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Palaeoceanography

Salty seas sway global glacial cycles

Kaustubh Thirumalai

Analysis of microfossils in marine sediments spanning the past 1.2 million years suggests that increased intrusion of highly saline waters from the Indian Ocean into the South Atlantic propelled Earth's deglaciations during this period. **See p.306**

Earth's climate fluctuated remarkably over the past one million years, yo-yoing between long-lived ice ages, called glacials, and brief periods of relative warmth known as interglacials. Each maximum in global ice volume was reached several tens of thousands of years after the initial onset of glacial conditions, but transitions into interglacial periods, termed deglaciations, involved rapid global warming and were generally complete within fifteen thousand years or so[1,2]. Delineating the precise order of ocean and atmospheric mechanisms associated with this sawtooth-like pattern of glaciation and deglaciation has remained an outstanding problem in Earth science. On page 306, Nuber *et al.*[3] suggest that intrusions of highly saline waters from the Indian Ocean into the less salty Atlantic Ocean provided the necessary pushes to deglaciate the planet during the past 1.2 million years.

How might the distribution of salt across oceanic basins be related to global climate change? To answer this question, we must first address why certain parts of the ocean are saltier than others. Ocean salinity is defined as the concentration of salt-forming ions dissolved in a given volume of seawater. Although the atmosphere can alter surface-ocean salinity by removing or adding fresh water (through evaporation and precipitation, respectively), salinity can also change as a result of the movement and mixing (advection) of water parcels originating from distinct source regions[4]. For instance, the advection of fresh water derived from riverine run-off or ice melt can cause sharp variations in ocean salinity. And in ocean settings away from the coast, vertical advection along the water column and mixing of waters by oceanic currents can induce changes in the salt content of seawater[4,5].

Surface and deepwater currents in the Atlantic Ocean are pivotal components of the global climate system because they help to regulate hemispheric distributions of oceanic heat and salt (thermohaline fluxes). This system of currents, known as the Atlantic meridional overturning circulation (AMOC), is driven partly by patterns of prevailing winds, and partly by buoyancy forces arising from gradients in seawater density — which, in turn, depend on seawater salinity and temperature[2].

In the modern ocean, the AMOC moves heat and salt from the South Atlantic into the North Atlantic. As portions of the transported water masses journey polewards in the Northern Hemisphere, they become cool and salty enough to reach densities that cause them to sink, forming deep waters[2,6]. These waters then travel southwards at the sea floor and ultimately resurface in upwelling zones, primarily in the Southern Ocean. Owing to its capacity to deliver heat and salt to the high-latitude regions of the North Atlantic, variations in the AMOC are a major factor in mechanisms of glacial-to-interglacial transitions[2,7].

It has been suggested that changes in the thermohaline characteristics of waters flowing into the southern Atlantic can cause swings in AMOC variability[8]. Today, relatively cool and fresh waters move into the South Atlantic gyre (a large, rotating system of wind-driven currents) from the Southern Ocean, whereas warmer and saltier waters from the subtropical

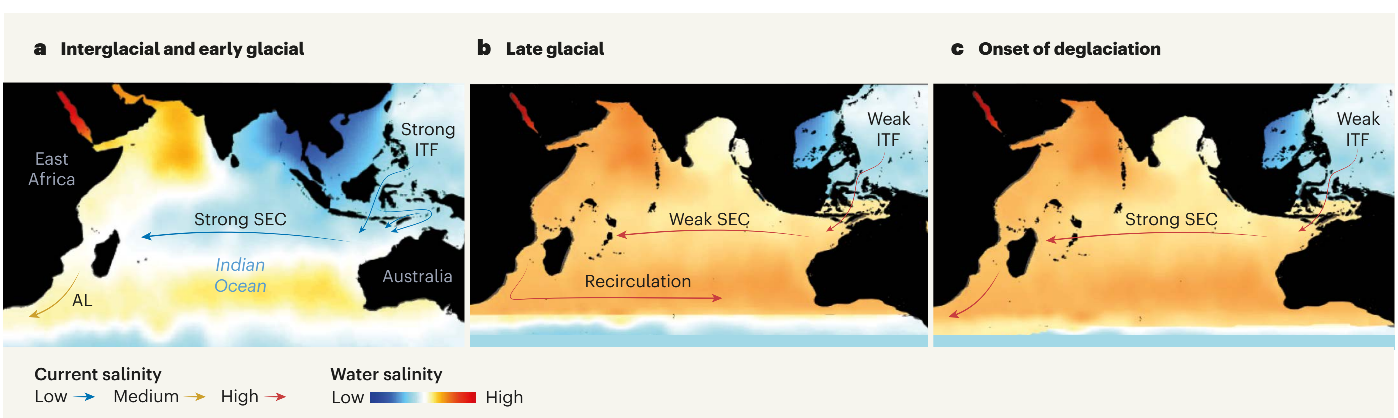

Figure 1 | Salinity in the Indian Ocean affects ocean currents. a, Nuber *et al.*[3] propose that, during warm (interglacial) periods and early in cold (glacial) periods, sea levels are relatively high and the Indonesian archipelago is largely submerged. The Indonesian throughflow (ITF) currents are strong, and carry fresh waters to the Indian Ocean, which contribute to the South Equatorial Current (SEC). A current called the Algulhas Leakage (AL) around the tip of Africa intrudes into the Atlantic Ocean. **b**, In the second half of a glacial period, sea levels are low, exposing more land in the Indonesian archipelago. The ITF is therefore weaker and saltier, lowering the import of fresh water to the Indian Ocean. The SEC is weak and AL reduces, so that saline water recirculates and builds up in the Indian Ocean. **c**, At the onset of deglaciation, sea levels are still low but the AL resumes, releasing highly saline waters to the Atlantic. This would boost the northward flow of warm and salty waters in the Atlantic (not shown), accelerating deglaciation. The coloured shading representing seawater salinity illustrates broad trends, rather than modelled data. (Adapted from Fig. 4 of ref. 3.)

Indian Ocean 'leak' into the southern Atlantic from the Agulhas Current system[2,9] (which runs southwards along the eastern edge of southern Africa). Increases in the salinity of northward-bound waters in the Atlantic are associated with a stronger AMOC[4], and accordingly, Agulhas leakage has been proposed as an key driver of AMOC change during deglaciations and rapid climate events[2,5,7]. The salinity of the subtropical Indian Ocean is itself influenced by the influx of less salty waters advected from the tropical Pacific Ocean by the Indonesian throughflow (ITF) current – which is therefore a further factor that can modulate the thermohaline composition of southern Atlantic waters[6].

Nuber *et al.* investigated patterns of salinity change in the Indian Ocean and the ocean waters next to southeastern Africa over the past 1.2 million years using a series of marine sedimentary records, including a newly developed one for offshore Madagascar. The authors carried out geochemical measurements of the calcium carbonate shells of microscopic plankton, called foraminifera, found in these sediments. This allowed them to determine changes in the composition of the stable oxygen isotopes in seawater that had occurred over time at each site, using established protocols to correct for the confounding influence of other factors. The oxygen-isotope composition of seawater is commonly used as a proxy for ocean salinity, because both quantities are controlled by evaporation, precipitation and advection[4,5].

Intriguingly, Nuber *et al.* found that pronounced trends of warming and salinification occurred in the Indian Ocean about 20,000 years, on average, before the onset of global deglaciations. The authors contend that the resulting build-up and subsequent further transfer of saline Indian Ocean waters into the South Atlantic region eventually boosted the AMOC, and with it, the northward transport of heat required for each global deglaciation.

Nuber and colleagues support their assertions with palaeoclimate simulations of glacial climates that have a suppressed AMOC. Using a state-of-the-art climate model, the authors artificially increased the salinity of southern Atlantic Ocean waters to simulate the intrusion of salty water masses from the Indian Ocean. The simulations suggest that this saline influx can speed up the recovery of the AMOC from a subdued state in just a few centuries, even when fresh water is persistently introduced into the North Atlantic Ocean (to resemble the addition of meltwater from disintegrating ice sheets during deglaciation).

So, what causes salinity in the Indian Ocean to rise 20,000 years before deglaciation? Nuber *et al.* discount atmospheric drivers, surmising that the ITF current has a key role in modulating basin-wide salinity anomalies in the Indian Ocean over these timescales.

The ITF brings fresher waters to the Indian Ocean from the Pacific Ocean through marine passages in the Indonesian archipelago. The authors use a model of sea-level topography to show that the maximum change in sea–land surface distribution across the Indonesian archipelago occurs when global sea levels are about 40–60 metres lower than today – values that, on average, resemble global sea-level around 20,000 years before deglaciations. Accordingly, Nuber *et al.* propose that changes in sea level, and the associated exposure of continental shelves in the Indo-Pacific region, led to constricted ITF flows and the eventual build-up of salinity in the Indian Ocean (Fig. 1).

This study presents a tantalizing working hypothesis for how the climate system transitions from glacial to interglacial states. However, questions remain about the proposed mechanism of advected salinity, regarding the importance of evaporative fluxes, winds and the role of the Southern Ocean. Furthermore, it is not straightforward to tie ITF strength to the exposure of continental shelves[10,11], and evidence suggests that portions of the Indonesian shelves were permanently exposed before about 400,000 years ago[12] – which complicates interpretations of the effects of ITF change over the past million years. Nevertheless, Nuber and colleagues' findings and proposed mechanism represent an advance in our understanding of ice-age climates, and highlight the multifaceted nature and enigma of glacial–interglacial climate change.

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Politics

US prison population data reveal racial disparities

Jessica M. Eaglin

A public data set on the size and racial composition of US prison populations has been generated. Its analysis indicates how biases in sentencing lengths shape prisons' racial make-up in the United States. **See p.344**

Fifty years ago, the United States initiated an unprecedented increase in its prison population that disproportionately affected its racial minorities (see go.nature.com/3knvxcf). From 2009, numbers of incarcerated people began to stabilize and modestly decline[1]. Klein *et al.*[2] report on page 344 that conditions created by the COVID-19 pandemic led to a dramatic reduction in prison populations in every state. The authors find that Black people remained in prison disproportionately during this period, and provide evidence that this might be because they receive notably longer sentences than do white people. The findings highlight the enduring importance of racially disparate sentencing in the US criminal system.

From 2009 to 2019, the US prison population declined by 11% nationwide, probably as a result of legal reforms adopted by some states – drug courts, algorithmic risk assessments and criminal-code revisions that shortened sentence lengths for specific offences, for instance[3,4]. But delineating the impact of various reforms on incarceration or racial disparities has been challenging, owing to a lack of coherent data-reporting methods across prisons and states.

To overcome this challenge, Klein *et al.* built a remarkable public data set. They collected and analysed monthly – and in some cases weekly – observations on the size and racial composition of the prison populations in all 50 US states, as well as in Washington DC