The deep Southern Ocean is key to more intense ice ages

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Researchers from the University of Bern analysed a 169-metre-long sediment core collected at the bottom of the Southern Ocean by the research vessel JOIDES Resolution, in conjunction with the International Ocean Drilling Project (IODP). Credit: IODP

Over the last million years, ice ages have intensified and lengthened. According to a study led by the University of Bern, this previously unexplained climate transition coincides with a diminution of the mixing between deep and surface waters in the Southern Ocean. The study confirms that the Antarctic region plays a crucial role during periods of climate change.

An analysis of marine sediments collected at a depth of more than 2 km has just provided an answer to one of the riddles of the earth's climate history: the mid-Pleistocene transition, which began around one million years ago. Thereafter, ice ages lengthened and intensified, and the frequency of their cycles increased from 40,000 years to 100,000 years. The study, which appeared in the journal *Science*, shows one of the keys to this phenomenon lies in the deep waters of the Southern Ocean surrounding Antarctica.

Ocean waters contain 60 times more carbon than the atmosphere. Consequently, small variations in the carbon dioxide (CO_2) concentration of the waters play a major role in climate transitions. Led by Samuel Jaccard, SNSF Professor at the University of Bern, the new study traced the evolution of mixing between deep and surface waters in the Southern Ocean. Mixing is a major factor in the global climate system, because it brings oceanic CO_2 to the surface, where it escapes into the atmosphere.

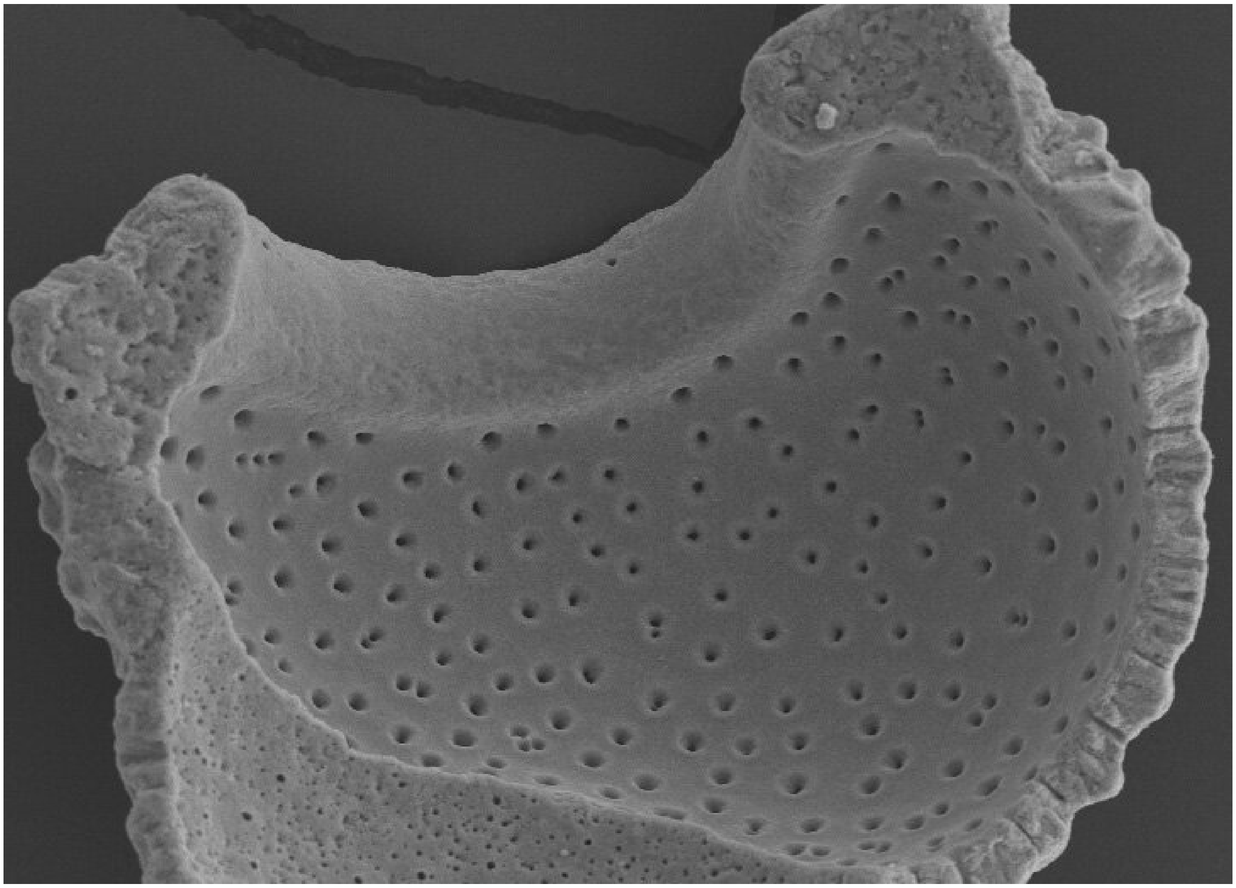
The findings show that mixing was significantly reduced at the end of the Mid-Pleistocene Transition, about 600,000 years ago. Moreover, they explain how the reduced mixing diminished the amount of CO_2 released by the ocean, which in turn reduced the greenhouse effect and intensified ice ages. The study thus sheds light on feedback mechanisms capable of significantly slowing or accelerating ongoing climate change.

"The dynamics of the global climate system are very complex", says

Samuel Jaccard. "Concentrations of atmospheric greenhouse gases, especially CO_2, play an important role. They are obviously linked to emissions due to human activities, but also to natural phenomena and especially to degassing of carbon dioxide contained in the oceans. Mixing plays a very important role in this case, because it brings the dissolved CO_2 from the deep waters to the surface, from where it is transferred to the atmosphere and contributes to the greenhouse effect. A better understanding of these phenomena is crucial, because they are also a factor in present-day global warming."

Consequences for global warming

The researchers determined the difference in salinity and temperature between the surface and deep waters, because these two factors determine the intensity of mixing, among other things. The findings show that two opposing processes have intensified during the climate transition to longer ice ages: the surface waters became simultaneously colder and less salty.



Chemical analysis of these shells (found in marine sediment below the Southern Ocean floor, and seen here under an electron microscope) enabled researchers to trace the evolution of water mixing, a crucial phenomenon in climate transitions. These foraminifera live either at the ocean bottom, or in the surface waters (picture). Credit: Adam Hasenfratz / University of Bern

As a result, the mixing of layers decreased considerably during ice ages. By reducing the amount of CO_2 released by the oceans into the atmosphere, this phenomenon helped to lessen the greenhouse effect and prolong a cold climate, thus ushering in a period of "global cooling", says Jaccard. "This is a typical example of a feedback loop: mixing diminishes, and precipitation and glacier melt accumulate at the surface of the ocean and stay there for a longer time; that in turn decreases the salinity and density at the water surface, reinforcing the attenuation of the mixing process."

These results are relevant to the current situation, says Jaccard: "In recent decades we've observed more intense westerly winds as climate warms, which promotes mixing and thus release of oceanic CO_2 into the atmosphere. But this trend could be compensated by other effects: for example, a warmer climate could increase precipitation and glacier melting, thereby adding freshwater to the surface. We cannot yet predict what will happen; we need climate simulations to better understand how the circulation dynamics of the Southern Ocean will evolve in the future."

Getting down to the nitty-gritty

The historical reconstruction of the ocean mixing was done using a sediment core 169 metres long, taken from beneath the ocean floor at a depth of 2800 metres, some 2500 km off the coast of South Africa. The core was extracted during the 1990s as part of the International Ocean Drilling Project (IODP) and stored since then in Germany. The team had access to the core through Switzerland's active participation in the IODP, which has been supported by the Swiss National Science Foundation.

During his Ph.D. at ETH Zurich, Adam Hasenfratz cut the core into thousands of centimetre-thick slices, each corresponding to roughly a century's worth of deposits. From each slice, he isolated and analysed shells from foraminifera, protozoa with a calcite skeleton. The chemical composition of the shells depends on the marine conditions during the shells' formation, in particular salinity and water temperature.

"At first, all the experts told us that our project was doomed because the number of foraminifera would be too small to carry out the necessary chemico-physical analyses", says Samuel Jaccard. "But Adam succeeded in developing new techniques which allowed him to analyse very small quantities of material. This enabled us to trace the evolution of the salinity and the water temperature." Hasenfratz identified two species that live either on the ocean floor (Melonis pompilioides) or at the ocean surface (Neogloboquadrina pachyderma). That enabled him to obtain information on the temperature and salinity of both deep and surface waters over a period of more than a million years.

As it happens, the ratio of magnesium to calcium present in a foraminifera shell depends on the temperature of the water as the shell is being formed. That bit of data makes it possible to deduce the salinity of the water based on the ratio of two isotopes of oxygen (O16 and O18) present in the calcite ($CaCO_3$) shell, which reflects both the temperature and salinity of the water. Because seawater containing the light isotope O16 evaporates more readily, the ratio of the oxygen isotopes provides an indication of the rate of evaporation and consequently the salinity and temperature of the water.

The analysis shows that the surface waters cooled over the course of the last million years, especially during ice ages. This reduced the temperature difference between the surface and the cold, deep waters, which in principle should have intensified mixing. But this trend was reversed by the marked decrease in salinity of the surface waters, which became less dense and thus less susceptible to mixing with the deep layers. The study shows that mixing of the waters diminished significantly, which allowed the deep waters to sequester more dissolved CO_2, with important consequences for climate evolution.

More information: Adam P. Hasenfratz et al. The residence time of Southern Ocean surface waters and the 100,000-year ice age cycle, *Science* (2019). DOI: 10.1126/science.aat7067 Adam P. Hasenfratz et al. The residence time of Southern Ocean surface waters and the 100,000-year ice age cycle, *Science* (2019). DOI:

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