NEWS & VIEWS

CLIMATE CHANGE

Greenland's ice on the scales

Tavi Murray

Satellite measurements of changes in Earth's gravity field reveal ice loss from Greenland's ice sheet. Over the past four years, this melt has contributed to global sea-level rise at an accelerating rate.

The volume of the ice sheet that covers most of Greenland is so large that, were it to melt completely, sea levels across the world would rise by about 7 metres. Furthermore, an increase in its delivery of fresh water to the oceans could weaken or disrupt the 'thermohaline' circulation of oceanic salt water[1], profoundly altering the climate of the Northern Hemisphere.

Such doomsday scenarios are well rehearsed, but — expressed in this way — not necessarily accurate. If cold areas such as the centre of Greenland warm up, it might actually snow more. That would, in turn, thicken the ice sheet and remove water from the global oceans. The very different densities of snow, ice and water mean that measuring the volume of the Greenland ice sheet does not provide the complete answer as to whether it is growing or shrinking. The ideal method is to measure how the mass of the ice sheet is changing with time.

In two complementary studies, Velicogna and Wahr (on page 329 of this issue)[2] and Chen *et al.* (published online in *Science*)[3] do just that. They show that the Greenland ice sheet lost between 192 million and 258 million tonnes of ice each year between April 2002 and April 2006 (equivalent to a volume of 212–284 km^3). This rate of ice loss is equivalent to a rise in sea level of 0.5 ± 0.1 mm yr^{-1}, which is higher than many previous estimates. Both studies also show that the rate at which ice was being lost increased dramatically in the course of the study: the loss rate in the period 2004–06 was 2.5 times higher than that between 2002 and 2004 (ref. 2).

Both studies used data from the Gravity Recovery and Climate Experiment (GRACE), funded by NASA and the German Aerospace Center (DLR), which measures Earth's gravity field from space. GRACE consists of two satellites orbiting Earth. These satellites are separated by a distance of around 220 km that varies slightly as the satellites pass over anomalies in the gravity field. Since their launch in March 2002, the GRACE satellites have mapped the global gravity field every 30 days (Fig. 1). Over time, that field should show evidence of changes in the ice-sheet mass.

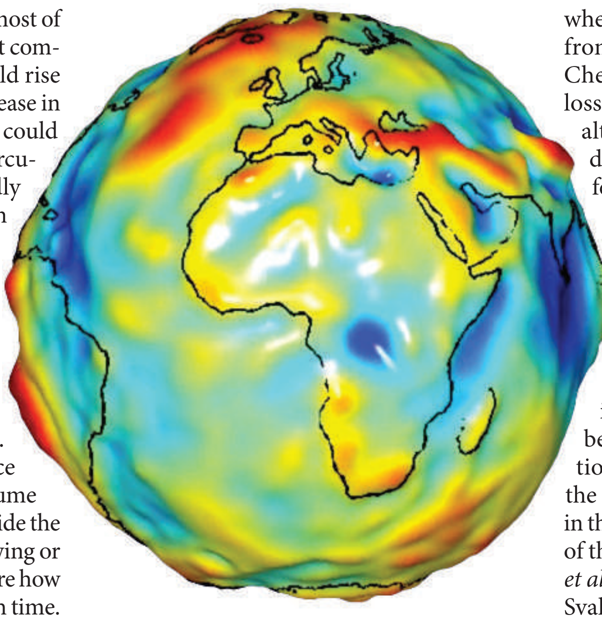

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Figure 1 | Amazing GRACE. **Anomaly map of Earth's gravity field, as measured by the NASA/DLR GRACE satellite.**

But calculated ice-mass changes are only as accurate as the models used to remove other mass-change signals — those caused by tidal and non-tidal changes in the oceans, and by changes in the atmosphere and in Earth's mantle as it rebounds after the last ice age. At high latitudes, these models are not without error. The GRACE studies[2,3] attempt to account for these other variations and their uncertainties, leaving a residual signal that results from the net loss of glacier ice into the oceans alone.

In particular, the high density of mantle rocks means that the gravity signal is very sensitive to even small errors in the model of rebound. But Velicogna and Wahr's estimate of uncertainty in the rebound rate[2] would have to be increased by a factor of ten to change their conclusion of an overall loss of ice-sheet mass to an overall gain. And as this error would be constant over the timescale of the GRACE measurements, the change in the rate of mass loss is a highly stable result.

The GRACE data can also be used to indicate where the ice is being lost. Most of the loss is from south or southeast Greenland[2,3], with Chen *et al.* reporting an additional area of loss in the northeast[3]. Airborne and satellite altimetry over the ice sheet shows further detail of the spatial pattern, albeit over different periods. The central portions of the ice sheet, with elevations above 1,500 m, are indeed thickening, fed by increased snowfall[4]. The margins, in contrast, are thinning[5]. The outlet glaciers that feed ice from the centre of Greenland to the ocean are also depleting rapidly (Fig. 2, overleaf). This is occurring particularly in the southeast, where thinning rates can be more than 10 m yr^{-1} (ref. 6). This depletion coincides with mass loss identified in the southeast using GRACE[2,3]. The mass loss in the northeast[2] is possibly caused by thinning of the northeast Greenland ice stream[4]. Chen *et al.* postulate that changes in glaciers in the Svalbard archipelago, which lies northeast of Greenland between Norway and the North Pole, might be part of the explanation[3].

The short period over which the GRACE observations were made means that the measured changes in the rate of mass loss could simply be the result of variations in snowfall or summer melt. Indeed, 2002–03, which preceded the mass-loss acceleration, was a year of unexpectedly high snowfall in southeast Greenland[6], and 2005, which immediately followed it, was a year of record melt[7]. But the difference between snow accumulation and meltwater run-off accounts for only around a third of the mass loss from Greenland[8]. The remainder is lost through the calving of icebergs at the margins of fast-flowing outlet glaciers. The flow rate of many of Greenland's outlet glaciers increased between 1996 and 2000, and again in the period to 2005, especially in the south[8]. In spring 2004 — at the same time as the increase in mass loss recorded by GRACE[2] — significant accelerations in the flow and calving rate of two major outlet glaciers occurred[9].

The agreement of the GRACE results[2,3] with measurements of glacier dynamics[8] on the scale and the timing of the mass loss suggests that the accelerating contribution to sea-level rise — which in 2004–06 was equal to almost

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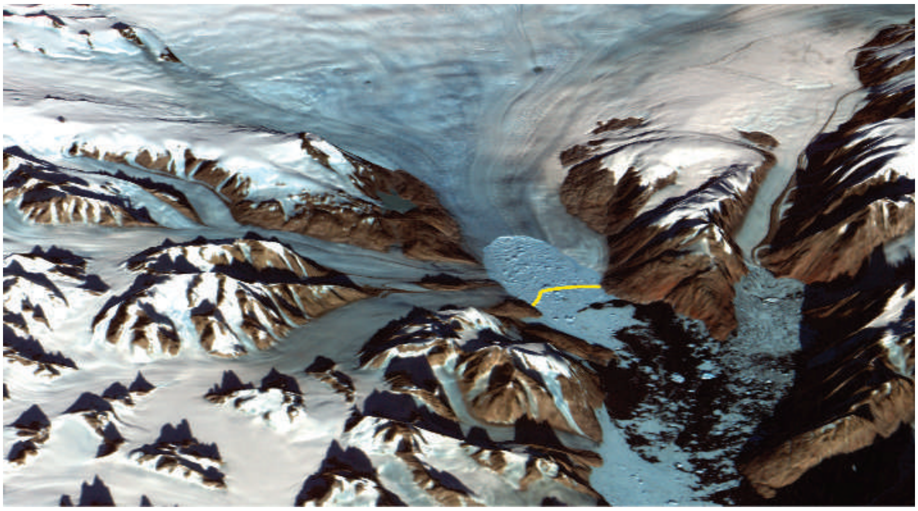

Figure 2 | Accelerated slippage. A 2005 image of Kangerdlugssuaq, an outlet glacier of the Greenland ice sheet, from a Disaster Monitoring Constellation satellite. The glacier's calving speed doubled during 2004; the yellow line shows marginal position in 2000, about 4 km in front of imaged position.

0.7 mm yr^{-1} (ref. 2) — results from changes in the dynamics of outlet glaciers. Current model predictions from the Intergovernmental Panel on Climate Change suggest a sea-level rise of 0.5 ± 0.4 m during the 21st century. But these models contain only a small component of the dynamic response of glaciers[10], and the GRACE results indicate that more rapid changes are occurring than the models predict. The GRACE results can thus help us to re-evaluate the rates of loss from the ice sheet that we should expect through climate warming.

It is clear that there is much we don't understand about the current response of the Greenland ice sheet. Records over short periods have to be treated with caution, and we cannot be certain that changes represent a profound alteration in the behaviour of the sheet. But several independent sources now confirm overall mass loss from the Greenland ice sheet, together with unexpected and rapidly changing behaviour. Uncertainties remain, but the GRACE results provide one of the best estimates of overall mass balance of the ice sheet.

They do not, however, reveal the detailed pattern, at least not yet. It is vital that we use a variety of instruments and techniques to make continued observations of the ice sheet's response, and complement these with studies aimed at understanding the processes that are driving the observed changes. Such a programme will allow us to improve our predictive models of the Greenland ice sheet, and assess the timing and extent of its future contribution to sea-level rise. ■

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PALAEOANTHROPOLOGY

A precious little bundle

Bernard Wood

The three-million-year old skeleton of a three-year-old child provides an outstanding resource to understand the development of a human ancestor that seems to have both walked upright and climbed through trees.

The fragile bones of infants rarely survive long enough to make it into the hominin fossil record. But if they do, they provide precious evidence about the growth and development of the individual and its species. This helps researchers not only to understand how such processes have changed during hominin evolution, but also to interpret the function and the taxonomic significance of the better-sampled adult specimens. In this respect, the remarkably complete 3.3-million-year-old skeleton of a three-year-old *Australopithecus afarensis* female, found in Dikika, Ethiopia, is a veritable mine of information about a crucial stage in human evolutionary history. In this issue, the fossil is described by Alemseged *et al.* (page 296)[1], and its geological and palaeontological context is reported by Wynn *et al.* (page 332)[2].

Thanks to efforts in Ethiopia and elsewhere, we already know a good deal about *A. afarensis*. It has been called an 'archaic' hominin for at least two reasons. First, it is old: its fossils date from between 4 million and 3 million years ago. Second, its morphology is archaic, in the sense that its brain case, jaws and limb bones are much more ape-like than those of later taxa that are rightly included in our own genus, *Homo*. When adjusted for its body size, the brain of *A. afarensis* is not much larger than that of a chimpanzee, and although it has lost the large canines that distinguish apes from hominins, other aspects of its dentition, such as its relatively large chewing teeth, are still primitive (Fig. 1).

There remains a great deal of controversy regarding the posture and locomotion of *A. afarensis*. Most researchers accept that it could stand upright and walk on two feet, but whether it could climb up and move through trees is still disputed. Some suggest that its adaptations to walking on two feet preclude any significant arboreal locomotion, and interpret any limb features that support such locomotion as evolutionary baggage without any useful function[3]. Others suggest that a primitive limb morphology would not have persisted unless it served a purpose[4].

The Dikika infant is not the first early hominin infant to be found. That distinction belongs to the Taung child, whose discovery was reported just over 80 years ago[5]. What makes the Dikika infant remarkable is its unprecedented completeness for such a geologically ancient specimen. The infant was found in sediments that formed the bottom of a small channel close to where a river discharged into a lake[2]. This was not a turbulent stream or river. The flow was sluggish, typical of the type of braided streams that make up a river delta. The corpse of the infant was buried more or less intact, and the sediment in flood waters must have swiftly covered it.

Some parts of the specimen — the pelvis, the lowest part of the back and parts of the limbs — are still missing, but what is preserved is remarkably complete. The face, the brain case and the base of the cranium, the lower jaw, all but two of the teeth (including unerupted adult teeth still in the jaw), both collar bones, the vertebrae down to the lower back, many ribs, both knee caps and the delicate bone that holds open the throat, the hyoid, are all there. Even the medial epicondyle of the humerus has survived. This is the bony projection on