OCEANOGRAPHY

A sea butterfly flaps its wings

Ocean acidification is predicted to harm the ocean's shell-building organisms over the coming centuries. Sea butterflies, an ecologically important group of molluscs in the Arctic and Southern oceans, are already suffering the effects.

Justin B. Ries

As atmospheric carbon dioxide levels continue their inexorable rise due to fossil fuel burning, cement production and deforestation, more carbon dioxide is entering the surface ocean. The pH of sea water has declined as a result. According to both field and laboratory experiments, this process of ocean acidification will impair the ability of calcifying organisms — such as corals, clams, snails, urchins and some calcareous algae — to build their protective shells and skeletons within the next few centuries[1,2]. Writing in *Nature Geoscience*, Bednaršek and colleagues[3] show that shells of sea butterflies (Fig. 1a) — a key group of planktonic pteropod molluscs inhabiting the high-latitude oceans — are already beginning to dissolve.

Many marine organisms use calcium carbonate in the form of either aragonite or calcite to build their shells and skeletons. However, as the ocean acidifies, concentrations of carbonate ions, a constituent of calcium carbonate, decline. When carbonate ion concentrations drop sufficiently to cause the aragonite saturation state of sea water to fall below 1 (a condition referred to as undersaturation), non-biological calcium carbonate starts to dissolve, replenishing the dwindling carbonate pool. The resultant decline in seawater carbonate ion concentrations could limit the growth of calcifying marine organisms and potentially trigger their dissolution. The aragonite form of calcium carbonate is more susceptible to dissolution than the calcite form, rendering aragonite-based organisms at greater risk of dissolution as the ocean acidifies. Indeed, laboratory incubations suggest that shells of aragonite-based molluscs, including clams, conchs and whelks, start to dissolve at aragonite saturation states greater than 1 (refs 2,8).

In addition to acidification by carbon dioxide from the atmosphere, upwelling of deep, CO_2-rich waters can also lower the pH of surface waters. Such upwelling is common along the coast and in areas where water masses converge and push deeper waters to the surface. Pteropods, an ecologically important group of planktonic molluscs that construct their shells from the aragonite form of calcium carbonate, tend to congregate along these upwelling zones, where nutrient levels are high. Although the shells of dead[5,6] and larval pteropods[7] have been shown to dissolve in undersaturated conditions, the vulnerability of live adult pteropods to these conditions has remained uncertain.

Bednaršek and colleagues[3] used a high-magnification scanning electron microscope to visualize the shell surfaces of live pteropods collected from an area of the Scotia Sea, in the Atlantic sector of the Southern Ocean, which is influenced by deep upwelling. The dissolution was striking: pteropods collected from upwelling zones showed signs of dissolution along the entire length of their shells. The sea water from which these corroded pteropods were collected was undersaturated with respect to aragonite. These findings show that undersaturated conditions can cause the shells of living pteropods to dissolve in the same manner as non-biological aragonite.

To confirm their field observations, Bednaršek *et al.* conducted controlled shipboard experiments, exposing the

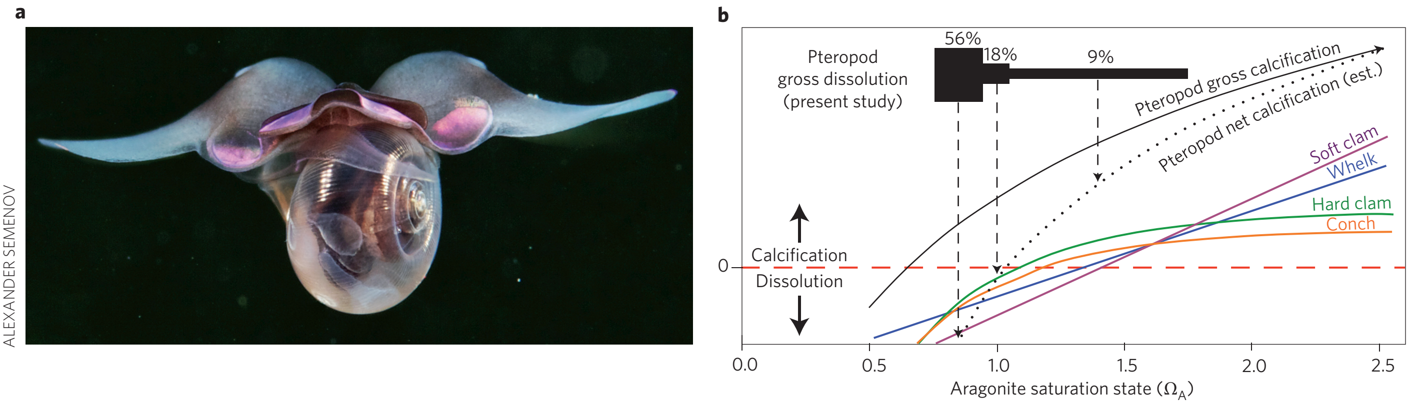

Figure 1 | Impacts of ocean acidification. **a**, The pteropod *Limacina helicina*. Bednaršek *et al.*[3] show that shells of living adult sea butterflies *Limacina helicina antarctica* (shell diameter ~1 cm) are showing signs of significant dissolution in the Southern Ocean. **b**, Gross dissolution of the *Limacina helicina antarctica* pteropod accelerates when the aragonite saturation state falls below 1 (black bars). Previous work shows that gross calcification of the closely related *L. helicina* pteropod declines with decreasing aragonite saturation (solid black curve[13]). Net calcification (dotted black curve) can be roughly estimated by subtracting the dissolution of *L. helicina antarctica* from gross calcification of *L. helicina*. Net calcification ceases when the aragonite saturation state falls below 1. Shells of certain species of clam (green and violet curves), conch (orange curve) and whelk (blue curve)[2,8] also cease to grow when the aragonite saturation state falls to between 1.5 and 1. Part **a** courtesy of Alexander Semenov, White Sea Biological Station, Moscow State University.

same pteropod species sampled in the Southern Ocean to the range of aragonite saturation states that they measured along zones of upwelling. As expected, pteropod dissolution accelerated when aragonite saturation states dropped below 1.

Bednaršek *et al.* argue that the mixing of upwelled waters with surface waters affected by anthropogenic carbon dioxide has now lowered the aragonite saturation state of portions of the Southern Ocean to levels that favour dissolution. Global warming may also play a role by increasing atmospheric pressure gradients and thereby wind speeds across the ocean's surface, increasing upwelling intensity.

Although these corrosive conditions are presently restricted to deeper waters and zones of upwelling, models predict that increasing carbon dioxide levels in the atmosphere will render most surface waters in the Southern Ocean undersaturated with respect to aragonite as early as the year 2070[4]. Thus, the corrosion of pteropod shells in upwelling zones documented by Bednaršek *et al.* may be a harbinger of what is in store for pteropods throughout much of the Southern Ocean.

Pteropods, and molluscs in general, seem more sensitive to the effects of ocean acidification than other calcifying marine organisms, such as crustacea, calcareous algae, urchins and corals[1,2,9,10]. This may stem from the fact that molluscs exert little control over the pH and carbonate chemistry of their calcifying fluid[11]. This makes them more susceptible to the effects of ocean acidification than calcifiers (such as corals) that can elevate the pH of their calcifying fluid relative to the surrounding sea water[2,9,10,12].

Bednaršek *et al.* elegantly document gross dissolution of the shells of live adult pteropods[3]. However, the study falls short of quantifying the effect of ocean acidification on net pteropod shell production; that is, gross calcification from within the shell minus gross dissolution of the exterior. If pteropods produce new shell material faster than they lose it, as observed in aragonite-based corals[10], then they could continue to grow on a net basis in undersaturated conditions. Fortuitously, the effect of ocean acidification on gross calcification of a closely related pteropod from the Arctic Ocean, *Limacina helicina*, was quantified previously[13]. Although gross calcification falls with the aragonite saturation state, the pteropod continues to produce new shell material in undersaturated conditions. Thus, despite corrosion of their shell exterior, these pteropods could, in theory, continue producing new shell down to an aragonite saturation state even below the levels reported by Bednaršek *et al.* for upwelling zones in the present-day Southern Ocean.

The impact that anthropogenic ocean acidification will have on net pteropod calcification can be roughly estimated by subtracting the gross dissolution rates reported by Bednaršek *et al.* from the gross calcification rates reported for the closely related pteropod *L. helicina* (Fig. 1b). According to this analysis, net production of pteropod shells ceases when the aragonite saturation states falls below 1, a condition that seems to be common in the region studied.

This article's title alludes to meteorologist Edward Lorenz's 'butterfly effect' — the notion that small changes in a system's initial conditions, such as the flapping of a butterfly's wings, may trigger large-scale alterations in that system[14]. Despite their small size, pteropods are important food sources for predators at multiple tiers of the food chain, including zooplankton, herring, salmon, sea birds and even whales. Without shells, pteropods would be defenceless against predation, which could cause their populations — and those of their predators — to collapse. A decline in pteropod shell mass would also reduce the ballast available for sinking pteropods' inorganic[15] and organic carbon[16] to the deep sea, potentially disrupting the global carbon cycle.

The corrosion of Southern Ocean pteropods documented by Bednaršek and colleagues[3] has yet to trigger a butterfly effect. However, the study suggests that the dual impacts of ocean acidification and global warming render the flapping more ominous by the day. ❐

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PALAEOCLIMATE

A history of outbursts

The catastrophic drainage of glacial Lake Agassiz about 8,500 years ago is linked to abrupt climate change. A layer of sediments deposited during the previous interglacial period suggests that such outburst flooding is not unique to the Holocene epoch.

Patrick Lajeunesse

At the end of the last deglaciation, a giant lake covered parts of northeastern North America. Known as Lake Agassiz, it was formed as glacial meltwaters were trapped behind the margin of the retreating Laurentide Ice Sheet.

At its maximum extent, glacial Lake Agassiz covered a vast area extending from the present-day southern Hudson Bay to northern Minnesota[1] (Fig. 1). About 8,500 years ago, Lake Agassiz drained completely and catastrophically, probably in less than one year[2]. The drainage released a vast volume of freshwater and icebergs into the North Atlantic Ocean, and may have triggered a rapid cooling event about 8,200 years ago[3–5]. The final drainage of Lake Agassiz is considered a