Glacial meltwater modeling to simulate streamflow and lake levels in Taylor Valley, Antarctica

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Study Site: Taylor Valley, Antarctica

77°40′ S, 162°30′ E

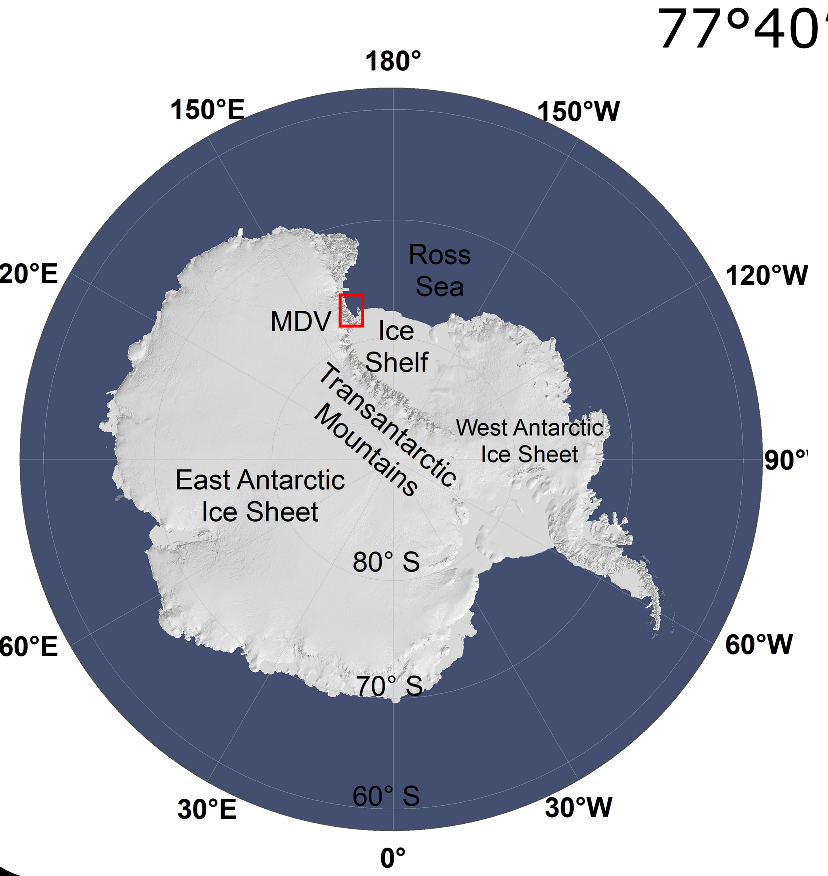

Figure 1. (at left) Map showing the location of the McMurdo Dry Valleys (MDV) region within Antarctica. The MDV, the largest ice-free region (4,500 km²) in Antarctica. The MDV are a polar desert: annual temperature of -18° C and precipitation <50 mm w.e. yr^{-1} (Fountain et al. 1999).

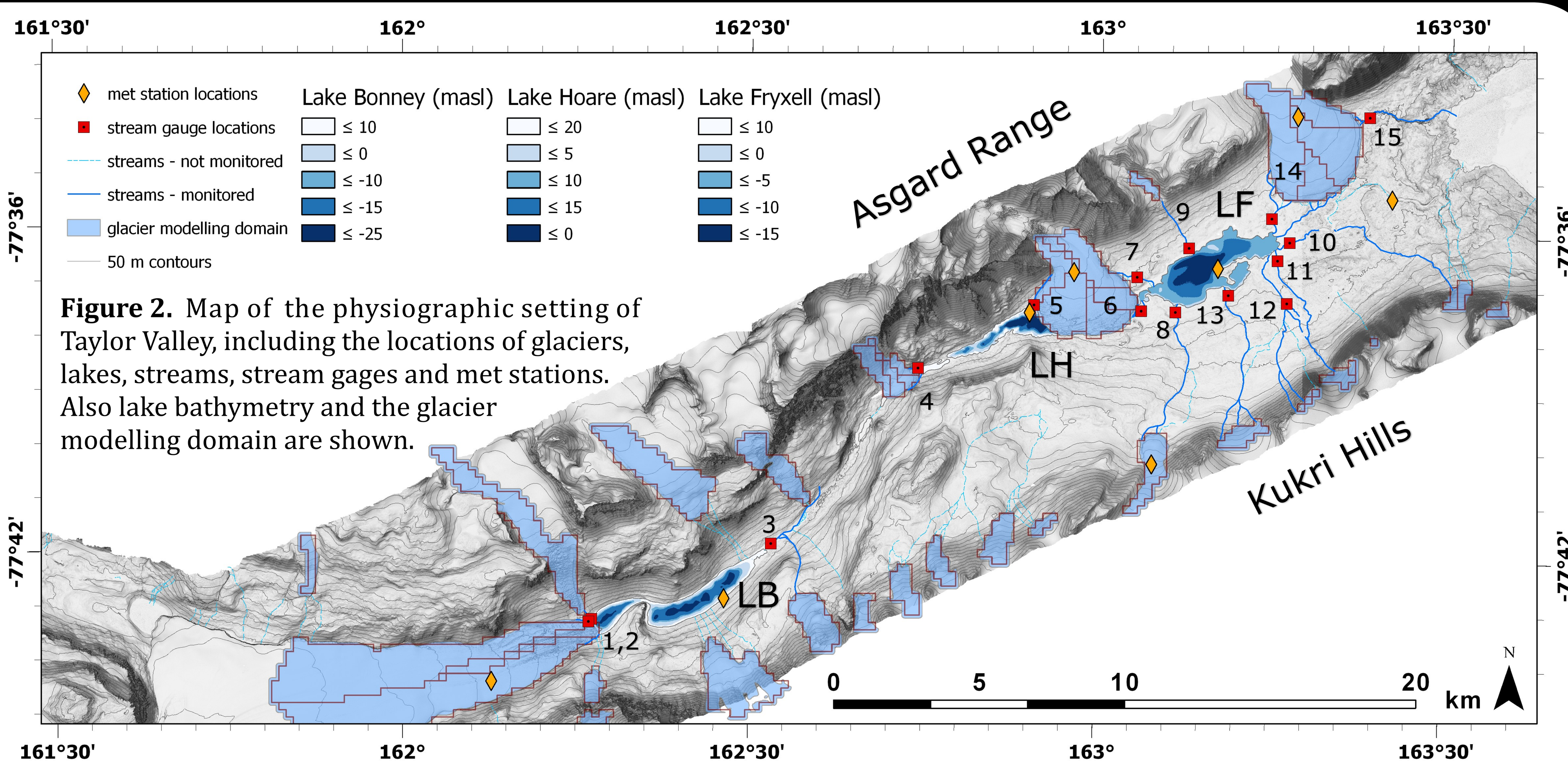

Figure 2. Map of the physiographic setting of Taylor Valley, including the locations of glaciers, lakes, streams, stream gages and met stations. Also lake bathymetry and the glacier modelling domain are shown.

I. Introduction

Three **closed-basin, perennially ice-covered lakes** occupy the valley floor: lakes Bonney, Hoare and Fryxell. **Glacial meltwater** accounts for nearly the **total inflow** to these lakes. **Groundwater flux** is essentially **non-existent**. **Outflow** is through **sublimation** of the frozen lake surface. Lake levels are highly sensitive to changes in climate and are **mediated by the surface energy balance of the glaciers**. With mean summer air temperatures are below 0°C, glacier ablation shows a complex sensitivity to solar radiation and wind speed. (Fountain et al. 1999)

Objectives:

- Simulate streamflow and lake level change in Taylor Valley.
- Test meltwater and lake water balance model assumptions.

II. Methods

The distributed ICEMELT model (Hoffman et al. 2016) is applied to simulate streamflow and lake level from 1995 to 2013 at a grid resolution of 250 m. The meltwater model:

- is a **distributed, physically-based** energy balance model
- is driven by gridded **local weather measurements**
- was **calibrated** using **ablation measurements at Taylor and Canada glaciers**
- is tuned specifically to local ice and meteorological conditions
- **assumes direct** (same-day) **meltwater routing**
- Additionally, the model accounts for solar radiation penetration into the ice, the spatial variability of albedo, and glacier topography that affects microclimate.

Lake Water Balance Equation:

$$\frac{dV}{dt} = \underbrace{Q_{direct} + Q_{stream} + Q_{ground}}_{Q_{glacier}} + [\overset{0}{\cancel{P}} - S - \overset{0}{\cancel{E}}]A$$

Simplified to:

$$\frac{dV}{dt} = Q_{glacier} - S * A$$

A simple water balance method was used to estimate annual lake volume and level. The lake model relies on the following assumptions:

- **simplifies inflows**, treating glacier meltwater as the sole inflow
- **accounts for sublimation** from the lake ice surface and **ignores groundwater and precipitation** inflows
- basin geometry determined from 2 m lidar

Data Sources:

Doran, P. 2016. McMurdo Dry Valleys Lake Levels. www.mcmlter.org.
Gardner, C. 2007. McMurdo Dry Valleys Basic GIS Map Layers. www.mcmlter.org.
Gooseff, M., and D. McKnight. 2016. McMurdo Dry Valleys Streamflow Daily Averages. www.mcmlter.org.
McKnight, D., and M. Gooseff. 2017. McMurdo Dry Valleys Stream Descriptions. www.mcmlter.org.
Priscu, J., and J. Schmok. 1995. McMurdo Dry Valleys Bathymetric Hypsographic Function Values. www.mcmlter.org.

IV. Lake Level Results

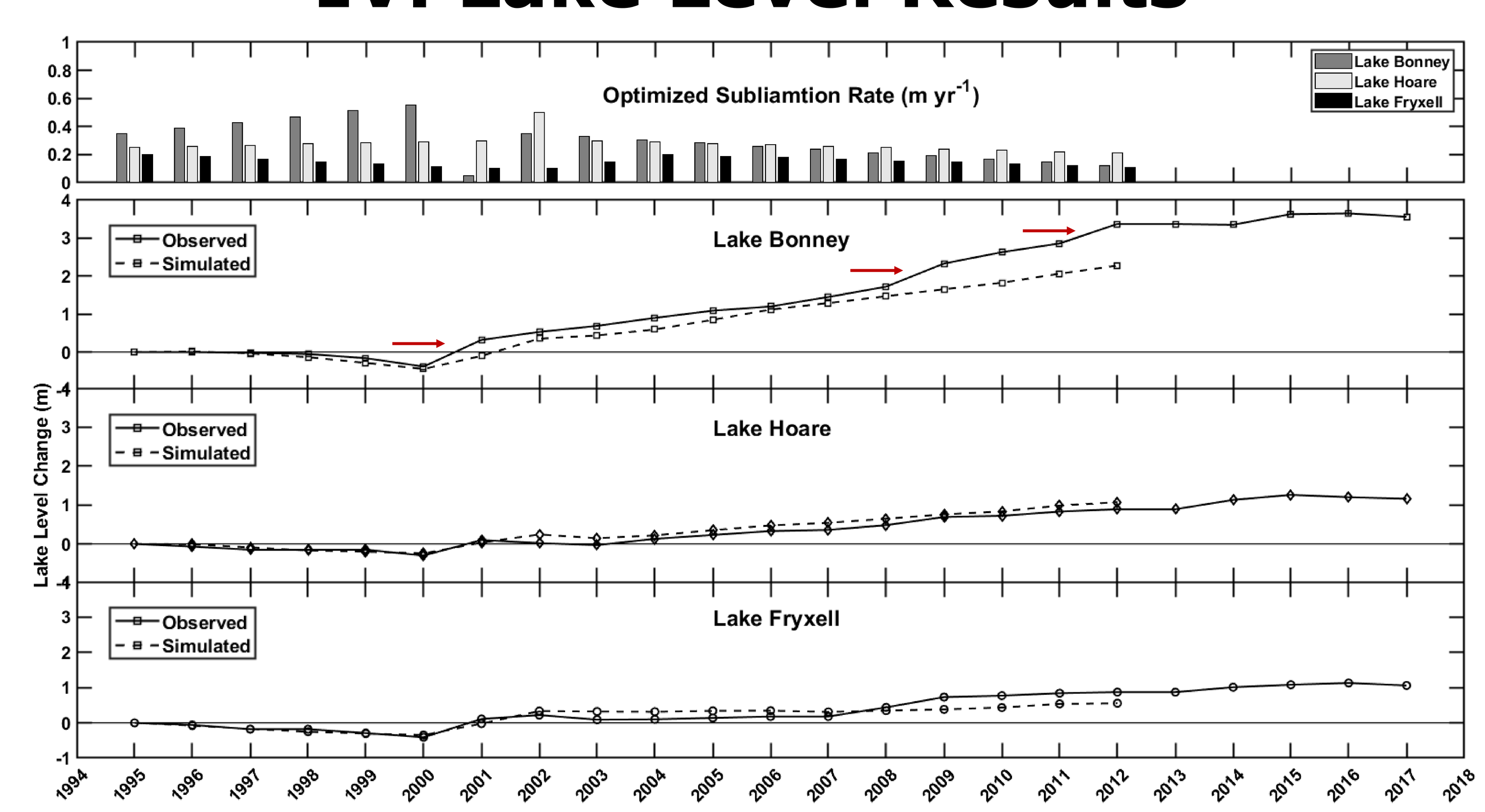

Figure 7. Simulated (dashed) versus observed (solid) lake level change from 1995 level based on annual, end-of-season water balance. Years on the x-axis indicate the starting year of the melt season (e.g. 1995 for November 1995 to March 1996). Sublimation rates were adjusted to find best agreement of lake level change. Red arrows show 'flood years' lake level response.

V. Conclusions

- With an adjustment of –0.05 to albedo, the meltwater model can **predict streamflow moderately well.**
- Predicted runoff results show higher efficiency in simulating dynamics but lower efficiency in simulating observed flow magnitudes.
  - Suggesting that routing assumptions hold (**high dynamical efficiency**)
  - Some meltwater sources are being neglected, e.g. ablation zone size or high elevation snow melt (**low magnitude efficiency**).
  - Meltwater model results are **better for Canada and Taylor** (Bonney basin) glaciers.
  - **Increased model bias on Commonwealth and Kukri Hills glaciers** suggest that unaccounted ice surface properties, e.g. surface roughness length, are present.
- Lake model results show that **under-predicting melt inflow** limits ability to model lake level change.
  - **Particularly at Lake Fryxell** and **during flood years** of 2001-02, 2008-09 and 2010-11.
- **Lake surface sublimation rates** required to fit lake level rise (0.01 to 0.5 m yr^{-1}) are less than estimated, real-world values (0.35 to 1 m yr^{-1}).

References:

Fountain et al. 1999. Physical Controls on the Taylor Valley Ecosystem, Antarctica. *BioScience*.
Hoffman et al. 2016. Distributed modeling of ablation (1996–2011) and climate sensitivity on the glaciers of Taylor Valley, Antarctica. *Journal of Glaciology*.

III. Streamflow Results

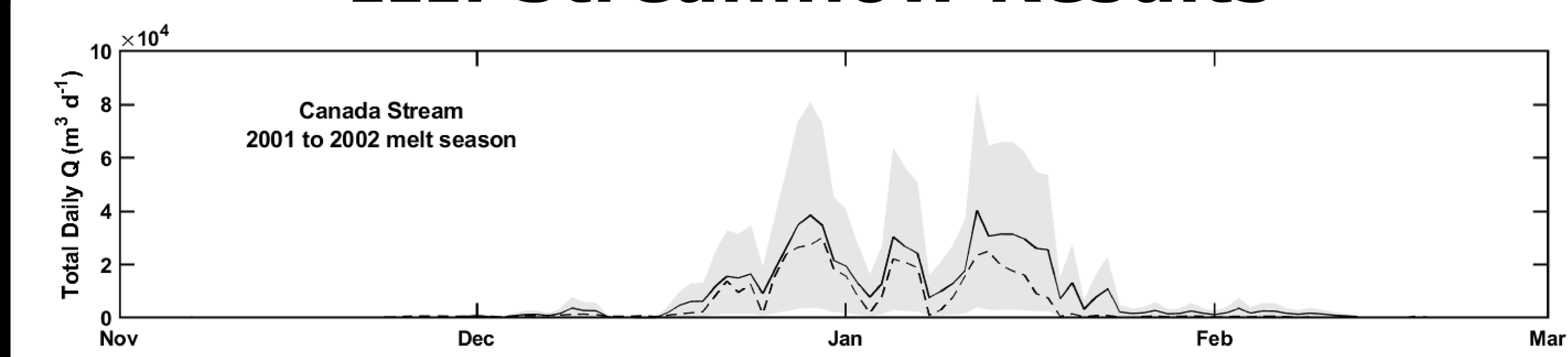

Figure 3. Simulated (dashed) versus observed (solid) daily runoff totals at Canada Stream (7) for the 2001-02 melt season. Associated daily streamflow measurement uncertainty (5-25%) is shown as the grey shaded area. This season was an anomalous 'flood year'.

A

		E	nRMSE	r^2
1	Santa Fe	-0.05	1.03	0.34
2	Priscu	0.72	0.53	0.78
3	Lawson	0.57	0.66	0.92
4	House	0.60	0.64	0.76
5	Andersen	0.68	0.56	0.86
6	Green	-0.13	1.06	0.94
7	Canada	0.62	0.61	0.94
8	Delta	0.81	0.44	0.89
9	Huey	-0.24	1.11	0.77
10	Aiken	-0.36	1.17	0.79
11	Von Guerard	-0.52	1.23	0.64
12	Harnish	-0.34	1.16	0.66
13	Crescent	0.30	0.84	0.61
14	Lost Seal	0.49	0.72	0.79
15	Commonwealth	-0.11	1.06	0.80
	All	**0.66**	**0.58**	**0.78**

B

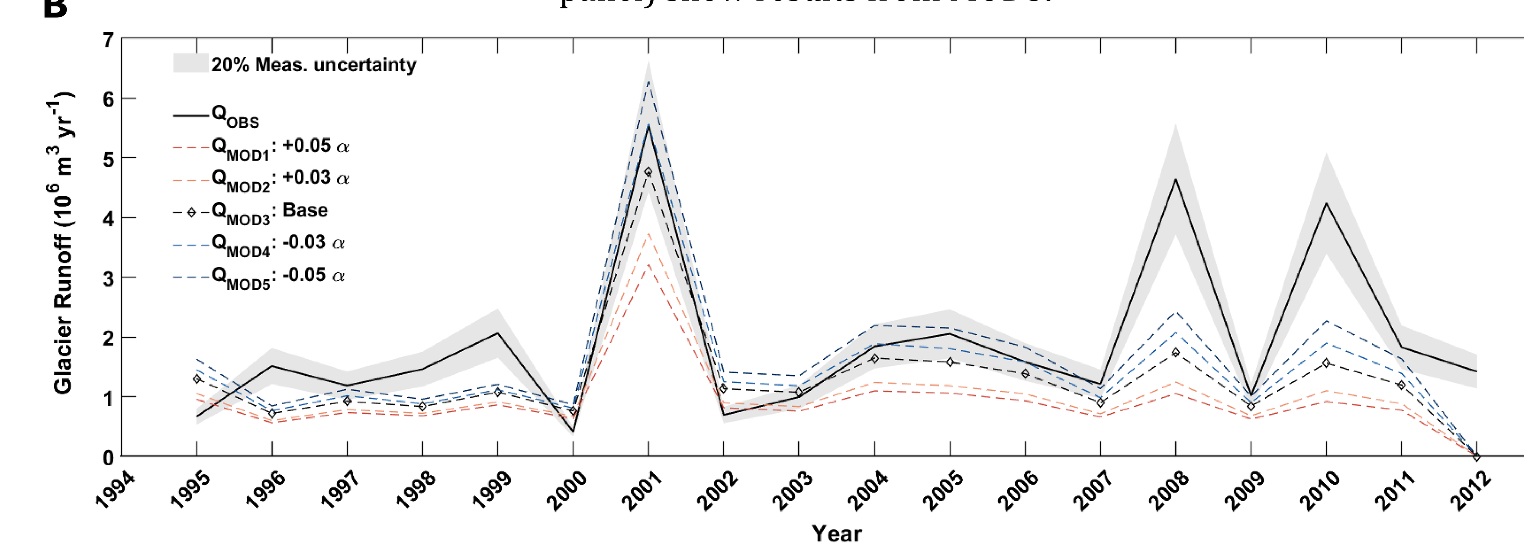

Figure 4. Top panel (A) shows model efficiency in predicting total daily discharge using the Nash-Sutecliffe Efficiency (E), normalized root-mean-square error (nRMSE) and the coefficient of determination (r^2) for all 15 streams. The bottom row shows efficiency metrics for the entire model period across all basins. The bottom panel (B) shows simulated (dashed) versus observed (solid) total annual runoff for all 18 modeled seasons based on 5 different models (MOD1 to MOD5). Model 3 is the base model with no global adjustment to albedo. MOD5 is the highest efficiency model with albedo lowered by 0.05, within the instrumental uncertainty of measured albedo values. All figures (including top panel) show results from MOD5.

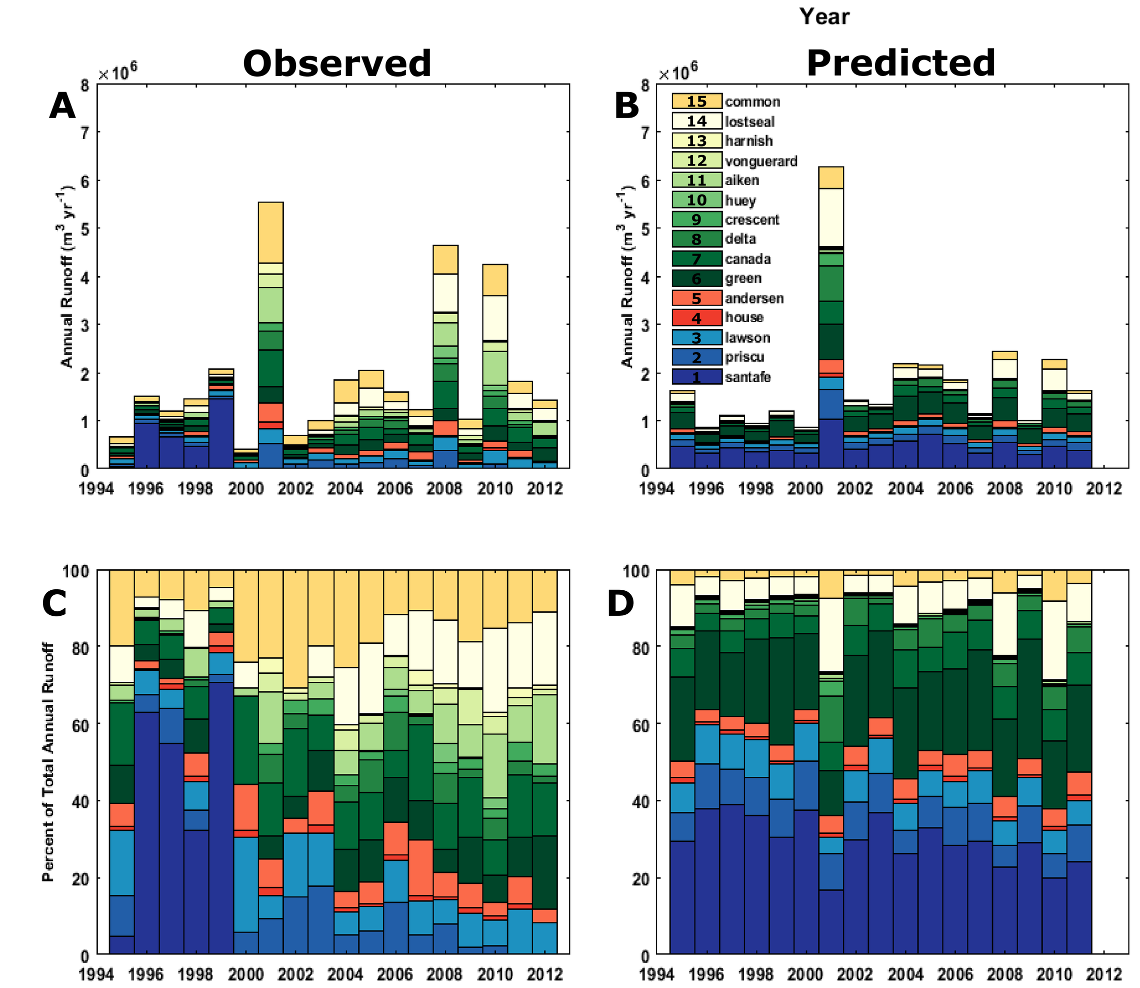

Figure 5. Stacked bar plot of observed (A) and predicted (B) total annual runoff for all streams. Stacked bar plot of observed (C) and predicted (D) percent of total annual runoff for all streams. Blue colors represent streams that flow into Lake Bonney, red colors for streams flowing into Lake Hoare and green colors for streams flowing into Lake Fryxell. The beige color represents Commonwealth Stream, which flows to McMurdo Sound.

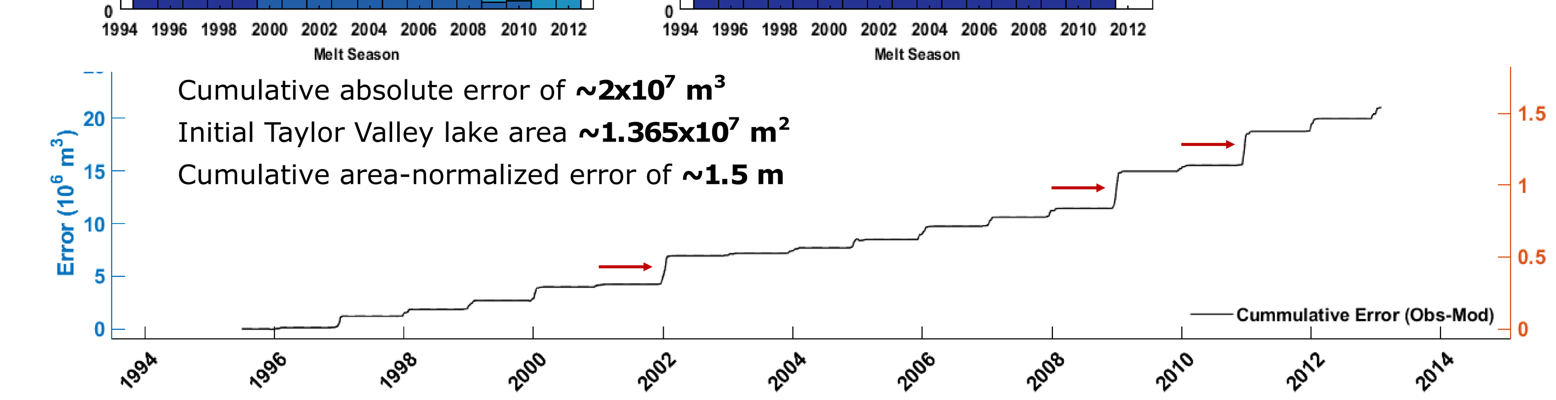

Figure 6. Cumulative absolute (left axis) model error (observations minus predictions) for total daily discharge. Absolute model error was divided by the sum of all three lake areas from 1995 to give an area-normalized model error (right axis). Red arrows show 'flood years'.