MODERN AND PALEOCLIMATE RELATIONS OF ROCK GLACIERS AND RELATED ROCK-ICE FEATURES (RIFs) OF THE SIERRA NEVADA, CALIFORNIA, USA

CONSTANCE MILLAR AND ROBERT WESTFALL

USDA Forest Service, Sierra Nevada Research Center, Albany, CA

BACKGROUND

Rock glaciers and related periglacial rock-ice features (RIFs) are abundant yet little-studied landforms in many temperate mountain ranges. While many of these features are Pleistocene relicts and do not retain ice, a large proportion are active, suggesting embedded and underlying ice. Rock-mantling insulates ice in RIFs, and their activity and equilibrium with climate considerably lag typical ice glaciers. RIFs will increase in importance as high-elevation water reservoirs during conditions of global warming.

RIFs are abundant in cirques and canyons of the Sierra Nevada, CA south of Lake Tahoe (Fig. 1), and occur in many forms (Figs. 2, 3, and 4). Several large valley rock glaciers have been studied for climate and neo-glacial relationships (Clark et al. 1998; Konrad & Clark 1998). We have developed a taxonomic classification and inventory of features in the Sierra Nevada that includes 400 RIFs (Millar & Westfall 2006). These were classified into 4 Condition States, 6 Location Classes, and 18 Position Types. The features ranged from 2225 m – 3932 m (mean of active RIFs: 3333 m); aspects were primarily NW to NE for the rock glaciers, while other forms had diverse locations.

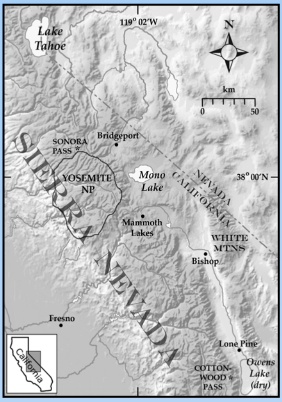

Fig 1. Study Area

GOALS

Analyze modern and paleoclimate relationships of RIFs of the Sierra Nevada using the classification and database of Millar & Westfall (2006).

Fig 3. Rock Glacier near Taboose Pass

Fig 2. Goethe Rock Glacier

METHODS

Modern Climates

Location data for features were imported into GIS as point coverages (lat/long of centers). These groups were intersected with newly available climate data from the PRISM climate model (Daly et al., 1994) and downscaled using local lapse rates. We extracted layers for January and July minimum and maximum temperatures, and for annual, January, and July precipitation. Climatic differences among Location Classes were assessed by discriminant analysis.

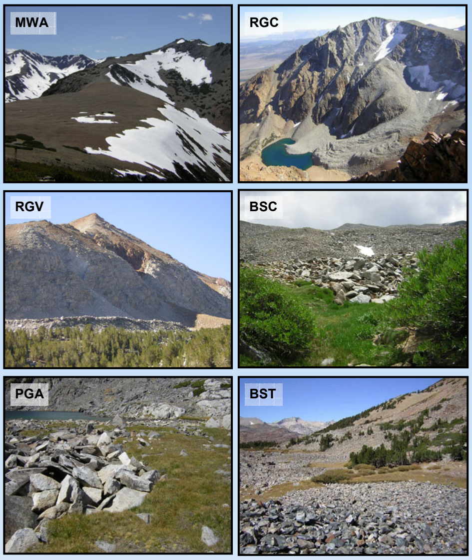

Fig 4. Examples of the six RIF classes listed in Table 1.

Paleoclimates

We calculated differences between modern and Late Glacial Maximum (LGM) climates in two ways, one based on elevation differences of paired modern and relict RIFs and standard lapse rates (-6.5°C/km), the other comparing direct PRISM climate estimates of locations for active versus relict features.

RESULTS & DISCUSSION

Modern Climates

Table 1 shows mean climate values from the PRISM model for active RIFs east of the Sierra crest, grouped by the six Location Classes of Millar and Westfall (2006). The coldest RIFs are the solufluction fields (MWA) and cirque rock glaciers (RGC), whose mean annual air temperatures are estimated from PRISM as < 1°C. These means are maximum value estimates because they are adjusted from the average PRISM tile only for elevation and not for aspect and local topography. Thus, several of the RIF categories likely have MAAT ≤ 0°C, as has been calculated for the nearby White Mtns, indicating the presence of permanent ice. The first three vectors of the canonical correlation analysis explained 95% of the variation (Table 2). January and July maximum temperature, annual and July minimum temperatures, and July precipitation were strongly correlated to the canonical vectors.

Table 1. Summary of ten mean climate values for six RIF Location Classes derived from the $4km^2$ PRISM model. Active features only, PRISM values adjusted for elevation.

Location Class[1]	N	Annual Temp °C	Annual T min °C	Annual T max °C	January T min °C	January T max °C	July T min °C	July T max °C	Annual Precip mm	January Precip mm	July Precip mm
MWA	22	0.57	-5.70	6.84	-12.55	-1.26	3.46	17.93	1126	198	24
RGC	113	0.90	-5.65	7.45	-12.01	-0.54	3.27	18.46	1050	184	19
RGV	67	1.01	-5.84	7.86	-11.98	-0.03	2.96	19.00	1055	187	18
BSC	63	1.72	-4.90	8.34	-11.71	-0.08	4.30	19.61	1004	178	26
PGA	8	1.95	-4.97	8.87	-11.37	0.40	3.73	20.16	1027	189	16
BST	21	2.17	-4.77	9.11	-11.37	0.60	4.14	20.47	1019	181	21

[1] MWA – Mass Waste Alpine Slopes; RGC – Rock Glacier Cirque; RGV – Rock Glacier Valley; BSC Boulder Stream Scree; PGA Patterned Ground Alpine; BST – Boulder Stream, Stream Course

Paleoclimates

Using the standard lapse rates and mean elevation difference between paired active and relict RIFs from the same watershed, we estimated the difference in temperature between modern and LGM to be -4.3°C (Table 3). Estimating modern temperature differences from the active and relict features directly using downscaled PRISM and assuming lapse rates have not changed significantly over time, the modern versus LGM temperature was -3.5°C for mean maximum temperature and -1.7°C for mean minimum temperature (Table 3).

Table 3. Differences in temperatures estimated for modern versus Pleistocene climates based on lower elevations of paired active (A) versus relict Pleistocene (P) rock glaciers within watersheds

Watershed	Age	Elev (m)	Latitude	Longitude	Mean Diff in Elev A – P (m)	Std Lapse Diff in T ann A - P (°C)	PRISM-Estimated Diff in Temperature					
							T max	Jan T max	A – P Jul T max	T min (°C)	Jan T min	Jul T min
Tamarack	P	2747	38.1442	119.3160								
Tamarack	A	3372	38.1027	119.3193	625	-4.1	-0.3	0.2	-0.7	-0.3	-0.2	-0.2
Dunderberg	P	2637	38.1033	119.2485								
Dunderberg	A	3422	38.0692	119.2730	785	-5.1	-3.0	-2.6	-3.4	-0.8	-0.6	-0.7
Deer Crk	P	2526	38.0262	119.2165								
Deer Crk	A	3166	38.0017	119.2237	640	-4.2	-5.6	-4.3	-6.8	-1.1	-1.0	-1.0
Dechambeau	P	2690	38.0159	119.1889								
Dechambeau	A	3416	37.9931	119.2192	726	-4.7	-2.1	-1.2	-2.1	-0.2	0.0	-0.1
Warren	P	3037[1]	37.9892	119.1853								
Warren	A	3351	37.9782	119.2126	314	-2.0	-2.8	-2.2	-3.5	-0.4	-0.6	-0.3
LV Cyn Dana	P	2505	37.9415	119.2125								
LV Cyn Dana	A	3484	37.9023	119.2168	979	-6.4	-4.7	-2.9	-4.7	-2.0	-1.4	-1.7
Gibbs Cyn	P	2615	37.9138	119.1578								
Gibbs Cyn	A	3202	37.8971	119.2012	587	-3.8	-2.6	-2.0	-3.9	-0.6	-1.2	-0.6
Bloody Cyn Clot	P	2613	37.8664	119.1735								
Bloody Cyn	P	3086[1]	37.8581	119.1939								
Bloody Cyn	A	3314	37.8486	119.1961								
Bloody Cyn	A	3523	37.8454	119.1889	569	-3.7	-3.9	-2.2	-4.6	-2.4	-2.2	-2.1
Bloody Cyn Gibbs	P	3123[1]	37.8625	119.2002								
Bloody Cyn Gibbs	A	3665	37.8787	119.2073	542	-3.5	-1.7	-1.7	-2.0	-0.5	-0.9	-0.6
Parker Lk	P	2594	37.8326	119.1403								
Parker Kuna	A	3652	37.8212	119.2095	1058	-6.9	-5.6	-4.1	-6.1	-3.0	-3.4	-2.6
Hilton Cr	P	2264	37.5611	118.7666								
Hilton Cr	A	3454	37.4606	118.7653	1190	-7.7	-8.0	-6.5	-8.5	-4.7	-5.9	-4.1
Francis Cr	P	3169[1]	37.4428	118.7141								
Francis Cr	A	3673	37.4160	118.7277	504	-3.3	-8.1	-6.1	-9.7	-4.8	-4.2	-5.0
Bishop Cr N Fk	P	2858	37.2275	118.6282								
Bishop Cr N Fk	A	3490	37.2374	118.6364	632	-4.1	-1.5	-0.9	-1.8	-0.3	-0.3	0.1
Poison Cr Walker	P	2615	38.2902	119.4771								
Poison Cr Walker	A	3055	38.2741	119.4866	400	-2.6	-1.6	-1.2	-2.1	-1.2	-0.9	-0.8
Cottonwood Cr	P	3121	36.4686	118.1918								
Center Basin	A	3507	36.7262	118.3616	386	-2.5	-0.4	-0.9	0.1	-2.5	-4.7	-0.6
AVERAGE					**662**	**-4.3**	**-3.5**	**-2.6**	**-4.0**	**-1.7**	**-1.8**	**-1.3**

[1] Lower elevation truncated by mainstem valley-glacier erosion or range-front faulting.

Table 2. Canonical correlations from discriminate analysis among nine climate variables from the PRISM climate model and correlations of the first three canonical vectors (CV) with the climate variables.

	Annual precip	January precip	July precip	Annual T max	January T max	July T max	Annual T min	January T min	July T min
Annual precip	1.000								
January precip	0.927	1.000							
July precip	-0.060	-0.183	1.000						
Ann T max	0.028	0.168	0.187	1.000					
Jan T max	-0.069	0.003	0.029	0.877	1.000				
July T max	0.033	0.182	0.228	0.975	0.772	1.000			
Annual T max	-0.139	-0.083	0.516	0.786	0.574	0.810	1.000		
January T max	-0.109	-0.032	0.129	0.809	0.780	0.760	0.825	1.000	
July T min	-0.201	-0.199	0.668	0.595	0.347	0.659	0.941	0.622	1.000
CV 1	-0.095	-0.037	-0.393	0.373	0.593	0.347	-0.068	0.211	0.178
CV 2	-0.311	-0.201	0.625	0.714	0.529	0.715	0.735	0.436	0.737
CV 3	0.118	0.077	0.507	-0.280	-0.311	0.195	-0.155	-0.346	0.015

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