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Exploring the Antarctic Circumpolar Current: A Five Million Year Climate Journey Synchronized with Earth's Orbital Symphony

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On March 27, 2024, Frank Lamy, Gisela Winckler, Helge W. Arz, and scientists from various global research institutions published a research paper in Nature titled “Five million years of Antarctic Circumpolar Current strength variability.” The research team, through analyzing sediment cores from the seafloor of the southern Pacific Ocean, unveiled the long-term variability of the Antarctic Circumpolar Current (ACC) strength since the late Neogene. As the largest oceanic current system on Earth, the ACC has profound effects on global climate patterns, ocean circulation, and the stability of the Antarctic ice sheet. The study found that over the past five million years, the strength of the ACC did not show a linear trend but experienced a shift from intensification to weakening over a scale of millions of years, closely related to Earth's orbital cycles and the reconfiguration of the Southern Ocean. This discovery provides important new insights into the role of the ACC in the global climate system and for predicting future climate change.

1 Analysis of Experimental Data

In this study, scientists utilized two key sediment cores from the Southern Antarctic Zone (SAZ) at approximately 3 600 meters depth, gathered during the 383rd voyage of the International Ocean Discovery Program (IODP), sites U1540 and U1541. By analyzing the composition of microfossils, isotopes, and soluble salts within these sediment cores, the team was able to trace the changes in the ACC’s strength over the past five million years. Notably, these sedimentary records contain information on changes in both the ACC’s strength and the ocean surface temperature and salinity of the region, providing valuable data for understanding how the ACC responds to global climate changes. The study of sortable silt within the sediments allowed the team to infer variations in the speed of bottom water flow, a crucial indicator of ACC strength. The comprehensive analysis of these data revealed significant changes in ACC strength throughout past geological periods, offering a window into how the world’s largest oceanic current system responded to environmental transitions.

Figure 1 depicts the simulated ocean velocity of the modern ACC at a depth of 100 meters, with blue representing weaker flows and white indicating stronger flows. This model, based on the Finite-volumE Sea ice - Ocean Model (FESOM2) under the ROSSBY4.2 setting, showed ACC fronts derived from satellite altimetry from north to south as follows: NB (north boundary), SAF (Subantarctic Front), PF (Polar Front), SACCF (Southern ACC Front), and SB (Southern Boundary). Core and drilling locations are marked with white stars, providing direct data support for studying changes in the ACC.

Figure 2 shows the historical changes in temperature and atmospheric carbon dioxide content recorded in Antarctic ice cores, as well as the variations in ACC strength. The black and blue curves respectively represent temperature changes in the EPICA Dome C ice core and atmospheric CO_2 concentrations, displaying notable glacial-interglacial cycles. The colored curves show the reconstructed values of ACC strength at different sites, indicating fluctuating trends over time. The changes in ACC strength are temporally correlated with the temperature and CO_2 records, particularly a decrease in ACC strength during glacial periods and an increase during interglacials. This reflects the critical role the ACC plays in the global climate system, especially its regulatory effect on past climate changes. The records from seabed sediments further confirm these variations, providing essential data for studying Antarctic climate history and ACC dynamics.

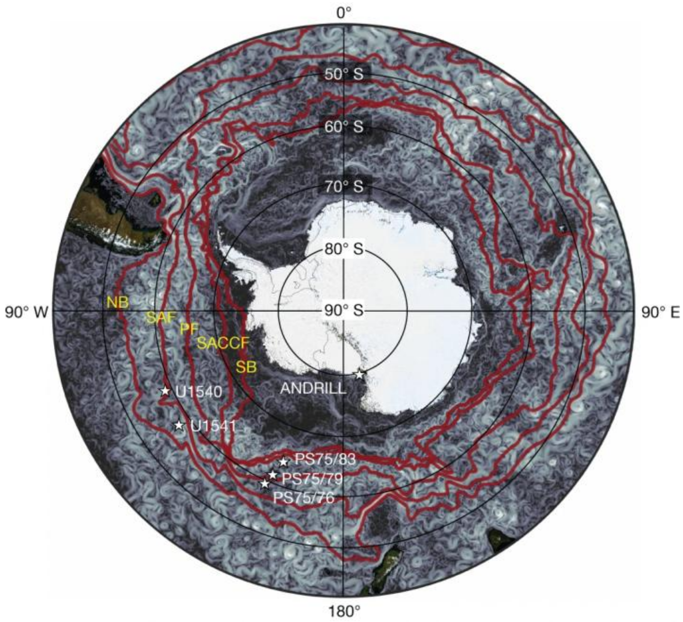

Figure 1 Visual display of modern Antarctic circulation

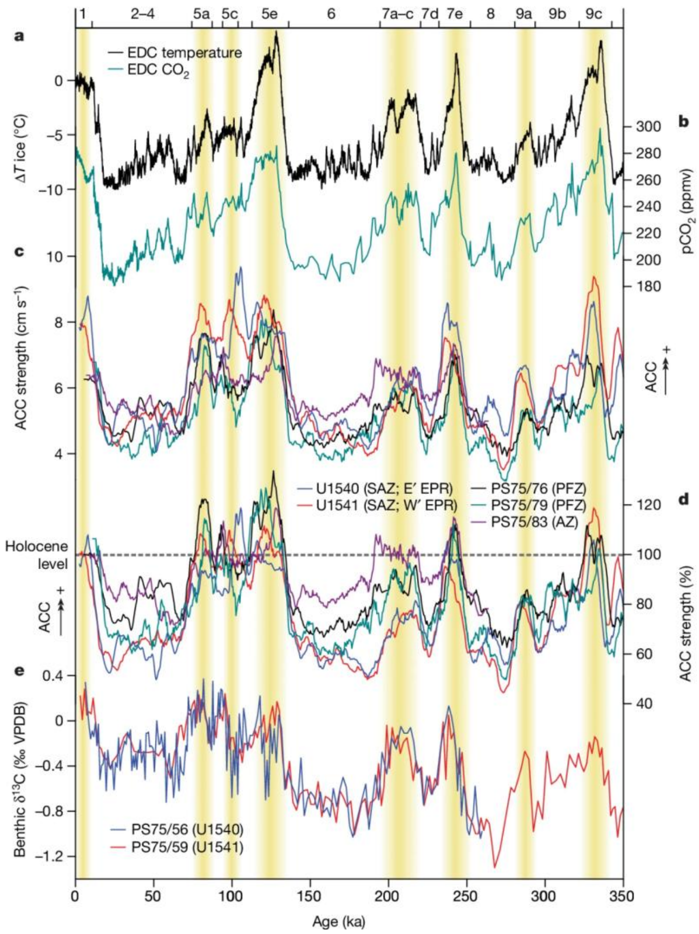

Figure 2 ACC strength changes over the past three glacial cycles

Figure 3 presents the development of the ACC over the past 1.5 million years. The black curve represents the accumulation of oxygen isotopes from benthic foraminifera, revealing changes in ocean temperature and ice volume. The blue curve shows the atmospheric CO_2 content recorded in Antarctic ice cores, with both collectively presenting the history of Earth's climate changes. The red curve represents the relative ACC strength changes at the entrance of the Drake Passage, core PS97/93, while other colored curves indicate the relative ACC strength changes at sites U1540, U1541, and core PS75/76. These data show that during the early Mid-Pleistocene Transition (MPT), the ACC experienced a noticeable increase in strength. Lastly, the black, blue, and red bar graphs reflect changes in the content of biogenic opal (Opal) in sediments at different locations, providing paleobiogeographic evidence of past changes in the ACC. The comparison of these multiple records reveals the complex connection between the ACC and global climate transitions.

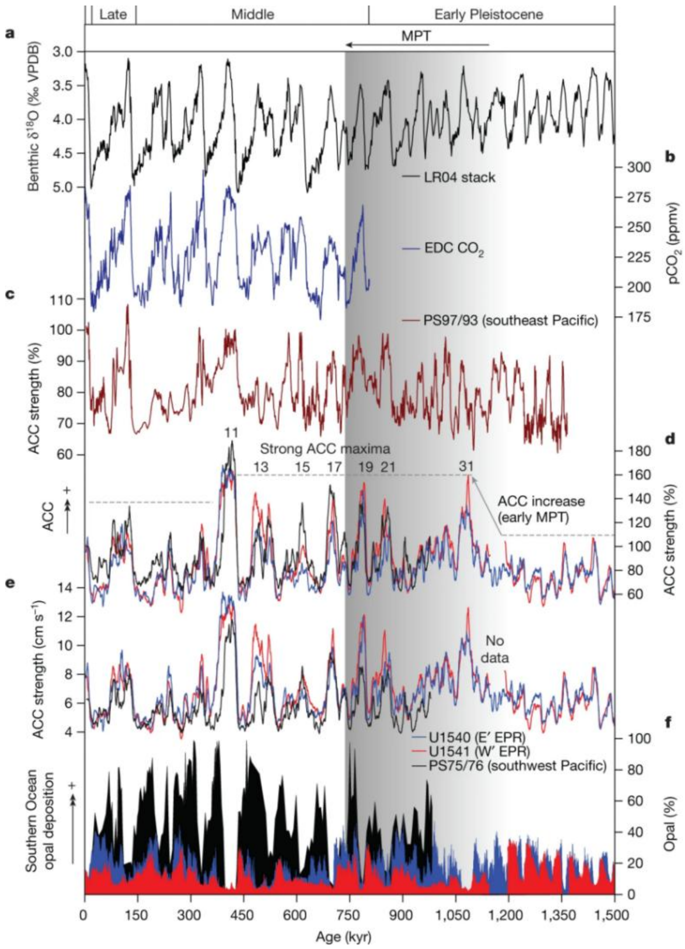

Figure 3 ACC development over the past 1500 kyr

Figure 4 details the development history of the ACC since the Pliocene. The black line represents the long-term record of oxygen isotopes from benthic foraminifera, reflecting ocean temperature changes over the past several million years. The model data, combined with the ice sheet expansion reconstruction results from ANDRILL (AND-1B), depict the ice dynamics in the Ross Sea. The red and blue curves represent the measured changes in ACC relative strength at sites U1540 and U1541, while the black smoothed line reveals the trend of ACC strength over a million-year scale. Additionally, the figure shows the magnetic susceptibility record of the East Asian monsoon intensity, changes in the North Pacific carbonate accumulation rate, and variations in the ratio of biogenic opal to $CaCO_3$ at sites U1540 and U1541. These are important indicators for understanding the historical strength variations of the ACC. Figure 4 provides valuable historical evidence for studying the global climate system and the role of the ACC within it.

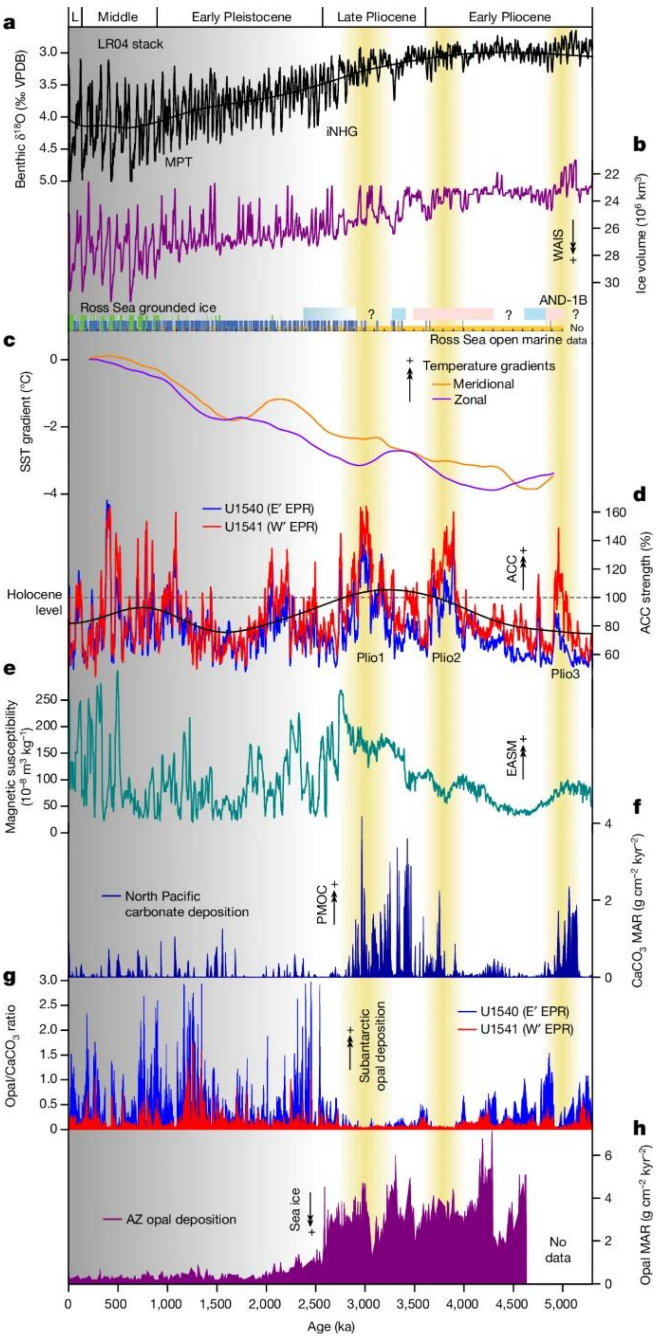

Figure 4 ACC development since the pliocene

Figure 5 with three idealized cross-sectional diagrams, vividly displays the million-year trends of ACC strength and their driving forces during three different geological periods: the Early Pliocene, the Late Pliocene, and the Early Pleistocene (about 1.5 million years ago). Each diagram depicts a north-south transect from Antarctica across the Pacific. Figure 5a shows the weaker Southern Westerly Winds (SWW) and Antarctic ice sheet (AIS) during the Early Pliocene, as well as smaller ocean temperature gradients. Figure 5b shows that during the Late Pliocene, the strengthening of the SWW and the increase in ocean temperature gradients led to an intensification of the ACC. Figure 5c shows that after the Early Pleistocene, following the reconfiguration of the Southern Ocean and the growth of the Northern Hemisphere ice sheets (iNHG), the ACC strength was affected by changes in several oceanic and atmospheric processes, such as the strengthening of the SWW, changes in ocean temperature gradients, and the intensity of the East Asian Monsoon (EASM). These pattern changes indicate complex interactions between ACC strength and the Antarctic ice sheet.

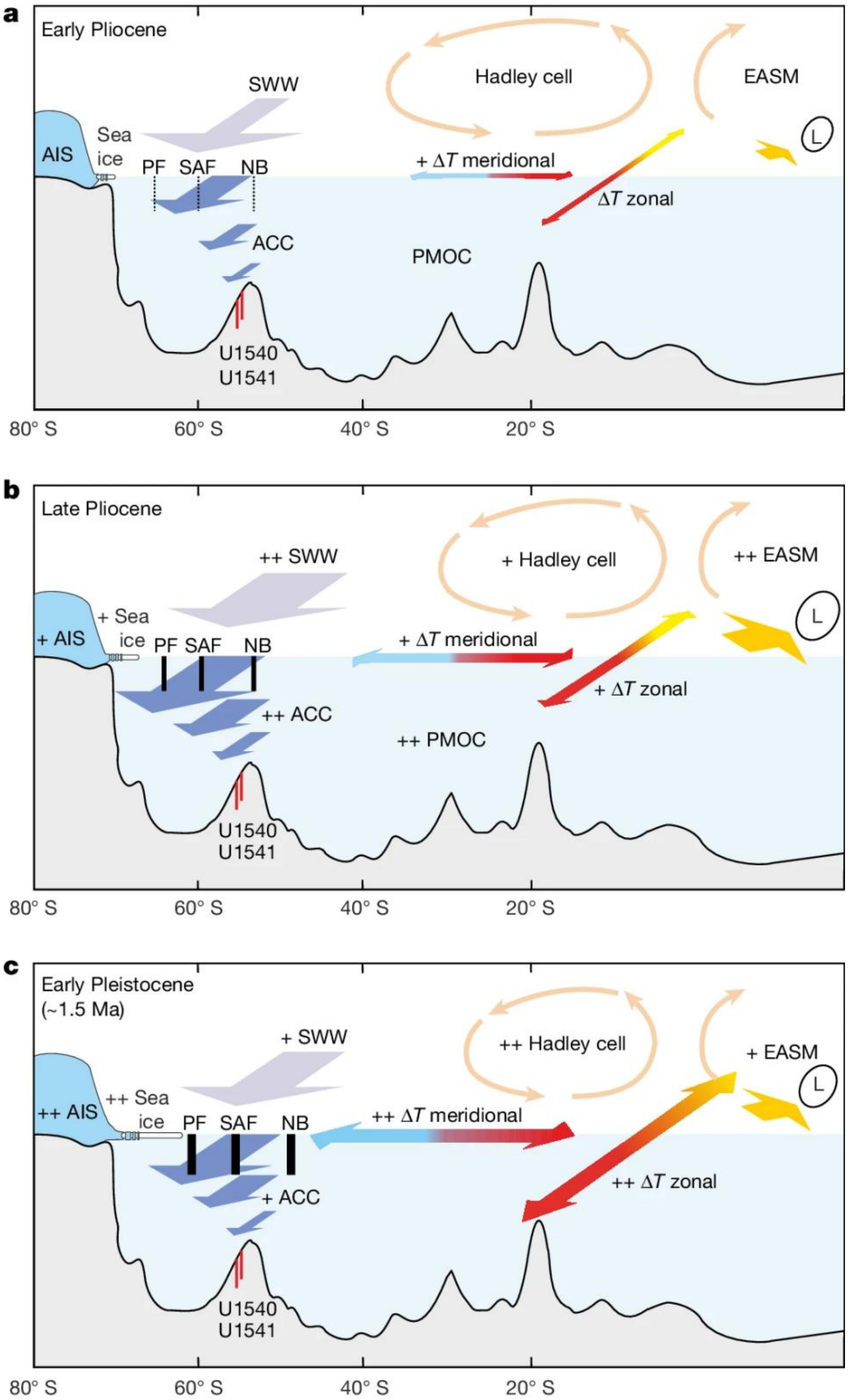

Figure 5 Schematic illustrating key atmospheric and oceanic processes influencing million-year trends in ACC strength

2 Analysis of Research Results

The study reveals that changes in ACC strength are closely connected to Earth's orbital parameters, especially the approximately 400 000-year eccentricity cycles of Earth's orbit. This finding suggests that the long-term variations of the ACC are influenced not only by local oceanic processes but also by global climatic changes driven by Earth's orbital cyclical changes. Under the regulation of orbital cycles, changes in the South Pacific Jet might adjust ACC strength by altering wind-driven ocean surface circulation and the pattern of deep water upwelling, further influenced by temperature variability in the tropical Pacific.

The variations in ACC strength are closely related to the development of the Antarctic ice sheet. Periods of weakened ACC strength typically correspond to the expansion of the West Antarctic ice sheet. This could be due to a weaker ACC reducing water exchange in the surrounding seas, leading to lower local ocean temperatures and favoring ice sheet expansion. Conversely, during periods of strengthened ACC, the ice sheet tends to retract. This pattern suggests that the ACC plays an important role in regulating Antarctic climate and ice sheet dynamics.

It is noteworthy that these long-term changes in ACC strength over the past few million years were not uniform but displayed significant turning points that matched Earth's orbital cycles. Particularly during the Mid-Pleistocene Transition (MPT), as Earth's climate shifted from approximately 41 000-year glacial-interglacial cycles to about 100 000-year cycles, there was also a clear shift in ACC variability patterns. This may indicate that during the MPT, the ACC responded to a fundamental reorganization of deep ocean circulation and global ice volume changes.

3 Research Evaluation

The outstanding contribution of this study lies in the high-precision geological records it provides and the detailed analysis of historical strength changes in the Antarctic Circumpolar Current (ACC). The fine interpretation of paleoclimatic data not only consolidates our understanding of the role of the ACC in the global climate system but also offers new insights into its function in the climate changes of the past few million years. Notably, the study highlights the direct correlation between ACC strength variations and Earth's orbital cycles, revealing complex interactions between the ocean and atmosphere within the global climate system. Moreover, the interaction between the ACC and the Antarctic ice sheet is crucial for understanding the transitions of Earth's glacial-interglacial cycles, providing valuable historical references for predicting future climate changes. Overall, this research deepens our understanding of Earth's paleoclimatic mechanisms and offers critical calibration points for models simulating future climate changes.

4 Conclusion

This study demonstrates the ACC as a dynamic system, whose variations are influenced by a combination of factors, including Earth's orbital periodic changes, atmosphere-ocean interactions, and polar ice sheet dynamics. These changes of the ACC have profound implications for the global climate system. The results emphasize that future climate models and predictions must consider this complex natural variability of the ACC and its central role in the Earth system. The ACC is not only an indicator of past climate change but may also be a key factor in the stability of future climates. By understanding its past behavior patterns, we can better predict the likelihood and extent of future climate changes, thereby formulating more scientific strategies to address global climate changes.

5 Access the Full Text

Lamy F., Winckler G., Arz H.W., Farmer J.R., Gottschalk J., Lembke-Jene L., et al., 2024, Five million years of antarctic circumpolar current strength variability, Nature, 627(8005): 789-796. https://rdcu.be/dDtoS

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