The Cryoconite Ecosystem: A Bi-Polar Study of Biogeochemical Cycling upon Glacier Ice

Outline proposal submitted to the IPY by Dr. A.J. Hodson on behalf of 8 researchers from institutions across Europe and the USA.

Introduction

Recent research has accrued compelling evidence for the existence of viable microbial food webs upon the surfaces of polar glaciers and ice sheets, especially within small melt pools known as cryoconite holes (Figure 1). These observations challenge the conventional assumption that icy surfaces in the polar regions are largely abiotic environments. Further, since life thrives in these environments, they might even offer vital refugia during more extreme conditions such as those upon "NeoProterozoic Snowball Earth" and other icy planets. This project will therefore unite key groups involved in the initial characterisation of this cryoconite ecosystem in order to present a focused, bi-polar study of the biogeochemical processes that occur in cryoconite holes. The scope of the project therefore falls directly into the remit of the IPY by contributing to a more complete understanding of the present status of the polar ecosystem (IPY Theme 1) and by providing new insights into three Specific Issues related to the IPY concept: 1) structure and function of the polar ecosystem; 2) the role of the polar regions in the global carbon cycle and 3) the tight integration of physical, chemical and biological systems.

Biogeochemical and microbiological evidence for a cryoconite ecosystem

Cryoconite holes are small, water-filled depressions (typically < 1m in diameter and usually < 0.5m deep) that form on the surface of glaciers when solar heated inorganic and organic debris melts into the ice (Figure 1). It has been known for some time that the holes are occupied by diverse yet poorly understood microbial foodwebs (Steinbeck, 1935; Charlesworth, 1957; Gerdel & Drouet, 1960; Wharton *et al.,* 1981; Takeuchi *et al.,* 2000, Porazinska et al, 2004), but little has been done to quantify and further characterise ecosystem functioning. The recent development of nutrient budgets by the Principal Investigator in polar catchments suggests that this is a major oversight. This is because the nutrient economy polar glaciers in both the European Arctic and maritime Antarctic show the striking effects of P, NH_4 and organic N assimilation by abundant cryoconite holes which are bathed in a continuous supply of snow and icemelt during the melt season (Hodson et al, In Press and Hodson, Unpubl. Data). Other investigators named on this proposal have demonstrated that nutrient cycling is also important under even colder conditions, such as those of the Dry Valleys, Antarctica (Tranter et al, 2004). Here, cryoconite holes are nearly always entombed by surface ice cover, and only flushed on decadal timescales during relatively hot summers. The nutrient flushed from the holes is believed to be an important influence on continuation of primary production in the downstream ice-covered lakes (Foreman et al, in press). Otherwise, photosynthesis most often occurs in the ice-lidded cryoconites, whose isolation from the atmosphere causes the gradual development of extreme geochemical conditions, including pH values as high as 11 and $\log_{10} p(CO_2)$ values as low as –7 (Tranter et al, 2004). Further, the dominance of organic forms of N over inorganic forms in these holes confirms that there is a well-adapted microbial consortium recycling organic nutrients in the absence of fresh inorganic inputs. This is also a key feature of nutrient cycling in parts of the maritime polar regions, where the abundance of organic nutrients is enhanced by local mammal and sea bird excreta. Lastly, Hodson et al (In Press) show that surface microbes in the European High Arctic may also be fertilised by NH_4-rich pollution episodes associated with the rapid advection of air masses from Europe.

Biological process measurements in cryoconite holes

Hodson and Laybourn-Parry conducted a pilot study on a Svalbard glacier during 2000. This involved the collection of fixed material whose analysis is reported by Säwström et al (2002) and is, to our knowledge, the first quantitative and qualitative investigation of the biology and primary production in cryoconite holes. The holes on the Svalbard glacier contained truncated microbial food webs similar to those described for continental Antarctic lakes (Laybourn-Parry, 1997; James *et al.,* 1998; Priscu *et al.,* 1999; Laybourn-Parry *et al*., 2001a) but with far fewer ciliated protozoa. Virus-like particles (VLP) were also abundant in the holes, as they are in Antarctic lakes (Kepner & Wharton, 1998; Laybourn-Parry *et al*., 2001b). The virus: bacteria ratios seen in the cryoconite holes were similar to those in Antarctic lakes, and so it is likely that viruses play an important role in biogeochemical cycling within them.

Photosynthesis was measured in cryoconites on the Svalbard glacier surface on four occasions in 2000. The striking feature is that relatively high levels of photosynthesis were found, and levels of carbon fixation, especially at the bottom of the cryoconite holes, were higher than those typically reported for Arctic and Antarctic freshwater lakes

(O'Brien, 1992; Bayliss *et al.,* 1998; Markager *et al.,* 1999; Laybourn-Parry *et al*., 2001a). Given the high density of holes on the surfaces of many polar ice masses, the photosynthetic demand for inorganic nutrients alone may account for a significant proportion of the N in the nutrient budgets described above. Further, conversion of labile dissolved organic nitrogen when other inorganic nitrogen sources are extremely limited might reflect bacterial use of amino acids. Finally, the first bacterioplankton assays using microorganisms removed from Svalbard cryoconite material have been undertaken, showing clear P-limitation to productivity during the summer (Anesio, Unpublished Data).

Objectives

Our understanding of the "cryoconite ecosystem" is undermined by little information regarding the rates of biological, geochemical and physical processes that operate within this habitat. Consequently, there is little basis with which to deduce the likely changes that may occur as a consequence of climate change, when cryoconite holes may either become vital refugia (extreme cold periods) or contribute to/interact with downstream microbial habitats in other ice-marginal environments (warm periods). Our principal aim is therefore to produce quantitative data that describe the structure, functioning and dynamics of the cryoconite ecosystem in several Arctic and Antarctic sites. In doing so, we will:

1) Produce integrated heat, water and nutrient budgets for glacial surfaces occupied by microbial consortia in cryoconite holes;

2) Characterise microbial habitat dynamics by studying cryoconite hole inception / survival (during winter), cryoconite entombment and isolation from the atmosphere and dispersal/fertilisation by meltwater, and;

3) Study cryoconite microbial community structure, functioning and dynamics throughout all of the stages identified in the life cycle of this habitat using geochemical, microbiological and molecular measurements.

Approach

Our approach will capitalise upon the fact that cryoconite holes represent one of the few ecosystems that may be monitored and manipulated in their entirety – giving us great confidence in our ability to deduce process rates and characteristics. Hence we will establish small plots upon three glaciers that are well known to the investigators. Here we will produce integrated heat, water and nutrient budgets for the holes upon which measurements of microbial community composition, functioning and dynamics will be mapped. These detailed observations will then themselves be integrated into a simpler spatial sampling framework enabling: 1) clear depiction of cryoconite diversity along simple environmental gradients (e.g. up-glacier along energy gradients generated by lapse rates and along nutrient availability gradients caused by snowpack recession), and 2) greater indication of the microbial and chemical evolution of the holes through time-space substitution.

Field Sites

Biogeochemical processes occuring in cryoconite holes operate within a range of conditions. The end-members of this spectrum are: a) holes that open each summer following the retreat of a melting snowpack (typical of the maritime Arctic and Antarctic); b) holes that are closed to the atmosphere (lidded) for some time, but where low rates of snow accumulation still enable photosynthesis (typical of colder, continental sites). We therefore propose three logistically favourable sites that enable both end-member and intermediate cryoconite habitats to be studied. They are: **A**) Midre Lovenbreen, Svalbard (78 ^{o}N, European High Arctic); **B**) Sørsdal Glacier, Vestfold Hills (68 ^{o}S, Australian Sector, Antarctica); **C**) The Dry Valleys (75 ^{o}S, McMurdo, Antarctica). Field work will be undertaken over the course of one full year at each of these sites during the IPY programme. In each case, field operations will be supported by a locally established research station that is available to this project. These include Davis Base (Australian Antarctic); McMurdo (US Antarctic) and Ny Ålesund (BAS, UK).

Personnel

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References

Bayliss, P., Ellis-Evans, J.C. & Laybourn-Parry, J. (1997) Temporal patterns of primary production in a large ultra-oligotrophic Antarctic freshwater lake. *Polar Biol.* **18:** 363-370.

Charlesworth J.K. (1957) The Quaternary Era. Edward Arnold, London.

Chin-Leo,G. & Kirchman, D.L. (1988) Estimating bacterial production in marine waters from the simultaneous incorporation of thymidine and leucine. *Appl. Environ.Microbiol*., **54:** 1934-1939.

Foreman CM, Wolf CF and Priscu JC. Impact of episodic warming events on the physical, chemical and biological relationships of lakes in the McMurdo Dry Valleys, Antarctica. Aquatic Chemistry (in press).

Fountain, A.G., Tranter, M., Nylen, T., Lewis, K. and Muller, D. In Review. Evolution of Cryoconite Holes and their Contribution to Melt-water Runoff from Glaciers in the McMurdo Dry Valleys, Antarctica, *Journal of Glaciology*.

Fuhrman J.A. (1999) Marine viruses and their biogeochemical and ecological effects. *Nature* **399:** 541-548

Gerdel R.W., Drouet F. (1960) The cryoconite of the Thule area, Greenland. *Trans. Am. Micro. Soc.* **79:** 256-272

Hodson, A.J., Mumford, P.N., Kohler, J. and Wynn, P.M. In Press. The High Arctic glacial ecosystem: new insights from nutrient budgets, *Biogeochemistry*.

James M.R., Hall J.A., Laybourn-Parry J. 1998. Protozooplankton of the Dry Valley Lakes of Southern Victoria Land. In: *Ecosystem Dynamics in a Polar Desert*. J.C. Priscu (ed.) Antarctic Research Series Academic Press 72: 225-268.

Kepner, R.L. & Wharton, E.A. 1998. Viruses in Antarctic lakes. *Limnol. & Oceanogr.*, **43:** 1754-1761.

Laybourn-Parry, J. 1997. The microbial loop in Antarctic lakes. In *Ecosystem Processes in Antarctic Ice-Free Landscapes*. (eds. C. Howard-Williams et al.,), Balkema, Rotterdam, pp 231-240.

Laybourn-Parry J., Roberts E.C., Bell E.M. 2000a. Protozoan growth rates in Antarctic lakes. *Polar Biol.* **23:** 445-451

Laybourn-Parry J., Hofer J., Sommaruga R. 2001a. Viruses in Antarctic freshwater and saline lakes. *Freshwater Biol*. **46:** 1279-1287

Laybourn-Parry J., Quayle W., Henshaw T., Ruddell A., Marchant H.J. 2001b. Life on the edge: the plankton and chemistry of Beaver Lake an ultra-oligotrophic epishelf lake, Antarctica. *Freshwater Biol*. **46:** 1205-1218

MacIntyre N.F. 1984. Cryoconite hole thermodynamics. *Can. J. Earth Sci*. **21:** 152-156

Markager S., Vincent W.F., Tang E.P.Y. 1999. Carbon fixation by phytoplankton in high Arctic lakes: implications of low temperature for photosynthesis. *Limnol. Oceanogr*. **44:** 597-607

O'Brien W.J., Hershey A.E., Hobbie J.E., Hullar M.A., Kipphut G.W., Miller M.C., Moller B., Vestal J.R. 1992. Control mechanisms in Arctic lake ecosystems: a limnolcorral experiment. *Hydrobiologia* **240:** 143-188

Porazinska, D.L., Fountain, A.G., Nylen, T.H., Tranter, M., Virginia, R.A. and Wall, D.H. 2004. The biodiversity and biogeochemistry of cryoconite holes from McMurdo Dry Valleys, Antarctica*, Arctic, Antarctic and Alpine Research*, **36**, 84 – 91.

Priscu, J.C., Wolf, C.F., Takacs, C.D., Fritsen, C.H., Laybourn-Parry, J., Roberts, E.C. & Lyons, W.B. 1999. Organic carbon transformations in the water column of a perennially ice-covered Antarctic lake. *Bioscience*, **49,** 997-1008.

Säwström, C., Mumford, P. Marshall, W., Hodson, A & Laybourn-Parry, J. 2002. The microbial communities and primary productivity of cryconite holes on an Arctic glacier (Svalbard 75^{o}N). *Polar Biology* **25**(8): 591-596

Steeman-Nielsen, E. 1952. The use of radioactive carbon (^{14}C) for measuring organic production in the sea., *J. Cons. Int. Explor. Mer*. **18:** 117-140.

Steinbeck O. 1936 Cryoconite holes and their biological significance. *Zeit. F. Gletscherkunde* **24:** 1-21

Takeuchi, N., Kohshima, S., Yoshimura, Y., Seko, K. and Fujita, K. 2000. Characteristics of cryoconite holes on a Himalayan glacier, Yala Glacier Central Nepal. *Bull. Glaciol. Res*., **17:** 51-59.

Takeuchi, N., Kohshima, S., Shiraiwa, T and Kubota, K. 2001. Characteristics of cryoconite (surface dust on glaciers) and surface albedo of a Patagonian glacier, Tyndall Glacier, Southern Patagonia Icefield. *Bull. Glaciol. Res.*, **18:** 65-69.

Tranter, M., Fountain, A., Fritsen, C., Lyons, B., Statham, P. and Welch, K. 2004. Extreme hydrochemical conditions in natural microcosms entombed within Antarctic Ice, *Hydrological Processes,* **18***, 379 – 387*..

Wharton R.A., Vinyard W.C., Parker B.C., Simmons G.M., Seaburg K.G. 1981. Algae in cryoconite holes on the Canada Glacier in southern Victoria Land, Antarctica. *Phycologia* **20:** 208-211.