

## SECTION 1

## RESULTS OF PRIOR SUPPORT

The MCM3 (McMurdo Dry Valley LTER) team was: W. Lyons (PI, geochemist), A. Fountain (PI, glaciologist-meteorologist), P. Doran (paleolimnologist), M. Gooseff (hydrologist/modeler), D. McKnight (stream ecologist/hydrologist), J. Priscu (limnologist), D. Wall (soil ecologist), and R. Virginia (ecosystem ecologist). During MCM3, we produced 119 papers in refereed journals, 27 book chapters, and 22 theses. An additional 3 journal articles are in press (See details in Table S-1). We supported 49 graduate students, 13 post doctoral fellows, and involved 63 undergraduates and 2 high school students and their teacher. More than 76 collaborators were involved in MCM3 research.

### 1.1. THE MCMURDO DRY VALLEYS: CLIMATE SENSITIVE ECOSYSTEMS PROVIDING INSIGHTS FOR OUR CHANGING WORLD.

The following syntheses representing our integrated understanding of the McMurdo Dry Valleys (MDV) were published in MCM1-2: (1) a special issue of *BioScience* (1999, vol. 49, no. 12.); (2) the book *Ecosystem Processes in Antarctic Ice-Free Landscapes* (Lyons et al. 1997, Balkema Press) and (3) the book *Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica* (Priscu 1998, American Geophysical Union's Antarctic Research Series). During MCM3, much of our work was published in timely synthesis volumes aimed at diverse audiences, which connected our research with other LTER's and to other polar and extreme environments on our planet and Mars. Six of the MCM investigators authored chapters in *Polar Lakes and Rivers*, a book published for the International Polar Year (IPY). These chapters compared and contrasted Antarctic and Arctic freshwater ecosystems. Our other IPY contribution was the children's book, *The Lost Seal*, which was published as the second book in the LTER Schoolyard Book Series and was favorably reviewed in *Nature Geoscience*. An additional synthesis volume of MCM3 is *Life in Antarctic Deserts and other Cold Dry Environments*, which was edited by Doran, Lyons and McKnight. Since the initial exploration of Mars in the Mariner program of the 1970's, the MDV has been recognized as the most Mars-like environment on Earth. This volume was solicited by Cambridge University Press for their Astrobiology series and provides a resource in the ecological literature as well as the expanding field of astrobiology.

Through our research in MCM3, we continued to present compelling insight into how extreme or low diversity ecosystems may respond to climate change. Our paper on the responses of the dry valley ecosystem to a 15-yr cooling trend (Doran et al 2002b) received attention not only among ecologists and climate researchers, but also from the media and the "global warming skeptic" community, provoking an incorrect citation of our research by Michael Crichton in his novel *State of Fear*, for example. In 2006, Doran published an Op-Ed article in the *NY Times* commenting on the extent to which our research has been misrepresented by agenda-driven factions of the popular and social media. The article was the second-most read on nytimes.com that day. Our research has yielded new insight, as well as analytical and modeling tools, for understanding processes of particular importance as ecosystems worldwide undergo climate-driven changes. Below we highlight specific research areas and explain the relevance to understanding climate and land use change now and in the future.

**1.1.1. Ecological tipping points.** MCM research is contributing to the recognition that ecosystem responses to climate change are not necessarily gradual or directional (e.g. Peters and Havstad 2006; Jentsch et al. 2007). For example, Wall (2007, P.Trans. Roy. Soc B) in an invited review "Global change tipping points: above- and below-ground biotic interactions in a low diversity ecosystem" discussed potential changes in the MDV associated with future warming. In addition, six MCM investigators contributed to the New Zealand Latitudinal Gradient Synthesis volume (*Antarctic Science*, 2006, vol. 18) highlighting our understanding of the sensitivity of these ecosystems to climate change, and challenges for conservation of Antarctic biodiversity (e.g., Wall 2005; Ayres et al. 2008). Virginia and Wall contributed to the Polar Systems Chapter of the *Millennium Ecosystem Assessment* (MEA 2005) and Wall was co-lead author of a Chapter on Implications of the MEA. The general conclusion of this MCM

research is that low diversity ecosystems do not respond linearly to environmental change and may be particularly vulnerable, an insight that has implications for many more diverse and productive ecosystems (Doran et al. 2002b; Barrett et al. 2008b).

**1.1.2. Impact of climate warming on ecosystems influenced by ice and snow.** Fountain was the co-organizer, with the Palmer LTER, of a Network Synthesis Workshop in April 2009 entitled, “Ecosystem response to changing ice, snow, and permafrost in a warming climate”. This inter-site activity evaluated the effects of changing climate on duration of snow cover, for example. The results are combined in a cross-site paper in progress. A follow up meeting was held to integrate social science perspectives towards writing a cross-site proposal for the forthcoming call for interdisciplinary proposals from NSF.

**1.1.3. Processes occurring in glacial ecosystems.** In response to climate warming, interest in glacial meltwater biogeochemistry is increasing (Hood et al. 2009). Melt water from MDV glaciers is limited to the ice surface, unlike glaciers in temperate regions, and largely flows along flow paths within 0.5 m of the surface (Fountain et al. 2004), which has important consequences for meltwater biogeochemistry (Tranter, et al. 2004; 2005). These passageways host viable cyanobacteria and invertebrates (Poranzinska et al. 2004; Foreman et al. 2007) and photosynthesis by cyanobacteria can create high pH conditions that affect the geochemistry of the runoff (e.g., Fortner et al. 2005; Barrett et al. 2007; Hodson et al. 2008). Fountain organized a special section of *Journal of Geophysical Research – Biogeosciences* to highlight the microbial communities of these supraglacial ecosystems (Fountain and Tranter 2008).

**1.1.4. Lake-ice ecological processes.** Global warming has decreased the duration of ice-cover on lakes throughout the northern hemisphere (Magnuson et al. 2000) leading to dramatic effects on lakes and their surrounding ecosystems (Fang and Stefan 2009; Mueller et al. 2009; Desai et al. 2009; Graham and Vinebrooke 2009). This trend has driven limnologists to consider processes occurring within lake ice and their role in overall ecosystem dynamics (Fang and Stefan 2009). Our past research showed that diverse cyanobacterial and bacterial populations (Gordon et al. 2000) thrive in liquid water inclusions in the perennial ice cover on dry valley lakes (Priscu et al. 1998; 2005; Paerl and Priscu 1998) and has provided a basis for study of the role of microbial processes in winter ice-covers in temperate lakes.

**1.1.5. Dissolved organic material in surface waters.** Increasing concentrations of DOM have been observed over the past 20 years in surface waters ranging from Scandinavia to the northeastern US and Canada, but the biogeochemical processes driving these trends are not resolved. Many studies examining these trends are using approaches to characterize the chemical quality and source of DOM that were developed based on studies of DOM in dry valley lakes, where the DOM is derived solely from microbial biomass (McKnight et al 2001; Cory and McKnight 2005). Our work has helped understand the quantity and quality of DOM in glacial ice (Lyons et al. 2007), which is relevant to understanding the large fluxes of DOM entering the ocean from glacial melt in the Arctic (Hood et al. 2009).

**1.1.6. Climatic controls on mineral weathering.** One unknown for predicting the global scale geochemical outcome of global warming has been the prospect of warmer temperatures accelerating weathering rates in polar regions, causing an increase in the flux of weathering products to the oceans (Wadham et al. in review). Within dry valley streams, chemical weathering rates are as high as rates in temperate regions due to rapid hyporheic zone exchange (Nezat et al. 2001; Maurice et al. 2001; Gooseff et al. 2002; Lyons et al. 2003). This unexpected result together with an associated hydrological exchange model was used as a case study in a recent geochemistry textbook (Maurice 2009).

## **1. 2. ECOSYSTEM RESPONSES IN THE MCMURDO DRY VALLEYS.**

Below we summarize the primary results of our research on each of the main landscape units and our progress in modeling and synthesis:

**1.2.1. Meteorology.** Collection of meteorological data has continued since MCM1. Doran et al. (2002a) provided a summary of all automatic weather station data collected through 2000 and showed that between 1986- 2000 temperature decreased by 0.7 °C per decade (Doran et al. 2002b). The cooling was most pronounced in the summer and fall, and was associated with a decrease in wind and solar radiation. Nylén et al. (2004) examined the climatology of katabatic winds, which are important in transporting biologic material across the ecosystem (Sabacka et al. 2009), and concluded that significant seasonal temperature changes can result from differences in katabatic frequency alone. Doran et al. (2008) contrasted an unusually warm and an unusually cold summer and showed that the warm summer was associated with increased frequency of katabatic winds. Our meteorological data were fundamental to developing meltwater and energy balance models summarized below (**Glaciers**). Fountain et al. (in press) defined, for the first time, the spatial and temporal variation of precipitation in the valleys and identified a strong precipitation gradient with much less precipitation up valley. Fountain et al. also showed that ~50% of the snow accumulation on the valley floor is due to snow redistribution from the valley walls. Statistical modeling (Cozzetto 2009) revealed that the recent warm summers were associated with different large scale climatic conditions than those associated with warm summers before 1990.

**1.2.2. Glaciers.** Long term records of glacier mass balance show that the glaciers are in equilibrium, although recent data suggest that they may be losing mass (Fountain et al. 2006). Any current glacier advance is apparently the result of the ice becoming more ductile with climate warming over a 1000 year period (Fountain et al. 2004). Because summer air temperatures are typically below freezing and the glaciers are on the cusp of melting, small changes in available energy result in large changes in melt production (Ebner et al. 2005). Thermodynamic constraints were outlined in a physical model that predicted the mass loss for 11 years of data (Hoffman et al. 2008) providing a first step in a valley-wide model of meltwater production.

**1.2.3. Streams.** Stream gauging and algal transect networks in Taylor and Wright Valleys have continued since the inception of the MCM. From the early 1990's to present, stream flow decreased in response to cooler temperatures (Doran et al. 2002b), except during the summers of 2001-02 and 2008-09 when major floods occurred. Because of streambed scouring, these floods acted as resetting events in those streams where the algal mats were sparse, but had less of an effect where mats were abundant. Our use of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  signatures to investigate the connections of snow, ice, stream water, and lake waters shows that substantial isotopic fractionation occurs between source (snow and ice) and sink (streams and lakes), providing a tool for understanding hydrologic changes (Gooseff et al. 2006). Experimental work combined with analysis of stream gauge records indicate that the hyporheic zone is responsible for substantial thermal buffering of stream temperatures, and that evaporation from streams limits the mid-day peak in stream water temperatures, which can be as high as 18 °C (Cozzetto et al. 2006; Cozzetto 2009). Experiments focusing on nutrient dynamics showed that DOC can limit heterotrophic activity in streams with no algal mats (Koch et al. 2010). We also showed that, in streams supporting microalgae, endemic diatoms are more common in "harsh" systems with longer periods of intermittent flow, whereas widespread species are more abundant in streams with stable flow regimes (Esposito et al. 2006; 2008). A taxonomic database of diatoms in the streams has been expanded to include species found in other Antarctic and sub-Antarctic regions.

**1.2.4. Lakes.** The absence of sunlight in winter remains an important but poorly understood biogeochemical control of ecosystem processes. Our studies show that most organisms in the lakes are not just "surviving the extremes" but are actively feeding, growing and reproducing through the winter (e.g., Lizotte et al. 1996; Takacs and Priscu 1998; Laybourn-Parry et al. 2005). In 2008, we studied the MCM lakes during the transition from 24 h sunlight to polar night and showed that while photosynthetic primary productivity decreased during the summer-winter transition, chemoautotrophic carbon fixation continued, providing a source of new organic carbon to heterotrophs through the dark winter months.

Measurements of protein and DNA synthesis in heterotrophic bacteria also revealed a shift in cellular function from growth to maintenance during this solar transition.

Measurements of lake level, ice thickness and ice transparency have been ongoing. After a long period of lake level rise (1903 to ca. 1990), levels receded for a decade in response to cooler summers and decreased meltwater flow (Doran et al. 2002b), and then rebounded as a result of the floods of the 2001-02 and 2008-09 summers (Doran et al. 2008). Lake ice thickness increased since 1986 by an average of 11 cm yr<sup>-1</sup> in response to the lower temperatures (Doran et al. 2002b; Priscu unpubl.). Below-ice PAR is correlated to ice thickness, sediment load and bubble properties (Adams et al. 1998; Fritsen et al. 1998), and has been used to produce a hyperbolic tangent model that accurately predicts phytoplankton productivity in the lakes (Fritsen and Priscu 1999; Priscu et al. 1999). Measurements of chemistry and microbial activity have also continued. The distribution of phytoplankton species in the lakes changed from 1993 to 2000, presumably in response to thicker lake ice and reduced stream inflows (Tursich 2002). We initiated phytoplankton bioassays to assess nutrient deficiencies (Priscu 1995; Dore and Priscu 2001). Sediment traps were deployed in Lake Bonney in 2000 to evaluate the magnitude and timing of sediment flux from the ice covers and to assess C, N, and P loss from the euphotic zones of the lakes. In addition, we found that more than 70% of the bacteria in Lake Bonney are infected with viruses (Lisle and Priscu 2004; Sawstrom 2008) indicating that viruses play a major role in regulating bacterial numbers and DOC turnover.

We used genomic tools in MCM3 to investigate microbial diversity in dry valley lakes. Thus far, 16S rRNA gene analysis has revealed that the ancient waters beneath the chemoclines are highly individualistic, whereas the near surface fresh waters share many similar bacterial phylotypes (Takacs-Vesbach et al. 2010). Using an innovative high throughput culturing approach, we have isolated a large diversity of novel psychrophilic bacteria from the lakes (Stingl et al. 2008). To overcome inherent problems associated with conventional clone library analysis, we have used a deep sequencing approach of small subunit rRNA gene tags (Huber et al. 2007) through our participation in the MIRADA-LTER project (<http://amarallab.mbl.edu/mirada/mirada.html>). Through this study we will more fully understand prokaryotic and eukaryotic diversity and begin making cross-site comparisons with other LTER aquatic systems. A unique microbial consortium was detected in the water of Blood Falls, the glacial outflow of Taylor Glacier (Mikucki and Priscu 2007; Mikucki et al. 2009), which influences the diversity and geochemistry of Lake Bonney. Isotopic investigations of N<sub>2</sub>O in Lake Bonney (Lizotte et al. 1996; Priscu 1997) revealed the most isotopically depleted N<sub>2</sub>O yet observed in a natural environment (Priscu et al. 2008). Functional genomic analysis and contemporary biogeochemical thermodynamics (Lee et al. 2004a) cannot explain this peak, which appears to be a legacy of previous conditions within the lake. Continued minor element and isotopic measurements have described the different sources of solutes to the lakes, as well as their evolutionary histories (Lyons et al. 2005; Witherow et al. in review).

**1.2.5. Soils.** MCM investigators have been leaders in the international Antarctic soil community and organized a NSF sponsored workshop that culminated in a special issue of *Soil Biology and Biochemistry* (2006, vol. 38); papers by these LTER investigators described our advances in understanding relationships among climate, biodiversity and ecosystem functioning during MCM3. Our work shows that the dominant nematode contributes disproportionately to soil carbon turnover (Barrett et al. 2008a) and that invertebrate species are sensitive to climate variation (Doran et al. 2002b; Barrett et al. 2008a,b; Simmons et al. 2009a). We refined our habitat suitability model (Virginia and Wall 1999) to reflect the imprint of ancient and recent landscape history on invertebrate communities (Nkem et al. 2006a,b; Ayres et al. 2007, 2008; Barrett et al. 2008b; Poage et al. 2008; Simmons et al. 2009b). Poage et al. (2008) quantified the influence of soil salinity gradients on the occurrence of complex soil communities using a predictive model, while Nkem et al. (2006a) found that saline soils lacking higher invertebrates could become suitable habitats with leaching. These are important insights given the emergence of wetted soil habitats following permafrost melt (Lyons et al. 2005). Our work on ecological genomics and the

molecular genetics of stress response systems in soil nematodes is providing a functional context for understanding adaptations to these extreme environments (Adhikari et al. 2009).

Our research has demonstrated that key ecosystem processes including soil respiration are particularly sensitive to climate variation (Parsons et al. 2004; Ball et al. 2009). Ball et al. (2009) showed that soil CO<sub>2</sub> flux is a function of biological respiration and physical mechanisms, controlled by temperature and mediated by soil water and mineralogy. Since controls over soil C balance are also influenced by events occurring over glacial time scales, e.g., lake inundation (Burkins et al. 2000), rapid changes in climate have the potential to significantly alter C dynamics. Recently, Bate (2008) used stable isotopes to show that different fractions of organic matter have distinct origins (e.g., terrestrial and lacustrine) and long-term incubation studies imply that these fractions are differentially sensitive to temperature and therefore climate change. The progression of results over MCM3 clearly indicate that decadal C residence times estimated for legacy sources of paleolake-derived organic matter are too short for this C pool to be the sole, or in many cases the predominant source of C to soil communities (Barrett et al. 2005; 2006a).

Our recent work examining the linkages among dry valley landscapes has demonstrated strong connectivity among terrestrial and aquatic ecosystems. Wind and water are the major vectors behind ecosystem connectivity and are responsible for redistribution of organisms and nutrients across regional and local spatial scales (Nkem et al. 2006b; Adams et al. 2007; Barrett et al. 2007; Sabacka et al. 2009). While we have previously demonstrated the importance of aquatic ecosystems on soils (e.g., lake inundation), we have now shown that soils also influence the nutrient dynamics of streams and lakes (Barrett et al. 2007; Bate et al. 2008; Barrett et al. 2009). For example, soils in the dry valleys vary significantly in N:P ratio based upon their surface geology and landscape history (Bate et al. 2008). This variation in soil geochemistry is reflected in the stoichiometry and productivity of lakes (Barrett et al. 2007). As the wetted margins of streams and lakes expand and contract with climate variation these environments may become important exchange sites for transfers of biota and nutrients between the soil, streams and lakes (Ayres et al. 2007; Gooseff et al. 2007; Northcott et al. 2000; Barrett et al. 2009).

**1.2.6. Ecological Modeling.** Our modeling efforts include development of conceptual and mathematical models, both within the MCM project and in conjunction with other US and international colleagues. Our mathematical models include budgetary and dynamic formulations of biological, geochemical and physical phenomena. Models of the surface energy balance of glaciers and melt water generation are being developed by Fountain (Hoffman et al. 2008). We are currently generating new stream models of coupled hydrology and biogeochemical dynamics using records of streamflow and electrical conductivity from stream gauge sites. Hunt et al.'s (2007) soil water retention model examines variations in available moisture for biotic activity and Moorhead et al.'s (2002) model showed nematode responses to temperature and soil moisture. A statistical model based on limnological data from Lake Hoare revealed that photosynthetically active radiation (PAR) and P are the primary factors controlling primary production in the water column (Herbei et al. in review; Fritsen and Priscu 1999). Priscu developed a forward difference model for Lake Bonney to show that N<sub>2</sub>O turnover rates can exceed 10<sup>3</sup> years, revealing that this gas is a relict of past biological activity (Priscu 1997; Priscu et al. 2008). Using data from late and early winter, Priscu showed that a PAR driven hyperbolic tangent model could be used to predict both integrated and vertical profiles of phytoplankton primary productivity with more than 80% precision (Priscu 2009).

### **1. 3.    RESPONSE TO SITE REVIEW**

In summarizing our advances in understanding the Taylor Valley ecosystem during MCM3 we have benefitted from points raised by the site review team (2008). While we do not specifically address each of their suggestions here, our new hypotheses and tests of these hypotheses were developed through serious consideration of their report, especially the recommendation to explore changes in connectivity across the dry valley landscape.

## SECTION 2

## PROJECT DESCRIPTION

### 2. 1. INTRODUCTION

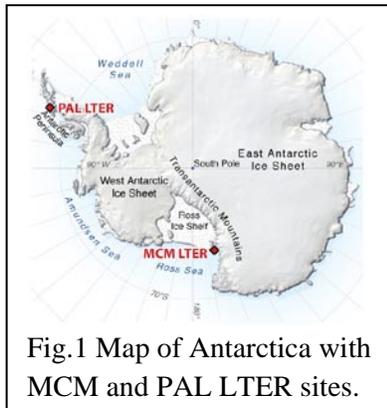


Fig.1 Map of Antarctica with MCM and PAL LTER sites.

The global average annual temperature in the 20<sup>th</sup> century has increased nearly 1°C and is predicted to rise for decades (IPCC 2007). The effects of this change (i.e., temperature, moisture) are manifested differently across our planet owing to differential temperature change and ecosystem sensitivity. Consistent with the projections of climate models, polar regions are warming faster than the rest of the earth (Chapin et al. 2005). In the north, the Arctic has warmed twice as fast as other regions, resulting in melting sea ice and glaciers, shrinking habitat for humans and other organisms and feedbacks that increase greenhouse gases and affect climate (IPCC 2007; Chapin et al. 2005). On the Antarctic continent, warming is also occurring faster than expected in certain areas: the Antarctic peninsula has warmed five times faster than the global average (2.5 °C since 1945), and the warming of the southern ocean and associated loss of sea ice has resulted in a shift in penguin species and their food sources (Montes-Hugo et al. 2009; McClintock et al 2008). In contrast to the changes in the Antarctic Peninsula, temperatures in the vast interior of the Antarctic continent have remained stable or cooled owing to the presence of a high Southern Annular Mode (SAM Index) thought to be caused in part by stratospheric ozone depletion (Thompson and Solomon 2002). As the ozone hole diminishes, temperatures have been predicted to increase gradually throughout the continental interior and in the McMurdo Dry Valleys (MDV) (Walsh 2009; Chapman and Walsh 2007). The NSF currently has two LTERs in Antarctica that are investigating the effects of climate change on ecosystem structure and function (**Fig. 1**): The PAL is studying rapid warming on marine systems whereas the MCM LTER has been focusing on ecosystem responses to cooling, and now in this proposal, the connectivity of terrestrial-freshwater systems caused by presses and pulses of warming. Like the PAL system, the transition to warmer, wetter conditions in the MDV will likely have profound effects on biodiversity and biogeochemical cycling, and may leave this ecosystem more vulnerable to other drivers of environmental change, such as invasive species.

Ecosystem responses to climate trends have received much attention, particularly in arid environments (e.g., Clark et al. 2009; Peters et al. 2004; 2008; Okin et al. 2009). Ecosystem processes in arid environments are often influenced by discrete climate events, traditionally described as pulses (Gebauer and Ehleringer 2000; Schwinning et al. 2003; 2004). Discrete climate events can be extreme in terms of magnitude (e.g., intense precipitation or ice melt events), but may not have negative impacts on the ecosystem. In fact, such temporal climate variability is a characteristic property that contributes to both the structure (i.e., community composition) and functioning (e.g., biogeochemistry and production) of desert ecosystems (e.g., Reynolds et al. 2004). Discrete climate events can have a disproportional influence over ecosystems relative to the temporal scales over which they occur (Pennington and Collins 2007). These effects can vary spatially over time and can influence ecosystem heterogeneity at many scales (Schimel et al. 2007; Clark et al. 2009). This sensitivity to discrete climate events is particularly true for polar deserts (Robinson et al. 1998; Convey et al. 2003) because massive water reserves are present as ice in alpine and terminal glaciers, as seen in the satellite image of the MDV (**Fig 2**). For example, pulses of liquid water following melt have been observed to rapidly reactivate soil and stream biota (Barrett et al. 2002b; Treonis and Wall 2005; McKnight et al. 2007), and increase nutrient loading and primary productivity in adjacent lake ecosystems (Foreman et al. 2004; Doran et al. 2008; 2009).

#### 2.1.1. Evolution of the MCM Conceptual Model

Our overarching hypothesis in **MCM1** was: **The structure and function of the MCM was controlled by physical constraints.** Habitat suitability, defined by the presence and composition of biota, was determined primarily by physical factors (Freckman and Virginia 1997) and much of the organic material supporting these soil communities was produced in paleolakes that filled some of the valleys >10k years

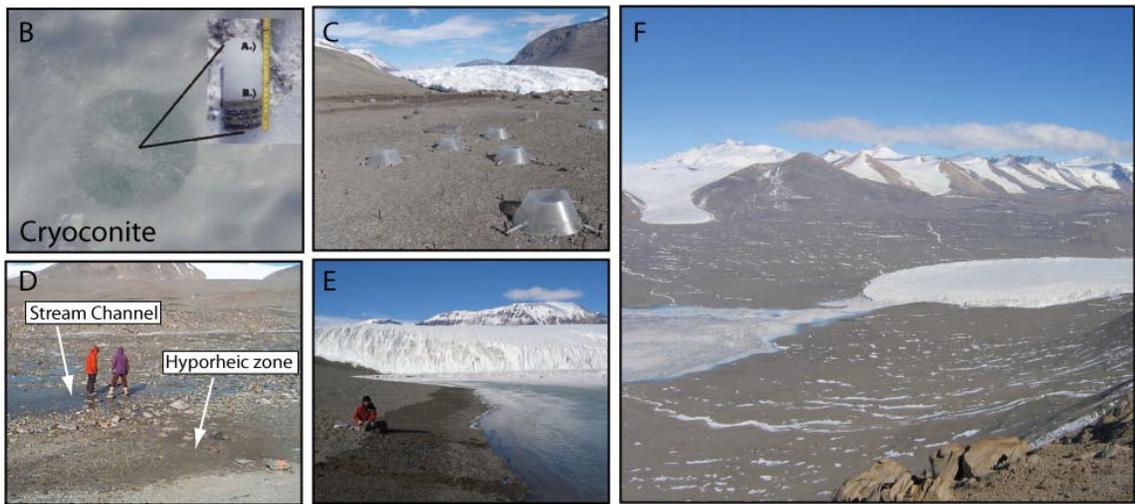
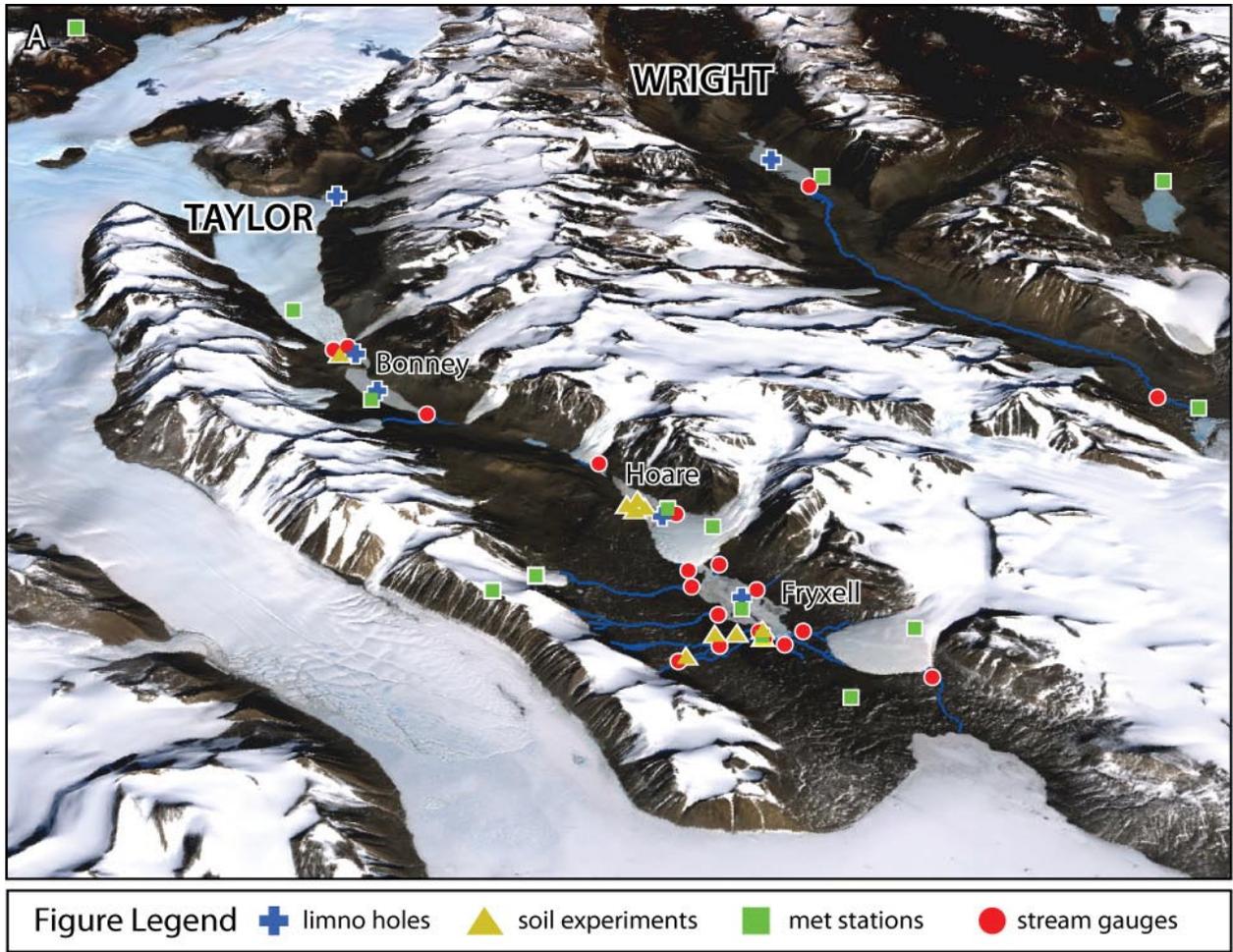


Figure 2. Map (A) of Taylor Valley (showing Bonney, Hoare, and Fryxell Basins) and Wright Valley indicating the distribution of current monitoring and experiment locations. Examples of environments with potential for enhanced biodiversity in response to greater water availability: (B) cryoconite holes, (C) experimental soil plots, (D) stream channels and the hyporheic zone, (E) lake margins. Overview of Fryxell Basin (F) showing alpine glaciers at higher elevations in the Kukri Hills.

ago under a different climate regime (Burkins et al. 2000). Similarly, we found that the nutrient status and distribution of phytoplankton in the lakes reflect differences in long-term accumulation of solutes determined by landscape position and past climates (Priscu 1995; Lyons et al. 2000). The discovery of linkages between past dry valley climate and contemporary ecosystem functioning led to the central hypothesis of **MCM2: Past climates in polar desert environments strongly overprint present ecosystem structure and function**. In MCM2, ecological legacies (e.g., salts, organic matter) were found to also influence biodiversity. For example, many of the phototrophic microbes in soils and streams reflect the legacy of benthic mat communities deposited by paleolakes, whereas other species have more contemporary origins (Brambilla et al. 2001; Nadeau and Castenholz 2001; Wood et al. 2008). This led to the central hypothesis for **MCM3: Biodiversity and ecosystem structure and function in the McMurdo Dry Valleys are dictated by the interactions of climatic legacies with contemporary biotic and physical processes**. Using molecular tools, we showed that the diversity of phyto- and bacterioplankton in the lakes is structured by ancient nutrient pools (Glatz et al. 2006; Priscu et al. 2008) and nematode diversity is related to desiccation survival (Adhikari et al. 2009).

## 2.2. HYPOTHESES

### 2.2.1. Overarching Hypothesis

MCM4 will incorporate our conceptual advances on interactions of ecological legacies and climate (at decadal to millennial time scales) with a new set of hypotheses to examine how the MDV will respond to the latest predictions for climate in this region of Antarctica. The MDV is an environment poised for dramatic change. New large-scale climate models (Walsh 2009; Chapman and Walsh 2007) indicating a continent wide warming trend over the next 50 to 100 years, in concert with our current understanding of contemporary MDV function in relation to past climate legacies, lead us to our current overarching hypothesis for this MCM4 proposal: **Climate warming in the McMurdo Dry Valley ecosystem will amplify connectivity among landscape units leading to enhanced coupling of nutrient cycles across landscapes, and increased biodiversity and productivity within the ecosystem**.

The anticipated climate transitions in the MDV region provide an excellent opportunity to examine contemporary patterns in ecological connectivity and predict how these patterns may change in the future. The reasons that measurements of rates of change and connectivity across the landscape are facilitated in the MDV are several: 1) landscapes are old ( $>10^6$  years) with little direct anthropogenic impact; 2) food webs are simple with low diversity of metazoan taxa (there are no vascular plants or vertebrates); 3) although considered a desert, the MDV contains a massive amount of water as ice; and 4) summer temperatures hover near 0 °C and moderate summer warming can greatly increase hydrologic connectivity (through pulsed flood events and gradual increase in glacier melt). Our past studies have shown the influences of a decadal cooling trend and intense seasonal warming events (Doran et al. 2002b; Foreman et al. 2004). Based on these observations we predict that the ecological impacts of sustained warming will be mediated by changes in hydrologic and wind-driven connectivity. Our conceptual model of changes in connectivity (**Fig. 3**) provides a basis for developing new models of MDV dynamics under a warming climate.

We believe that climate warming will be manifested as a slow press of warmer summers as ozone depletion is ameliorated, upon which transient pulse events of high summer flows and katabatic winds will be overprinted (**Fig. 4**). These pulse events are driven by a confluence of changes in local weather patterns causing increased air temperature and a cascade of physical changes (Doran et al. 2008). The two events we observed in summer 2001-02 and 2008-09 altered the landscape by increasing stream flow and melting permafrost (Lyons et al. 2005; Barrett et al. 2008b). These changes reactivated a wetland area (**Fig. 5**), altered the species composition of soil and stream communities, and increased

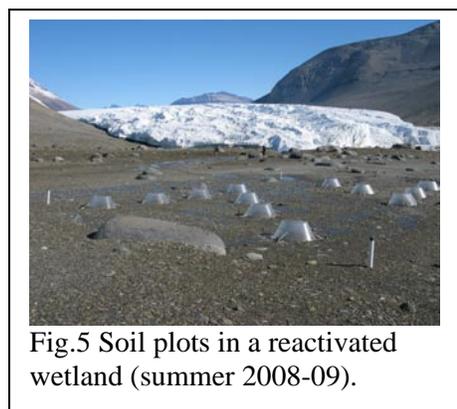
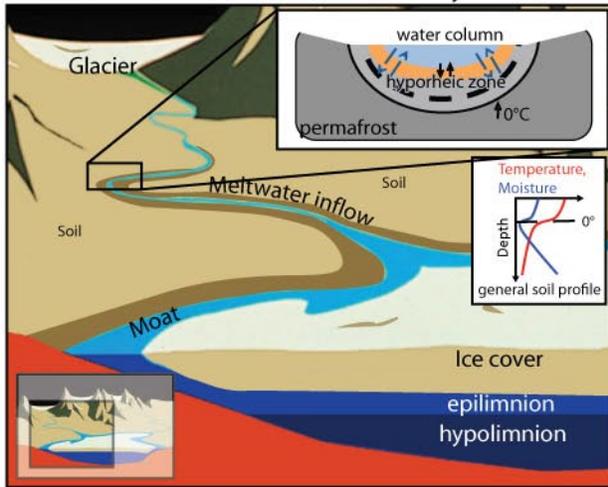


Fig.5 Soil plots in a reactivated wetland (summer 2008-09).

Cold Summer – Discrete Connectivity



Warm Summer – More Connectivity

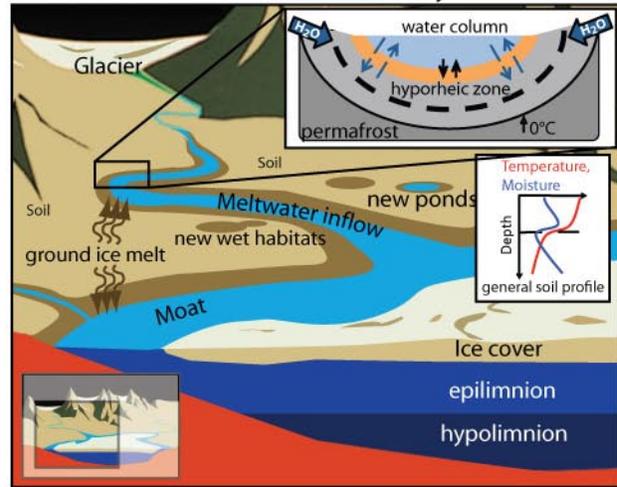


Figure 3. Depiction of connectivity across the MDV landscape for cold summers and warm summers. The warm summer diagram indicates more ground-ice melt creating ponds, deeper soil thaw, enhanced soil moisture, newly wetted soil habitats, more streamflow, deeper hyporheic zones, more streams, less perennial lake ice cover, and overall new hydrologic connections of soils to lakes and streams. The permafrost boundary is denoted by a dashed line in the soil temperature and moisture profiles insets.

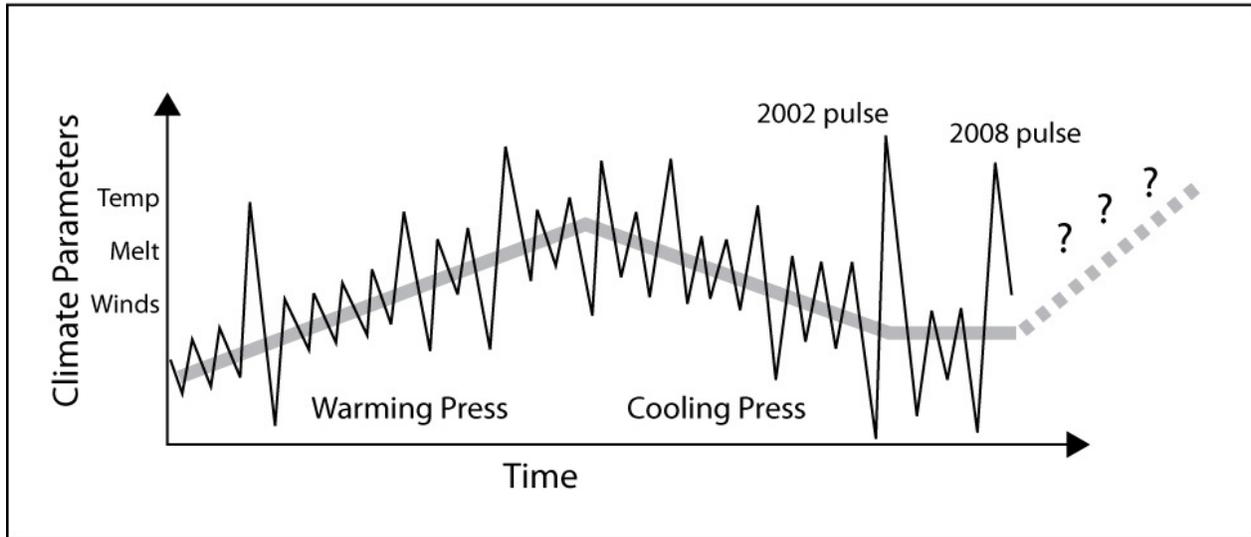


Figure 4. Conceptual model of climate driven presses and pulses in the MDV ecosystem. Influences of presses (grey line) are a linear function of duration and magnitude whereas pulses (events represented as variability in the black line) influence climate disproportionately to their duration. Pulses and presses can elicit non-linear responses from ecosystems depending upon initial conditions and nature (sign, magnitude, duration) of the changes. For example, in the MDVs a long-term cooling press limited melt-water generation and streamflow, decreasing productivity in lake and soil biota over a decadal time scale. In contrast, the warm windy summers of 2001-02 and 2008-09 enhanced hydrological connectivity, offsetting previous changes from a decade of cooling. Climate models predict that the role of pulses in driving the behavior of the MDV ecosystem will increase in the immediate future.

nutrient loading to the lakes affecting species composition and production. These events clearly show that hydrologic connectivity between and within glaciers, streams, soils, and lakes is strongly linked to climate conditions.

### 2.2.1. Working Hypotheses

#### **H1. Pulse events (wind and melt) increase hydrological and biological connectivity across landscape units.**

Based on data collected during MCM3, together with recently published 50-100 year climate models of Antarctica, we contend that “floods” produced by warming events and katabatic windstorms of increased magnitude and/or frequency will accelerate movement of biota and nutrients across the dry valley landscape (**Fig. 6**). Data collected from summers of high glacial melt reveal that sediments, nutrients and particulate organic matter are transported from the glaciers and soils to the streams where they eventually enter the lakes (Foreman et al. 2004). Furthermore, summers of high flow co-occur with frequent and strong katabatic winds (Doran et al 2008; **Fig. 6C**). Aeolian traps and acoustic particle sensors show that most wind-blown particles (with associated organic matter) are mobilized during katabatic winds exceeding  $10 \text{ m s}^{-1}$  originating from the Polar Plateau (**Fig. 6D&E**).

More specifically, large pulses in melt water should enhance connectivity by increasing habitat suitability for microalgae and invertebrates and effectively expanding the range of many taxa. Melt water pulses should also provide a conduit where organisms can be transported across the landscape. Elevated and more frequent winds will increase aerial dispersal of organisms resulting in more homogenous distribution of biodiversity across the region. Our observations of soil biota in aeolian traps and cryoconite holes (cylindrical holes formed when windblown sediment melts into ice often supporting microbial metabolism, **Fig. 2B**) indicate high winds facilitate broad scale distribution across the landscape (**Fig. 7**). Thus, if organisms are transported to newly wetted areas their growth will produce patches of enhanced diversity, biogeochemical cycling and biomass production. Examples of such patches are stream beds, lake ice, cryoconite holes, snow patches on soil, wetted lake margins and hypolithic environments (Gooseff et al. 2003; Fountain et al. 2004; Priscu et al. 1998; Christner et al. 2003; Cary et al. 2010) (**Fig 2**). Movement of specific organisms with water and wind-blown material should resemble source pools within a given valley because the valleys are aligned with prevailing winds (**Fig. 2**).

#### **H2. Summer pulses of liquid water produce transient moist habitats with altered biological diversity and ecological complexity.**

Increased glacial and permafrost melt will generate newly inundated environments not only on the margins of dry valley streams and lakes, but also as wet patches in depressions and increased soil moisture across the landscape. Responses of biotic communities to this increased connectivity are expected to be complex. For example, while wet sediments in stream channels and on lake margins typically have larger populations and more diverse invertebrate communities than dry environments (Treonis et al. 1999; Ayres et al. 2007), the changes in these communities across continuous moisture gradients are not unidirectional. Much of our understanding of the response of soil biota to increased water availability comes from studies of spatial gradients (e.g., Treonis et al. 1999; Ayres et al. 2008; Takacs-Vesbach et al. 2010; Zeglin et al. in review). A few examples demonstrate temporal community responses to changes in resource availability (Barrett et al. 2008b). Specifically, for dry valley streams endemic diatom species in microbial mats become dominant during cold summers, when flow may cease for several days at a time. In contrast, widespread species are dominant during summers with high flow, resulting in greatest diversity during summers of moderate but steady flow (Esposito et al. 2006; **Fig. 8**).

Genomic studies have revealed that bacterial richness is greatest in soils outside the wetted margins of the lakes and streams compared to the saturated sediments in the stream channels and the lake water itself (Takacs-Vesbach et al. 2010; Glatz et al. 2006). Bacterial 16S rRNA genes detected in drier habitats most closely resembled cosmopolitan taxa, while the lower diversity communities from saturated sediments resembled taxa isolated from other polar or alpine environments. This contrasts with invertebrate

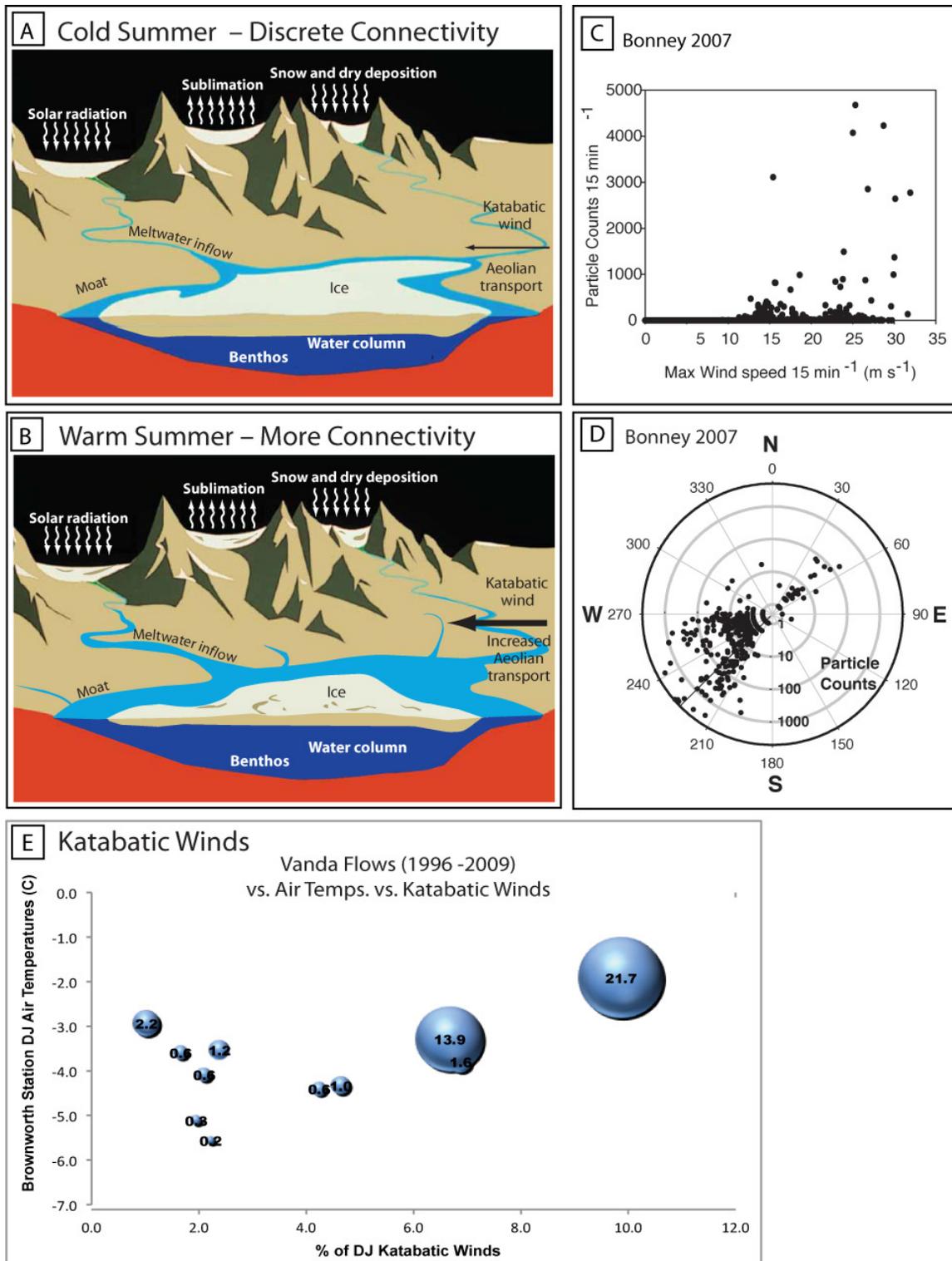


Figure 6. Conceptual diagrams for (A) cold and (B) warm summers. (C) Particle counts from sensors mounted 20 cm aboveground vs. maximum windspeed; showing that particles are not transported by winds  $< 10 \text{ m s}^{-1}$ , and (D) windrose plot of the same data; showing that most particles are transported by katabatic winds from the SW. (E) Annual flow of the Onyx River (noted as bubble size) in relation to December (D) and January (J) air temperature and percent of time in DJ with katabatic winds.

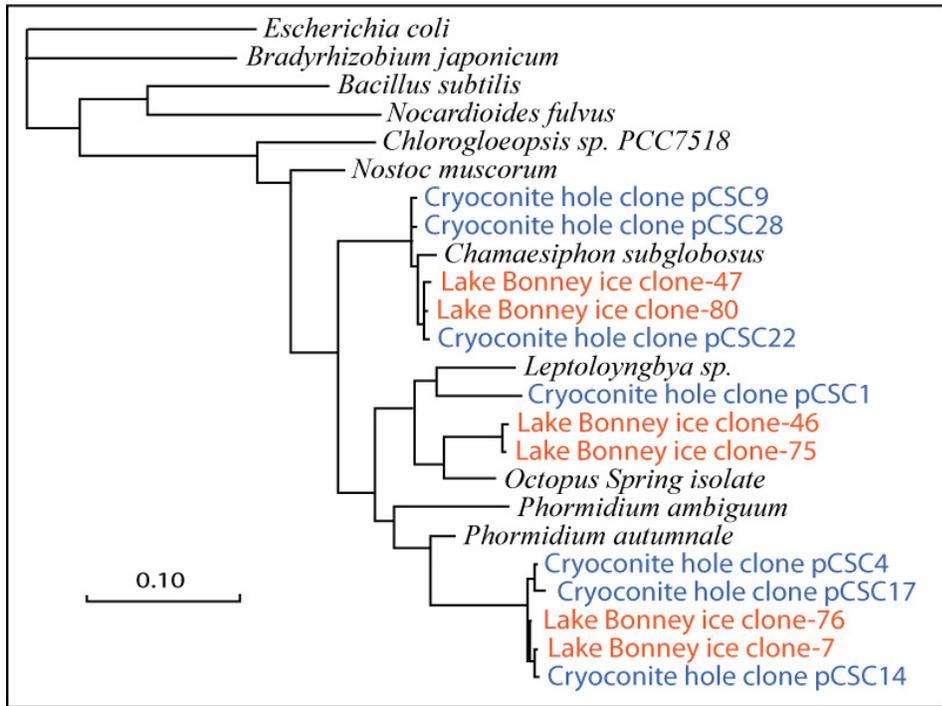


Figure 7. Phylogenetic analysis of cyanobacterial-derived 16S rDNA sequences. DNA molecules used to construct the maximum likelihood tree corresponded to the region from nucleotides 106–781 of the *E. coli* 16S rDNA. The scale bar indicates 0.1 fixed substitutions per nucleotide position. Clustering of clones from cryoconite holes (blue) and Lake Bonney (red) indicates that organisms in these habitats were seeded by wind from the surrounding landscape.

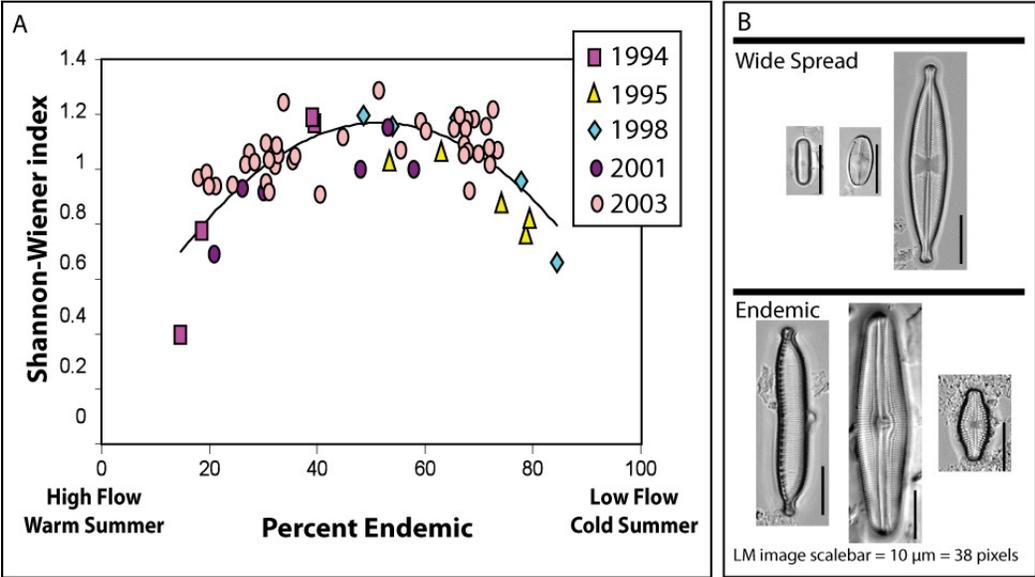


Figure 8. Stream diatom diversity changes with flow conditions. (A) Coexistence of widespread and endemic species during moderate flow summers maximizes diversity. (B) Examples of diatoms found in dry valley streams and described in the Antarctic Freshwater Diatom database (<http://huey.colorado.edu/diatoms/about/index.php>).

communities where the driest environments support the endemic species, *S. lindsayae* (Freckman and Virginia 1997). Moreover, Barrett et al. (2006b) found no relationship between the diversity of bacteria and invertebrate communities. If dry valley invertebrate and bacterial communities respond in opposite ways to saturation, then the most complex communities (i.e., those characterized by moderate levels of bacterial, cyanobacterial and invertebrate diversity) may occur in the ecotones between saturated sediments and arid soil environments. If warm climates enhance hydrologic connectivity by expanding the saturated zones, these ecotones between wet sediment and dry soil environments may also be expanded, thus contributing to more biological complexity within the dry valley landscape.

### **H3. Increased connectivity enhances rate, variance and the coupling of biogeochemical processes across the landscape.**

Past data have shown that linkages between terrestrial and aquatic ecosystems developed over glacial time scales have significant influences on contemporary biogeochemical processes; one cannot know the system's current state without looking at its history (Priscu 1995; Burkins et al. 2000; Lyons et al. 2000). We recognize that these ancient linkages are enhanced during warm summers, and may act to "reset" the dry valley ecosystem. For example, warming events may recharge water, nutrient and organic matter reserves in soils and lakes. This recharge is particularly important because ratios of NPP:Respiration in soils and lakes are typically <1 (Priscu et al. 1999; Barrett et al. 2006c). Warming events may also reset the physical substrate in stream channels scoured by high flow and alter glacier surfaces.

The influence of enhanced connectivity on biogeochemical processes was clearly seen in the lake systems when elevated nutrient loads stimulated rates of primary productivity in post-flood years (Foreman et al. 2004; **Fig. 9**). As high melt years become more frequent, increased lake levels may also enhance biogeochemical connectivity as lakes inundate soils and mobilize nutrients, which are often present in higher concentration in the evaporative margins around lakes (Fritsen et al. 2000; Northcott et al. 2009; Barrett et al. 2009). However, there is currently great variation among dry valley lakes in their nutrient profiles and the response of specific lakes to this greater connectivity will be constrained by local topography, hydrology and soil geochemistry. For example, Lake Miers, the only "flow-through lake" in the MDV, has much lower nutrient concentrations than Lake Fryxell, a closed-basin lake (**Fig. 10**). Furthermore, Lake Bonney in western Taylor Valley is the most phosphorus deficient lake in the MDV (Priscu 1995; Dore and Priscu 2001) because it occurs on substrate with low overall phosphorus availability and very high nitrate concentrations (Barrett et al. 2007; Bate et al. 2008). Thus, increased connectivity may accentuate variation in nutrient limitation among the lakes (e.g., Priscu 1995).

In streams, high flows may cause scouring of cyanobacterial mats from the streambed (McKnight et al. 1999) and contribute to high organic matter and nutrient loading to lakes. In soils, high melt years are associated with changes in soil communities (Barrett et al. 2008b; **Fig. 11**) and the mobilization of salts (Simmons et al. 2009). Increased snow patch and permafrost melting during warm years would also increase solute and nutrient fluxes into the stream and lakes and "desalt" the soils (Lyons et al. 2005; Harris et al. 2007). Thus in both streams and soils, mobility of nutrients may be enhanced in high melt years, but increases in production may lag behind actual warming events.

### **H4. The emergence of wetted habitats varies with local geography (i.e., slope, aspect, elevation and geomorphology) and history of landscape development.**

The elevational and longitudinal gradients characterizing the local physical geography will constrain development of newly or intermittently wetted habitats resulting from increased frequency of summer warming events and increased hydrological connectivity. The cooler conditions that occur at greater elevation results in vertical gradients in moisture and generation of melt water, whereas distance to the ocean influences longitudinal gradients in salt accumulation through the valleys (Bockheim 1997; Lyons et al. 2000). Thus, habitat suitability varies greatly along both gradients in both soils and streams. In Taylor Valley, we have observed that increased hydrologic connectivity leads to the "wetting up" of the terrestrial landscape and increased solute and nutrient transport to streams and lakes. The "de-salting" of the soils may create more suitable invertebrate habitat. Future increases in melt from glaciers, permafrost, or snow pack will increase connectivity by enhancing areas that are intermittently wet, thus increasing

suitable habitats at higher elevations. Increases in melt will also create newly wetted habitats at further inland high elevation basins that currently have no active streams, potentially providing new suitable habitats for endemic species adapted to extremely dry conditions. At the same time, the expansion and longer duration of wetted conditions at lower elevations may make these areas more suitable habitats for widespread species and more vulnerable to invasive species.

The topography of the valley floor determines the hydrologic configuration of the landscape (**Fig. 12**). In some valley basins, the melt water generated flows into a closed-basin lake, whereas in other valleys there are no lakes and the meltwater that does not seep into the ground or sublimate eventually reaches the coastal bays. In lower Garwood Valley, Garwood Stream has essentially gone underground for several km due to extreme thermokarsting (**Fig. 11C**). As previously mentioned, the one “flow-through” lake, Lake Miers, has physical and geochemical profiles and biogeochemical processes that are distinct from those in the closed-basin Taylor Valley lakes (**Fig. 10**). With warmer summer conditions, some currently closed basin lakes may become flow through lakes like Lake Miers. This change would be expected to influence the connectivity of the lake microbial communities. Currently, the bacterioplankton and phytoplankton are similar in surface waters of the Taylor Valley lakes, but are distinct among the deep waters, reflecting the long-term isolation of deep waters from the surrounding landscape.

## 2.3. BACKGROUND

### 2.3.1. The McMurdo Dry Valley Ecosystem

The MDV comprise the largest ice-free area of the Antarctic continent (Ugolini and Bockhiem 2008) and hosts a variety of landscapes including glaciers, perennially ice-covered lakes, melt-water streams and arid soils (**Fig. 2**). Glacial meltwater is the primary source of water to dry valley streams and lakes (Fountain et al. 1999); snow is an important source of water for soils (Gooseff et al. 2003). The glaciers of the MDV are cold-based and most mass loss occurs as sublimation rather than as melt (Hoffman et al. 2008). Biotic activity of the glacier surface occurs in cryoconite holes, which occur where depressions cause accumulation of sediment and melting of the ice in summer (Foreman et al. 2007; **Fig. 2B** and **Fig. 13**). Cryoconites host biotic communities of cyanobacteria, tardigrades, rotifers, protozoa and eukaryotic algae (Poranzinska et al. 2004, Christner et al. 2003). The geochemistry of glacier melt can reflect biogeochemical processes occurring within cryoconites during high-melt periods (Tranter et al. 2004).

Glaciers feed melt-water streams for up to 12 weeks during the summer (McKnight et al. 1999). Streams are an important conduit of material and water across the dry valley landscape, linking glaciers, lakes and soils. Inter-annual variation in stream flow is large, e.g., from  $10^5$  to  $>10^6$  m<sup>3</sup> total inflow to Lake Fryxell between 1990 and 2003 (Jaros 2003). Stream channels are underlain by a hyporheic zone in the shallow active layer of the permafrost (see **Fig. 2C**) where most of the chemical weathering and exchanges between streams and soils occur (Runkel et al. 1998; Nezat et al. 2001; Gooseff et al. 2002; Maurice et al. 2002). Microbial mats are abundant in streambeds stabilized by stone pavement (McKnight et al. 1998).

Lakes are the only perennial liquid water environments in the MDV; they maintain biological activity year-round with food webs dominated by phytoplankton and bacteria (Laybourn-Parry 1997; Priscu et al. 1999; McKnight et al. 2000). Perennial ice-cover limits turbulent mixing and most lakes are strongly stratified by temperature and salinity (Spigel and Priscu 1998; **Fig. 12**). The major influences on the chemical composition of lakes are their landscape positions and climate history (Lyons et al. 2000; Dore and Priscu 2001).

Arid soils are the most extensive landform of the MDV occupying 95% of glacier ice-free surfaces below 1000 m (Burkins et al. 2001). Dry valley soils are derived from bedrock and tills composed of granites, sandstones, dolerites and meta-sedimentary rocks that range from Holocene to Miocene in age. Soils are typically alkaline, coarse textured, low in organic matter content, and often have high concentrations of soluble salts (Barrett et al. 2006c). No vascular plants or vertebrates inhabit the dry valleys, and food webs (**Fig. 14**) are dominated by bacteria, cyanobacteria, fungi, yeasts, protozoa and few taxa of metazoan invertebrates (Freckman and Virginia 1997; Adams et al. 2006; Cary et al. 2010).

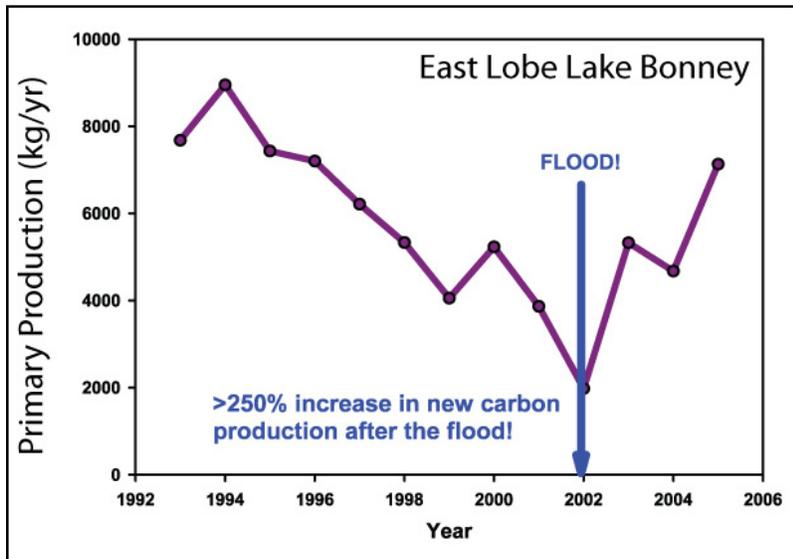


Figure 9. Trends in primary production in the east lobe of Lake Bonney, showing the increase following a flood event in summer 2001-02. Primary production was computed as described by Priscu et al. (1999).

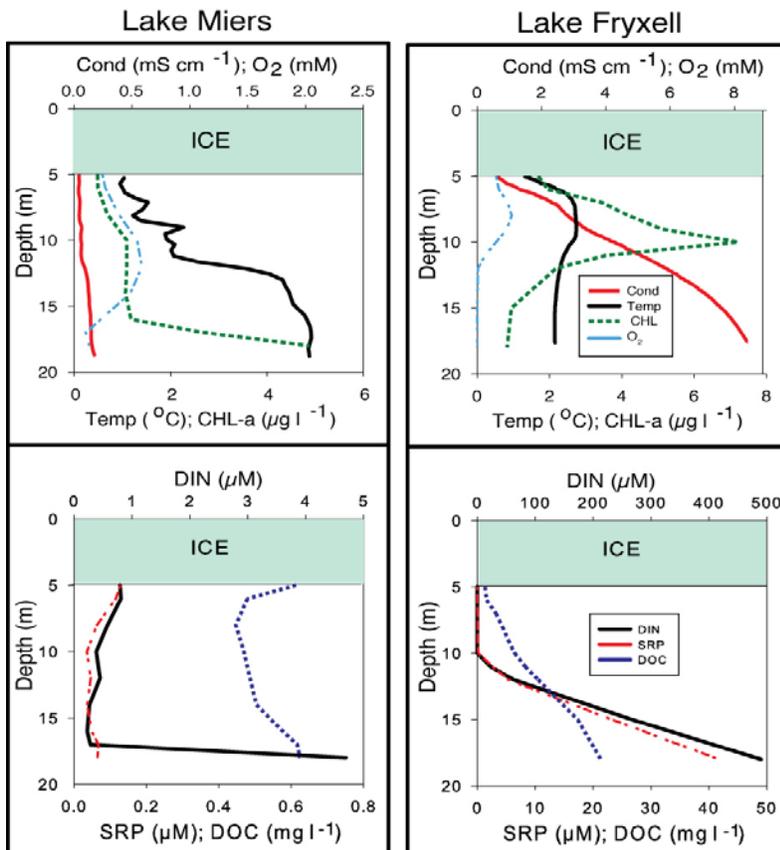


Figure 10. Comparison of lake profiles between Lake Miers and Lake Fryxell reveals the diluting effect that flow through has on physical, chemical and biological properties of Lake Miers. DIN =  $(\text{NH}_4^+ + \text{NO}_2^- + \text{NO}_3^-)$ , SRP = soluble reactive P; DOC = dissolved organic carbon; Cond = conductivity; CHL-a = chlorophyll-a.

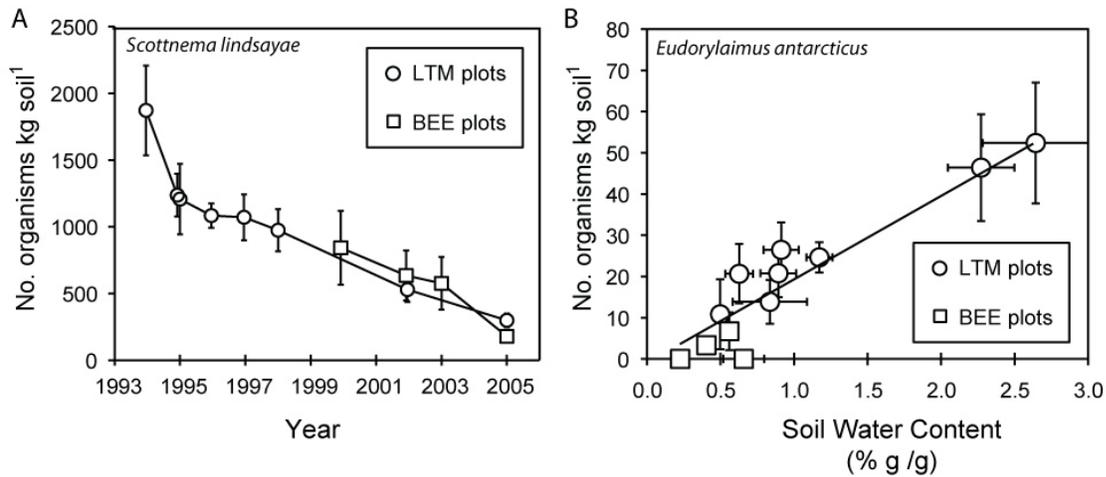


Figure 11. Long-term trends in mean abundance of (A) the microbial-feeding nematode *Scotttnema lindsayae* and (B) the algal-feeding nematode *Eudorylaimus antarcticus* vs soil water content in soils (Barrett et al. 2008b). *S. lindsayae* declined during a cooling trend in the MDV, while inter-annual variation in *E. antarcticus* was associated with greater soil moisture during summer 2001-02.

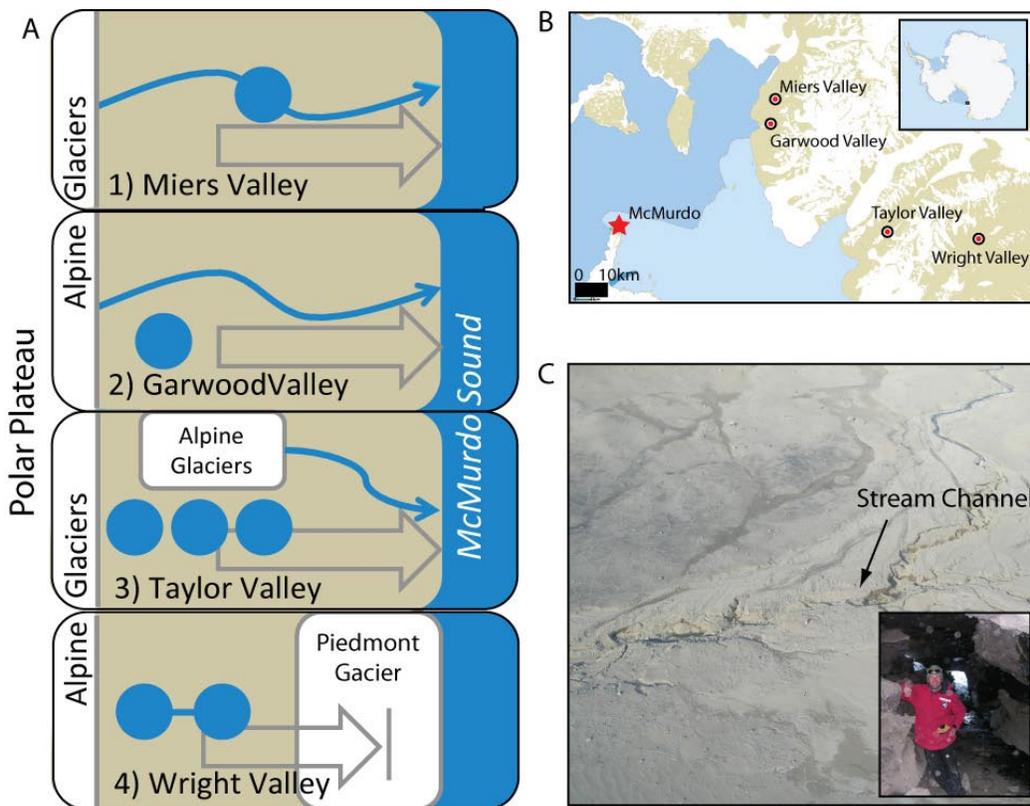


Figure 12. (A) Changes in connectivity mediated by geographic variation among valleys: 1) aeolian (gray arrow) and freshwater fluxes interact with flow-through lake, 2) aeolian and freshwater fluxes from distal sources carried by a large stream, 3) aeolian and freshwater fluxes from near-coast sources with closed basin lakes, and 4) piedmont glacier blocks all but aeolian sources. (B) Location map of MDV. (C) Thermokarst erosion of Garwood Stream after warm summer of 2001-02.

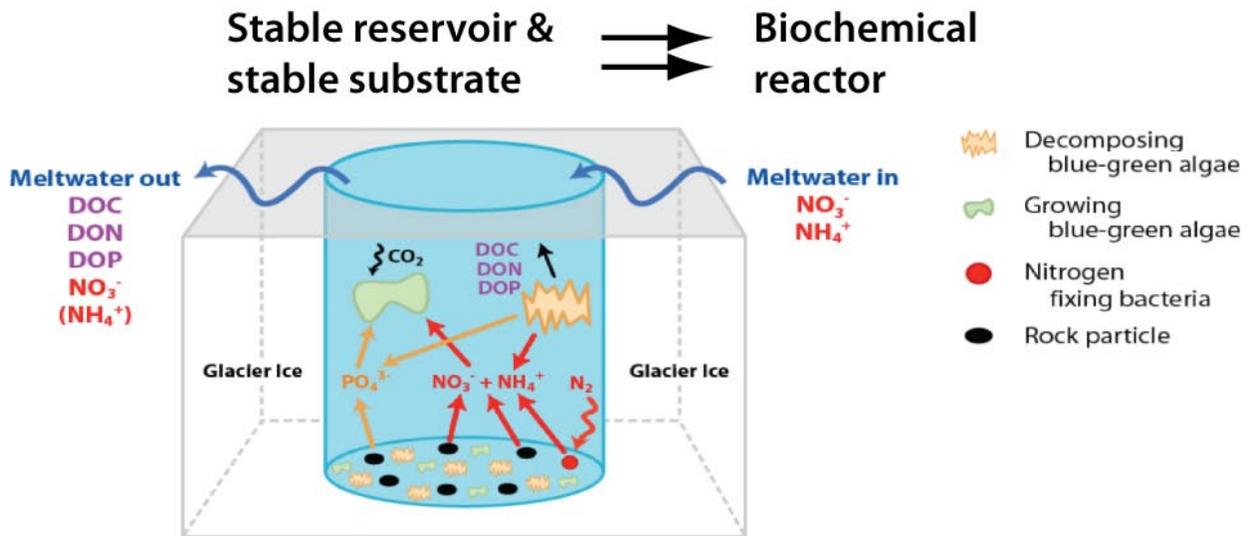


Figure 13. Diagram showing biogeochemical transformations that occur within cryoconite holes (after Foreman et al. 2007).

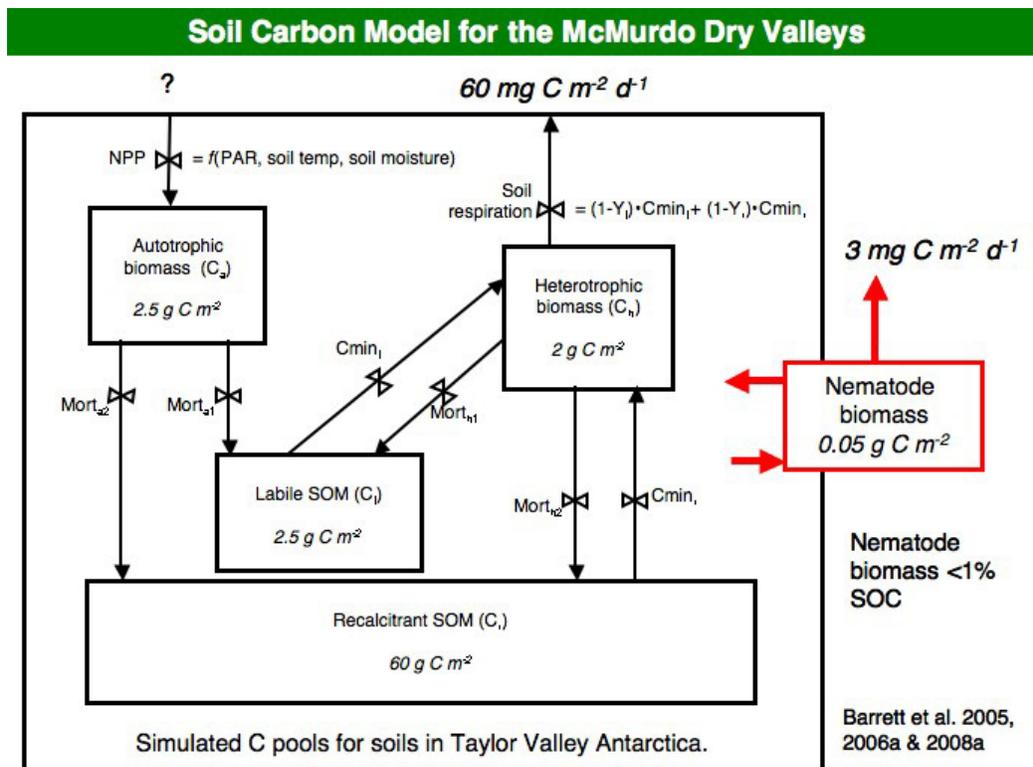


Figure 14. Estimates of standing C stocks and fluxes of different pools of organic matter in Taylor Valley soils. Distribution of C in labile and recalcitrant pools is based upon long-term incubation studies (Barrett et al. 2005; 2006a; Bate 2008). An analytical model based upon parameters derived from these incubations suggests that contemporary C inputs (e.g., production or aeolian deposition) are necessary to balance seasonal losses of C through soil respiration. Estimate of nematode contribution to C cycling are based upon in situ <sup>13</sup>C-labelling studies (Barrett et al. 2008a).

Specific responses of these landscape units to climate variation will depend upon the direction, magnitude and duration of temperature change, increases in solar radiation, and changes in wind speed and direction (**Fig.3**). The low annual precipitation within the region (2-50 mm water equivalent; Fountain et al. 2009) results from the strong rain shadow cast by the Transantarctic Mountains (Monaghan et al. 2004; 2006), with precipitation exhibiting a strong spatial gradient with  $\sim 50 \text{ mm yr}^{-1}$  along the coast decreasing to  $\sim 3 \text{ mm yr}^{-1}$  20 km inland. Air temperatures average  $-17^\circ\text{C}$  and range between  $\sim 0$  and  $-65^\circ\text{C}$  between summer and winter (Doran et al. 2002a). The strong katabatic winds of the MDV can reach speeds of  $37 \text{ m s}^{-1}$ . These winds not only influence the morphology of the valleys (Marchant and Head 2007) and dispersal of organisms (Nkem et al. 2006b; Sabacka and Priscu 2009), they also warm the valleys due to compressional heating as the winds descend to from the Polar Plateau. Air temperature increases of  $30^\circ\text{C}$  in a few hours can occur during winter katabatics (Nylen et al. 2004).

### **2.3.2. Climate Change Scenarios for McMurdo Dry Valley Ecosystem.**

The regional climate in the MDV has changed dramatically during the Holocene. Large lakes expanded to cover almost the entire floor of many valleys during the late Pleistocene and early Holocene (Stuiver 1981; HENDY 2000; Hall et al. 2001). The growth of lakes is thought to have resulted from melting of glacier ice. Ice cores from nearby (100 km) Taylor Dome revealed that air temperatures cooled by about  $4^\circ\text{C}$  over the past  $10^4$  years (Steig et al. 2000) and by 1200 years ago, many lakes were drawn down to small pools (Wilson 1964; Lyons et al. 1999). This decrease in lake size was a result of only a  $\sim 1^\circ\text{C}$  decrease in mean annual temperature (Lyons et al. 1999). For the past 1000 years, the lakes have been refilling with freshwater overlying relict brines in certain basins.

Recently, Doran et al. (2002b) recorded a local cooling of the MDV as part of a larger cooling of Antarctica (except the Peninsula) from 1986 to 2000. The underlying cause for this trend has been attributed to intensification of the Southern Annular Mode (SAM; Thompson and Solomon 2002). The SAM is the first component of the surface pressure field over Antarctica representing pressure differences between continental air masses and those over the southern ocean (Thompson and Wallace 2000). A strengthening SAM index represents enhanced circulation around Antarctica at  $\sim 60^\circ\text{S}$ , and is associated with cooling of the continent. The proximal cause for intensification of the SAM is human-induced ozone depletion over the continent (**Fig. 15A**) resulting in radiative heat loss, which intensifies the polar vortex in spring and isolates cold polar air masses (Kindem and Christiansen 2001; Thompson and Solomon 2002; Gillet and Thompson 2003). While modeling studies support the role of ozone depletion in the intensification of the SAM (Shindell and Schmidt 2004; Arbaster and Meehl 2006), reconstructions by Steig et al. (2009) suggest that cooling could also be driven by changes in sea surface temperatures and sea ice extent. The trend of increasing SAM intensity appears to have leveled off since the mid 1990s (Monaghan et al. 2008). Further, recent satellite gravity measurements suggest that the coastal regions of East Antarctica are losing ice mass (Chen et al. 2009). These observations may presage projections from climate models that summer warming will eventually dominate as the ozone hole is “repaired” in the future. Overall, future regional climate variation in the MDV may be driven by the global influences of ozone, greenhouse gases, changes in ocean circulation, and alterations in sea ice.

These future changes in climate will be drivers for changes in glacial melt; the source of stream flow that drives the hydrological system (Doran et al. 2008; Ebnnet et al. 2005; Fountain et al. 1998). When summer air temperatures are near freezing on the valley floor, the cooler temperatures at the higher elevations of the alpine glaciers control the extent of glacier surface contributing melt. Thus, small increases in temperature can greatly expand the area of glacier surface generating melt, yielding a large increase in stream flow and an abrupt rise in lake levels (**Fig. 15B**; Ebnnet et al. 2005; Doran et al. 2008). Further, ice-rich permafrost and deposits of massive ice are found only a few 10s of cm below the soil surface and warming may mobilize this water and its entrained nutrients (Bockheim 2002; Harris et al. 2007).

The recent trend of low stream flows associated with cold summers (Doran et al. 2002b) has been interrupted by two warm summers with high stream flows, as seen in the record for the Onyx River (**Fig. 15 C**). These summer pulse events, which may foreshadow future warming, were characterized by

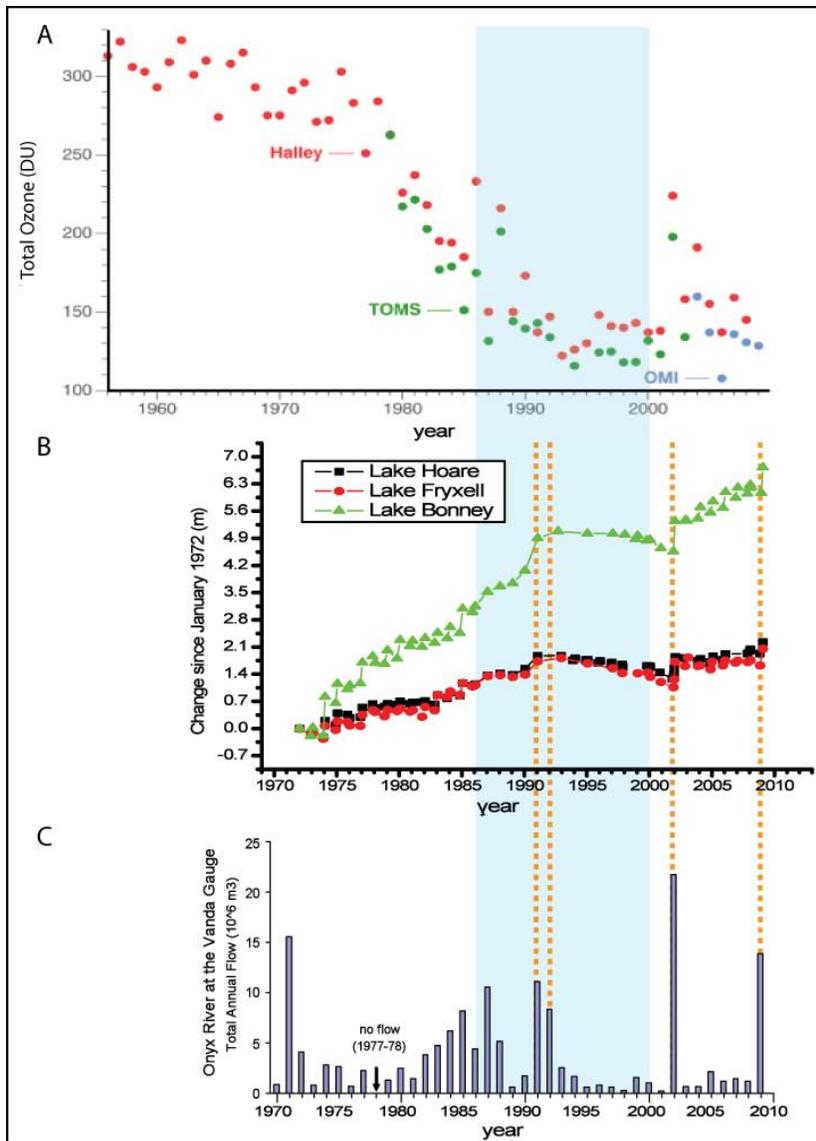


Figure 15. (A) Ground based and satellite measurements of decreasing ozone concentrations over Antarctica. (B) Trends in Taylor Valley lake levels changed inversely with ozone concentration from 1970 to 1990. (C) Trends in total annual flow of Onyx River (shown below) from 1970 to 2009; total flow for the austral summer is shown with the date for the January of that summer. Our data suggest that the two high flow summers during the 2000s are related to deficiencies in radiation-absorbing ozone occurring directly over the MDV which lasted into December.

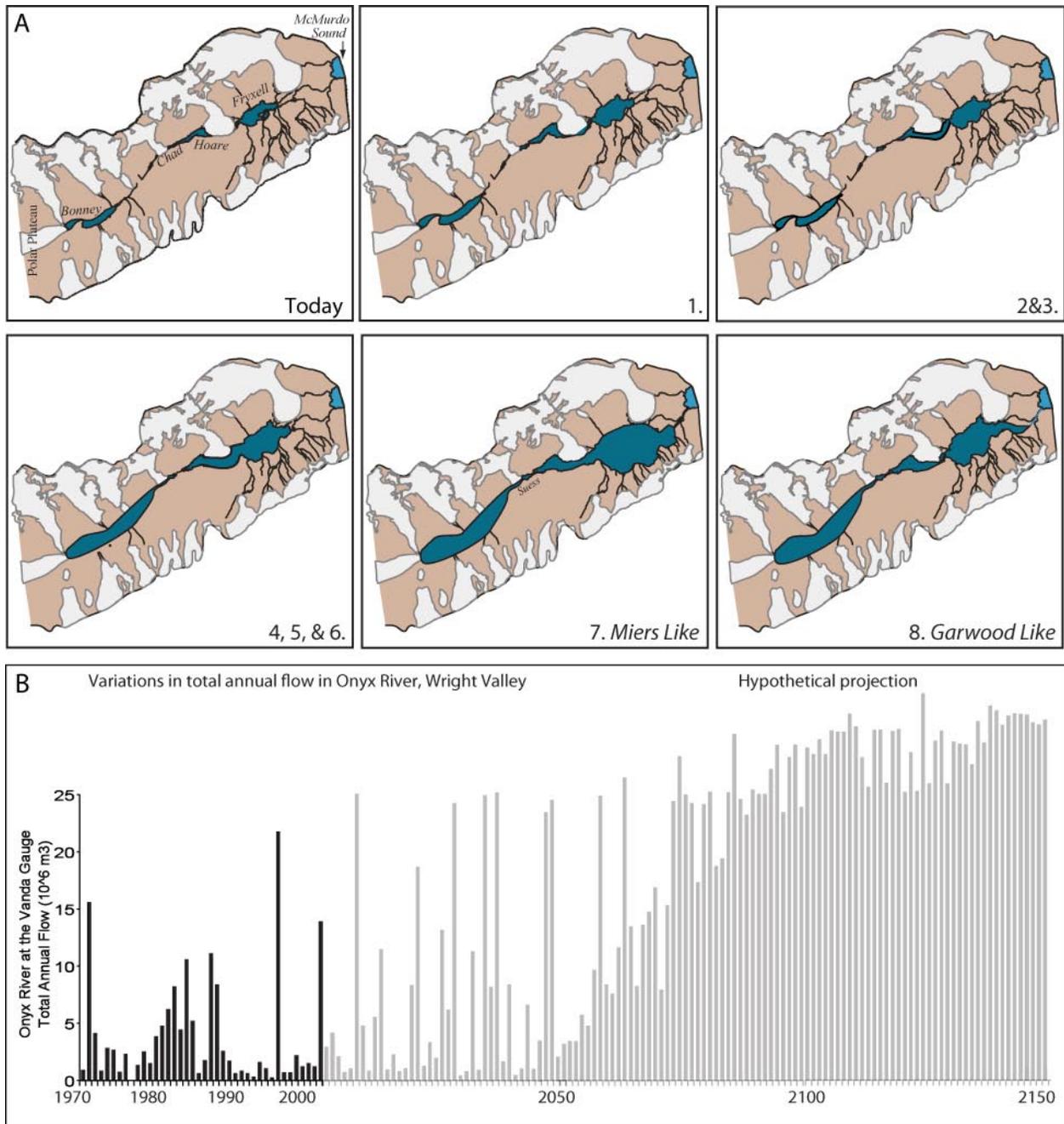


Figure 16. (A) Hypothetical sequence of changes in Taylor Valley under prolonged warming. (B) Projected Onyx River total annual flows; the pattern during 1990-2010 is projected to persist for the duration of the ozone hole (~2011 to 2060). Afterwards the current “high flows” may become common.

unusual climate conditions: (1) low 500 mb geopotential heights, (2) high incoming shortwave radiation associated with low total column ozone concentrations over the valleys in November-December, and (3) low glacier albedo associated with frequent katabatic winds in December and January. These katabatic winds deposited significant amounts of sediment on the glaciers and lake ice. Unlike the ice sheet forming the Polar Plateau, where high shortwave radiation is reflected by snow and ice, shortwave radiation in the MDV is absorbed by the ice-free valley floor, and by glaciers and lake ice darkened by dust deposition. In concert with our observations (**Fig. 6**), these climate patterns suggest that high stream flow and increased frequency of katabatic winds will co-occur. Thus, during MCM4 and in the following two decades we expect that the frequency of pulse events will be controlled by the interplay between (1) continent-wide, springtime stratospheric ozone influences leading to cooler summers and (2) localized valley-wide, late spring/summer stratospheric ozone depletion leading to high incoming shortwave radiation.

The mean summertime conditions of the past, which caused gradual lake level rise, are not likely to occur while the ozone hole persists (**Figs. 15, 16**). However, when the ozone hole diminishes due to degradation of CFCs, high stream flows will eventually become dominant and lake level rise will be sustained, leading to expansion of lakes in the valley floors (**Fig. 16A**). The hypothetical Onyx River flow record (**Fig. 16B**) under the projected warming are assumed to be constrained by the elevation of source glaciers and the limited duration of continuous sunlight in the MDV. Nonetheless, the Taylor Valley lakes could coalesce into one large lake and empty to the sea in a few centuries. The sequence depicted in Fig 16A goes from the current distribution of lakes and glaciers (Today) to state 1, where levels of Lakes Bonney, Hoare, and Fryxell have increased but the lakes remain confined to separate basins, to states 2 and 3, where Lakes Hoare and Fryxell become connected, to states 4-6, where all the lakes are connected, but remain a closed-basin lake to state 7 where this large lake flows out to McMurdo Sound, draining the valley (similar to the conditions in Miers Valley), to stage 8, where thermokarst erosion at the outlet of the lake in the eastern end of the valley down-cuts the base level of the lake reaching a steady-state spill elevation (similar to conditions in Garwood Valley).

### **2.3.3. The McMurdo Dry Valleys: a Mosaic of Interconnected Landscapes.**

Here, we describe contrasts in landscape connectivity during cold and warm summers. Such changes will be mediated by variation in geography of specific valleys, which predisposes some areas to greater or lesser climate-induced changes in connectivity (e.g., H4). For example, in upper Garwood and Miers Valleys, which are smaller than Taylor and Wright Valleys, contemporary lakes occupy a larger proportion of basin area, increasing the valley-wide role of lakes on organic matter and nutrient budgets (Elberling et al. 2006; Hopkins et al. 2008). Moreover, the glaciers that feed lakes in Garwood and Miers occur at lower elevations than most of the glaciers in Taylor and Wright Valleys. Thus, regional warming could trigger earlier and greater melt pulses and stream flow in Miers and Garwood relative to Taylor and Wright Valleys (Fountain et al. 1999). Perhaps as a consequence, Lake Miers is not a closed basin lake, as are the lakes in Taylor, Wright and Victoria Valleys, but flows into McMurdo Sound through lower Miers Stream in high melt years. Thus, the physical geography and landscape history constrain hydrological connectivity and emergence of wetted habitats over multiple scales in the MDV (H4).

**The McMurdo Dry Valleys Ecosystem during a cold summer:** In cold summers, glacial melt is low and cryoconites are ice-covered and have limited connectivity with adjacent cryoconites. Consequently, much of the meltwater entering streams is derived from the steep glacier faces that receive direct sun for several hours each day and do not accumulate snow. During these summers, streams typically flow for only up to four weeks, with peak flows of only  $1 \text{ ft}^3 \text{ s}^{-1}$  ( $0.028 \text{ m}^3 \text{ s}^{-1}$ ). The depth of water covering the algal mats in stream channels may only be a few cm which is sufficient for growth of the desiccation-tolerant filamentous cyanobacteria and associated diatoms which comprise the mats (Alger et al. 1997). Even in cold summers, soil temperature will exceed freezing conditions for at least a few hours per day for several weeks (Aislabie et al. 2006; Barrett et al. 2008a), though biological activity is still constrained by low water availability (Treonis et al. 2000; Barrett et al. 2008b; Ball et al. 2009).

The direct impact of a cold summer on MDV lake ecosystems is decreased phytoplankton productivity due to high light attenuation from a thicker ice cover (which has reached 7m) (Doran et al. 2002b). The ice-cover on the lakes is maintained by the ice-freezing on the bottom of the ice-cover and ablation on the surface (Adams et al. 1998). Because the rate of ablation is greater under warm sunny conditions, the long-term impact of several years of cold conditions is an increase in ice thickness, further attenuating light availability. Steady decreases in lake level also occur because ablation losses are not matched by incoming streamflow. Another indirect influence of cold summers is decreased stream nutrient loading, which increases the importance of relict nutrients diffusing upward from deeper zones in supporting phytoplankton and bacterioplankton production (Priscu 1995; Takacs et al. 2001). In fact, P:R ratios in the water columns of MDV lakes are  $< 1$  implying that light limitation is so severe that ancient carbon is supporting much of the present day heterotrophic activity (Priscu et al. 1999). Relatively low stream nutrient loads from 1992 through 2001 were presumably responsible for the changes observed in phytoplankton diversity during this time (Tursich 2002).

**The McMurdo Dry Valleys Ecosystem during a warm summer:** During extended periods of unusually warm summer weather, meltwater generation and transport from the surface of glaciers increases dramatically, resulting in record stream flow (Jaros 2003), rapid lake-level rise (Doran et al. 2008) and increased sediment and nutrient loads to lakes (Foreman et al. 2004). On the glaciers, cryoconite holes may expand and increase connectivity with other cryoconite holes (Fountain et al. 2004), activating supra-glacial stream networks and greatly accelerating melt and transport of water to dry valley streams.

During warm summers, the soils warm and permafrost may melt rapidly enough to generate seeps seen as wet patches on the landscape (Lyons et al. 2005). Enhanced belowground connectivity can occur at spatial scales of meters, where subsurface melt contributes to greater soil water availability (Gooseff et al. 2003). Melting of snowfields or ground ice can also drive subsurface flows that emerge as large seeps some distance away depending upon topography (Lyons et al. 2005; Harris et al. 2007). For example, during the summers of 2001-02 and 2008-09, melting of large snow packs and subsurface ice in the Kurki Hills, approximately 0.5 km uphill from a long-term soil monitoring experiment, resulted in both overland flow and flow in a relict stream channel (Simmons et al. 2009a, **Fig. 5**). These events altered the geochemical conditions of the soils (Lyons et al. 2005; Harris et al. 2007). Further, the reactivated wetland had distinctive biota (Barrett et al. 2008b; Simmons et al. 2009) and cyanobacterial mats emerged in the stream channel, indicating that the biotic response to increased connectivity was rapid.

High stream flows can cause the lake levels to rebound, gaining back in one summer the decrease in level that occurred progressively over more than a decade (Doran et al. 2008, **Fig. 15**). The key biogeochemical influence is that the lakes receive a surge of suspended sediments and freshly mobilized nutrients from the streams while also diluting chloride concentrations (Foreman et al. 2004; Barrett et al. 2008b). During high flow summers, production initially decreases because of increased turbidity, but in following years the nutrients drive greater phytoplankton growth after the sediments settle to the bottom (**Fig. 9**). The lake ice-cover also thins during high flow as the result of (1) bottom melting caused by the elevated heat flux associated with streamwater entering the lake and (2) increased ablation at the surface caused by sediment deposition associated with the greater frequency of katabatic winds (**Fig. 6**).

## 2. 4. RESEARCH PLAN

The hypotheses for MCM4, founded on results from MCM1-3, provide a logical progression for evaluating how climate warming in the MDV will amplify connectivity across the landscape. We will employ a multifaceted approach, including monitoring, experiments and ecological models. Monitoring and experimental methods can be found at [http://www.mcmlter.org/data\\_methods2.htm](http://www.mcmlter.org/data_methods2.htm). The relationship between our hypotheses and the research plan are summarized below and in **Table 1**.

### 2.4.1. Pulses and connectivity (H1).

Hypothesis 1 addresses the role of pulsed events (liquid water and wind) on connectivity across landscape units, and how this connectivity influences ecosystem structure and function. Our extensive network of

**Table 1. Relationship of Research Plan to MCM4 Hypotheses**

Hypothesis	MCM4 Activities
<p><b>H1. Pulse events (wind and melt) increase hydrological and biological connectivity across landscape units</b></p>	<p><u>Monitoring:</u> met stations; <i>in situ</i> stream, soil, aeolian particle counters, and lake sensors; glacier mass balance; glacial sediments/cryoconites; stream flow; lake level and lake ice variations; lake chemistry and biological activity; focused sampling along environmental gradients; time-series lake sediment traps; expansion to Miers and Garwood Valleys; aeolian traps ; soil active layer monitoring</p> <p><u>Experiments:</u> surface and subsurface soil wetting experiments; lakewater enrichment experiments; metagenomic analysis across landscapes</p> <p><u>Modeling:</u> valley scale mechanistic transport models that include both routing of meltwater from the glaciers through the streams to the lakes, formation of new wetland systems, and aeolian transport of sediment onto glaciers and lake ice during strong katabatic wind events</p>
<p><b>H2. Summer pulses of liquid water produce transient moist habitats with altered biological diversity and ecological complexity</b></p>	<p><u>Monitoring:</u> meteorological stations; <i>in situ</i> stream; soil and lake sensors; glacier mass balance; geochemistry/biology of cryoconite holes; soil active layer monitoring</p> <p><u>Experiments:</u> surface and subsurface soil wetting experiments; lakewater enrichment experiments; experiments to determine adaptive response of biota to climate driven hydrology; ongoing soil stoichiometry experiments; bacteria and invertebrate density in margin habitats; phylogeny/function via metagenomic analysis; production/respiration rates; landscape specific stoichiometry</p> <p><u>Modeling:</u> As described for H1</p>
<p><b>H3. Increased connectivity enhances rate, variance and the coupling of biogeochemical processes across the landscape.</b></p>	<p><u>Monitoring:</u> As in H1 with the addition of: C:N:P ratios and metagenomic analyses (phylogeny/function) measured on material collected over an annual cycle in the aeolian and lake traps and related to stoichiometry and phylogeny from potential source pools (e.g., wetted soils, stream mats, lake mats); expansion to Miers and Garwood Valleys; geochemistry/biology of cryoconite holes</p> <p><u>Experiments:</u> surface and subsurface soil wetting experiments; lakewater enrichment experiments; experiments to determine adaptive response of biota to climate driven hydrology; ongoing soil stoichiometry experiments; biomass of bacteria and invertebrates across landscape units, and rates of NPP and respiration under both dry and wet conditions and under experimentally modified soils</p> <p><u>Modeling:</u> As described for H1</p>
<p><b>H4. Emergence of wetted habitats varies with local geography and history of landscape development.</b></p>	<p><u>Monitoring:</u> Quickbird imagery; <i>in situ</i> sensors; telemetry to define locations of new wetland habitats; mapping, image analysis of buried ice and groundwater seeps</p> <p><u>Modeling:</u> As in H1 but refined to include permafrost melt</p>

meteorological stations within and beyond Taylor Valley provides high spatial and temporal resolution on the climatic conditions that define previous pulse events (e.g., high wind, warm temperature). One of the greatest surprises of our work to date is the rapid response of the ecosystem components in the MDV to large increases in the flux of liquid water. In MCM4 we will deploy a network of *in situ* stream, soil and lake sensors to characterize the expression of these pulse events within the different landscape units. We will also conduct new manipulative experiments to examine the ecological and biogeochemical responses of individual ecosystem components during simulated pulses. These experiments will include sustained soil wetting experiments that will reveal the response of soil invertebrates and microbes to the reactivation of dormant wetlands, and new lake bioassay experiments that will examine phytoplankton and bacterioplankton responses to addition of glacial meltwater, stream water, soils, and aeolian sediment. These experiments will extend our results from long term experiments in soil (Simmons et al. 2009) and studies of soil and stream communities in a channel that was experimentally reactivated in MCM1. Coupled with sampling along environmental gradients and at aquatic-terrestrial ecotones, these experiments will test hypotheses about how connectivity controls habitat suitability (e.g., biodiversity) and ecosystem functioning. These monitoring and experimental results will be synthesized and extended forward in time by development of valley scale mechanistic models that include routing of meltwater from the glaciers through the streams to the lakes, formation of new wetland systems, and aeolian transport of sediment onto glaciers and lake ice during strong katabatic wind events.

#### **2.4.2. Pulses of liquid water expand habitat space and alters ecosystem structure and function (H2).**

In concert with the soil measurements described above, we will measure biological complexity in selected landscape units using metagenomic tools, direct counts of biomass of bacteria and invertebrates, and rates of production and respiration under experimentally altered moisture and nutrient conditions. Particulate organic C:N:P stoichiometry will also be measured and related to phylogenetic diversity, the presence of functional genes, and DNA copy number. These measurements will allow us to evaluate the biogeochemical role and evolutionary response of biota to climate driven connectivity through increases in soil moisture and in margin habitats. These measurements will also allow for the eventual incorporation of ecosystem processes into the transport model for climate driven changes in connectivity.

#### **2.4.3. Connectivity enhances the coupling of biogeochemical processes across the landscape (H3).**

We will fully integrate Sensit<sup>tm</sup> particle sensors and aeolian traps into our meteorological station network allowing us to examine particle count, and kinetic energy of particles at selected heights. Particulate organic C:N:P ratios and metagenomic analyses (phylogeny/function) will be measured on material collected over an annual cycle in the traps and related to stoichiometry and phylogeny from potential source pools (e.g., wetted soils, stream mats, lake mats). These measurements will allow us to determine the extent to which large wind events increase connectivity in phylogenetic and metabolic diversity across the landscape. With our continued measurements of glacial mass balance, stream flow, lake levels and benthic lake flux we will be able to link gradual and pulsed changes in climate variables to nutrient loads within each lake basin. As noted previously, the phytoplankton in the lakes, are strongly nutrient deficient (by P or a combination of N+P). We will conduct nutrient bioassay experiments in early and late summer on lake surface waters (1 m beneath the ice) to determine the influence of hydrologic connectivity on phytoplankton and bacterioplankton productivity (using <sup>14</sup>C<sub>2</sub>O<sub>2</sub> and <sup>3</sup>H-thymidine incorporation, respectively). Glacial melt water, stream water, soil and aeolian sediment leachate, and controlled additions of N and P will be used as the inocula in these experiments. The metagenome will be examined in these treatments to determine the influence of landscape connectivity on potential changes in biodiversity and metabolic potential. The metagenome and elemental stoichiometry will also be measured on stream and stream margin habitats during early summer before liquid water is present and in late summer when the streams have been flowing for a month or more. Finally, we will refine our sediment flux measurements in east and west Lake Bonney to include metagenomic analysis, and C:N:P ratios on samples collected every 3 weeks over the annual cycle using McLane time-series sediment traps deployed just above the bottom. These benthic flux measurements will provide an endpoint for characterizing climate driven changes in connectivity within the ecosystem.

#### **2.4.4. Emergence of wetted habitats varies with local geography and history of landscape development (H4).**

Taylor Valley has been the focus of most of the past MCM research and the three major lake basins of this valley each contain glaciers, streams and lakes with various geomorphologies, geochemistries and biology, providing an ideal background to test this hypothesis. We will use our detailed mapping resources (e.g., LIDAR) and Quickbird imagery to define projected locations of potentially new wetland habitats. This will be done by locating permanent snow patches from the photos, adding our previously collected information on buried ice and “groundwater” seeps (Harris et al. 2007) and utilizing depth to permafrost information. These locations will then be sampled for water content, geochemistry, organic matter (C:N:P), and phylogenetic/functional diversity using metagenomic analysis during cold and warm summers to compare the influence of climate on these processes. Models will be developed to quantify landscape connectivity and will include permafrost melt. These models will be evaluated using monitoring data and satellite imagery. Along with our focus on Taylor Valley, annual observations of wetted areas using satellite imagery will be made in Wright and Miers Valleys to support inter-valley comparisons of the appearance of newly wetted areas.

### **2.5. LONG-TERM MONITORING**

We have developed an extensive monitoring network of meteorological stations, stream gauges, and lake stations across Beacon, Victoria, and Wright Valleys, with the greatest density located in Taylor Valley (see **Fig. 2**). With our focus on connectivity in MCM4, we are proposing to extend our research to two southern valleys (Miers and Garwood) so that we can examine our hypotheses in a broader landscape context. We have chosen these two valleys because they have unique characteristics that will help us understand the potential future conditions in Taylor Valley. As noted previously, Lake Miers is not a closed basin lake but a “flow through” system. Both the Lake Miers outlet and the Garwood Stream flow directly into the ocean (**Fig. 10**). Currently only one small stream in Taylor Valley (Commonwealth Stream) flows into the McMurdo Sound (and it does not come from a lake). As the climate continues to warm and the lakes within Taylor Valley coalesce, the resulting merged lake will flow into McMurdo Sound (**Fig. 16**). Therefore, both Miers and Garwood Valley streams are analogues for potential future conditions in Taylor Valley. Miers Stream is an especially appropriate analogy because Lake Miers acts like a bioreactor for incoming stream flow exerting an important influence on the outflowing water—similar to what Anthropocene Lake Washburn will have in Taylor Valley (**Fig. 16**). As such, we are proposing the redistribution of some resources to accomplish our new goals, while continuing to collect several key long-term data sets. In addition, we are proposing three new integrated monitoring activities: (1) metagenomics of organisms across landscape units and valleys (see section 2.7.4.), (2) aeolian material fluxes using automated acoustic particle counters, building on recent short-term monitoring activities, and (3) soil active layer monitoring.

#### **2.5.1. Meteorology.**

MCM currently maintains 12 permanent meteorological stations: 1 in Beacon Valley, 8 in Taylor Valley (W-E: Taylor Glacier, Lakes Bonney and Hoare, Howard Glacier, Canada Glacier, Lake Fryxell, Commonwealth Glacier, and Explorer’s Cove), 2 in Wright Valley (W-E: Lakes Vanda and Brownworth), and 1 in Victoria Valley (Lake Vida). MCM also maintain 4-5 temporary/roving meteorological stations that have been dedicated to short-term experiments or monitoring. We propose to redeploy the Beacon Valley station (collaborator R. Sletten, has deployed a station in Beacon Valley and will provide us with data from this site) along with 3 new meteorological stations to measure inter-valley trends as follows: 1 in Miers Valley, adjacent to Lake Miers (78°6’S), 1 in Garwood Valley (77°9’S) in a mid-valley position, and 1 at an elevated site between these two valleys to characterize gradients in meteorological properties with elevation (*sensu* Doran et al. 2002b). Other sites will be maintained.

#### **2.5.2. Lakes.**

Our lake monitoring efforts are comprised of three activities: (1) maintaining monitoring equipment which collects stage, ablation, ice thickness, surface PAR and underice PAR data continuously, (2) “limno runs”, in which water column physical, chemical and biological rate measurements are made at

high depth resolution, and (3) monitoring benthic mat biomass, productivity, and biogeochemistry. Given the addition of Lake Miers to our monitoring program and the addition of other new activities on streams, we have carefully evaluated our lake monitoring activities and will curtail some of them. This includes reducing the frequency of sampling of deep water in the limno runs and reducing the annual frequency of limno runs in the Taylor Valley lakes. We will continue to maintain monitoring equipment and conduct limno runs at Lake Bonney (E and W lobes) and Lake Fryxell (in Taylor Valley) and will move monitoring equipment from Lake Hoare to Lake Miers; limno runs will be discontinued at Lake Hoare and initiated at Lake Miers.

Benthic mat monitoring will continue at Lake Fryxell and will be initiated at Lake Miers. Preliminary data from Lake Miers shows that it does not have a strong chemocline, which is typical in Taylor Valley lakes, and the highest phytoplankton productivity occurs just above the bottom (~20 m beneath the surface of the ice at a PAR level ~ 0.1% of incident; Fig. 10).

### **2.5.3. Streams.**

Our long-term stream database is composed of three parts: (1) hydrology, (2) chemistry, and (3) algal mat surveys. We currently maintain 16 stream gauges in Taylor (14) and Wright (2) Valleys. The two gauges on the Onyx River (Wright Valley) are associated with the longest continuously gathered environmental records in Antarctica (since 1968), and will continue to be maintained. In Taylor Valley, we propose removing two gauges (House Stream and Lost Seal Stream) due to the logistical challenges of acquiring reliable records from these sites. We will establish 3 gauges in Miers Valley (2 in streams above Lake Miers, one in the outlet stream) and one gauge in Garwood Valley. Samples for stream chemistry will be collected at routine intervals at each stream gauge (major ions, alkalinity, DOC, pH, etc.) with higher frequency collections made during high pulsed flow periods. We have conducted surveys of benthic algal mats in Canada Stream, Aiken Creek, Von Guerard Stream (upper and lower), Delta Stream (upper and lower), and Green Creek every 3 years for the past 15 years. We will expand our algal mat monitoring by establishing new survey sites in Miers and Garwood Valleys to obtain algal biomass and morphotype/phyloptype distribution across a latitudinal gradient in valleys representing different ages and geochemistries within the MDV.

### **2.5.4. Soils.**

We will maintain long-term studies of soil biodiversity and biogeochemical processes in soils of Taylor Valley and extend monitoring activities to Miers and Garwood Valleys. An elevational transect (established in 1993) and control plots in ongoing experiments such as the biotic effects experiment (established 1999) and long term manipulation experiment (established 1993) are the core of MCM soil monitoring in which invertebrate communities, microbial biomass, soil chemistry and soil respiration are measured on 2 to 3 year rotations (e.g. Porazinska et al. 2002; Ayres et al. 2008; Barrett et al. 2008a, b; Simmons et al. 2009). The Lake Bonney catchment, site of previous warming pulses, will have permanent transects established to determine the long term effect of increased water connectivity on biotic and soil-sediment variability across the landscape. New soil monitoring plots will be established in Miers and Garwood Valleys to enhance our understanding of long-term soil dynamics in warmer valleys and to help us predict what may occur in Taylor Valley as climate warms. Additionally, we will establish a new monitoring study of moss and algal ground cover and production in near-stream environments and dry soils using similar protocol to the stream algal mat surveys described above. Such information is essential to refine C models for dry valleys soils (Burkins et al. 2001; Barrett et al. 2005; 2006a; Hopkins et al. 2008) and work toward closing the dry valley organic matter budget (**Fig. 14**).

### **2.5.5. Glaciers and Active Layer/Permafrost.**

The mass balance of the Canada, Commonwealth, Howard, Suess, Hughes, and Taylor Glaciers (all in Taylor Valley) have been measured on an annual basis since the inception of the MCM. We will continue a subset of these measurements and add three more glaciers – Adams and Miers Glaciers in Miers Valley, and Garwood Glacier in Garwood Valley to gain a latitudinal perspective of the response of glacial mass to climate variables. Studies conducted before the advent of the MCM along with detailed research in

MCM2 and MCM3 revealed that cryoconite holes contain copious amounts of liquid water during the summer months (Fountain et al. 2004; 2005). These systems provide a novel habitat in what would otherwise appear to be an inhospitable environment that nurtures wind-blown organisms from across the MDV (Christner et al. 2003) and are “hotspots” for biogeochemical activity (Foreman et al. 2007) (**Fig. 13**). Much of the geochemistry in glacial melt has been modified by microbially mediated weathering reactions within these cryoconite holes, which cover about 10% of the ablation area of most alpine glaciers in the MDV (Fountain et al. 2004). Consequently, cryoconite holes play a major role in the climate driven connectivity between glaciers, streams and lakes. Measurements of primary and bacterial productivity, phylogeny/physiology (using a metagenomic approach), chemistry, chlorophyll-a, bacterial cell density and invertebrate density will be made on 3 cryoconites holes from the Commonwealth Glacier (Fryxell basin), Taylor Glacier (Bonney basin) and Adams Glacier (Miers basin) when liquid water is present (December-January) in each year of MCM4. These data will allow us to assess biological and biogeochemical connectivity cause by both wind and liquid water driven events.

Active layer/shallow permafrost monitoring sites will be established at four locations in accordance with the protocols used in the International Arctic Tundra Experiment project (Molau and Molgaard 1996), as implemented in northern Victoria Land, Antarctica (Guglielmin 2006). These sites will be established in Miers Valley, Garwood Valley, and two locations in each of Taylor and Wright Valleys, in close association with meteorological stations and ongoing and planned long-term soils studies. We will also deploy temperature monitoring arrays in streambeds near selected stream gauges to monitor the temporal evolution of the hyporheic zone (saturated active layer under streams).

## **2.6. CONTINUING LONG-TERM EXPERIMENTS**

To address hypotheses in previous proposals, several long-term experiments were initiated that provided us with important information toward our understanding of changes in connectivity in the MDV; these continuing experiments described below will help us address our hypotheses in MCM4.

### **2.6.1. Relict Channel Reactivation (established in 1995).**

In MCM1, we initiated a long-term full scale “reactivation” of a stream channel which is pertinent to the hypotheses of MCM4, as we predict actual reactivation of relict channels as the climate warms (**Fig. 17**). In January 1995 we routed water to a relict channel which had last flowed in 1969 based on aerial photography of Taylor Valley. Within a few days of wetting, dormant algal mats began growing rapidly and had higher rates of net primary productivity than mats in streams with regular summer flow, due to greater solute and nutrient concentrations in the relict channel, similarly rates of N<sub>2</sub>-fixation were also greater in the relict channel compared to other streams (McKnight et al. 2007). This experiment revealed that algal mats can survive desiccation for long periods and respond quickly to hydration. In the first warm summer of the past decade, the surge in meltwater scoured the streambed above the diversion structure (a sand bag wall), routing even more water to the relict channel and making the reactivation more permanent. In MCM3 we explored the relationships between habitat and dispersal controls on biodiversity of invertebrates and microbial mats as well as ecosystem function. Biogeochemical and biodiversity measurements made in the relict channel during a cold and a warm summer showed that the stream invertebrates are not only more abundant in the cold summer, but that they preferentially occupy the microbial mats. Conversely, under high flows the invertebrates are more abundant in the underlying sediments than in the mats, even though organic content of the mat was generally unchanged. These results indicate a strong physical control on the stream ecosystem interactions.

In MCM4 we will continue to study microbial mats and invertebrate interactions at the seven established sites in the relict channel, representing decreasing extents of hydration during the cold summers of the late 90’s. We will measure (1) microbial processes (NPP and N<sub>2</sub>-fixation), (2) algal species diversity using microscopic and molecular techniques, (3) C:N:P in the mats, (4) stream channel and hyporheic zone water chemistry, and (5) variations in the abundance and distribution of nematodes, tardigrades and rotifers in soil/stream transects. N and P uptake at the stream scale will be measured by conducting nutrient tracer experiments (Koch et al. 2009).

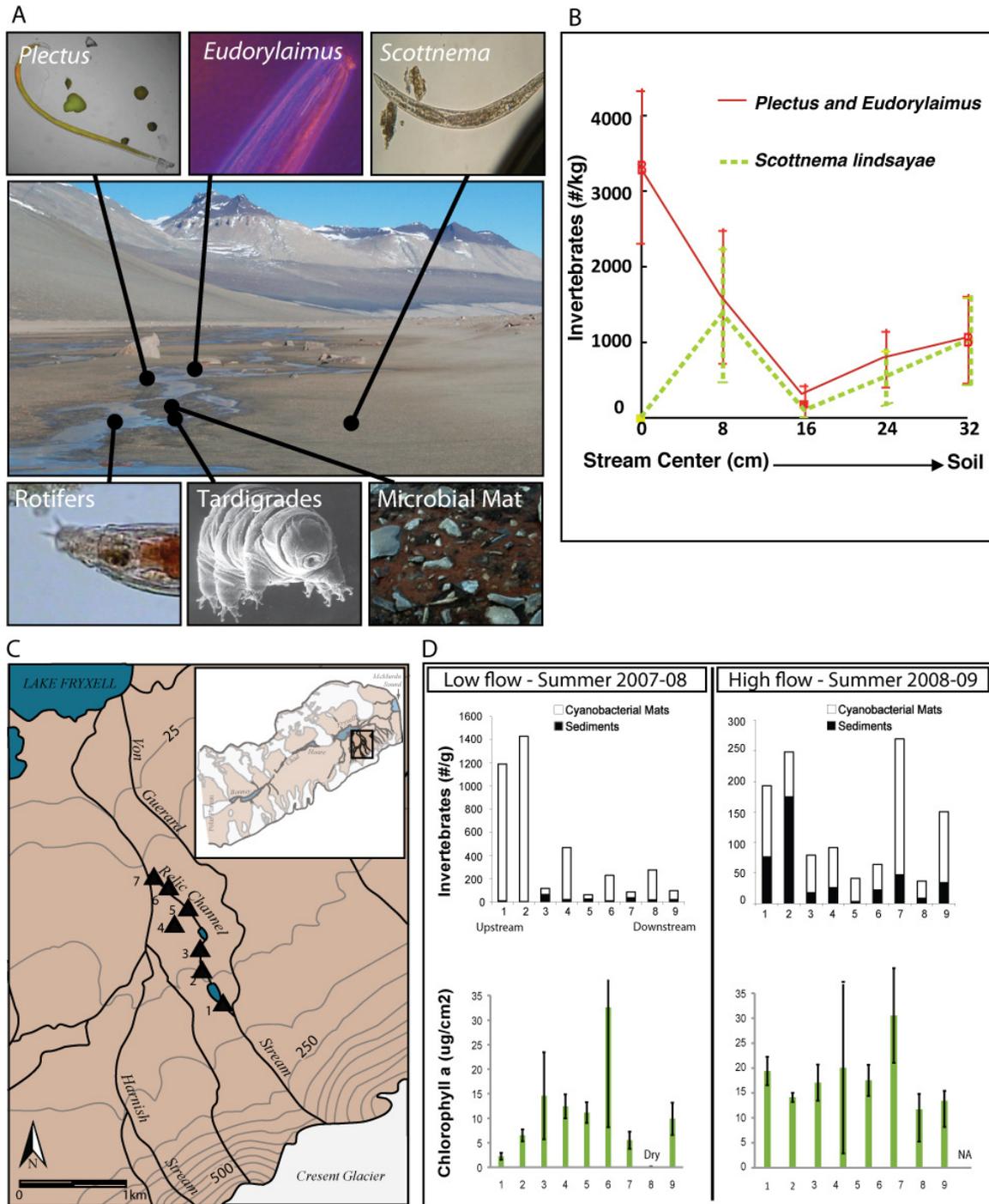


Figure 17. Changes in invertebrates and microbial mats in the Relict Channel Reactivation Experiment. (A) Habitat preferences of invertebrates in dry valley stream.s. (B) Variation in abundance of invertebrates with distance from stream center. (C) Site map, site 1 is just below diversion. (D) Changes in invertebrate abundance in cyanobacterial mats and sediments between low flow and high flow summers; high flows suppressed invertebrate abundance in mats despite similar chlorophyll-a content.

## 2.6.2 Stoichiometry Experiment (established in 2007).

We established a multiple nutrient addition experiment to examine how biotic responses to nutrient addition are constrained by landscape history and environmental stoichiometry, i.e., soil N:P ratios. We manipulated C, N and P availability at two sites in Taylor Valley, one near Lake Fryxell where soils have high levels of bulk P and soluble phosphate and one near Lake Bonney where soils have low concentrations of P and moderate to high concentrations of nitrate. We used factorial additions of mannitol, N as  $\text{NH}_4\text{NO}_3$ , and  $\text{PO}_4^{3-}$  administered in solution at molar ratios of 100:10:1 C:N:P in 1 m<sup>2</sup> replicated plots. Rates of *in situ* soil respiration, microbial biomass and populations and of invertebrates have been examined bi-annually. This stoichiometry experiment will be continued in MCM4 with some modifications (described below) to address H2 and H3 and provide valuable information on the influence of changes in hydrological connectivity on biogeochemical cycling and biotic activity.

## 2.7. NEW EXPERIMENTS

### 2.7.1. Hydrological Connectivity in Terrestrial Ecosystems (H1-H4).

Our working hypotheses focus on climate driven changes in the hydrological linkages among soil and aquatic landscapes and the responses of resident biota and associated biogeochemical processes to these changes. We propose to manipulate movement of water across dry valley landscapes in an experiment designed to test all of our working hypotheses. To manipulate soil moisture, we propose simulating snow melt, surface run-off, and in the subsurface to simulate melting of permafrost, buried ice, and subsequent subsurface flow. Our previous research in western Taylor Valley studying a flood event during the summer of 2008-09 allowed us to examine the effects of enhanced connectivity between aquatic and terrestrial environments and the resulting change in soil biota (Fig.5). However, limited observations from before the flood constrain interpretation of these data. Therefore, these new studies are designed to increase surface soil water availability and movement in a controlled manner through diversion of stream waters during high-flow conditions in mid-January (similar to approach used in relict channel study), and to increase subsurface water availability (simulated permafrost melt) through trenching and water additions. Moisture increases are predicted to improve soil habitat suitability, but this response may be modified by redistribution of salts and by soil microclimates (e.g., Gooseff et al. 2003). Consequently this experiment will be conducted at locations differing in soil salinity and soil C:N, C:P and N:P ratios. We will establish control, surface, and subsurface moisture augmentation plots near Lake Fryxell (low salinity, high C and P) and Lake Bonney (moderate salinity, low C and P) where the long-term stoichiometry experiments described above (section 2.6.2.) are in progress.

### 2.7.2. Soil Moisture Augmentation (H1, H2 and H3).

Our previous water addition experiments (LTM and BEE) have used single seasonal applications to small plots during the middle of the summer. This new experiment will provide a prolonged application of water diverted from streams to larger plots to (1) take into account the important influence of soil heterogeneity on ecosystem response to moisture increases, and (2) provide more opportunity for soil excavation to examine variation in response variables at different depths. This approach is a better simulation of the changed hydrology we observed during the 2001-02 and 2008-09 summers. Plots will be established in the first year of the project for pre-treatment measurements and to install soil probes to continuously monitor temperature and moisture and salinity and for baseline measurements of chemistry, biota, and ecosystem function. Following water application these variables will be measured each year from spatially referenced positions at appropriately spaced intervals down slope. Water will be applied during mid-summer while streams are flowing and soil temperatures have reached their maximum seasonal levels (~10°C). Three plots (7.5 by 15 m) will be established at each site on moderate slopes. Water will be diverted from an adjacent stream onto the soil surface at the upper end of the plot (7.5-m reach), or applied in a narrow 5-m long trench dug to the depth of permafrost and water applied to the top of the permafrost layer. We will record the temperature and estimate the volume of the applied water to the plots to account for thermal effects. This experiment will directly address H2 and H3 by providing information on soil moisture dynamics and linkages to salinity and biota, helping us to define habitat suitability during increased connectivity caused by a changing climate. We know little about subsurface

flow in dry valley soils and results from this experiment will also address H4 and be used in the hydrologic modeling of soil connections to streams and lakes.

### **2.7.3. Aeolian Connectivity Across Soil, Glacial and Lake Ecosystems (H1, H3).**

We will test the influence of aeolian sediment transfer on hydrological and biogeochemical connectivity with a sediment addition experiment designed to examine the influence of sediment loading on meltwater generation, geochemistry and biological complexity, especially in cryoconite holes (**Fig. 13**). In the nutrient deficient environment of the MDV, we contend that aeolian transfer plays a key role in ecosystem structure and function (H1, H3). We propose to apply soil material to ice surfaces on the Canada Glacier and the surface ice of Lake Fryxell in lower Taylor Valley, at a rate of sediment accumulation that has been observed on soil surfaces in the dry valleys (Nkem et al. 2006a; Jepsen et al. in press). Soils will be collected from locations in lower and upper Taylor Valley having distinct C:N:P ratios (Lyons et al. 2003; Barrett et al. 2007). Surface soils will be collected and sieved (<63  $\mu\text{m}$ ) to isolate the fraction most commonly transported by wind (Lancaster 2002; Sabacka and Priscu 2009) and applied to two 100 m<sup>2</sup> plots on the Canada Glacier and surface ice of Lake Fryxell. Adjacent control plots will also be delineated at each of these locations to serve as a reference for ongoing study. Subsamples of the pre-distributed sediments will be examined for biogeochemical (soluble nutrients, major ions, pH, DOC, POC) and biological (biomass and metagenomic) characteristics (Porazinska et al. 2004; Priscu et al. 2005; Tranter et al. 2005; Foreman et al. 2007).

Before sediment application, we will characterize the biogeochemical characteristics and biota of the ice, seasonal melt-water, and sediments, as well as the ablation rate of the ice on the glacial and lake surfaces (Priscu et al. 1998; Fountain et al. 2006). Melt-water chemistry of these plots will be monitored for 2 years to establish a reliable baseline, before sediments are applied with a hand-held grass seed spreader to achieve uniform deposition (*sensu* Jepsen et al. in press). After application of the simulated aeolian sediment, we will monitor the biogeochemical characteristics and biological composition (as above) of the ice and associated melt-water (melt-water flow, cryoconite hole water, lake ice melt) for two summers. We will track ablation rates to evaluate difference relative to pre-treatment and reference plots. We expect that solar heating of the sediments will increase melt-water generation, form surface and subsurface ice pools, and then cryoconites (e.g., Adams et al. 1998; Fritsen et al. 1998; Fountain et al. 2004). Initially, these will reflect the geochemical and biotic characteristics of the deposited sediment (e.g., Gordon et al. 2000; Lyons et al. 2003; Barrett et al. 2007). Over time, these test plots are expected to generate a melt-water habitat with a unique biogeochemical and biotic signature that may eventually be transported to other landscape units via ablation, glacier melt-water generation, stream water flow and melting through the lake ice to the water column of the lakes (Priscu et al. 2005; Barrett et al. 2007).

### **2.7.4. Responses of Biota to Enhanced Biogeochemical Connectivity (H2, H3).**

The diversity and abundance of biota in the MDV reflects both biotic and abiotic drivers (Lisle and Priscu 2004; Takacs et al. 2001; Barrett et al. 2006a). The ecological impact of these drivers on organismal adaptation include stoichiometric and food quality constraints, which impair development of higher trophic levels and limit the development of community composition (Elser and Hamilton 2007). Ecological stoichiometry integrates across all levels of biogeochemical organization and accounts for emergent properties of ecological systems by focusing on the nutrient and energy requirements of organisms in an evolutionary framework (Sterner and Elser 2004; Elser and Hamilton 2007). Differences in relative soil N and P availability in the MDV have cascading influences in terrestrial and aquatic ecosystems. For example, low soluble P content in soils and lakewater of the Bonney basin is associated with greater activity of phosphatase enzymes in soil and lake bacteria (Zeglin et al. 2009; Dore and Priscu 2001; Barrett et al. 2007) and lower rRNA gene copy numbers in soil nematodes (Adams unpublished; **Fig. 18**). Similarly, in soils with excessive N content where N:P ratios greatly exceed biochemical stoichiometry (e.g. >100 N:P by atoms), foodwebs are truncated with no metazoan taxa evident (Barrett et al. 2006c). We will continue to use stoichiometry to examine (1) adaptations of biota to local geochemical conditions and (2) the differential responses of biota to coupled nutrient additions in soils with varying N:P ratios. This will inform our predictions about evolutionary ramifications of landscape history and

optimal life history strategies. For example, we predict that organisms in P-deficient soils and lake water will have slower growth, reduced overall P concentrations, lower RNA transcript concentrations, and lower rRNA gene copy number than their sister taxa from sites that are not P-deficient (Mulder and Elser 2009; Elser et al. 2000; 2003; Gillooly et al. 2005). Using these stoichiometric approaches with molecular tools, we plan new experiments to test the above predictions in the context of climate driven hydrological changes and redistribution of nutrients across landscape units. These experiments will directly address the following questions and associated hypotheses: What is the adaptive response of biota to climate driven hydrological changes (H2)? How do these changes cascade and/or impact biodiversity, community composition and ecosystem functioning (H2, H3)?

The first experiment identifies microbial and metazoan responses to C, N and P additions in soils. We will implement this study by leveraging the ongoing stoichiometry experiment that was initiated as part of MCM3 (see section 2.6.2), which was established to examine the effects of C, N, P and water amendments in soils with different native N and P content (**Fig. 18**). We will use this experiment to explore the ecological effects of these amendments by comparing the evolutionary responses of biota (changes in P content, life history traits, rRNA content, rDNA copy number) across these treatments. Biotic C, N and P content will be measured with a CN analyzer and wet chemistry (P), organismal (bacteria, cyanobacteria, invertebrate) biomass will be measured by microscopy and growth rates will be estimated using  $^3\text{H}$ -leucine incorporation (bacteria),  $^{14}\text{CO}_2$  incorporation (cyanobacteria) and changes in organismal density in a culture setting (invertebrates). Ribosomal RNA content and rDNA copy number will be estimated via qPCR twice per month in January over a two year period. Significant differences in response variables between treatments and controls will be identified and tested for correlations with responses in geochemistry, biodiversity, community structure and ecosystem functioning (respiration) using canonical analysis. The magnitude and direction of these changes can be used to inform models that extrapolate to predicted changes across different landscape units.

A second hydro-biogeochemical experiment will be conducted on the extremely P-deficient surface waters of east lobe Lake Bonney (Priscu 1995; Dore and Priscu 2001, **Fig. 19**), which supports populations of bacteria and microalgae (few non-photosynthetic protists and metazoans exist in this lake). Water (4 liter bottles) from 6 m will be amended with  $20\ \mu\text{M}\ \text{NH}_4^+$ ,  $2\ \mu\text{M}\ \text{PO}_4^{3-}$ , a combination of N and P, and with melted Taylor Glacier water, soil leachate and stream water (10% additions to lake water) and incubated with an unamended control *in situ* for 10 days (which approximates the doubling time of the prokaryotes and microalgae in the lake water). Changes in particulate organic P, rRNA and rDNA copy number will be made along with C, N and P content (and ratios). Productivity will be estimated using time-series  $^3\text{H}$ -leucine and  $^{14}\text{CO}_2$  incorporation as shown in **Fig. 19**.

### **2.7.5. Integrative Metagenomics (H1, H2, H3).**

Since the inception of the MCM, our hypotheses have addressed either directly or indirectly the environmental factors controlling structure (what types of organisms are found in any particular component of the landscape) and function (e.g., transformations of C, N and P) of the ecosystem. However, given the microbial nature of our system and the inability to isolate and study a majority of these organisms in pure culture, we know little about which organisms are doing what (we know next to nothing about their physiology and thus about their ecology and roles in biogeochemical cycles). To truly understand connectivity within the MDV (and hence, to address our hypotheses in MCM4), requires an understanding of the functional role of specific organisms within the environment in response to climate driven pulses and presses. This is particularly important in the MDV where legacies of past environments overprint contemporary biodiversity and associated ecosystem processes. For example, many of the contemporary nitrogen and sulfur gradients observed in the water columns of the lakes occur at depths that are not thermodynamically favorable for contemporary biogeochemistries. Presumably these gradients are legacies left behind during the climate driven evolution of the lakes when the free energy was present to support different biochemistries (e.g., Lee et al. 2004a; b; Priscu et al. 2008). If we are to understand how biodiversity begets function as climate driven connectivity increases in the MDV ecosystem, we must know which organisms respond to climate pulses and presses.

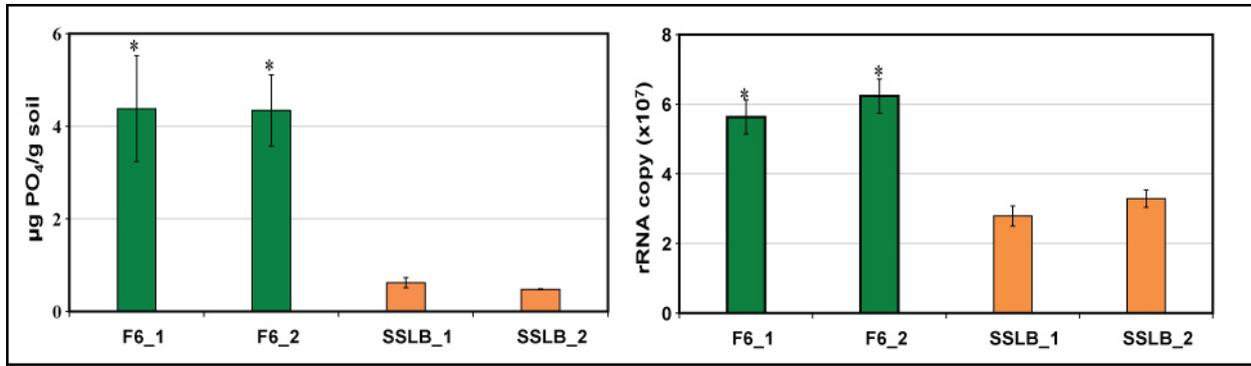


Figure 18. Geographic variation in soil N:P ratios influences life history traits of resident biota: qPCR indicates that nematodes in P-deficient soils have lower rRNA gene copy numbers than the same species in P-rich environments (Adams unpublished). This same geochemical variation constrains the carbon fixation in moat cyanobacteria communities (Fig. 19 below).

### East Lobe Bonney Moat Bioassay

### Fryxell Moat Bioassay

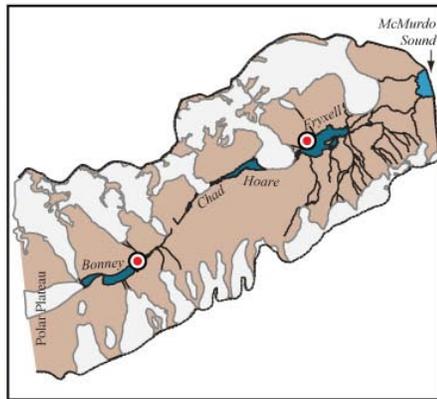
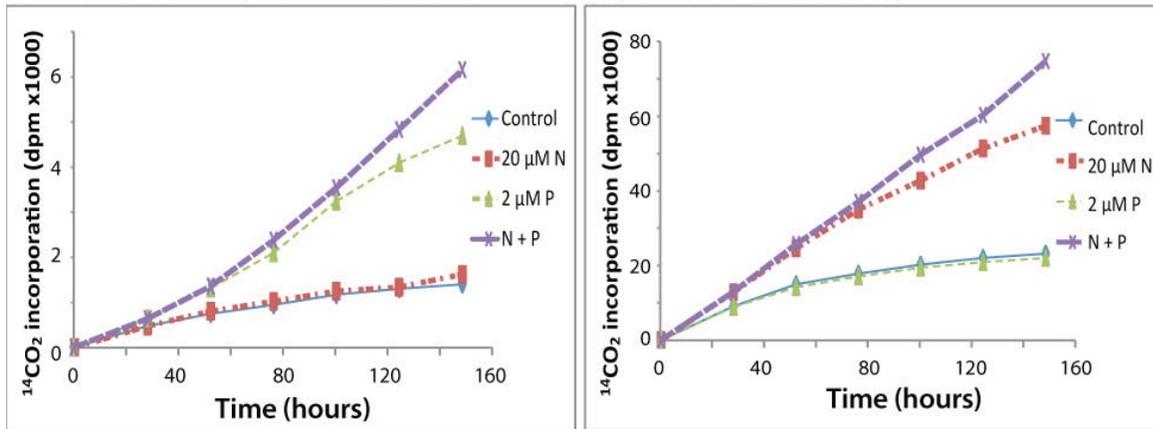


Figure 19. Results from time-course phytoplankton nutrient bioassay experiments conducted on the open moats of Lakes Bonney and Fryxell during January 2010. Phytoplankton photosynthesis was measured using <sup>14</sup>CO<sub>2</sub> incorporation into cellular material. Results indicate that Bonney is P-deficient whereas Fryxell is N-deficient. N was added as NH<sub>4</sub><sup>+</sup>, each data point represents the mean of 2 replicates. The maps show the location of the sampling sites; the moats were 0.8 m deep at the time of collection.

Previous microbial 16S and 18S rRNA gene assays in the MDV have produced a large diversity of sequences from both terrestrial and aquatic habitats (Gordon et al. 2000; Glatz et al. 2006; Barrett et al. 2006; Porazinska et al. 2009). Although bacterial 16S rRNA gene libraries contain a high proportion of unique sequences, these libraries are dominated by only a few major groups including the Bacteroidetes, Gammaproteobacteria, and Acidobacteria (Mikucki and Priscu 2007; Aislabie et al. 2007; Zeglin et al. in review). Presumably, not all detected sequences represent active populations (some may be “players” while others are “freeloaders”); very little information is known about the specific functional roles of any of these organisms *in situ*.

We propose to use a metagenomics approach to determine the metabolic potential and functional response of prokaryotic and metazoan organisms in many of the experiments described above. Inclusion of metagenomics in these experiments will provide us with a detailed phylogenetic and physiological map across the MDV ecosystem allowing us to assess which organisms are most susceptible to enhanced connectivity, and importantly, how these organisms respond to simulated connectivity within the context of our proposed experiments. Because most MDV diversity is dominated by singletons (unique sequences), we will use a comparative metagenomics approach based on 454 pyrosequencing (Margulies et al. 2005). Pyrosequencing will give us more sensitive, broader coverage of organismal diversity, enabling us to identify a greater number of taxa and predicted genes. As a participant in the MIRADA-LTER project (<http://amarallab.mbl.edu/mirada/mirada.html>), Priscu is already using pyrosequencing-based 16S and 18S rRNA gene surveys to examine the phylogeny and functionality in the lakes. Similar work has been begun by Takacs-Vesbach on dry valley soils through a new NSF grant. Results from these diversity surveys, in concert with the metagenomic responses we will be investigating in MCM4, will provide important data to compare the organismal diversity and function with other LTER sites (**Fig. 20**).

DNA will be extracted from environmental samples optimized for broad taxonomic coverage (Hall et al. 2008; Wu et al. 2009). These methods have produced high quality DNA from dry valley aquatic and soil samples of sufficient concentration for direct pyrosequencing and other molecular techniques (~ 10µg of >25 kb DNA with little visible shearing). We will distinguish potentially viable from non-viable phylotypes by performing DNA extractions of duplicate samples that have had non-viable cells chemically removed with ethidium monoazide (Nocker and Camper 2006). All sample handling and extractions will be performed in a class 100 laminar flow hood, and DNA extractions and the various steps of pyrosequencing (e.g., library construction, amplification) will be performed in separate rooms to avoid contamination. DNA sequencing will be performed on a pyrosequencer at BYU (purchased with NSF MRI grant to Adams), which currently results in sequences >400 nt long, but we expect reads up to 1000 nt by the time this work begins. We have budgeted for approximately one plate of pyrosequencing per year, which is sufficient for the experiments we propose (approximately 1,000,000 sequences). Samples will be barcoded to enable us to run all samples on one plate (Huber et al. 2007). One quarter of the plate will be reserved for 16S rRNA gene sequencing (Huber et al. 2007).

DNA sequence data will be assembled using the Newbler assembler and submitted to the MG-RAST server (<http://metagenomics.nmpdr.org/>) for automated annotation. The MG-RAST server performs gene prediction/identification, phylogenetic classification of 16S and 18S rRNA and functional genes, and metabolic classification of identified genes. Attention will be given to identifying metabolic pathways of biogeochemical significance with the aid of the metabolic map provided in MG-RAST. The bacterial phylogeny of individual samples will be compared using Amphora (Wu and Eisen 2008), which provides a diversity profile of individual metagenomic samples based on housekeeping genes. The functional profiles of the samples will be distinguished using cluster analysis of the abundance and metabolic classification of genes identified during annotation (Tringe et al. 2005). These analyses will enable us to identify the phylogeny and potential metabolic function of our environmental samples and to compare differences among control and treated samples from our experiments. Because we will be removing DNA from non-viable cells using ethidium monoazide and applying a comparative metagenomics approach, functional differences among our treatments will be detectable without using RNA based methodology (Tringe et al. 2005; Edwards et al. 2006), which would be challenging in this low activity ecosystem.

## Microbial Inventory Research Across Diverse Aquatic (MIRADA)

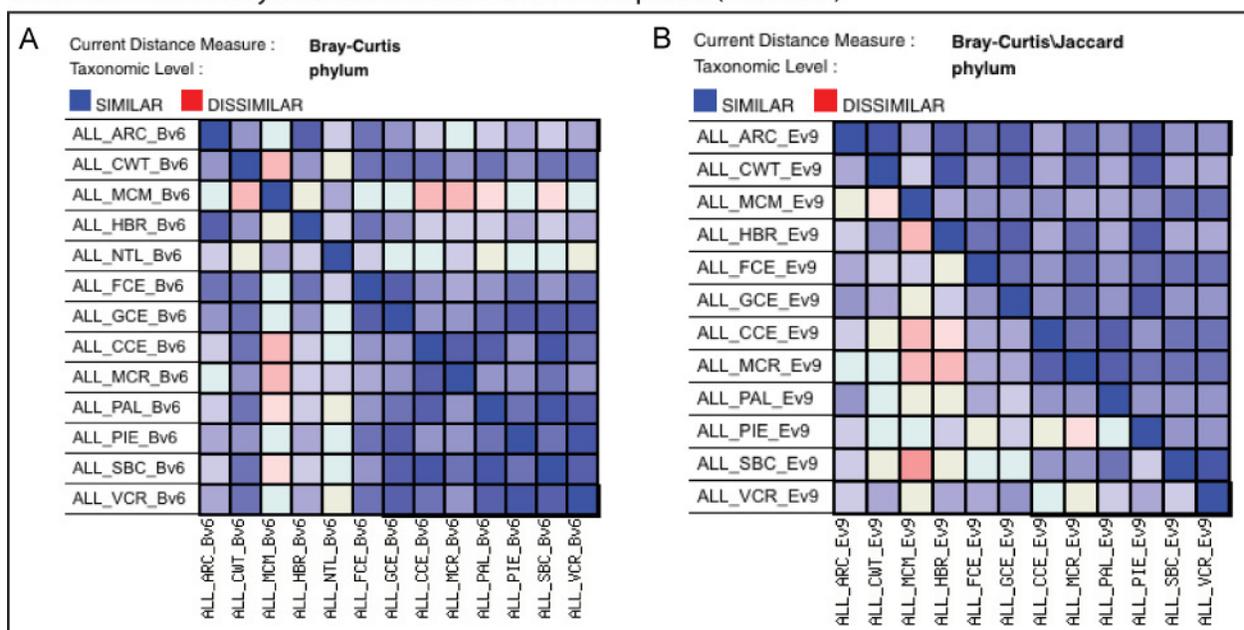


Figure 20. Heatmaps comparing phylum level distance of (A) Bacteria and (B) Eukarya across aquatic LTER sites based on 16S (Bv6, variable region 6) and 18S (Ev9, variable region 9) rRNA genes (unpublished results, Amaral-Zettler). Bray-Curtis distance is shown for Bacteria. For Eukarya Bray-Curtis is given on the left of the diagonal and Jaccard is given on the right. Data are compiled by LTER site (e.g., ALL\_MCM\_Bv6 includes all MCM bacterial samples). Data were generated through the Microbial Inventory Research Across Diverse Aquatic (MIRADA) LTERs project (Dr. Linda Amaral-Zettler, MBL) using a 454-based rDNA tag sequencing strategy that samples both common and rare members of microbial populations, providing a common metric across aquatic LTER sites to relate microbial diversity with ecosystem type. These data reveal that: (1) marine bacterial assemblages (FCE-VCR) are more similar to each other than are freshwater bacterial assemblages (ARC-NTL); (2) bacteria from NTL and MCM are the most distinct with respect to other sites; (3) there is more similarity among freshwater and marine eukaryotic organisms for presence/absence of the phyla (Jaccard distance); (4) all sites differ significantly with respect to the abundance of each phylum (Bray-Curtis).

All genetic data and metadata will be submitted to Genbank and Camera (<http://camera.calit2.net/>) databases and the MG-RAST annotation will be made public within two years of upload. Metadata (following the minimum information about a metagenomic sequence/sample standards given by the Genomics Standards Consortium <http://gensc.wordpress.com/>) will also be available from our MCM server with links to databases to enable users to easily locate all our data (see Section 4).

#### **2.7.6. Inter-valley comparisons (H4).**

To address Hypothesis 4, in a broader context we will extend our research focus to two valleys south of Taylor Valley: Miers and Garwood Valleys. The rationale for this expansion is that climate predictions indicate that Taylor Valley will warm over the next 50-100 years, which will increase lake levels in the Taylor Valley until a threshold is reached where the lakes will eventually coalesce and flow to the sea (**Fig. 16**). Because a connection with the sea occurs now in both Miers and Garwood Valleys (**Fig. 10 and 12**), this expansion of our research will help us understand key processes, such as thermokarst formation, that are expected in the future in Taylor Valley.

Our expansion in these two valleys will build upon existing MCM data and will be based largely on telemetered data augmented with synoptic on-site campaigns during MCM4. The Antarctic New Zealand program has had a consistent presence in Miers Valley since the 1980's, yielding intermittent streamflow, lake level and meteorological records, and the MCM limnology team has conducted limno runs on Lake Miers occasionally for the past 16 years; no continuous monitoring has occurred in either Miers or Garwood Valleys. We plan to deploy meteorological stations and stream gauges in both valleys to begin obtaining a consistent and detailed environmental record of how climate influences hydrological pulses in these areas. Our synoptic campaigns will focus on three sites spanning from the heads of each valley to the coast and will include the collection of biological (diversity and function based on the metagenome, organismal abundance), geochemical and physical data as outlined previously in this proposal.

### **2.8. SPATIAL INTEGRATION AND SYSTEMS SYNTHESIS (H1-H4)**

Since its inception, the MCM LTER has used conceptual models as a framework for addressing hypotheses and integrating our research across the physical, biotic and ecosystem processes (Moorhead et al. 2003; Hunt et al. 2007). Quantitative models linking changes in hydrology and temperature are key to expanding our new research to directly addressing connections and fluxes among landscape units. For example, models by Moorhead et al and Hunt et al on the response of soil biota to changes in soil temperature and moisture provide a baseline for predictions of when biota are active in nutrient cycling.

#### **2.8.1. Spatial Connectivity Model.**

In MCM4, we will build upon these previous studies to develop a spatially distributed numerical model of matter and energy flux and transformation at the landscape scale. The model will have three components: (1) surface energy balance model, (2) hydrology model, and (3) a core biological/biogeochemical model, particular to soils, streams, glacier and lakes (**Fig. 21**). This integrated model will emphasize connectivity among the components and utilize (1) high resolution digital elevation models (from airborne LIDAR data) so that the spatial reference of each modeled segment is properly connected to others, (2) on-going high resolution remote sensing (Quickbird and Worldview) imagery to classify status of every control volume, (3) previous research findings to determine biogeochemical cycling rates, food web/population dynamics, and stoichiometry of material and energy transformation within each control volume, and (4) matter and energy transfer at the surface via aeolian or water transport, and in the subsurface via energy conduction and unsaturated/saturated groundwater flow (shallow); all of these later components will be driven directly by meteorological station and stream hydrology records. One advantage of the spatially explicit process based model is that the presence of particular genes, microbes, or nutrients at any point in the landscape can be tested to determine if they were transported there by water or by wind. Specifically, hydrological connections will be strongly constrained by surface topography, whereas aeolian connections will be defined by predominant wind directions during high wind events.

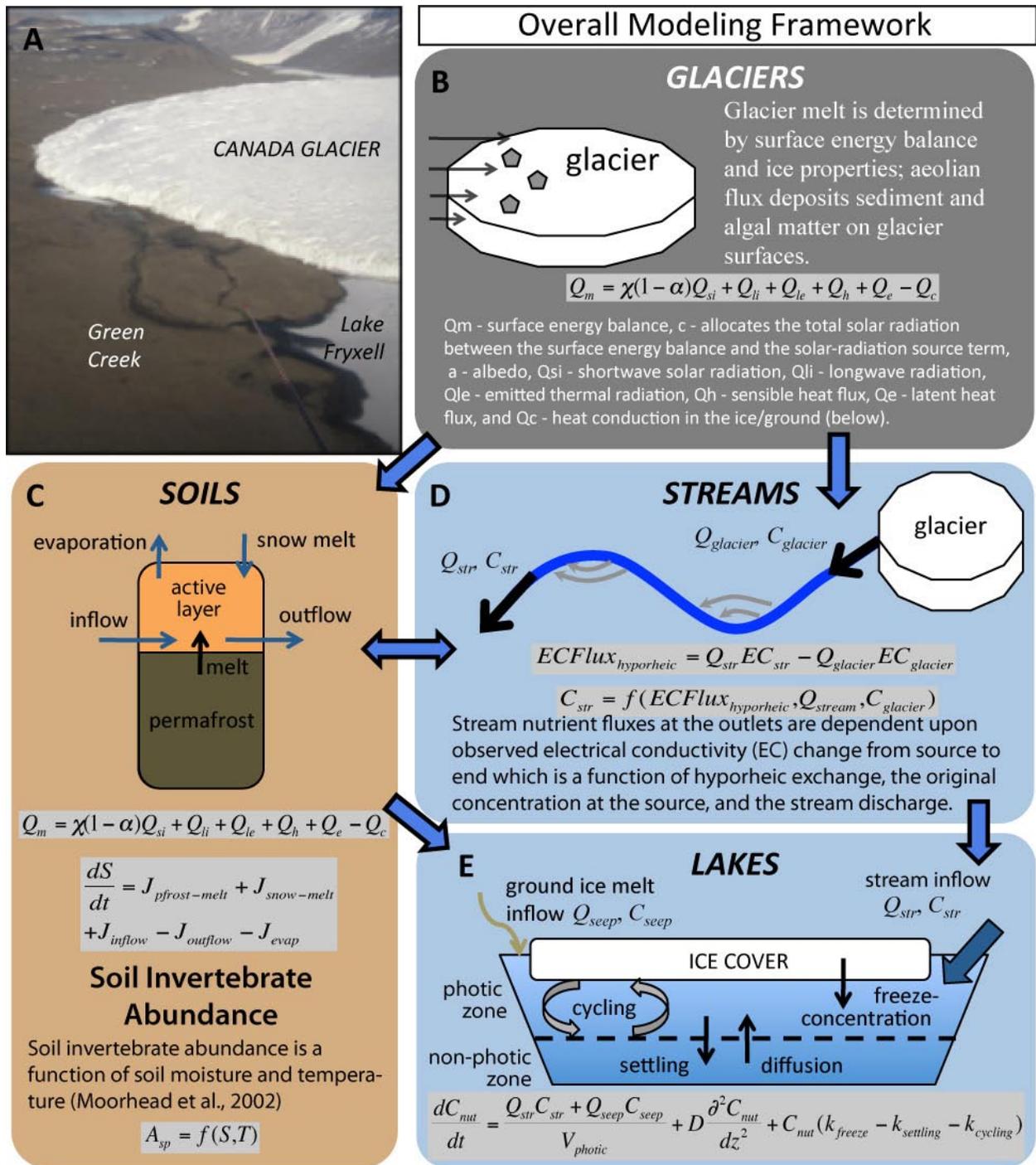


Figure 21. Modeling approach for coupled (A) glacier, soils, stream, and lake. Glacier melt model (B) will be based on the surface energy balance model of Hoffman et al. (2008). Glaciers are connected to (C) soils in which thermodynamic, hydrologic, and species abundance models will be developed ( $J$  = water flux). Soils, glaciers are connected to (D) streams in which concentrations are a function of melt water and interaction with the hyporheic zone. Soils, streams are connected to (E) lakes in which we will develop a biogeochemical model for the photic zone. All sub-models will be connected in a spatially explicit manner using digital elevation model and land cover data. Sub-models will be calibrated using long term data from MCM1-3 and data from new experiments. Details described in text.

This integrated model will allow us to test H1-H4 by simulating a variety of historic conditions (for calibration) and projected meteorological conditions. Importantly, the model will allow us to quantify the location, magnitude, and frequency of the connectivity of landscape units. Physical connectivity will be compared by quantifying fluxes of water, energy, and material (sediment, nutrients, organic matter) in a spatially explicit manner at a sub-daily time scale. Biological connectivity will be characterized by assessing potential for direct biological transfer (aeolian and water transport) and biological responses to material transfers (e.g., transfer of nutrients). Results will allow us to understand the basis for species range expansion and predict NPP over time in the soils and streams. The model will be calibrated with Taylor Valley data, and extended to Miers and Garwood Valleys. H1 will be tested by focusing on analysis of predicted responses to the frequency, magnitude, and duration of meteorological pulses (katabatic winds, warm air temperatures, etc.). The model will allow, for the first time, analysis of responses to historic pulse events of record. We will test H2 at the broader valley scale by determining the transport of material and then revising our numerical biogeochemical model to include results from the new wetting experiments. The ecosystem model will support the test of H3 by building upon H1 and H2 tests to predict the potential coupling of biogeochemical processes across the landscape, providing us with sampling targets for biogeochemical and diversity measurements. H4 will be tested by assessing the predicted redistribution of water across the landscape due to enhanced melt from high elevation sources. These simulations will be constrained by remote sensing imagery, a new data stream for our project. Finally, we will test the hypothesis that climate change will modify biological connectivity across the landscape by simulating gene flow across landscape units and throughout valleys. This model will be informed by metagenomic and phylogeographic analyses of prokaryotes from glaciers, soils and waters within Taylor, Miers, and Garwood Valleys.

### **2.8.2. The response of lakes to increased hydrologic connectivity.**

Across the MDV, differences in size, topography and geomorphology of valleys creates a large range of hydrologic variation, and predisposes some valleys to greater or lesser climate-induced changes in connectivity. To examine the response of the lakes to increased hydrological connectivity we will develop a biogeochemical model of the photic zone of Lakes Bonney, Fryxell and Miers that will account for inputs (streamflow, ground seeps, precipitation), outputs (lake ice dynamics, exchange with hypolimnion, outflow in the case of Miers), and internal cycling of nutrients (**Fig. 21**). This will be accomplished working with one of our young investigators, Dr. Castendyk, who began to collect circulation data this past field season. The model will be developed and calibrated from our long-term database and experimental data from the lakes (to provide information on reaction kinetics for example). We will then develop a web interface for the model so that it can be updated in real time with new measurements of inputs (i.e., streamflow loads). New data will be plotted as limnology samples are processed and the model will be actively calibrated and revised yielding an open model revision process in which the model will be updated after each field season and revisions will be carefully documented with older versions of the model and model runs archived on the web. Our approach will provide a documented model evolution process that will be available for use in any ecosystem or biogeochemical modeling application or class. This lake nutrient budget model will be useful for our understanding of the processes that contribute to lake dynamics, and for predicting potential changes to connectivity across our ecosystem. The effect of up-gradient changes in connectivity of glaciers and ground ice to soils, to streams, or directly to lakes can be estimated directly with this model, which directly addresses all of our working hypotheses.

## **2.9. SOCIAL SCIENCE INTEGRATION: AN ENVIRONMENTAL HISTORY OF THE MCMURDO DRY VALLEYS**

In 1903, Captain Scott and his two companions became the first humans ever to see the MDV. Since then, relatively few people have ever visited the region, and the majority of these visitors have been involved in scientific activity. In keeping with the Integrative Science for Society and the Environment (ISSE) research initiative established by the LTER network, we propose to use environmental history to examine the interactions between human activity, scientific research, and environmental change in this unique region over the past 100 years (**Fig. 22**). In much the same way as the simplicity of the MDV ecosystems makes the area an ideal location for formulating ecological theory, the reductionism of the area's human

history – in terms of its short timeframe and the small number of people involved – makes it an excellent location for integrating the theory and practice of environmental history with the ecological research of the LTER network. It is easier, for example, to trace historical interconnections between science, policy, and environmental change in the MDV than at other sites with more complex human-environment coupling. By taking advantage of the relative simplicity of the region’s environmental history, this research will make a major contribution to theoretical discussions within the LTER network about the integration of science and society (Redman et al. 2004).

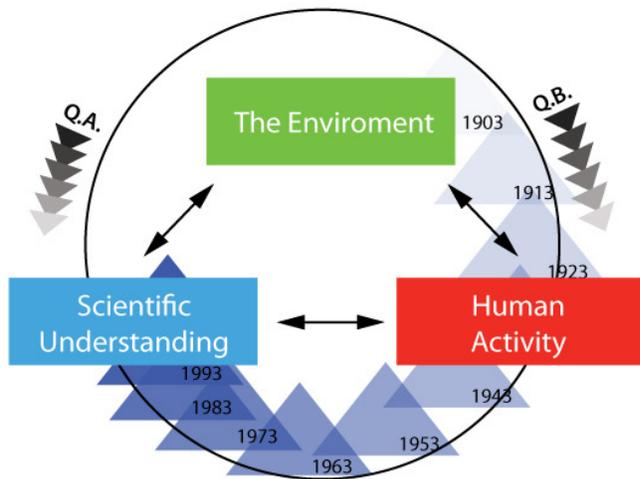
A central theme of this environmental history research in the MDV will be a consideration of the human dimensions of the idea of “connectivity.” It will focus on two well-known observations about scientific research in the MDV: it is highly integrative and there are effective international collaborations with scientists and policy makers. This connectivity is particularly apparent in relation to climate change and its consequences (**Fig. 22**). In exploring the mechanisms that enhance connectivity across disciplines and nations, the research will ask questions such as whether disciplinary integration was a product of NSF cross directorate or other mechanisms? And how important was the Antarctic context in encouraging international collaborations? The final research product will be a comprehensive environmental history of the MDV from 1903 to the present that will add a historical dimension to the scientific work of the MCM team and will assist in making projections of future ecological change in the region.

The accumulation of data for the social science integration will involve quantitative and qualitative historical research in four countries with significant involvement with the MDV: the United States, Great Britain, Australia, and New Zealand. In each of these countries, archival research will be conducted in government archives, scientific institutions, and environmental organizations. Oral history interviews will be conducted with active and retired scientists, policy makers, and environmentalists. The research will begin by drawing upon the scientific expertise of the MCM to think about how the environment of the MDV has changed over the past 100 years, especially as a result of anthropogenic change. The research will then consider how human activity in the region has changed over time, and how scientific understanding of the region has developed. Throughout the research, historical data will be posted on the MCM website, and the results of the research will be published in a series of scholarly articles and in an academic monograph.

## **2.10. INTERSITE COMPARISONS WITHIN THE LTER NETWORK**

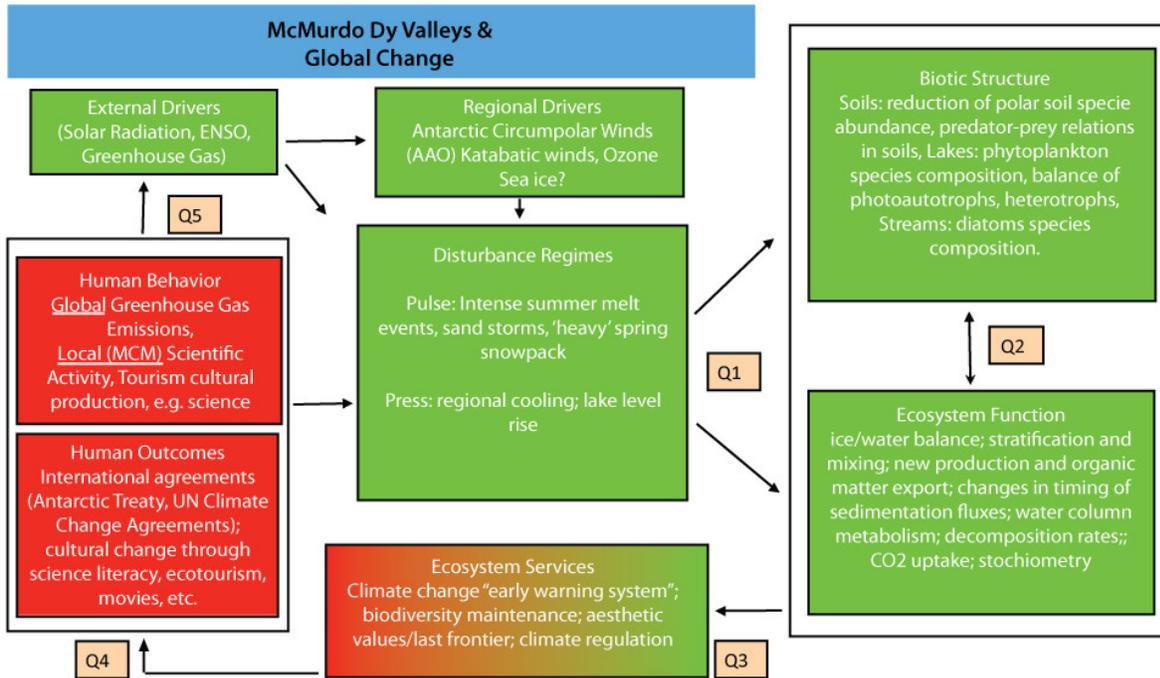
The MCM is active in cross-site activities, as well as in international collaborations (Section 3). Priscu is participating with 13 other LTERs in MIRADA (Microbial Inventory Research Across Diverse Aquatic) LTERs, which is a large metagenomic intersite comparison among aquatic (lakes and marine) systems within the LTER network (see Fig.20). During MCM3 we became a member of the Global Lake Ecological Observatory Network (GLEON), an active network of lake observatories around the world. During the 09/10 season, we began contributing lake and meteorological data to the network in real-time through the installation of telemetry equipment in collaboration with Paul Hanson from NTL. GLEON has strong LTER roots, and our involvement in this globally important network along with other sites such as ARC and NTL will enhance data synthesis among LTER sites that have lake ecology as a focus. Adams is leading a NSF Biotic Surveys and Inventories project to catalog the biodiversity of tardigrades of the terrestrial LTER sites, primarily those of North America. The tardigrade research of MCM is providing value-added components to that project via access to the field and samples. The tardigrade diversity and distribution information will be linked to other biotic and geophysical parameters across all sampled LTER sites. In other on-going cross-site work: McKnight has teamed with R. Jaffe (FCE) to organize LTER workshops on the use of spectroscopic methods to characterize the chemical quality of dissolved organic material as part of monitoring and biogeochemical studies; Wall organized an OPP-sponsored workshop “Synthesis of soil biodiversity and Ecosystem Functioning in Victoria Land, Antarctica” which involved participants from MCM, ARC and NWT; Takacs-Vesbach did an intersite comparison of microbial diversity in sediments and geochemistry of the SEV and MCM; and Priscu is participating in an LTER wide initiative to describe the importance of long-term lake data (originating out of a workshop at ASM 2009). Lyons served on the Network’s Executive Board from 2006-2009.

## Social Science Research



**Q.A.** How have humans changed the environment of the McMurdo Dry Valleys? How has scientific understanding of the region responded to a changing environment? And how have these developing scientific understanding shaped human activity in the region?

**Q.B.** How has the environment of the McMurdo Dry Valleys shaped human activity in the region? How has human activity led to developments in scientific understanding of the region? And how have scientific developments changed perceptions of the McMurdo environment?



**Q1:** How do short term weather events influence life history adaptations of ice, water, and soil –based species that compose the microbial ecosystem of the McMurdo Dry Valleys?  
**Q2:** How are feedback interactions between microbial diversity, function, and biogeochemical processes affected by changing short term climate change?  
**Q3:** How will changes to the biotic structure and ecosystem function of the McMurdo Dry Valleys act as early warning systems to broader climate change events?  
**Q4:** How does the human population respond to the complexity of climate variations in the Antarctic environment?  
**Q5:** How do human decisions and actions vis a vis Treaty structures, pressure to control carbon emissions, affect pace and results of climate change?

Figure 22. Integration of social science research with MCM and ISSE program.

### 2.10.1. PAL Exchange.

We propose two scientific exchanges. First, a member of our soils team will work with the PAL site to examine the soil biodiversity on the rapidly warming Antarctic Peninsula. This comparison with the McMurdo site will be valuable because the warmer climate and greater biodiversity at the PAL site will provide a view into the future for the MDV. This study will also add to the latitudinal transect of soil biodiversity completed from McMurdo to Cape Hallett. Priscu and Ducklow have planned a scientific exchange to compare the response of bacterioplankton and phytoplankton productivity to climate induced changes in temperature and nutrient state. Priscu has already included measurements of bacterial productivity used at PAL in MCM “limno runs” to make these data as comparable as possible. These Antarctic cross-site comparisons will allow us to expand our results to another region of the continent currently experiencing intense climate warming.

## 2.11. SUMMARY OF PROPOSED RESEARCH

Results obtained during MCM1-MCM3, in concert with predictions of future warming in Antarctica, have led us to the overarching hypotheses of MCM4: **Climate warming in the McMurdo Dry Valley ecosystem will amplify connectivity among landscape units leading to enhanced coupling of nutrient cycles across landscapes, and increased biodiversity and productivity within the ecosystem.** We will examine contemporary patterns in ecological connectivity in the MDV and predict how these may change under the future scenario of climate change. We believe that eventual climate warming in the MDV will be manifested as a slowly developing, long-term press of warmer summers as ozone depletion is ameliorated upon which transient pulse events of high summer flows and strong katabatic winds are overprinted. These pulse events are driven by a confluence of seasonal changes in local weather patterns causing increases in air temperature and/or solar radiation producing a cascade of physical and geochemical changes. We have developed four specific hypotheses that focus on pulses of wind and water across the MDV landscapes, and how these pulses are manifested in contemporary and future ecosystem structure and function. Based on climate predictions for the MDV region, we predict a scenario where the closed basin lakes of the Taylor Valley will eventually coalesce and drain to the sea. To gain an understanding of what conditions may be like in this scenario, resources will be allocated to the study the more southerly Miers and Garwood Valleys, which already drain to the sea. We will expand our monitoring within the Taylor Valley to include high-resolution measurements of aeolian particle flux and the delineation of regions where pulses of water and wind borne particles may change the biocomplexity of the system. Importantly, integrative genomics will be incorporated into our research to understand the responses of specific organisms to the connectivity that we predict will occur in a warming climate. Inclusion of metagenomics will yield a detailed phylogenetic and physiological map across the MDV ecosystem allowing us to assess which organisms are most susceptible to enhanced connectivity, and how these organisms respond to simulated connectivity within the context of our proposed experiments. Genomic data together with growth and stoichiometric data from our experimental manipulations will allow us to address our hypotheses and provide a logical progression for evaluating how climate warming in the MDV will amplify connectivity across the landscape. MCM4 also includes a novel social science component that will use environmental history to examine interactions between human activity, scientific research, and environmental change in the MDV region over the past 100 years. In much the same way as the simplicity of the MDV ecosystems makes the area an ideal location for exploring ecological theory, the simplicity of the area’s human history – in terms of its short timeframe and the small number of people involved – makes it an excellent location for integrating the theory and practice of environmental history with the ecological research of the LTER network. Thus, this research will make a major contribution to theoretical discussions within the LTER network about the integration of science and society.

## SECTION 3

## SITE MANAGEMENT

McKnight assumed leadership of MCM3 in September 2009 and will continue as lead PI for MCM4; she will undergo annual reviews by the MCM PIs. As shown in the MCM Internal Links diagram (**Fig. 23**), the Executive Committee (EC) provides guidance to help manage all phases of the project. This system has worked well since the project began and will be continued. McKnight has appointed 4 new EC members for MCM4 including 2 from the new PIs named below and will hold monthly conference calls with them. The management office of MCM is at the Institute of Arctic and Alpine Research (INSTAAR) at CU. Currently, Jeff Walters provides administrative assistance for the grant and coordination of interactions among the PIs. In MCM4, this role will be filled by a fulltime staff person. The CU staff person will coordinate field logistics and work with Lyons at OSU to prepare the field planning documents that are due before each field season. OSU provides a fieldwork coordinator during the 4-month field season. This preparation includes the allocation of field personnel, field equipment, helicopter hours, and chemical analysis of samples at the Crary Laboratory in McMurdo Station.

The PIs meet twice a year (**Fig. 23**). In the interim, communication among PIs occurs through email and bi-weekly conference calls. The first meeting is in February/March to review the activities of the past field season and to plan for the next one. The summer meeting has a science focus and includes students, technicians, post docs, and collaborators. The meeting site has rotated among the home institutions of all the PIs. In July 2008, 22 people attended the science meeting at UIC. In addition, a small workshop on lake modeling was convened subsequently. A science meeting attended by current PIs as well as the new PIs for MCM4 was held at Dartmouth (July 2009) and focused on the role of connectivity in MDV landscapes. MCM scientists and students had an official meeting during the LTER All Scientists Meeting in September 2009.

There are major changes to our organization in MCM4. We have gone from 8 to 12 PIs with the 4 new PIs bringing diverse expertise to the project. Gooseff has already replaced Hunt as the PI for ecosystem modeling. Adams is an expert in soil invertebrate ecology and phylogeography. Barrett is a biogeochemist with interests in terrestrial-aquatic linkages. Howkins is an environmental historian with extensive polar history connections in England and throughout South America. Takacs-Vesbach is a molecular ecologist who focuses on microbial biodiversity and function in extreme environments; she will replace Lyons as the PI responsible for information management (IM) for MCM4. As a PI with expertise in this area and proximity to the network office, Takacs-Vesbach has excellent understanding of the potential uses of the genomic data within a relational framework and she will serve as a liaison between MCM and network IM activities. New developments for IM will also be facilitated by the Data Management Committee comprised of two PIs and technical staff.

We continue to receive numerous requests from both US and foreign scientists and students to work at the MCM site. However, we are limited by NSF to 29 people each field season due to logistical constraints. To maintain our breadth and depth, while minimizing the logistical and financial loads, we have a “formal collaborator” designation, which is limited to established scientists who episodically participate in our fieldwork or modeling efforts. These collaborators are listed in Table 3.1. Hugh Ducklow, lead PI of PAL, is a close colleague and collaborator. We are active members of GLEON, of which Paul Hanson of NTL-LTER is a leader. Hanson worked with Doran during the 2009/10 field season and will collaborate with us on future lake modeling. MCM has been a leader in the LTER network with regard to international cooperation, especially during the International Polar Year (IPY). Johanna Laybourn-Parry works on the physiology of protozooplankton and their interannual variations in the lakes. Martin Tranter is a collaborator working with us on the biogeochemistry of cryoconite holes on the glacier surface. We maintain ties with New Zealand scientists involved in the Antarctica New Zealand program, including our collaborators, Ian Hawes, who has worked with Doran investigating the benthic algal mats in Taylor Valley lakes and Ian Hogg who has collaborated with Wall on invertebrate communities. MCM PIs also are important US contributors to SCAR (Scientific Committee of Antarctic Research), as exemplified by

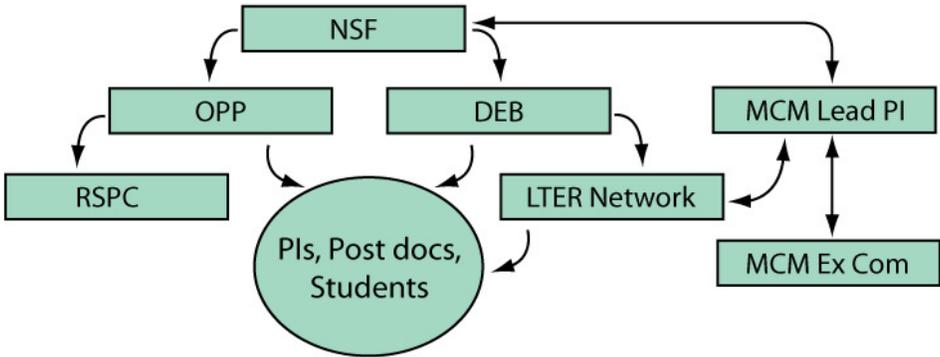
Priscu being a US representative to the SCAR Life Sciences Standing Scientific Group, chairing the international committee on Antarctic subglacial lakes, and acting as co-chair of the international organizing committee for the next SCAR open science conference (Aug 2010, Buenos Aeries, Argentina), and McKnight serving as the Chair of the newly established Martha M. Muse Award committee. We will continue our international collaborations during MCM4. This will include workshops at the upcoming SCAR meeting. Each of these collaborators brings an important tool and/or approach to MCM that is currently unavailable, and allows us to integrate and expand our research efforts.

In addition to formal collaborators, we have established a relationship designated “investigator.” Investigators are scientists who have postdoctoral experience with two or more seasons associated with MCM and/or who have demonstrated a commitment to polar research through the development of new research proposals that fall within the overall themes of the MCM. These scientists may be supported by MCM and/or other projects, or may be building an independent research program whose focus includes polar regions. This category allows MCM to help develop young scientists for future leadership roles in the MCM, polar research, and the LTER program. All but one of the new PIs in MCM4 were investigators in MCM3. We continue to encourage and promote diversity within MCM. Currently, 3 of the 12 PIs, two of five investigators, and two of six formal collaborators are women.

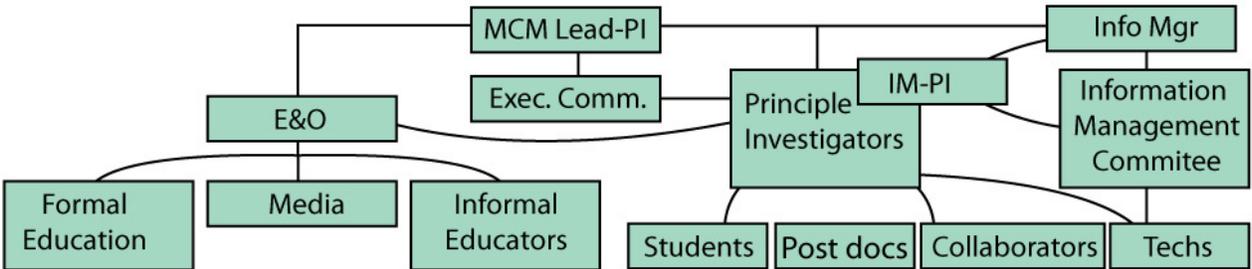
Table 3.1 Formal collaborators and investigators involved in MCM4 research activities

Formal collaborators		Investigators	
Fabien Kenig	University of Illinois	Jill Mikucki	Dartmouth College
Johanna Laybourn-Parry	Univ of Tasmania	Devin Castendyk	State University of New York, College at Oneonta
Martyn Tranter	University of Bristol, UK	Rachael-Morgan Kiss	University of Miami, Ohio
Hugh Ducklow	Marine Biological Laboratory	John Dore	Montana State University
Ian Hogg	Univ. Waikato	John Lisle	USGS, Tampa
Ian Hawes	NIWA, NZ	Brent Christner	Louisiana State University
Christine Foreman	MSU	Steve Jepsen	USGS, Boulder
Paul Hanson	University of Wisconsin	Diana Nemergut	CU
Paul Morin	University of Minnesota		

## MCM External Communication Pathways



## MCM Internal Links



## MCM Timeline

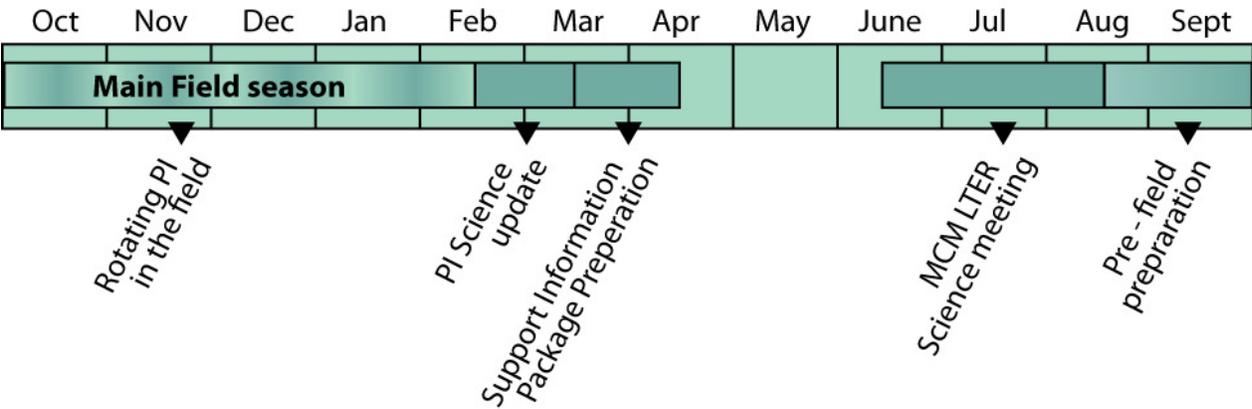


Figure 23. Wire diagram showing the management strategy for MCM4. The diagram explicitly shows external communication pathways and internal links between all interacting components of the MCM. The lower portion of the figure shows the typical timeline we will follow during each year of the project.

## SECTION 4

## INFORMATION MANAGEMENT

### 4.1. OVERVIEW

Information management (IM) is integral to the McMurdo LTER. The objective of our data and IM system is to support site science and network goals by facilitating access and ensuring the integrity, security, and usefulness of MCM data and metadata. The MCM IM system is presently managed by Lyons at OSU, but will be moved to the UNM in 2010 and managed by Takacs-Vesbach. The move will take advantage of existing IM infrastructure and culture at UNM, where the LTER Network Office (LNO) and the SEV LTER are located. A full-time information manager will work with previous MCM staff and LNO personnel to make the transition seamless. The information manager will be responsible for systems administration, our database, the webpage, and GIS. Many protocols and improvements developed in MCM3 will be continued. Additionally, the IM system will be expanded in MCM4 to include molecular diversity and genomic data, an historical archive of human activity in the MDV, and we will document our modeling routines and results (**Fig. 24**).

### 4.2. MCM LTER INFORMATION MANAGEMENT IMPLEMENTATION AND DESIGN

**4.2.1. Scope.** The MCM database, including metadata, tabular, and spatial data from 1993 to present (in addition to pre-LTER data since 1967), and a list of publications supported by the MCM are available on our website. Our project is linked to other datasets and collections, such as the USGS Onyx River real-time streamflow, and the Freshwater Diatom Collection at INSTAAR. We aim to make all data available within two years of collection. Exceptions are made for ongoing unpublished experiments or data with extensive QA/QC needs. The data manager notifies the lead PI on a monthly basis about the status of data submissions. We have an effective procedure to address substantial delays or lack of response.

Our GIS data have been updated: VALMAP layers have been organized, attributed layer features, and QA/QC'd to create new spatial layers (e.g., glacier stake, meteorology station, and stream gauge locations, DEMs, and vector bathymetric contour maps). Additional metadata have been associated with existing VALMAP layers. Many GIS layer features are now encoded with parameterized URLs to related up-to-date data through the web, which allows users to directly access tabular data through the GIS from the interactive online map or downloaded GIS layers. New datasets with a fundamental spatial component are being developed, which will be joined with existing data entirely within the relational database so spatially-referenced data can be utilized directly within the GIS. We now provide three methods for researchers to access our GIS data: and online interactive map, direct connection to our Oracle database as an ArcGIS client, and by downloading exported layers.

**4.2.2. Design.** The overall infrastructure of the McMurdo information management system is summarized in **Fig. 24**. The core of our IM system is a centralized database that is available on our website. Computing hardware consists of a Sun Microsystems SunFire V480 server running an Oracle relational database, which holds all data and GIS layers. For security purposes, IM personnel have sole editing privileges within Oracle database. The database is protected by a firewall and all end-user access is available only through the web page. The server runs the dynamic website and serves GIS layers to the online map and remote ArcGIS users through ArcSDE and ArcGIS Server. GIS database edits are made using a database connection in ArcMap on PC by a user with editing privileges, while most researchers have read-only privileges.

A secondary SunBlade 1500 system automatically replicates and updates the entire Oracle and ArcSDE databases and the entire primary system, and operates ArcGIS Server, the online mapping application. Monthly backups are transferred to external hard drives, which go offsite for further data redundancy. A SunBlade 1000 server is maintained at INSTAAR for processing stream hydrology data and additional storage space. With the transition to UNM, the primary server will be replaced by a new machine located in the LNO server room, but the overall architecture of our IM system will be maintained.

**4.2.3. Webpage.** Our website ([www.mcmlter.org](http://www.mcmlter.org)) was redesigned in 2006 to be more user-friendly, dynamic, up-to-date and attractive to public visitors. It currently conforms to all recommendations specified by the LTER Web Site Design Working Group. Users can access data quickly and easily – core data are downloaded with 3 clicks on our webpage. Core data are kept entirely in the Oracle relational database and web output includes the MCM data use agreement and metadata URLs with data in a comma-delimited format. Users may browse data by season, perform a custom data query, or retrieve the entire dataset directly through the metadata. Many useful derived datasets are also available through custom tools. Statistics for continuously measured data (i.e. stream flow and meteorology), table joins and unit conversions are all done automatically by the database and available on the web. The website also features many new enhanced tools related to website management. The site has a fully searchable database of publications and student theses/dissertations, a personnel list, MCM LTER news (distributed across the web through RSS), outreach events, website and data usage statistics and a database of ancillary field projects. MCM personnel may make additions to these databases online through the restricted area of the website.

**4.2.4. Documentation.** We have documented the MCM information management system architecture, procedures, and protocols locally and online (in the restricted access area of our website) as recommended by the LTER IM committee, which has helped us maintain continuity during past transitions. A distinguishing feature of the MCM LTER is the high degree of coordination in planning each field season, which carries over to the IM system. An up to date list of current and past projects is maintained by the information manager as a mechanism to track data in a centralized manner. During MCM4, we will better capture data from ancillary projects and student theses. Templates for data entry and cross-relational file structure are prepared in anticipation of data submittal. At the end of the field season, the data manager receives the actual sampling schedule (e.g., sampling dates and depths for each lake, sample dates and location for glacier, soil and stream field measurements and samples) in the specified templates.

**4.2.5. Review.** Annual review of the MCM LTER IM system will be conducted by the MCM Executive Committee to ensure that the MCM system is meeting LTER data management objectives or addressing recommendations by previous reviewers. Communication with PIs is frequent and aided by a MCM IM group that includes the professional staff who submit data and 2 PIs. The new information manager will attend LTER IM meetings (formal and informal, like the virtual water cooler), and take advantage of SEV and LNO personnel at UNM, to stay informed of LTER IM system expectations and future directions.

### **4.3. INFORMATION MANAGEMENT SYSTEM SUPPORT FOR SITE, NETWORK, AND COMMUNITY SCIENCE**

**4.3.1. Integration with Site Science.** Data are entered into electronic files in the field and at PIs home universities. Data sets are typically submitted electronically in spreadsheet format after quality assurance. When appropriate, both original measurements and final results resulting after the investigator's revisions are submitted. Metadata are updated to reflect seasonal variances in instrument status and measurement practices, especially for meteorological and hydrologic data. When MCM took responsibility of the analytical chemistry lab at McMurdo Station, our information manager developed a system to ensure data integrity throughout the life cycle of sample processing. Each team uses a web page outlining protocols to be followed from field to data submission. Downloadable chain of custody (COC) forms ensure that sample names and date/times are entered consistently in database. These forms are entered into a web-accessible database that allows analysts to copy and paste sample names into their instrument software, allows the IM to ensure all expected data are received, and allows the IM to incorporate field notes from the COCs into data tables.

**4.3.2. Metadata and Data.** During MCM3, all metadata were converted to Ecological Metadata Language (EML) used by the LTER Network at "level 5." Metadata are harvested daily by the LTER Network servers for inclusion in global metadata searches. These metadata are updated to keep pace with seasonal variances in instrument status and measurement practices. Investigators are responsible for primary QA/QC, and the information manager works with investigators to document the quality of all

data sets. The MCM Data Access Policy complies with the LTER Network Data Access Policy and is stated on our website ([http://www.mcmlter.org/data\\_guidelines.html](http://www.mcmlter.org/data_guidelines.html)). MCM utilizes direct links to metacat for display of all metadata documents, and metadata access is tracked by the LNO through metacat. Website access of [www.mcmlter.org](http://www.mcmlter.org) is tracked with Google Analytics.

**4.3.3. Contribution to LTER Network and community activities.** Our data manager will participate in LTER and community activities such as annual meetings, committees, workshops, tool development, and the “virtual watercooler”. Our system contributes to LTER Network-level databases MetaCat, ClimDB, and HydroDB, which are automatically updated by data transformation scripts. Our database is linked to other community databases such as EcoTrends (<https://www.ecotrends.info/EcoTrends/index.jsp>, which houses >1200 long-term ecological datasets from diverse ecosystems to promote synthesis across sites) and GLEON ([http://www.gleonrcn.org/index.php?pr=Home\\_Page](http://www.gleonrcn.org/index.php?pr=Home_Page)). We are linked to the real-time Onyx River streamflow data hosted by the USGS (<http://wy.water.usgs.gov/projects/antarctica/htms/ice.htm>) and the Freshwater Diatoms Database (<http://huey.colorado.edu/diatoms/about/index.php>). The Antarctic Master Directory (AMD, <http://idn.ceos.org/KeywordSearch/Home.do?Portal=amd&MetadataType=0>) has only a link to our webpage because they use DIF instead of EML. In MCM4, we will develop a “crosswalk” XML script so that our metadata are searchable through the AMD.

#### 4.4. FUTURE PLANS

Our IM system is now functioning at a level equivalent to the best in the LTER Network and we have a track record of engagement in LTER IM activities. As recommended by the site review team in MCM4 we plan to better capture ancillary data produced by graduate students and make these available online. Our new data manager has expertise in the management of data from diverse disciplines, including genetic data and GIS. We are planning the following improvements for our IM system:

**4.4.1. Genetic Data.** Because we anticipate generating substantial genetic data and modeling results, the information manager, in consultation with the PIs and the LNO, will be tasked with developing innovative solutions to archiving this information. As a first step, we will be submitting our data and linking with the Genbank and Camera databases. However, a significant amount of comparable molecular diversity data have been collected from all LTER sites, and current national genetic databases do not facilitate convenient cross-site queries. We will develop a new genetic data management framework to increase the potential for synthesis of these data across all LTER sites. Additionally, we will document our modeling routines and share our results online. This work will be undertaken in collaboration with information managers at other LTER sites through the virtual water cooler initially, but also at the All Scientist Meeting or an Information Manager workshop.

**4.4.2. GIS.** GIS will be expanded in MCM4 by developing what we call “data-specific” interactive maps, EML files will be made for datasets that have a fundamental spatial component and linked to interactive maps and the tabular source data. These files will be cross-listed within GIS layers and their discipline (e.g., soils). An example is given here of soil species distribution across the valleys ([http://www.mcmlter.org:9001/soil\\_biota/](http://www.mcmlter.org:9001/soil_biota/)). In addition, we will be incorporating new spatial layers into the database such as Quickbird images that we have been acquiring, and as suggested by a site reviewer, we will begin creating metadata for all layers through ArcCatalog, and a script will convert the metadata to EML to be harvested by the LNO. We also plan to create layers in Google Earth with links to data and photos taken by MCM team members as part of our outreach, and add additional functionality to the online map. The new information manager will be a member of the LTER IM GIS Working Group.

**4.4.3. Human Activity in the McMurdo Dry Valleys.** In MCM4, the social science component of MCM will use environmental history to consider the human dimensions of the idea of “connectivity.” An environmental history of the MDV from their discovery in 1903 up to the present will be developed. Archival research, oral history interviews, and data from field visits will be compiled into various electronic forms to be integrated into our information management system and shared on our website.

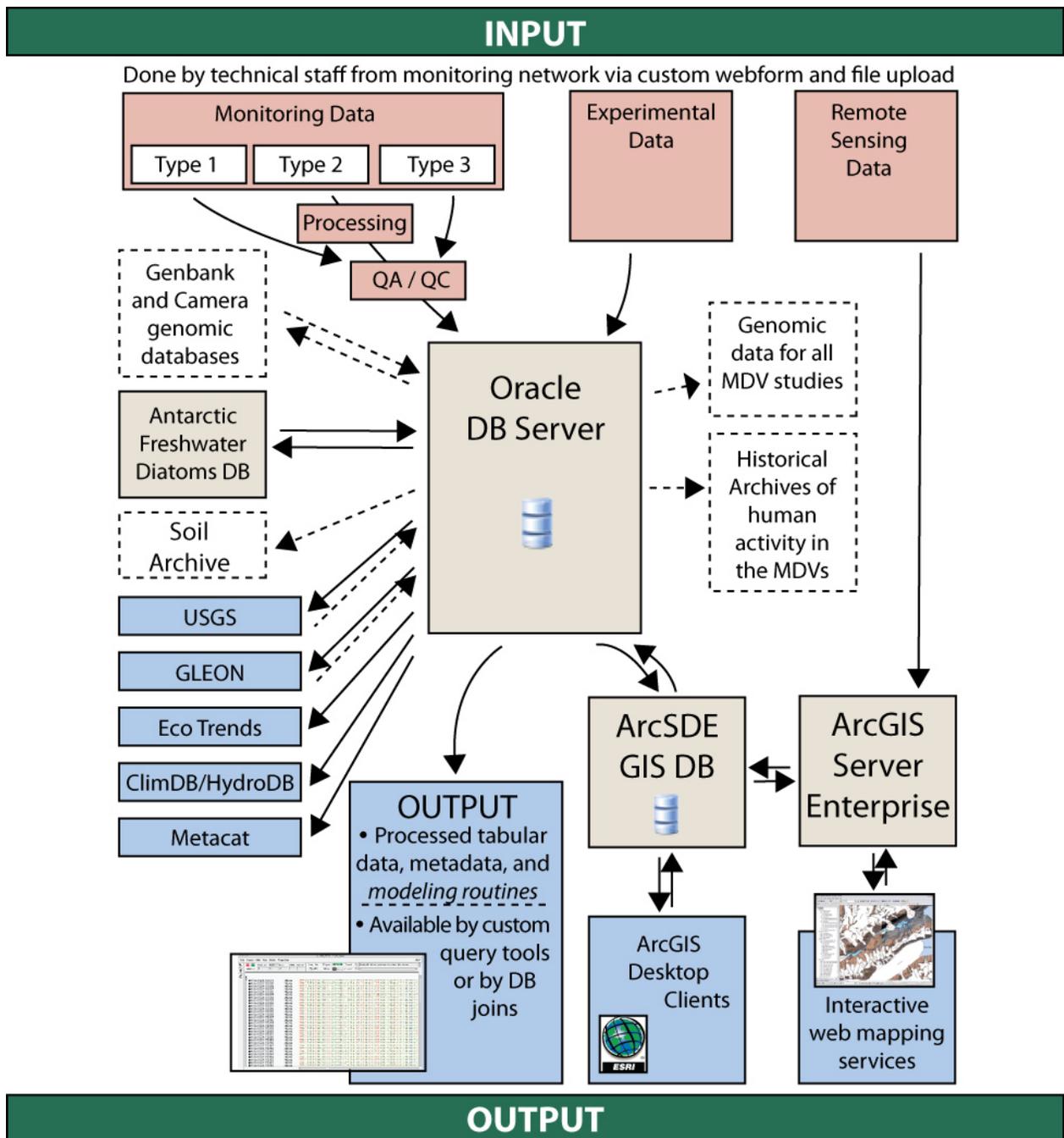


Figure 24. The MCM-LTER Information Management System (IM). Solid boxes and lines represent current components, dashed boxes and lines represent features to be implemented in MCM4. Our IM is supported by an Oracle relational database hosted on our project server (which will transition to UNM). Primary data pass through two levels of QA/QC prior to upload onto the IM. All primary data are publicly available within two years and can be accessed using custom query tools or precompiled tables through our website ([www.mcmlter.org](http://www.mcmlter.org)). Spatial information is supported by a robust GIS that is publicly accessible through our interactive web mapping tool, using ArcGIS. MCM contributes to public databases (e.g., EcoTrends, GLEON, and MetaCat). New content for MCM4 includes a genomic database, a catalogue of remote sensing images, integration of our soil archive into the relational framework, and an expansion of links to other databases, e.g. the Antarctic Master Directory.

## SECTION 5

## OUTREACH

MCM scientists participate in a wide array of outreach efforts ranging from presentations in K-12 classrooms to bringing undergraduates and teachers to the dry valleys to gain research experience in this environment. During MCM4, we will build on our current outreach programs and expand our efforts to reach both broader online audiences and groups traditionally underrepresented in science arenas.

### 5.1. K-12 OUTREACH

During MCM3, Carol Landis of OSU has been one of the leaders of the Schoolyard LTER program (SLTER) and co-chaired the Network's Education Committee. She conducted a program focused on "river studies" in which high school students from the Columbus Area collected and analyzed river samples following the same protocols as the Stream Team in the MDV. Also, Landis developed a MDV interactive educational DVD targeted for high school students and teachers. Landis is planning a phased retirement, and we are expanding our SLTER program to connect with K-12 students and teachers in a manner that focuses on the MDV experience.

During MCM3, McKnight and colleagues initiated the LTER children's book series, which consists of three titles with three more in progress. The second book in this series, *The Lost Seal*, is an elementary-level book recounting a true story about a Weddell Seal that had wandered into the dry valleys (**Fig. 25**). The MCM website presents information about the MDV for teachers using the book as a resource and has a searchable library of associated children's artwork. The book series was recently highlighted at the Presidential Awards for Excellence in Mathematics and Science Teaching Recognition Program. Books with an associated teaching curriculum CD were distributed to the award-winning teachers and McKnight spoke at a session on School Yard Ecology about using narrative to promote active science learning.

During MCM4, McKnight will be working with three NSF GK-12 Fellows at CU and Barb Monday, a K-8 educator from CU's Science Discovery program, to further develop the lesson plans included in the curriculum for the book. The GK-12 Fellows and Monday were members of the Steam Team in the MDV during 2009-10. The finalized curriculum will be made available to MCM scientists for use in outreach activities and the book with the CD will be distributed as a teacher's edition by the publisher. Based on her experiences, Monday will develop a week-long summer camp centered on climate change and ecology of extreme environments to be offered through Science Discovery. One goal of the camp will be to explain current and future changes in Antarctica in a manner that is comprehensible to children and their families (e.g. **Fig. 26**).

In addition, Virginia served on the PolarTrec section panel for 2010-2011 research projects. PolarTREC (Teachers and Researchers Exploring and Collaborating in the Arctic and Antarctic) is a program of the Arctic Research Consortium of the United States (ARCUS), funded by NSF in which K-12 teachers participate in polar research, working closely with scientists as a pathway to improving science education. In a project with the National Science Teachers Association (NSTA) Vesbach is developing two web seminars about climate change and microbial biogeography using our research in Antarctica as the focus. NSTA web seminars are 90 minute live professional development opportunities in which teachers interact with experts and receive credit for participating.

### 5.2. OUTREACH TO UNDERGRADUATES AND EARLY CAREER SCIENTISTS

The MCM will expand our outreach to early career polar scientists around the world through a joint effort with Dr. Jenny Baesemen, Director of the Association of Polar Early Career Scientists (APECS: <http://apecs.is>) that will contribute to APECS' education and outreach resources. APECS offers in-person workshops, participates in education and outreach projects, and hosts online resources for early career polar scientists. By partnering with the University of the Arctic (UArctic) and the International Antarctic

Institute (IAI), APECS courses can be taken by students for academic credit. As recommended by the site review team, we will develop an online course about life in Antarctic deserts, using our book “Life in Antarctic Deserts and other Cold Dry Environments” (Doran et al. in press) as the text. The course will follow the chapters in the book and consist of online lectures (live and recorded for later viewing and subsequent courses) given by the authors. New research from each season will be incorporated into the curriculum to provide inquiry based exercises in data analysis. In addition, our senior researchers will serve as mentors and provide content for APECS events.

The MCM investigators have a strong record of involving graduate students in the MCM research and these efforts will be expanded during MCM4. Virginia is PI on the NSF IGERT Polar Environmental Change graduate program at Dartmouth (2008-13). An IGERT fellow participated in the 2009-10 MCM soils field team. MCM will be a valuable training resource for the Dartmouth IGERT and this collaboration will be shared to the broader graduate community on IGERT.org. In addition, MCM students and post-docs will be encouraged to take the APECS Career Development Course, which is coordinated through the NSF-funded ARCSS Thermokarst project. The course provides training for early career scientists in scientific and general public writing, media relations, education and outreach, working with policy makers, time management, and general guidance on beginning a career in research. The course is in the process of being approved by the University of the Arctic (UArctic) and the International Antarctic Institute (IAI), which will enable students to take the course for credit.

### **5.3. OUTREACH TO A BROADER AUDIENCE**

**5.3.1. Outreach to Spanish-speaking members of the Antarctic Treaty system and underrepresented groups in the U.S.** McKnight and Howkins, the social science MCM investigator, are now working on a Spanish-language version of the Lost Seal children’s book. The text for this edition will include more information about historic exploration of the continent done by Spanish-speaking Antarctic Treaty countries and will incorporate information about their current Antarctic stations. Children’s art work for inclusion in the book will be collected from countries such as Argentina, Chile, Mexico, and Spain. Howkins will work with colleagues who are interested in helping with this project at the newly created Center for Hemispheric and Polar Studies in Viña del Mar, Chile. Further, in coordination with the US Embassy, Santiago, Chile, Lyons is involved in an effort to translate the Dry Valleys’ interactive educational DVD into Spanish. His collaborators are Dr. Ricardo Rozzi at the University of North Texas, who directs the Omora Ethnobotanical Park in Southern Chile, colleagues at the University of Magallanes, Punta Arenas, Chile, and Angela Swafford Posada, a Columbian-born educator and science journalist with a high visibility in the United States and South American Spanish media.

**5.3.2. Enhancing online outreach experiences.** Our MCMLTER website is accessed by many individuals wishing to learn more about Antarctica. We have enhanced the website by organizing our pictures of the MDV and making them easily downloadable. During MCM4, Lyons and Landis plan to post the contents of the MDVs interactive educational DVD online at the “<http://www.mcmlter.org>” website so that these materials are available to the general public. Gooseff plans to work with Paul Morin to create a virtual web-based helicopter flight through Taylor Valley by draping images over digital elevation maps and setting up a video through Google Earth. As a viewer “flying” over Taylor Valley would be able to click on a feature such as a soil warming plots near Lake Fryxell, and learn about the experiments being conducted. Finally, we will contribute to APECS-sponsored podcasts called Frost Bytes. The podcasts are an international video and audio outreach program that shares polar research throughout the world via the International Polar Year education and outreach networks. The Frost Bytes series consists of 30 second sound bytes where researchers provide video or photos from their field sites combined with audio that describes their research and its broader importance.

## The Lost Seal

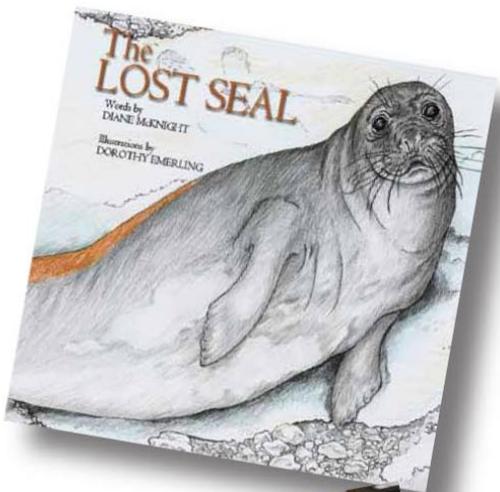
Text by Diane McKnight  
 Illustrations by Dorothy Emerling  
 Published by Moonlight Publishing  
<http://www.moonlight-publishing.com/>

### The Lost Seal's adventure

The story of the Lost Seal describes the first documented encounter with a live seal in the remote McMurdo Dry Valleys of Antarctica. This educational story tells of one seal's travels in a polar desert and provides an engaging framework for conveying how different Antarctica and the Dry Valleys are from the environments with which children are familiar.

### More about The Lost Seal

The Lost Seal was published as an outreach activity for the International Polar Year. The story and information on the Dry Valleys were sent to teachers in the U.S., U.K., New Zealand and Australia, reflecting involvement of explorers from these countries in Dry Valleys research. Children created artwork (viewable on the book website) which was included in the book. This artwork illustrates that children around the world are fascinated by Antarctica and demonstrates which details are especially interesting, such as scientists wearing red coats so that they can be easily found if they get lost. Footage of the real "lost seal" at various points in his misadventure is posted on the website for use by educators, and a CD of classroom activities is also available.



The Lost Seal is included in Polar Books Club ([www.unep.org/publications/polarbooks](http://www.unep.org/publications/polarbooks))

Books can be purchased from Moonlight Publishing or Amazon.com More at <http://www.mcmter.org/lostseal/>  
 Video at [http://www.mcmter.org/lostseal/photo\\_video.html](http://www.mcmter.org/lostseal/photo_video.html)



The mission of the Schoolyard Series is to engage children and their families in learning about the earth's ecosystems, both locally and internationally, through narratives that reflect the dynamic research being conducted at the National Science Foundation's Long-Term Ecological Research Sites.



Figure 25. Page describing the outreach activities associated with The Lost Seal which was included in materials presented to award-winning teachers at NSF in January 2010.



Figure 26. Cartoon about climate change in the MDV for use in the Science Discovery summer camp.

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