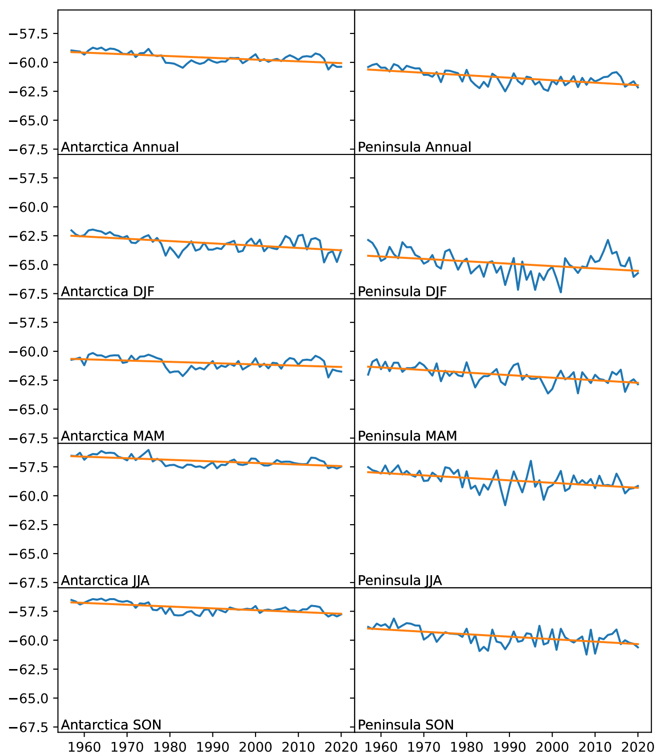

Fig. 3. Time series (blue line) of the annual ZIL at averaged for the whole Southern Ocean and for the AP (40°–85°W). The yellow line shows the linear trend during the period 1957–2020. All trends exhibit a p-value of <0.05.

continent, the ZIL showed a migration of 16.8 km decade^{-1}, but over the AP the shift was much higher, of 23.8 km decade^{-1}.

Southward migrations of the ZIL are found in all seasons on the Atlantic and Indian sectors of the Southern Ocean. The only exception appears in autumn in the Indian sector. Trends in summer are largest, except on the AP, reaching a 80 km decade^{-1} shift at 20° E (Fig. S6). The maximum ZIL migration averaged over the continent was 22.1 km decade^{-1} in summer. The AP presents a very stable migration in all seasons, with a maximum of 24.6 km decade^{-1} in March.

SAM-congruent trends had little effect on ZIL migration on an annual scale, with none of them significant at $p < 0.05$ (Fig. 4b, c and Table 2). The largest changes correspond to the AP, where SAM has contributed significantly to the ZIL retreat by approximately 11 km decade^{-1} annually and 3–17 km decade^{-1} in different seasons. After removing SAM-congruent trends, ZIL retreat is 12.7 km decade^{-1} over the AP and 18.0 km decade^{-1} over the entire Southern Ocean.

3.2.2. How do CMIP6 models reproduce ZIL and its recent trends?

Fig. S7 shows the mean annual position of the ZIL for different CMIP6 historical simulations from 1957 to 2014 compared with the ERA5 reanalysis for the same period. The different CMIP6 simulations present a great variability with differences in some regions up to ca. 10° latitude. CMIP6 simulations generally show a shift of the ZIL to higher latitudes in all seasons. The greatest differences occur in summer and in the African and Indian sectors of the Southern Ocean. In the vicinity of the AP, the southward shift is <1° in latitude, except in the Weddell Sea in summer. In this season, the lower resolution of the AP mountains in the CMIP6 models compared with ERA5 is evidenced in the ZIL crossing the Trinity Peninsula instead of bordering it as happens in the case of ERA5 data (Fig. S7).

In Fig. 5 we compared the trends of the different CMIP6 historical simulations with those of ERA5 from 1957 to 2014. All CMIP6 simulations, except BCC-CSM2, show a southward migration in all seasons, ranging from 5 to 25 km decade^{-1}. The mean migration of the ZIL for the various models is consistent with that of the ERA5 and differs annually by only 1 km decade^{-1}. The different CMIP6 simulations present larger differences in mean ZIL migration over the AP (Fig. 5b). However, the mean migration of the ensemble of CMIP6 simulations remains consistent with that of ERA5.

These results indicate that, although individual CMIP6 models do not properly simulate the true position of the ZIL, their trends are comparable in magnitude with those observed in the historical reanalyses and can be used to assess future trends under different scenarios (Zakari et al., 2022).

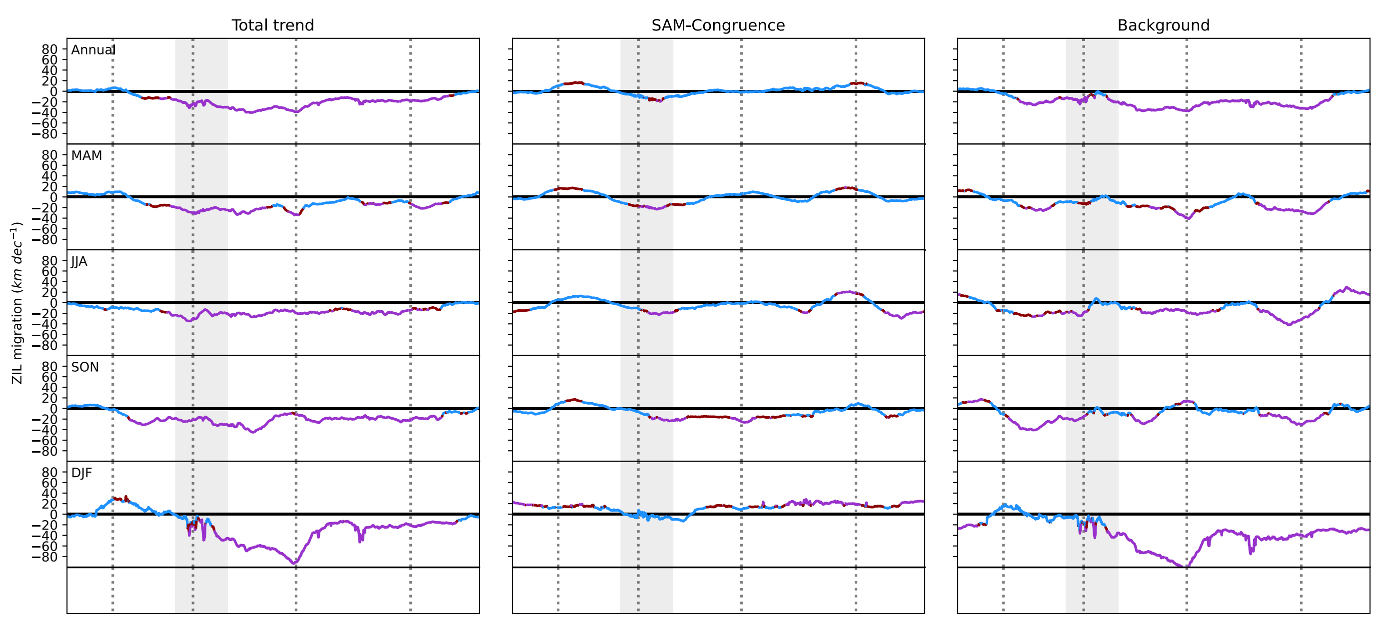

Fig. 4. (a) Trends of ZIL (in km decade^{-1}) by longitude, (b) SAM-congruent trends and (c) background trends. Line colour indicates the statistical significance of the trend with p-value > 0.1 in blue, 0.1 > p-value > 0.05 in red and p-value < 0.05 in violet. Grey shaded area indicates the AP region. On the bottom there is a map of Antarctica for reference. Vertical dotted lines indicate the four longitudes showed at Fig. S4. Data source: ERA5.

Table 2
Mean trends of the ZIL retreat, SAM congruence and Background retreat for the whole Southern Ocean and for the AP (40°–85°W) during the period 1957–2020. Positive values indicate southward shifts in km decade^{-1}. All trends exhibit a p-value of <0.05.

	Trend		SAM congruence		Background	
	Antarctica	Peninsula	Antarctica	Peninsula	Antarctica	Peninsula
Annual	16.8	23.8	−1.2	11.1	18.0	12.7
MAM	12.3	24.6	0.2	17.3	12.1	7.2
JJA	15.1	23.7	4.9	15.2	10.2	8.5
SON	17.4	23.8	7.6	12.2	9.8	11.5
DJF	22.1	22.9	−12.5	3.4	34.5	19.5

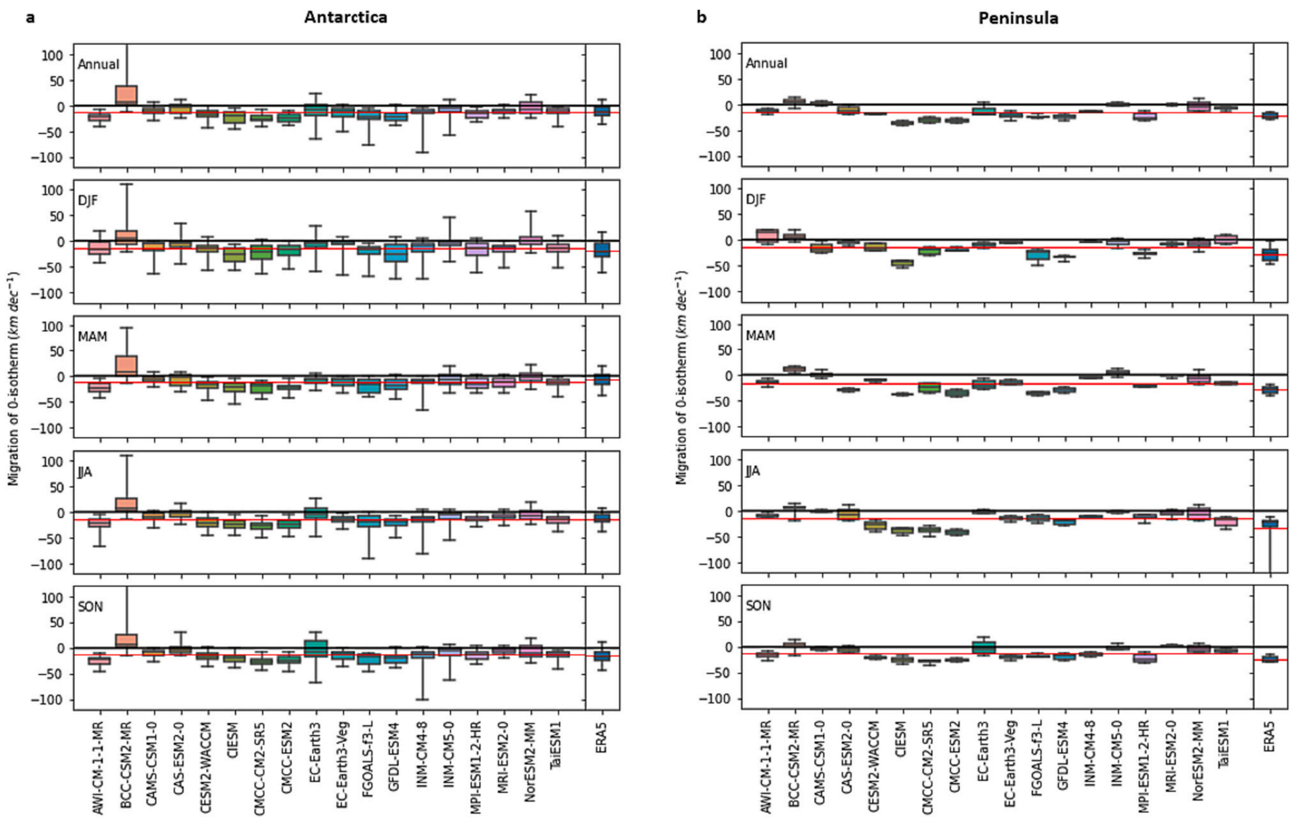

Fig. 5. Boxplots of ZIL trends at every longitude from 1957 to 2014 at the different CMIP6 Historical simulations and ERA5 at (a) the whole Southern Ocean and (b) the AP. Boxes denote the 25th–75th percentile ranges and whiskers span the 1st–99th percentiles. Red line indicate the mean of the CMIP6 models and the mean of ERA5 for comparison.

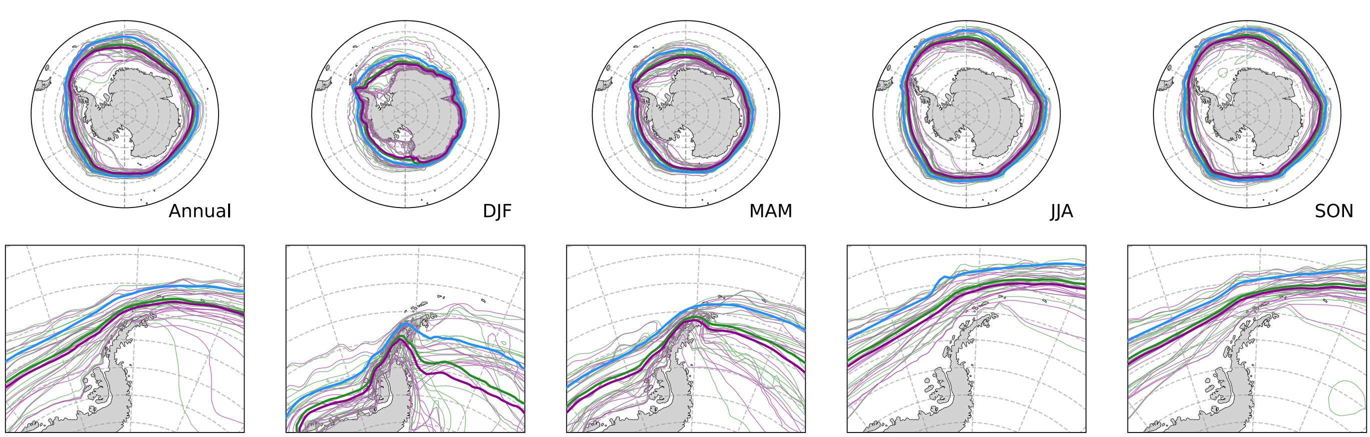

Fig. 6. Mean annual ZIL position in different CMIP6 SSP2-4.5 simulations for the periods 2040–2069 (green lines) and 2070–2099 (magenta lines). Bold green and magenta lines indicate the mean of the CMIP6 simulations for the periods 2040–2069 and 2070–2099, respectively. For comparison, CMIP6 Historical simulations (1957–2014) are shown bold blue lines. Scales are not conserved in this projection.

3.2.3. Projections of ZIL retreat from CMIP6 models

Projections of ZIL migration were evaluated using CMIP6 models for SSP2-4.8 and SSP5-8.5 scenarios. Fig. 6 shows a comparison of the mean annual ZIL position over the 30-year period 2040–2069 (green lines) and 2070–2099 (magenta lines) for the medium radiative forcing scenario SSP2-4.5. This scenario shows a major ZIL retreat around 1–2° in latitude (ca. 100–200 km) occurring mostly before mid-century. During the second part of the century, the retreat would slow down. This differs from the SSP5-8.5 projection, which shows a continuous retreat of the ZIL during the second half of the century (Fig. S8). In total, the southward shift of the ZIL would be 24 ± 12 km decade^{-1} in the SSP2-4.5 scenario with simulations ranging from 7 to 46 km decade^{-1} (Fig. 7a), and 50 ± 19 km decade^{-1} in the SSP5-8.5 scenario with simulations ranging from 18 to 82 km decade^{-1} (Fig. S7a). Over the AP, the ZIL migration presents higher variability between simulations, ranging from −4 to 52 km decade^{-1} and averaging 23 ± 17 km decade^{-1} in the SSP2-4.5 scenario (Fig. 7b), and from 13 to 95 km decade^{-1} and averaging 56 ± 26 km in the SSP5-8.5 scenario (Fig. S9b).

The ZIL migration simulated by the CMIP6 projections is very constant at most longitudes, but larger and more variable in the Ross Sea sector (around 180° longitude), especially when annually averaged (Figs. 8 and S8). In summer, the African sector (around 0° longitude) also exhibits a larger southward migration of the ZIL compared to other longitudes, especially in the SSP5-8.5 simulations. For every longitude, 13 or more out of the 18 different simulations, show a significant southward migration of the ZIL in SSP2-4.5 simulations, and in some parts of the AP all 18 exhibit significant southward migration. In SSP5-8.5 simulations 17 or more of the models show significant trends at all longitudes.

4. Discussion

4.1. Factors shaping ZIL trends

The results reveal a rapid southward migration of the ZIL. However, this migration is not uniform around Antarctica. Notably, the Atlantic, Indian, and Western Pacific sectors of the Southern Ocean have displayed a significant southward shift, especially during the spring and summer seasons. In contrast, the Eastern Pacific sector has remained relatively stable. The absence of migration in the Eastern Pacific sector may be attributed to the increasing trend in sea ice over the Ross sea, linked to the deepening of the Amundsen Sea Low (ASL) (Eayrs et al., 2021; Parkinson and Cavalieri, 2012). This ASL, a non-annular component of the SAM, has intensified due the positive phase of the SAM, pulling cold air from the Antarctic continent in its western flank. Nevertheless, it is worth noting that our results show that the SAM trends had a little impact on the ZIL position in this particular area. The other large-scale trends do not appear to respond to changes in the meridional circulation associated to the zonal wave number three, but to a widespread warming over the Southern Ocean (Gillett et al., 2008; Jones et al., 2016, 2019; Thomas et al., 2009). This is consistent with the climate model results, underscoring the reliability of these trends. Even if small-scale patterns and absolute values of variables such as temperature or wind are not accurately represented by climate models, it is often assumed that trends can be trusted (Zakari et al., 2022). Climate models confirm a widespread robust southern migration of the ZIL in the coming decades.

In contrast to the recent abrupt decline in sea ice since 2016, which followed years of growth (Eayrs et al., 2021), the trends in ZIL movement have been more gradual and progressive. This suggests that the atmosphere's role in influencing sea ice, and the reciprocal relationship, is secondary, in line with findings from various studies (Eayrs et al.,

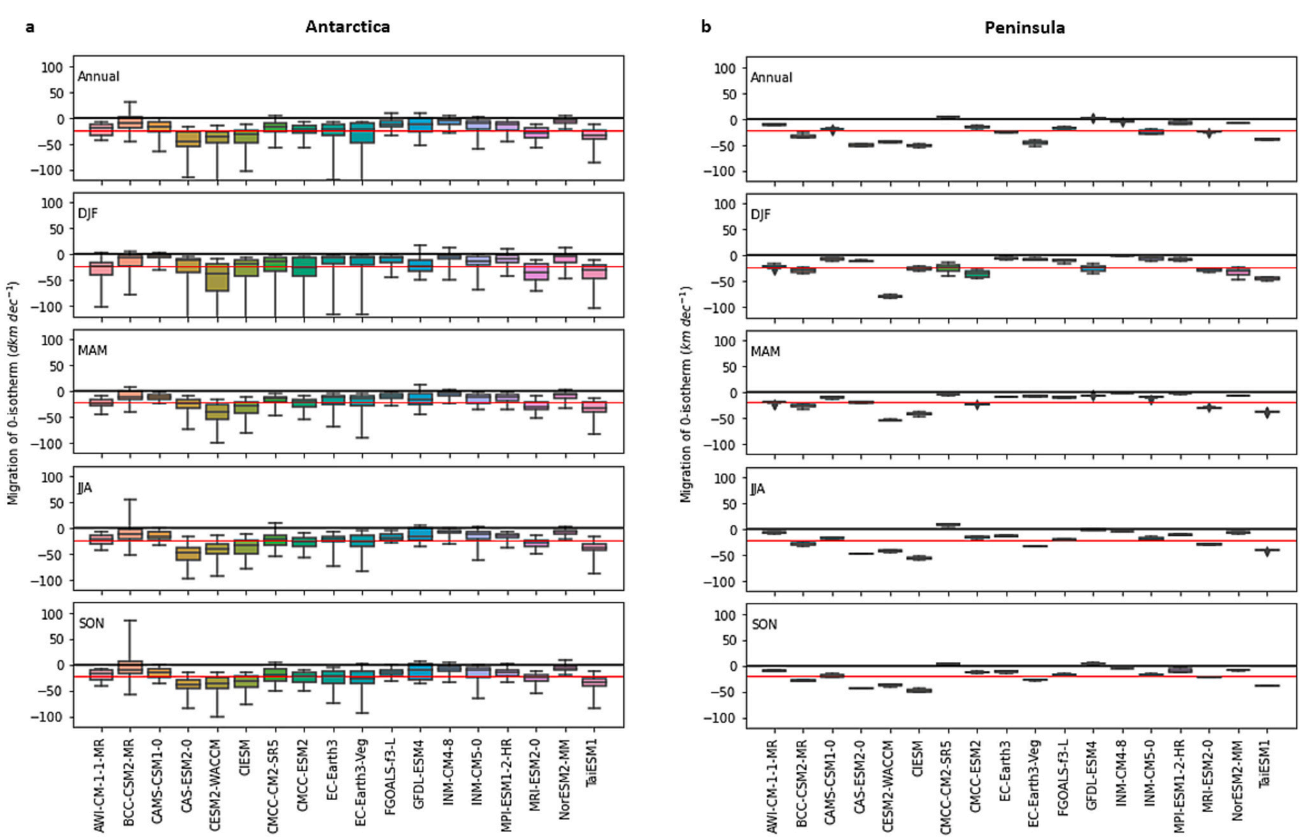

Fig. 7. Boxplots of ZIL trends at every longitude from 2015 to 2099 at the different CMIP6 SSP2-4.5 simulations at (a) the whole Southern Ocean and (b) the AP. Boxes denote the 25th–75th percentile ranges and whiskers span the 1st–99th percentiles. Red lines indicate the mean of the CMIP6 models.

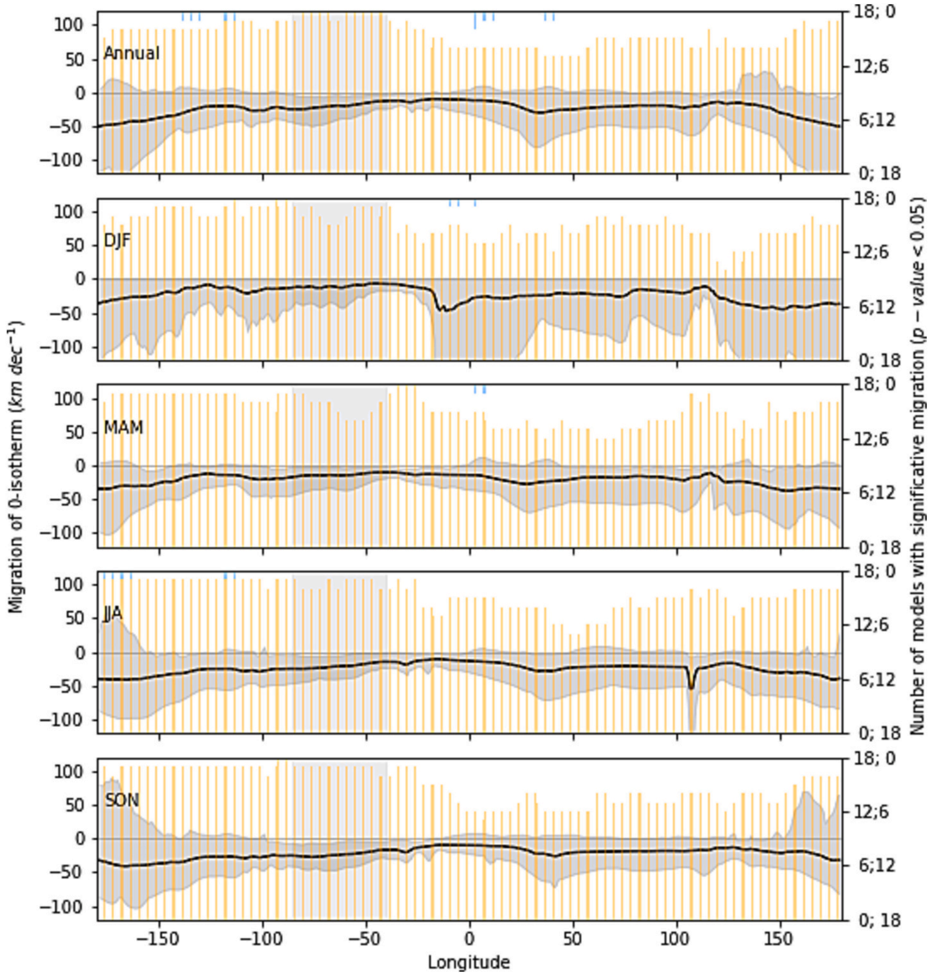

Fig. 8. Mean trends (black line) and standard deviation (grey area) of the mean annual ZIL at every longitude in CMIP6 SSP2-4.5 simulations from 2015 to 2099. Yellow and blue bars indicate the number of models with significative southward and northward migration at every longitude, respectively. Light grey area indicates the position of the AP region.

2021; Meehl et al., 2019; Purich and Doddridge, 2023). While the atmosphere has been recognized as a significant driver of Antarctic sea ice variability (Schlosser et al., 2018; Turner et al., 2022; Yadav et al., 2022), the warm subsurface conditions in the Southern Ocean appear to be the likely driver of large-scale changes (Ferreira et al., 2018; Purich and Doddridge, 2023). A continued lack of sea ice, thinner sea ice, and less snow on top of the sea ice can create feedback that will alter the exchange between the atmosphere and the ocean, ultimately altering the climate over the Southern Ocean and the continent (Raphael and Handcock, 2022). A warmer ocean leads to thinner ice formation, allowing easier breakup by wind and wave action (Raphael and Handcock, 2022). Indeed, the regions experiencing a significant southward migration of the ZIL are associated with positive mean annual changes in sea ice concentration from 1979 to 2018 (Eayrs et al., 2021). The long-term impact of the ZIL on sea ice remains uncertain, and Section 4.7 presents several possible drivers of change.

The connection between ZIL migration and observed changes is most evident on land. Monthly ZIL data that exclusively traverses land are on the AP, and the variations in this region (as depicted in Fig. 3) illustrate the rapid warming observed over the AP until 1998 (Vaughan et al., 2003), as well as changes associated with the cooling period recorded during the early 21st century (Gonzalez and Fortuny, 2018; Oliva et al., 2017; Turner et al., 2016). In this region, ZIL shifts modify the duration of the melting season, a factor not solely determined by latitude as observed in the different stations analysed, underscoring the importance of local conditions. Changes in the ZIL may have far-reaching consequences across various components of the cryosphere and ecosystems. These consequences are discussed in the following sections.

4.2. *Effects of ZIL migration on precipitation and snowpack*

The rising near-surface air temperature is expected to increase surface precipitation by the end of the century at a rate similar to the Clausius-Clapeyron relation. For example, under the high-emission scenario SSP5-8.5 a change of +31 % is expected across the continent (Bracegirdle et al., 2020). This will also probably increase frequency of extreme precipitation events over the AP, which are associated with rain-to-mixed precipitation phases at temperatures close to 0 °C (González-Herrero et al., 2023). Indeed, as the ZIL shifts southwards, the precipitation phase will change and rainfall will be more common in the lowlands along the Antarctic coasts. An increase in liquid precipitation between 4.6 and 11.3 mm y^{-1} has been estimated for the period 2015–2034 to 2081–2100 under the SSP5-8.5 scenario (Vignon et al., 2021). This will also lead to an increase of rain-on-snow events (Würzer et al., 2017, 2016) that will affect snowpack dynamics and albedo, and in turn influence glacial processes and surface energy balance (e.g. Box et al., 2022; Serreze et al., 2021) as well as geomorphological dynamics in ice-free areas (Peeters et al., 2019; Tichavský and Horáček, 2022). As has been demonstrated in other mountain areas of the world, snow dynamics are most sensitive in a temperature regime that fluctuates around 0 °C (Schmucki et al., 2015), which corresponds to the ZIL in polar regions. Given that snowfall is currently increasing in the AP

(Thomas et al., 2017) but temperatures will continue to increase, we expect two counteracting trends. Snow on the AP will continue to increase for some time before it changes to a regime of general reduction driven by the increase of rain versus snow as ZIL migrates. This will also favour higher snowfall variability due to the alternation of warm and cold winters in the region.

4.3. Effects of ZIL migration on permafrost

Permafrost, a key component of the cryosphere, has not been studied in detail in Antarctica with only a few very general studies focusing on the AP (Bockheim et al., 2013; Vieira et al., 2010). Therefore, the effects of ZIL changes on permafrost dynamics in the AP region remain uncertain. Biskaborn et al. (2019) identified a warming permafrost trend in Antarctica of 0.37 ± 0.10 °C from 2007 to 2016, significantly higher than the atmospheric warming (annual mean of 0.10 ± 0.55 °C) and more than the global temperature increase (0.29 ± 0.12 °C). However, the small number of boreholes taken in permafrost studies, and their concentration in a limited number of areas impedes abilities to infer patterns for the entire continent and their connection with ZIL variations. Recently, Hrbáček et al. (2023) examined changes in active layer dynamics over the last 15 years in Antarctica. However, once again the small number of monitoring sites and the high spatial variability of the data prevents drawing trends. Furthermore, factors such as topography, lithology, vegetation, and snow cover influence active layer thickness and therefore make the relation with climate trends challenging.

We hypothesize that future ZIL shifts over the AP will accelerate soil temperature increase as climate warms. Permafrost will thaw in lowland areas of the northern part of the region, accompanied by an increase in the active layer thickness. However, this trend might be counterbalanced by thicker snow cover in some regions, which has also been detected over some parts of the AP region, and this has led to a thinning of the active layer thickness (Oliva et al., 2017). In general, soil temperatures will increase in line with atmospheric warming, although under anomalous local conditions, thinner snow may lead to colder soils (Bender et al., 2020). Therefore, in the southern and eastern sides of the Peninsula, where ground temperatures are not close to 0 °C, ground thermal regimes would shift to warmer conditions with warmer permafrost and thicker active layer in ice-free environments. In addition, following glacial retreat of warm-based glaciers permafrost will form in newly exposed areas and will likely degrade in proglacial environments left by the retreat of cold-based glaciers.

4.4. Effects of ZIL migration on the ice shelves

The effects of the ZIL migration on ice shelves is extremely difficult to quantify, as ice shelves are simultaneously affected by atmosphere-driven and ocean-driven processes. Ice shelves, particularly those in the north-eastern AP coast, are strongly affected by surface melting (Banwell et al., 2023) which, in turn, are governed by the zero-isotherm location. Massive surface melting causes surface meltwater ponding and contributes to hydrofracturing, whereby surface crevasses become filled with meltwater, which increases the pressure tending to open and deepen crevasses, sometimes down to the base of the ice shelf or until they reach a basal crevasse (Banwell et al., 2023; Scambos et al., 2009). When this occurs at a large scale, it can eventually lead to ice shelf disintegration, as occurred in the Larsen A and Larsen B ice shelves in 1995 and 2002 (Rott et al., 1996; van den Broeke, 2005), respectively. Such disintegrations have been attributed to hydrofracturing resulting from intense regional atmospheric warming (Banwell et al., 2013; Scambos et al., 2009). Ice-shelf thinning, however, clearly favours both enhanced iceberg calving and ice-shelf collapses, and much of this thinning is attributed to basal ice-shelf melting by warmer ocean waters (Pritchard et al., 2012). The role of warmer ocean waters, rather than atmospheric warming, has also been identified as the main driver of ice-shelf thinning on the western AP (Hogg et al., 2017). Regarding projections of future evolution, modelling by Edwards et al. (2021) indicates that the ice-shelf collapse scenario has little effect on the projections of ice mass losses from the AP to the end of the 21st century. The effect is small because surface meltwater is not projected to be enough to cause collapses until the second half of the century (Seroussi et al., 2020).

4.5. Effects of ZIL migration on the Antarctic Peninsula ice sheet

Consensus estimates of the mass balance of the Antarctic ice sheet, and in particular of the Antarctic Peninsula Ice Sheet (APIS), did not become available until recently (Shepherd et al., 2012, 2018) due to the large variety of techniques employed, such as the input-output method, laser and radar altimetry changes, and gravity field changes, and to the different periods covered by the various studies. Moreover, the fact that these are mostly large-scale studies impedes easy correlation with the ZIL migration. However, the zero-degree isotherm has already been used to define the surface melt potential over the ice sheet (Orr et al., 2023). Furthermore, as noted in Sections 3.2.1 and 3.2.2, the zero-isotherm only crosses the northernmost part of the AP (Trinity Peninsula, i.e. the region north of ca. 64°S) during summer time (DJF), remaining parallel to the western coast of Graham Land (the region north of ca. 69°S). This suggests that so far there has been little influence of the zero-isotherm location for the bulk of the AP, except on its northernmost part. Of course, a near-future migration of the ZIL further south under global warming is expected to exert a stronger effect on the APIS evolution. This limited influence of the atmospheric drivers is reinforced by recent observations indicating that increased ice flow in the region is unrelated to ice-shelf collapse, in particular in the south-western coast of the AP. This ice shelf collapse can be attributed to thinning of ice-shelves and their tributary glaciers, as well as retreat of marine-terminating glacier fronts by increased calving, both induced by upwelling of warm and saline circumpolar depth water (Cook et al., 2016; Hogg et al., 2017).

Things change when considering future projections. The CMIP6 mean projected locations of the zero-isotherm for 2040–2069 and 2070–2099 cross the AP not only for summer but also for autumn, and at higher latitudes compared to the historical observations and simulations (Fig. 6). Although in recent decades the possible direct effects of the zero-isotherm migration on APIS evolution have been small, and limited to the summer period, its indirect effects have been more relevant. Among these indirect effects of the ZIL migration, the most relevant has been its influence on ice-shelf disintegration, which in turn causes acceleration of the glaciers feeding the ice shelves (Rott et al., 2018). This glacier acceleration has contributed to enhanced mass losses by ice discharge from the APIS, though they have been partially offset by increased snowfall (Fox-Kemper et al., 2021). The mass-loss rates increased from 6 ± 13 Gt a^{-1} for 1997–2002 to 35 ± 17 Gt a^{-1} for 2007–2012, in response to the ice-self collapses in 1995 and 2002, but it stabilized afterwards at 33 ± 16 Gt a^{-1} for 2012–2017 (Shepherd et al., 2018). These indirect effects of the zero-isotherm migration are, however, expected to decrease in the coming decades, because further massive ice-shelf collapses are not projected to be triggered until the second half of the century. In fact, the APIS is projected to show little detectable temperature dependence, due to the approximate balancing of mass changes by snowfall accumulation and ice loss. Furthermore, in most model projections for the AP region the mass gain by snowfall accumulation increases more under high emission scenarios than mass loss, because the latter is predominantly ocean-induced (Edwards et al., 2021).

4.6. Effects of ZIL migration on the mass balance of the peripheral glaciers of the Antarctic Peninsula

The glaciers disconnected from the main body of the APIS are mostly located in the periphery of the AP, particularly on its neighbouring islands. Glaciers on the South Shetland Islands (SSI) or islands surrounding the northernmost part of the AP (i.e. the Trinity Peninsula), such as Vega or James Ross Islands, are particularly relevant, as they are located north of the zero-degree isotherm during the summer. Unfortunately, there exist just three long time series (>10–20 years) of surface mass balance (SMB) observations in this zone (Engel et al., 2018; Marinsek and Ermolin, 2015; Navarro et al., 2013). All of these SMB series started in the 21st century and their records mostly correspond to the recent cooling period observed in the northern AP and the SSI (Oliva et al., 2017). Nevertheless, the zero-isotherm location is expected to have a very high impact on these glaciers, as they are extremely sensitive to temperature changes around 0 °C. The reason is that much of their area is concentrated in relatively narrow altitudinal ranges with summer temperatures close 0 °C. Consequently, relatively small summer temperature changes can produce a shift from melting to non-melting conditions, or vice versa. For example, modelling of melt on Johnsons glacier has shown that mean summer air temperature changes of ±0.5 °C can change the surface melt by ±50 % (Jonsell et al., 2012). These results are consistent with those of Costi et al. (2018) regarding surface melt and runoff modelling based on ERA-Interim reanalysis data, which span a wider geographical area, and cover the entire AP. Although the current mass loss from wastage of glaciers in the Antarctic periphery, and in particular in the AP region (which includes 63 % of them by area) are currently small (Hugonnet et al., 2021; Zemp et al., 2019), substantial increases are projected by the end of the 21st century (Edwards et al., 2021).

4.7. Effects of ZIL migration on sea ice

In the following section we only discuss possible effects on sea ice if temperatures increase over 0 °C, without discussing any other drivers of Antarctic sea ice evolution, which are partly reviewed in Section 4.1. While current sea ice trends in Antarctica are regionally variable and still not well understood (Eayrs et al., 2021; Turner et al., 2013; Yu et al., 2022), it is clear that temperatures close to zero will affect the precipitation phase, increasing the fraction of liquid precipitation, which will likely decrease snow depth (Dou et al., 2021, 2019), which in turn will decrease albedo, increase surface melt, decrease snow ice formation and reduce sea ice cover in general (Webster et al., 2018). Furthermore, as observed in the Arctic, the movement of the ZIL will also lead to earlier melt onset, later freezing, longer melt seasons (Markus et al., 2009) and more heat uptake by the ocean, leading to less ice in the following winter (Perovich et al., 2007). Additionally, as discussed above, increasing frequency of rain-on-snow events following a southward movement of the ZIL will change the thermal properties of the snowpack (insulation from air above) as well as the albedo (Dou et al., 2021; Sturm and Massom, 2016), initiating positive snow–ice albedo feedback and leading to earlier melt onset (Dou et al., 2019). A change in albedo between dry snow and wet snow is in the order of 0.05 to 0.15 (Perovich et al., 2002), depending on snow thickness.

In Antarctica, flooding of the sea-ice surface and the resulting snow-ice formation adds to the variability of sea ice thickness (Arndt et al., 2017; Haas et al., 2001; Massom et al., 2001; Nicolaus et al., 2009). This so-called snow-ice not only changes sea-ice thickness and the resulting thermal and optical properties, but can also change the salinity and brine volume and increase the ocean freshwater budget (Massom et al., 2001). Surface flooding is estimated to affect about 15–30 % of the Antarctic sea ice (Arndt, 2022; Arrigo, 2014). The process of surface flooding in a warmer and wetter climate with more snowfall could stabilize the sea ice cover in future climate scenarios (Fichefet and Morales Maqueda, 1999) by thickening sea ice even under warmer climate conditions. But this is only possible if there is a persistent snowpack with a high albedo that is capable of reflecting most of the shortwave radiation and is heavy enough to keep flooding the ice.

A southward moving ZIL could affect atmospheric physical processes and increase melt-triggering weather patterns, such as enhanced southward transport of warm and moist air (more clouds) which would increase downward longwave radiation and the energy available for surface melt, as has been shown for the Arctic (Mortin et al., 2016). The strong feedbacks between increasing temperatures, which lead to more liquid precipitation and less snow, and an earlier melt onset-longer melt season-later freeze-up in longer melt season have the potential to significantly reduce Antarctic ice cover (as warmer temperatures have done in the Arctic) with large implications for the Earth's energy balance (more heat absorption into the ocean) and marine ecosystems (see Section 4.8).

4.8. Effects of ZIL migration on the marine and terrestrial biodiversity of the Antarctic Peninsula

Changes in temperature affect both the survival and productivity of the living organisms in Antarctica. Specifically, in terrestrial ecosystems the movement of the ZIL south indicates a transition on land from a frozen to liquid state, and liquid water is the essential requirement for life on land (Convey et al., 2014). In the oceans the ZIL signifies the transition from a freezing surface to a melting one, where not only the salinity of local environment changes, but many other factors including light availability and wind mixing increase substantially. There is large productivity at sea ice edges and they move south with the ZIL. For both terrestrial and marine systems and biodiversity the ZIL indicates a significant transition in terms of biological activity and functional capacity. The ZIL migration will have, therefore, a profound impact in the exosystemic self-regulation of the northern AP biodiversity (Robinson, 2022), since the water freeze-point threshold provides a strong limiting factor for much of the biological activity, determining the present and future potential habitability of ice-free areas for organisms (Lee et al., 2022b). For one, the higher water availability associated with the southern migration of the ZIL would increase the overall metabolic activity and net primary photosynthesis of native species, including cryptogams (Beltrán-Sanz et al., 2022) and phaneorogams, yet with different adaptability between the two native vascular species (Sanhueza et al., 2022), altering overall ecosystem functioning. Moreover, it would also alter organic matter consumption and mobilization among primary consumers and the phenology of breeding across the ecosystem including in top predators. Another critical aspect is the effect of accumulated temperatures above zero on the different (and critical) stages of the life cycle of Antarctic terrestrial fauna. Specifically, the frequency of freezing and thawing cycles determines the range of soil invertebrate organisms adapted for surviving in the cold (Bartlett et al., 2020). Exposure to subzero temperatures generates a physiological stress as well as increased mortality from the risk of water crystallization. Thus, southern migration of the zero isotherm brings opportunities for non-native alien species establishment, especially for non-freezing-resistant species, as observed experimentally for a range of soil invertebrates (Bartlett et al., 2020; León et al., 2021; Pertierra et al., 2021, 2020). Current ecological modelling studies on forecasting distributional changes from rising temperatures warn that the existing trends would drastically favour the potential establishment and/or expansion of non-native species (Duffy et al., 2017; Vega et al., 2021). Emblematic native macrofauna, especially apex predators such as penguins, seals and whales will be bound to shift their ranges to re-adjust to the changing environmental conditions and prey availability (Clucas et al., 2014). In addition, since the ZIL is associated with the snow-rain transition, increased amounts of mud, runoff and rainfall due to the southern migration of the ZIL will endanger penguin nests and chicks, endangering breeding success (Demongin et al., 2010; Massom et al., 2006). This would very likely alter the population dynamics across the distribution range with the conditions of some colonies becoming more favourable and other more unfavourable. However, range readjustments can only be possible to new suitable sites that mirror their preferred conditions, and thus habitat loss would affect specialists disproportionately. For instance, a regional catastrophic breeding failure event in emperor penguin colonies of the Bellingshausen sea region was observed in 2022 from the extreme reduction of sea ice extent (Fretwell et al., 2023). This shows that extreme events are affecting, in some instances, the whole regional metapopulation and thus severely limiting any adaptive resilience over years by severely reducing offspring recruitment. Thus, both the periodicity of extreme events as well as the basal performance will be critical aspects to determine the resilience of native organisms of Antarctica to withstand the climate change.

ZIL changes also affect the functioning of Antarctic marine ecosystems. There are three main elements to Antarctic marine ecosystems, intertidal, pelagic and benthic. There is currently no year-round ice-free intertidal habitat on the Antarctic continent, though such habitats do exist on some of the islands around the continent (Peck, 2018). With the southward migration of the ZIL more year-round ice-free intertidal will become available on the islands, and eventually this will extend to the continent. A major concern here is that the most likely non-native species to colonise marine Antarctic habitats in the future will arrive by ship and hence be species that usually inhabit shallow waters (McCarthy et al., 2019). Furthermore, the AP has direct ship connections with a large number of sites across the globe, including cold northern latitudes and the Arctic (McCarthy et al., 2022). Similar to terrestrial environments, ZIL migration will substantially increase the available habitat for non-native species to colonise maritime Antarctica, especially on the AP. Pelagic marine systems in the Southern Ocean are strongly affected by ice cover. There are several aspects of this, including reducing light during spring, until sea-ice has melted, which impacts phenology as well as productivity (Nardelli et al., 2023). There are also species that use under ice, epontic productivity as a food source during winter, including some life stages of krill (Schmidt et al., 2014). Shorter sea-ice seasons result in smaller phytoplankton blooms and a change in balance of large and small phytobionts, with fewer diatoms. This will impact primary consumers differently and alter the food web (Nardelli et al., 2023). The movement of the ice front south with the ZIL is already affecting pelagic ecosystem functioning on the AP, and this will likely accelerate with further southward progression. Ice cover also has powerful effects on life on the seabed, the benthos, where over 90 % of Antarctica's 20,000 marine species live. This includes changes in the frequency of iceberg impacts, because more bergs are produced from retreating glaciers, and the opening of new seabed for colonisation that increases blue carbon sequestration (Barnes et al., 2018). Iceberg scour in shallow sites destroys benthos and can remove all macro-organisms from a site (Peck et al., 1999), though recovery might be more rapid than previously thought (Zwerschke et al., 2021). There is also a pervasive effect of warming in shallow marine sites, and though the ZIL transition does not affect seawater temperatures beyond the very shallowest depths, for organisms living there even a 1 °C rise in temperature can double growth rates in benthos (Ashton et al., 2017) and can cause an even greater change in embryonic development rates (Peck, 2016).

Ultimately, current terrestrial and marine Antarctic ecosystems are facing unprecedent biodiversity re-distribution and alterations to physiological and functional processes that threaten their stability and potentially their very existence (Convey and Peck, 2019).

4.9. Societal costs of the erosion of Antarctica's environments and biodiversity

A dire consequence of the shift in the zero-degree isotherm, is a wide array of derived impacts on ecosystem services (Díaz et al., 2018) provided by the AP region (Pertierra et al., 2021). We have previously provided examples of the various changes in the atmosphere that would affect Earth abiotic regulating systems. Moreover, non-material services from biotic regulation derived from the natural functioning of ecosystems would be also eroded. For instance, those related with carbon sequestration and cycling. Blue carbon stocks in the Southern Ocean are now regarded as one of the world's most important elements of carbon fixation, storage and sequestration (Barnes et al., 2021; Bax et al., 2021). Furthermore, the expected increased metabolic activity of soil organisms in tundra and polar desert ecosystems from higher temperatures will also play an increasing role in mobilizing carbon stocks, causing a positive climate warming feedback (Potapov et al., 2023).

In addition to the regulating services supporting life on Earth, a remarkable diversity of cultural ecosystem services in the region are expected to be affected. Among cultural services, climatic disturbances affect the natural functioning of ecosystems, that subsequently erodes the immense value of scientific study of unaltered biodiversity in an historically semi-pristine (almost unparallelled) environment. This is evident in research topics like paleogeography, ecology and evolution, where ecosystem responses to the Anthropocene hinder the capability to comprehend the natural functioning of ecosystems and to track the history of life in the continent by altering these highly preserved patterns and processes. Moreover, station-based activities of expeditioners of Antarctic Treaty national research programs such as their temporary living conditions, seasonal research windows, freshwater provisioning and resupply logistics can be directly impaired in various ways. Similarly, the historic building heritage preservation and indirectly the functioning of educational recreation hubs such as Port Lockroy (UK) can be equally affected. For instance, buildings can be damaged due to soil destabilization processes. Safeguarding station foundations is already recognized as a growing issue (González-Posada Elechiguerra et al., 2022; Goyanes and Yermolin, 2016), where permafrost thawing has caused a need for repairs and normal scientific activities have been impaired.

In addition, recreational services from the tourist industry in Antarctica will also be affected, similarly to much of the polar tourism on Earth (Shijin et al., 2020). Specifically Antarctic tourist sites of interest will likely readjust in response changing landscapes and iconic species range distribution. This shift has been linked to an increasing ice-free soil availability and diminishing coastal ice extent, profoundly reshaping Antarctic habitats (Lee et al., 2017). Thus, it is expected the ZIL migration would also consequently alter the selection of preferred tourist landing sites by the tour operator industry, and thus increase the associated human footprint in the continent (Pertierra et al., 2017). For example, by following relocated bird colonies that rely on non-soaked soils to nest over the whole breeding period. Furthermore, the isotherm fluctuation directly exacerbates the local human footprint pressure from outdoor activities in the ice-free areas of the region. Snow melting makes vegetation pathways increasingly muddy, and denudated when combined with heavy tourist loads. Modification of local visitation strategies will be required, as has already occurred in Barrientos Island (Tejedo et al., 2016). This will result in furthering the need for relocating visitor sites to new operating localities.

Ultimately, political tensions derived from environmental changes linked to snow and ice melting are likely to grow, posing risks for the preservation of the outstanding symbolic status of international peace and cooperation in the region (Lee et al., 2022a). Ship traffic has increased substantially in Antarctica over the last decade (McCarthy et al., 2022), putting increasing pressure on a limited number of sites, especially on the AP. In the marine realm there is increasing activity attempting to identify biomolecules of value to society, primarily from biotechnology applications (Avila et al., 2008; Clark et al., in press). There are increasing pressures on fisheries that are currently controlled by CCAMLR fishing quota limits and Marine Protected Areas (MPAs), but with shifting thermal regimes such as the ZIL, exploited species ranges will change making control and interactions between regulators and the fishing industry more difficult (Chown et al., 2012). Beyond this, Antarctica is a repository for minerals, the exploitation of which is currently not allowed, but in the medium- and long-term the continuance of this depends on the renegotiation of treaties and the compliance of both treaty and non-treaty parties.

5. Conclusions

As the climate warms in the Southern Ocean, the position of the ZIL will change. Trends in the ZIL provide a measure of the rate at which this change occurs and might be used as an indicator for monitoring overall climate change around Antarctica (Fig. 3). The ZIL southward migration during the period 1957–2020 has been estimated as 16.8 km decade^{-1} for all the continent and 23.8 km decade^{-1} over the AP, accounting for a faster poleward movement than the global mean velocity of temperature changes estimated as 4.2 km decade^{-1} (Loarie et al., 2009). This velocity is expected to further increase to 24 ± 12 km decade^{-1} under the SSP2-4.5 scenario and 50 ± 19 km decade^{-1} under the SSP5-8.5 scenario for all of Antarctica. Corresponding numbers for the AP are 23 ± 17 km decade^{-1} (SSP2-4.5) and between 13 and 95 km decade^{-1}, averaging 56 ± 26 km decade^{-1} (SSP5-8.5). Although the impacts of the southward migration of the ZIL are still uncertain for some components of the cryosphere (e.g. ice shelves and the APIS), important changes are expected in the precipitation phase that will affect snow and permafrost in many deglaciated regions, which might start a series of cascading events with consequences to both terrestrial and marine ecosystems.

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CRediT authorship contribution statement

Sergi González-Herrero: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Francisco Navarro:** Investigation, Writing – original draft, Writing – review & editing. **Luis R. Pertierra:** Investigation, Writing – original draft, Writing – review & editing. **Marc Oliva:** Investigation, Writing – original draft, Writing – review & editing. **Ruzica Dadic:** Investigation, Writing – original draft, Writing – review & editing. **Lloyd Peck:** Investigation, Writing – original draft, Writing – review & editing. **Michael Lehning:** Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data and codes are available in open access repositories.

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Data availability

ERA5 temperature datasets can be downloaded from https://cds.climate.copernicus.eu/. CMIP6 climate projections can be downloaded from https://esgf-node.llnl.gov/search/cmip6/. The dataset generated in this research with the precipitation extremes for each model at every grid point and for different durations are available via González-Herrero, Sergi. (2023). Zero-degree isotherm latitude (ZIL) position over Antarctica: Historical and Projections [Data set]. Zenodo. doi:10.5281/zenodo.10046608. The codes used in this study are available via Sergi González Herrero. (2023). sergigonzalezh/ZIL-Antarctica: Zero-degree isotherm latitude (ZIL) position over Antarctica [Code] (1.0). Zenodo. doi:10.5281/zenodo.10063849.

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