Supplementary Information File for:

Climate change and the global pattern of moraine-dammed glacial lake outburst floods

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Despite numerous inventories of Glacial Lake Outburst Floods (GLOFs) at regional scales, no global database has been created and analyzed to place GLOFs in their wider context. This means that we are unable to answer some important questions concerning their historical behaviour and therefore the changing magnitude and frequency of GLOFs globally through time, and their likely evolution under future global climate change. This latter point is made even more difficult by the lack of long-term climate data from many mountain regions. Given the size and impacts of GLOFs in many mountain regions, better understanding their links to present and future climate change is of great interest to national and regional governments, infrastructure developers and NGOs. There is currently also a strong focus on climate change adaptation, and glacial hazard research must now be seen through this lens.

As a result, the motivation for the paper is the widely held assumption that the magnitude and frequency of GLOFs in all glaciated mountain regions is increasing in response to global climate change. The logic supporting this is that recent climate change is driving mountain glacier recession (Fig. SI 1a,b) from their late Holocene moraine limits, this is contributing to the development of proglacial and supraglacial lakes and these eventually drain catastrophically following failure of moraine dams. We wished to test this assertion. Only GLOFs associated with collapse, breaching or overtopping of moraines damming glacial lakes were counted. Such events are generally triggered

by ice and rock falls or rock slides into lakes creating seiche waves or displacement waves[6]. While climate change plays a dominant role in the recession of glaciers, downwasting glacier surfaces debuttress valley rock walls leading to catastrophic failure[19] . Other climatically induced triggers include: increased permafrost and glacier temperatures leading to failure of ice and rock masses into lakes and the melting of ice cores in moraine dams which leads to moraine failure and lake drainage. A methodologically sound detection and attribution study needs first to formulate a hypothesis of potential impact of climate change[15]. The reasoning supporting the association between climate change and GLOFs is that climate warming results in glacier recession and glacial lake formation and evolution behind moraine dams which become unstable and fail catastrophically.

GLOF database

As a result, we produce a database of 191 GLOFs developed from a collation of regional inventories (e.g. GAPHAZ and GLACIORISK databases and the GLOF Database provided under ICL)and reviews [43-49]. Only those GLOFs that could be dated to a specific year were included. Around 65% of GLOFs occurred between 1930 and 1990. Thirty five GLOFs occurred in the mountains of western North America between 1929 and 2002 (SI Table 1). Fifteen of these occurred in western Canada, 13 in the Cascades Range of the US and four in Alaska. One occurred in Mexico. In the South American Andes we identified 64 GLOFs. Nine occurred in Chile between 1913 and 2009 (including the huge one in Patagonia at Laguna del Cerro Largo in 1989); five in Colombia between 1985 and 2008 and 50 in Peru between 1702 and 2012. Fourteen GLOFs are listed from the European Alps. Three are from Austria between 1890 and 1940; five from Switzerland between 1958 and 1993; one from France in 1944 and five from Italy between 1870 and 1993. Two GLOFs are listed from Russia.

In the Pamir and Tien Shan mountains we identified 20 GLOFs from this region of central Asia, with most of these dating from the late 1960s to the early 1980s. The largest number of GLOFs are reported from the Hindu Kush Himalaya including the mountains of Bhutan and Tibet. Here a total of 55 GLOFs have been reported. Apart from one, all GLOFs here date from the 20th and 21st century. Thirty are from Tibet (between 1902-2009); 12 from Nepal between 1964 and 2011(and one is reported to have occurred in 1543), and five in Pakistan between 1878 and 1974.

Conclusions and important note.

The takeaway points of this supplement, buttressing the points made in the main article, are that the timescales for the responses of debris-covered glaciers to climate change are long, and the limnological response timescales and GLOF trigger timescales are additional to that. Hence, climate changes that may spur lake development and outburst flooding may eventually manifest in GLOF activity a century or two centuries, or even longer, after the climatic perturbation. The GLOF record showing an upsurge in GLOF activity starting in the 1930-1950 timeframe thus probably represents a response to post-Little Ice Age warming rather than anthropogenic warming, and the decreased GLOF incidence starting late in the last century likely pertains to the stabilization of climate after the post-LIA warming but before anthropogenic warming started in earnest.

We emphasize that these results should not be construed as saying that anthropogenic climate change is somehow not affecting glacial lakes or not involved in the hazards due to them. Clearly,

warming is occurring worldwide and must be affecting the growth rates of existing lakes and the inception of new ones, and some fraction—perhaps a small fraction at present—of GLOFs are triggered by recent climatic warming. We may infer that GLOF incidence rates are likely to increase later this century as anthropogenic warming takes an increasing toll on the health of glaciers worldwide.

Supplementary Information File Figures

Figure SI 1a Changes in the length of 169 glaciers worldwide from the 18th to the 21st century (after Oerlemans 2005). Figure SI 1b: annual change in global glacier thickness (left axis, meters of water equivalent, m/yr) and cumulative value (right axis, m), based on surface area-weighted mass balance observations.

SI Table 1. Inventory of Glacial Lake Outburst Floods in mountain regions.

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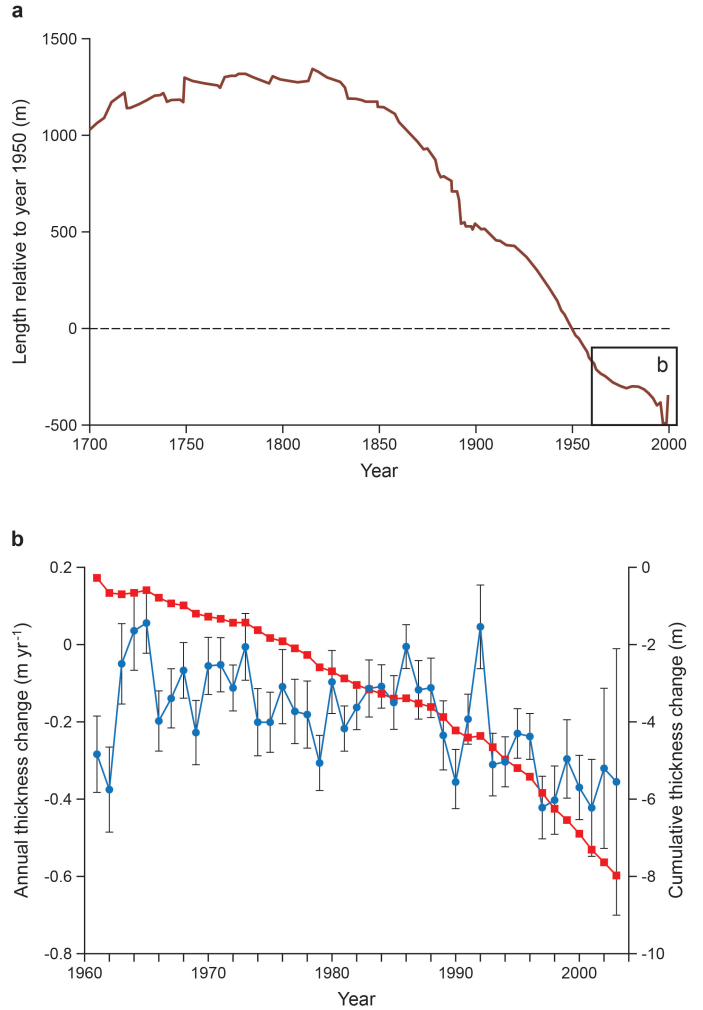
a
1500
1000
500
0
-500
Length relative to year 1950 (m)
b
1700
1750
1800
1850
1900
1950
2000
Year
b
0.2
0
-0.2
-0.4
-0.6
-0.8
Annual thickness change (m yr-1)
0
-2
-4
-6
-8
-10
Cumulative thickness change (m)
1960
1970
1980
1990
2000
Year

Political Unit	Site	Lake Name	Glacier or Mountain Name	Latitude	Longitude	Month	Year	Outburst Volume (Million cumecs)	Peak Q cumecs	Probable trigger	Damage
Europe + European Russia											
AT	Ötztaler_Alps		Gallruttferner	47.05	10.78		1890				
AT	Eastern_Alps	Preiml	Hochalmkees	47.02	13.33	10	1932	0.30		Ice avalanche	One wooden bridge was destroyed as well a pasture land, alpine tracks and wood.
AT	Ötztaler_Alps		Winnebachferner	47.10	11.05		1940				
CH	Western_Alps	Nr_3	Gruben	46.17	7.97	8	1958				No damage
CH	Western_Alps	Nr_3	Gruben	46.17	7.97	7	1968	0.17		Subglacial discharge	
CH	Western_Alps		Sidelen	46.50	8.42	8	1987			Heavy rainfall	Alps and a street in the Gerental were damaged.
CH	Western_Alps		Dolent	45.92	7.07	7	1990	0.03			
CH	Western_Alps	Sirwolte	Griessernuhorn	46.21	7.99	9	1993	0.30	90.00	Heavy rainfall	10-20m high moraine breach, damage on Simplon highway, destroyed gauge station.
FR	Mont_Blanc_Massif		Nantillons	45.90	6.90	9	1944			Rapid discharge in proglacial lake	Houses in Chamonix flooded, and Montenvers railway track damaged.
IT	Piemonte	Galambra	Galambra	45.11	6.85		1932	0.50			No damage
IT	Piemonte		Gemelli_di_Ban	46.40	8.35	10	1971				No damage
IT			Mulinet S	45.02	7.17	9	1993				
IT			Sissone	46.12	9.73		1950				
IT	Aosta_Valley		Trajo	45.61	7.27		1870				
RU	Adyr-sy (Djalovchat)			43.31	41.50	8	1940			Rockfall	Chkheri bridge destroyed. Terek River dammed, livestock killed and crops damaged.
RU	Adyr-sy (Kullumkol)			43.25	42.01	7	1983				
Hindu Kush Himavala											
BT	Himalaya		Unnamed				1950				Destroyed part of Punakha Dzong.
BT	Himalaya	Tarina		28.11	89.90		1957				Destroyed part of Punakha Dzong.
BT	Himalaya	Tarina		28.11	89.90		1959				Damaged half of Punakha Dyong
BT	Himalaya (Pho Chu)	Unnamed					1960				
BT	Himalaya	Bachamancha	Bachamancha	28.03	90.68		1960				
BT	Himalaya		Unnamed				1968				Several houses, Punakha valley temple and Wangdi Phodrang bridge washed away.
BT	Lunana_Basin	Lugge	Lugge	28.09	90.29	10	1994	28.00	2500.00		26 people died & significant property damage
BT	Lunana_Basin						1996	45.00		Moraine dam breach	27 dead. Floodwave of 2 m at 200km from source.
BT	Lunana_Basin	Lugge	Lugge	28.09	90.29	4	2009	1.50			
CN	Tibet	Zhanlonba					1902				
CN	Tibet	Tara		28.29	86.13	8	1935	0.60		Ice avalanche	66700m^2 of wheat fields, livestocks and others damaged.
CN	Tibet	Qiongbixia		27.83	88.91	7	1940			Ice avalanche	Water level of Xiasim, Yadong rose 4-5m, streets flooded and buildings damaged
CN	Tibet	Sangwang		28.23	90.10	7	1954	5.00		Ice avalanche	400 deaths in cities of Gyangze and Xigaze 200km downstream. 57km^2 of farmland
CN	Tibet		Tara Cho (Boqu River)	28.28	86.13	7	1964			Piping and moraine failure	
CN	Tibet	Damenhai	Damenhai	29.93	93.15	9	1964	0.20	2812.00	Rock avalanche	Blocked Nyang River for >10hrs, damaged houses and highway.
CN	Tibet	Gelhaipu	Gelhaipu	27.96	87.81	9	1964	23.36		Heavy rainfall	Casualties and heavy economic loss including to Chentang-Riwo Highway.
CN	Tibet	Zhangzhangbo		28.06	86.06	9	1964	19.00	15920.00		No damage
CN	Tibet	Longda		28.61	85.34	8	1964	0.50		Ice avalanche	
CN	Tibet	Jilai				9	1964	0.50		Ice avalanche	
CN	Tibet	Aya		28.34	86.49	8	1965			Ice avalanche	Road, bridges and others damaged.
CN	Tibet	Longda		28.61	85.34	8	1968			Ice avalanche	
CN	Tibet	Damenhai	Damenhai	29.93	93.15	8	1968			Ice avalanche	
CN	Tibet	Aya		28.34	86.49	8	1968			Ice avalanche	Damaged highway and bridge of Desha.
CN	Tibet	Aya		28.34	86.49	8	1969			Ice avalanche	Damaged highway and bridge of Desha.
CN	Tibet	Aya		28.34	86.49	8	1970	5.00			Flood damaged the highway and concrete bridges of Desha No 1.
CN	Tibet	Qiongbixiama		27.83	88.91	7	1970				
CN	Tibet	Bugyai		31.77	94.81	7	1972			Ice avalanche	
CN	Tibet	Poge				7	1972			Ice avalanche	
CN	Tibet	Zhari				6	1981			Ice avalanche	
CN	Tibet	Zhangzangbo		28.06	86.06	7	1981	19.00	15920.00	Glacier_avalanche	Damaged highway, bridge, hydropower station and farmland.
CN	Tibet	Jzierma		28.08	86.07	7	1981			Ice avalanche	
CN	Tibet	Jin		28.00	87.16	8	1982	0.50		Ice_avalanche	>1600 livestock and 280 cultivated fields lost. Houses in eight villages damaged.
CN	Tibet	Gule		29.50	94.50	7	1988			Ice avalance	
CN	Tibet	Mitui				7	1988	0.01	1250.00	Ice avalanche	
CN	Tibet	Guangxie				7	1988	0.30		Ice avalanche	
CN	Tibet	Zana	Trisuli	28.66	85.37	6	1995				Destroyed 28km road.
CN	Tibet		Degapu			9	2002			Ice avalanche	
CN	Tibet		Zhemalco			7	2009			Ice avalanche	

CN	Tibet		Cliaco			7	2009			Ice avalanche	
PK							1878		18700		
PK	Karakoram	Karambar	Karambar	36.62	74.18	6	1905				Damage to villages above the Gilgit. Some bridges in Gilgit were destroyed.
PK	Karakoram					6	1967				
PK	Karakoram		Batura				1972				
PK	Karakoram		Balt Bare			Spring	1974	5.00	63cumec		Killed 1 person. Destroyed 120m bridge, part of KH.
NP							1964				
NP	Khumbu Himal	Nare	Nare	27.82	86.84	9	1977	5.00	1200.00	Melting of ice cored moraine	3 people killed. Damage to HE, road, houses. Bridges destroyed to 35km downstream.
NP	Khumbu Himal	Nagma		27.86	87.86	6	1980			Moraine collapse	Destroyed villages 71km from source and forest.
NP	Khumbu Himal					7	1985				
NP	Khumbu Himal	Dig	Langmoche	27.87	86.58	8	1985	6.00	1600.00	Ice avalanche	Four or five people killed. Damage to houses, HEP, infrastructure and agricultual land.
NP	Khumbu Himal	Chubung	Ripimosar	27.87	86.45	7	1991	1.00		Ice avalanche	Na livestock killed, bridge destroyed. Beding 1 fatality, flour mills, fields destroyed.
NP	Khumbu Himal	NA	Amadablam	27.81	86.85		1993			Ice avalanche	Loss of livestock and farmland and two people died.
NP	Khumbu Himal	Tam	Sabai	27.74	86.84	9	1998	17.00	30000.00	Ice avalanche	Numerous fatalities and widespread damage. Damage cost around 2 million USD.
NP	Manaslu Himal	Kabache		28.45	84.13	8	2003			Moraine collapse	
NP	Manaslu Himal	Kabache		28.45	84.13	8	2004				
NP	Himalaya		Unnamed	30.26	81.46	6	2011			Ice avalanche	Damaged farmland.
North America											
CA	British Columbia	Tide	Frank Mackie				1929			Meltwater incision	
CA	British Columbia	South Macoun					1949	0.40	1000.00		
CA	British Columbia						1965				
CA	British Columbia		Bridge				1967	2.00	1000.00		
CA	British Columbia	Klattasine	Homathko Icefield	51.17	-124.75		1972	1.70	1000.00	Heavy rainfall	
CA	British Columbia	Cathedral					1978				
CA	British Columbia	Flood lake					1979				
CA	British Columbia	Peyto					1983				
CA	British Columbia	Flood lake					1983				
CA	British Columbia	North Macoun				7	1983				
CA	British Columbia	Nostetuko	Cumberland	51.20	-124.40	7	1983	6.50	900.00	Ice avalanche	Two gauging stations on Nostetuko River damaged. Damage to large tracts of forest.
CA	British Columbia	Flood lake					1984				
CA	British Columbia	Fyles					1984				
CA	British Columbia	Tats				6	1990	0.00		Heavy rainfall	
CA	British Columbia	Queen Bess	Diadem	51.25	-124.51	8	1997	8.00	1000.00	Rainfall	Floodwater eroded Quaternary deposits, damaged vegetation and forest in Nostetuko
US	Cascade Range	NA	Eugene	44.11	-121.78	8	1933		350.00		
US	Cascade Range	Jefferson Park	NA			8	1934	0.01	600.00	Rapid ice melt	
US	Cascade Range		Waldo	44.66	-121.79		1937				
US	Sierra Nevada California		Conness	37.96	-119.31		1939				
US	Cascade Range		Eugene	44.11	-121.78		1941				
US	Cascade Range			44.12	-121.82	7	1942		360.00		
US	Cascade Range		Collier	44.16	-121.77	7	1942	0.46	545.00		
US	Cascade Range		Waldo	44.66	-121.79	7	1951				
US	Cascade Range			48.40	-121.27		1955	0.20			
US	Cascade Range						1957	0.00	300.00		
US	Cascade Range			44.46	-121.83		1960	0.01			
US	Cascade Range			44.08	-121.68	10	1966	0.32	380.00	Ice avalanche	
US	Cascade Range					9	1970	0.33	297.00		
US	Cascade Range		Diller	44.14	-121.77	9	1970	0.32	490.00		
US		Shoestring					1980				
US	Cascade Range			44.46	-121.83		1984	0.01			
US	Alaska	Peters					1986				
US	Alaska	Hubbard				5	1986				
US	Alaska	Hubbard				10	1988				
US	Alaska	Black Rapids				11	2002				
MX			Popocatepetl			1	2001				
South America											
AR		Lago Plomo		-33.12	-70.03		1984				
CL	Patagonia		Glaciar Piedras Blancas			12	1913				
CL	Patagonia		Rio Engano			3	1977		7.36		

CL			Tronquitos	-28.53	-69.72		1985			Glacier flood	
CL	Patagonia	Laguna del Cerro Largo	Soler	-46.91	-73.15	3	1989	229.00		Meltwater discharge	No damage
CL	Patagonia		Rio Lacaya				2000		3.14		
CL	North Patagonian Icefield	Calafate				12	2000	2.00		Rock avalanche	
CL	Patagonia		Glaciar Olvidado				2003				
CL	Patagonia	Ventisquero Negro		-41.20	-71.82	5	2009	10.00	4100.00	High precipitation	
CO	Nevado del Ruiz			4.90	-75.32		1985			Volcanic eruption and glacier melt	30000 death toll.
CO	Nevado del Huila			3.55	-76.05	6	1994				
CO		Lagunillas		4.88	-75.30		1995				
CO	Nevado del Huila			3.55	-76.05	4	2007				
CO	Nevado del Huila			3.55	-76.05	4	2008				
PE	Cordillera Huayhuash					2	1869				Destroyed several houses
PE	Cordillera Blanca	Rajucolta		-9.52	-77.34	6	1883				Many fatalities. Destroyed schools, houses and cemetery.
PE	Cordillera Huayhuash					6	1883				Damage and many deaths
PE	Cordillera Huayhuash					2	1911				Destroyed a small village
PE	Cordillera Blanca		Huascaran Norte	-9.10	-77.62	1	1917				
PE	Cordillera Huayhuash	Soltera	Solteracocha	-10.23	-76.93	3	1932				No damage
PE	Cordillera Blanca	Magistral					1938				32 houses and 13 bridges destroyed.
PE	Cordillera Blanca	Artesa	Pacllashcocha	-9.11	-77.51	1	1938	0.50		Ice avalanche	No damage
PE	Cordillera Huayhuash					1	1938				Local damage, no deaths
PE	Cordillera Blanca					4	1939				
PE	Cordillera Huayhuash	Suero		-10.63	-76.69	4	1941				Damaged farmland.
PE	Cordillera Huayhuash					12	1941	4.00			6000 dead
PE	Cordillera Blanca	Palca	Palcacocha	-9.39	-77.38	12	1941	4.00		Ice avalanche	Approximately 6000 people died in Huaraz and part of the city destroyed.
PE	Cordillera Blanca	NA	Quebrada Santa Cruz	NA	NA		1942				
PE	Cordillera Huayhuash					1	1945				Destroyed the historic ruins at Chavin; many deaths
PE	Cordillera Blanca	Ayhuinyaraju	Huantsan	-9.51	-77.31	1	1945		14000.00	Rock avalanche	500 people died and damage to archaeological sites.
PE	Cordillera Blanca	Jancarurish	Kogan	-8.85	-77.67	10	1950	10.00	8000.00	Ice avalanche	About 500 people were killed.
PE	Cordillera Huayhuash					10	1950				Severe damage to water intake, Canon del Pato; 200-500 deaths
PE	Cordillera Blanca	Allicocha					1950				
PE	Cordillera Blanca	Chacru					1950				
PE	Cordillera Blanca	Arteson	Caraz	-8.97	-77.64	7	1951	1.13		Ice avalanche	No damage
PE	Cordillera Blanca	Arteson	Caraz	-8.97	-77.64	10	1951	3.52			No damage
PE	Cordillera Blanca	Millua		-8.79	-77.70	11	1952				Little damage.
PE	Cordillera Huayhuash					3	1953				Destruction of three hamlets and one town; many deaths
PE	Cordillera Blanca	Tullparaju		-9.16	-77.55	6	1954				
PE	Cordillera Blanca	Tullparaju		-9.16	-77.55	12	1959				
PE	Cordillera Blanca		Huascaran Norte	-9.12	-77.60	1	1962			Ice avalanche	4000 deaths; destruction of Ranrahirca, mine and nine hamlets
PE			Glaciar 511	-9.11	-77.64		1962			Ice avalanche	
PE			Glaciar 511	-9.11	-77.64		1970				
PE		Laguna Yanahuin				3	1971			Rock Avalanche	A mining camp destroyed resulting in 400-600 deaths.
PE	Cordillera Huayhuash					1	1965				Localised damage, few deaths
PE	Cordillera Blanca	Tumarina		-9.49	-77.34	1	1965			Ice avalanche	10 fatalities. Two houses and a path destroyed.
PE	Cordillera Blanca		Huascaran Norte			5	1970				Earthquake killed 60,000 and sturzstrom killed 20,000.
PE	Cordillera Blanca	Libron				5	1970				
PE	Cordillera Blanca	Yanaraju				5	1970				
PE	Cordillera Blanca	Alli					1970				
PE	Cordillera Blanca	Safuna Alta	Pucajirca	-8.84	-77.62	6	1970			Earthquake	
PE	Cordillera Huayhuash	Sarapococha				2	1981				Highway, bridge and Cajatambo area damaged.
PE	Cordillera Blanca	Millua		-8.79	-77.70	8	1982				Destroyed bridges and roads.
PE	Cordillera Blanca		Huascaran	-9.12	-77.60	12	1987			Avalanche	Yungay damaged
PE	Cordillera Blanca		Huascaran	-9.12	-77.60	1	1989			Avalanche	Yungay damaged
PE	Cordillera Blanca		Hualcan				1991			Lake level artificially lowered causing glacier collapse	Several farms and a bridge destroyed.
PE	Cordillera Blanca	Pacliash				1	1997			Ice avalanche	Destroyed bridges, roads and cultivated land.
PE	Cordillera Huayhuash	Artizon		-8.94	-77.61	5	1997				Santa Cruz trail damaged and Huaylas area damaged.
PE		Salcantay					1998			Glacier flood	
PE	Cordillera Blanca	Safuna Alta	Pucajirca	-8.84	-77.62	4	2002			Rock avalanche	Security structures installed to secure the lake were damaged and cattle killed.
PE			Hualcan			10	2003			Avalanche	9 killed
PE	Cordillera Blanca	Palca	Palcacocha	-9.39	-77.38	3	2003			Landslide	No damage
PE	Cordillera Blanca	513	513.00			4	2010			Rock avalanche	Damaged infrastructure, houses, agriculture and killed cattle

PE	Santa Cruz	Artizón Bajo				2	2012			Flood wave from lake upstream
Central Asia										
KZ	Zailiskiy Alatau	Malaya Almatkinka				Summer	1944			
KZ	Zailiskiy Alatau	Malaya Almatkinka				Summer	1951			
KZ	Zailiskiy Alatau	Malaya Almatkinka				Summer	1956			
KZ		Issyk		43.19	77.53	Summer	1958			
KZ		Akkul				7	1963			
KZ	Talgar		Glacier 151	43.12	77.34	7	1970			
KZ	Talgar		Glacier 151	43.12	77.34	7	1971			
KZ	Tuyuksu		Tuyuksu Glacier	43.05	77.08	7	1973	0.35		
KZ	Talgar		Glacier 182	43.12	77.34	7	1974			
KZ	Zailiskiy Alatau	Bolshaya Almatinka		c.43.070	c. 76.988	Summer	1975			
KZ	Kombelsu		Glacier 117			8	1975			
KZ	Zharsai		Glacier 205			7	1977			
KZ		Moraine_Lake_No_13				8	1977	0.00	11000.00	
KZ	Talgar			-43.12	77.34	Summer	1979			
KZ	Kaskelen		Glacier 35			7	1980		30000.00	
KZ	Talgar			-43.12	77.34	Summer	1993			
KZ	Zailiskiy Alatau	Bolshaya Almatinka		43.07	76.99	Summer	1994			
KZ			Archa-Bashy lake				1998			
KYZ	Teskey Ala-Too	Zyndan				7	2008	0.44		
KYZ	Pamir		Shakdhara Valley			Summer	2002	0.25		Drainage of supraglacial lake

KEY
AR=Argentina
AT=Austria
BO=Bolivia
BT=Bhutan
CA=Canada
CH=Switzerland
CL=Chile
CN=China
CO=Colombia
FR=France