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

S. Harrison et al.

Correspondence to: Stephan Harrison (stephan.harrison@exeter.ac.uk)

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 (Reynolds and Richardson 2000). While climate change plays a dominant role in the recession of glaciers, downwasting glacier surfaces debuttress valley rock walls leading to catastrophic failure (e.g. Jiang et al 2004). 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 (Clague and Evans 2000). 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 GLOFs developed from a collation of regional inventories (e.g. GAPHAZ and GLACIORISK databases and the GLOF Database provided under ICL) and reviews. Only those GLOFs that could be dated to a specific year were included.

Conclusions

Given the remote nature of many of the GLOF sites, the absence of remote sensing data from the early part of the record to corroborate GLOF observations and inconsistent use of lake, glacier, region or mountain names to describe GLOFs, these and other factors complicate the creation of GLOF inventories. We are aware that some GLOFs in the record may have been given different names by different authors in inventories and this could lead to confusion. When inventories are consolidated this might, on occasion, lead to double-counting. Similar issues represent a challenge for all Detection and Attribution research on individual climatic or earth system events. As a result, all such inventories are inherently uncertain. In our inventory for consistency we have kept all GLOF records as defined by the original authors. These may be subject to future change.

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.

References for GLOF inventory (numbers refer to final column in SI Table)

1 GLACIORISK (2003) - http://www.nimbus.it/glaciorisk/gridabasemainmenu.aspGridbase

2 GAPHAZ databasehttp://www.mn.uio.no/geo/english/research/groups/remotesensing/projects/gaphaz/

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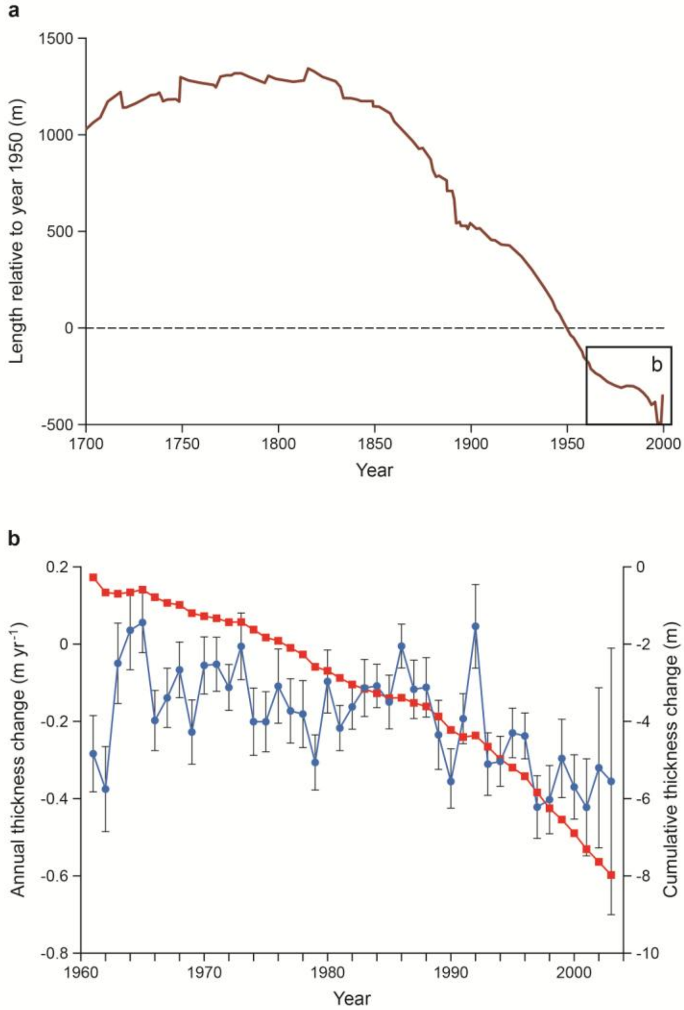
SI Figure 1



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

Political Unit	Site	Lake Name	Glacier or Mountain Name	Latitude	Longitude	Mth	Yr	Outburst Vol (M cumecs)	Peak Q cumecs	Probable trigger	Damage	Ref.
Europe + European Russia												
AT	Ötztaler_Alps		Gallruttferner	47.05	10.78		1890					1
AT	Eastern_Alps	Preiml	Hochalmkees	47.02	13.33	10	1932	0.30		Ice avalanche	One wooden bridge was destroyed as well as pasture land, alpine tracks and wood.	1
AT	Ötztaler_Alps		Winnebachferner	47.10	11.05		1940					1
CH	Western_Alps	Nr_3	Gruben	46.17	7.97	8	1958				No damage	4
CH	Western_Alps	Nr_3	Gruben	46.17	7.97	7	1968	0.17		Subglacial discharge		3,4
CH	Western_Alps		Sidelen	46.50	8.42	8	1987			Heavy rainfall	Alps and a street in the Gerental were damaged.	4
CH	Western_Alps		Dolent	45.92	7.07	7	1990	0.03				2
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.	2
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.	1
IT	Piemonte	Galambra	Galambra	45.11	6.85		1932	0.50			No damage	1
IT	Piemonte		Gemelli_di_Ban	46.40	8.35	10	1971				No damage	1
IT			Mulinet S	45.02	7.17	9	1993					2
IT			Sissone	46.12	9.73		1950					
IT	Aosta_Valley		Trajo	45.61	7.27		1870					2
Hindu Kush Himayala												
BT	Himalaya		Unnamed				1950				Destroyed part of Punakha Dzong.	3
BT	Himalaya	Tarina		28.11	89.90		1957				Destroyed part of Punakha Dzong.	3,5
BT	Himalaya	Tarina		28.11	89.90		1959				Damaged half of Punakha Dyong	33
BT	Himalaya (Pho Chu)	Unnamed					1960					5
BT	Himalaya	Bachamancha	Bachamancha	28.03	90.68		1960					5
	Himalaya		Unnamed				1968				Several houses, Punakha valley temple and Wangdi	3
BT	Lunana_Basin	Lugge	Lugge	28.09	90.29	10	1994	28.00	2500.00		26 people died & significant property damage	2,5
BT	Lunana_Basin						1996	45.00		Moraine dam breach	27 dead. Floodwave of 2 m at 200km from source.	6
BT	Lunana_Basin	Lugge	Lugge	28.09	90.29	4	2009	1.50				27
CN	Tibet	Zhanlonba					1902					10
CN	Tibet	Tara		28.29	86.13	8	1935	0.60		Ice avalanche	$66700m^2$ of wheat fields, livestocks and others damaged.	5
CN	Tibet	Qiongbixia		27.83	88.91	7	1940			Ice avalanche	Water level of Xiasim, Yadong rose 4-5m, streets flooded	3
CN	Tibet	Sangwang		28.23	90.10	7	1954	5.00		Ice avalanche	400 deaths in cities of Gyangze and Xigaze 200km	3,5
CN	Tibet		Tara Cho (Boqu River)	28.28	86.13	7	1964			Piping and moraine failure		10
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.	3,5
CN	Tibet	Gelhaipu	Gelhaipu	27.96	87.81	9	1964	23.36		Heavy rainfall	Casualties and heavy economic loss including to Chentang-	3,5
CN	Tibet	Zhangzhangbo		28.06	86.06	9	1964	19.00	15920.00		No damage	5
CN	Tibet	Longda		28.61	85.34	8	1964	0.50		Ice avalanche		5
CN	Tibet	Jilai				9	1964	0.50		Ice avalanche		19
CN	Tibet	Aya		28.34	86.49	8	1965			Ice avalanche	Road, bridges and others damaged.	5
CN	Tibet	Longda		28.61	85.34	8	1968			Ice avalanche		3
CN	Tibet	Damenhai	Damenhai	29.93	93.15	8	1968			Ice avalanche		3
CN	Tibet	Aya		28.34	86.49	8	1968			Ice avalanche	Damaged highway and bridge of Desha.	3
CN	Tibet	Aya		28.34	86.49	8	1969			Ice avalanche	Damaged highway and bridge of Desha.	3
CN	Tibet	Aya		28.34	86.49	8	1970	5.00			Flood damaged the highway and concrete bridges of	2,5
CN	Tibet	Qiongbixiama		27.83	88.91	7	1970					3
CN	Tibet	Bugyai		31.77	94.81	7	1972			Ice avalanche		10
CN	Tibet	Poge				7	1972			Ice avalanche		5
CN	Tibet	Zhari				6	1981			Ice avalanche		5
CN	Tibet	Zhangzangbo		28.06	86.06	7	1981	19.00	15920.00	Glacier_avalanche	Damaged highway, bridge, hydropower station and	5, 11
CN	Tibet	Jzierma		28.08	86.07	7	1981			Ice avalanche		10
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.	5
CN	Tibet	Gule		29.50	94.50	7	1988			Ice avalance		10

CN	Tibet	Mitui				7	1988	0.01	1250.00	Ice avalanche		10
CN	Tibet	Guangxie				7	1988	0.30		Ice avalanche		19
CN	Tibet	Zana	Trisuli	28.66	85.37	6	1995				Destroyed 28km road.	5
CN	Tibet		Degapu			9	2002			Ice avalanche		25
CN	Tibet		Zhemalco			7	2009			Ice avalanche		25
CN	Tibet		Cliaco			7	2009			Ice avalanche		25
PK							1878		18700 m3			17
PK	Karakoram	Karambar	Karambar	36.62	74.18	6	1905				Damage to villages above the Gilgit. Some bridges in Gilgit	2
PK	Karakoram					6	1967					17
PK	Karakoram		Batura				1972					17
PK	Karakoram		Balt Bare			Spr	1974	5.00	63cumecs		Killed 1 person. Destroyed 120m bridge, part of KH.	17
NP							1964					12
NP	Khumbu_Himal	Nare	Nare	27.82	86.84	9	1977	5.00	1200.00	Melting of ice cored	3 people killed. Damage to HE, road, houses. Bridges	12
NP	Khumbu_Himal	Nagma		27.86	87.86	6	1980			Moraine collapse	Destroyed villages 71km from source and forest.	12
NP	Khumbu_Himal					7	1985					12
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,	1, 2
NP	Khumbu_Himal	Chubung	Ripimosar	27.87	86.45	7	1991	1.00		Ice avalanche	Na livestock killed, bridge destroyed. Beding 1 fatality, flour	2, 5
NP	Khumbu_Himal	NA	Amadablam	27.81	86.85		1993			Ice avalanche	Loss of livestock and farmland and two people died.	2,5
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.	5
NP	Manaslu_Himal	Kabache		28.45	84.13	8	2003			Moraine collapse		5
NP	Manaslu_Himal	Kabache		28.45	84.13	8	2004					5
NP	Himalaya		Unnamed	30.26	81.46	6	2011			Ice avalanche	Damaged farmland.	3,5
North America (mainly Alaska												
CA	British_Columbia	Tide	Frank_Mackie				1929			Meltwater incision		15
CA	British_Columbia	South_Macoun					1949	0.40	1000.00			15
CA	British_Columbia						1965					
CA	British_Columbia		Bridge				1967	2.00	1000.00			15
CA	British_Columbia	Klattasine	Homathko_Icefield	51.17	-124.75		1972	1.70	1000.00	Heavy rainfall		14
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					15
CA	British_Columbia	Nostetuko	Cumberland	51.20	-124.40	7	1983	6.50	900.00	Ice avalanche	Two gauging stations on Nostetuko River damaged.	2, 3
CA	British_Columbia	Flood lake					1984					
CA	British_Columbia	Fyles					1984					
CA	British_Columbia	Tats				6	1990	0.00		Heavy rainfall		15
CA	British_Columbia	Queen_Bess	Diadem	51.25	-124.51	8	1997	8.00	1000.00	Rainfall	Floodwater eroded Quaternary deposits, damaged	2, 21
US	Cascade_Range	NA	Eugene	44.11	-121.78	8	1933		350.00			16
US	Cascade_Range	Jefferson Park	NA			8	1934	0.01	600.00	Rapid ice melt		16
US	Cascade_Range		Waldo	44.66	-121.79		1937					16
US	Sierra_Nevada_California		Conness	37.96	-119.31		1939					16
US	Cascade_Range		Eugene	44.11	-121.78		1941					16
US	Cascade_Range			44.12	-121.82	7	1942		360.00			13
US	Cascade_Range		Collier	44.16	-121.77	7	1942	0.46	545.00			16
US	Cascade_Range		Waldo	44.66	-121.79	7	1951					16
US	Cascade_Range			48.40	-121.27		1955	0.20				16
US	Cascade_Range						1957	0.00	300.00			16
US	Cascade_Range			44.46	-121.83		1960	0.01				16
US	Cascade_Range			44.08	-121.68	10	1966	0.32	380.00	Ice avalanche		13
US	Cascade_Range					9	1970	0.33	297.00			13
US	Cascade_Range		Diller	44.14	-121.77	9	1970	0.32	490.00			16
US		Shoestring					1980					
US	Cascade_Range			44.46	-121.83		1984	0.01				16
US	Alaska	Peters					1986					
US	Alaska	Hubbard				5	1986					
US	Alaska	Hubbard				10	1988					
US	Alaska	Black Rapids				11	2002					

MX			Popocatepetl			1	2001					8
South American Andes												
CL		Lago Plomo		-33.12	-70.03		1984					**8**
CL	Patagonia		Rio Leones				2000					**30**
CL	Patagonia		Rio Engano			7	1955					**30**
CL	Patagonia		Glaciar Piedras Blancas			12	1913					**30**
CL	Patagonia		Rio Engano			4	1976		7.36			30
CL			Tronquitos	-28.53	-69.72		1985			Glacier flood		8
CL	Patagonia	Laguna del Cerro Largo	Soler	-46.91	-73.15	3	1989	229.00		Meltwater discharge	No damage	**30**
CL	Patagonia		Rio Lacaya				2000		3.14			30
CL	North Patagonian Icefield	Calafate				12	2000	2.00		Rock avalanche		22
CL	Patagonia		Glaciar Olvidado				2003					30
CL	Patagonia	Ventisquero Negro		-41.20	-71.82	5	2009	10.00	4100.00	High precipitation		26, 30
CO		Lagunillas		4.88	-75.30		1995					8
PE	Cordillera_Blanca	Rajururi	Huandoy			1	1725			earthquake /	destruction of Ancash village	35
PE	Cordillera_Huayhuash					2	1869				Destroyed several houses	7
PE	Cordillera_Blanca	Rajucolta		-9.52	-77.34	6	1883				Many fatalities. Destroyed schools, houses and cemetery.	18, 35
PE	Cordillera_Huayhuash					2	1911				Destroyed a small village	7
PE	Cordillera Blanca		Huascaran Norte	-9.10	-77.62	1	1917					7
PE	Cordillera_Huayhuash	Soltera	Solteracocha	-10.23	-76.93	3	1932				No damage	2
PE	Cordillera_Blanca	Magistral					1938				32 houses and 13 bridges destroyed.	18
PE	Cordillera_Blanca	Artesa	Pacllashcocha	-9.11	-77.51	1	1938	0.50		Ice avalanche	No damage	2, 35
PE	Cordillera_Blanca	Unnamed	Q. Ulta			4	1939	0.01				16, 35
PE	Cordillera_Huayhuash	Suero		-10.63	-76.69	4	1941	8,0 - 11,0			Damaged farmland.	18
PE	Cordillera_Blanca	Palcacocha		-9.39	-77.38	12	1941	4.00		Ice avalanche / piping-	Approximately 6000 people died in Huaraz and part of the	2, 35
PE	Cordillera_Blanca	Ayhuinyaraju	Huantsan	-9.51	-77.31	1	1945	0.86	14000.00	ice-rock avalanche	500 people died and damage to archaeological sites.	2, 35
PE	Cordillera_Blanca	Jancarurish	Kogan	-8.85	-77.67	10	1950	2,0 - 10	8000.00	Ice avalanche	About 500 people were killed.	2, 35
PE	Cordillera_Blanca	Chacrucocha					1945	0.30				16, 35
PE	Cordillera_Blanca	Artesoncocha	Caraz	-8.97	-77.64	7	1951	1.13		Ice avalanche	No damage	2, 35
PE	Cordillera_Blanca	Artesoncocha	Caraz	-8.97	-77.64	10	1951	2,8 - 3,52		ice avalanche	No damage	2, 35
PE	Cordillera_Blanca	Milluacocha		-8.79	-77.70	11	1952	0,03-0,05			Little damage.	7, 18, 35
PE	Cordillera_Huayhuash					3	1953				Destruction of three hamlets and one town; many deaths	7, 18
PE	Cordillera Blanca	Tullparaju		-9.16	-77.55	3	1953	3.10		landslide in moraine		31, 35
PE			Glaciar 511	-9.11	-77.64		1962			Ice avalanche		8
PE			Glaciar 511	-9.11	-77.64		1970					8
PE		Laguna Yanahuin				3	1971			Rock Avalanche	A mining camp destroyed resulting in 400-600 deaths.	7
PE	Cordillera_Blanca	Tumarina		-9.49	-77.34	12	1965			Ice avalanche	10 fatalities. Two houses and a path destroyed.	18, 35
PE	Cordillera Blanca	Yanaraju				5	1970			earthquake /		18, 35
PE	Cordillera_Blanca	Safuna_Alta	Pucajirca	-8.84	-77.62	6	1970	> 4,0		Earthquake-triggered		13, 35
PE	Cordillera Huayhuash	Sarapococha				2	1981				Highway, bridge and Cajatambo area damaged.	31
PE	Cordillera_Blanca	Unnamed	Q. Artizon	-8.94	-77.61	5	1997			landslide in moraine	Santa Cruz trail damaged and Huaylas area damaged.	31, 35
PE		Salcantay					1998			Glacier flood		8
Central Asia (mainly Pamir and												
KZ	Zailiskiy Alatau	Malaya Almatkinka				Sum	1944					23
KZ	Zailiskiy Alatau	Malaya Almatkinka				Sum	1951					23
KZ	Zailiskiy Alatau	Malaya Almatkinka				Sum	1956					23
KZ		Issyk		43.19	77.53	Sum	1958					23
KZ		Akkul				7	1963					16
KZ	Talgar		Glacier 151	43.12	77.34	7	1970					24
KZ	Talgar		Glacier 151	43.12	77.34	7	1971					24
KZ	Tuyuksu		Tuyuksu Glacier	43.05	77.08	7	1973	0.35				24
KZ	Talgar		Glacier 182	43.12	77.34	7	1974					24
KZ	Zailiskiy Alatau	Bolshaya Almatinka		c.43.070	c. 76.988	Sum	1975					23
KZ	Kombelsu		Glacier 117			8	1975					24
KZ	Zharsai		Glacier 205			7	1977					24
KZ		Moraine_Lake_No_13				8	1977	0.00	11000.00			16
KZ	Talgar			-43.12	77.34	Sum	1979					23
KZ	Kaskelen		Glacier 35			7	1980		30000.00			24
KZ	Talgar			-43.12	77.34	Sum	1993					23
KZ	Zailiskiy Alatau	Bolshaya Almatinka		43.07	76.99	Sum	1994					23
KZ			Archa-Bashy lake				1998					

KYZ	Teskey Ala-Too	Zyndan				7	2008	0.44				24
KYZ	Pamir		Shakdhara Valley			Sum	2002	0.25		Drainage of supraglacial		29

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