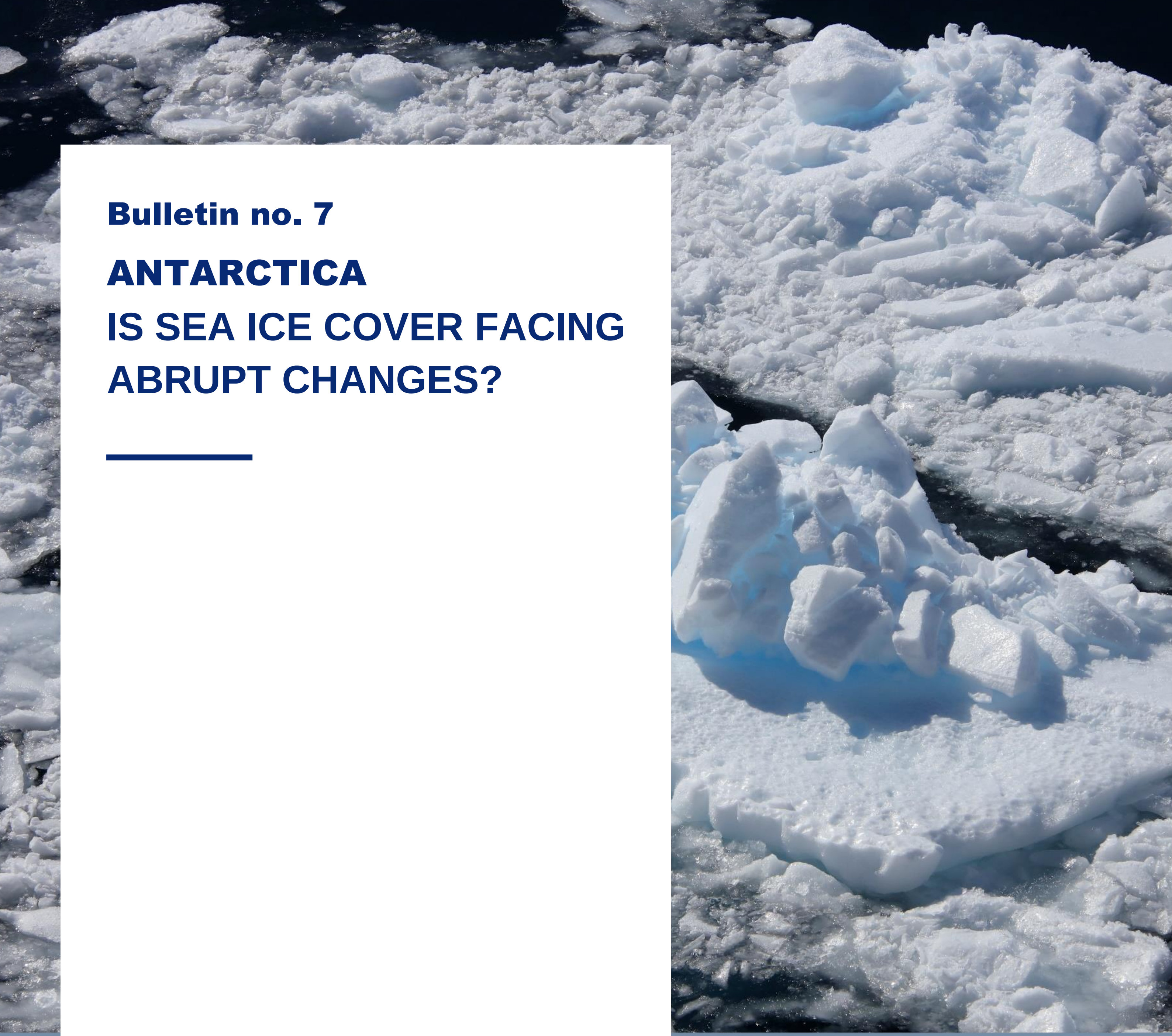

Bulletin no. 7

ANTARCTICA
IS SEA ICE COVER FACING ABRUPT CHANGES?

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POLAR WATCH

Polar Regions Monitoring and Forecasting

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Moving Toward a Critical Transition of the Antarctic Sea Ice System?

Is the sharp decline in Antarctic sea ice cover in spring 2016, followed by exceptionally low ice cover since, including the summer of 2025, signaling a regime shift in the future?

Until the mid-2010s, Antarctic sea ice has stood out from its Arctic counterpart due to its apparent resistance to the effects of climate change. While the latter, an emblematic symbol of the vulnerability of polar regions to global warming took center stage in the scientific debate, satellite observations available since 1978 were demonstrating a relative stability of Antarctic sea ice. Until the early 2000s there was a persistent multi-decadal trend toward an increase in the average annual sea ice extent, even though this increase remained small and statistically insignificant. The trend then accelerated, becoming significant in spring and fall, then for all months until the beginning of 2012 when a period of particularly strong and persistent anomalies began, culminating in the fall of 2015.

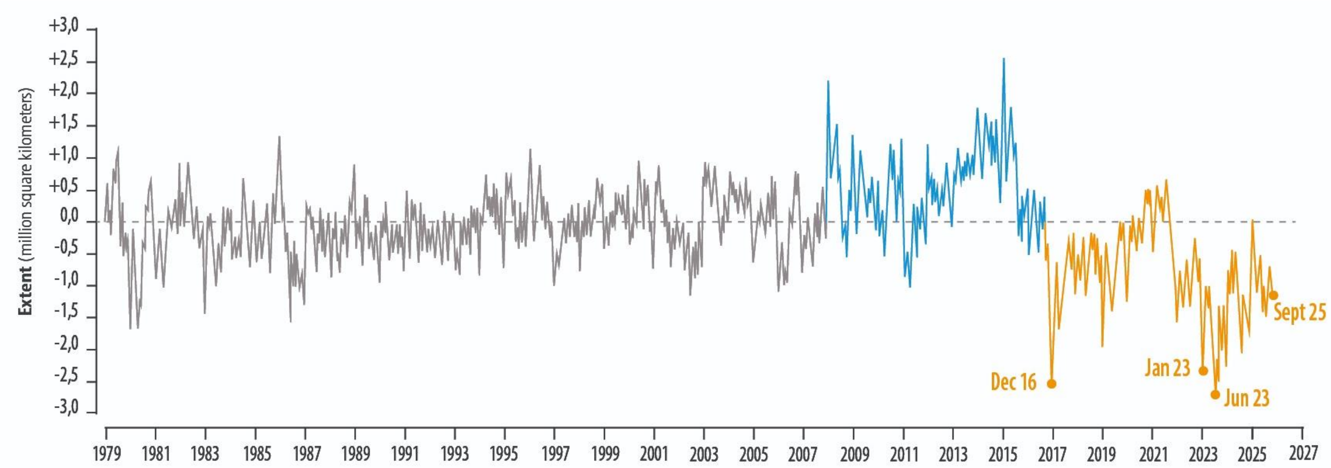

Figure 1: Evolution of the sea ice extent monthly anomalies over the satellite observational period (1979-2025). The time series shows the rapid decay over the last decade (in yellow) after a period of relatively slow increase (in blue) which accelerated in 2012 to culminate in the largest positive anomalies in 2015. These anomalies are calcultated relative to the monthly climatological average over the period 1981-2010. Adapted from A. Purich and E. W. Doddridge, 2023 (*Source: NOAA*) and Zackary Labe, 2025.

> ***'The persistence of negative anomalies in Antarctic sea ice cover since 2016 has revealed the major role of the Southern Ocean'***

A record level of sea ice extent was observed between the winter of 2014 and the fall of 2015, resulting in the strongest positive multi-decadal trend ever estimated since satellite observations began. The greatest daily sea ice extent was observed in September 2014 reaching 20.2 million km^2, which is 1.7 million km^2 above the climatological average for September.

The increase in the average annual extent of the Antarctic sea ice cover for the period 1979-2014 reached +2% per decade relative to the climatological average[1], corresponding to an annual expansion of the sea ice cover of more than 22,000 km^2. This rate was twice the trend that had prevailed before the 2000s, which had always remained below +1% per decade. Record rates were also recorded for the month of the annual minimum (February, +4.9% per decade) and the annual maximum (September, +1.2% per decade) of the sea ice extent.

This trend, which stood in stark contrast to the dramatic and persistent decline in sea ice in the opposite hemisphere (where the average annual extent had been decreasing by around 5% per decade over the same period), could be partly explained by the completely different nature of Arctic and Antarctic sea ice. Unlike its Arctic counterpart Antarctic sea ice is not constrained by continental boundaries at its northern limit and therefore drifts more freely under the influence of winds and currents. The Southern Ocean is dominated by a circumpolar regime of westerly winds, the strongest on the planet, located north of an atmospheric pressure trough formed between latitudes 60°S and 70°S by the numerous depressions that travel around the Antarctic continent. An increase in the intensity of these westerly winds could partly explain the spread of sea ice towards the north.

The modest trends toward an increase in the overall extent of Antarctic sea ice were actually masking a more complex reality not only characterized by strong seasonality, but also by more pronounced regional trends that offset each other on a circumpolar scale. Consequently, strong and significant positive and negative trends had been emerging since the late 1990s in the Ross Sea and Amundsen-Bellingshausen Sea areas respectively. While the sea ice extent increased significantly in the Ross Sea, it declined dramatically in the area west of the Antarctic Peninsula, particularly in terms of its summer extent with a multi-decadal trend exceeding -12% per decade in 2006, a value comparable to those recorded for Arctic sea ice. At the same time, the melting season

[1] The climatological average of sea ice extent is calculated as the average of the extent values over the period 1981-2010. For a given month, it corresponds to the average of the extents for that month.

had lengthened, in some places by almost three months over the period 1979-2012, which, to continue the comparison between the two hemispheres, is twice the lengthening observed in some Arctic areas most affected by the decline in summer sea ice. At the same time the ice season increased by almost two months over the same period in the western Ross Sea.

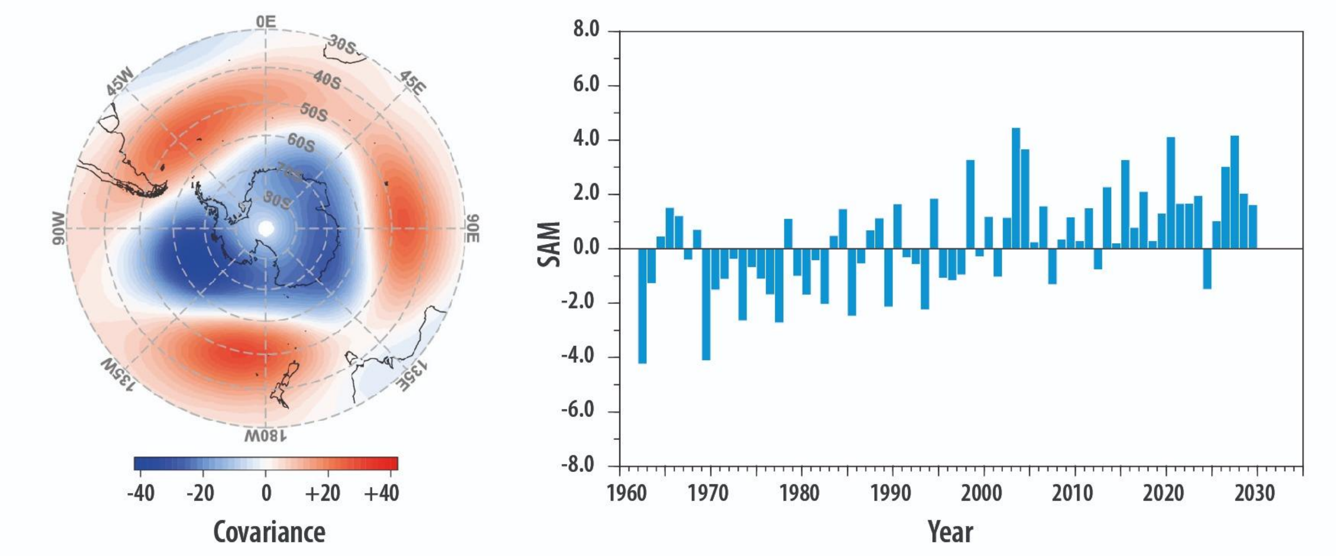

Figure 2: Spatial pattern and time evolution of the Southern Annular Mode (SAM), the principal mode of extra-tropical atmosphere variability in the Southern Hemisphere: (a) SAM-related atmospheric pressure anomalies at 500 hPa; (b) SAM index over the period 1957-2024. *Source: Wachter et al., 2020; NERC-BAS An observation-based Southern Hemisphere Annular Mode Index*.

During the years 2012-2014 scientific debate focused on the causes of what had been dubbed "the Antarctic paradox" [2], namely the expansion of Antarctic sea ice even while the climate was warming, a paradox that some did not hesitate to invoke to question the very reality of global warming. While the variability of surface winds in the Southern Ocean was recognized as a potential contributor to variations in the circumpolar sea ice extent, understanding the causes of this variability, the dynamic or thermodynamic nature of its influence on sea ice, and its regional disparities remained challenging. In particular, the intensity and meridional position of the westerly winds vary on semi-annual, interannual and interdecadal scales, with the dominant expression of this variability being an annular mode, the SAM (Southern Annular Mode). Although interannual variations in the sea ice drift clearly responded to variations in the SAM, the increasingly positive phase of the SAM between 1980 and the end of the last century explained only a small proportion of the multi-decadal trends in the sea ice extent.

[2] King, J., A resolution of the Antarctic paradox, *Nature, 505*, January 2014

Regional contrasts in the evolution of Antarctic sea ice further showed that it did not behave as a coherent circumpolar entity, suggesting the importance of regional wind features. In particular, the role of the Amundsen Sea Low (ASL), a major low-pressure center located in the high latitudes of the South Pacific off the Ross and Amundsen Seas, which has a major influence on the climate of West Antarctica by controlling the variability of meridional winds, proved to be essential. The deepening of the ASL may have contributed to strengthening the relatively warm northerly winds on its eastern flank, promoting the retreat and melting of the sea ice in the Amundsen Sea, while the relatively cold southerly winds on its western flank promoted ice formation in autumn and the northward expansion of the sea ice in the Ross Sea.

The trends observed in both the SAM and the ASL are linked to the increase in greenhouse gases and the widening of the ozone hole, even if this relationship with anthropogenic forcing is not always clear. Atmospheric variability around the Antarctic continent is also closely linked to natural multi-decadal variability in tropical regions (particularly related to variations in ocean surface temperature) via atmospheric teleconnections. Accordingly, the influence of climate indices such as ENSO (El Niño Southern Oscillation), the IPO (Interdecadal Pacific Oscillation), and even the AMO (Atlantic Multidecadal Oscillation) is particularly significant in the South Pacific sector of Antarctica.

The deepening of the Amundsen Sea Low between 2000 and 2014 following the IPO's shift into its negative phase contributed to the redistribution of the sea ice responsible for the dipole anomaly between the Ross Sea and the Amundsen-Bellingshausen-Weddell Seas. ENSO in its La Niña phase, coupled with SAM, may also have reinforced the ASL and thus delayed the advance of the sea ice to the west of the Peninsula in the fall. All these links have been factors, both anthropogenic and natural, that contributed to the multi-decadal variability of the sea ice cover.

The mechanisms highlighted above did not take into consideration the possible influences of the ocean on sea ice. However, the Southern Ocean has undergone profound changes in recent decades, including a surface cooling by approximately -0.1°C/decade between 1980 and 2010, which contrasted with the warming of the water column below the surface layer, and with the more global ocean warming linked to the increase in atmospheric greenhouse gas concentration. The concomitant decrease in the ocean surface salinity may have facilitated sea ice growth in the fall and limited its melting in the spring by maintaining a stable subsurface stratification (measured by the density difference between the surface layer and the layer underneath) that isolates sea ice from the warmer waters below. Numerous positive and negative feedbacks between the ocean and the sea ice can thus amplify or limit the actual impact of the ocean on the sea ice.

The sharp decline in the Antarctic sea ice extent in spring 2016, followed by exceptionally low sea ice extents since then, marked a major transition while highlighting the central role of the ocean in the observed changes. The marked decline in the annual minimum of the sea ice extent recorded in 2016 was triggered by exceptional atmospheric circulation anomalies, including a negative SAM event and a transition to a positive IPO, an amplification of the low-high pressure systems around Antarctica, and an intensification of the meridional winds, which resulted in a massive transport of relatively warm air towards the ice pack. December 2016 thus recorded an anomaly of the monthly sea ice extent of an amplitude unmatched since 1979, exceeding -2 million km^2.

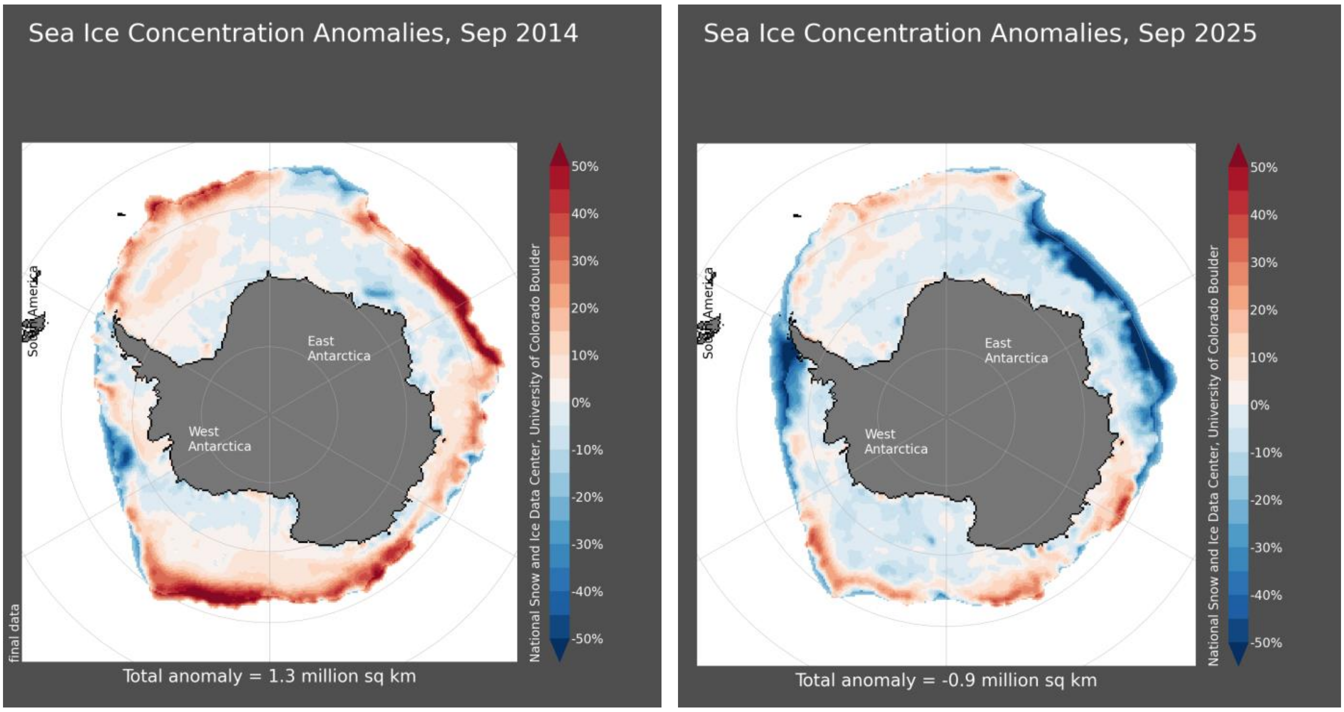

Figure 3: Distribution of monthly sea ice concentration anomalies (concentration defined as the percentage of a given ocean area covered by ice) at the annual maximum of sea ice coverage: (a) September 2014, as the year of maximum positive anomaly over the period 1979-2025, highlighting the sea ice anomaly dipole between the Amundsen-Bellingshausen Sea and the Ross Sea; (b) September 2025, as the most recent year highlighting the now predominating negative concentration anomalies, including in a wide sector off East Antarctica. *Source: NSDIC.*

Over the following decade and until today, the monthly extent anomalies have remained negative and of high amplitude, with the exception of a short period between 2020 and 2021, which saw a rebound to extents closer to climatology. The year 2023 was exceptional, with a dramatic early winter decrease in the sea ice extent leading to a new monthly anomaly record of -2.4 million km^2 in July 2023 (unmatched to date), and the lowest average annual extent ever recorded.

After a slow but significant increase in its extent over several decades Antarctic sea ice was then subject to a very rapid decline, representing a radical change. On a multi-decadal scale 2023 marks a pivotal year in the trend in the average annual sea ice extent: positive (0.18% per decade) over 1979-2022, it became negative (-0.28% per decade) over 1979-2023. Trends in the average monthly extents since 1979 are now negative, although not significant, even though in 2025, February (annual minimum) and September (annual maximum) ranked 4th and 3rd respectively among the least ice-covered months since 1979. A very significant trend in the sea ice extent decrease has thus developed over the last decade: since 2014, the average annual extent of Antarctic sea ice has decreased by 2.9 million km^2, a decrease 1.5 times greater than that experienced by Arctic sea ice in 45 years.

The persistent decline in Antarctic sea ice since 2016 is the result of a decisive contribution from the ocean. While the sea ice retreat in 2016 certainly benefited from the warming of surface waters around the Antarctic continent (which was the ocean's rapid response to the sudden change in atmospheric circulation that year) it also probably benefited from the cumulative effect of the sustained intensification of westerly winds during the preceding decades. This resulted in a gradual upward lift of the warmer subsurface waters. The heat content of these waters, which became more readily accessible to the surface layer during winter episodes of vertical mixing, may have contributed to limiting sea ice growth over the last decade.

When viewed in a longer-term context thanks to sea ice extent reconstructions, the recent decline in Antarctic sea ice is unprecedented in terms of its rate and magnitude over the last 100 years. It could therefore be interpreted as an acceleration of a slower decline that occurred throughout the 20th century. In this context, the period of extended sea ice cover responsible for the positive trend during the satellite period, or the negative trend of the 1960s that led to low ice cover at the beginning of the satellite observation period, would be a manifestation of decadal variability superimposed on multi-decadal trends. While the 2016 event and the persistence of reduced sea ice cover since then are partly a manifestation of the natural variability of the climate system (particularly in the tropics) there has been a warming of the deep waters in the Southern Ocean over recent decades. This is a manifestation of climate change and could well contribute to maintaining, or even reinforcing through positive feedback, the negative trend in the sea ice extent that we are seeing today.

Beyond the reduction in its extent, Antarctic sea ice as a dynamical system appears to have entered a new "regime"[3]: the spatio-temporal characteristics of its variability have changed radically, with ice extent anomalies now being larger in amplitude, more persistent, and more spatially coherent. The current amplitude of the monthly and interannual variability is well beyond the natural variability of Antarctic sea ice over the last few centuries and could indicate the beginning of a critical transition to come. The longer persistence of anomalies suggests a growing inability of sea ice to recover from the disturbances it faces. Finally, the greater coherence of the variability between the different regions around Antarctica reflects the growing influence of the ocean on a circumpolar scale through self-sustaining interactions with the ice. Examples of such interactions include the link between a decrease in sea ice thickness, its anticipated retreat in spring, and subsequent ocean warming; or the recent evidence of a circumpolar increase in the surface salinity of the Southern Ocean, correlating with the decline in the sea ice cover since 2016, which reflects a decrease in subsurface stratification and an increase in ocean heat flux to the ice.

It is difficult to conceive of what this new Antarctic sea ice regime is telling us about its future evolution. To date, climate models, the main tools used for climate projections, show significant bias when it comes to reproducing even the mean characteristics of Antarctic sea ice. This lack of capacity is largely due to the complex nature of the ice pack, both in terms of its physical characteristics and formation mechanisms involving the snow cover and its dynamic response to the exceptionally intense storms and swells prevailing in the Southern Ocean. The result is an environment with highly diverse and variable structural morphologies, a heterogeneous and often fragmented pack, but also highly deformed multi-year ice along the coastline, which all constitute a challenge for models regarding their representation.

Models also struggle to accurately represent the observed sea ice variability and trends. In particular, models inappropriately simulate a decrease in the overall extent of Antarctic sea ice over the period prior to 2015, with large disparities between simulations. This poor performance is a real problem when it comes to making projections as simulated current trends are likely to be partly reflected in future trends. According to the IPCC's 6th report published in 2021, while models predict a decrease in sea ice in a warming scenario by the end of this century, the level of confidence in these

[3] A regime shift is a large amplitude, often sudden, change of a system state to a long lasting, radically different state. In climate sciences, a regime shift can be linked to a tipping pint when the system state evolves beyond a critical threshold.

projections remains very low. Despite recent evidence of radical changes underway and the potential for certain interaction mechanisms to drive Antarctic sea ice toward abrupt change in the future, the recently published Global Tipping Points Report 2025[4] confirms the high levels of uncertainty surrounding the probability of occurrence of such a change and its possible reversibility.

Resolving these difficulties requires a better understanding and representation of the interactions and couplings between sea ice and the other components of the climate system, such as the ocean and atmosphere, but also ice shelves and marine terminating outlet glaciers of the Antarctic Ice Sheet, and their variability. For example, the inability of models to represent the pre-2015 trend in Antarctic sea ice is generally attributed to the presence of a warm ocean bias over this period in the simulations. Quantifying the respective roles of these different components in the multi-decadal trends observed in sea ice is also essential for assessing the proportion of natural variability versus anthropogenic variability in these trends and understanding their predictive capacity. The lack of observations, including long-term observations, is a major obstacle to a more detailed understanding of sea ice and to contextualizing its variability. Difficulties in accessing the Southern Ocean and the waters on the Antarctic continental shelf make this area the least observed part of the ocean. Unlike the Arctic Ocean these regions have not benefited from large-scale deployments of autonomous measuring devices such as buoys and drifting stations, even though such devices are urgently needed if we are to move towards a synoptic and continuous view of Antarctic sea ice and its changes. This view is necessary if regional and global impacts of a persistent decline of the Antarctic sea ice cover are to be anticipated for the oncoming decades. Some of these impacts are already at play and detectable, for instance on the Southern Ocean and its capacity to absorb the excess of atmospheric heat and carbon dioxide, and in fine to regulate global climate.

Marie-Noëlle HOUSSAIS[5] for POLAR WATCH[6]

[4] Lenton, T. M., et al. (eds), 2025, *The Global Tipping Points Report 2025*. University of Exeter, Exeter, UK.

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[6] The views expressed in this article are those of the author. They do not reflect the official policy or position of any entities of which the author is or was a member.

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