BIOGEOCHEMISTRY

Riverine carbon dioxide release

Inland waters are increasingly recognized as important to the global carbon cycle. Detailed measurements in the United States suggest that significant amounts of carbon dioxide are released from streams and rivers, particularly the smaller ones.

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Traditionally, much attention has been paid to the role of the oceans and the terrestrial biosphere in carbon cycling, and the contribution of streams, rivers and lakes has been overlooked. However, these inland waters are often supersaturated with CO_2 and, as a result, tend to release carbon to the atmosphere. The lands surrounding inland waters supply a sizable fraction of the carbon that supports this flux, as do aquatic photosynthetic organisms, which fix CO_2. The contribution of inland waters to continental-scale carbon cycling has remained uncertain, however, due to a paucity of data[1,2]. Writing in *Nature Geoscience*, Butman and Raymond[3] provide a regional-scale analysis of CO_2 evasion from streams and rivers in the United States.

One of the main hurdles in establishing a regional-scale analysis of carbon efflux from inland waters is the scarcity of measurements of the three main components needed for such an analysis: CO_2 concentrations in surface waters, the areal extent of rivers and streams, and the rate of exchange of CO_2 between the water and the atmosphere. Determining the surface area of streams and rivers has proved especially difficult. Advances in remote sensing have led to improved estimates of the areal extent of lakes and wetlands. However, the area covered by streams and rivers is less certain, at least on a regional scale. The length of streams and rivers can be readily obtained from maps, but their widths are less certain, as measurements are typically made at gauging sites that do not capture the wide range of widths.

Butman and Raymond[3] overcome these difficulties by making use of an extensive and long-term dataset provided by the US Geological Survey, which documents the temperature, pH and alkalinity of inland waters at 4,138 sites throughout the southern 48 states. Combining these data with measurements of the areal extent of the waterways, and the rate of CO_2 exchange between the water and the atmosphere, they estimate that streams and rivers in the US contribute on average 2,370 g carbon m^{-2} per year to the atmosphere — equivalent to approximately 10% of net ecosystem exchange in the US. The uncertainties are large, however, highlighting the need for experimental examination of the physical processes controlling gas exchange.

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Figure 1 | Riverine release. Butman and Raymond[3] show that streams and rivers in the US release a significant amount of CO_2 to the atmosphere. Their regional-scale analysis suggests that small streams are a major contributor, given the high concentration of CO_2 in these waters, together with rapid mixing with the atmosphere and a large total surface area.

One key finding is that first-order streams, the smallest streams that typically appear on maps, contribute the largest proportion — around 36% — of the CO_2 that is out-gassed to the atmosphere (Fig. 1). The high levels of evasion from these waters stem from the high CO_2 concentrations in small streams, coupled with high gas exchange rates and large total surface areas. Zero-order streams, the smallest streams with the closest contact with soils, are not included. If they were, they would probably increase the overall magnitude of CO_2 evasion from small streams. Provocatively, Butman and Raymond also note a positive correlation between precipitation and CO_2 efflux. The mechanistic explanation for this correlation may involve the flushing of soils by infiltrating rainfall or snowmelt and, on a longer timescale, the evolution of catchment morphology as a function of rainfall. These mechanisms are worthy of further investigation.

Extrapolating these findings to all streams and rivers stretching between 25° and 50° N yields a flux of around 0.5 Pg carbon per year, which is considerably higher than previous estimates. Although reasonable, additional studies are needed in temperate regions on other continents to verify this estimate. Direct measurements of CO_2 concentrations in streams and rivers are now practical. It is essential to make these measurements if well-constrained calculations of efflux are to be made on a continental scale.

The findings of Butman and Raymond[3] are founded on extensive data and a careful assessment of uncertainties in CO_2 efflux, and so provide a template for the type of analyses that are needed in other regions. They also highlight the importance of often undervalued monitoring programmes for assessing environmental conditions and changes, such as those coordinated by the US Geological Survey. It is apparent that the efflux of carbon to the atmosphere from streams and rivers can substantially exceed fluvial transport of organic and inorganic carbon to the ocean[4]. The interpretation of these fluxes in the context of the global carbon cycle remains ambiguous, however, and questions remain regarding the source of the carbon released and the influence of anthropogenic perturbations, such as acidification, erosion and damming, on efflux.

Carbon fluxes from inland waters, as derived by Butman and colleagues[3], could play an important role in the terrestrial carbon budget, even if mainly by relocating terrestrial respiration. If this effect is important, then the terrestrial CO_2 sink may prove smaller than thought. ❐

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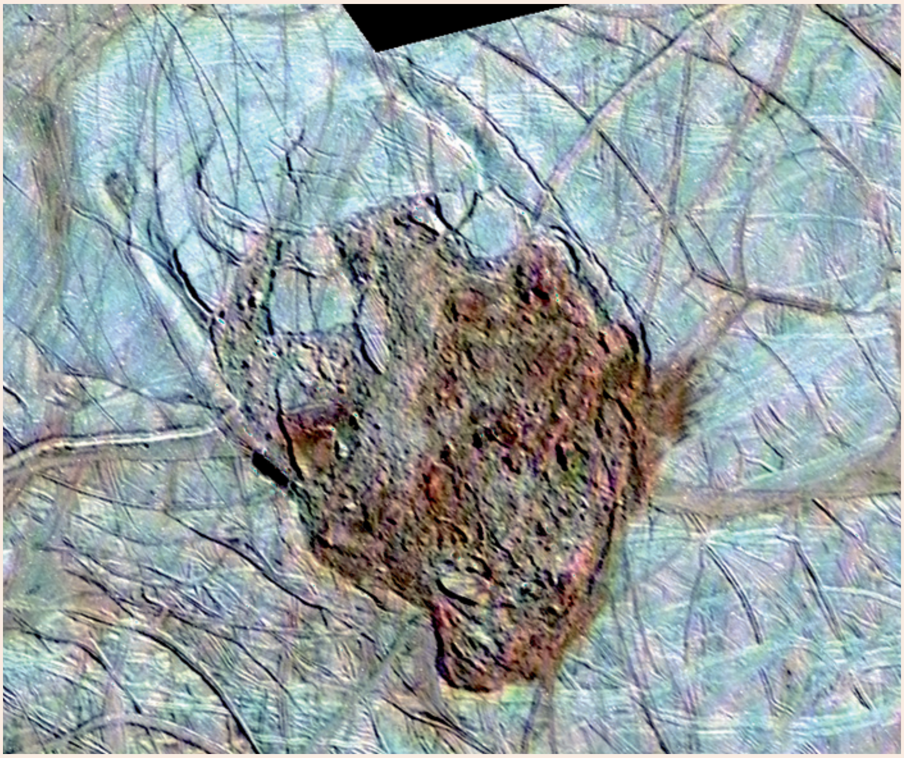
PLANETARY SCIENCE

Chaos and water



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Europa, the smallest of Jupiter's four Galilean satellites, has intrigued generations of planetary scientists. Its thick shell of ice is thought to cover a liquid ocean, kept from freezing by tidal energy. Where there is liquid water, there might be life. Not surprisingly, this moon has enjoyed much attention from astrobiologists, as well as from NASA.

Despite the widespread interest, it has been difficult to determine how Europa's relatively young surface developed its distinct cracks and streak. The provenance of more morphologically complex regions, termed chaos terrains, has also not yet been fully explained. In these regions, crustal blocks of ice — interspersed with different materials — resemble icebergs in a frozen ocean.

Now Britney Schmidt and colleagues re-interpret archival images from the Galileo probe that met its fate in Jupiter's atmosphere in 2003 (*Nature* **479,** 502–505; 2011). They focus on two regions of chaos on Europa's surface, and analyse them in the light of current understanding of ice, brine and water dynamics in Earth's volcanic craters and ice shelves.

Schmidt and colleagues propose that ascending plumes of relatively warm ice induce subsurface melting and the formation of ice-enclosed lenses of meltwater. Because ice melt leads to a reduction in volume, the overlying ice surface collapses and fractures. Subsequent brine injection and refreezing can explain the observed surface morphology in the chaos terrains. If so, lenses of liquid water should exist at depths of only about 3 km within the satellite's icy crust. According to this interpretation, one of the studied chaos terrains on Europa, Thera Macula, is currently actively deforming.

Compared with earlier estimates of 10–30 km of ice above any of Europa's liquid water, a frozen crust of only 3 km may sound almost penetrable and may give hope to those searching for life in the extraterrestrial Universe. Long before sampling of Europa's liquid water comes within reach, however, we should be able to test the proposed model for chaos formation: extensive surface modification in the active chaos terrain should already have produced noticeable changes in the morphology at Thera Macula since the Galileo images were taken.

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