silicates and carbonates on the Antarctic continent during the Eocene. Moreover, the increased erosion seems to occur in two pulses, coincident with the two steps of ice growth on Antarctica. This led Basak and Martin to argue that the ice growth itself may have provided a positive feedback, triggering more weathering on Antarctica and further CO_2 drawdown. Their observations imply that the rather inconspicuous process of weathering may have played a central role in bringing about one of the largest global environment changes in Earth's history.

Despite this astute and robust advance, many questions about the greenhouse-to-icehouse transition remain, perhaps most fundamentally those of rate and timing. For instance, if higher weathering rates provided the drawdown of atmospheric CO_2 that was critical for the initiation of ice accumulation, why did this process become climatically manifest only during the late Eocene? CO_2 levels in the millions of years leading up to the Eocene–Oligocene transition were equally high. Moreover, like tectonic forcing of climate, forcing by weathering also occurs over a prolonged period: is this somehow consistent with the two pulses observed by Basak and Martin? This could be the case; unlike tectonics, a climate forcing mechanism that affects atmospheric CO_2 concentrations may exhibit nonlinear behaviour and trigger rapid changes once a threshold has been passed.

Although climatically forceful, atmospheric CO_2 is but a small component of this planet's complex carbon cycle, involving terrestrial and marine biota, storage and return of deep ocean carbonate pools that are buffered by dissolution and subject to changes in ocean circulation, and even interactions with more stochastic elements such as the dissolution of methane clathrates. Like weathering, all of these latter aspects of the carbonate and carbon systems will affect the carbon pools of the ocean and atmosphere. These additional components might also be argued to operate on timescales more consistent with the changes seen at the Eocene–Oligocene transition. Nevertheless, it is evident that an environmental steady state that had broadly persisted since before the start of the Cenozoic era was lost during the Eocene–Oligocene transition, and the climatic feedbacks maintaining warmth were altered so that the planet began to cool.

Basak and Martin[6] present evidence for a causal link between weathering and the abrupt start of these transformations, similar to a threshold being passed. Considering the current rise of atmospheric CO_2 concentrations, the loss of ice from both poles and the increasing corrosiveness of the ocean[8,9], the most important question may now be whether our modern environment is undergoing a similar transition, but in reverse. ❐

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CLIMATE SCIENCE

The heat is on in Antarctica

The Antarctic Peninsula has long been thought to be the only part of Antarctica that has warmed in recent decades. Careful detective work confirms that West Antarctica is also warming rapidly.

Eric J. Steig and Anais J. Orsi

The ice-covered continent of Antarctica seems to have been sitting on the sidelines when it comes to global warming. Certainly, the Antarctic Peninsula (a relatively small area of land that juts northwards from the main Antarctic continent towards South America) has been warming rapidly for the better part of a century. However, the Antarctic Peninsula has been thought to be an anomaly, with the rest of Antarctica isolated from the influence of climatic changes at more northerly latitudes. Writing in *Nature Geoscience*, David Bromwich *et al.*[1] show that central West Antarctica — some 1500 km inland from the Peninsula — has warmed over the past five decades at a rate rivalling that of any other location on Earth[1].

Some regions in Antarctica may indeed be insensitive to the climatic changes affecting the rest of the planet. Antarctica is encircled by persistent westerly winds that limit the advection of heat from further north. These westerlies have accelerated in the past decades, partly in response to the loss of stratospheric ozone and consequent changes in the vertical temperature structure of the atmosphere[2]. Furthermore, the polar plateau of East Antarctica, which comprises two-thirds of the total area of the continent, averages around 3,000 m in altitude. The steep continental slope that runs between the ocean and the plateau prevents atmospheric eddies — the only significant source of heat to central Antarctica during the dark polar winter — from penetrating very far into the interior of East Antarctica.

However, these arguments do not apply to West Antarctica, which is much lower in elevation than East Antarctica, and whose climate is moderated by the adjacent Amundsen and Bellingshausen seas. Relatively warm, moist marine storms regularly penetrate into the interior of West Antarctica, occasionally reaching across the entire West Antarctic ice sheet to the South Pole. Moreover, sea ice cover has declined nearly monotonically in the region for at least the past 30 years[3], providing a significant source of local heat and storm activity. As such, there is reason to expect the West Antarctic ice sheet to have been warming along with the Antarctic Peninsula. Determining whether or not this is actually the case has proved challenging, owing to a severe paucity of instrumental weather data in central Antarctica.

Observations from satellites provided the first direct evidence for warming in West Antarctica, particularly in winter and spring[4]. However, satellite observations began only in 1982. Evidence that warming began at least two decades earlier stems primarily from the interpolation of temperature data from weather stations at considerable distances from West Antarctica[4]. Such interpolation, no matter how carefully applied, cannot rival direct local observations.

Only one location on the West Antarctic ice sheet has direct temperature observations spanning the past half century: Byrd station (80° S, 120° W), located near the centre of the ice sheet. Unfortunately, there are occasional gaps in the records, and a switch to an automated system following a hiatus between 1975 and 1980 raises the prospect of errors in the calibration of temperature sensors.

Recognizing the importance of having a reliable, long-term temperature record for West Antarctica, Bromwich *et al.*[1] decided to salvage the Byrd station record. Doing so required some detective work. The researchers took advantage of the return of the Byrd automated weather system to the University of Wisconsin-Madison in 2011 for an upgrade to evaluate the temperature sensor. They found that there was significant temperature-dependent drift. Accounting for this drift in the sensor allowed them to confidently combine pre- and post-1980 data. They used two different approaches to deal with smaller gaps in the data set: interpolation from other weather stations, as in previous work, and incorporation of the best available weather forecast data.

According to their analysis, the greatest warming at Byrd station has occurred in austral winter and spring, in line with earlier findings[4–6]. However, they document a greater degree of warming in these seasons than previously reported[4–6], and they reach the novel conclusion that the austral summer has also warmed significantly. Overall, the rate of annual warming in the updated Byrd record — on average nearly 0.5 °C per decade between 1958 and 2010 — is comparable to that observed on the Antarctic Peninsula.

Borehole temperature measurements support the warming documented by Bromwich *et al.*[1] (Fig. 1). Polar snow and ice preserve a record of surface temperatures affected only by smoothing of the signal by the slow diffusion of heat. The expected subsurface temperature profile, given the surface temperature changes documented by Bromwich *et al.*, compares well with that collected from a borehole in the West Antarctic ice sheet 160 km east of Byrd[7], providing independent support for the validity of the updated Byrd record.

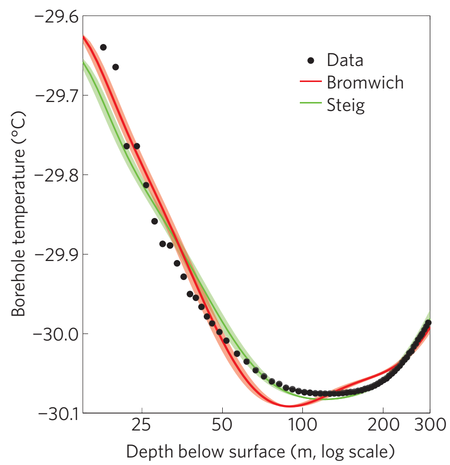

Figure 1 | West Antarctic warming. The subsurface temperature profile in a borehole 160 km east of Byrd station[7] in the West Antarctic ice sheet (black circles) reveals a sharp rise in temperatures between a depth of about 100 m and the surface, indicative of recent surface warming. Bromwich and colleagues[1] used observational and model data to piece together the temperature record for Byrd station. The borehole temperature profile agrees well with that derived from an advection-diffusion calculation[7] assuming the same surface temperature history as documented by Bromwich *et al.*[1] (red) or Steig *et al.*[4] (green). Shading illustrates the influence of ±10% uncertainty in the thermal diffusivity.

The demonstration of rapid warming in central West Antarctica is at odds with the expectation of summer cooling in response to stratospheric ozone depletion[2]. This does not necessarily imply that our understanding of the impact of ozone depletion is wrong — perhaps the summer warming would be even greater if it were not for the ozone hole. But it does suggest that other influences on Antarctic summer climate are more important. Winter and spring warming trends in West Antarctica have previously been attributed to atmospheric circulation changes over the Amundsen Sea, driven by anomalous convection in the tropical Pacific[5,9]. Similar mechanisms can also be important in summer, as exemplified by the high summer sea surface temperatures observed near West Antarctica during the prominent 2009–2010 El Niño event[10]. The findings of Bromwich *et al.* support this earlier work, adding to a growing body of literature suggesting that the low latitudes play a significant role in driving climate change in Antarctica.

West Antarctic warming also has implications for the ice sheet itself. The same atmospheric circulation changes that have brought increased temperatures to West Antarctica have also driven changes in ocean circulation[11]. The resulting increase in the delivery of warm ocean waters to the margin of the West Antarctic ice sheet has led to the thinning of floating ice shelves[12]. This causes the flow of outlet glaciers that drain the ice sheet to accelerate, which in turn contributes to sea level rise[13]. Bromwich *et al.* suggest that if current trends continue, significant surface melting of the already-vulnerable ice shelves could occur[1]. Summer surface melting has been the primary mechanism driving the collapse of ice shelves on the Antarctic Peninsula.

Whether the observed trends in West Antarctic temperature are likely to continue is unclear. Climate model simulations[14] that accurately capture the circulation and sea ice trends of the past few decades also tend to capture the warming now confirmed by Bromwich *et al.* Nevertheless, unconstrained models yield more widely divergent trends[14], suggesting that projection of future climate changes over West Antarctica remains subject to considerable uncertainty.

The reconstruction by Bromwich *et al.*[1] of the Byrd temperature record establishes central West Antarctica as one of the most rapidly warming regions on the planet. The results should mark an end to speculation about whether the region is warming, and call for the routine incorporation of the updated Byrd station record into compilations of global temperature change. ❐

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