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Hydrological Connectivity of the Landscape of the McMurdo Dry Valleys, Antarctica

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Abstract

The McMurdo Dry Valleys (MDV) of Antarctica are composed of nearly 2000 km^2 of ice-free terrain, supporting a vibrant cold desert ecosystem despite harsh conditions. The ecosystem is largely regulated by the hydrologic cycle within the MDV, which is controlled by climate dynamics. The strength and timing of connections among the hydrologic reservoirs of the MDV (atmosphere, glaciers, soils and permafrost, streams and their hyporheic zones, and lakes) are dependent upon daily, seasonal, and annual surface energy balance. For example, glacier melt occurs during short periods in the summer, providing stream flow to closed-basin lakes. Similarly, the magnitude of sublimation of snow on valley floors and perennial ice covers on lakes is a function of wind, temperature, radiation, and atmospheric water content (humidity). Here, we describe these reservoirs and connections across the landscape to provide an overview of our current understanding of the system, as it is poised to change in response to changing climate in the coming decades. Measurement of hydrologic fluxes and states of hydrologic reservoirs in the MDV provides both a context for quantifying responses to climate change and a careful characterization of the potential direct drivers of ecosystem response. The MDV also provide a unique real-world laboratory in which to study fundamental hydrologic processes (with the exception of rainfall).

Introduction

The McMurdo Dry Valleys (MDV) of Antarctica encompass approximately 2000 km^2 of ice-free terrain, situated between McMurdo Sound to the east and the Transantarctic Mountains to the west (Figure 1). While the climate is very cold (mean annual air temperature of −18 °C) and dry (<10 cm water equivalent of precipitation per year), the hydrologic cycle in the valleys is defined by 'hydrologic reservoirs' (i.e. stores of water) of the atmosphere, glaciers, streams, soils, permafrost, and lakes. These reservoirs interact with each other through processes observed in many catchments worldwide including snowfall, glacier melt, stream flow, soil water movement, lake ice generation, evaporation of liquid water, and sublimation of ice and snow. In the MDV, hydrology is a critical vector distributing water, energy, and matter (e.g. salts, nutrients, sediment, algae) across this landscape, thereby facilitating the persistence of a cold desert ecosystem. This unique ecosystem is populated by microbial and algal communities in soils, glaciers, streams, and lakes; small and infrequent patches of moss occur in the riparian zones of streams; and

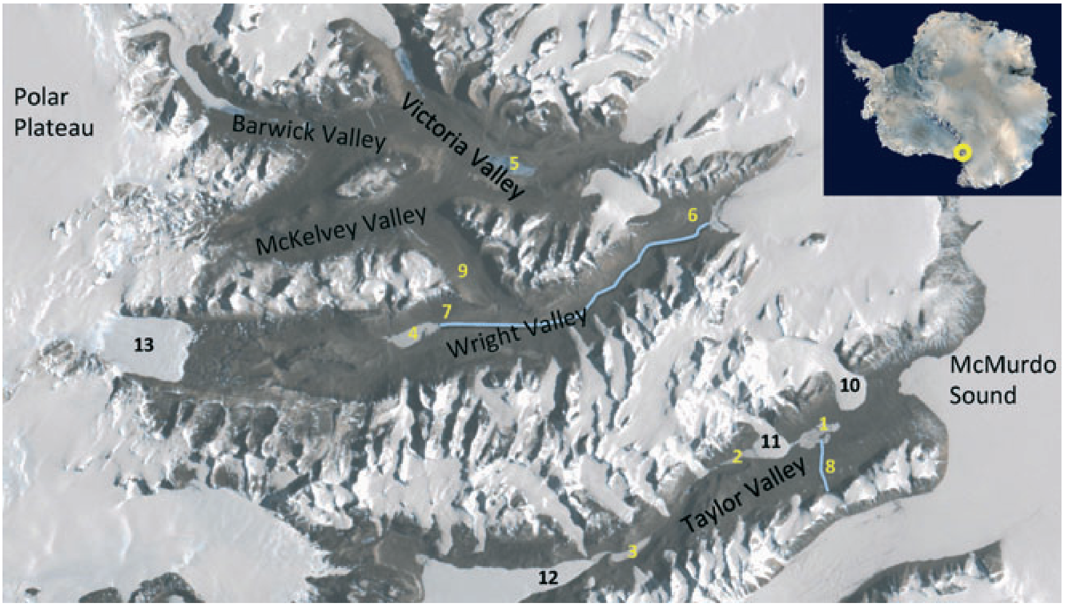

Fig. 1. Map and images of the McMurdo Dry Valleys (MDV) landscape with the following features noted: 1. Lake Fryxell, 2. Lake Hoare, 3. Lake Bonney, 4. Lake Vanda, 5. Lake Vida, 6. Onyx River at Lower Wright stream gauge, 7. Onyx River at Vanda stream gauge, 8. Crescent Stream, 9. Bull Pass, 10. Commonwealth Glacier, 11. Canada Glacier, 12. Taylor Glacier, and 13. Upper Wright Glacier. In the inset map of the Antarctic continent, the Transantarctic Mountains extend south and east from the indicated location of the MDV.

invertebrates inhabit soils and sediments throughout the MDV. There are no terrestrial plant canopies, and no indigenous vertebrates (though seal and penguin carcasses are scattered throughout the valleys, evidence of dispersal attempts from their coastal habitats). Furthermore, the MDV soils are fairly course and rocky. Hence, the MDV are often studied as an extraterrestrial analog (Doran et al. 2010).

Similar to the rest of the world, the hydrologic cycle of the MDV is strongly driven by climate; however, in the MDV, surface energy balance has a stronger control on the hydrologic cycle than precipitation. In the MDV, the size of and connectivity among the hydrologic reservoirs are controlled by the daily, seasonal, and annual cycles of surface energy balance (i.e. net radiation, sensible and latent heat exchanges) across the landscape. A strong positive surface energy balance in the austral summer, driven by warm temperatures and 24 h of solar radiation, allows for liquid water to be present on glaciers, in streams, at the edges of ice-covered lake surfaces and in some soils. However, despite the 24 h sunlight, the energy available for glacier melt can vary considerably over the diurnal timescale due to variations in solar aspect and topographic shading. During the winter, liquid water is present only in lakes, under ~4 m of ice cover. The lack of vegetation canopy in the MDV means that there is no buffer of energy or hydrologic exchanges between the atmosphere and the landscape.

Here, we present our current understanding of the hydrologic cycle of the MDV with a focus on the connections among the different hydrologic reservoirs within the system, and the spatiotemporal dynamics of these connections. Whereas the MDV are often considered a 'simple system' because of the lack of vegetation canopy and extensive groundwater systems, the real world heterogeneities are sufficient to provide a full-scale hydrologic laboratory within which we can test new ideas about fundamental hydrologic processes.

Hydrologic Reservoirs, Processes, and Connectivity

A simple and commonly used conceptual model of hydrologic systems is composed of reservoirs of water (i.e. places where water is stored such as soils, groundwater, lakes, streams, vegetation), and of the fluxes into, out of, and among these reservoirs. The timing and magnitude of connectivity is a primary control on the spatial and temporal distribution of water (in all phases) across a landscape. The MDV hydrologic reservoirs include: the atmosphere, glaciers, soils/permafrost, streams and their hyporheic zones, and lakes. We describe the hydrologic system of the MDV by discussing each reservoir, its fluxes and connections to other reservoirs, and then the sensitivity of the system to changing climate (i.e. boundary conditions).

ATMOSPHERE – PRECIPITATION AND CLIMATE

The MDV polar desert receives little precipitation due to the strong precipitation shadow cast locally by the Transantarctic Mountains (Monaghan et al. 2005). Indeed the MDV are quite dry, with annual water equivalent precipitation, which is dominated by snow, in the valley bottoms of 2–50 mm (Fountain et al. 2010), most of which sublimates prior to melting (Chinn 1993). Air temperatures are cold, with annual averages near −18 °C, winter values reaching −65 °C and summer values typically within a few degrees of freezing (Figure 2; Doran et al. 2002). A characteristic feature of the MDV is the katabatic winds (i.e. drainage winds), which flow from the polar plateau at the western edge of the

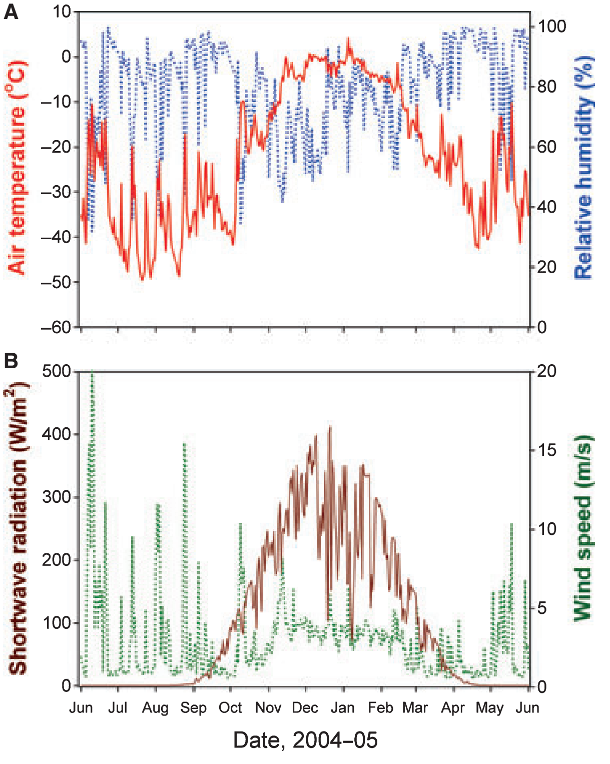

Fig. 2. Daily average values for June 1, 2004 to June 1, 2005 for (A) air temperature and relative humidity (dotted line), and (B) solar radiation and wind speed (dotted line), as measured at the Lake Fryxell meteorological station.

MDV to the coast at the eastern end of the MDV. These winds reach speeds of 37 m/s. Not only are they an important factor in the valley morphology (Marchant and Head 2007), and biology through wind dispersal of organisms (Sabacka et al. forthcoming), they also warm the valleys due to compressional heating as the winds descend to lower elevations. Air temperature increases of 30 °C in a few hours have been recorded and for every 1% increase in the average frequency of katabatic wind events, summer air temperatures increase by 0.4 °C and winter air temperatures increase by 1.0 °C (Nylen et al. 2004).

In the MDV there is little seasonal variability in snowfall observed but the spatial gradient is quite strong with values of ~50 mm water equivalent along the coast decreasing to ~3 mm 20 km inland (Fountain et al. 2010). The precipitation maximum at the coastal margin of Taylor Valley, in particular, is caused by the winter convergence of local wind regimes that produce localized uplift. Snow patches accumulated on the valley floors are composed of direct precipitation and drifting snow, which can accumulate in any wind-sheltered location, such as behind boulders and within stream channels. Katabatic winds transport snow from the valley walls and glaciers, and occasionally from the Antarctic Plateau (just west of the MDV), and account for about half of the measured snow accumulation. The persistence of snow on the valley floors is greater in winter than in summer, but is subject to large spatial variability (Gooseff et al. 2003a). Winter snow lasts the longest at Lake Vida where it persists nearly all winter, but it rarely lasts more than a few weeks at Lake Bonney (Figure 1). The difference is probably due to the mass of snow accumulated at each site and the frequency of wind events that erode and sublimate the snow cover. Sublimation is the most significant process ablating snow on the valley floors. On valley walls, nivation hollows (small depressions that occur and persist due to snow patch accumulation, frost weathering, melt water erosion, and subsequent gelifluction) that collect snow often provide substantial melt that flows down the walls in narrow streaks (Levy et al. 2008).

GLACIERS

The glaciers of the MDV are polar, meaning that their average temperature is well below freezing and the glacier bottom is frozen to the substrate (Chinn 1985; Fountain et al. 2006). In contrast, glaciers in the temperate alpine regions may be at the melting point throughout their thickness and water exists at the glacier bottom, which aids basal sliding. Polar glaciers provide very little melt water compared to glaciers in temperate and alpine regions and move by ice deformation alone, and as such, have very low velocities. All the glaciers in the Dry Valleys, with a few exceptions, are alpine glaciers, that is, small glaciers that originate at high elevations (Figure 3), and a few, like Taylor Glacier or Wright Upper Glacier, are outlet glaciers (i.e. termini) of the East Antarctic Ice Sheet. The spatial trend in climate within the valleys exerts a strong control on glacier mass balance and glacier position (Fountain et al. 1999). The valleys become drier, warmer and windier inland, which reduces snowfall and increases sublimation. Consequently, the equilibrium line altitude, where annual snow accumulation equals annual loss through melting and sublimation, rises inland such that the alpine glaciers are at lower elevations closer to the coast and at higher elevations inland. A simple multiple linear regression, based on distance from the coast and from the valley bottom accounts for 64% of the variance in mass-balance values, which is useful for interpolating mass-balance values for unmeasured glaciers (Fountain et al. 2006).

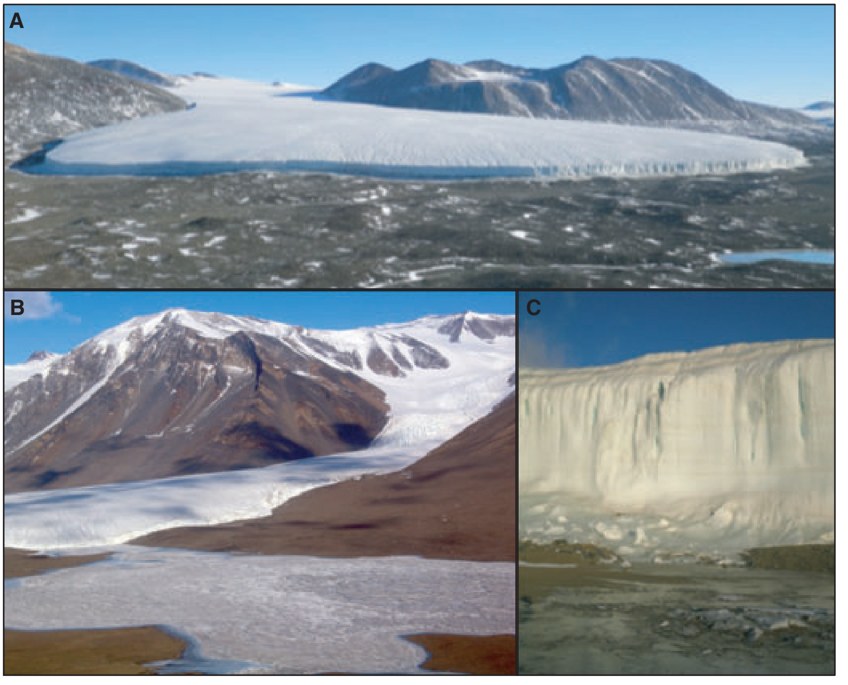

Fig. 3. Glaciers in Taylor Valley, (A) Commonwealth Glacier, (B) Canada Glacier, with Lake Fryxell in the foreground, and (C) the terminus of the Canada Glacier, which is approximately 20 m of vertical ice face.

Numerous glaciers reach the valley bottom where total energy balance (including warm summer temperatures) is sufficient to melt surface ice. Melt water runoff creates ephemeral streams that flow to perennially ice-covered lakes. Stream flow is quite flashy because the ice temperature at the glacier surface is typically at the cusp of melting during the austral summer, such that only small changes in the energy balance at the ice surface turn water flow on or off (Hoffman et al. 2008; Lewis et al. 1998). Indeed, a thin layer of new snow only a few cm thick can terminate meltwater production due to the increased albedo of the ice surface. This new snow layer can persist for days to weeks due to the little sensible heat in the atmosphere. Runoff differs for each glacier, not from glacier surface area, but mostly in response to surface conditions that alter the energy balance. Therefore, runoff generation is strongly affected by valley position (i.e. solar radiation, winds, air temperature, and snowfall) of source glaciers and by surface roughness that alters turbulent heat exchange with the atmosphere.

SOILS AND PERMAFROST

The MDV landscape is completely underlain by thick permafrost (>100 m), but at the surface, active layer soils thaw during the austral summer to depths of 60–70 cm, harboring vibrant microbial and invertebrate communities (Treonis et al. 1999). A majority of the ice-free MDV landscape below 1000 m elevation (61%) is underlain by dry permafrost (frozen soil with very little water content) (Bockheim et al. 2007). As with most soils, the thermal regime of MDV soils is a consequence of surface energy balance and internal characteristics of the soil. However, in the MDV, soil thermal regime is punctuated by strong surface variability annually, with greatest thaw depths typically observed in early January

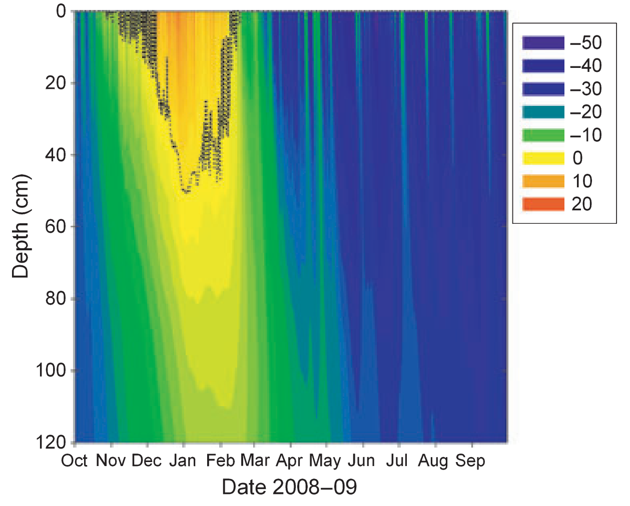

Fig. 4. Near-surface soil temperature dynamics from October 2008 to September 2009 at Bull Pass (see Figure 1 for location). Black line denotes 0 °C isotherm. Data from USDA data archives.

(Figure 4). Given the low soil moisture, the beginning and end of the summer are characterized by daily freeze–thaw cycles penetrating 10–20 cm deep in most locations. Hence, connections between soils and atmosphere vary greatly with soil heat content.

With no rain and little snowmelt, soils across the MDV are generally dry, except where sustained sources of liquid water are present. Soils that border streams and lakes are locations of consistent wetness during the austral summer. Water moves from the water bodies into the soil and gets wicked away from the shoreline or stream edge due to capillary suction (a result of the surface tension of water and the pore sizes of the soil and sediments). Hence, the local slope and soil particle distribution have some control on the extent to which these wetted margins around water bodies occur (Gooseff et al. 2007). The windy, dry conditions above these soils drive evaporation of this soil water, which induces more capillary suction, moving stream or lake water through these soils (Northcott et al. 2009). As a result, these margins collect salts from evapoconcentration of solutes in the soils (Barrett et al. 2009). In comparison to dry soils across the MDV landscape, the soils in wetted margins tend to be more thermodynamically buffered because of the high water content and potential for evaporation, with smaller swings in daily and seasonal temperatures (Ikard et al. 2009). In the case of streams these zones may support mosses just on the streamside edge of the salt crust that occurs at the edge of the wetted margins.

STREAMS AND HYPORHEIC ZONES

Streams of the MDV provide a critical linkage between glaciers and lakes, and deliver substantial water to soils and sediments along the stream corridor. Stream channels are stable and well-defined, ranging in length from <1 km to over 24 km. However, melt water flows in streams for only 8–12 weeks per year, when surface energy balance on MDV glaciers is great enough to produce melt water (Figure 5A). Hence, connections of streams to glaciers, soils, and lakes are spatially consistent and temporally short. Even on a daily time scale streamflow is variable because the greatest amount of melt is generated

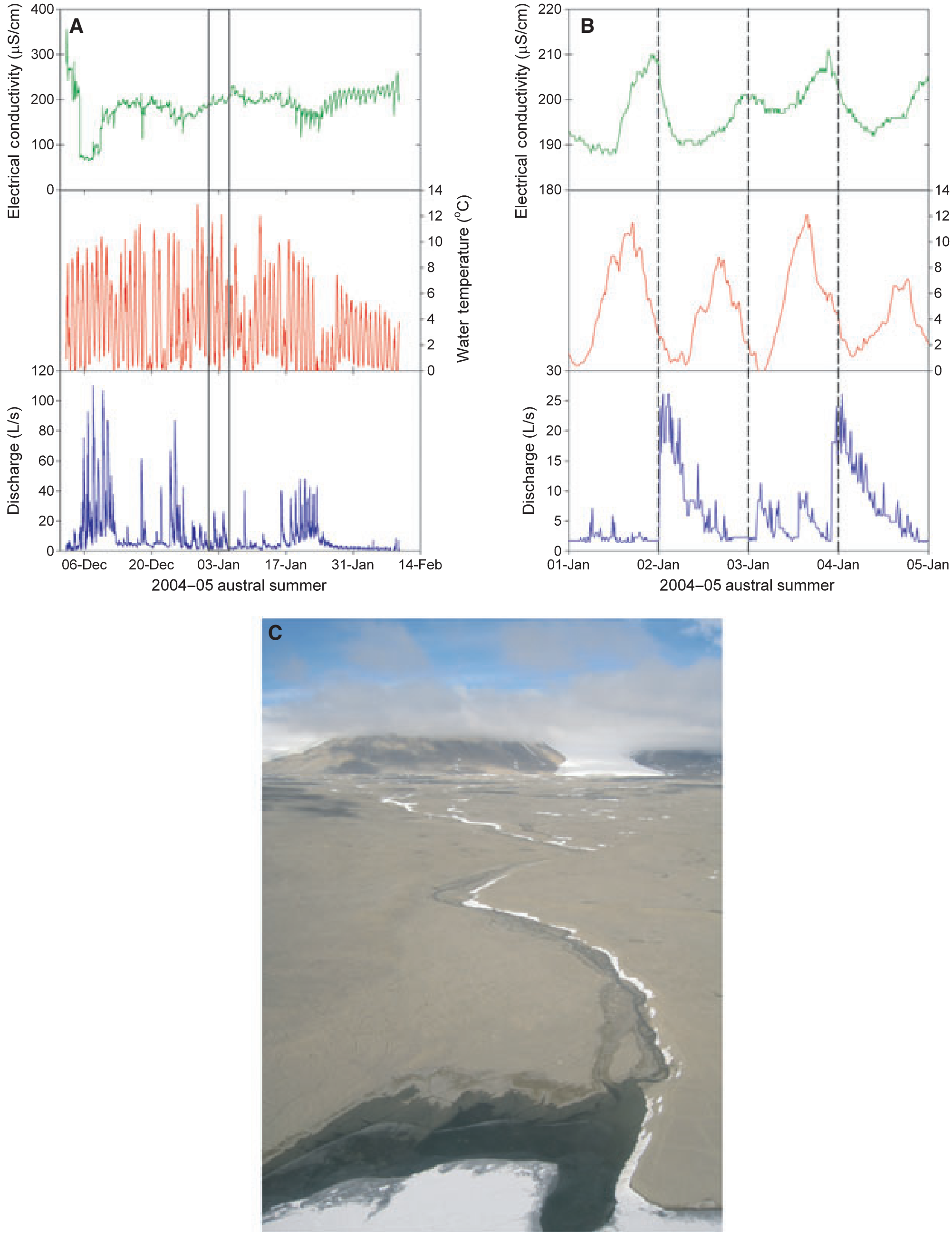

Fig. 5. Streamflow records (electrical conductivity, water temperature, and discharge) for Crescent Stream (see Figure 1, location 8) in the austral summer of 2004–2005 for (A) the entire flow season, and (B) January 1–5, 2005. Vertical dashed lines in (B) denote midnight. Note that the timing of peak electrical conductivity precedes midnight and discharge peaks just after midnight, whereas water temperatures peak in the early evening. (C) Stream flowing into the south end of Lake Fryxell adjacent to Crescent Stream.

when the sun shines directly on the glacier faces, causing a melt pulse that moves down the stream with the prominent leading edge (due to flow resistance induced by the streambed) (Koch et al. 2011) (Figure 5B). Many dry valley streams have extended reaches with wide channels where the streambed is armored by a stone pavement (flat sides of rocks are exposed at the surface) and most of the sediment moved in the channels comes from undercutting of the banks. These very stable sections of streams are often covered with extensive microbial mats structured by several algal species, but generally dominated by orange-colored *Phormidium* in the middle of the channels, and black-colored *Nostoc* on the edges of streams (McKnight et al. 1999).

Streams are connected to soils through hyporheic zones, which are thawed volumes of sediment and soil adjacent to a stream channel through which stream water exchanges, extending <10 m from stream edge. Unlike most temperate streams, in the dry valleys the lateral extent of the hyporheic zone can be directly observed as a damp band of sediment adjacent to the stream. Exchange of water through hyporheic zones of MDV streams has been identified as a critical process driving stream ecosystem biogeochemistry (Gooseff et al. 2004; Koch et al. 2010; McKnight et al. 2004). Hyporheic zones represent an important control on stream flow during 'low flow' summers (i.e. those with low glacial melt water production) because they are essentially porous 'sponge reservoirs' making up streambeds that must be filled before water can flow downstream. Hence, longer streams tend to demonstrate a more pronounced influence of hyporheic storage than small streams (Conovitz et al. 1998; Koch et al. 2011). In fact, for some longer streams during colder summers only a small portion of the glacial melt water may reach the receiving lake in the valley floor because a majority is retained in the extensive hyporheic zone, whereas in shorter streams, streamflow is more likely to reach the lake because the hyporheic storage provides a smaller volumetric threshold to overcome.

When liquid water is available in streams and/or hyporheic zones, there is a consistent link to the atmosphere through evaporation. Gooseff et al. (2003b) observed evaporation rates on the order of 6 mm/day from direct measurements in a short-term pan experiment. In the longest and largest monitored Antarctic river, the Onyx River, analyses of discharge at an upstream and downstream gauge indicate that not all stream water that passes the upper gauge (Lower Wright) passes the lower gauge (Vanda) (Figure 6A), with deficits (i.e. streamflow volume that passes the upstream gauge does not pass the downstream gauge) as great as 1.7 million m^3 annually (Figure 6B). Isotopic signatures of river water along the length of the Onyx River become more enriched in $\delta^{18}O$ and δD, suggesting that evaporation is occurring along the length of the river as the water molecules with lighter atoms are preferentially evaporated from the river (Figure 6C). Note in particular in Figure 6C that the collection of water samples at the upstream (LWRT) and downstream (Vanda) stream gauges are grouped separately, and that a synoptic sampling along the river between these two gauges shows a pattern of more enriched water from upstream to downstream. After melt water generation ceases, stream flow may partly freeze in the channel in patches and pools. Over the fall and winter, any liquid or frozen water in stream channels and hyporheic zones can evaporate or sublimate, respectively, causing over-winter water losses that also must be refilled before streamflow can move downstream in the following austral summer.

In addition to controlling the amount of glacial melt reaching the lakes, physical and biogeochemical processes occurring in the stream ecosystems act to modulate the quality of that water, and thereby the fluxes of heat, nutrients particulate material and major ions entering the lakes. At low flows, the streamwater can be warmed as it flows over the wide streambed under the intense sunlight, reaching temperatures as high as 15 °C during the time of day when solar radiation is greatest (Cozzetto et al. 2006). Because these peak temperatures occur simultaneously in all the streams flowing into the lake, a daily heat pulse is generated that may contribute to the melting out of the moat areas around the

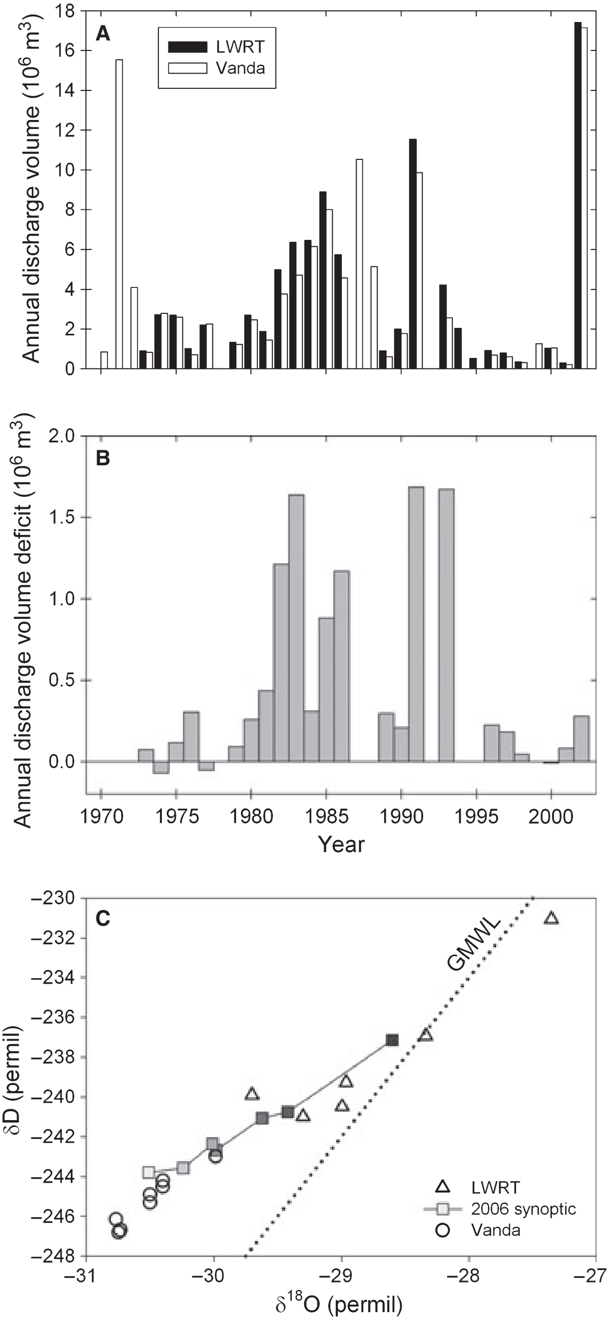

Fig. 6. (A) Onyx River total flows at the LWRT gauge (upstream) and Vanda gauge (downstream), (B) flow deficits (computed as flow passing Vanda less flow passing LWRT), and (C) isotope enrichment. GMWL is the global meteoric water line, a representation of worldwide precipitation. Squares represent a synoptic sampling campaign that occurred in January 2006, in which symbol colors go from dark (upstream) to light (downstream).

lake edges. The warm stream environment and wide stable channels promotes the growth of perennial microbial mats composed chiefly of cyanobacteria and diatoms (McKnight et al. 1999). Uptake of nitrate and phosphate by these microbial mats regulates the nutrient flux to the lakes, with most of the nutrient flux coming from streams that are too rocky and steep or too sandy to support these microbial mats. These mats are also a source of particulate organic material that is carried primarily at the daily peak in flow to the littoral zone of the lakes (Figure 5B).

Chemical weathering rates in MDV streams are extremely high. The sediments of these streambeds are unconsolidated and relatively 'fresh' materials. Dilute stream water (glacial melt) actively exchanges between the open channel and the thawed streambed sediments. When thawed, water stored in the streambed actively dissolves the minerals there (Maurice et al. 2002). Thus, as the dilute stream water exchanges with the high-solute hyporheic water and stream water, concentrations of silica, potassium, and other dissolved weathering products increase downstream (Gooseff et al. 2002). Because there is not a groundwater system and the precipitation that falls as snow sublimates, watershed areas of MDV streams correspond essentially to the surface area of the streambed and its hyporheic zone. Hence, chemical weathering yields per unit area of 'watershed' are some of the highest on earth (Lyons et al. 1997; Nezat et al. 2001).

LAKES

Most lakes in the MDV are closed basins. All inflow is via surface streams and some component of subsurface melt and the only outlet is through evaporation of free water in the summer months, and sublimation of the ice cover year-round. All lakes of the MDV also have perennial ice covers. For most, during the summer months a 'moat' opens in the shallow shore region of the lake to allow stream flow to get under the ice cover and reach hydrostatic equilibrium. There are a few lakes where this does not happen. One of the largest of these lakes, Lake Vida in Victoria Valley, has such a thick ice cover that summer stream flow ends up perched on top of the >15 m-thick ice where it freezes at the end of the summer (Doran et al. 2003).

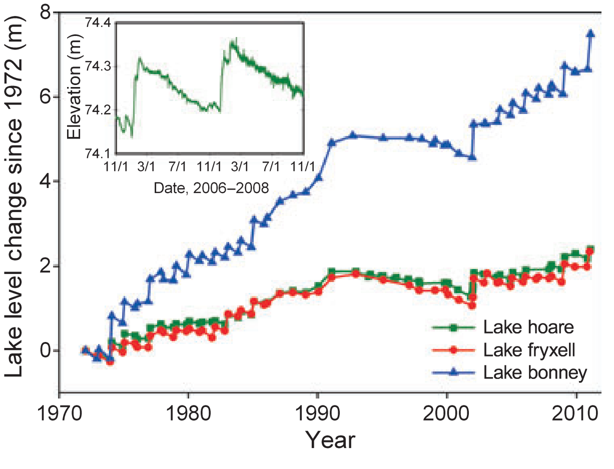

Fig. 7. Lake level changes since 1972 for Lakes Fryxell, Hoare and Bonney (all in Taylor Valley), and inset of Lake Hoare from 2006 to 2008. All three lakes are closed-basin lakes. Hence, the increasing lake levels since 1972 suggest an overall net positive energy balance that is producing more melt during the summer than is lost to sublimation (year-round) and evaporation (during the summer). The decrease in lake level during the winter is a result of sublimation losses of the ice cover.

The water volume of the lakes is balanced between stream flow additions in the summer time and evaporation/sublimation over the year. If the balance is positive, the lakes gain in volume and height (Figure 7). If the balance is negative, the lakes decrease in volume to the point where a lake may shrink to a brine pool. Lake level rise is largely driven by a positive energy balance during the summer, which is strongly influenced by warm air temperatures over the brief summer period.

Continuous lake level measurements (Figure 7, inset) show a strong sublimation loss in the winter. In the warmer summer months, ablation is offset and outweighed by the stream inflow, which induces a net rise in lake levels. Close inspection of Figure 7 inset shows that the most rapid drop in lake level is in the shoulder months before and after the stream flow season. Even though the winter months are windier (i.e. Figure 2B), the combination of solar radiation, and warmer temperatures accelerates evaporative loss in the summer.

HYDROLOGIC RESERVOIR CONNECTIONS

McMurdo Dry Valley hydrologic reservoirs are dynamically linked in space and time, as dictated by climatic forcing. Throughout the year, MDV glaciers, lakes, and soils are connected to the cold, dry, windy atmosphere. Hence, fluxes from these reservoirs to the atmosphere occur through sublimation and evaporation (Chinn 1993; Gooseff et al. 2003b). The short duration of streamflow means that streams are only connected to other reservoirs (or providing connections between glaciers and lakes), for part of the summer, and completely as a function of climatic conditions that influence melt water generation. Thus, it is the climatic conditions that drive energy balance for phase change of water (either from ice to liquid, or from liquid/ice to vapor) that significantly control the fluxes and timing of connections among MDV hydrologic reservoirs.

The MDV ecosystem has evolved in the context of and as a function of the dynamic hydrologic connections. For example, lake phytoplankton communities receive inflowing nutrients from streams only during the short flow season during the austral summer, yet persist year-round under a permanent ice cover (Priscu 1995). They are primarily light-limited, rather than nutrient limited. Cyanobacterial mats in streams are able to desiccate for 9–10 months of the year (i.e. between flow seasons) and longer, and become biologically active within hours of becoming re-wetted (McKnight et al. 2007).

Implications for Ecosystem Function and Advancing Research on Hydrologic Controls of Ecosystem Processes

The hydrologic system within the MDV represents a real-world laboratory in which to study specific hydrologic processes, such as hyporheic exchange (the movement of stream water between the main channel and the hyporheic zone), impacts of snow on glacier dynamics, and lake ice melt and sublimation dynamics, and evaporation. Two specific hydrologic processes we highlight are hyporheic exchange, and soil moisture movement. The advantage of studying these processes in the MDV comes from being able to easily observe locations of high soil moisture (i.e. wetted soils are darkened). In the case of hyporheic exchange, the extent of the hyporheic zone adjacent to the channel is clearly identified where soils transition from wet to dry. This is not the case in temperate streams where observations require more involved hydrologic/chemical methods to delineate the hyporheic zone. However, surface vegetation and soil variability adjacent to temperate streams mask any potential surface evidence of hyporheic zone location. Furthermore, the shallow depth of thaw beneath and adjacent to MDV streams clearly limits the total volume and extent of the hyporheic zone. This is in contrast to temperate streams, where the continuum from hyporheic zone to deeper alluvial aquifer is not easy to distinguish. The presence of permafrost as a 'no-flow' boundary limits the potential for regional subsurface flow. Soil moisture generation (snow or glacier melt), movement, and evaporation in the MDV are obvious at the surface where fine-grained material is coincident. When coarse-grained material occurs at the surface, the capillary forces decrease and wetting does not occur. Time lapse observations/measurements of wetted extent and *in situ* monitoring of soil moisture content can be targeted directly at affected soils in the MDV. In addition, direct sampling for soil ecosystem characteristics can also be clearly targeted to wet and dry soils. In temperate watersheds, the presence of vegetation and substantial organic matter in surface soils can interfere with our ability to easily identify wet soils versus dry soils. The direct observation of hydrologic reservoirs and interactions among reservoirs in the MDV makes this a unique laboratory for studying hydrological processes and associated influence on ecosystem processes.

Another significant feature of the MDV hydrologic cycle is that the sizes of the hydrologic reservoirs and the magnitude and duration of hydrologic processes can be directly measured and related to changing climatic conditions. Surface energy input to the MDV during the austral summer season is variable from year to year (e.g. note flow variations in the Onyx River in Figure 6A). Hence, the variable boundary conditions and consequences for interactions among hydrologic reservoirs provide the opportunity to directly inform our understanding of fundamental hydrological processes. The polar regions are most sensitive to changing climate because warming is accelerating faster in these regions than in the rest of the world (Holland and Bitz 2003; Walsh 2009) and because these earth systems contain extensive reservoirs of ice. Antarctica is projected to warm over the next several decades (Chapman and Walsh 2007; Walsh 2009). If a trend of increasing energy (e.g. from warmer temperatures or more solar input due to fewer clouds) input to the MDV occurs over the coming decades, we expect that the connectivity among hydrologic reservoirs will be substantially increased (Figure 8). As such, it is expected that more wetted soils would occur across the landscape and as a consequence a substantial shift in soil habitat would occur. More streams from higher elevations of glaciers are likely to develop, potentially expanding stream habitat for algae and specifically diatom communities. In addition, reactivation of formerly wet stream habitats (channels that have not had flow in a long time) such as dry streambeds that may have supported life in the recent past is also likely to occur (e.g. McKnight et al. 2007). Lake levels will rise, expanding the water column habitat within, shortening streams, and inundating soils that had previously interacted directly with the atmosphere (at least for the past 100s of years). The cold-based glaciers of the MDV would have to warm significantly to before basal sliding would occur, though such a transition would likely occur from lower to higher elevations influencing valley-bottom parts of glaciers prior to their mountain sources. The frequency and intensity of 'warm years' will directly influence the extent to which inter-annual legacies develop and influence the ecosystem or the hydrological processes that occur the following year(s). As long as there is significant ice in the system (glaciers and permafrost), the hydrologic system is likely to be most sensitive to surface energy balance unless precipitation regime changes significantly to warmer (i.e. rain dominated) and wetter. Whereas the overall system is sensitive to inter- and intra-season variability in climatic conditions, the state of the physical system and the structure and function of the ecosystem are consequences of both past and current processes. The MDV hydrologic system provides an excellent bellwether for even slight changes to the climatic conditions of Antarctica.

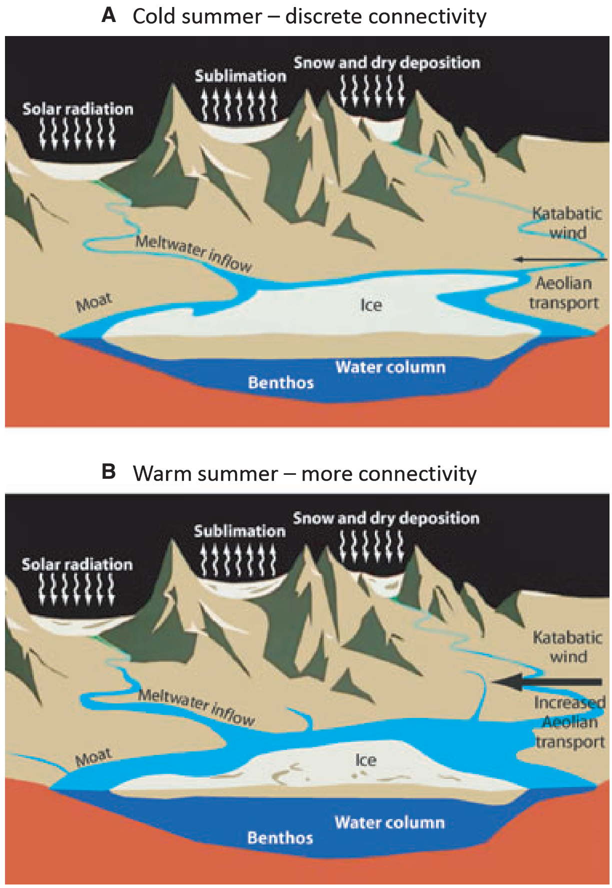

Fig. 8. Comparison of conceptual models of hydrologic connections in cold (A) and warm (B) austral summers.

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Short Biographies

Michael N. Gooseff's research is focused on the influence of hydrology on ecosystems, particularly in the context of stream–groundwater interactions, climate change, and in polar regions. His field research sites span the world from arctic Alaska to the McMurdo Dry Valleys of Antarctica. Current interdisciplinary research projects are addressing permafrost degradation in response to a warming climate in the Arctic, responses of nutrient cycling in arctic river networks in response to changing seasonality, controls of discontinuous snow pack on soil microbial communities and associated biogeochemical cycling in Antarctica, modeling ecosystem processes in Antarctica, and the influence of valley floor hydrology on stream–groundwater interactions during annual stream baseflow recession. Before moving to Penn State University, Gooseff taught at the Colorado School of Mines and Utah State University. He earned a Bachelors of Civil Engineering at Georgia Tech and MS and PhD degrees in Civil Engineering at the University of Colorado.

Diane M. McKnight's research is focused on the interactions of hydrology, biology and chemistry in natural systems ranging from polluted acid mine drainage streams to aquifers in south Asia, to pristine polar ecosystems in northern Alaska and Antarctica. Her biogeochemical research has addressed the fate of trace metals and natural organic matter in the environment, and has involved the development of reactive solute transport models. McKnight has been a professor at the University of Colorado since 1996. Prior to that, she was a research hydrologist with the US Geological Survey. She earned a Bachelor of Science in Mechanical Engineering, an MS in Civil Engineering, and her PhD in Environmental Engineering at the Massachusetts Institute of Technology.

Peter Doran's research is focused on aquatic, climate, quaternary, and astrobiological sciences. He has conducted extensive field research in the Arctic and Antarctic. Recent research projects include addressing the paleoenvironmental reconstruction, sedimentology and 3D biogeochemical mapping of ice-covered lakes in Antarctica. Doran became a Leopold Fellow in 2008 and has been a professor at University of Illinois at Chicago since 1998. He earned a Bachelors of Science degree in Geography from Trent University, an MS degree in geography from Queen's University and his PhD degree in Hydrology/Hydrogeology at the University of Nevada, Reno.

Andrew G. Fountain's research directly addresses the basic physical controls earth surface processes, with an emphasis on cryospheric processes. He has conducted research on atmospheric ice physics, lake ice and sea ice dynamics, and glaciers. Recent research projects have been directed toward understanding glacier dynamics in response to climate changes. Fountain has been a professor at Portland State University since 1996 after working as a research hydrologist for the US Geological Survey. He earned a Bachelors of Science degree in Physics from St. Lawrence University, an MS degree in Atmospheric Sciences from the University of Alaska Fairbanks, and his PhD degree in Civil Engineering from the University of Washington.

W. Berry Lyons' research addresses biogeochemistry of terrestrial/aquatic systems in response to climate change, including chemical and physical weathering dynamics, and the impact of anthropogenic activities (urbanization and agriculture) on water quality. He has conducted field research in a variety of systems including tropical watersheds in Panama, agricultural and urban settings in the American Midwest and Antarctica. Lyons has been a professor at the Ohio State University since 1999. Prior to moving to Ohio State University, he was a professor at the University of Alabama, the University of Nevada, Reno, and the University of New Hampshire. He earned a Bachelor of Arts degree in Geology from Brown University, and his MS and PhD degrees in Chemical Oceanography at the University of Connecticut.

Note

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