

## **Supplementary material**

### **Vegetation dynamics in Alpine glacier forelands tackled from space**

Andrea Fischer (1)\*, Thomas Fickert (2), Gabriele Schwaizer (3), Gernot Patzelt (4), Günther Groß (5)

(1) Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences,  
Technikerstr. 21a, 6020 Innsbruck, Austria.

(2) Faculty of Arts and Humanities, University of Passau, Innstraße 40, 94032 Passau, Germany.

(3) ENVEO IT GmbH, Fürstenweg 176, 6020 Innsbruck, Austria.

(4) Patscher Strasse 20, 6080 Igls

(5) Oberrain 205, 6721 Thüringerberg

\* Correspondence should be addressed to A.F. (email: [andrea.fischer@oeaw.ac.at](mailto:andrea.fischer@oeaw.ac.at))

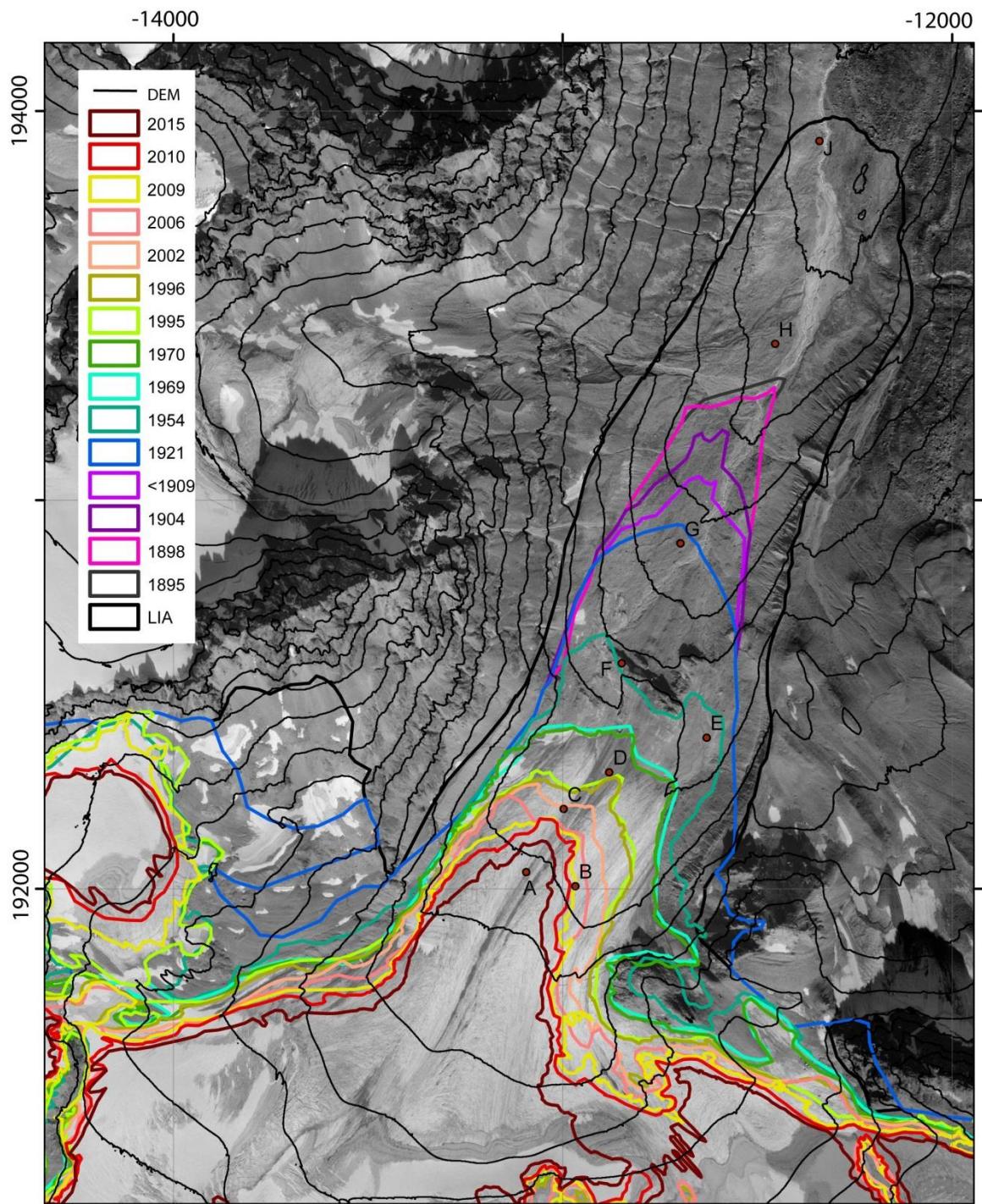


Fig. S1: Extent of Jamtalferner in various years between LIA maximum and 2015, as well as contour lines (DEM of 2006) superimposed on an orthophoto from 1970 (source: Land Tirol - [data.tirol.gv.at](http://data.tirol.gv.at) CC BY 4.0).

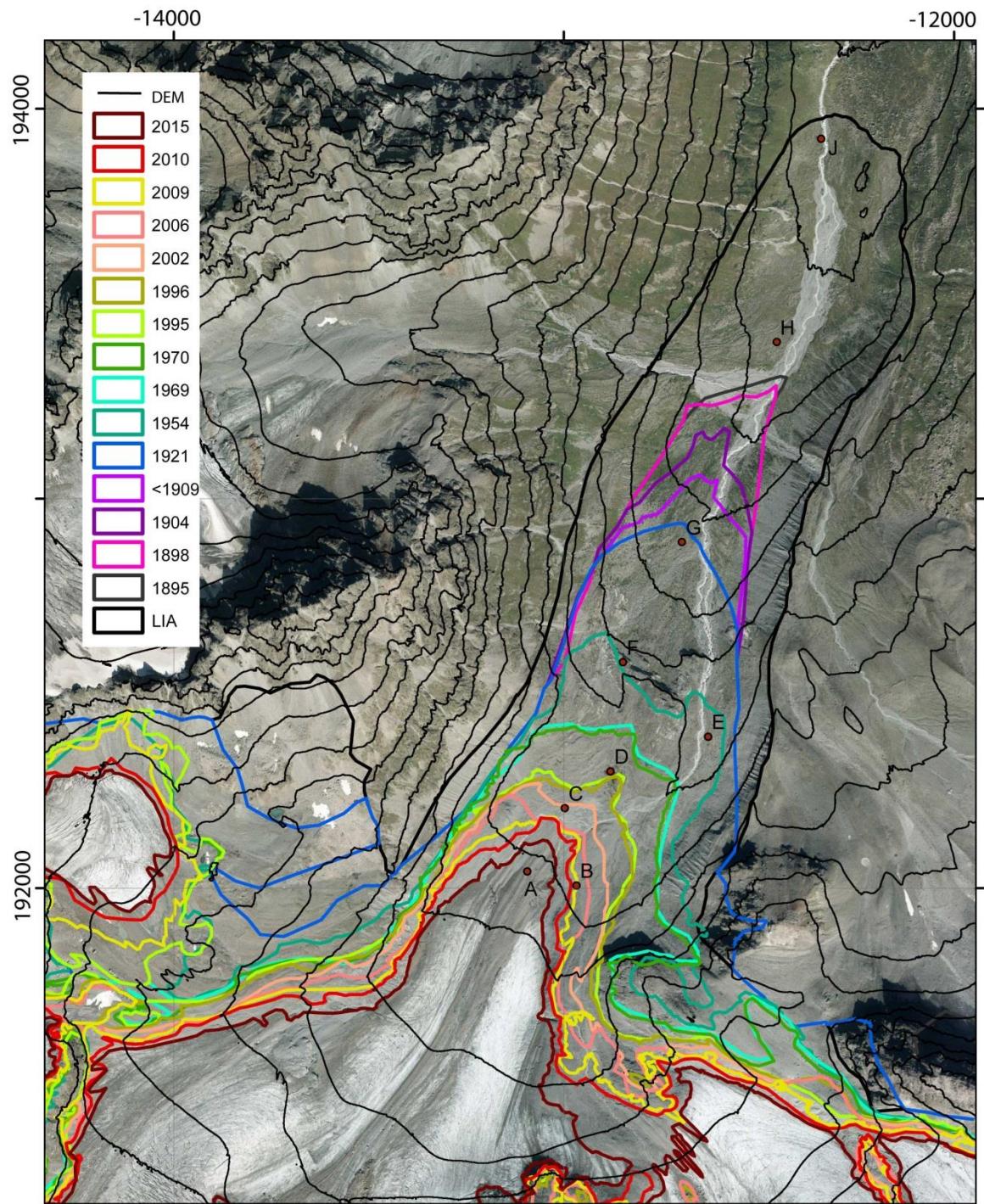


Fig. S2: Extent of Jamtalferner in various years between LIA maximum and 2015, as well as contour lines (DEM of 2006) superimposed on an orthophoto from 2015 (source: Land Tirol - [data.tirol.gv.at](http://data.tirol.gv.at) CC BY 4.0).

Table S1: Monthly, seasonal and annual means of air temperature and precipitation sums at the Galtür station (1587 m, 1951-2000) and precipitation at the rain gauge at the tongue of Jamtalferner (2400 m, 1989-2017), provided by the Hydrographical Service of the Federal Government of Tyrol. % of Galtür: percentage of precipitation at the glacier tongue compared to precipitation measured in Galtür. See also the insert in Figure 1.

Galtür	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	May-Sep	Oct-Apr	year
Temperature in °C	3.9	-1.7	-5.0	-5.9	-5.0	-2.2	1.3	6.3	9.5	12	11.2	8.2	9.4	-2.1	2.7
Precipitation in mm	60	64	62	66	57	60	54	81	123	147	142	97	590	423	1013
Jamtalferner	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	May-Sep	Oct-Apr	year
Precipitation in mm	102	97	98	94	93	93	90	120	183	195	205	137	840	667	1507
% of Galtür	170	151	159	142	163	155	167	148	149	133	144	141	142	158	149

Table S2. Fossil trees (*Pinus cembra*) found close to the Jamtal hut with lab code and results.

sample ID	laboratory ID	altitude	14C age BP	calibrated age BC (2σ)
FT-1	VRI-1990	2290	4630±60	3631-3116
FT-2	VRI-1991	2240	4550±60	3500-3020

**Table S3: Species list with information on mean ground cover at the plots, as well as family and life form affiliation (Th = therophytes, G = geophytes, H herb, H gram = herbaceous and graminoid hemicryptophytes, Ch = chamaephytes, NaPh, MakPh = nano- and macrophanerophytes, lichen, moss) and dispersal mode.**

Chronosequence Jamtalferner		time since deglaciation in a elevation in m a.s.l.	1-2	7	15	25	55	70	90	120	150	
species	family	life form	dispersal mode	A	B	C	D	E	F	G	H	J
<i>Tussilago farfara</i>	Asteraceae	G	trichometeochorous	0.040	0.0033							
<i>Epilobium angustifolium</i>	Oenagraceae	H herb	trichometeochorous	0.247	0.0270	0.0097	0.0220					
<i>Sagina saginoides</i>	Caryophyllaceae	H herb	bolechorous	0.0087	0.1477	0.0017		0.0017	0.0003			
<i>Cerastium uniflorum</i>	Caryophyllaceae	Ch	bolechorous	0.0057	0.7050	0.3240	0.5867	0.0323	0.0433			
<i>Geum reptans</i>	Rosaceae	H herb	trichometeochorous	0.0007	0.1710	0.0407	0.0833	0.0917	0.6303			
<i>Veronica alpina</i>	Veronicaceae	H herb	bolechorous	0.0017	0.0133	0.0453	0.0107	0.0010	0.0153			
<i>Doronicum clusii</i> ssp. <i>clusii</i>	Asteraceae	H herb	trichometeochorous	0.0033		0.0627		0.0873	0.5793	0.0067		
<i>Epilobium angustifolium</i>	Oenagraceae	H herb	trichometeochorous	0.0040		0.0167				0.0333		
<i>Poa laxa</i>	Poaceae	H gram	trichometeochorous	0.0070	0.5023	0.1123	0.7333	0.5200	0.3883	0.4113	0.4167	
<i>Hieracium intybaceum</i>	Asteraceae	H herb	trichometeochorous	0.0100							0.6733	
<i>Sedum alpestre</i>	Crasulaceae	Ch	bolechorous	0.0073	0.0050	0.0243	0.0417	0.0087	0.0143	0.0030	0.0123	
<i>Saxifraga bryoides</i>	Saxifragaceae	Ch	bolechorous	0.0017	0.2057	0.8517	2.8933	2.2603	0.5383	0.3513	0.0273	0.0133
<i>Gnaphalium supinum</i>	Asteraceae	H herb	trichometeochorous	0.0063	0.0070	0.0530	0.0323	0.0013	0.0323	0.0027	0.0037	
moss		moss		0.0380	1.9187	7.7500	3.4633	9.7667	13.1333	23.7000	24.4333	12.2333
<i>Festuca pumila</i>	Poaceae	H herb	pterometeochorous	0.0100								
herbaceous Asteraceae undetermined	Asteraceae	H herb	???	0.0003								
<i>Arenaria biflora</i>	Caryophyllaceae	Ch	bolechorous	0.0007								
<i>Saxifraga exarata</i> ssp. <i>exarata</i>	Saxifragaceae	Ch	bolechorous	0.0017			0.0167					
<i>Arabis alpina</i>	Brassicaceae	Ch	bolechorous	0.0077			0.0020					
<i>Silene excapa</i>	Caryophyllaceae	Ch	bolechorous	0.0067			0.0167					
<i>Salix reticulata</i>	Salicaceae	Ch	trichometeochorous	0.0133			0.0067					
<i>Oxyria digyna</i>	Polygonaceae	H herb	pterometeochorous	0.0067		0.0833	0.0017	0.0073				
<i>Dryopteris expansa</i>	Dryopteridaceae	H herb		0.0043	0.0940	0.1807		0.0367	0.0017	0.0023		
<i>Salix herbacea</i>	Salicaceae	Ch	trichometeochorous	0.0133				0.8353	2.3140	1.0333	0.0067	0.1430
<i>Cardamine resedifolia</i>	Brassicaceae	H herb	ballochorous	0.0003	0.0153	0.0317	0.0007	0.0027	0.0007	0.0013	0.0003	
<i>Salix retusa</i>	Salicaceae	Ch	trichometeochorous	0.0167	0.0183		2.6100	1.5173	3.0333	0.1333	0.2600	
<i>Epilobium fleischeri</i>	Oenagraceae	H herb	trichometeochorous	0.2670							0.0500	
<i>Salix hegetschweileri</i>	Salicaceae	NaPh	trichometeochorous	0.0533		2.5667	0.2333		5.3000	0.5667	0.5500	
<i>Leucanthemopsis alpina</i>	Asteraceae	H herb	bolechorous	0.1180	0.4547	1.5307	0.1140	0.8893	0.1160	0.0087	0.0013	
<i>Pois alpina</i>	Poaceae	H gram	trichometeochorous (ps.-vivipar)	0.0170				0.2123				
<i>Adenostyles alliariae</i>	Asteraceae	H herb	trichometeochorous	0.0500				0.3073				
<i>Gymnocarpium dryopteris</i>	Woodsiaceae	G		0.0003					0.0333			
<i>Stereocaulon alpinum</i>	Stereocaulaceae	Lichen		0.0117	0.0003	3.5747	0.1317	0.6510	1.4167	0.3877		
<i>Agrostis alpina</i>	Poaceae	H gram	pterometeochorous	0.1340	0.0033	0.0227	0.0300	0.0873	0.4557	0.1567		
<i>Sereocincus incanus</i> spp. <i>carniolicus</i>	Asteraceae	H herb	trichometeochorous	0.0453	0.9803	0.3127	1.1580	0.3750	0.4407	0.2280		
<i>Leontodon hispidus</i>	Asteraceae	H herb	trichometeochorous	0.0333	0.0457	0.0370	0.0350	0.0850	3.2233	1.8123		
<i>Campanula scheuchzeri</i>	Campanulaceae	H herb	bolechorous	0.0400	0.0003			0.0683		0.0150		
<i>Phyteuma globulariifolium</i>	Campanulaceae	H herb	bolechorous	0.0003								
<i>Primula hirsuta</i>	Primulaceae	H herb	bolechorous	0.0067								
<i>Saxifraga oppositifolia</i>	Saxifragaceae	Ch	bolechorous	0.0033								
<i>Luzula alpina</i>	Juncaceae	H gram	stomatochorous (ants)	0.0003				0.0033				
<i>Luzula alpinoplosa</i>	Juncaceae	H gram	stomatochorous (ants)	0.0500	1.5000	1.3950	0.2167					
<i>Hieracium alpinum</i>	Asteraceae	H herb	trichometeochorous	0.0013	0.0013	0.0367	0.1563		0.1590			
<i>Vaccinium gauthierioides</i>	Ericaceae	Ch	endochorous	0.8667						4.9300		
<i>Salix helvetica</i>	Salicaceae	NaPh	trichometeochorous	21.3340	24.3907	22.2000	8.4333	1.4667				
<i>Euphrasia minima</i>	Orobanchaceae	Th	bolechorous	0.0203	0.0003	0.2633	0.0850	0.0177				
<i>Homogyne alpina</i>	Asteraceae	H herb	trichometeochorous	0.0067	0.0003	0.0120	0.0120					
<i>Arabis caerulea</i>	Brassicaceae	H herb	bolechorous	0.0003								
<i>Phleum commutatum</i>	Poaceae	H gram	pterometeochorous	0.1767								
<i>Cirsium spinosissimum</i>	Asteraceae	H herb	trichometeochorous	0.2447				0.0500				
<i>Lotus corniculatus</i>	Fabaceae	H herb	bolechorous	1.5370								
<i>Trifolium pratense</i> ssp. <i>nivale</i>	Fabaceae	H herb	pterometeochorous	6.0667	14.2500	15.8367	13.5333					
<i>Saxifraga paniculata</i>	Saxifragaceae	Ch	bolechorous	0.5667								
<i>Empetrum hermafroditum</i>	Ericaceae	Ch	endochorous	0.0007								
<i>Loiseleuria procumbens</i>	Ericaceae	Ch	bolechorous	0.8333								
<i>Lycopodium alpinum</i>	Lycopodiaceae	Ch		0.0033								
<i>Bartsia alpina</i>	Orobanchaceae	H herb	bolechorous	0.1167	0.0133	0.4043						
<i>Cetraria islandica</i>	Parmeliaceae	Lichen		0.1917	0.4667	3.7867						
<i>Rhododendron ferrugineum</i>	Ericaceae	NaPh	bolechorous	3.1875	7.3833	8.9667						
<i>Vaccinium myrtillus</i>	Ericaceae	Ch	endochorous	0.0500								
<i>Huperzia selago</i>	Lycopodiaceae	Ch		0.0993	0.0317	0.0180						
<i>Campanula barbata</i>	Campanulaceae	H herb	bolechorous	0.7133	1.2000	0.1770						
<i>Pyrola rotundifolia</i>	Ericaceae	H herb	cystometeochorous	0.0033	0.0100	0.2433						
<i>Larix decidua</i>	Pinaceae	MakPh	pterometeochorous	0.1450	0.0200	0.1317						
<i>Hieracium bifidum</i>	Asteraceae	H herb	trichometeochorous	0.3333	7.0333	2.5000						
<i>Solidago virgaurea</i> ssp. <i>minuta</i>	Asteraceae	H herb	trichometeochorous	0.0833	0.0167							
<i>Gentiana nivalis</i>	Gentianaceae	Th	bolechorous	1.1100								
<i>Alchemilla glabra</i>	Rosaceae	H herb	pterometeochorous	0.0050								
<i>Thesium alpinum</i>	Santalaceae	H herb	stomatochorous (ants)	0.0017								
<i>Orthilia secunda</i>	Ericaceae	Ch	cystometeochorous	0.1040	0.0033							
<i>Anthonysia vulgararia</i> ssp. <i>alpina</i>	Fabaceae	H herb	cystometeochorous	0.0340	0.0033							
<i>Potentilla aurea</i>	Rosaceae	H herb	bolechorous	0.0017	0.0007							
<i>Sempervivum montanum</i> ssp. <i>montanum</i>	Crassulaceae	Ch	bolechorous	0.0033	0.0600							
<i>Agrostis agrestifolia</i>	Poaceae	H gram	pterometeochorous	0.6000								
<i>Anthoxanthum alpinum</i>	Poaceae	H gram	trichometeochorous	4.0807								
<i>Poa variegata</i>	Poaceae	H gram	trichometeochorous	0.4167								
<i>Phyteuma hemisphericum</i>	Campanulaceae	H herb	bolechorous	0.0010								
<i>Gentiana punctata</i>	Gentianaceae	H herb	bolechorous	0.2000								
<i>Festuca nigricans</i>	Poaceae	H herb	pterometeochorous	1.1500								
<i>Cladonia spec.</i>	Cladoniaceae	Lichen		0.0733								
<i>Alectoria ochroleuca</i>	Parmeliaceae	Lichen		0.0650								
<i>Carex curvula</i>	Cyperaceae	H gram	cystometeochorous	0.0050								
<i>Picea abies</i>	Pinaceae	MakPh	pterometeochorous	0.2667								
<i>Calluna vulgaris</i>	Ericaceae	NaPh	cystometeochorous	3.2400								

Table S4: NDVI 2016, as well as means and changes for two periods (1985-1991, 2009) at the sample sites with altitude. \* glacier area at that date.

Ice-free years	Sample	Altitude	NDVI mean 1985-1991	NDVI mean 2009	NDVI 85_91-2009	NDVI 2016
1	A	2464	*	*	0.09	-0.03
7	B	2430	*	*	0.12	0.00
15	C	2409	*	0.03	0.08	0.11
25	D	2405	0.01	0.13	0.11	0.21
55	E	2389	0.16	0.29	0.13	0.40
70	F	2384	0.16	0.29	0.13	0.40
90	G	2271	0.27	0.29	0.02	0.35
120	H	2177	0.32	0.40	0.08	0.46
150	J	2123	0.36	0.43	0.07	0.50
average			0.11	0.20	0.09	0.27

Table S5: Maps and DEMs of Jamtalferner with source and date. GI1,2,3: part of the glacier inventory. BW: Black and white images. \* The LIA maximum state has been reported for 1864, based on a conversation of Greim with Gottlieb Lorenz (1844-1911), who was a shepherd in Jamtal in his 20s. This oral reported date is not consistent with other literature, for example, Richter's observation about the contact of Jamtalferner and Totenfeldferner and older maps. Therefore, this date must be considered uncertain. TIRIS: orthophotos of surveys of the federal government of Tyrol.

Year	Type	Source	Remarks
2015	orthophoto	TIRIS	
2010	orthophoto	TIRIS	
2006	LiDAR	TIRIS	GI3
2002	orthophoto	TIRIS	
2002	orthophoto		BW GI2
1996	orthophoto		GI2
2009	orthophoto	TIRIS	
1995	orthophoto	TIRIS	BW
1970	orthophoto	TIRIS	BW
1969	orthophoto		BW GI1
1954	orthophoto	TIRIS	BW
1921	map	[20]	1:15,000
not specified	map	[35]	1:25,000
1909	map	[20]	1:15,000
1904	map	[20]	1:15,000
1898	map	[20]	1:15,000
?	map	[40]	1:50,000
1895/1897	map	[25]	1:10,000
1888	point		
1870	point		
	map	[34]	1:50,000
~1864*	LIA moraine	[20]	GI LIA

Table S6: List of remote-sensing images used in the study.

Satellite sensor	Date	Path/Row
Landsat 5 TM	19850813	193/027
Landsat 5 TM	19900802	194/027
Landsat 5 TM	19900811	193/027
Landsat 5 TM	19910830	193/027
Landsat 5 TM	19980808	194/027
Landsat 5 TM	20040801	193/027
Landsat 5 TM	20060823	193/027
Landsat 5 TM	20070826	193/028
Landsat 5 TM	20090806	194/027
Landsat 5 TM	20090815	193/027
Landsat 5 TM	20090831	193/028
Landsat 8 OLI	20130801	194/027
Landsat 8 OLI	20150731	193/027
Landsat 8 OLI	20160825	194/027

Table S7: Spectral bands used for this study with wavelength range and spatial resolution for the sensors in Table 4.

Satellite sensor	Red wavelength range (nm)	Resolution (m)	NIR wavelength range (nm)	Resolution (m)
Landsat 5 TM	630-690	30	760-900	30
Landsat 8 OLI	636-673	30	851-879	30