McMurdo Dry Valleys Long-Term Ecological Research

McMurdo Dry Valleys Long-Term Ecological Research (LTER): An overview of 1995–1996 research activities

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The McMurdo Dry Valleys Long-Term Ecological Research (LTER) project is an interdisciplinary study of the aquatic and terrestrial ecosystems in a cold desert region of Antarctica. The McMurdo Dry Valleys, the largest ice-free area (approximately 4,800 square kilometers) on the antarctic continent, are located on the western coast of the Ross Sea (77°00'S 162°52'E). The McMurdo Dry Valleys LTER site (currently research is focused in Taylor Valley) is far colder and drier than any of the other 17 established LTER sites. The perennially ice-covered lakes, ephemeral streams, and extensive areas of soil within the valleys are subject to low temperatures, limited precipitation, and salt accumulation. The dry valleys represent "end-member" environments that contain microbial-dominated ecosystems. An important aspect of the McMurdo LTER research is its potential contribution to general ecological understanding through studies of processes that may be better resolved in these relatively simplified ecosystems (cf. more complex ecosystems). The McMurdo LTER advances two key hypotheses:

- The structure and function of the dry valley ecosystems are differentially constrained by physical and biological factors.
- The structure and function of dry valley ecosystems are modified by material transport.

In addressing these hypotheses, the interdisciplinary group is conducting a program of systematic data collection, long-term experiments, and model development. Research activities, which are spread across different disciplines, include physical, chemical, and biological modeling and information science.

The McMurdo LTER project has successfully completed three field seasons beginning in 1993. During the 1993–1994 field season, 18 scientists deployed to McMurdo Station and Taylor Valley to conduct research associated with the LTER project. These scientists initiated a core measurements program to obtain baseline, ecologically relevant data from the atmosphere, glaciers, streams, soils, and lakes. During the 1994–1995 field season, 26 scientists visited the dry valleys to continue the core measurements and research program. The first two seasons took place during the austral summer period (October to February). The third field season, 1995–1996, began in August (winter) so that research could focus on the changes in lake chemistry and biology during the transition between total winter darkness and the return of light in the spring.

We now summarize some of the research highlights resulting from the efforts of 27 scientists during the 1995–1996 field season. These highlights are expanded upon in eight subsequent papers prepared by LTER scientists.

Because of the lack of precipitation, the major source of water in the dry valleys is the melting of glaciers during the austral summer. Lewis, Fountain, and Langevin explain how the terminus cliff melt from the Canada Glacier in Taylor Valley is the largest contributor to streamflow in Anderson Creek. They report that the melt on the terminus cliffs is surprisingly heavier than the flow from surface ablation from the glacier. Local energy balance of the Canada Glacier terminus was measured along with the resulting flow in Anderson Creek. Lewis et al. conclude that because of the large radiation flux along the terminus cliffs, ablation was possible with temperatures as low as –20°C. They concluded that peak streamflow from the Canada Glacier can be mostly attributed to terminus cliff melt as melt continues from the cliffs with cooler temperatures.

In a related study, Dana, Wharton, and Fountain report the effects of solar radiation on three different glaciers—Commonwealth, Howard, and Taylor. Incoming and outgoing solar radiation were measured using Eppley pyranometers located on the three glaciers. They show that Taylor Glacier had a greater net solar radiation compared to the Commonwealth and Howard Glaciers due to its relatively lower albedo. The Taylor Glacier's lower albedo is attributed to lack of snow cover and a greater extent of "bare ice." The Commonwealth and Howard Glaciers, both closer to the coast, receive more snowfall due to the prevailing winds and cloud coverage. The resulting snowfall on these glaciers produces higher albedos and lower net solar radiation.

In another paper focused on the influence of the Taylor Valley glaciers on the dry valley ecosystems, Fountain, Lewis, and Dana discuss "calving" and its contribution to mass loss on the Canada, Commonwealth, Howard, and Taylor

Glaciers. Photographs and on-site observation of glacier cliffs indicate that on average, calving blocks are 50 centimeters thick and that they can occur in widths of 10–100 meters. In this study, the energy balance of the ice surfaces was determined to assess the mass loss resulting in potential meltwater. In comparing precipitation totals for winter and summer snowfall to the amount of ablation, Fountain et al. find totals for ablation to be generally the same for both seasons. Therefore, they conclude, calving is the result of stress and strain from ice movement, rather than from fatigue of daily heating and cooling from solar radiation.

During the austral summer, meltwater from the glaciers results in ephemeral streams, which contain variably productive microbial communities. In an effort to understand more fully the stream ecosystems in Taylor Valley, Moorhead and McKnight examine the correlation between discharge patterns for streams in McMurdo Dry Valleys and evaluate the relationship between daily discharge, mean daily temperature, and total incident shortwave radiation. Using data obtained from the LTER's network of stream gauges and meteorological stations, they conclude that a weak relationship exists between stream discharge and incoming shortwave radiation. Factors that appear to be important in affecting stream discharge include location and orientation of the glaciers that feed the streams, as well as stream geometry and slope.

The perennially ice-covered lakes in the McMurdo Dry Valleys contain relatively productive planktonic and benthic microbial communities. Kepner and Wharton studied the protozoan communities in lakes Fryxell and Hoare using polyurethane foam units (PFUs) as artificial substrates to collect protozoa. These scientists used a method similar to one used 18 years earlier to collect and classify protists taken from six sampling holes in the same two lakes. Forty-one taxa of protozoa were identified from lakes Fryxell and Hoare. On a site-by-site basis, 32 taxa were found in Fryxell (western end), 18 taxa were found in the center of Lake Hoare, and 15 taxa were found in the western end of Lake Hoare. In detailed comparisons of community composition, made at a variety of spatial scales, Kepner and Wharton found that fewer protist species inhabit deeper anaerobic waters compared to shallower aerobic waters.

The perennial ice covers also affect lake dynamics by minimizing temperature-driven turnover and wind-driven mixing. Lyons, Welch, Tyler, and Sharma question the past belief of permanent stratification and little or no advective movement within the dry valley lakes. A relative argument showed that downward mixing due to water density occurred in Lake Fryxell with the discovery of tritium at depth. For a better understanding of the source of solutes in the McMurdo Dry Valley lakes, they compared Miller and Aiken's data (1996) to Carlson's earlier data (1990), then observed their own samples taken from Lake Hoare at depths of 10 and 12 meters. The samples taken from Lake Hoare indicated relatively modern chlorofluorocarbon concentrations, suggesting that lake "mixing" occurred. They conclude that the biogeochemical dynamics of the valley lakes may have to be rethought if density-driven mixing is found to be a major process.

Understanding the biogeochemical cycles in the ice-covered lakes also requires accurate assessments of lake bathymetry. Doran, Wharton, and Schmok report on new bathymetric maps developed for lakes Bonney, Fryxell, and Hoare, created from a combination of

- U.S. Geological Survey topographic maps,
- color aerial photographs flown in 1993,
- differential global positioning system (GPS) rapid-static surveys,
- additional lead-line measurements, and
- ground-penetrating radar (GPR) surveys.

These maps should allow for more accurate determinations of lake productivity and nutrient chemistry.

The soils in the McMurdo Dry Valleys are indeed a harsh environment—low temperatures and moisture and high salt concentrations. Studying the genetic diversity of the Taylor Valley's soil nematodes, Courtright et al. find that the cold temperatures and low moisture of the dry valley limit the dispersal and establishment of soil nematodes. They provide results of genetic analyses, which allow them to suggest that two distinct species of *Scottnema lindsayae*, the dominant nematode, are evolving in the dry valleys.

Data from the above research are now being incorporated into an interactive database, which is specifically designed for the McMurdo LTER by McMurdo's data and information manager, Ken McGwire. Data management activities for the LTER site over the last 8 months have included the development of direct Internet access to online datasets through user-friendly World Wide Web interfaces. Initial examples include

- an interface for extracting meteorological data based on user-defined date, time, and location;
- downloadable aerial photography of the Taylor Dry Valleys; and
- a catalog of data sets and other items which have been submitted to the LTER data management office.

The next generation of data management being developed for the LTER site will use a hybrid relational/object-oriented database management system (DBMS) to allow direct access to data. This approach will give the DBMS the flexibility to handle a wide variety of data types, such as temperatures, species lists, and stream chemistry measurements, within a consistent query-based interface. Existing data submissions to the LTER data management office are being tested against this hybrid DBMS model to ensure that a variety of data sources can be handled.

The McMurdo Dry Valleys LTER Web Site can be accessed through *http://mcm.maxey.dri.edu/lter*.

This research is supported by National Science Foundation grant OPP 92-11773.

McMurdo Dry Valleys LTER: The role of terminus cliff melt in streamflow, Taylor Valley, Antarctica

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In polar regions, slope angle can play a large role in glacial meltwater generation. Because of the low sun angle, steep surfaces, although they face the Sun for only limited spans of time, receive far more intense radiation than corresponding low-angle surfaces. A comparison of terminus and surface ablation stake data from the Canada Glacier, Taylor Valley, indicates that ablation on the terminus cliffs ranges from one to seven times the average surface ablation (Fountain, Lewis, and Dana, *Antarctic Journal*, in this issue). Consequently, although terminus cliffs represent a much smaller area than the glacier surface ablation zone, the cliffs contribute disproportionately to the meltwater runoff from the glacier. Because terminus cliff melt is far more heavily dependent on time of day than surface melt, we expect to see strong meltwater inputs to the streams at times when the terminus cliffs feeding the streams are facing directly into the Sun.

To assess quantitatively the contribution of meltwater from the ice cliffs on streamflow, we measured the local energy balance of the cliffs at the Canada Glacier terminus. This location was chosen because

- the cliff is bordered by a gauged stream;
- ablation stakes have been placed at five locations along the section of cliff feeding the stream;
- the stream is very short so water loss to evaporation is minimal; and
- the cliff and meteorologic station are within 300 meters of camp, so regular monitoring is feasible.

In addition, ablation stake, meteorologic, and eddy correlation data are available for the glacier surface.

The terminus meteorologic station was located on the western side of the Canada Glacier roughly 500 meters north of the Lake Hoare shore (figure 1). The instruments were mounted 1.3 meters from the terminus cliff on an iron bar frozen into the ice at the base of the cliff to measure characteristics associated with the cliff face. The shortwave radiation sensors were oriented horizontally into and away from the cliff face. Both the shortwave sensors and the temperature and relative humidity probe were mounted approximately 1 meter above the ground. Data were collected from 10 December 1995 to 22 January 1996.

The correlation between the air temperatures in excess of 0°C and stream discharge is shown in figure 2. When the terminus cliff air temperature is below freezing, the streamflow declines or shuts down. When temperatures are above freezing, the stream discharge and air temperature curves are positively correlated.

The air temperature on the glacier surface is generally cooler than at the terminus cliffs (Chinn 1987), which allows for a longer melt season on the terminus cliffs than on the glacier surface. In addition, though streamflow slows or shuts down when air temperatures drop below 0°C, melt on the terminus cliffs can occur at air temperatures well below 0°C during periods of large incoming radiation flux. Because the streambed is generally frozen when the air temperature is below 0°C, however, this meltwater refreezes before reaching the stream gauge.

Shortwave radiation receipt on the terminus cliffs differs significantly from that on the glacier surface. Unlike the surface, which receives nearly continual sunlight modified only by surrounding topography (i.e., shading by local mountains), the cliffs receive energy only for a short period of the day when the Sun faces the cliffs. During these periods, the shortwave energy flux can exceed 500 watts per square meter (W m^{-2}) for a span of a few hours. On average, the cliffs receive roughly 50 W m^{-2}. In contrast, surface values rarely exceed 300 W m^{-2} but average roughly 150 W m^{-2}.

In general, for any point on the terminus cliff, we would expect to see a daily radiation peak. Instead, we measured two shorter peaks (one at 1500–1700 hours and another at 1900–2400 hours) due to the local topography, which blocks

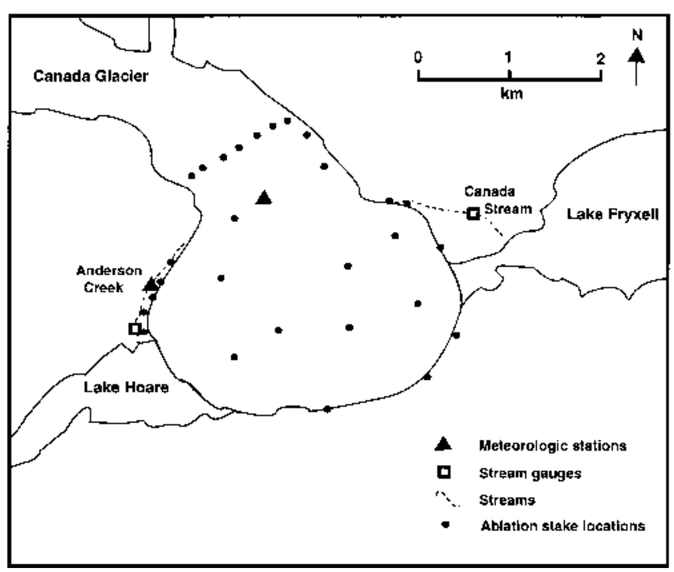

Figure 1. The Canada Glacier, showing the terminus and surface meteorologic stations, the terminus ablation stakes near the terminus meteorological station, and Anderson Creek.

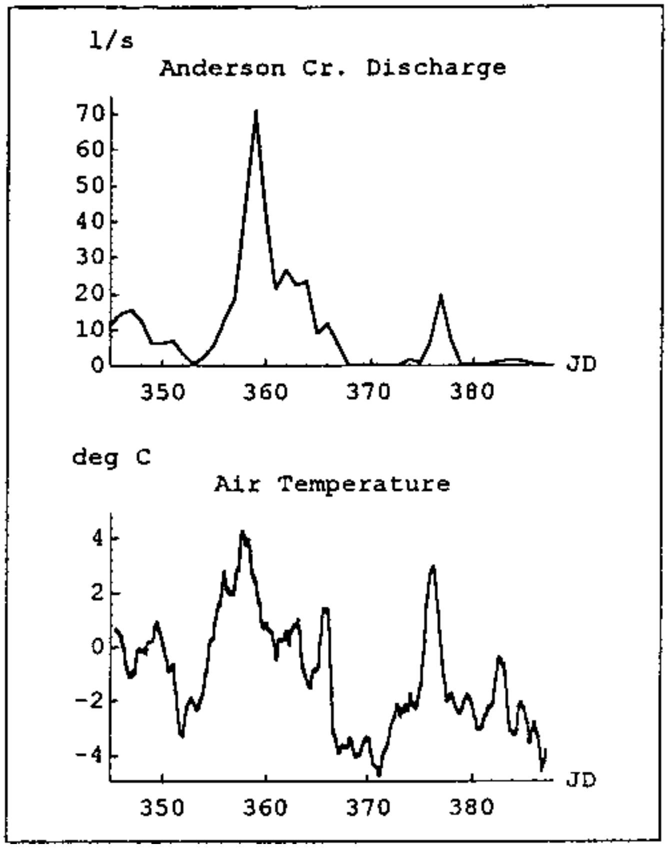

Figure 2. Anderson Creek discharge (in liters/second) and terminus cliff air temperature data, plotted as 24-hour running averages, austral summer 1995–1996.

the Sun for a few hours during the middle of its passage across the cliff face. The bi-daily radiation peaks are generally accompanied by corresponding discharge peaks. The timing of the latter shows more variation than the former but in general occurs between 1630–2000 and 2100–0100 hours. Discharge peaks fail to appear during cloudy periods and periods when the air temperatures are well below 0°C. This 2-hour lag between peak radiation and peak melt is probably indicative of the time delay between increased melt and subsequent travel to the streambed.

Unlike on the glacier surface, where up to 70 percent of ice ablation is due to sublimation (Lewis et al. 1995), along most of the terminus cliff wind speeds are low, and thus the sensible and latent heat fluxes are small (Chinn 1987). Net radiation is the dominant source of incoming energy, and most of this energy goes to melt. Therefore, we can estimate the terminus meltwater contribution to Anderson Creek for the summers of 1994–1995 and 1995–1996 by assuming that the ablation recorded on the terminus ablation stakes is due to melt.

The terminus cliff bordering Anderson Creek is roughly 20 meters high by 2,000 meters long. If we assume the melt across this entire face is equal to the average of the ablation stake measurements, 16 centimeters (cm) for the 1995–1996 summer, the resulting flow is 6,400 cubic meters (m^3). The recorded seasonal flow for Anderson Creek is 39,200 m^3, implying 16 percent of the streamflow is due to terminus melt. Similar calculations for 1994–1995, using an average ablation of 15.5 cm and a total flow of 16,050 m^3, indicate 39 percent of the streamflow during that summer came from terminus melt. The difference between terminus meltwater contribution and total flow must be accounted for through glacier surface melt, because no other significant source of available meltwater exists.

Clearly, the terminus cliffs cannot be neglected when calculating glacial water and mass balances. In particular, peak streamflow can be attributed almost entirely to terminus cliff melt.

This research was supported by National Science Foundation grant OPP 92-11773.

References

Chinn, T. 1987. Accelerated ablation at a glacier ice-cliff margin, dry valleys, Antarctica. *Arctic and Alpine Research*, 19(1), 71–80.

Fountain, A.G., K.J. Lewis, and G.D. Dana. 1996. McMurdo Dry Valleys LTER: Spatial variation of glacier mass balances in Taylor Valley, Antarctica. *Antarctic Journal of the U.S.*, 31(2).

Lewis, K.J., G.D. Dana, A.G. Fountain, and S. Tyler. 1995. The surface-energy balance of the Canada Glacier, Taylor Valley. *Antarctic Journal of the U.S.*, 30(5), 280–282.

McMurdo Dry Valleys LTER: Solar radiation on glaciers in Taylor Valley, Antarctica

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The continuous influx of solar radiation during the austral summer is an important driving force for hydrological and ecological systems in the McMurdo Dry Valleys, Antarctica. Spatial and temporal variations in radiative fluxes may influence glacier mass balance and stream discharge, as well as distribution and production of biological communities in the dry valleys. Because solar radiation plays an important role in these polar deserts, the primary goal of this study was to assess differences in solar radiation on three glaciers in Taylor Valley, Antarctica, over a 2-year period using data collected as part of the McMurdo Dry Valleys Long-Term Ecological Research (LTER) study.

Solar radiation data were continuously collected during 1994–1995 from the ablation zones on the surface of three glaciers in Taylor Valley (77°00'S 162°52'E):

- The Commonwealth Glacier flows from the Asgard Range on the north side of the valley and is the nearest of the three glaciers [4 kilometers (km)] to McMurdo Sound.
- The Howard Glacier, on the south side of the valley, is in the Kurkri Hills and 13 km upvalley from McMurdo Sound.
- The Taylor Glacier lies at the head of Taylor Valley, 36 km inland.

For glacier locations, see figure 1 in Fountain, Lewis, and Dana (*Antarctic Journal*, in this issue). The elevations of the sites varied: 290 meters (m) on the Commonwealth Glacier, 327 m on the Taylor Glacier, and 437 m on the Howard Glacier. Although measurements were made over the entire 2-year period on the Commonwealth and Howard Glaciers, the site on the Taylor Glacier was not established until late in 1994. Incoming and outgoing solar radiation was measured with Eppley pyranometers (model PSP), and data were stored on a Campbell Scientific datalogger (model CR10). Further details on the three sites and coincident meteorological measurements can be found in Doran et al. (1995).

A comparison showed that the mean monthly amount of incoming solar radiation was different at each site. Taylor Glacier received up to 20 percent more solar radiation than the Commonwealth and Howard Glaciers, and the Commonwealth received up to 50 percent more radiation than the Howard (figure 1). These differences were even greater for net solar radiation (incoming minus reflected). For example, during November 1995 the Taylor Glacier on average absorbed 155 watts per square meter (W m^{-2}), 2.5–3.5 times more solar energy than the Commonwealth and Howard Glaciers, which absorbed on average, 65 and 44 W m^{-2}, respectively. Annual solar energy budgets bear out these trends as well as interannual differences existing between the Commonwealth and Howard Glaciers. Total amount of annual solar energy impinging on both of these glaciers increased between 1994 and 1995 (figure 2). The annual energy increased from 3,422 to 3,474 megajoules per square meter per year (MJ m^{-2} yr^{-1}) on the Commonwealth Glacier and from 2,990 to 3,115 MJ m^{-2} yr^{-1} on the Howard Glacier from 1994 to 1995. The annual net solar energy absorbed by the two glaciers, however, actually decreased from 1994 to 1995, from 1,061 to 780 MJ m^{-2} yr^{-1} on the Commonwealth Glacier and from 670 to 565 MJ m^{-2} yr^{-1} on the Howard Glacier.

The greater net solar radiation observed on the Taylor Glacier can largely be attributed to its much lower albedo and, to a smaller extent, the greater amount of incoming radiation it receives. Mean monthly albedos on the Taylor Glacier ranged between 49 and 66 percent whereas albedos on the Commonwealth and Howard Glaciers were usually much higher, between 61 and 90 percent. Snow cover present at the measurement sites of the Commonwealth and Howard Glaciers during most of 1994–1995 conferred the higher albedos measured on those two glaciers, whereas the mostly ice-covered (i.e., relatively snow-free) surface of the Taylor Glacier resulted in its lower albedo.

Albedo changes may also explain the small decrease in net solar radiation on the Commonwealth and Howard Glaciers from 1994 to 1995, despite the slight increase in incoming solar energy over the same time period (figure 2). In December and January 1994, a large expanse of bare ice was present at the measurement sites of these two glaciers, and mean monthly albedos ranged from 58 to 61 percent (figure 1, December 1993 not shown). New snow accumulation subsequent to January 1994 caused albedos to increase, and from 1994 to 1995, the mean annual albedo increased from 72 to 81 percent on the Commonwealth Glacier and from 76 to 83 percent on the Howard Glacier. The slightly higher annual averaged albedos on the Howard Glacier compared with the Commonwealth contribute to its lower net solar radiation.

Both the lower albedo and higher incoming solar radiation on the Taylor Glacier can be explained by the climatic regime in Taylor Valley. Precipitation is highest near McMurdo Sound, where low-pressure systems and easterly winds transfer moist air over the dry valleys (Bromley 1985). Precipitation, and presumably cloudiness, decreases westward with distance from the ocean (Bull 1966, pp. 177–194; Keys 1980). Of the three glaciers studied, the ablation zone of the Taylor Glacier is the farthest, 36 km, from the ocean

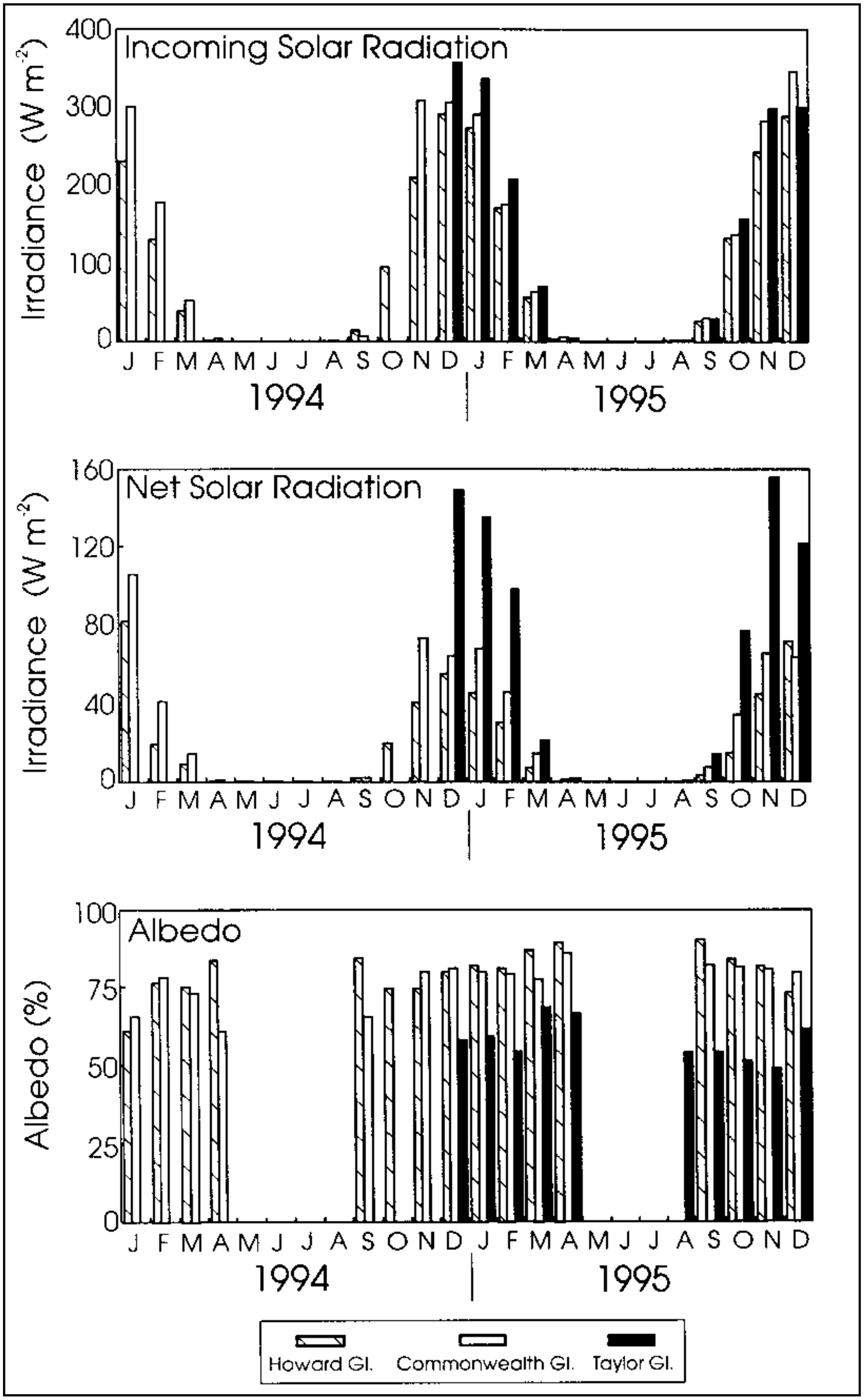

Figure 1. Mean monthly incoming solar radiation (top panel), net solar radiation (middle panel), and albedo (lower panel) of three glaciers in Taylor Valley, Antarctica, during 1994–1995. Measurements did not begin on Taylor Glacier until 1995. Data are missing from the Commonwealth Glacier in October 1994 due to data-logger failure. Albedos are calculated only for time periods in which light is present.

and receives less snow (Fountain et al., *Antarctic Journal*, in this issue).

Given the observed climatic gradient in the dry valleys, it would be expected that the Commonwealth Glacier, which is closest to McMurdo Sound, would have the lowest solar energy budget of the three glaciers, but this is not the case. The greater flux of incoming and net solar radiation on the Commonwealth compared with the Howard Glacier requires other explanations. What is most different between these two glaciers that could influence the solar radiation budget is their aspects and elevations. The higher elevation of the Howard Glacier may result in a greater incidence of clouds, and its north-facing orientation in relation to the topographic relief of the surrounding Kukri Hills may result in more terrain shading than the Commonwealth Glacier. Solar modeling incorporating terrain features would be a useful tool in understanding the differences in solar radiation we have observed among the glaciers in the McMurdo Dry Valleys.

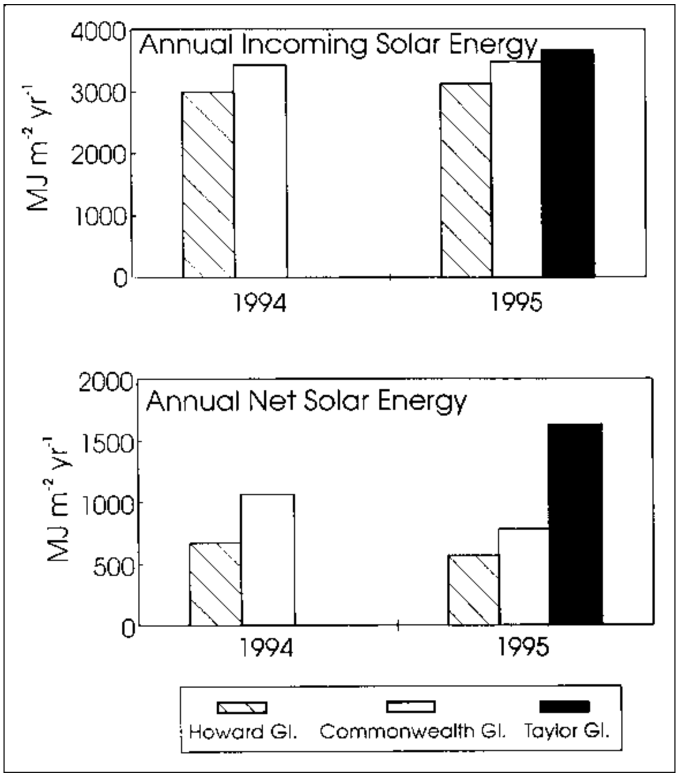

Figure 2. Integrated annual incoming solar energy (top panel) and net solar energy (lower panel) for three glaciers in Taylor Valley, Antarctica, during 1994–1995. Measurements did not begin on Taylor Glacier until 1995. In calculating annual energy for the Commonwealth Glacier, mean monthly October 1994 values were estimated using linear interpolation.

This research was supported by National Science Foundation grant OPP 92-11773, with additional support from a Desert Research Institute Nevada Medal Research Fellowship and a National Aeronautics and Space Administration Global Change Fellowship to G. Dana. We thank Karen Lewis, Paul Langevin, Peter Doran, and Paul Sullivan for assistance in the field and Robert Stone and Robert Davis for their invaluable advice on solar radiation measurements in cold regions.

References

Bromley, A.M. 1985. *Weather observations in Wright Valley, Antarctica* (Information Publication No. 11). Wellington: New Zealand Meteorological Service.

Bull, C. 1966. Climatological observations in ice-free areas of southern Victoria Land, Antarctica. In M.J. Rubin (Ed.), *Studies in antarctic meteorology* (Antarctic Research Series, Vol. 9). Washington D.C.: American Geophysical Union.

Doran, P.T., G.L. Dana, J.R. Hastings, and R.A. Wharton, Jr. 1995. McMurdo LTER: LTER automatic weather network (LAWN). *Antarctic Journal of the U.S.*, 30(5), 276–280.

Fountain, A.G., K.J. Lewis, and G.L. Dana. 1996. McMurdo Dry Valleys LTER: Spatial variation of glacier mass balance in Taylor Valley, Antarctica. *Antarctic Journal of the U.S.*, 31(2).

Keys, J.R. 1980. *Air temperature, wind, precipitation and atmospheric humidity in the McMurdo region* (Department of Geology publication No. 17, Antarctic Data Series No. 9). Wellington, New Zealand: Victoria University.

McMurdo Dry Valleys LTER: Spatial variation of glacier mass balance in Taylor Valley, Antarctica

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The McMurdo Dry Valleys, next to McMurdo Sound at 76°30' to 78°30'S and 160° to 164°E (figure 1), are the largest of the antarctic ice-free regions, which account for 5 percent of the continental area (Drewry, Jordon, and Jankowski 1982). The hydrology of the dry valleys originates from glacial meltwater. During the summer months, from late November and into February, the glaciers melt providing the only source of water for the streams. Snowfall in the valleys does not contribute to the streams or to the general hydrology because it usually sublimates before melting (Chinn 1981). To assess the mass change of the glaciers, we have established surface measurements of mass change on four glaciers in Taylor Valley (Fountain, Vaughn, and Dana 1994). To determine the component of mass loss resulting in meltwater, we are measuring the energy balance of the ice surface (Lewis et al. 1995; Lewis, Fountain, and Langevin, *Antarctic Journal*, in this issue) and collecting meteorological information on four glaciers (Doran et al. 1995; Dana, Fountain, and Wharton, *Antarctic Journal*, in this issue). In this article, we summarize the findings of the mass balance measurements for the Commonwealth, Canada, Howard, and Taylor Glaciers (figure 1).

Snowfall in Taylor Valley occurs any time of the year. During our study period, from November 1993 through January 1996, more snow accumulated in the winter period (February through October) than during the summer period (November through January). Measurements of net snow accumulation on the upper Commonwealth and Howard Glaciers show that during summer, accumulation did not exceed 3.3 centimeters (cm)

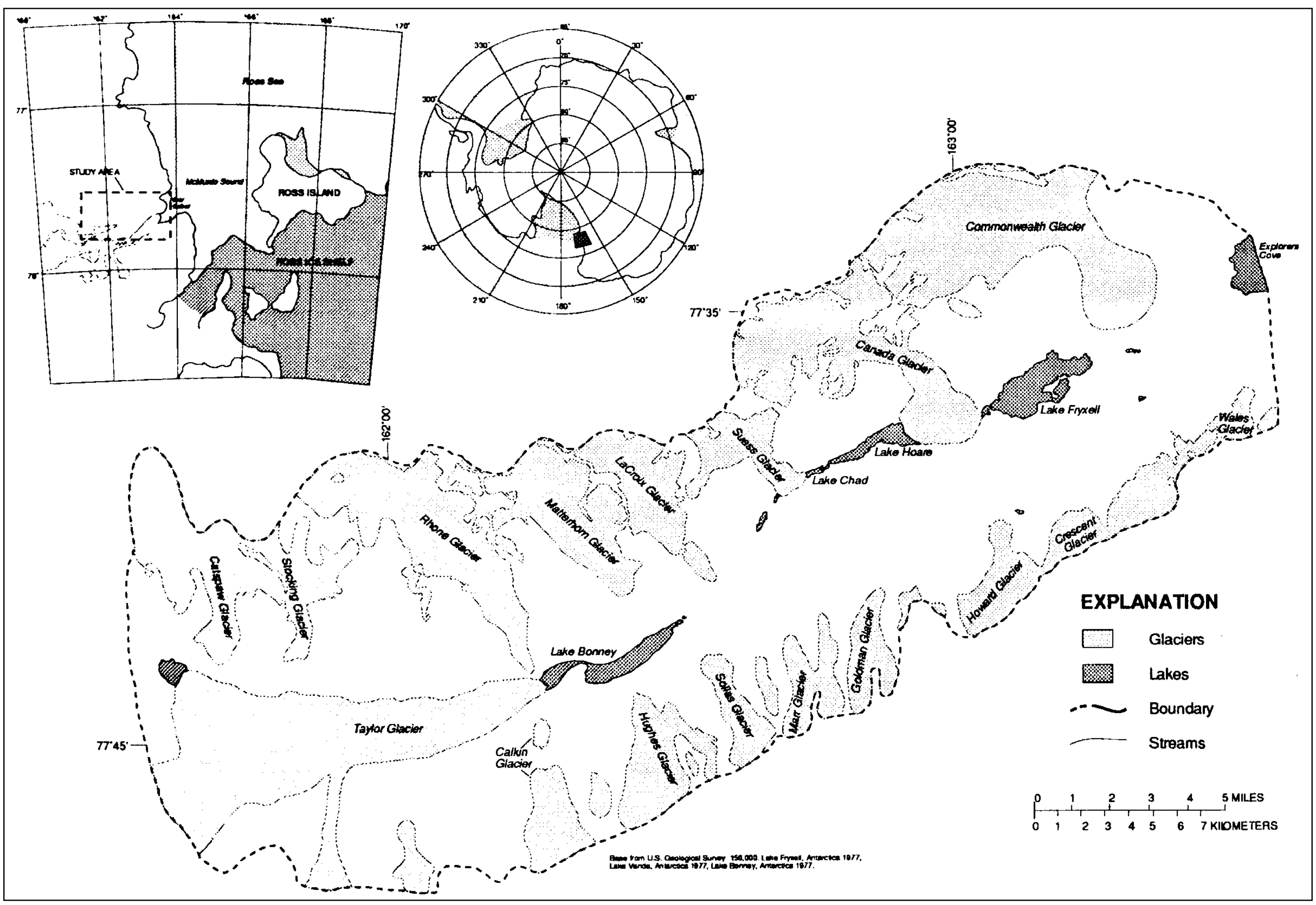

Figure 1. Base map and location of glaciers in Taylor Valley, Antarctica.

water equivalent, and many measurements were near or below 0 cm. Winter accumulation did not exceed 11.3 cm water equivalent; most values were 3 cm water equivalent or more. These findings contrast with those of Chinn (1985) for the Wright Valley. It is not clear if this difference is due to the span of time and the variation in meteorological conditions or whether it is due to distinctly different climatic regimes between the two valleys. Chinn (1980) suggests that a local lake effect creates snowfall on the adjacent ridges. We do not observe the same phenomenon in Taylor Valley.

Figure 2 illustrates the spatial variation of glacier mass balance. Individual values of measured mass balance are shown for all four glaciers. For any given elevation, a valley gradient exists in which the mass balance is more negative upvalley and further away from the ocean. Taylor Glacier is about 36 km from the ocean, whereas Howard is about 13 km, Canada is 12 km, and Commonwealth is 4 km. Clearly, Taylor Glacier has more negative values than Canada and Howard, and these glaciers have more negative values than Commonwealth. The change in altitude of the equilibrium line reflects this valley gradient. The equilibrium line starts at about 375 meters (m) for Commonwealth and rises to about 1,200 m for the alpine glaciers near the Taylor Glacier. The altitude was determined from the elevation contours on published topographic maps. Taylor Glacier has no equilibrium line in Taylor Valley because it is an outlet glacier of the east antarctic ice sheet, and its extension into Taylor Valley is completely within the ablation zone. Thus, within Taylor Valley a strong climatic gradient exists that significantly affects the glaciers. We conjecture that the gradient is largely controlled by a decrease in precipitation away from the coast, although some evidence suggests warmer air temperatures and stronger winds upvalley. Current efforts are underway to monitor the meteorological environment (Doran et al. 1995).

The magnitudes of ablation and accumulation are small, as expected for polar glaciers. Accumulation does not often exceed 15 cm water equivalent, and ablation does not exceed

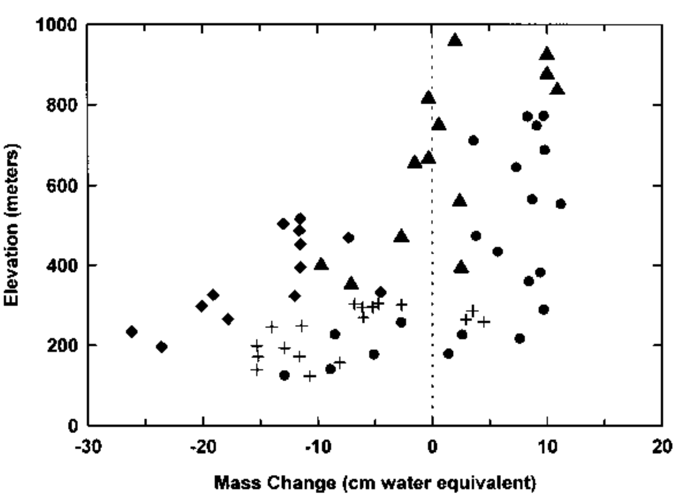

Figure 2. Annual mass balance values measured at specific stakes on four different glaciers in Taylor Valley. Dots indicate measurements on Commonwealth Glacier; plus signs, on Canada Glacier; open triangles, on Howard Glacier; and diamonds, on Taylor Glacier.

30 cm water equivalent. The exception to this characterization is ablation on the ice cliffs that forms the margin of many glaciers in the valley. The ablation of the ice cliff is typically 5–10 times the ablation of the adjacent top surface of the glacier. Measured values of ablation from the ice cliffs, excluding calving, ranges from 5 to 70 cm water equivalent. During our study, no snow has accumulated on the glaciers at elevations below about 200 m, suggesting that these zones ablate all year long. For the two glaciers with mass balance measurements in the accumulation zone (Howard and Commonwealth), the range of net seasonal snow accumulation is about the same, up to about 11 cm water equivalent. Although the sample size is small, we infer that for the same elevation, snow accumulation in the Kukri Hills is about the same as that in the Asgard Range.

The calving component of ablation is small, in agreement with the findings of Bull and Carnein (1970). Based on paired photographs of the glacier cliffs, taken in the beginning of the summer season and at the end of the season, and on on-site observations, we determined that calving blocks are typically 50 cm thick, and calving occurs over widths on the order of 10 to 100 meters. Averaged over the area of the ice cliff, ablation due to calving is about 1–3 cm water equivalent during each season or 2–6 cm for the year. No seasonal trend in calving is observed between summer and winter, indicating that calving results from the stress and strain of the ice movement rather than fatigue caused by daily heating and cooling from solar illumination.

This work was supported by National Science Foundation grant OPP 92-11773.

References

Bull, C., and C.R. Carnein. 1970. The mass balance of a cold glacier: Meserve Glacier, south Victoria Land, Antarctica. *International Association of Hydrological Sciences*, 86, 429–446.

Chinn, T.J. 1980. Glacier balances in the dry valleys area, Victoria Land, Antarctica. *International Association of Hydrological Sciences*, 126, 237–247.

Chinn, T.J. 1981. Hydrology and climate in the Ross Sea area. *Journal Royal Society of New Zealand*, 11, 373–386.

Chinn, T.J. 1985. Structure and equilibrium of the dry valley glaciers. *New Zealand Antarctic Record*, 6, 73–88.

Dana, G., R. Wharton, Jr., and A. Fountain. 1996. McMurdo Dry Valleys LTER: Solar radiation on glaciers in Taylor Valley, Antarctica. *Antarctic Journal of the U.S.*, 31(2).

Doran, P.T., G.L. Dana, J.T. Hastings, and R.A. Wharton, Jr. 1995. McMurdo LTER: LTER automatic weather network (LAWN). *Antarctic Journal of the U.S.*, 30(5), 276–280.

Drewry, D.J., S.R. Jordan, and E. Jankowski. 1982. Measured properties of the antarctic ice sheet: Surface configuration, ice thickness, volume and bedrock characteristics. *Annals of Glaciology*, 3, 83–91.

Fountain, A.G., B.H. Vaughn, and G.L. Dana. 1994. Glacier mass balances of Taylor Valley, Antarctica. *Antarctic Journal of the U.S.*, 29(5), 226–227.

Lewis, K., G. Dana, A. Fountain, and S. Tyler. 1995. McMurdo LTER: The surface-energy balance of the Canada Glacier, Taylor Valley. *Antarctic Journal of the U.S.*, 30(5), 280–282.

Lewis, K., A. Fountain, and P. Langevin. 1996. McMurdo Dry Valleys LTER: The role of terminus cliff melt in the hydrological cycle, Taylor Valley, Antarctica. *Antarctic Journal of the U.S.*, 31(2).

McMurdo Dry Valleys LTER: Stream discharge as a function of ambient temperature and incoming shortwave radiation in Taylor Valley, Antarctica

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Of the several streams in the McMurdo Dry Valleys, southern Victoria Land, Antarctica, many are relatively short (less than 4 kilometers), receiving water primarily from melting glaciers and flowing only during the brief, austral summer. Benthic microbial mats are widespread in many streams (Alger et al. 1996), exhibit substantial net primary production (Howard-Williams and Vincent 1989), and transform a considerable fraction of the inorganic and urea nitrogen entering the streams into other organic forms (Howard-Williams et al. 1989). In a recent modeling study, Moorhead, McKnight, and Tate (in press) noted the influence of stream discharge rate on nitrogen uptake by benthic mats. Thus, factors controlling discharge rates are likely to have a considerable impact on the nitrogen dynamics of dry valley streams. The objectives of this study were to examine the correlations between discharge patterns for streams in the McMurdo Dry Valleys and to evaluate the relationships between daily discharge, mean daily temperature, and total incident shortwave radiation.

As part of the U.S.-sponsored, McMurdo Dry Valley Long-Term Ecological Research (LTER) program, discharge of streams and local meteorological conditions in Taylor Valley (77°S 163°E) are being recorded (Von Guerard et al. 1994; Doran et al. 1995). Measurements of streamflow for use in this study were obtained from the U.S. Geological Survey (H. House, via U.S. Geological Survey Antarctic Hydrology homepage, *http://srvdwimdn.er.usgs.gov/hrhdocs/index.html*). Meterological observations were obtained for three meteorological stations located near Commonwealth Glacier, Lake Hoare, and Lake Fryxell, Taylor Valley, from the McMurdo LTER (K. McGwire, via the LTER homepage, *http://mcm.maxey.dri.edu/lter/*).

We examined the temporal patterns of discharge for eight streams draining into Lake Fryxell, Taylor Valley (Canada Stream, Huey Creek, Lost Seal Stream, Aiken Creek, Von Guerard Stream, Crescent Stream, Delta Stream, and Green Creek), during the period of maximum flow (15 December through 25 January) in the austral summers of 1993–1994 and 1994–1995. Hydrological observations were concurrent with meteorological records available through the McMurdo LTER. The pattern of daily discharge during these summers showed peak values in early January 1994, sometimes exceeding 3 cubic meters per day, although considerable differences existed between streams and between years (figure 1). When discharges were expressed as the fraction of the maximum value recorded for each stream in each year, a similar pattern emerged; streams showed peak discharges in late December and early January. Such patterns suggest a likely correlation to ambient temperature and radiant energy levels, which also peak during this time. Thus, we hypothesized that

- stream discharges would be correlated to each other and
- discharge would be correlated with the average ambient temperature and total incident radiation on a daily basis.

Pearson product-moment correlations of daily stream discharge were calculated for each pair of streams. Relationships between stream discharge and these climatic factors then were analyzed with multiple linear regressions using relative daily discharge as the dependent variable and climatic factors as independent variables.

Strong correlation existed between daily discharge for all streams, ranging between 0.743 (Huey Creek and Aiken Creek) and 0.979 (Green Creek and Crescent Stream); most correlations exceeded 0.9. Multiple linear regressions, however, revealed that stream discharge was weakly related to radiation and temperature, with overall R^2 values rarely exceeding 0.4 (table). Moreover, an overall regression (all streams in both years) yielded a low coefficient of regression (R^2=0.163, N=440) between stream discharge and climatic factors.

Temporal patterns of stream discharge were nonlinear and peaked only during a brief period in both summers,

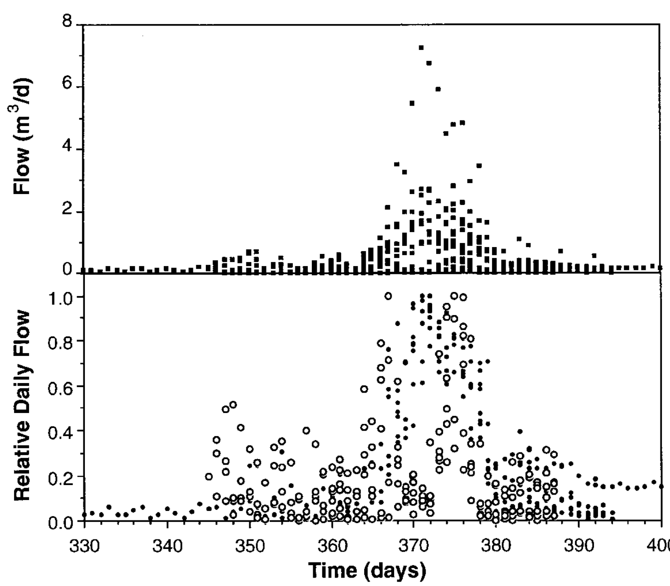

Figure 1. Daily discharge values in 1993–1994 and 1994–1995 austral summers for eight streams in the Lake Fryxell basin, Taylor Valley, Antarctica. (*Top*) Discharge values in cubic feet per day. (*Bottom*) Daily discharge as a fraction of maximum discharge per stream for each year. Filled circles: 1993–1994; open circles: 1994–1995. (cf/d denotes cubic feet per day. Multiply cubic feet by 0.03 to obtain cubic meters.)

implying a seasonal control on streamflow that was partly independent of general radiation and temperature regimes. Contrasting patterns of discharge for Canada Stream, Aiken Creek, and Von Guerard Stream also suggest that controls differ among streams (figure 2):

- Aiken Creek showed peak discharge values between 9 and 11 January of both years;
- Von Guerard Stream showed peak values approximately 5–10 days earlier than Aiken Creek;
- Canada Stream showed high discharge at both times.

A number of geographic and climatic factors apparently control streamflow (cf. McKnight, House, and Von Guerard 1994; House, McKnight, and Von Guerard 1995; Conovitz et al. in press). For example, Canada Stream is short (less than 2 kilometers) and receives meltwater from northern faces of Canada Glacier (west of Lake Fryxell). Thus, discharge should reach relatively high values early in the summer and remain high, as seen in figure 2. In contrast, Von Guerard Stream is longer than Canada Stream (approximately 5 kilometers) and is fed by the northwest face of a glacier located in the Kukri Hills (southeast of Lake Fryxell). Thus, peak flows should occur somewhat later than for Canada Stream and be more temporally constrained by the orientation of the source glacier. Aiken Creek receives meltwater from two sources: the northwest face of Wales Glacier, in the Kukri Hills, and the south and east faces of Commonwealth Glacier, to the northeast of Lake Fryxell. Moreover, flows from the Wales and Commonwealth Glaciers combine to form Many Glaciers Pond, in which Aiken Creek has its source. Thus, peak flow of Aiken Creek may be delayed by the time required for the source pond to fill.

In conclusion, it is clear that simple multiple linear regressions of daily temperature and radiation regimes are insufficient to provide an accurate prediction of discharge patterns for streams of Taylor Valley. Discharge patterns appear to be strongly influenced by attributes of stream geometry and orientation of source glaciers, as noted by Conovitz et al. (in press). A more mechanistic, physically based approach where these attributes are quantified, may be useful in developing predictive relationships between climate and streamflow in the McMurdo Dry Valleys.

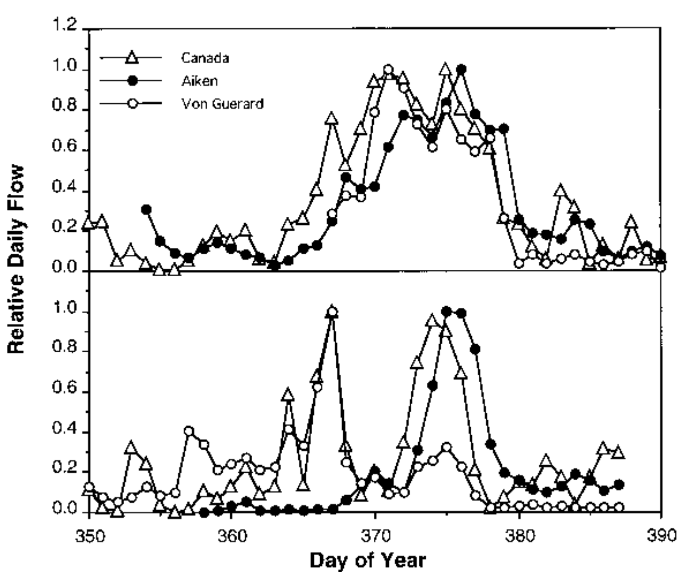

Figure 2. Daily discharge as a fraction of maximum discharge for three streams in Taylor Valley, Antarctica: (*top*) 1993–1994; (*bottom*) 1994–1995.

Results of multiple linear regressions between streamflow, ambient temperature, and incident solar radiation

Stream	Meteorological station					
	Commonwealth		Fryxell		Hoare	
	N	R^2	N	R^2	N	R^2
Canada Stream	100	0.377	47	0.345	86	0.358
Huey Creek	25	0.289	16	0.283	36	0.406
Lost Seal Stream	63	0.156	22	0.209	61	0.157
Aiken Creek	60	0.189	32	0.126	69	0.130
Von Guerard Stream	59	0.194	46	0.062	70	0.217
Crescent Stream	14	0.344	22	0.421	31	0.662
Delta Stream	57	0.206	44	0.053	67	0.244
Green Creek	60	0.235	45	0.055	70	0.282

This work was supported by a National Science Foundation grant OPP 92-11773.

References

Alger, A.S., D.M. McKnight, S.A. Spaulding, C.M. Tate, G.H. Shupe, K.A. Welch, R. Edwards, E.D. Andrews, and H.R. House. 1996. *Ecological processes in a cold desert ecosystem: The abundance and species distribution of algal mats in glacial meltwater streams in Taylor Valley, Antarctica.* Boulder: U.S. Geological Survey.

Conovitz, P.A., D.M. McKnight, L.M. MacDonald, and A. Fountain. In press. *Hydrologic processes influencing streamflow variation in Fryxell basin, Antarctica.* Washington, D.C.: American Geophysical Union.

Doran, P.T., G.L. Dana, J.T. Hastings, and R.A., Wharton, Jr. 1995. The McMurdo LTER automatic weather network (LAWN). *Antarctic Journal of the U.S.*, 30(5), 276–279.

House, H.R., D.M. McKnight, and P. Von Guerard. 1995. The influence of stream channel characteristics on streamflow and annual water budgets for lakes in Taylor Valley. *Antarctic Journal of the U.S.*, 30(5), 284–286.

Howard-Williams, C., R. Pridmore, M.T. Downes, and W.F. Vincent. 1989. Microbial biomass, photosynthesis and chlorophyll *a* related pigments in the ponds of the McMurdo Ice Shelf, Antarctica. *Antarctic Science*, 1(2), 125–131.

Howard-Williams, C., and W.F. Vincent. 1989. Microbial communities in southern Victoria Land streams (Antarctica) I. Photosynthesis. *Hydrobiologia*, 172, 27–38.

McKnight, D., H. House, and P. Von Guerard. 1994. McMurdo LTER: Streamflow measurements in Taylor Valley. *Antarctic Journal of the U.S.*, 29(5), 230–232.

Moorhead, D.L., D.M. McKnight, and C.M. Tate. In press. *Modeling nitrogen transformations in antarctic streams.* Washington, D.C.: American Geophysical Union.

Von Guerard, P., D.M. McKnight, R.A. Harnish, J.W. Gartner, and E.D. Andrews. 1994. *Streamflow, water-temperature, and specific-conductance data for selected streams draining into Lake Fryxell, Lower Taylor Valley, Victoria Land, Antarctica* (Open-file Report 94-545). Boulder, Colorado: U.S. Geological Survey.

McMurdo Dry Valleys LTER: Geophysical determination of bathymetry and morphology of Taylor Valley lakes

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The three main Taylor Valley lakes (Bonney, Hoare, and Fryxell) have been the subject of study since the discovery of the dry valleys by members of R.F. Scott's expedition in 1903 (Scott 1905, pp. 214–215). Since this time, bathymetric mapping of the lakes has been carried out by various investigators while conducting limnological studies. Standard "lead-line" sounding was the technique used for determining lake depth, but this technique limits the amount of data acquired to the number of holes that can be made in the 3–5-meter (m) thick perennial ice covers. Problems exist with all three bathymetric maps in general use today. The Lake Bonney map is based on 1963 soundings, which are marked without data in the original publication (Angino, Armitage, and Tash 1964), and the shoreline is significantly distorted (likely from parallax error in the air photo interpretation). The existing Lake Hoare map (Wharton and McKay 1986) is the most detailed of the three and includes sounding points and data. The Lake Fryxell map contains a great amount of detail (Lawrence and Hendy 1985), but the original sounding points and data are not available.

Modeling of hydrological and geochemical fluxes in these lake systems has been limited in the past by the lack of good morphometric and bathymetric data. Therefore, during November and December 1995, a geophysical study was conducted to improve the bathymetric and morphologic detail for all three Taylor Valley lakes. In this article, we report on new bathymetric maps for Lakes Bonney, Hoare, and Fryxell that were created from a combination of

- U.S. Geological Survey (USGS) topographic maps,
- color aerial photographs from flights in 1993 flown at 4,200 m,
- differential global positioning system (GPS) rapid-static surveys,
- additional lead-line measurements, and
- ground-penetrating radar (GPR) surveys.

The GPR measurements were best over the shallow moat areas and in isolated spots elsewhere. Prior to this study, it was thought that the high salinity of the lakes would be the largest obstacle to using GPR, but our survey suggests that trapped gas bubbles in the thick ice cover limit the GPR survey. Moat ice allows excellent penetration into subbottom sediments, but perennial ice obscures signals with backscattering and rapidly attenuates radar energy. The amplitude of this scattering is most extreme at Lake Hoare, followed by Lake Bonney, and then Lake Fryxell. Interestingly, when we performed GPR surveys on Lakes House and Vida, which were formerly believed frozen solid (our survey suggests a saline water body exists in Vida at approximately 19 meters), good detail of the ice structure for its entire thickness was obtained. It may be that the ice covers of Lakes Vida and House do not have the same bubble structure as, for examples, Lakes Fryxell, Bonney, and Vanda, because they are formed by the freezing of annual floodings on the ice surface.

To produce the maps presented in this paper, the lake margins were defined by digitizing the shoreline from the 1993 aerial photography and rectifying this to GPS perimeter surveys performed in November 1995. A GPS survey was not performed for Lake Fryxell, so the shoreline was established with an integration of the 1993 aerial photography and the 1:50,000 USGS topographic map. The lake margin was used in the contouring process as points with zero water depth. In addition, the aerial photographs show a distinct transition from the moat ice to the older white ice covering most of the lake. The 1995 radar data indicate that this corresponds closely to a "grounding line" where the floating ice changes into grounded ice. This grounding line was also digitized and assigned a depth as determined by the radar data.

The new bathymetric maps are shown in figures 1 to 3, and the resulting morphometric data are presented in the table. An interesting result of this study is the liquid-to-frozen water content in each of the lakes. Lake Fryxell is very different from the other two lakes in this respect, having more ice volume than liquid water volume. This finding has profound

Comparison of new morphometric values for the three main Taylor Valley lakes

Morphometric parameter	Lake Bonney	Lake Hoare	Lake Fryxell
Maximum length (km)	5.98±0.01	4.18±0.01	5.84±0.01
Maximum breadth (km)	0.90±0.01	1.01±0.01	2.06±0.01
Shore line length (km)	16.9±0.1	11.5±0.1	19.3±0.1
Maximum depth (m)	38.4±2.0	33.8±0.5	20.5±0.5
Mean ice thickness (m)	5.0±0.2	4.5±0.2	5.5±0.2
Mean piezometric thickness (m)	4.3±0.2	3.8±0.2	4.7±0.2
Surface area (km^2)	4.31±0.04	1.94±0.02	7.08±0.02
Mean depth (m)	18.4±1.84	12.5±0.63	7.6±0.63
Total lake volume (10^6 m^3)	79.49±7.95	24.34±1.21	53.57±1.21
Volume of liquid water (10^6 m^3)[a]	61.85±9.28	17.52±1.23	25.24±1.23
Volume of frozen water (10^6 m^3)	17.64±0.88	6.82±0.20	28.33±0.20
Liquid:frozen water ratio	3.5	2.6	0.9

[a]Ice density calculated based on ice thickness and water level in drill holes

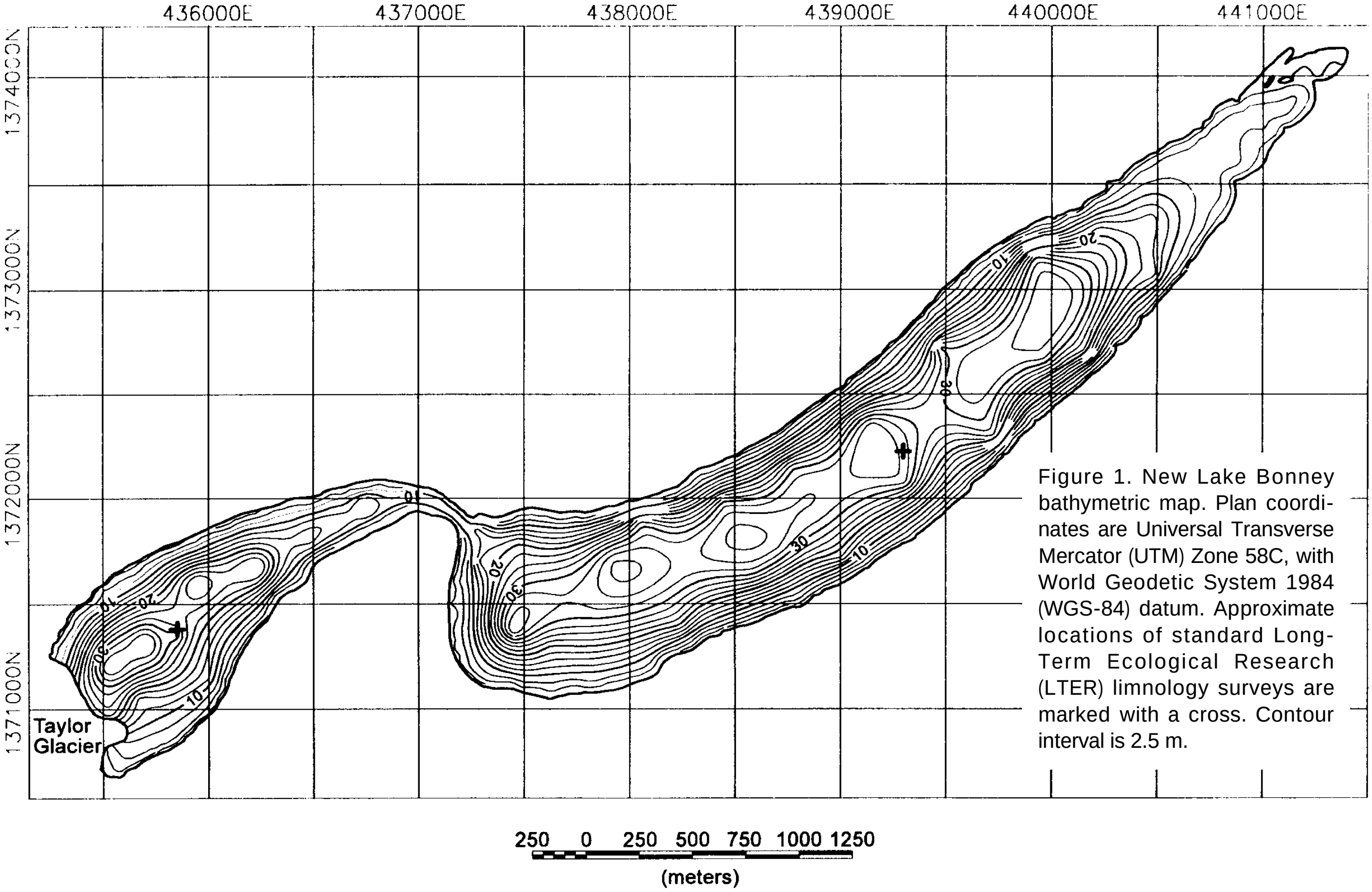

Figure 1. New Lake Bonney bathymetric map. Plan coordinates are Universal Transverse Mercator (UTM) Zone 58C, with World Geodetic System 1984 (WGS-84) datum. Approximate locations of standard Long-Term Ecological Research (LTER) limnology surveys are marked with a cross. Contour interval is 2.5 m.

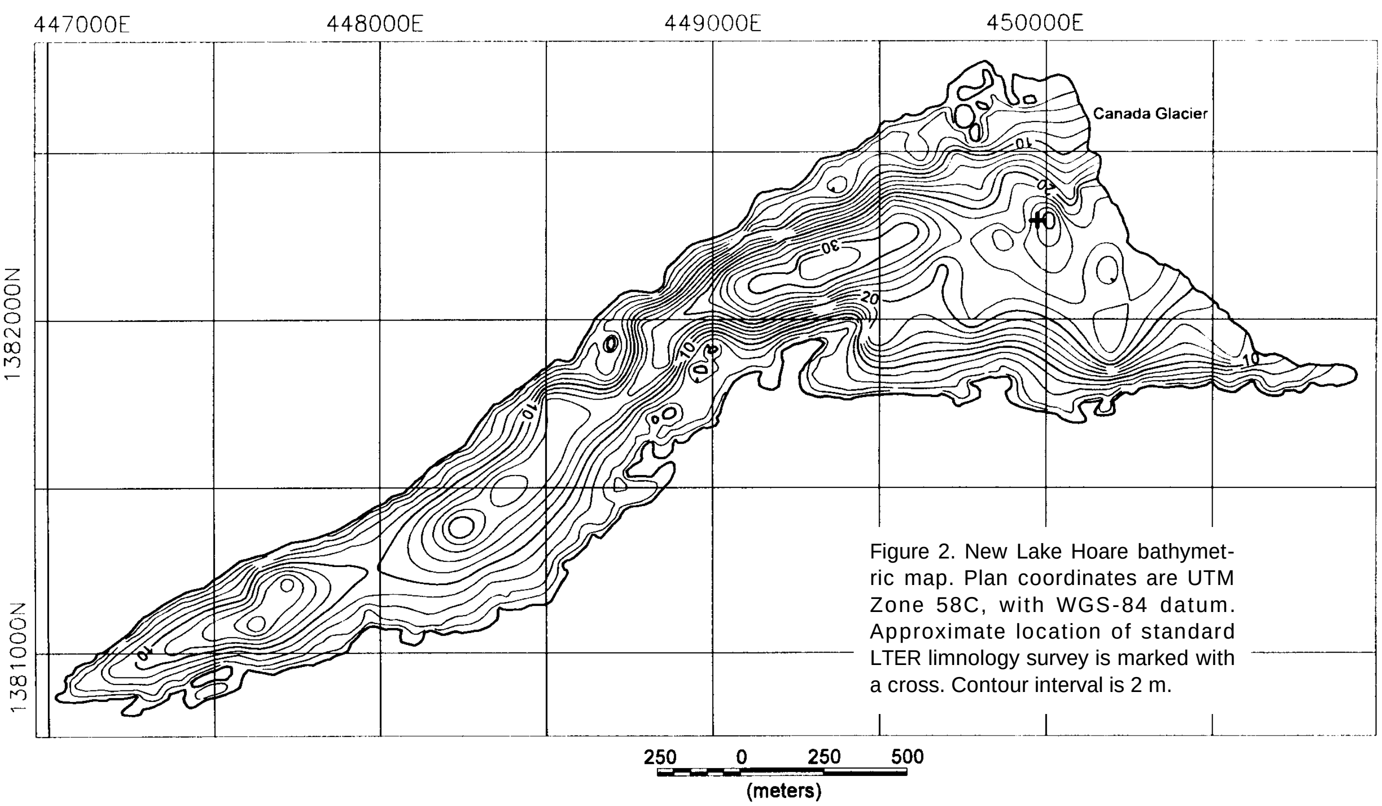

Figure 2. New Lake Hoare bathymetric map. Plan coordinates are UTM Zone 58C, with WGS-84 datum. Approximate location of standard LTER limnology survey is marked with a cross. Contour interval is 2 m.

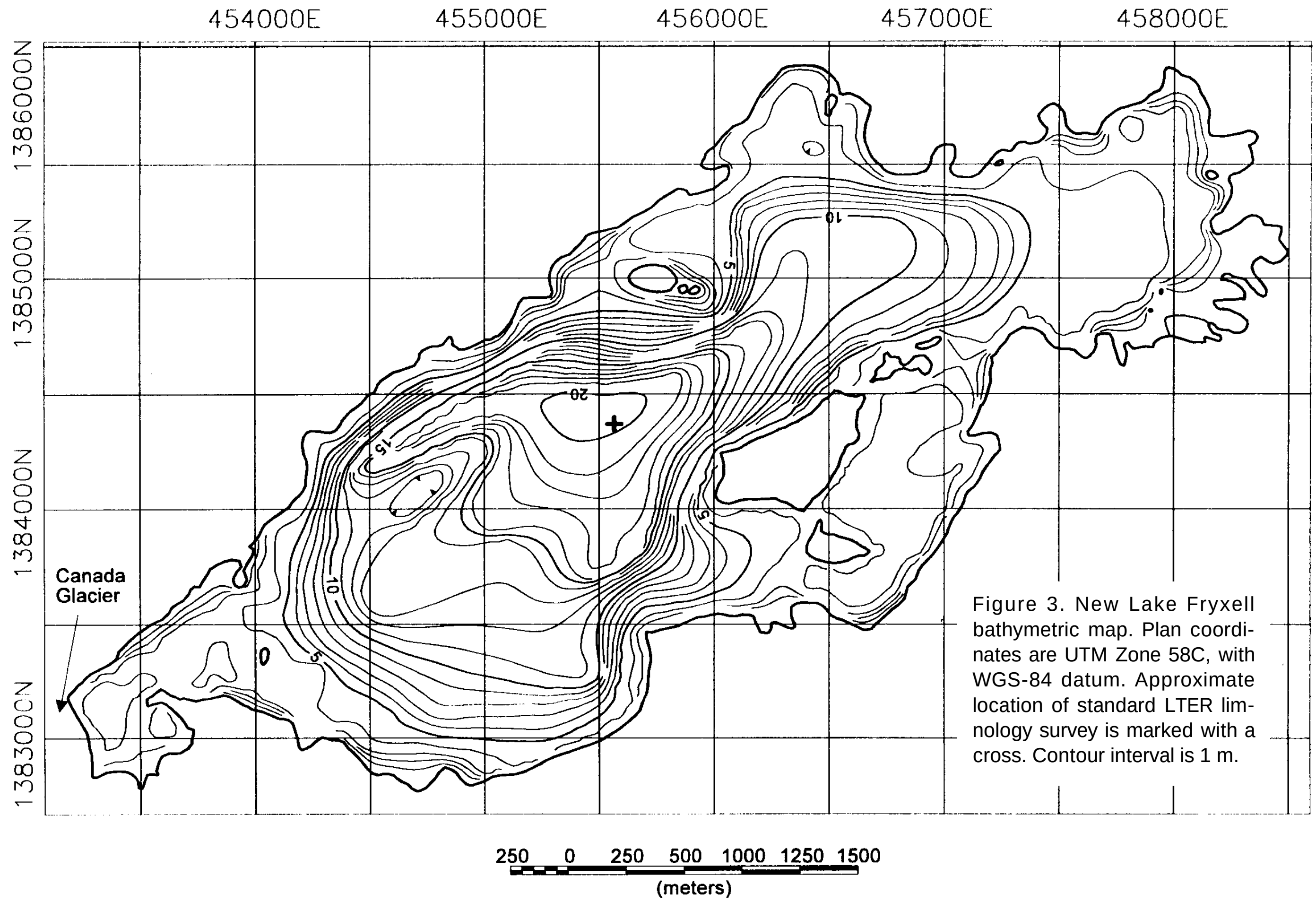

Figure 3. New Lake Fryxell bathymetric map. Plan coordinates are UTM Zone 58C, with WGS-84 datum. Approximate location of standard LTER limnology survey is marked with a cross. Contour interval is 1 m.

implications for both the comparative chemistry and hydrology of the lakes. For instance, if climatic warming were to cause the lake ice covers to melt, Lake Fryxell's salinity would decrease approximately 3.5 times more than Lake Bonney's (not accounting for the change in stream input). Therefore, we might expect the ecological impact caused by a warming to be greater in Lake Fryxell than in Lake Bonney. The mean depth (lake volume divided by lake area) also points to some interesting differences in the lakes. Lake Fryxell has a substantially larger evaporative surface area compared to volume than the other two lakes. This proportion should mean that Lake Fryxell's level is far more susceptible to changing climate than are the other two lakes. When just considering lake morphometry, Lake Fryxell's lake level should drop faster than either Lakes Bonney or Hoare during a dry-climatic period. Once the level dropped so that Lake Fryxell was contained in the west basin, all three lakes would behave similarly (since the mean depths would be more similar).

The full report is available at *http://mcm.maxey.dri.edu/lter*.

This research was funded by National Science Foundation grant OPP 92-11773. We also thank the sponsorship of Golder Associates, Ltd., and the National Research Council of Canada.

References

Angino, E.E., K.B. Armitage, and J.C. Tash. 1964. Physicochemical limnology of Lake Bonney, Antarctica. *Limnology and Oceanography*, 9(2), 207–217.

Lawrence, M.J.F., and C.H. Hendy. 1985. Water column and sediment characteristics of Lake Fryxell, Taylor Valley, Antarctica. *New Zealand Journal of Geology and Geophysics*, 28, 543–552.

Scott, R.F. 1905. *The voyage of* Discovery (Vol. 2). London: McMillan.

Wharton, R.A., and C.P. McKay. 1986. Oxygen budget of a perennially ice-covered antarctic lake. *Limnology and Oceanography*, 31(2), 437–443.

McMurdo Dry Valleys LTER: Characterization of protozoan communities in lakes Hoare and Fryxell using artificial substrates

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In an approach virtually identical to that taken 18 years earlier (Cathey et al. 1981, 1982), artificial substrates were collected from six main sampling sites between 8 and 22 January 1996 to characterize the protozoan communities of two McMurdo Dry Valley lakes. Samples were collected at paired shallow- and deep-water sampling holes in central Lake Hoare, western Lake Hoare, and western Lake Fryxell. We evaluated the degree of similarity in protozoan community composition at several spatial scales and compared our taxonomic findings with those previously obtained by Cathey et al. (1981, 1982).

Polyurethane foam units (PFUs) were used to collect protozoa at each site (Pratt and Kepner 1992). Triplicate PFUs were placed at three or four depths at each site, and deepest PFUs were actually in contact with lake bottoms. Substrates were colonized *in situ* for 3 weeks. For PFUs placed in Lakes Hoare and Fryxell, Cathey et al. (1982) reported that the time required to obtain 90 percent of the equilibrium species number of protozoa was 16 days. Thus, a 3-week colonization period should permit an adequate assessment of nearly all potential colonizers. PFUs allow replication and often provide richer collections than natural substrates. Three or four PFUs provide as good an estimate of species richness at a site as 10–12 samples from natural substrata (Pratt, Horowitz, and Cairns 1987).

Subsamples were systematically evaluated for taxonomic composition by direct microscopic observation of live material. Protists were identified to species where possible and all were identified at least to genus. Standard protozoological keys were used (e.g., Kudo 1966; Lee, Hutner, and Bovee 1985). Identified protozoa, classified according to the system of Levine et al. (1980), were also classified into functional feeding groups (Pratt and Cairns 1985).

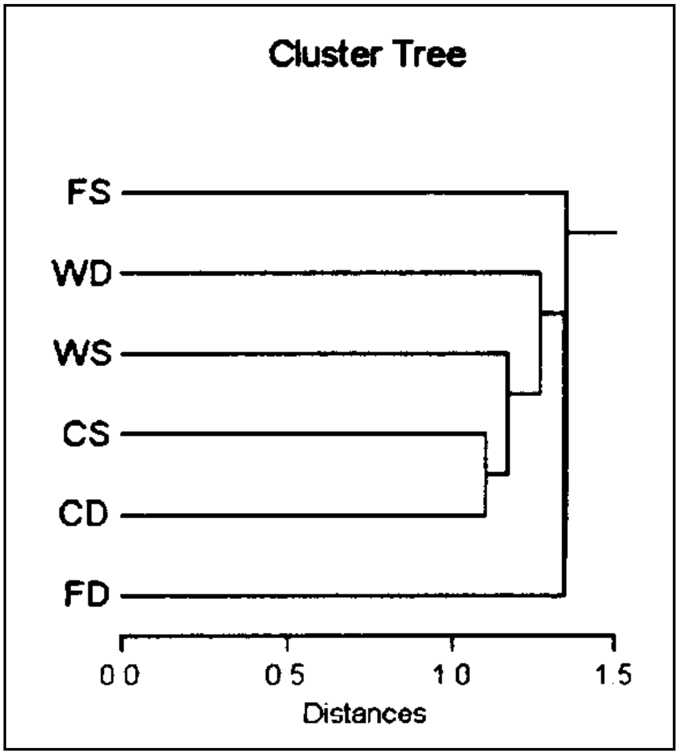
In total, 41 living protozoan taxa were observed in Lakes Hoare and Fryxell during this study. Greatest richness (24 taxa) was observed at the shallow Fryxell site. On a site-by-site basis, taxonomic richness was greatest in west Fryxell (32), followed by central Hoare (18), and then west Hoare (15). Removing "rare" taxa (those occurring in less than 10 percent of samples) left a total of 21 taxa from all sites for consideration. Removal of rare taxa acts as a noise filter by eliminating records based on single observations. Presence/absence data were used to calculate and compare community similarity indices using a permutation procedure (Pratt and Smith 1991, pp. 91–103). Jaccard's coefficient of community similarity was used to compute a test statistic comparing the mean similarity of replicate PFUs at one depth, sampling hole, site or lake, to the between depth, sampling hole, site, or lake similarity. Thus, detailed comparisons of community composition have been made at a variety of spatial scales.

Based on comparisons of calculated Jaccard's coefficients, several significant differences in community composition were observed ($p<0.05$, table). All differences were significant whether "rare" taxa were, or were not, included in the analyzed data set. Differences between sampling holes within Lake Fryxell were as great as those between sampling holes in different lakes. As expected, the greatest differences frequently involved samples collected from deeper, anaerobic waters, which harbor few species of protists. Assemblages from the shallow Fryxell hole were significantly different from samples collected below the oxycline at the deep water hole, whereas aerobic zone samples from the deep hole were not different from anaerobic samples collected from the same hole. Using

Significant differences in protozoan community structure (P<0.05) based on Jaccard's coefficient of similarity.

NOTE: C denotes central Hoare; W, west Hoare; F, west Fryxell; S, shallow hole; and D, deep hole. Numbers represent sampling depths in meters.

Comparison	Site	Significant differences
Between three sites (C, W, and F)	All	NS
Between six sampling holes (CS, CD, WS, WD, FS, and FD)	All	FS≠FD
Between samples collected at a single depth (5 m) at six sampling holes (CS, CD, WS, WD, FS, and FD)	All	FS≠WD FD≠WD CD≠WD
Between depths and sampling holes at a single site	C	CS8≠CS29 CS10≠CD29 CD26≠CD29
	W	WD5≠WD14
	F	FS5≠FD16 FS5≠FD19 FS6.5≠FD16 FS6.5≠FD19 FS8≠FD16 FS8≠FD19



Euclidean distances between six sampling holes. Cluster tree formed from species by sites matrix using single linkage (nearest neighbor) method. (C denotes central Hoare; W, west Hoare; F, west Fryxell; S, shallow hole; and D, deep hole.)

the presence/absence metric employed here, we detect significant differences in protozoan community structure at spatial scales of as little as 3 meters (m) in the vertical (table).

Euclidean distance measures were also used to evaluate community similarity between sampling holes. Mean-standardized abundance indices, based on frequency of observation, were used to calculate distance measures incorporating data from all sites and depths. Distance measures indicate that communities at proximate sampling holes were most similar to one another and that sampling holes in Lake Hoare clustered together in terms of community composition (figure). A distance of zero would mean that the exact same taxa were found in the exact same relative frequencies at two different sites (i.e., that communities at the two sites were identical).

No relationship was found between taxonomic richness and water column chlorophyll-*a* concentration (data collected roughly 1 week after collection of PFUs). Richness in the aerobic zone of the more-productive Lake Fryxell was consistently higher than at other sites, however. This richness was also the case during the 1978–1979 season (Cathey et al. 1981).

As is typical, these data show a skewed distribution of species abundances with numbers of species, that is, many more infrequently occurring than frequently occurring taxa were noted. On a sample-by-sample basis, the most frequently encountered taxa overall were the suctorian, *Sphaerophrya sp*., the kinetoplastid flagellate, *Bodo globosa*, the chrysomonad, *Ochromonas sp*. (probably *O. minuta* or *O. miniscula*), the volvocid, *Chlamydomonas globosa*, the cryptomonad, *Chroomonas lacustris*, and the peritrich ciliate, *Vorticella mayeri*; all of which were observed in roughly half the PFUs collected. Other common bodonid, chlamydomonad, and chrysomonad species were also frequently encountered and phytoflagellate groups were often numerically dominant in our collections. The ubiquitous nature of most of these taxa has been previously noted and the majority of species encountered also occur in temperate freshwater habitats.

Protozoa were classified into functional feeding groups, or guilds, used to examine further spatial patterns in community structure. Primary-producing flagellates (frequently cryptomonads and chlamydomonads) and bactivores dominate these lakes. Cathey et al. (1982) also found that phytoflagellates were the most abundant initial colonizers of PFUs. Functional feeding group distributions (as proportion of identified taxa) formed no consistent pattern with depth and, in general, similar proportions of the various feeding groups were found at each sampling hole. Organisms in functional feeding groups other than bactivores and primary producers constituted only 16 and 19 percent of taxonomic identifications made in lakes Fryxell and Hoare, respectively.

Further comparisons with historic taxonomic records are currently underway as are similar colonization studies in Lakes Bonney (east and west lobes), Joyce, Hoare, and Fryxell.

This research was supported by National Science Foundation grant OPP 92-11773.

References

Cathey, D.D., G.M. Simmons, Jr., B.C. Parker, W.H. Yongue, and M.R. Van Brunt. 1982. Protozoan colonization of artificial substrates in two antarctic lakes. *Transactions of the American Microscopical Society*, 101(4), 353–367.

Cathey, D.D., W.H. Yongue, G.M. Simmons, Jr., and B.C. Parker. 1981. The microfauna of algal mats and artificial substrates in southern Victoria Land lakes of Antarctica. *Hydrobiologia*, 85, 3–15.

Kudo, R.R. 1966. *Protozoology* (5th ed.). Springfield, Illinois: Thomas.

Lee, J.J., S.H. Hutner, and E.C. Bovee. 1985. *An illustrated guide to the protozoa*. Lawrence, Kansas: Society of Protozoologists.

Levine, N.D., J.O. Corliss, F.E.G. Cox, G. Deroux, J. Grain, B.M. Honigberg, G.F. Leedale, A.R. Loeblich, J. Lom, D. Lynn, E.G. Merinfeld, F.C. Page, G. Poljansky, V. Sprague, J. Vavra, and F.G. Wallace. 1980. A newly revised classification of the protozoa. *Journal of Protozoology*, 27, 37–58.

Pratt, J.R., and J. Cairns, Jr. 1985. Functional groups in the protozoa: roles in differing ecosystems. *Journal of Protozoology*, 32, 415–423.

Pratt, J.R., R. Horowitz, and J. Cairns, Jr. 1987. Protozoan communities of the Flint River-Lake Blackshear ecosystem (Georgia, USA). *Hydrobiologia*, 148, 159–174.

Pratt, J.R., and R.L. Kepner, Jr. 1992. Collecting *Aufwuchs* on artificial substrata. In J.J. Lee and A.J. Soldo (Eds.), *Protocols in protozoology*. Lawrence, Kansas: Allen Press, Inc.

Pratt, J.R., and E.P. Smith. 1991. Significance of change in community structure: A new method for testing differences. In *Biological criteria: Research and regulation* (EPA 440/5-91-005). Washington, D.C.: U.S. Environmental Protection Agency.

McMurdo Dry Valleys LTER: Genetic diversity of soil nematodes in the McMurdo Dry Valleys of Antarctica

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Biological systems in the McMurdo Dry Valleys of Antarctica are severely restricted by extreme environmental conditions including cold temperatures and low moisture levels, resulting in a cold desert ecosystem that is much simpler than temperate regions (Campbell and Claridge 1981). Continental Antarctica has a low diversity of soil nematodes: 11 species in six genera (Maslen 1979). Nematodes are a dominant soil fauna in the McMurdo Dry Valleys of continental Antarctica, and in the drier soils, they represent the top of the food chain (Freckman and Virginia 1991, in press). Only three genera have been found in McMurdo Dry Valley soils: the microbial feeders *Scottnema lindsayae* Timm 1971 and *Plectus antarcticus* de Man 1904 (Overhoff, Freckman, and Virginia 1993; Yeates et al. 1993) and the omnivore/predator *Eudorylaimus antarcticus* (Steiner 1916), Yeates 1970 (Yeates et al. 1993). *Scottnema* dominates McMurdo Dry Valley soil communities (Freckman and Virginia 1991) and is the only endemic genus in continental Antarctica (Maslen 1979). As such, *Scottnema* is an important component of the McMurdo Dry Valley soil ecosystem.

We examined the genetic diversity of *Scottnema lindsayae* to determine if variation across valleys was low, suggesting dispersal, or if valleys were associated with unique populations that evolved with little interaction between valleys. Biota were extracted from samples collected from 1-square-meter grids at sites in three McMurdo Dry Valleys during the 1993–1994 austral summer (table 1). Approximately 1,500 grams of soil per sample at 0–10 centimeters depth was collected with presterilized plastic sampling scoops (Nasco Sampling Equipment) and placed in sterile Whirl-pak® bags (Freckman and Virginia 1993). Soil samples were refrigerated at 1°C (Overhoff, Freckman, and Virginia 1993), and nematodes were extracted by sugar centrifugation within 48 hours of collection (Freckman and Virginia 1993).

The genetic variation of *Scottnema* was examined using molecular techniques because morphological variation indicated more than one interbreeding group may exist. *Scottnema* were extracted from samples collected at Lake Bonney, Lake Hoare, and Lake Fryxell in Taylor Valley, Victoria Lower Glacier in Victoria Valley, and Lake Brownworth in Wright Valley (table 1). Two segments of ribosomal DNA (rDNA) that encode the D2 and D3 expansion segments of the nuclear large rRNA subunit were sequenced. Genomic DNA was extracted from individual nematodes using 15-microliter lysis buffer (60 micrograms per milliliter proteinase potassium in 10-millimolar Tris pH 8.8, 50 millimolar potassium chloride, 2.5 millimolar magnesium chloride, 0.45 percent Tween 20, and 0.05 percent gelatin) (Williams et al. 1992).

Nematodes (living and dead) were found in 61 percent of all soils sampled. Three nematode species were found: *Scottnema lindsayae, Eudorylaimus antarcticus,* and *Plectus antarcticus* (table 1). Viable nematodes were found in 58 percent of all samples. *Scottnema* was the most abundant nematode in each valley. *Eudorylaimus* was found in both Taylor and Wright Valleys whereas *Plectus* was found at only one location (north shore of Lake Hoare in Taylor Valley). Only

Table 1. Abundance of living nematodes per kilogram dry soil for grids sampled in Taylor, Victoria, and Wright Valleys, Antarctica

Location	Coordinates	Nematodes per kilogram dry soil		
		Scottnema	*Eudorylaimus*	*Plectus*
Taylor				
Lake Bonney[a]	77°42.92'S 162°27.65'E	1±4[b]	—	—
Lake Hoare, north[a]	77°37.49'S 162°54.31'E	85±43	12±13	—
Lake Hoare, north	77°37.49'S 162°54.31'E	70±50	21±20	4±12
Lake Hoare, south[a]	77°38.03'S 162°52.75'E	952±466	—	—
Lake Fryxell[a]	77°35.94'S 163°22.68'E	4,360±1,943	—	—
Victoria				
Victoria Upper Glacier	77°17.35'S 161°33.03'E	—	—	—
Lake Vida	77°23.35'S 162°02.60'E	—	—	—
Victoria Lower Glacier[a]	77°21.81'S 162°19.11'E	1,255±473	—	—
Wright				
Labyrinth	77°33.04'S 160°43.15'E	19±13	5±7	—
Lake Vanda	77°32.56'S 161°30.66'E	—	—	—
Lake Brownworth[a]	77°26.13'S 162°42.61'E	76±208	—	—

[a]Nematodes were extracted from samples from these locations for the molecular work.
[b]Values are mean ± standard errors of nine samples in each grid.

one sample of the 99 total samples contained three living species, and 18 had two species. In all cases of two or three species complexes, *S. lindsayae* was present. *Scottnema* was the dominant nematode in all the samples indicating low species diversity and a one-link trophic chain.

Three different genotypes were identified for the D2 region based on 75 sequences (table 2). Sixty-six nematodes possessed a common genotype that has a cytosine (C) at position 91. Nematodes with this common genotype were found at all the locations sampled. Only three nematodes had a rare genotype with an adenine (A) at position 91. Nematodes with this rare genotype originated from soil samples collected at Victoria Lower Glacier in Victoria Valley. In addition, six individuals containing both an A and a C at position 91 in approximately equal ratios were identified from the following locations: Lake Bonney in Taylor Valley (one nematode) and Victoria Lower Glacier in Victoria Valley (five nematodes).

Three genotypes were also found for the D3 region based on 76 sequences (table 2). A common genotype that contains a C at position 103 was found in 69 nematodes and across all the sites sampled. A rare genotype that contains a thymine (T) at position 103 was found in two nematodes, one from Lake Fryxell in Taylor Valley and one from the north shore of Lake Hoare in Taylor Valley. Five individuals containing both a C and a T at position 103 in approximately equal ratios were identified from the following locations: the south shore of Lake Hoare in Taylor Valley (three nematodes) and Lake Brownworth in Wright Valley (two nematodes).

A common, rare, and combined genotype were identified for both D2 and D3 (table 2). The occurrence of individuals with both the rare and common sequence in approximately equal ratios suggests that *S. lindsayae* may be evolving into two species. The pattern of nuclear variation is most consistent with a single species of nematode defined morphologically as *S. lindsayae*.

S. lindsayae occurs more frequently in this harsh environment than the other two species (*E. antarcticus* and *P. antarcticus*). In this extreme environment, differences in the soil microclimate habitat and limitations to dispersal and establishment may be contributing to the evolution of two distinct species of *Scottnema* as evidenced by the nuclear variation in the D2 and D3 regions.

We thank M. Ho and L.E. Powers for their assistance in sampling and laboratory analyses. We also gratefully acknowledge the logistic support of the National Science Foundation (NSF) McMurdo Station laboratory staff and the U.S. VXE-6 and Royal New Zealand Air Force helicopter crews. This research was supported by NSF grant OPP 92-11773, the McMurdo Dry Valley Long-Term Ecological Research (LTER), and is a contribution to NSF grant OPP 91-20123 to D.W. Freckman and R.A. Virginia.

Table 2. Variable sites for* S. lindsayae *D2 and D3 nuclear rDNA expansion sequences

Genotype	Number of nematodes	Position
D2		**91**
1	66	C
2	6	A and C
3	3	A
D3		**103**
1	69	C
2	5	C and T
3	2	T

References

Campbell, I.B., and G.G.C. Claridge. 1981. Soil research in the Ross Sea region of Antarctica. *Journal of the Royal Society of New Zealand*, 11, 401–410.

Freckman, D.W., and R.A. Virginia. 1991. Nematodes in the McMurdo Dry Valleys of southern Victoria Land. *Antarctic Journal of the U.S.*, 26(5), 233–234.

Freckman, D.W., and R.A. Virginia. 1993. Extraction of nematodes from dry valley antarctic soils. *Polar Biology*, 13, 483–487.

Freckman, D.W., and R.A. Virginia. In press. Low diversity antarctic soil nematode communities: Distribution and response to disturbance. *Ecology*.

Maslen, N.R. 1979. Additions to the nematode fauna of the antarctic region with keys to taxa. *British Antarctic Survey Bulletin*, 49, 207–229.

Overhoff, A., D.W. Freckman, and R.A. Virginia. 1993. Life cycle of the microbivorous antarctic dry valley nematode *Scottnema lindsayae* (Timm 1971). *Polar Biology*, 13, 151–156.

Williams, B.D., B. Schrank, C. Huynh, R. Shownkeen, and R.H. Waterston. 1992. A genetic mapping system in *Caenorhabditis elegans* based on polymorphic sequence-tagged sites. *Genetics*, 131(3), 609–624.

Yeates, G.W., T. Bongers, R.G.M. de Goede, D.W. Freckman, and S.S. Georgieva. 1993. Feeding habits in soil nematode families and genera—An outline for soil ecologists. *Journal of Nematology*, 25(3), 315–331.

McMurdo Dry Valleys LTER: Density-driven mixing in Lake Hoare?

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One of the unusual aspects of the McMurdo Dry Valley lakes, relative to lakes in other regions of the Earth, is their perennial ice covers. This ice cover is responsible for many of the interesting properties of these lakes (Wharton et al. 1993). One of the obvious effects is the impact on lake dynamics. Simply stated, the ice cover minimizes temperature-driven turnover and wind-driven mixing. Therefore, it has been thought that the McMurdo Dry Valley lakes are characterized by permanent stratification and little to no advective movement. This paradigm has recently been challenged for Lake Fryxell by Miller and Aiken (1996). They have argued that downward mixing of denser water does occur at certain times in Lake Fryxell as evidenced by the presence of tritium at depth. This mixing is thought to occur due to water exclusion from ice formation during fall moat freezing and the sinking of these denser water masses (Miller and Aiken 1996).

As part of a large investigation to understand more fully the source of solutes to the McMurdo Dry Valley lakes, we measured chlorine-36 to chlorine ($^{36}Cl/Cl$) ratios in the surface and deep waters of all the Taylor Valley lakes (Lyons, Welch, and Sharma in preparation). These measurements were made, in part, to compare data from the 1990s to the earlier work of Carlson et al. (1990) from samples collected in the mid-1980s. These investigators had observed an extremely high value ($^{36}Cl:Cl \times 10^{-15}$= 1,660±180) in Lake Hoare surface waters that they attributed to glacial melt input from the atmospheric hydrogen bomb testing spike of the late 1950s (Carlson et al. 1990). Our surface water (approximately 5-meter) value collected 10 years later indicated a $^{36}Cl:Cl \times 10^{-15}$ ratio of 226±9 (Lyons et al. in preparation). During the 1995–1996 field season, samples were collected at 10 and 12 meters in Lake Hoare. These $^{36}Cl:Cl \times 10^{-15}$ values were 262±12 and 226±9, respectively. These more recent data indicate that the bomb spike observed by Carlson et al. (1990) during the 1984–1985 season has since "disappeared."

If we assume a mean increase of water-level rise of approximately 10 centimeters per year over this period (Chinn 1993, p. 1–51), an ice ablation rate of 35 centimeters per year (Clow et al. 1988) over the same period, and no mixing, the bomb spike observed in 1984–1985 should have been displaced from 4–5 meters depth to approximately 9–10 meters depth. (This shift was calculated simply by assuming a 45-centimeter inflow per year; this water displaces downward the "older" water.) Although the 10-meter $^{36}Cl:Cl$ ratio is higher than water that is currently above it and below it, it is not close to the values observed in 1984–1985.

Although we certainly cannot prove or disprove it with the data presented here, one possibility accounting for the bomb peak's demise is that it has been lost due to mixing and/or sinking. Again, we can only speculate at this time, but density-driven downwelling through moat refreezing as described by Miller and Aiken (1996) for Lake Fryxell may be important for Lake Hoare as well. Recent measurements (S. Tyler and P. Cook, unpublished data) indicate relatively modern chlorofluorocarbon concentrations at depth in Lake Hoare. This finding also suggests "mixing" has occurred. If it turns out that density-driven mixing is a major process in Lakes Fryxell and Hoare, the entire biogeochemical dynamics of these lakes will have to be rethought.

This work was supported by National Science Foundation grant OPP 92-11773.

References

Carlson, C.A., F.M. Phillips, D. Elmore, and H.W. Bently. 1990. Chlorine-36 tracing of salinity sources in Dry Valley of Victoria Land, Antarctica. *Geochimica et Cosmochimica Acta*, 54, 311–318.

Chinn, T.J. 1993. Physical hydrology of the Dry Valley lakes. In W.J. Green and E.I. Friedmann (Eds.), *Physical and biogeochemical processes in antarctic lakes* (Antarctic Research Series, Vol. 59). Washington, D.C.: American Geophysical Union.

Clow, G.D., C.P. McKay, G.M. Simmons, Jr., and R.A. Wharton, Jr. 1988. Climatological observations and predicted sublimation rates at Lake Hoare, Antarctica. *Journal of Climatology*, 1, 715–728.

Lyons, W.B., K.A. Welch, and P. Sharma. In preparation. Chlorine-36 in the waters of the McMurdo Dry Valley lakes, Southern Victoria Land, Antarctica: Revisited. *Geochimica et Cosmochimica Acta*.

Miller, L.G., and G.R. Aiken. 1996. Effects of glacial meltwater inflows and moat freezing on mixing in an ice-covered antarctic lake as interpreted from stable isotope and tritium distributions. *Limnology and Oceanography*, 41, 966–976.

Wharton, R.A., Jr., C.P. McKay, G.D. Clow, and D.T. Andersen. 1993. Perennial ice covers and their influence on antarctic lake ecosystems. In W.J. Green and E.I. Friedmann (Eds.), *Physical and biogeochemical processes in antarctic lakes* (Antarctic Research Series, Vol. 59). Washington, D.C.: American Geophysical Union.

McMurdo Dry Valleys LTER: Phosphorus deficiency and alkaline phosphatase activity in lakes of Taylor Valley, Antarctica

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Given the extreme seasonality experienced by the high-latitude, perenially ice-covered lakes of Taylor Valley, Antarctica, one might expect the availability of light alone to dictate the growth of their phytoplankton communities. It has been demonstrated that photosynthesis of Lake Bonney phytoplankton is not saturated by *in situ* irradiance (Lizotte and Priscu 1992); however, the maximum quantum yield of photosynthesis exhibited by these phytoplankton decreases with distance from the nutricline (Lizotte and Priscu 1994). Nutrient deficiency, therefore, has been suggested as a control on photosynthetic production in Lake Bonney (Lizotte, Sharp, and Priscu 1996). Similarly, nutrient bioassays have revealed enhanced photosynthetic carbon assimilation in incubations amended with ammonium and/or phosphate in all four of the Taylor Valley lakes examined (east and west lobes of Lake Bonney, Lake Hoare, and Lake Fryxell; Priscu 1995). Phosphate additions stimulated a dramatic and highly significant increase in photosynthesis in samples from Lake Bonney, whereas significant stimulation in samples from Lake Hoare and Lake Fryxell occurred only with simultaneous additions of ammonium and phosphate (Priscu 1995). These bioassay data, along with estimates of nitrogen and phosphorus flux ratios to the trophogenic zones of these lakes, have indicated a strong phosphorus deficiency in Lake Bonney phytoplankton and only mild phosphorus deficiency and/or nitrogen deficiency in Lake Hoare and Lake Fryxell phytoplankton (Priscu 1995).

During the 1995 Winfly deployment of the McMurdo Dry Valleys Long-Term Ecological Research program (McMurdo LTER), we undertook a preliminary study of the role of phosphorus in the ecology of Taylor Valley lake ecosystems. We report here some initial results of this phosphorus study from the highly density-stratified Lake Bonney (east lobe) and the fresh-water Lake Hoare. Fieldwork was carried out at Lake Hoare from 7 September to 19 September 1995 and at Lake Bonney from 24 September to 19 October 1995. Water samples were collected through a melthole in the ice according to standard LTER procedures. Soluble reactive phosphorus

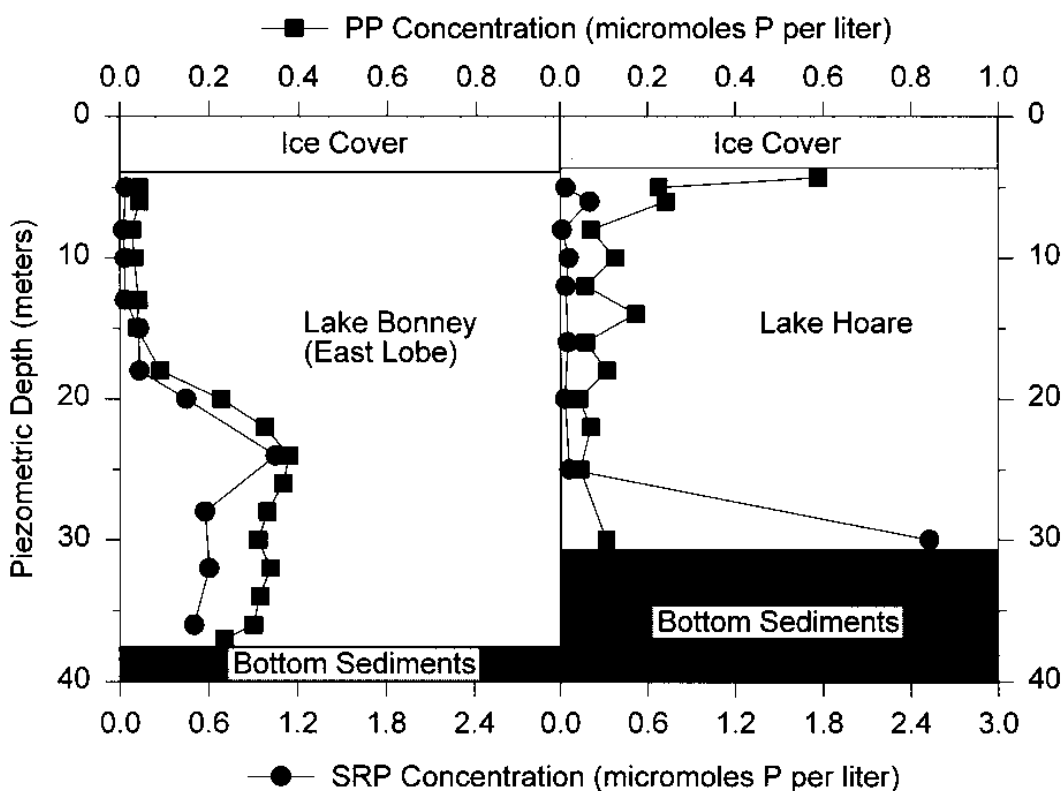

Figure 1. Water column profiles of soluble reactive phosphorus (SRP) and particulate phosphorus (PP) in two Taylor Valley lakes. Depth is given with respect to the water level in the sampling hole (piezometric depth). (P denotes phosphorus.)

(SRP) was analyzed by a standard manual colorimetric method (Strickland and Parsons 1972) and particulate phosphorus (PP) was measured as SRP after high-temperature combustion and acid hydrolysis of the filtered samples (Karl et al. 1991, pp. 71-77). The enzymatic activity of alkaline phosphatases was estimated using the organic monophosphate ester 4-methylumbelliferyl phosphate (MUP) as a substrate analog (Pettersson and Jansson 1978).

Water column concentration profiles of SRP and PP display several important differences between Lake Bonney (east lobe) and Lake Hoare (figure 1). SRP concentrations in the trophogenic zones (from the base of the ice cover to about 20 meters depth) are vanishingly small in both lakes, but PP is substantially higher in Lake Hoare, especially immediately below the ice. The decreasing trend with depth suggests that this sestonic PP is associated with phytoplankton. Although Lake Bonney was sampled later in the growing season than was Lake Hoare, no accumulation of PP is noted above 18 meters, suggesting that phytoplankton in Lake Bonney are growing with a low cellular phosphorus quota. Beneath the trophogenic layer of Lake Bonney, both SRP and PP concentrations are elevated, indicating SRP remineralization from organic detrital particles and/or SRP desorption from mineral phases in the dense brine of the deep layer. Lake Hoare exhibits no such detrital PP signature but does show elevated SRP in the deepest sample, where anaerobic decomposition of sedimentary organic material is likely contributing to the SRP pool. The deep SRP pools of these lakes may be a source of phosphorus to the trophogenic layers, but the extreme density stratification in Lake Bonney severely restricts the potential upward diffusion of SRP; conversely, the lack of density stratification in Lake Hoare may well allow a significant flux of deep SRP to the trophogenic zone (Priscu 1995).

The enzymatic activity of alkaline phosphatase (APase) is also greatly different between the two lakes. Substrate-saturated APase activities measured at 5 meters in Lake Bonney were an order of magnitude higher than those in Lake Hoare (figure 2). Considering that Lake Hoare was sampled earlier in the growing season, the APase activities on a per-cell basis are likely to display an even greater disparity between the two lakes. APase activity in Lake Bonney decreases with depth and is appreciably inhibited by the addition of phosphate (figure 3). The decrease in APase activity with depth is partly due to a decrease in biomass with depth, but the degree of inhibition by phosphate addition increases with distance from the chemocline, suggesting a greater degree of phosphorus deficiency in shallow populations. Size fractionation experiments (data not shown) reveal that the measured APase activity belongs mostly to bacterial and algal size classes, with very little free dissolved activity.

The above results support earlier studies that have suggested a high degree of phosphorus deficiency in the

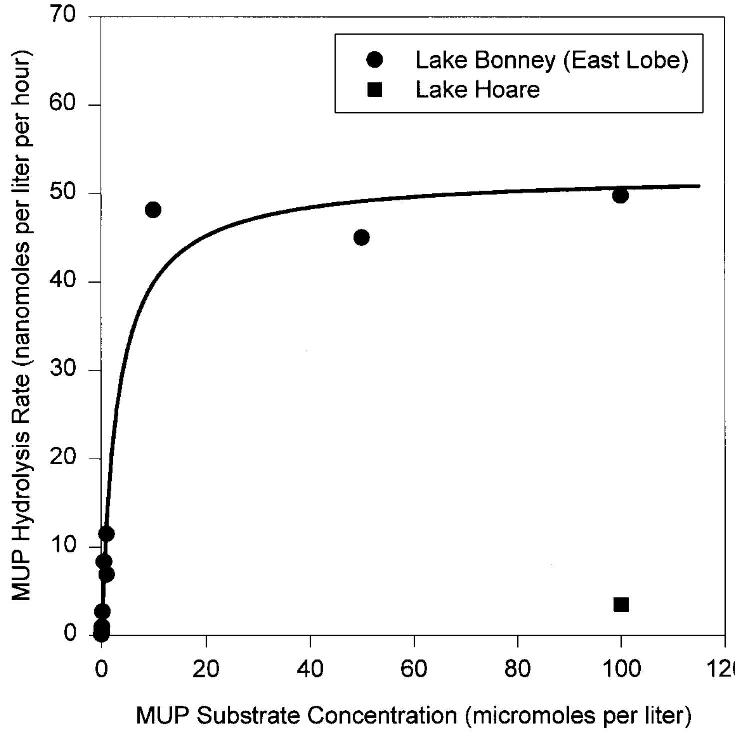

Figure 2. Substrate response of alkaline phosphatase (APase) activity at 5 meters in Lake Bonney (east lobe), with single data point from 5 meters in Lake Hoare for comparison. Incubations were carried out in the dark at a temperature near that *in situ* (4–5°C). APase activity is estimated by the rate of hydrolysis of the MUP substrate analog.

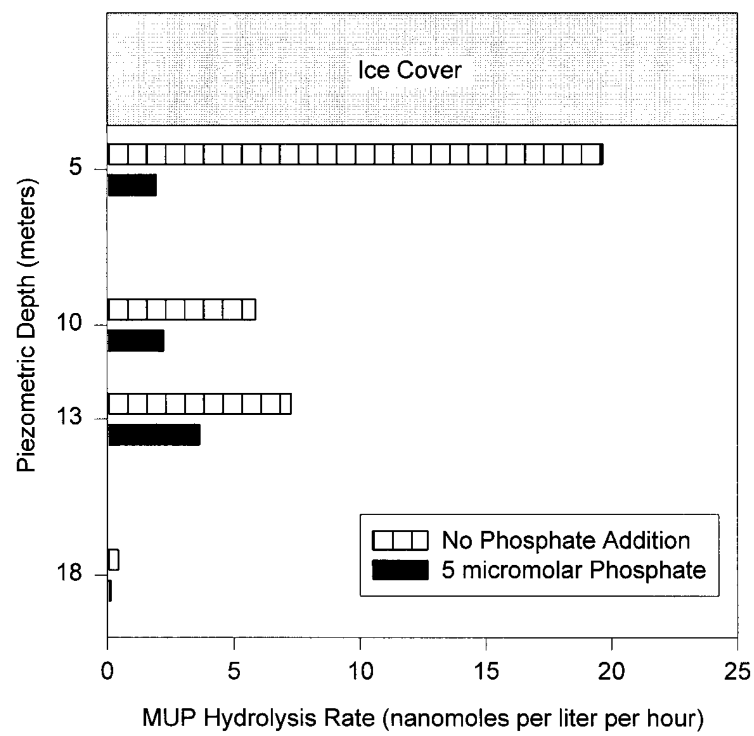

Figure 3. Depth distribution of APase activity in Lake Bonney (east lobe). APase activity is estimated as the MUP hydrolysis rate at 5, 10, 13, and 18 meters depth, with and without the addition of 5-micromolar phosphate. Incubations were carried out in the dark at sub-saturating substrate concentration (1 micromolar MUP) and a temperature of 4–5°C.

phytoplankton of Lake Bonney but only mild phosphorus deficiency in Lake Hoare phytoplankton. Further examination of the emerging data set will focus on quantification of phosphorus fluxes to the trophogenic zones of these lakes and on the potential bioavailability of different inorganic and organic phosphorus pools.

This research was supported by National Science Foundation grants OPP 94-19413 and OPP 92-11773 awarded to J.C. Priscu. We thank E. Adams, R. Edwards, C. Fritsen, D. Gordon, A. Lundberg-Martell, C. Takacs, C. Wolf, and the staff of Antarctic Support Associates for field and laboratory assistance.

References

Karl, D.M., J.E. Dore, D.V. Hebel, and C. Winn. 1991. Procedures for particulate carbon, nitrogen, phosphorus and total mass analyses used in the US-JGOFS Hawaii Ocean Time-series program. In D. Spencer and D. Hurd (Eds.), *Marine particles: Analysis and characterization* (Geophysical Monograph 63). Washington, D.C.: American Geophysical Union.

Lizotte, M.P., and J.C. Priscu. 1992. Photosynthesis-irradiance relationships in phytoplankton from the physically stable water column of a perennially ice-covered lake (Lake Bonney, Antarctica). *Journal of Phycology*, 28, 179–185.

Lizotte, M.P., and J.C. Priscu. 1994. Natural fluorescence and quantum yields in vertically stationary phytoplankton from perennially ice-covered lakes. *Limnology and Oceanography*, 39, 1399–1410.

Lizotte, M.P., T.R. Sharp, and J.C. Priscu. 1996. Phytoplankton dynamics in the stratified water column of Lake Bonney, Antarctica. I. Biomass and productivity during the winter-spring transition. *Polar Biology*, 16, 155–162.

Pettersson, K., and M. Jansson. 1978. Determination of phosphatase activity in lake water—A study of methods. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie*, 20, 1226–1230.

Priscu, J.C. 1995. Phytoplankton nutrient deficiency in lakes of the McMurdo Dry Valleys, Antarctica. *Freshwater Biology*, 34, 215–227.

Strickland, J.D.H., and T.R. Parsons. 1972. *A practical handbook of seawater analysis* (2nd ed.). Ottawa: Fisheries Research Board of Canada.