GLACIER MASS BALANCE BULLETIN

Bulletin No. 12 (2010–2011)

A contribution to

the Global Terrestrial Network for Glaciers (GTN-G)
as part of the Global Terrestrial/Climate Observing System (GTOS/GCOS),

the Division of Early Warning and Assessment and the Global Environment Outlook
as part of the United Nations Environment Programme (DEWA and GEO, UNEP)

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Compiled by

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Cover page

The year 2011 marks the 50th anniversary of continuous mass balance measurements at Hellstugubreen, a valley glacier in central Jotunheimen, Norway. Photo taken by L. M. Andreassen, 1 August 2013.

PREFACE

In-situ measurements of glacier mass balance constitute a key element in worldwide glacier monitoring as part of global climate-related observation systems. They improve our understanding of the involved processes relating to Earth-atmosphere mass and energy fluxes, and provide quantitative data at high (annual, seasonal, monthly) temporal resolution. Mass balance data is widely used to estimate the glacier contribution to runoff and sea level changes and enable numerical models to be developed for analyzing climate-glacier relationships. Together with more numerous observations of glacier length change and air- and space-borne spatial information on large glacier samples, this helps to increase our process understanding and allows improved quantitative modelling, and it bridges the gap between detailed local studies and global coverage. It also fosters realistic anticipation of possible future developments. The latter includes worst-case scenarios of drastic to even complete deglaciation in many mountain regions of the world as early as the next few decades. Changes in glaciers and ice caps are an easily recognized indication of rapid if not accelerating changes in the energy balance of the Earth's surface and, hence, are also among the most striking features of global climate change. The general losses in length, area, thickness and volume of firn and ice can be visually detected and qualitatively understood by all, whereas numeric values and comprehensive analysis must be provided by advanced science. And while the initial phases following the cold centuries of the Little Ice Age were most probably related to effects from natural climate variability, anthropogenic influences have increased over the past decades to such an extent that – for the first time in history – continued shrinking of glaciers and ice caps is now considered to have been brought about primarily by human impacts on the atmosphere.

International assessments such as the reports of the Intergovernmental Panel on Climate Change (IPCC), the Cryosphere Theme Report of the WMO Integrated Global Observing Strategy (IGOS 2007) or various GCOS/GTOS reports (for instance, the updated implementation plan for the Global Observing System for Climate in support of the UNFCCC; GCOS 2010) clearly recognize glacier changes as high-confidence climate indicators and as a valuable element of early detection strategies. The report on *Global Glacier Changes – facts and figures* published by the WGMS under the auspices of the UNEP (WGMS 2008) presents a corresponding overview and detailed background information. Glacier changes in the perspective of global cryosphere evolution are treated in the *Global Outlook for Ice and Snow* issued by the UNEP (2007).

In order to further document the evolution and to clarify the physical processes and relationships involved in glacier changes, the World Glacier Monitoring Service (WGMS) regularly collects and publishes standardized glacier data. The WGMS is a permanent service of the International Association for the Cryospheric Sciences of the International Union of Geodesy and Geophysics (IACS/IUGG) and of the World Data System within the International Council of Science (WDS/ICSU). The long-term activity is a contribution to the Global Climate/Terrestrial Observing System (GCOS/GTOS), to the Division of Early Warning and Assessment and the Global Environment Outlook as part of the United Nations Environment Programme (DEWA and GEO, UNEP), as well as to the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organisation (UNESCO). In close cooperation with the Global Land Ice Measurement from Space (GLIMS) initiative and the U.S. National Snow and Ice Data Center (NSIDC) at Boulder, Colorado, an integrated and multi-level strategy within the Global Terrestrial Network for Glaciers (GTN-G) of GTOS is used to combine in-situ observations with remotely sensed data, process understanding with global coverage, and traditional measurements with new technologies. This approach, the Global Hierarchical Observing Strategy (GHOST), applies observations in a system of tiers (cf. Haeberli et al. 2000, GTOS 2009). Tier 2 sites comprise detailed glacier mass balance measurements within major climatic zones for improved process understanding and calibration of numerical models. At tier 3 sites cost-saving methodologies are applied to determine regional glacier volume change within major mountain systems. The mass balance data compilation of the WGMS – a network of, at present, about 125 glaciers in 25 countries/regions, representing tier 2 and 3 sites – is published in the form of the bi-annual *Glacier Mass Balance Bulletin* as well as annually in electronic form. This broad sampling of glaciers around the world provides information on presently observed rates of change in glacier mass as well as on their regional distribution patterns and acceleration trends as an independent climate proxy.

The publication of standardized glacier mass balance data in the *Glacier Mass Balance Bulletin* is restricted to measurements which are based on the direct glaciological method (cf. Østrem and Brugman 1991). The request was made to contributors that the measurements provided are compared with and if necessary, adjusted to geodetic surveys repeated at approx. decadal time intervals (Zemp et al. 2013). In accordance with an agreement between the international organizations and the countries involved, preliminary glacier mass balance values are made available on the WGMS homepage (www.wgms.ch) one year after the end of the measurement period. The WGMS homepage also gives access to past and present issues of the *Glacier Mass Balance Bulletin*[1)], as well as explanations of the monitoring strategy.

The *Glacier Mass Balance Bulletin* series was designed at the beginning of the 1990s based on recommendations by an ICSI/IAHS (now IACS/IUGG) working group in order to speed up and facilitate access to information on glacier mass balances by reporting measured values from selected 'reference' glaciers at 2-year intervals. The results of glacier mass balance measurements are made more easily understandable for non-specialists through the use of graphic illustrations and numerical data. The *Glacier Mass Balance Bulletin* complements the publication series *Fluctuations of Glaciers* (WGMS 2012, and earlier volumes), where the full collection of available data, including geodetic volume changes and the more numerous observations of glacier front variations, can be found. It should also be kept in mind that this rapid and somewhat preliminary reporting of mass balance measurements may require slight correction and updating at a later time which can then be found in the *Fluctuations of Glaciers* series, available in digital and printed format from the WGMS.

The present *Glacier Mass Balance Bulletin* reporting the results from the balance years 2009/10 and 2010/11 is the twelfth issue in this long-term series of publications. It continues the well-established tradition of building up a strong data basis for scientific assessments of global glacier changes and related impacts, and solidly documents the united efforts of the WGMS scientific collaboration network to improve and extend the long-term monitoring of an essential climate variable (ECV). Although the present bulletin looks similar to the previous issues, it might be worthwhile to point out a few of the changes: (i) The number of glaciers with actively reported mass balances has more than doubled since the first bulletin. (ii) With the support of the WGMS, it was possible to resume the disrupted long-term mass balance programmes at Lewis Glacier (Kenya) and Golubin Glacier (Kyrgyzstan). (iii) Based on discussions at the „Workshop on Mass Balance Measurements and Modelling" in Skeikampen (Norway; IGS 2009) and at the „General Assembly of National Correspondents" in Zermatt (Switzerland; Zemp et al. 2011), the WGMS started to compile and disseminate point measurements related to glacier-wide balances, which can be calibrated with geodetic/photogrammetric surveys (see Figures 3.X.3). (iv) The terms used in this publication follow the *Glossary of Glacier Mass Balance and Related Terms* recently published by Cogley et al. (2011). (v) Digital Object Identifiers (DOI) were introduced and added to the citation recommendation in order to facilitate versioning and accessibility of the database.

Special thanks are extended to WGMS co-workers, data providers, and sponsoring agencies of recent decades for their long-term commitment, and to all those who have helped to build up the database which, despite its limitations, nevertheless remains an indispensable treasury of international snow and ice research, readily available to the scientific community as well as to a vast public.

Zurich, 2013

Michael Zemp
Director, World Glacier Monitoring Service

[1] The following series of reports on the variations of glaciers in time and space were published by the WGMS and its predecessor, the Permanent Service on the Fluctuations of Glaciers (PSFG):

- Fluctuations of Glaciers 1959–1965 (Vol. 1, P. Kasser)
- Fluctuations of Glaciers 1965–1970 (Vol. 2, P. Kasser)
- Fluctuations of Glaciers 1970–1975 (Vol. 3, F. Müller)
- Fluctuations of Glaciers 1975–1980 (Vol. 4, W. Haeberli)
- Fluctuations of Glaciers 1980–1985 (Vol. 5, W. Haeberli and P. Müller)
- Fluctuations of Glaciers 1985–1990 (Vol. 6, W. Haeberli and M. Hoelzle)
- Fluctuations of Glaciers 1990–1995 (Vol. 7, W. Haeberli, M. Hoelzle, S. Suter and R. Frauenfelder)
- Fluctuations of Glaciers 1995–2000 (Vol. 8, W. Haeberli, M. Zemp, R. Frauenfelder, M. Hoelzle and A. Kääb)
- Fluctuations of Glaciers 2000–2005 (Vol. 9, W. Haeberli, M. Zemp, A. Kääb, F. Paul and M. Hoelzle)
- Fluctuations of Glaciers 2005–2010 (Vol. 10, M. Zemp, H. Frey, I. Gärtner-Roer, S. U. Nussbaumer, M. Hoelzle, F. Paul and W. Haeberli)

- Glacier Mass Balance Bulletin No. 1, 1988–1989 (W. Haeberli and E. Herren)
- Glacier Mass Balance Bulletin No. 2, 1990–1991 (W. Haeberli, E. Herren and M. Hoelzle)
- Glacier Mass Balance Bulletin No. 3, 1992–1993 (W. Haeberli, M. Hoelzle and H. Bösch)
- Glacier Mass Balance Bulletin No. 4, 1994–1995 (W. Haeberli, M. Hoelzle and S. Suter)
- Glacier Mass Balance Bulletin No. 5, 1996–1997 (W. Haeberli, M. Hoelzle and R. Frauenfelder)
- Glacier Mass Balance Bulletin No. 6, 1998–1999 (W. Haeberli, R. Frauenfelder and M. Hoelzle)
- Glacier Mass Balance Bulletin No. 7, 2000–2001 (W. Haeberli, R. Frauenfelder, M. Hoelzle and M. Zemp)
- Glacier Mass Balance Bulletin No. 8, 2002–2003 (W. Haeberli, J. Noetzli, M. Zemp, S. Baumann, R. Frauenfelder and M. Hoelzle)
- Glacier Mass Balance Bulletin No. 9, 2004–2005 (W. Haeberli, M. Hoelzle and M. Zemp)
- Glacier Mass Balance Bulletin No. 10, 2006–2007 (W. Haeberli, I. Gärtner-Roer, M. Hoelzle, F. Paul and M. Zemp)
- Glacier Mass Balance Bulletin No. 11, 2008–2009 (M. Zemp, S. U. Nussbaumer, I. Gärtner-Roer, M. Hoelzle, F. Paul and W. Haeberli)

- World Glacier Inventory – Status 1988 (W. Haeberli, H. Bösch, K. Scherler, G. Østrem and C. C. Wallén)

- Global Glacier Changes: facts and figures (M. Zemp., I. Roer, A. Kääb, M. Hoelzle, F. Paul and W. Haeberli)

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1 INTRODUCTION

The *Glacier Mass Balance Bulletin* reports on two main categories of data: basic information and detailed information. Basic information on specific mass balance, cumulative specific balance, accumulation area ratio (AAR) and equilibrium line altitude (ELA) is given for 126 glaciers. Such information provides a regional overview. Additionally, detailed information such as mass balance maps, mass balance vs. altitude diagrams, relationships between AAR, ELA and mass balance, as well as a short explanatory text with a photograph, is presented for 17 glaciers. These were chosen because they represent a long and continuous series of direct glaciological measurements taken over many years. Long time series, based on high density networks of stakes and firn pits, are especially valuable for analyzing processes of mass and energy exchange at the glacier/atmosphere interface and, hence, for interpreting climate/glacier relationships. In order to provide broader-based information on glaciers from all regions worldwide, additional selected glaciers with shorter measurement series have been included.

1.1 GENERAL INFORMATION ON THE OBSERVED GLACIERS

The glaciers for which data is reported in the present bulletin are listed below (Table 1.1, Figure 1.1). Glaciers with long measurement series of 15 years and more are also listed.

Table 1.1: General geographic information on the 126 glaciers for which basic information for the years 2009/10 and/or 2010/11 is reported. The list also includes 24 glaciers with currently no data reported but long measurement series of 15 or more years.

No.	Glacier name [1)]	1st/last survey [2)]	Country	Location	Coordinates	
1	Bahía del Diablo	2000/2011	Antarctica	Antarctic Peninsula	63.82° S	57.43° W
2	Hurd	2002/2011	Antarctica	Antarctic Peninsula	62.69° S	60.40° W
3	Johnsons	2002/2011	Antarctica	Antarctic Peninsula	62.67° S	60.35° W
4	Brown Superior	2010/2011	Argentina	Andes Centrales	29.98° S	69.64° W
5	Conconta Norte	2010/2011	Argentina	Andes Centrales	29.98° S	69.64° W
6	Los Amarillos	2010/2011	Argentina	Andes Centrales	29.30° S	69.99° W
7	Martial Este	2001/2011	Argentina	Andes Fueguinos	54.78° S	68.40° W
8	Piloto Este	1980/2003	Argentina	Andes Centrales	32.22° S	70.05° W
9	Filleckkees	1964/1980	Austria	Eastern Alps	47.13° N	12.60° E
10	Goldbergkees	1989/2011	Austria	Eastern Alps	47.04° N	12.97° E
11	Hintereisferner	1953/2011	Austria	Eastern Alps	46.80° N	10.77° E
12	Jamtalferner	1989/2011	Austria	Eastern Alps	46.87° N	10.17° E
13	Kesselwandferner	1953/2011	Austria	Eastern Alps	46.84° N	10.79° E
14	Kleinfleisskees	1999/2011	Austria	Eastern Alps	47.05° N	12.95° E
15	Pasterze	1980/2011	Austria	Eastern Alps	47.10° N	12.70° E
16	Stubacher Sonnblickkees	1959/2011	Austria	Eastern Alps	47.13° N	12.60° E
17	Vernagtferner	1965/2011	Austria	Eastern Alps	46.88° N	10.82° E
18	Wurtenkees	1983/2011	Austria	Eastern Alps	47.04° N	13.01° E
19	Chacaltaya [3)]	1992/2008	Bolivia	Tropical Andes	16.35° S	68.12° W
20	Charquini Sur	2003/2011	Bolivia	Tropical Andes	16.17° S	68.09° W
21	Zongo	1992/2011	Bolivia	Tropical Andes	16.25° S	68.17° W
22	Baby Glacier	1960/2005	Canada	High Arctic	79.43° N	90.97° W
23	Devon Ice Cap NW	1961/2011	Canada	High Arctic	75.42° N	83.25° W
24	Helm	1975/2011	Canada	Coast Mountains	49.97° N	123.00° W
25	Meighen Ice Cap	1960/2011	Canada	High Arctic	79.95° N	99.13° W
26	Peyto	1966/2011	Canada	Rocky Mountains	51.67° N	116.53° W

No.	Glacier name [1)]	1st/last survey [2)]	Country	Location	Coordinates	
27	Place	1965/2011	Canada	Coast Mountains	50.43° N	122.60° W
28	Sentinel	1966/1989	Canada	Coast Mountains	49.90° N	122.98° W
29	Melville South Ice Cap	1963/2011	Canada	High Arctic	75.40° N	115.00° W
30	White	1960/2011	Canada	High Arctic	79.45° N	90.67° W
31	Amarillo	2010/2011	Chile	Central Andes	29.30° S	70.00° W
32	Echaurren Norte	1976/2011	Chile	Central Andes	33.58° S	70.13° W
33	Urumqi Glacier No. 1 [4)]	1959/2011	China	Tien Shan	43.08° N	86.82° E
	– East Branch [4)]	1988/2011	China	Tien Shan	43.08° N	86.82° E
	– West Branch [4)]	1988/2011	China	Tien Shan	43.08° N	86.82° E
34	Conejeras	2006/2011	Colombia	Cordillera Central	4.82° N	75.37° W
35	Antizana 15 Alpha	1995/2011	Ecuador	Eastern Cordillera	0.47° S	78.15° W
36	Argentière	1976/2011	France	Western Alps	45.95° N	6.98° E
37	Gebroulaz	1995/2011	France	Western Alps	45.30° N	6.63° E
38	Ossoue	2002/2011	France	Pyrenees	42.77° N	0.14° W
39	Saint Sorlin	1957/2011	France	Western Alps	45.17° N	6.15° E
40	Sarennes	1949/2011	France	Western Alps	45.14° N	6.14° E
41	Freya	2008/2011	Greenland	North-eastern Greenland	74.38° N	20.82° W
42	Mittivakkat	1996/2011	Greenland	South-eastern Greenland	65.67° N	37.83° W
43	Brúarjökull	1994/2011	Iceland	Eastern Iceland	64.67° N	16.17° W
44	Dyngjujökull	1994/2011	Iceland	Central-northern Iceland	64.67° N	17.00° W
45	Eyjabakkajökull	1994/2011	Iceland	Eastern Iceland	64.65° N	15.58° W
46	Hofsjökull E	1989/2010	Iceland	Central Iceland	64.80° N	18.58° W
47	Hofsjökull N	1988/2010	Iceland	Central Iceland	64.95° N	18.92° W
48	Hofsjökull SW	1990/2010	Iceland	Central Iceland	64.72° N	19.05° W
49	Köldukvíslarjökull	1995/2011	Iceland	Central Iceland	64.58° N	17.83° W
50	Langjökull S. Dome	1997/2011	Iceland	Central Iceland	64.62° N	20.30° W
51	Tungnárjökull	1994/2011	Iceland	Central Iceland	64.32° N	18.07° W
52	Chhota Shigri	2003/2010	India	Western Himalaya	32.20° N	77.50° E
53	Calderone	1995/2011	Italy	Apennine Mountains	42.47° N	13.62° E
54	Campo settentrionale	2010/2011	Italy	Central Alps	46.42° N	10.11° E
55	Caresèr [5)]	1967/2011	Italy	Central Alps	46.45° N	10.70° E
	Caresèr centrale [5)]	2010/2011	Italy	Central Alps	46.45° N	10.69° E
	Caresèr occidentale [5)]	2006/2011	Italy	Central Alps	46.45° N	10.69° E
	Caresèr orientale [5)]	2006/2011	Italy	Central Alps	46.45° N	10.70° E
56	Ciardoney	1992/2011	Italy	Western Alps	45.52° N	7.40° E
57	Fontana Bianca/ Weissbrunnferner	1984/2011	Italy	Central Alps	46.48° N	10.77° E
58	Lunga/Langenferner	2004/2011	Italy	Central Alps	46.47° N	10.62° E
59	Lupo	2010/2011	Italy	Central Alps	46.08° N	9.99° E
60	Malavalle/ Übeltalferner	2002/2011	Italy	Central Alps	46.95° N	11.12° E
61	Pendente/ Hangender Ferner	1996/2011	Italy	Central Alps	46.96° N	11.23° E
62	Ries occidentale/ Westlicher Rieserferner	2009/2011	Italy	Eastern Alps	46.90° N	12.10° E
63	Suretta meridionale	2010/2011	Italy	Central Alps	46.51° N	9.36° E

No.	Glacier name [1)]	1st/last survey [2)]	Country	Location	Coordinates	
64	Hamaguri Yuki [6)]	1981/2011	Japan	Northern Japanese Alps	36.60° N	137.62° E
65	Igli Tuyuksu	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
66	Manshuk Mametova	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
67	Mayakovskiy	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
68	Molodezhniy	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
69	Ordzhonikidze	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
70	Partizan	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
71	Shumskiy	1967/1991	Kazakhstan	Dzhungarskiy	45.08° N	80.23° E
72	Ts. Tuyuksuyskiy	1957/2011	Kazakhstan	Tien Shan	43.05° N	77.08° E
73	Visyachiy-1-2	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
74	Zoya Kosmodemyanskaya	1976/1990	Kazakhstan	Tien Shan	43° N	77.1° E
75	Lewis	1979/2011	Kenya	East Africa	0.15° S	37.30° E
76	Abramov	1968/1998	Kyrgyzstan	Pamir Alai	39.63° N	71.60° E
77	Akshiirak (No. 354)	2011/2011	Kyrgyzstan	Tien Shan	41.80° N	78.15° E
78	Golubin	1969/2011	Kyrgyzstan	Tien Shan	42.46° N	74.50° E
79	Kara-Batkak	1957/1998	Kyrgyzstan	Tien Shan	42.10° N	78.30° E
80	Suek Zapadniy	1971/2011	Kyrgyzstan	Tien Shan	41.78° N	77.78° E
81	Brewster	2005/2011	New Zealand	Tititea Mt Aspiring NP	44.08° S	169.44° E
82	Rolleston	2011/2011	New Zealand	Taramakau	42.88° S	171.52° E
83	Ålfotbreen	1963/2011	Norway	Western Norway	61.75° N	5.65° E
84	Austdalsbreen	1987/2011	Norway	Western Norway	61.80° N	7.35° E
85	Austre Brøggerbreen	1967/2011	Norway	Spitsbergen	78.88° N	11.83° E
86	Austre Lovénbreen	2011/2011	Norway	Spitsbergen	78.88° N	11.83° E
87	Blomstølskardsbreen	2007/2011	Norway	South-western Norway	59.98° N	6.36° E
88	Breidablikkbrea	1963/2011	Norway	South-western Norway	60.09° N	6.40° E
89	Engabreen	1970/2011	Norway	Northern Norway	66.65° N	13.85° E
90	Gråfjellsbrea	1964/2011	Norway	South-western Norway	60.10° N	6.40° E
91	Gråsubreen	1962/2011	Norway	Central Norway	61.65° N	8.60° E
92	Hansbreen	1989/2011	Norway	Spitsbergen	77.08° N	15.67° E
93	Hansebreen	1986/2011	Norway	Western Norway	61.75° N	5.68° E
94	Hellstugubreen	1962/2011	Norway	Central Norway	61.57° N	8.43° E
95	Irenebreen	2002/2011	Norway	Spitsbergen	78.65° N	12.10° E
96	Juvfonne	2010/2010	Norway	Central Norway	61.68° N	8.35° E
97	Kongsvegen	1987/2011	Norway	Spitsbergen	78.80° N	12.98° E
98	Langfjordjøkelen	1989/2011	Norway	Northern Norway	70.12° N	21.77° E
99	Midtre Lovénbreen	1968/2011	Norway	Spitsbergen	78.88° N	12.07° E
100	Nigardsbreen	1962/2011	Norway	Western Norway	61.72° N	7.13° E
101	Rembesdalskåka	1963/2011	Norway	Central Norway	60.53° N	7.37° E
102	Storbreen	1949/2011	Norway	Central Norway	61.57° N	8.13° E
103	Svelgjabreen	2007/2011	Norway	South-western Norway	59.98° N	6.28° E
104	Waldemarbreen	1995/2011	Norway	Spitsbergen	78.67° N	12.00° E
105	Artesonraju	2005/2010	Peru	Cordillera Blanca	8.95° S	77.62° W
106	Yanamarey	2005/2010	Peru	Cordillera Blanca	9.65° S	77.27° W
107	Djankuat	1968/2011	Russia	Northern Caucasus	43.20° N	42.77° E

No.	Glacier name [1]	1st/last survey [2]	Country	Location	Coordinates	
108	Garabashi	1984/2010	Russia	Northern Caucasus	43.30° N	42.47° E
109	Kozelskiy	1973/1997	Russia	Kamchatka	53.23° N	158.82° E
110	Leviy Aktru	1977/2009	Russia	Altay	50.08° N	87.72° E
111	Maliy Aktru	1962/2009	Russia	Altay	50.08° N	87.75° E
112	Vodopadniy (No. 125)	1977/2009	Russia	Altay	50.1° N	87.7° E
113	Maladeta	1992/2011	Spain	South Pyrenees	42.65° N	0.64° E
114	Mårmaglaciären	1990/2011	Sweden	Northern Sweden	68.83° N	18.67° E
115	Rabots glaciär	1982/2011	Sweden	Northern Sweden	67.89° N	18.53° E
116	Riukojietna	1986/2011	Sweden	Northern Sweden	68.08° N	18.08° E
117	Storglaciären	1946/2011	Sweden	Northern Sweden	67.90° N	18.57° E
118	Tarfalaglaciären	1986/2011	Sweden	Northern Sweden	67.93° N	18.65° E
119	Basòdino	1992/2011	Switzerland	Western Alps	46.42° N	8.48° E
120	Findelen	2005/2011	Switzerland	Western Alps	46.00° N	7.87° E
121	Gries	1962/2011	Switzerland	Western Alps	46.44° N	8.34° E
122	Limmern	1948/1985	Switzerland	Western Alps	46.82° N	8.98° E
123	Pizol	2007/2011	Switzerland	Western Alps	46.97° N	9.40° E
124	Plattalva	1948/1989	Switzerland	Western Alps	46.83° N	8.98° E
125	Rätzli (Plaine Morte)	2010/2011	Switzerland	Western Alps	46.38° N	7.52° E
126	Rhone	1885/1983	Switzerland	Western Alps	46.62° N	8.40° E
127	Silvretta	1960/2011	Switzerland	Eastern Alps	46.85° N	10.08° E
128	Tsanfleuron	2010/2011	Switzerland	Western Alps	46.32° N	7.23° E
129	Blue Glacier	1956/1999	USA	Washington	47.82° N	123.68° W
130	Columbia (2057)	1984/2011	USA	North Cascades	47.97° N	121.35° W
131	Daniels	1984/2011	USA	North Cascades	47.57° N	121.17° W
132	Easton	1990/2011	USA	North Cascades	48.75° N	120.83° W
133	Emmons	2003/2011	USA	Mt Rainier	46.85° N	121.72° W
134	Foss	1984/2011	USA	North Cascades	47.55° N	121.20° W
135	Gulkana	1966/2011	USA	Alaska Range	63.25° N	145.42° W
136	Ice Worm	1984/2011	USA	North Cascades	47.55° N	121.17° W
137	Lemon Creek	1953/2011	USA	Coast Mountains	58.38° N	134.36° W
138	Lower Curtis	1984/2011	USA	North Cascades	48.83° N	121.62° W
139	Lynch	1984/2011	USA	North Cascades	47.57° N	121.18° W
140	Nisqually	2003/2011	USA	Mt Rainier	46.82° N	121.74° W
141	Noisy Creek	1993/2011	USA	Washington	48.67° N	121.53° W
142	North Klawatti	1993/2011	USA	Washington	48.57° N	121.12° W
143	Rainbow	1984/2011	USA	North Cascades	48.80° N	121.77° W
144	Sandalee	1995/2011	USA	Washington	48.42° N	120.80° W
145	Sholes	1990/2011	USA	North Cascades	48.80° N	121.78° W
146	Silver	1993/2011	USA	Washington	48.98° N	121.25° W
147	South Cascade	1953/2011	USA	North Cascades	48.37° N	121.05° W
148	Taku	1946/2011	USA	Coast Mountains	58.55° N	134.13° W
149	Wolverine	1966/2011	USA	Kenai Mountains	60.40° N	148.92° W
150	Yawning	1984/2011	USA	North Cascades	48.45° N	121.03° W

1) Countries and glaciers are listed in alphabetical order.
2) Years of first and most recent survey available to the WGMS.
3) Chacaltaya disappeared entirely in 2009.
4) In 1993, Urumqi Glacier No. 1 divided in two parts: the East Branch and the West Branch.
5) Caresèr split into three parts: Caresèr occidentale, Caresèr orientale (2005) and Caresèr centrale (2009).
6) Perennial snowfield or glacieret.

1.2 GLOBAL OVERVIEW MAP

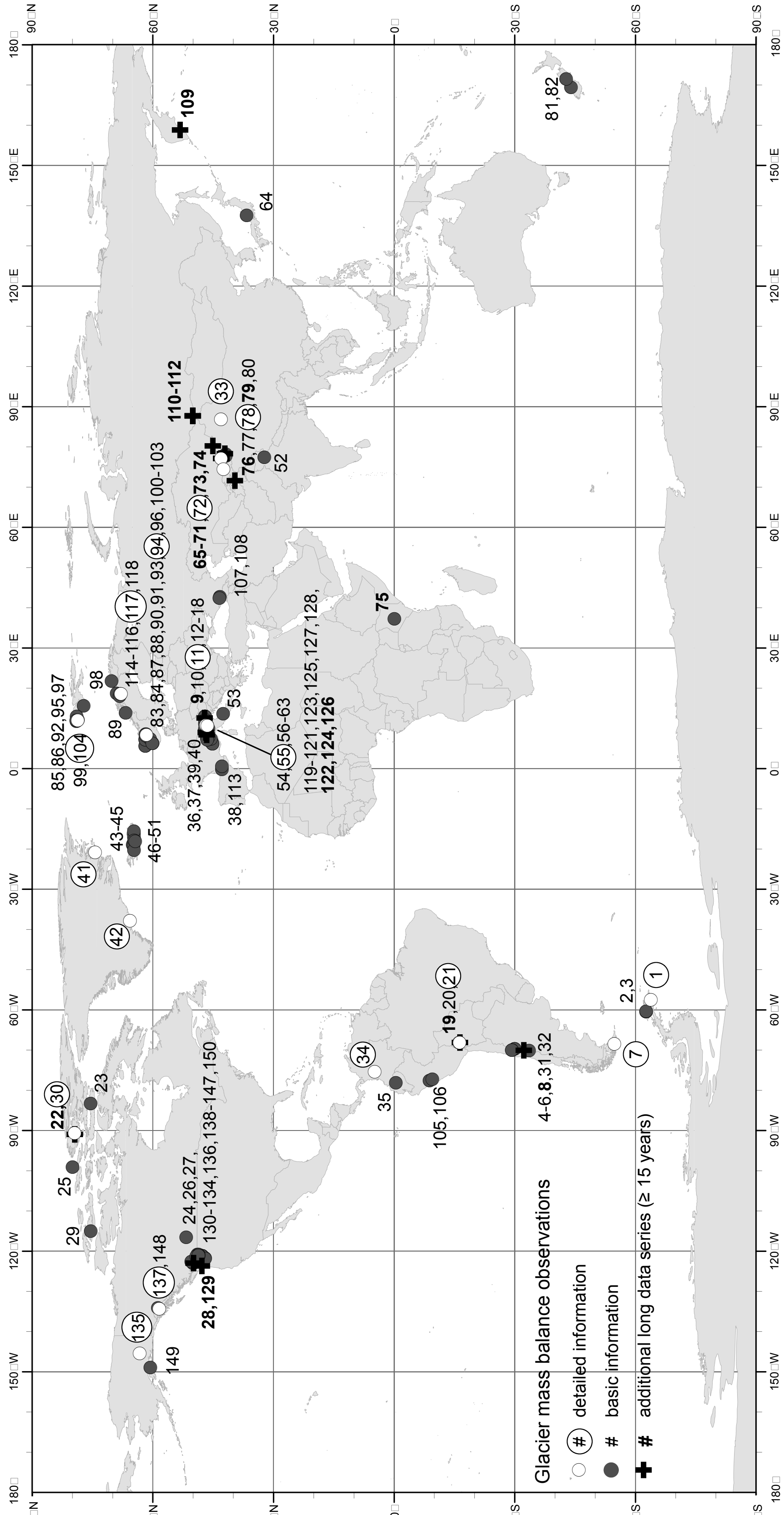


Figure 1.1: Location of the 126 glaciers for which basic information is reported. This overview also includes 24 glaciers with currently no data reported but long measurement series of 15 or more years.

2 BASIC INFORMATION

Specific mass balance (b), equilibrium line altitude (ELA) and accumulation area ratio (AAR) from the balance years 2009/10 and 2010/11 are presented in the table in Part 2.1. ELAs above and below the glacier elevation range are marked by > and <, respectively. In these cases, the value given is the glacier max/min elevation. The AAR values are given as integer values only.

Values for ELA$_0$ and AAR$_0$ are also listed. They represent the calculated ELA and AAR values for a zero mass balance, i.e., a hypothetical steady state. All values since the beginning of mass balance measurement-taking were used for this calculation on each glacier. Minimum sample size for regression was defined as six ELA or AAR values. In extreme years some of the observed glaciers can become entirely ablation or accumulation areas. Corresponding AAR values of 0 or 100 % as well as ELA values outside the altitude range of the observed glaciers were excluded from the calculation of AAR$_0$ and ELA$_0$ values. For the glaciers with detailed information, the corresponding graphs (AAR and ELA vs. specific mass balance) are given in Chapter 3.

The graphs in the second part (2.2), present the development of cumulative specific mass balance over the whole observation period for each glacier where three or more mass balances were reported, and the years 2009/10 or 2010/11 are included. Some of the time series have data gaps and hence have to be interpreted with care. In these cases, the overall ice loss cannot be derived from the cumulative specific mass balance graphs and has to be determined by other means, such as geodetic methods.

2.1 SUMMARY TABLE (MASS BALANCE, ELA, ELA$_0$, AAR, AAR$_0$)

Name	Country	b10 [mm w.e.]	b11 [mm w.e.]	ELA10 [m a.s.l.]	ELA11 [m a.s.l.]	ELA$_0$ [m a.s.l.]	AAR10 [%]	AAR11 [%]	AAR$_0$ [%]
Bahía del Diablo	Antarctica	+ 370	+ 20	< 75	322	356	100	62	55
Hurd	Antarctica	+ 540	+ 290	160	130	209	77	76	52
Johnsons	Antarctica	+ 510	+ 500	130	135	192	93	90	58
Brown Superior	Argentina	− 1029	− 2045	—	—	—	—	—	—
Conconta Norte	Argentina	− 1474	− 1018	—	—	—	—	—	—
Los Amarillos	Argentina	− 1089	− 756	—	—	—	—	—	—
Martial Este	Argentina	+ 976	− 319	1015	1084	1073	93	46	56
Goldbergkees	Austria	− 758	− 1878	2950	> 3100	2915	27	1	41
Hintereisferner	Austria	− 820	− 1420	3116	3285	2921	36	25	66
Jamtalferner	Austria	− 1014	− 1434	> 3200	> 3120	2760	2	9	57
Kesselwandferner	Austria	− 99	− 670	3158	3266	3116	65	26	69
Kleinfleisskees	Austria	− 216	− 1536	2950	> 3100	2851	48	0	63
Pasterze	Austria	− 1067	− 1268	2925	2950	2717	44	43	75
Stubacher Sonnblickkees	Austria	− 792	− 2260	2900	2955	2741	23	2	59
Vernagtferner	Austria	− 680	− 955	3246	3261	3081	23	19	66
Wurtenkees	Austria	− 519	− 1800	> 3100	> 3100	2901	20	0	36
Charquini Sur	Bolivia	− 2921	− 1205	5122	5219	5139	18	18	55
Zongo	Bolivia	− 671	− 221	5383	5429	5245	52	59	68
Devon Ice Cap NW	Canada	− 417	− 683	1950	1930	1016	—	—	71 [1)]
Helm	Canada	− 190	+ 650	2125	2010	1994	33	57	37
Meighen Ice Cap	Canada	− 387	− 1310	—	—	—	—	—	—
Peyto	Canada	− 340	− 360	2675	2680	2610	44	43	51

Name	Country	b10 [mm w.e.]	b11 [mm w.e.]	ELA10 [m a.s.l.]	ELA11 [m a.s.l.]	ELA_0 [m a.s.l.]	AAR10 [%]	AAR11 [%]	AAR_0 [%]
Place	Canada	+ 80	+ 120	2060	2053	2081	45	50	49
Melville South Ice Cap	Canada	− 939	− 1339	—	—	—	—	—	—
White	Canada	− 188	− 983	1134	1429	917	58	13	71
Amarillo	Chile	− 751	− 737	—	—	—	—	—	—
Echaurren Norte	Chile	− 2010	− 1270	—	—	—	—	—	—
Urumqi Glacier No. 1 [2)]	China	− 1327	− 945	> 4484	4230	4003	0	10	59
− East Branch [2)]	China	− 1441	− 1103	> 4267	> 4267	3950	0	0	64
− West Branch [2)]	China	− 1116	− 653	> 4484	4190	4029	0	28	64
Conejeras	Colombia	− 3856	− 1098	4916	4831	4814	0	4	10
Antizana 15 Alpha	Ecuador	− 938	+ 163	5260	5150	5062	47	63	70
Argentière	France	− 540	− 2010	—	—	—	—	—	—
Gebroulaz	France	− 340	− 1400	—	—	—	—	—	—
Ossoue	France	− 480	− 2460	—	> 3200	—	35	—	32
Saint Sorlin	France	− 1000	− 3020	—	—	2863	—	—	—
Sarennes	France	− 1530	− 4153	—	—	—	—	—	—
Freya	Greenland	− 806	− 934	> 1300	> 1300	—	6	5	—
Mittivakkat	Greenland	− 2160	− 2450	> 880	> 880	—	0	0	58
Brúarjökull	Iceland	− 1570	+ 515	1545	1105	1197	14	73	61
Dyngjujökull	Iceland	− 1540	+ 377	1675	1324	1338	22	65	63
Eyjabakkajökull	Iceland	− 1750	+ 525	1271	1050	1080	18	64	56
Hofsjökull E	Iceland	− 2830	—	—	—	1169	—	—	53
Hofsjökull N	Iceland	− 2400	—	—	—	1263	—	—	50
Hofsjökull SW	Iceland	− 3490	—	—	1290	1266	—	54	48
Köldukvíslarjökull	Iceland	− 2870	− 754	1828	1615	1327	8	39	60
Langjökull S. Dome	Iceland	− 3800	− 1279	> 1440	—	997	0	23	56
Tungnárjökull	Iceland	− 3510	− 1380	> 1680	1354	1143	0	33	61
Chhota Shigri	India	+ 330	—	—	—	—	—	—	—
Calderone	Italy	+ 702	− 1182	—	—	2670	84	—	59
Campo settentrionale	Italy	− 978	− 1588	3070	> 3180	—	18	0	—
Caresèr [3)]	Italy	− 962	− 1922	3250	> 3278	3089	9	0	44
Caresèr centrale [3)]	Italy	− 1853	− 2610	> 3112	> 3112	—	0	0	—
Caresèr occidentale [3)]	Italy	− 787	− 1382	3250	> 3278	—	10	0	—
Caresèr orientale [3)]	Italy	− 830	− 1873	3240	> 3267	—	11	0	—
Ciardoney	Italy	− 830	− 1710	3120	> 3150	2983	10	0	54
Fontana Bianca/ Weissbrunnferner	Italy	− 195	− 1142	3200	> 3355	3236	44	0	54
Lunga/Langenferner	Italy	− 659	− 1078	3270	> 3390	—	23	10	—
Lupo	Italy	+ 347	− 597	2540	2760	—	65	7	—
Malavalle/Übeltalferner	Italy	− 197	− 1198	3032	3297	2985	42	5	50
Pendente/Hangender Ferner	Italy	− 134	− 1800	2815	3002	2820	24	0	33
Vedretta occidentale di Ries/ Westlicher Rieserferner	Italy	− 469	− 816	3075	3150	—	21	10	—
Suretta meridionale	Italy	− 3	− 1706	2785	> 2925	—	56	0	—
Hamaguri Yuki [4)]	Japan	− 14	− 406	—	—	—	—	—	—
Ts. Tuyuksuyskiy	Kazakhstan	+ 32	− 313	3762	3800	3747	45	44	52
Lewis	Kenya	− 1543	− 1029	> 4871	> 4871	4789	0	0	55
Akshiirak (No. 354)	Kyrgyzstan	—	− 34	—	4190	—	—	50	—
Golubin	Kyrgyzstan	—	+ 70	—	3850	3810	—	65	72
Suek Zapadniy	Kyrgyzstan	—	− 314	—	4220	4247	—	63	47
Brewster	New Zealand	+ 222	− 1509	1930	2285	1976	52	1	54
Rolleston	New Zealand	—	− 2039	—	1818	—	—	5	—

Name	Country	b10 [mm w.e.]	b11 [mm w.e.]	ELA10 [m a.s.l.]	ELA11 [m a.s.l.]	ELA0 [m a.s.l.]	AAR10 [%]	AAR11 [%]	AAR0 [%]
Ålfotbreen	Norway	− 1840	− 845	> 1368	> 1368	1200	0	0	57
Austdalsbreen	Norway	− 2000	− 1350	> 1747	> 1747	1421	0	0	66
Austre Brøggerbreen	Norway	− 440	− 1004	403	525	289	13	—	50
Austre Lovénbreen	Norway	—	− 145	—	488	—	—	12	—
Blomstølskardsbreen	Norway	− 1230	− 971	> 1636	1600	—	0	6	—
Breidablikkbrea	Norway	− 1940	− 2286	> 1651	> 1651	1476	0	0	—
Engabreen	Norway	− 520	− 910	1240	1270	1157	47	41	60
Gråfjellsbrea	Norway	− 1840	− 2239	> 1651	> 1651	1460	0	0	—
Gråsubreen	Norway	− 1060	− 1130	2250	2275	2071	4	1	39
Hansbreen	Norway	− 14	− 280	350	330	307	39	54	55
Hansebreen	Norway	− 2220	− 1235	> 1310	> 1310	1157	0	0	56
Hellstugubreen	Norway	− 1340	− 2043	> 2230	> 2230	1839	0	0	58
Irenebreen	Norway	− 497	− 1293	419	609	290	7	1	35
Juvfonne	Norway	− 3240	—	> 1998	—	—	0	—	—
Kongsvegen	Norway	+ 130	− 434	547	607	536	52	26	48
Langfjordjøkelen	Norway	− 760	− 1257	1005	> 1050	728	12	0	62
Midtre Lovénbreen	Norway	− 200	− 920	364	524	301	29	1	54
Nigardsbreen	Norway	− 800	− 831	1770	1700	1559	14	29	59
Rembesdalskåka	Norway	− 1490	− 1500	> 1854	> 1854	1678	0	0	68
Storbreen	Norway	− 1760	− 1350	1990	2005	1719	4	3	59
Svelgjabreen	Norway	− 1640	− 1243	> 1636	1535	—	0	18	—
Waldemarbreen	Norway	− 577	− 1239	399	518	282	18	1	43
Artesonraju	Peru	− 1048	—	5071	—	—	42	—	—
Yanamarey	Peru	− 182	—	4912	—	—	28	—	—
Djankuat	Russia	− 600	− 680	—	—	3189	—	—	60
Garabashi	Russia	− 1240	—	3950	—	3790	40	—	60
Maladeta	Spain	+ 259	− 1504	3000	> 3200	3058	80	52	44
Mårmaglaciären	Sweden	− 500	− 1450	1635	1660	1601	18	9	33
Rabots glaciär	Sweden	− 1080	− 2110	1670	> 1930	1377	13	0	49
Riukojietna	Sweden	− 960	− 1080	> 1440	> 1365	1330	0	0	55
Storglaciären	Sweden	− 690	− 1060	1570	1585	1464	28	25	45
Tarfalaglaciären	Sweden	− 1060	− 1820	> 1800	> 1390	—	0	0	—
Basòdino	Switzerland	− 584	− 1000	2990	3100	2870	30	5	51
Findelen	Switzerland	− 470	− 880	3280	3365	3183	52	44	67
Gries	Switzerland	− 1307	− 2150	3085	3250	2821	11	1	56
Pizol	Switzerland	− 860	− 2024	> 2786	> 2786	—	0	0	—
Rätzli (Plaine Morte)	Switzerland	− 822	− 2271	2925	2925	—	5	0	—
Silvretta	Switzerland	− 268	− 1450	2814	> 3079	2759	44	0	55
Tsanfleuron	Switzerland	− 917	− 2336	> 2945	> 2945	—	1	0	—
Columbia (2057)	USA	− 210	+ 1470	1615	—	—	63	100	65
Daniels	USA	− 260	+ 1060	—	—	—	60	98	60
Easton	USA	+ 680	+ 1150	2030	1880	2087	77	89	65
Emmons	USA	+ 1020	− 20	2615	2640	2690	47	46	45
Foss	USA	− 110	+ 1300	—	—	—	62	92	65
Gulkana	USA	− 1630	− 1290	1917	1995	1723	36	26	64
Ice Worm	USA	− 380	+ 1340	—	—	—	60	100	63
Lemon Creek	USA	− 580	− 720	1075	1100	1011	55	47	62
Lower Curtis	USA	− 440	+ 940	1600	1580	1641	58	76	63
Lynch	USA	− 340	+ 980	—	—	—	56	88	66
Nisqually	USA	+ 20	+ 420	2540	2675	2634	72	53	53
Noisy Creek	USA	− 180	+ 1280	1815	1595	1797	34	100	50
North Klawatti	USA	+ 250	+ 750	2065	1998	2095	74	79	66
Rainbow	USA	+ 760	+ 1640	1650	1480	1693	80	92	66
Sandalee	USA	+ 240	+ 1150	2110	2010	2158	67	90	35
Sholes	USA	+ 940	+ 1450	—	—	—	84	84	63

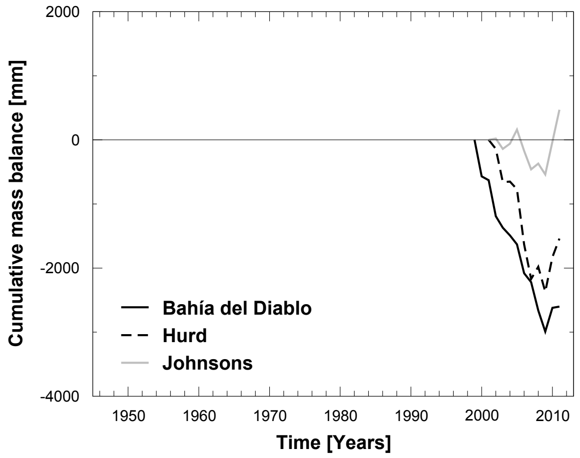
Name	Country	b10 [mm w.e.]	b11 [mm w.e.]	ELA10 [m a.s.l.]	ELA11 [m a.s.l.]	ELA_0 [m a.s.l.]	AAR10 [%]	AAR11 [%]	AAR_0 [%]
Silver	USA	+ 550	+ 730	2220	2030	2294	15	100	45
South Cascade	USA	− 810	+ 1210	1880	1760	1889	—	—	54
Taku	USA	− 120	− 550	1000	1025	974	—	—	—
Wolverine	USA	+ 30	− 1210	1105	1283	1150	—	—	63
Yawning	USA	+ 170	+ 1220	—	—	—	70	90	65

1) Based on AAR values from 1961–1980.
2) In 1993, Urumqi Glacier No. 1 divided in two parts: the East Branch and the West Branch.
3) Caresèr split into three parts: Caresèr occidentale, Caresèr orientale (2005) and Caresèr centrale (2009).
4) Perennial snowfield or glacieret.

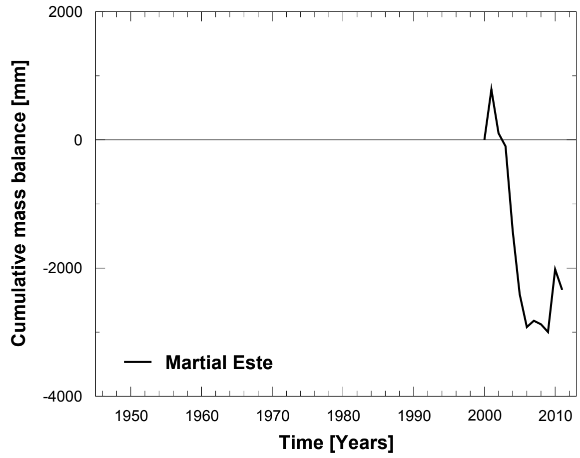
2.2 CUMULATIVE SPECIFIC MASS BALANCE GRAPHS

Note:
- Missing values are marked by gaps in the plotted data series, with graphs then restarting with the value of the previous available data point.
- Y-axes are scaled according to the data range of the cumulative mass balance graph.

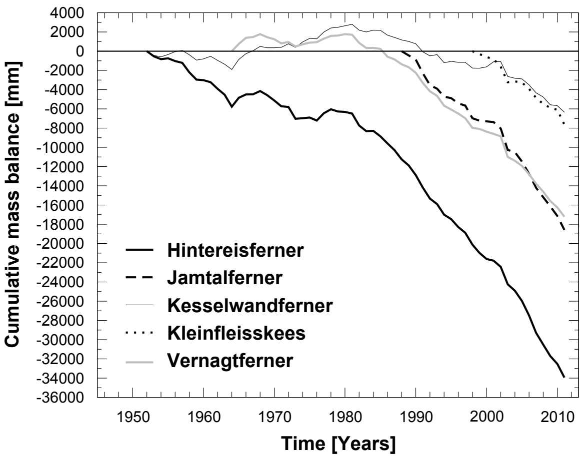
ANTARCTICA



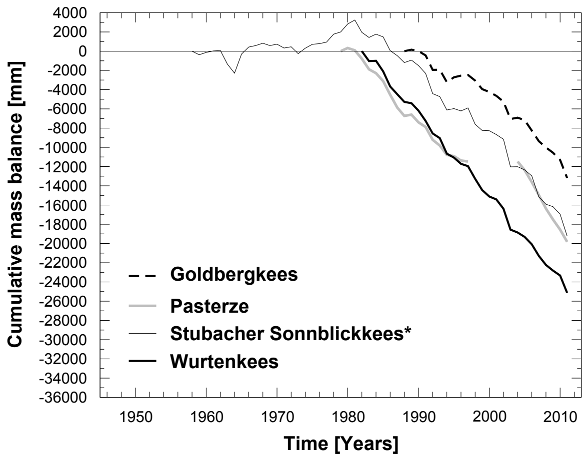
ARGENTINA



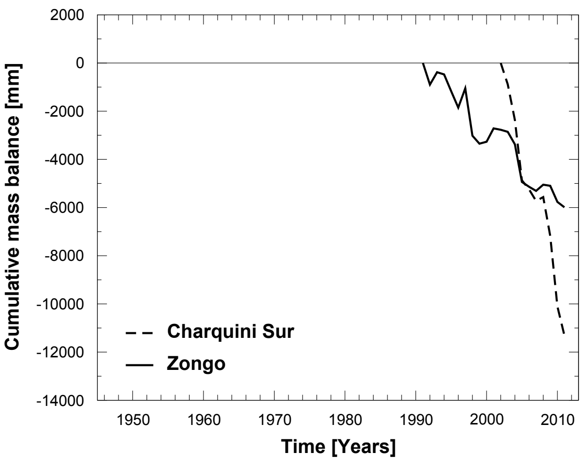
AUSTRIA 1



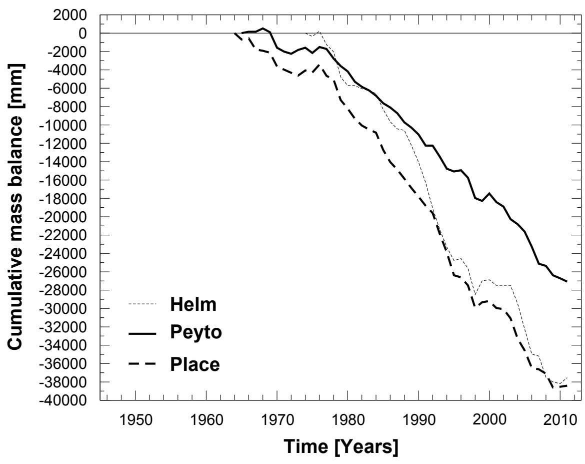
AUSTRIA 2



BOLIVIA

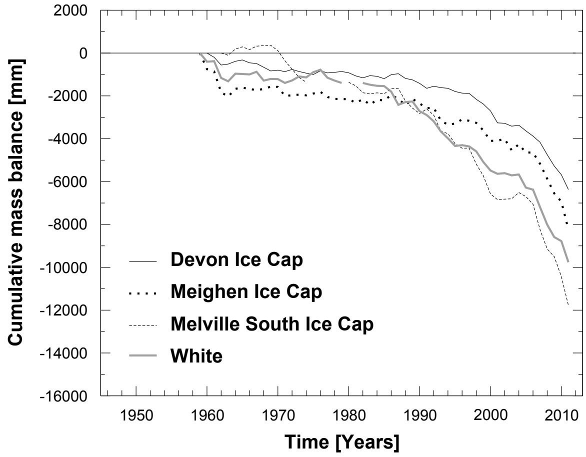


CANADA 1

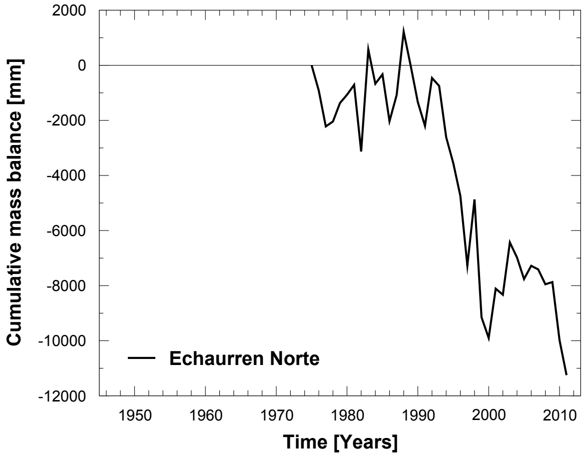


* Mass balance is determined by correlating observed ELA/AAR and mass balance using direct mass balance series from 1963/64 to 1979/80.

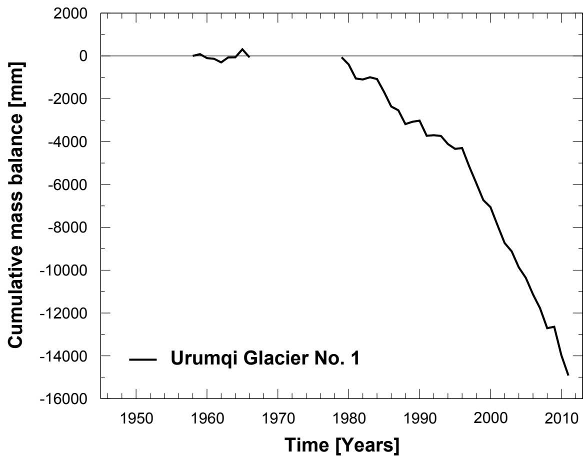
CANADA 2



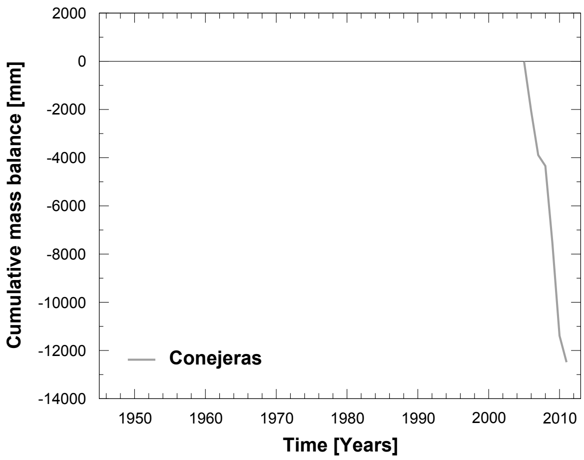
CHILE



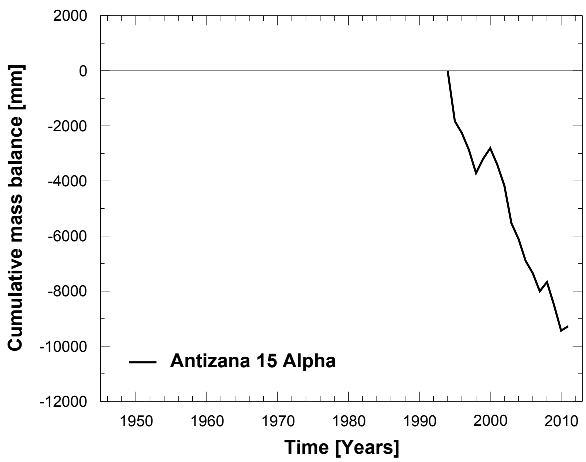
CHINA



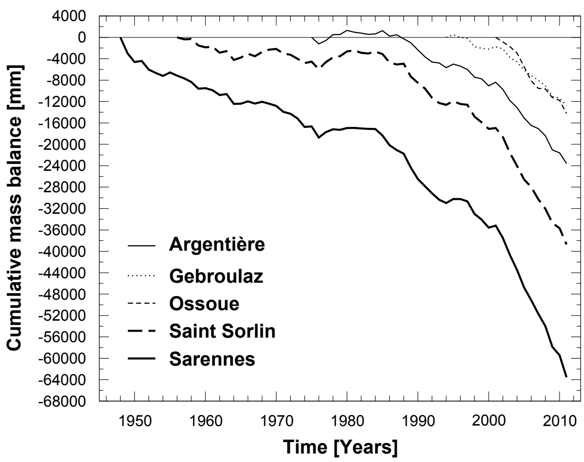
COLOMBIA



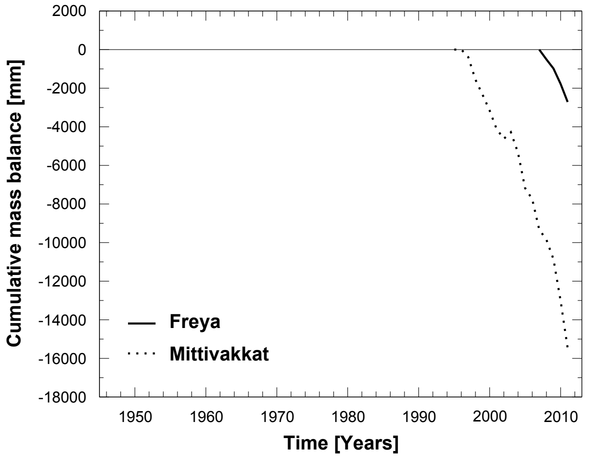
ECUADOR



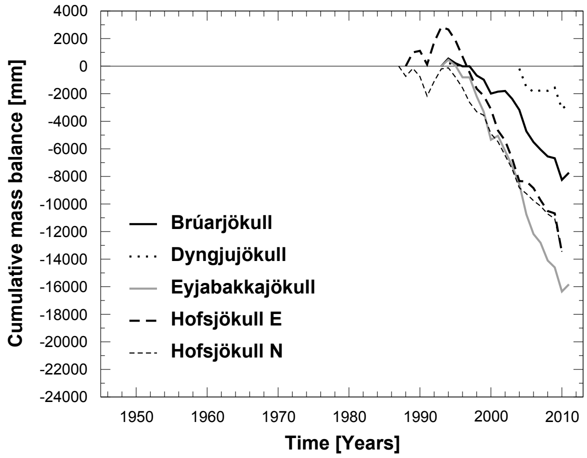
FRANCE



GREENLAND



ICELAND 1



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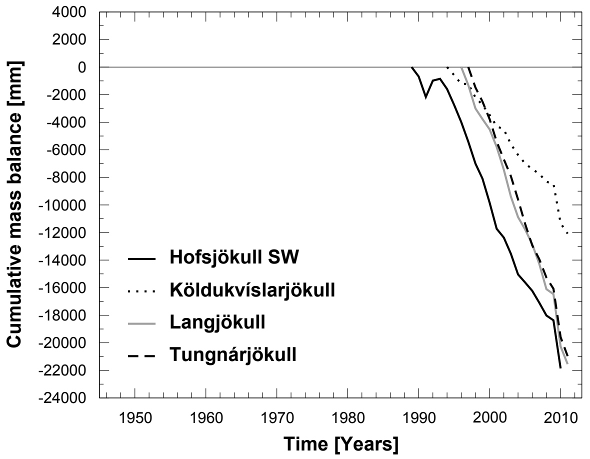

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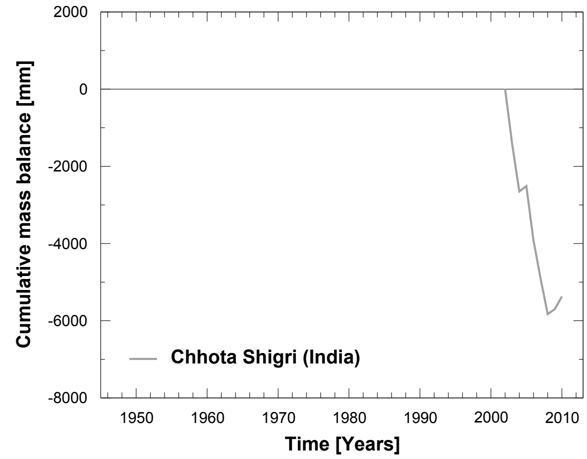

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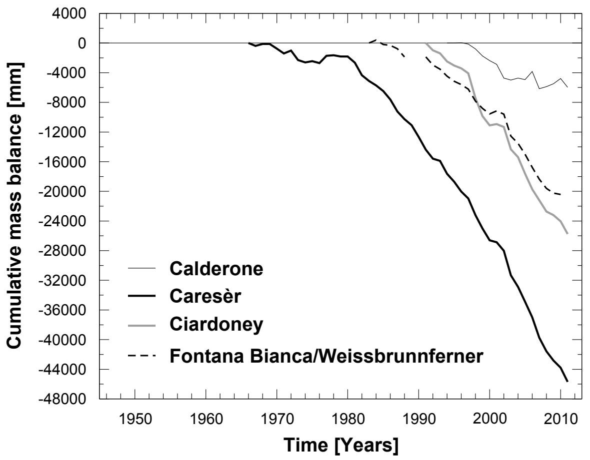
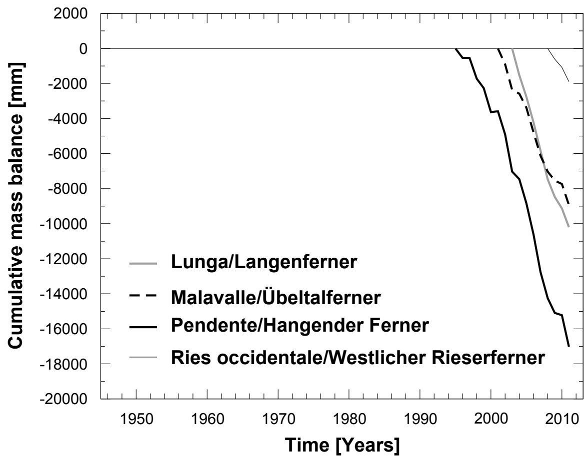


ITALY 2



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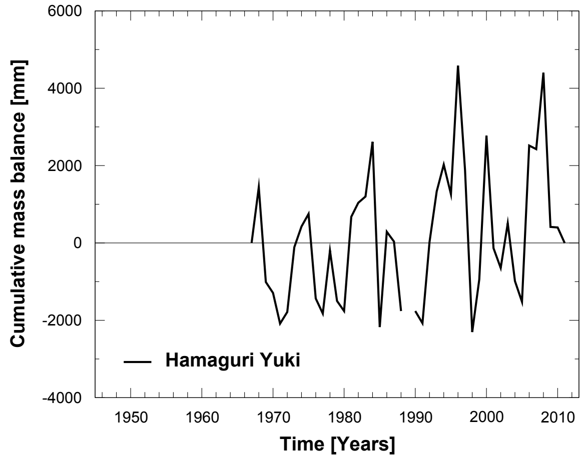

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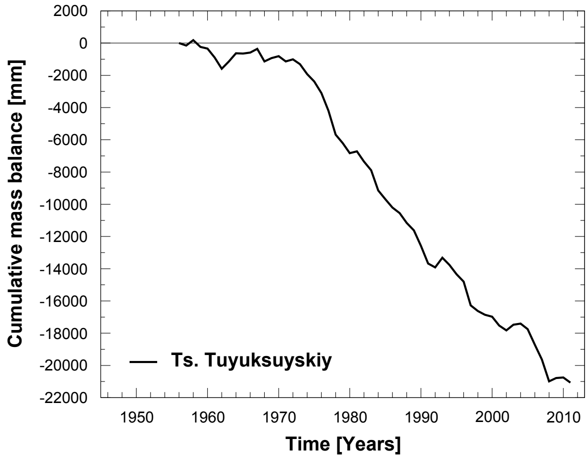

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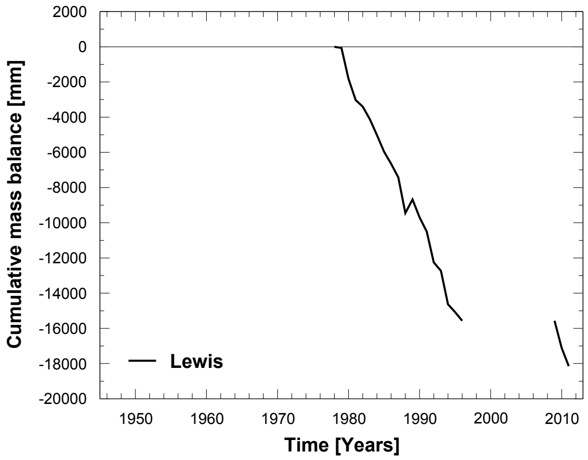
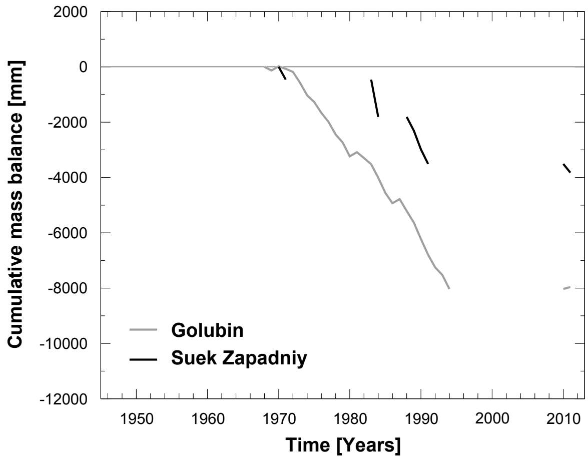
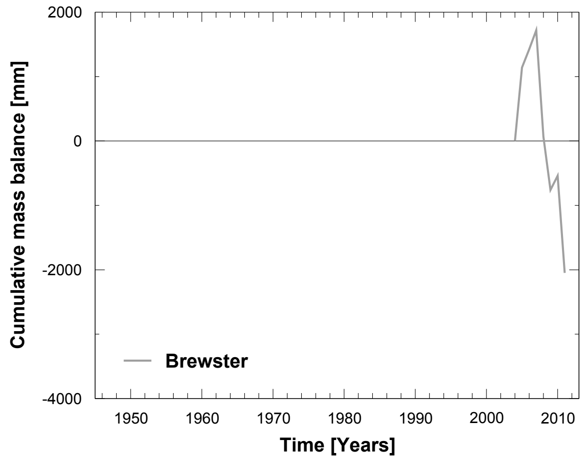


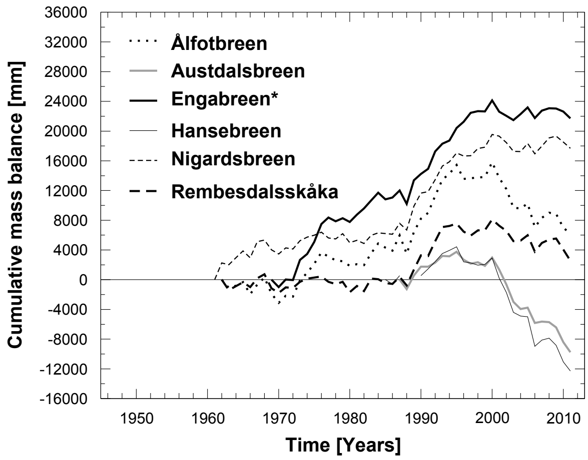
KYRGYZSTAN



NEW ZEALAND

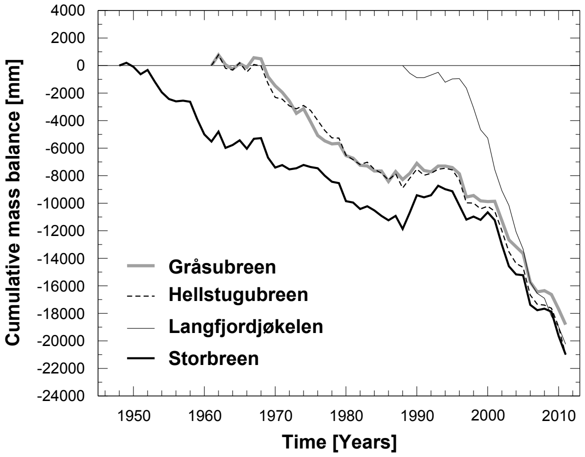


NORWAY 1

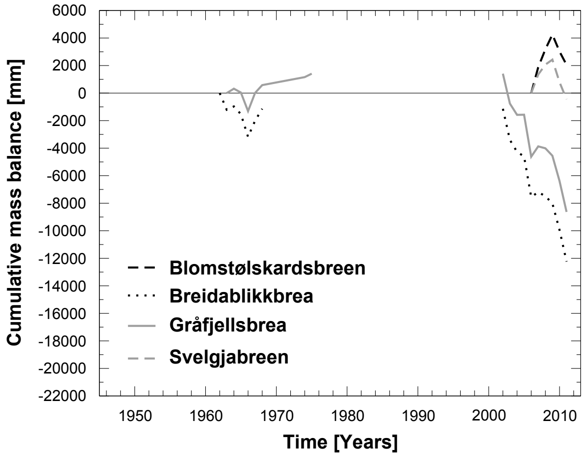


* Glaciological mass balances at Engabreen (Norway) presented here show large deviations when compared with geodetic mass balances, cf. T. Haug et al., Ann. Glaciol. 50, 191−197 (2009). A revision of the mass balance record is in preparation.

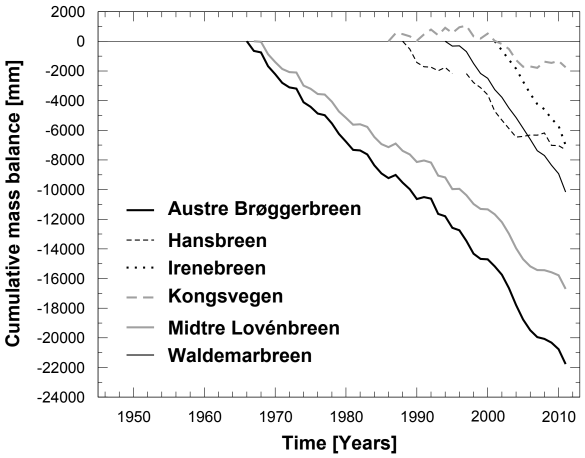
NORWAY 2



NORWAY 3



NORWAY 4 (SVALBARD)



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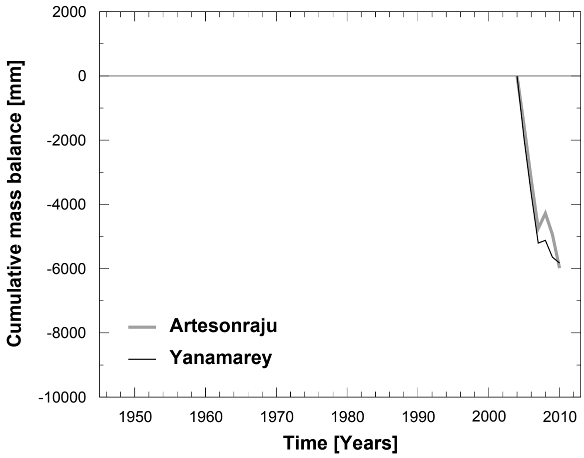

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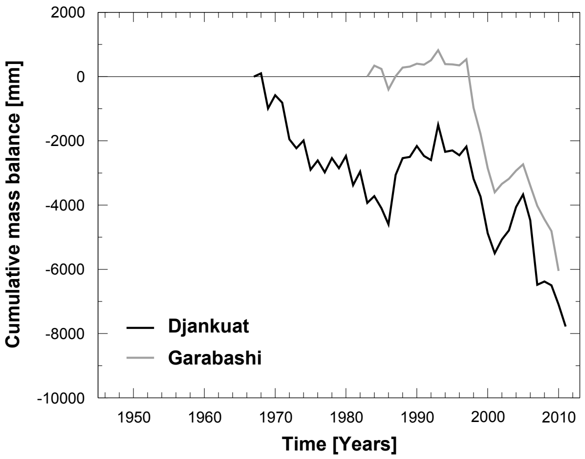

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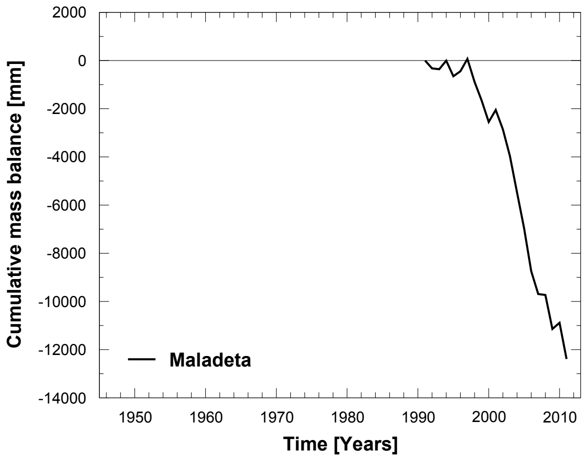
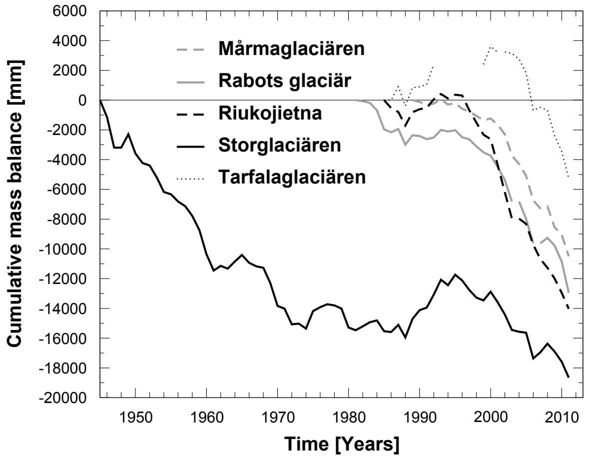
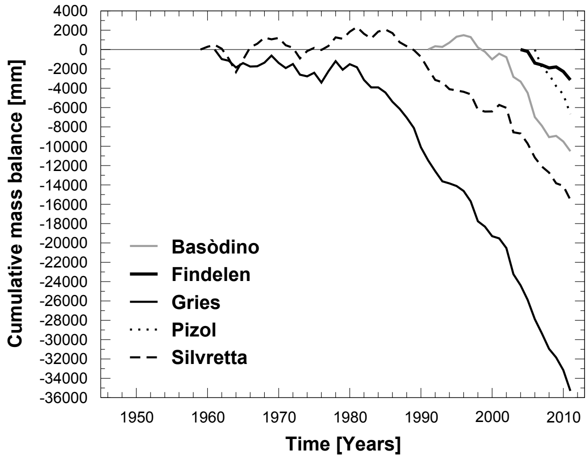


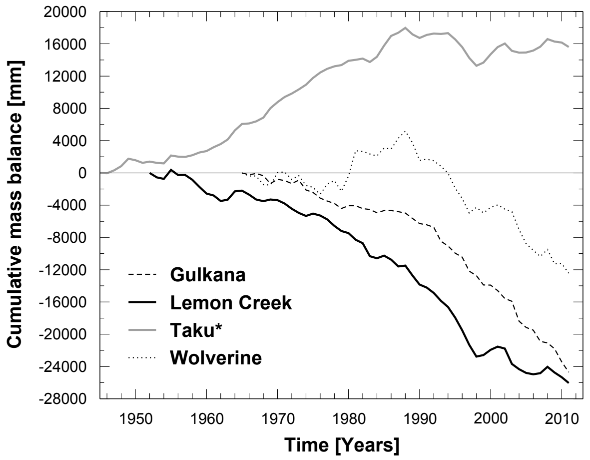
SWEDEN



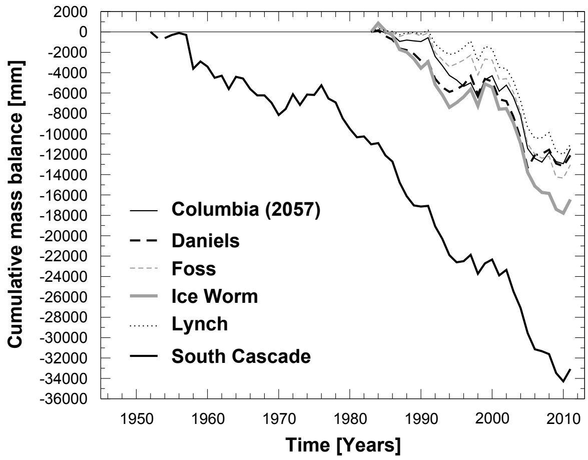
SWITZERLAND



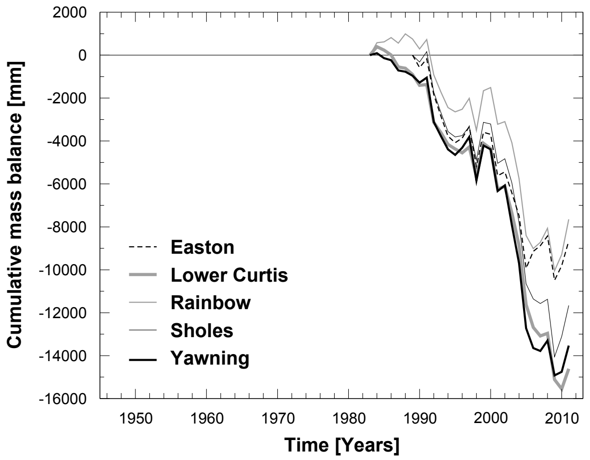
USA (ALASKA)



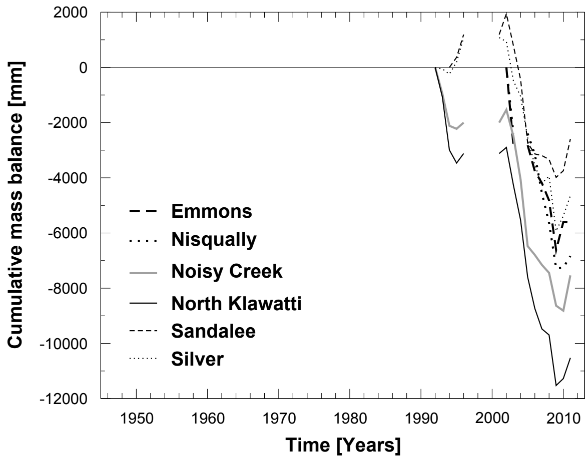
USA (WASHINGTON 1)



USA (WASHINGTON 2)



USA (WASHINGTON 3)



* The mass balance of Taku Glacier (USA) is determined by combining glaciological measurements in the accumulation area with those along a survey profile in the ablation area (cf. M. Pelto et al., Cryosphere 2, 147−157, 2008). The glacier is currently in the advance state of the tidewater glacier cycle (cf. M. Truffer et al., J. Glaciol. 55, 1052−1060, 2009).

3 DETAILED INFORMATION

Detailed information about selected glaciers with ongoing direct glaciological mass balance measurements in various mountain ranges is presented here, in addition to the basic information contained in the previous chapter. In order to facilitate comparison between the individual glaciers, the submitted material (text, maps, graphs and tables) was standardized and rearranged.

The text provides general information on the glacier followed by characteristics of the two reported balance years. General information concerns basic geographic, geometric, climatic and glaciological characteristics of the observed glacier which may help with the interpretation of climate/glacier relationships. A recent photograph showing the glacier is included.

Three maps are presented for each glacier: the first one, a topographic map, shows the stakes, snow pits and snow probing network. This network is basically the same from one year to the next on most glaciers. In cases of differences between the two reported years, the second was chosen, i.e., the network from the year 2010/11. The second and third maps are mass balance maps from the reported years, illustrating the pattern of ablation and accumulation. The accuracy of such mass balance maps depends on the density of the observation network, the complexity of the mass balance distribution, the applied technique for spatial extrapolation, and the experience of the local investigators.

A graph of glacier mass balance versus altitude is given for both reported years, overlaid with the corresponding glacier hypsography and point measurements (if available). The relationship between mass balance and altitude – the mass balance gradient – is an important parameter in climate/glacier relationships and represents the climatic sensitivity of a glacier. It constitutes the main forcing function of glacier flow over long time intervals. Therefore, the mass balance gradient near the equilibrium line is often called the ‘activity index’ of a glacier. The glacier hypsography reveals the glacier elevation bands that are most influential for the specific mass balance, and indicates how the specific mass balance might change with a shift in the ELA.

The last two graphs show the relationship between the specific mass balance and the accumulation area ratio (AAR) and the equilibrium line altitude (ELA) for the whole observation period. The linear regression equation is given at the top of both diagrams. The AAR regression equation is calculated using integer values only (in percent). AAR values of 0 or 100 % as well as corresponding ELA values outside the altitude range of the observed glaciers were excluded from the regression analysis. The regressions were used to determine the AAR_0 and ELA_0 values for each glacier (cf. Chapter 2). The points from the two reported balance years (2009/10 and 2010/11) are marked in black. Minimum sample size for regression was defined as 6 ELA or AAR values.

3.1 BAHÍA DEL DIABLO (ANTARCTICA/A. PENINSULA)

COORDINATES: 63.82° S / 57.43° W

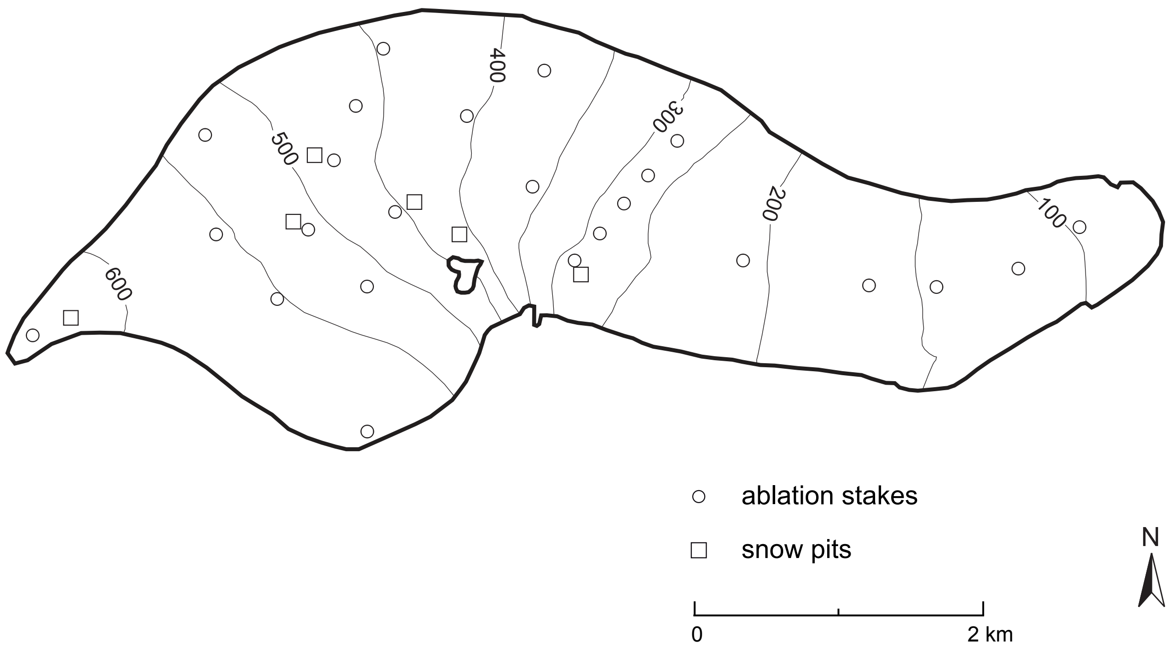
Photo taken by S. Marinsek, 13 March 2013.

This polythermal-type outlet glacier is located on Vega Island, north-eastern side of the Antarctic Peninsula. The glacier is exposed to the northeast, covers an area of ~12.9 km^2, and extends from an altitude of 630 m to 50 m a.s.l. The mean annual air temperature at the equilibrium line (around 400 m a.s.l.) ranges between −7 °C and −8 °C. The glacier snout overrides an ice-cored moraine on a periglacial plain of continuous permafrost. The mass balance measurements on this glacier began in austral summer 1999/2000, using a simplified version of the stratigraphic annual mass balance method because the glacier can be visited only once a year.

After 10 consecutive years of negative mass balance, the year 2009/10 was positive for the first time, with a relatively large mass surplus of +370 mm w.e. The mean summer air temperature recorded nearby the glacier was −0.9 ºC, which is the lowest for the 12-years series. Furthermore, in January 2010 the precipitation was unusually high resulting in snow cover extending over the entire glacier area for the rest of the summer. An ELA located below the lowest glacier elevation yielded an AAR of 100 %. Much lower, however, the mass balance for the year 2010/11 was also positive. The value of +20 mm w.e. is probably a remnant of the extraordinarily high previous mass balance and a relatively low mean summer air temperature of +0.3 ºC. The corresponding equilibrium line was at 322 m a.s.l. and the AAR was 62 %.

In 2013, the glacier area was reassessed (S. Marinsek, Nueva área del Glaciar Bahía del Diablo, Península Antártica, determinada con imágenes satelitales y Modelos Digitales de Elevación, 2013) and the mass balance series was adjusted accordingly.

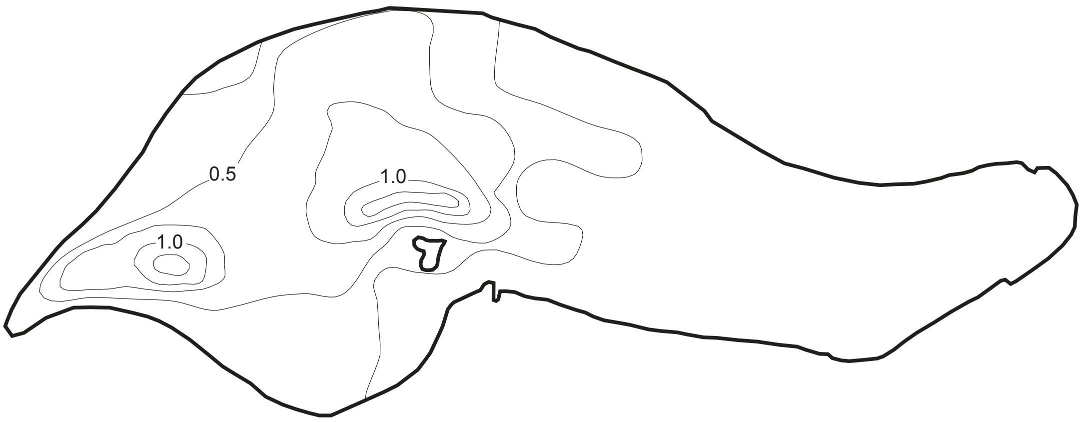
3.1.1 Topography and observation network

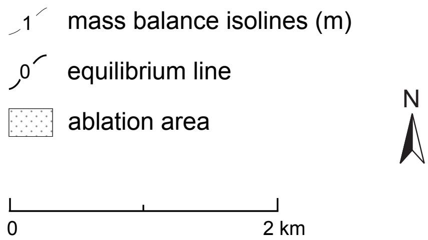


Bahía del Diablo (ANTARCTICA)

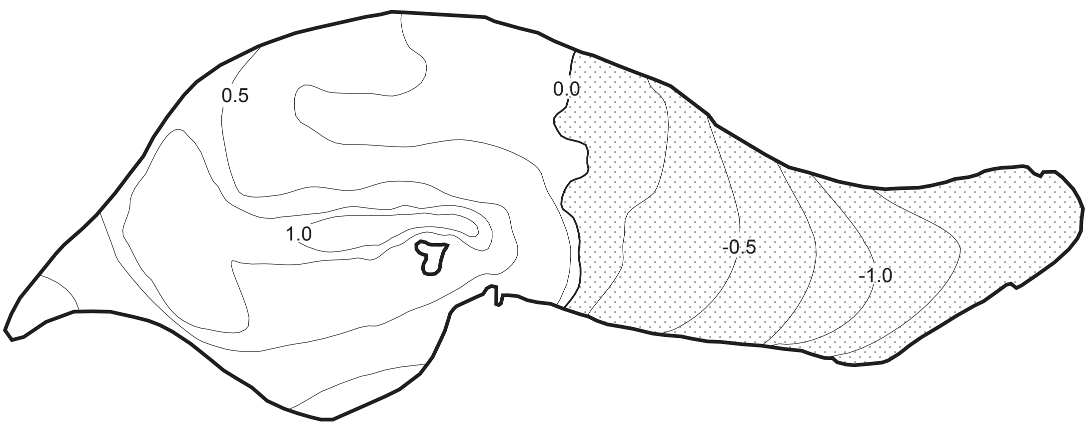
3.1.2 Mass balance maps 2009/10 and 2010/11

2009/10



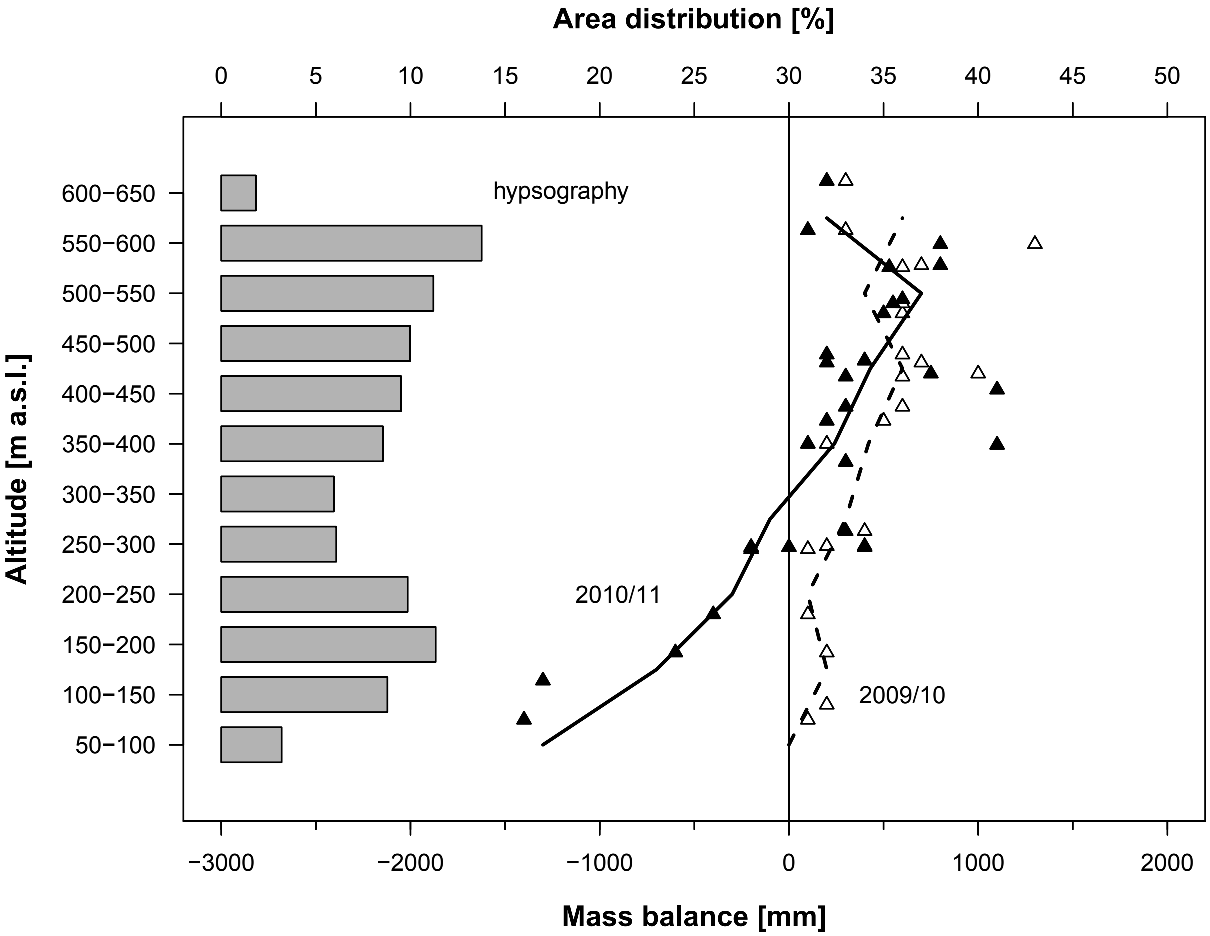


2010/11

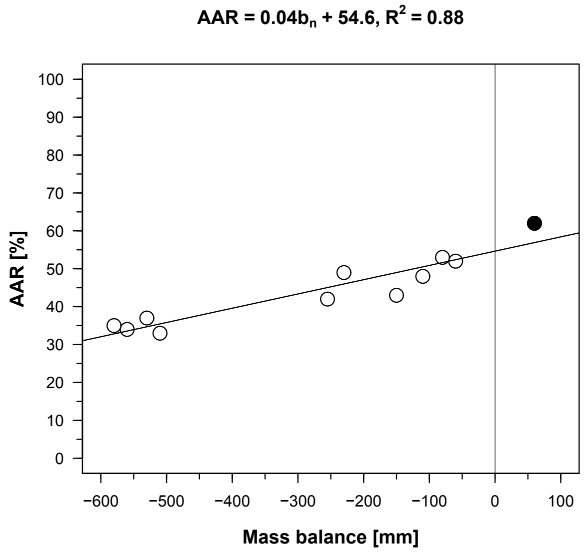


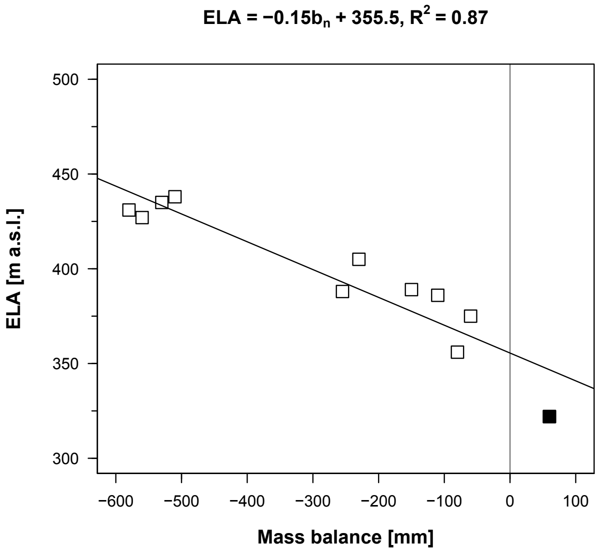
Bahía del Diablo (ANTARCTICA)

3.1.3 Mass balance versus altitude (2009/10 and 2010/11)



3.1.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period





Bahía del Diablo (ANTARCTICA)

3.2 MARTIAL ESTE (ARGENTINA/ANDES FUEGUINOS)

COORDINATES: 54.78° S / 68.40° W

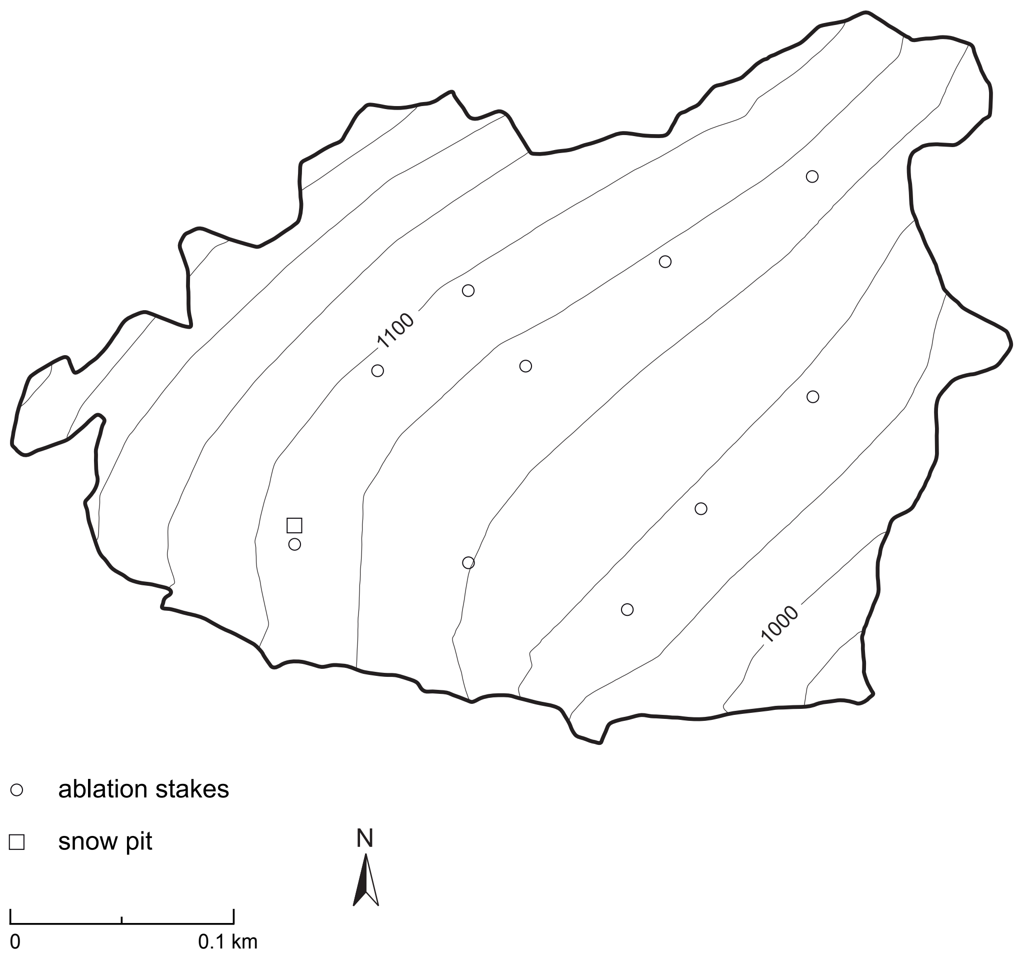
Photo of Martial Este Glacier by R. Iturraspe, 18 March 2011.

The Martial Este Glacier is one of the four small glaciers situated in the well-defined glacial cirque of the Cordón Martial (1319 m a.s.l. at Mt Martial) very close to Ushuaia city and to the Beagle channel, southern Tierra del Fuego. Glacier runoff contributes to the water supply of this city. The total ice area on this cirque attains 0.33 km^2. The Martial Este Glacier has a surface area of 0.1 km^2 that extends from 1180 m to 970 m a.s.l. with a mean slope of 29° and southeast orientation. It receives less direct solar radiation than the rest of the glaciers in the cirque, and it is protected from the wind.

Mean annual air temperature at the ELA_0 level (1075 m a.s.l.) is −1.5 °C and the average annual precipitation amounts to 1300 mm, extending over the whole year. The precipitation regime has no dry season. The hydrological cycle starts in April and the maximum accumulation on the glacier is reached in October or November. Since the Little Ice Age these glaciers have lost 75 % of their total area. According to topographic surveys, the annual rate of vertical thinning at the Martial Este Glacier from 1984 to 1998 was −0.5 m a^{-1} (−450 mm w.e. a^{-1}).

The mass balance 2009/10 was markedly positive (+976 mm w.e.). This unusual result was a consequence of the cold and humid spring and summer seasons. Those weather conditions resulted in a short melting period. The slightly negative 2010/11 balance (−319 mm w.e.) was due to sparse winter snow accumulation and normal summer conditions. According to the observations, the Martial Este Glacier showed stable conditions along the second half of the last decade and no significant changes were noticed during this period.

3.2.1 Topography and observation network

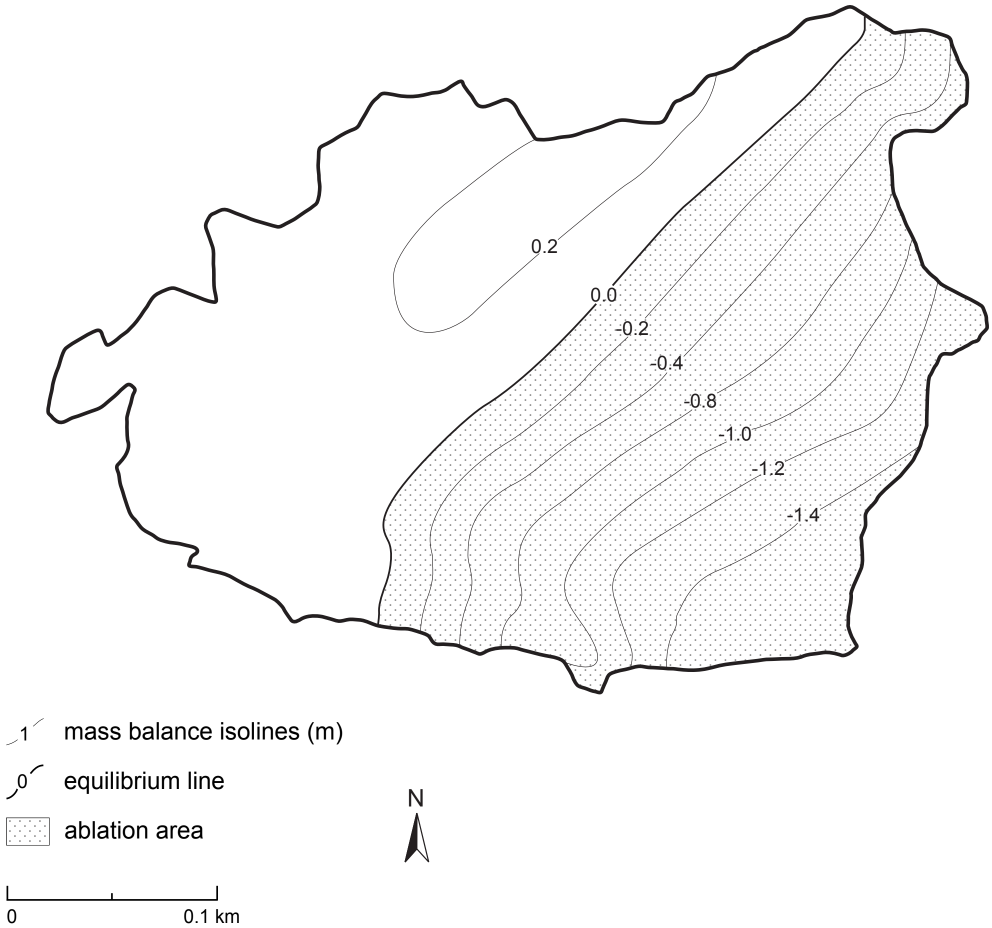


Martial Este (ARGENTINA)

3.2.2 Mass balance maps 2009/10 and 2010/11

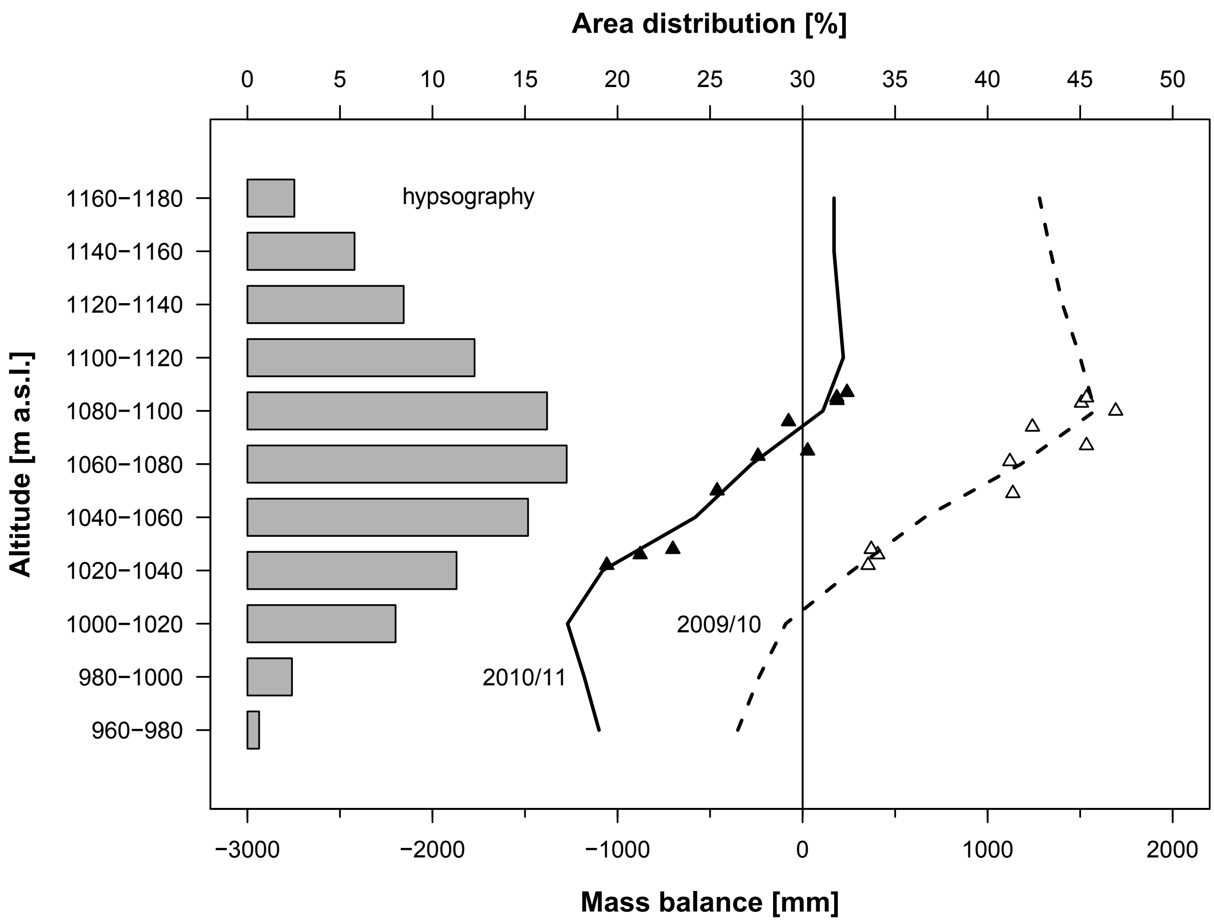
2009/10

2010/11

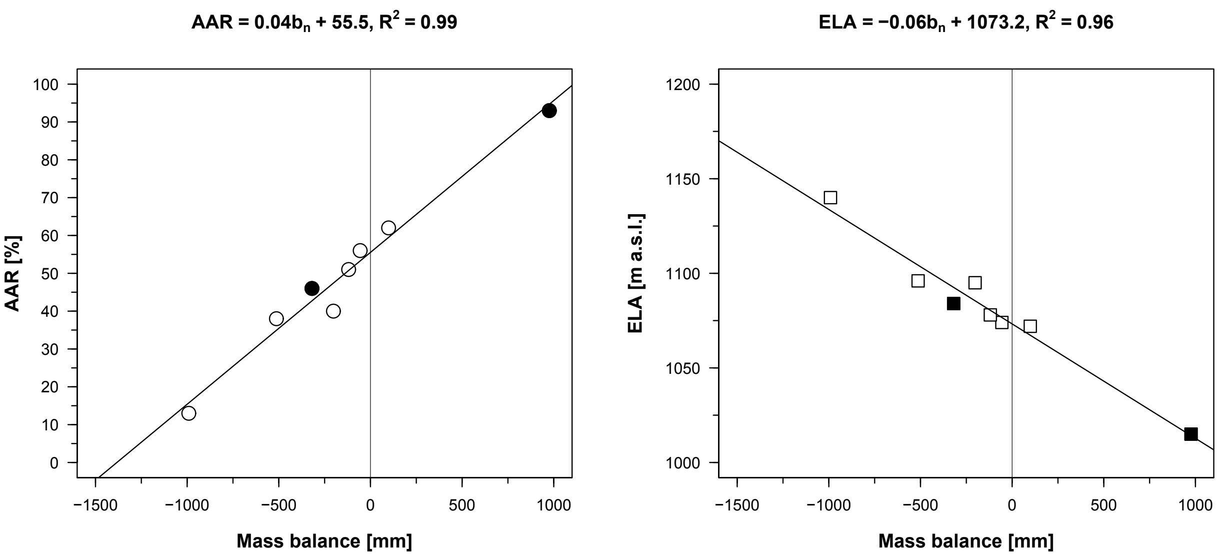


Martial Este (ARGENTINA)

3.2.3 Mass balance versus altitude (2009/10 and 2010/11)



3.2.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period



Martial Este (ARGENTINA)

3.3 HINTEREISFERNER (AUSTRIA/EASTERN ALPS)

COORDINATES: 46.80° N / 10.77° E

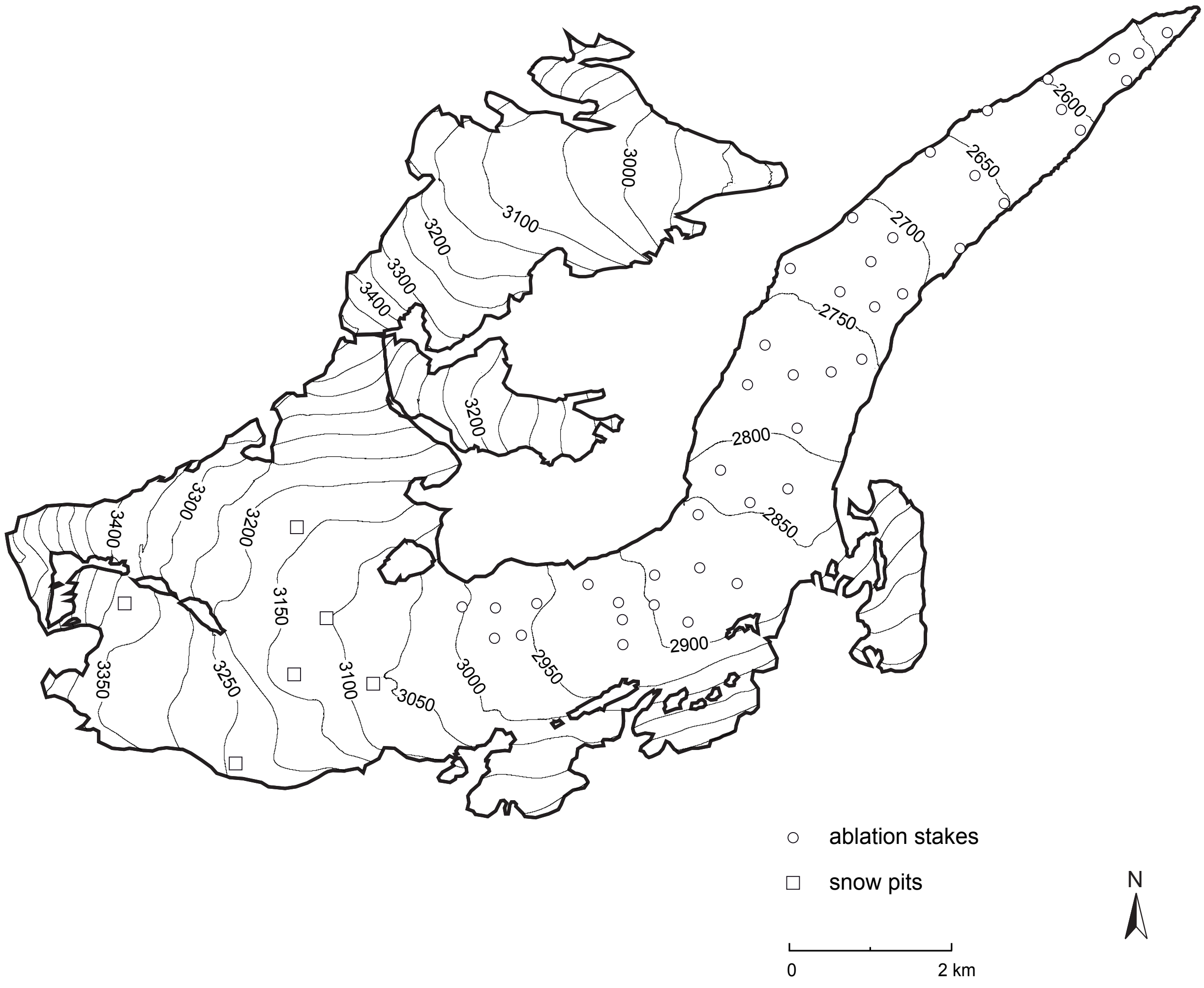
Photo taken by A. Fischer, 2 August 2011.

The mass balance of Hintereisferner has been measured with the direct glaciological method since 1952/53. Hintereisferner is a valley glacier which had several tributary glaciers in 1953. Most of these tributary glaciers meanwhile lost connection to the main tongue, the last to separate so far was Langtaufererjochferner in 2000. The glacier area decreased from 10.24 km^2 in 1953 to 6.88 km^2 in 2011. The highest point of Hintereisferner is the peak of Weisskugel/Pala Bianca with an altitude of 3739 m a.s.l. The tongue is located in a northeast-orientated valley, the firn area faces north, east and south. The lowest point was 2350 m in 1953, and 2507 m in 2011. The elevation losses between 1953 and 2011 exceed 160 m on parts of the glacier tongue, but are only a few metres in parts of the firn area.

The methods and the results of the mass balance measurements were published more or less regularly (e.g., by H. Hoinkes, R. Rudolph, G. Markl, M. Kuhn). The interpolation method and the database used for the mass balance analysis are described in detail by A. Fischer and G. Markl (Z. Gletsch.kd. Glazialgeol. 42, 47–83, 2009). In the mass balance year 2002/03 the topographic basis was changed from the DEM of the glacier inventory dating from 1997 to the airborne laserscan DEM of October 2001. In addition to the annual geodetic surveys carried out by H. Schneider, several airborne laserscan DEMs were compiled between 2001 and 2008 by T. Geist. In 2007, F. Albrecht and G. Merkel performed differential GPS measurements of stable points of the existing geodetic net and developed transformation parameters between the local Gauss-Krüger system and UTM/WGS84 coordinates allowing the comparison of old and new maps.

The mean of the air temperature (1906–2005) measured at the climate station Vent (1906 m a.s.l.) was 1.6 °C. The mean annual lapse rate is 0.57 °C/100 m with slight seasonal variations. Specific mass balance was –820 mm in 2009/10 and –1420 mm in 2010/11. The ELA was at 3116 m a.s.l. and 3285 m a.s.l., respectively.

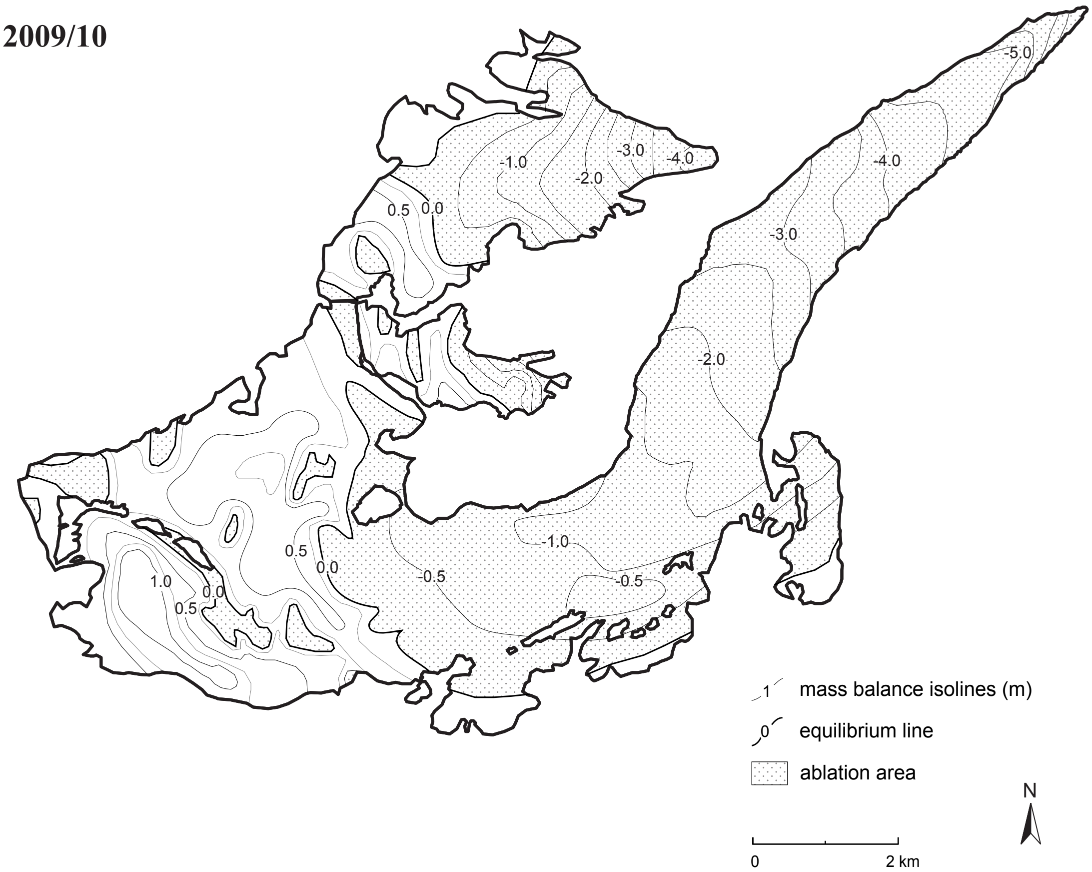
3.3.1 Topography and observation network



Hintereisferner (AUSTRIA)

3.3.2 Mass balance maps 2009/10 and 2010/11

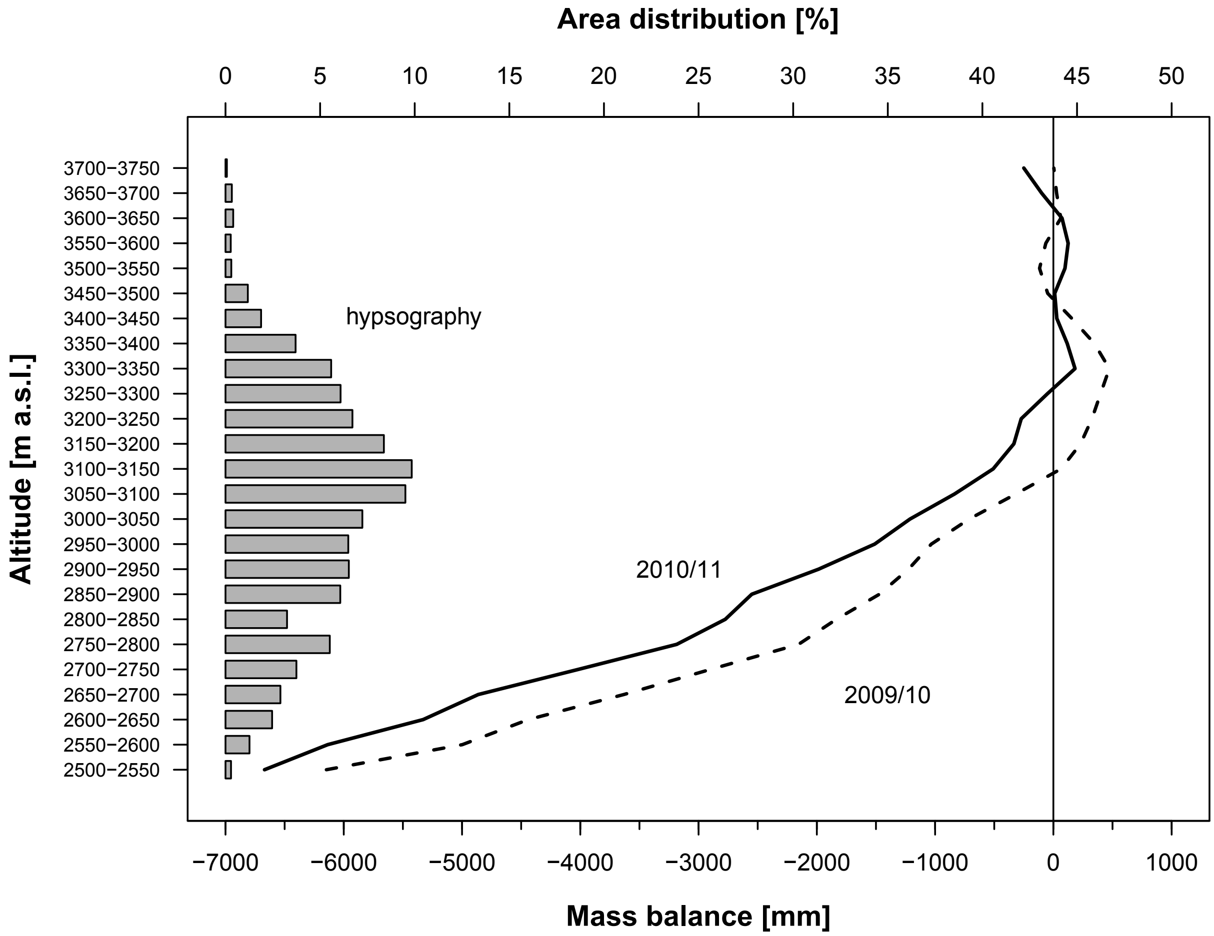
2009/10



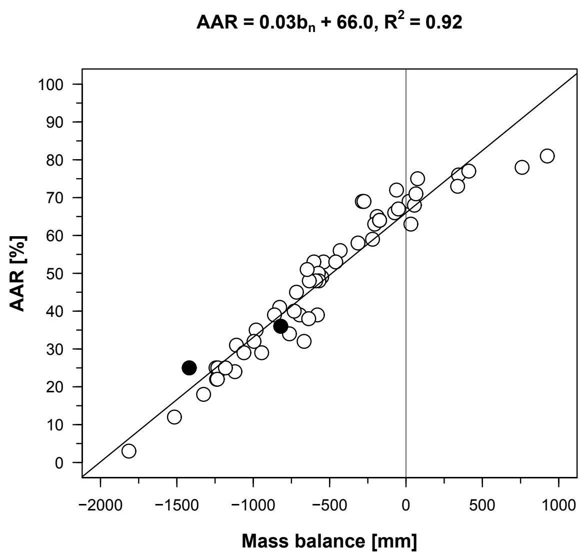
2010/11

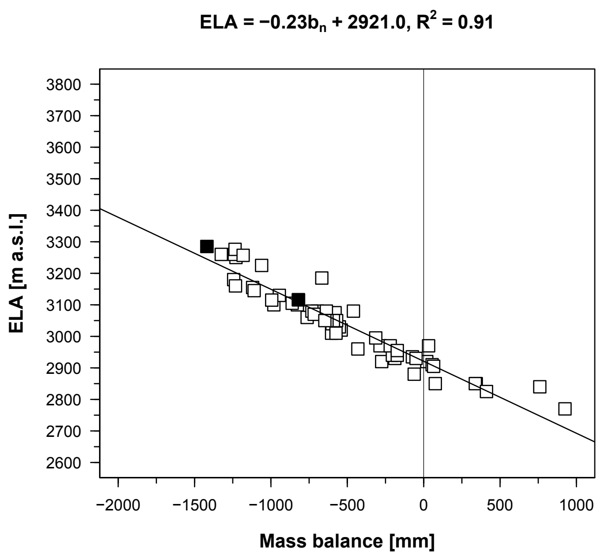
Hintereisferner (AUSTRIA)

3.3.3 Mass balance versus altitude 2009/10 and 2010/11



3.3.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period





Hintereisferner (AUSTRIA)

3.4 ZONGO (BOLIVIA/TROPICAL ANDES)

COORDINATES: 16.25° S / 68.17° W

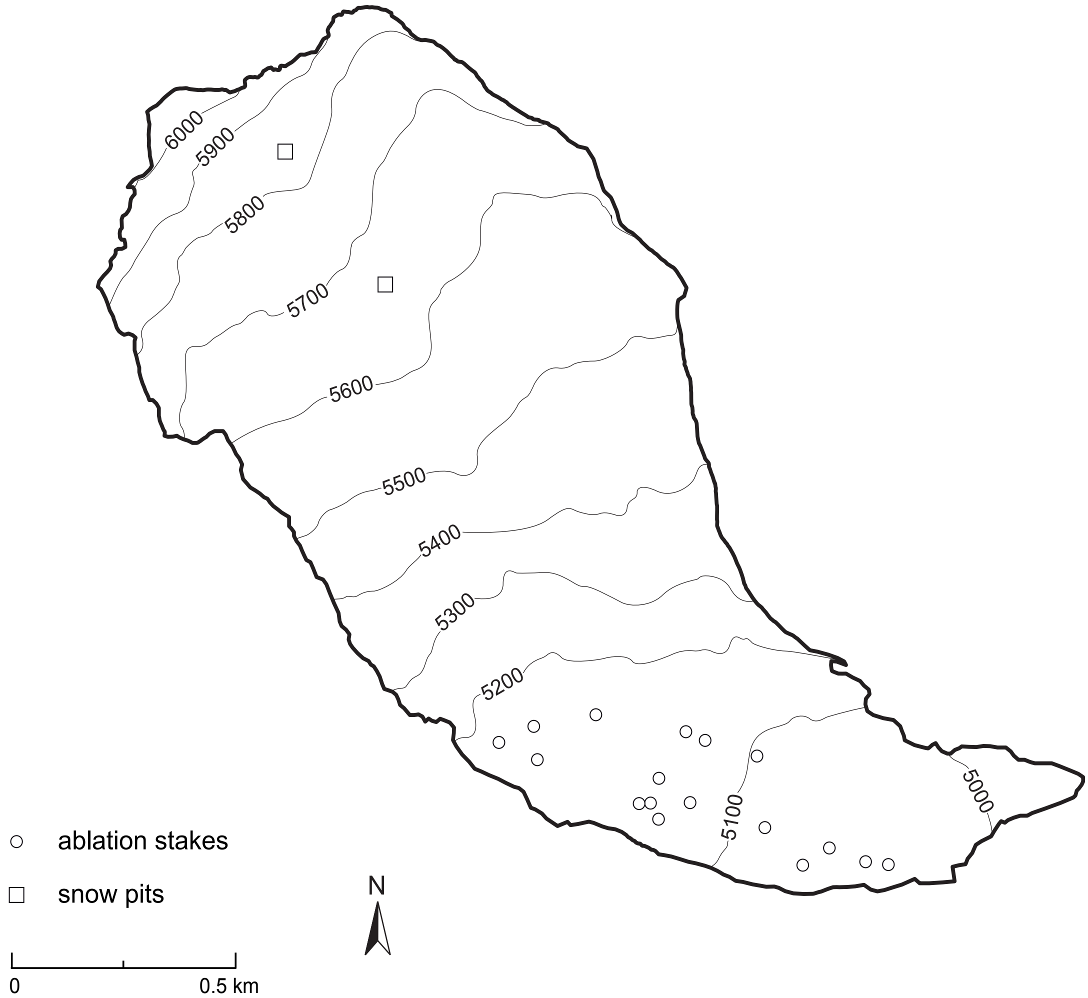
Photo provided by P. Ginot, 14 June 2011.

The Zongo Glacier is a temperate glacier covering an area of 1.9 km^2 (in 2011) over a catchment area of 3.3 km^2. Its length is around 3 km and its width is around 0.75 km, flowing from 6100 to 4900 m a.s.l., the average ice flow velocity is 15 m a^{-1} between 5200 and 4900 m a.s.l. Zongo Glacier is located in the Huayna Potosi region (Cordillera Real, Bolivia), 30 km north of La Paz city, between the dry Altiplano plateau in the northwest and the wet Amazonian basin in the southeast, under outer tropics meteorological conditions (strong seasonality in precipitation, low seasonality in temperature).

The last photogrammetric survey of the Zongo Glacier is based on photographs from 2006. Geodetic surveys using differential GPS are carried out each year over to measure the stakes and the contour of the ablation zone The surface areas of each contour line interval are obtained from the photogrammetric and geodetic surveys in each year.

The 2009/10 period presented a negative mass balance of –671 mm w.e. The 2010/11 period presented a mass balance of –221 mm w.e., however this year was close to the equilibrium state. Melting processes take place mainly during November and February (austral summer), between the precipitation peaks (January and March). The 2009/10 period was characterized by normal ENSO conditions. On the other hand, the 2010/11 period was characterized by a negative MEI (Multivariate ENSO Index), showing La Niña conditions. In all of the cases, the MEI variation was close to one standard deviation. The biggest loss (–2173 mm w.e.) took place during the El Niño event of 1997/98. Some periods (1996/97, 2000/01) with positive mass balances were concomitant with La Niña events.

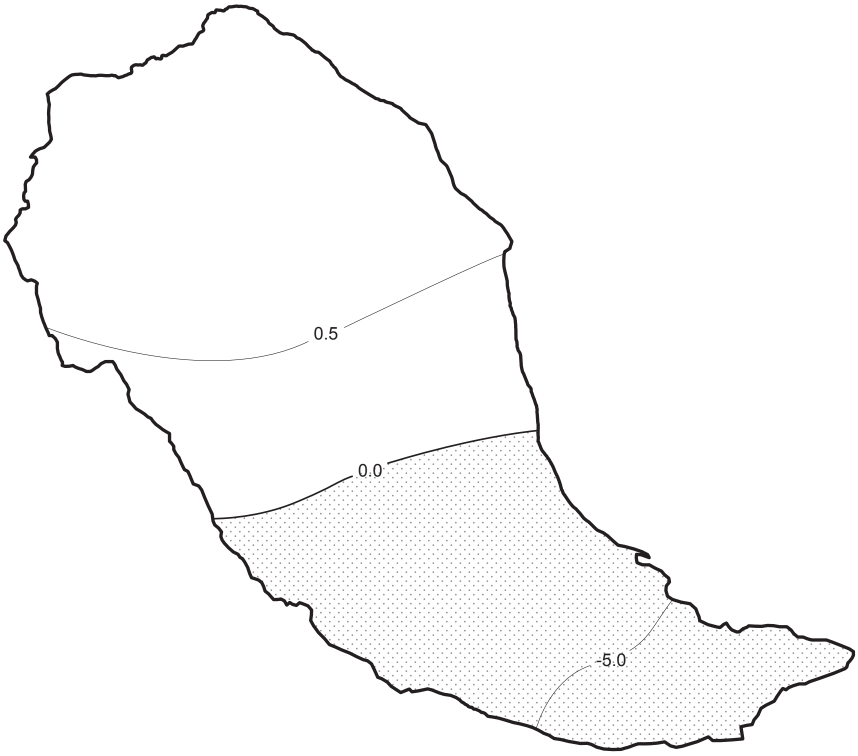
3.4.1 Topography and observation network



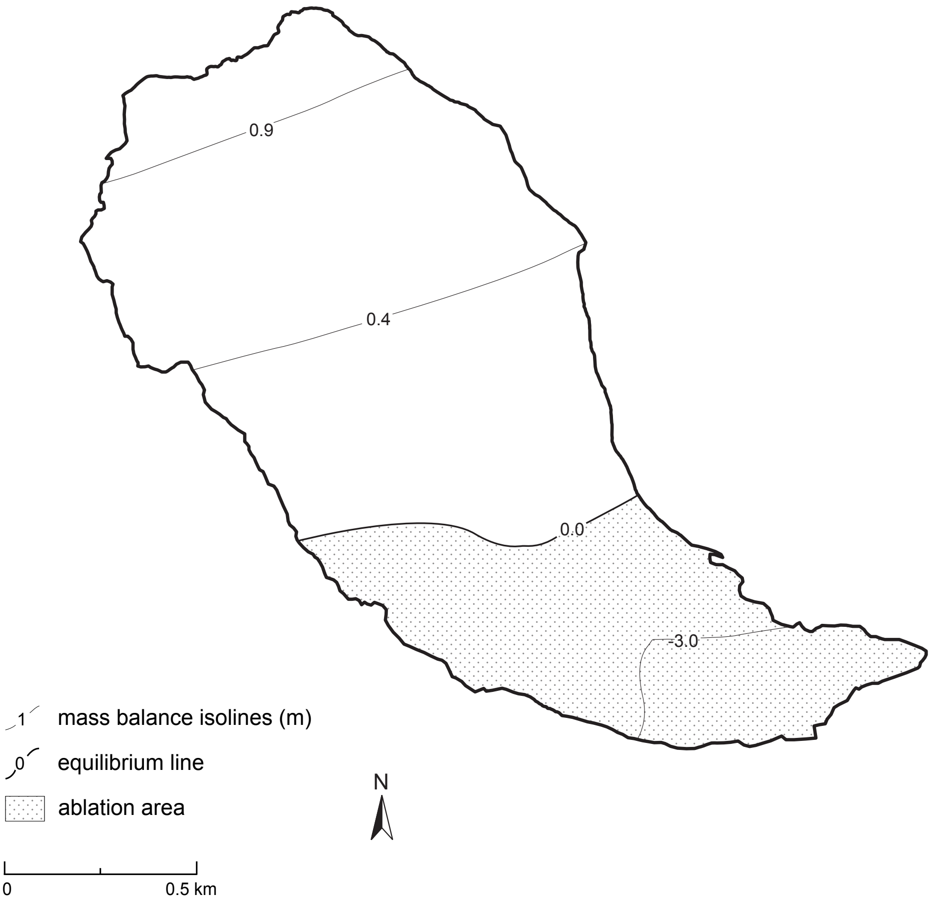
Zongo (BOLIVIA)

3.4.2 Mass balance maps 2009/10 and 2010/11

2009/10

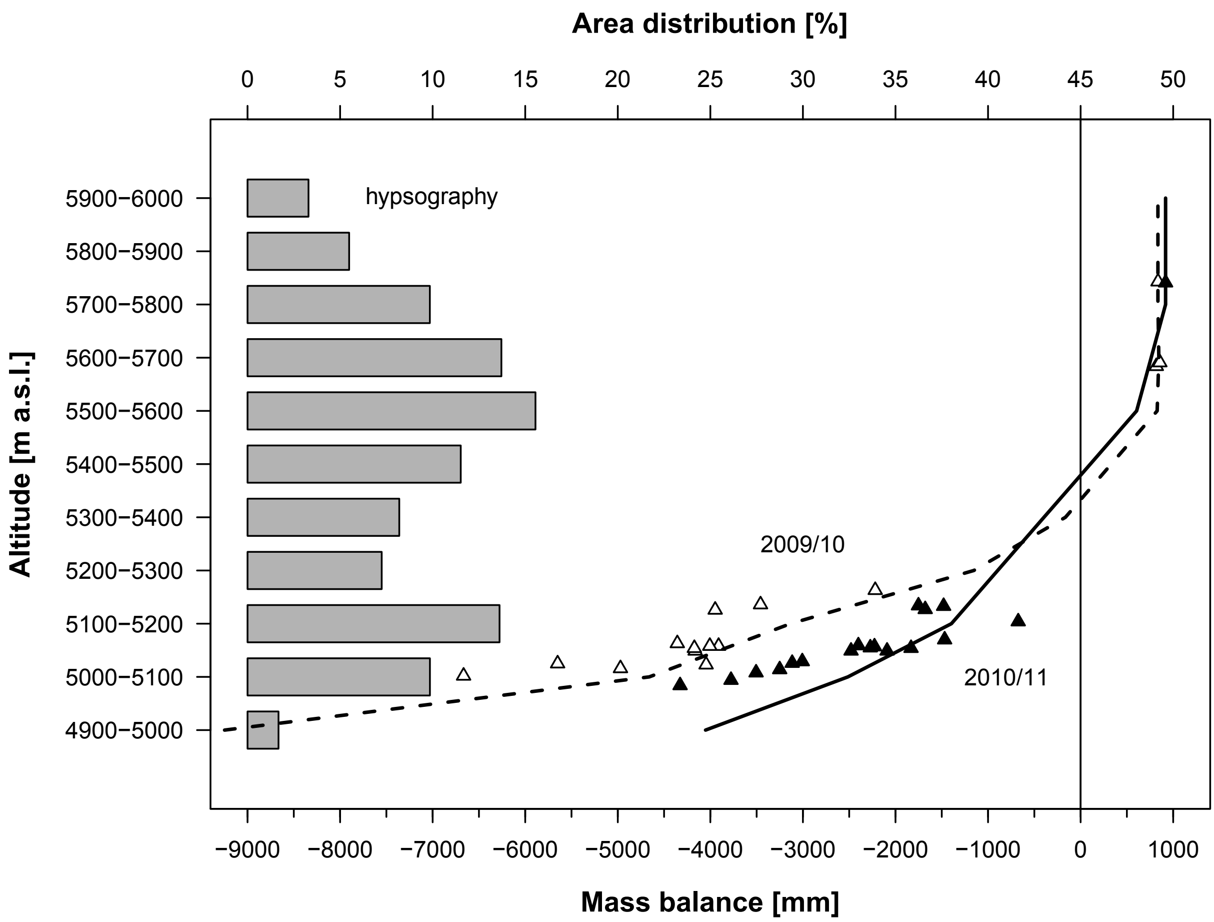


2010/11

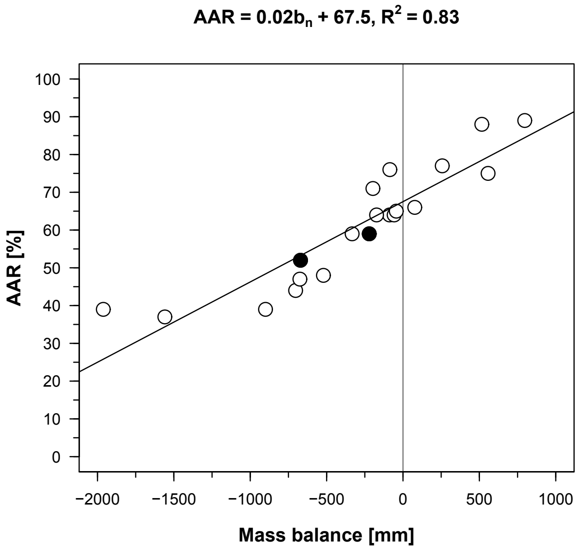


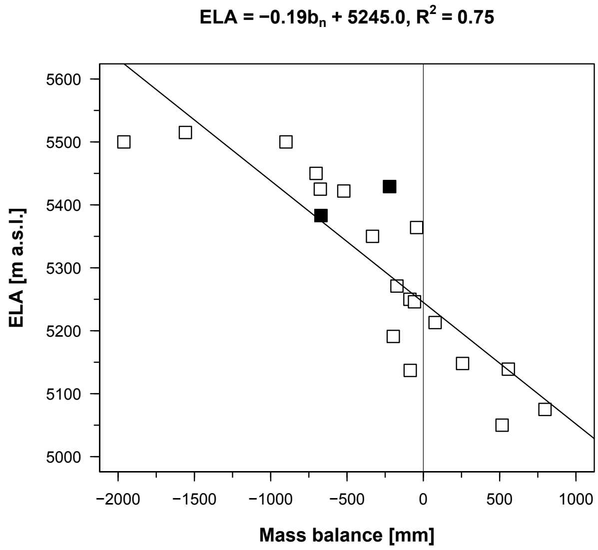
Zongo (BOLIVIA)

3.4.3 Mass balance versus altitude (2009/10 and 2010/11)



3.4.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period





Zongo (BOLIVIA)

3.5 WHITE (CANADA/HIGH ARCTIC)

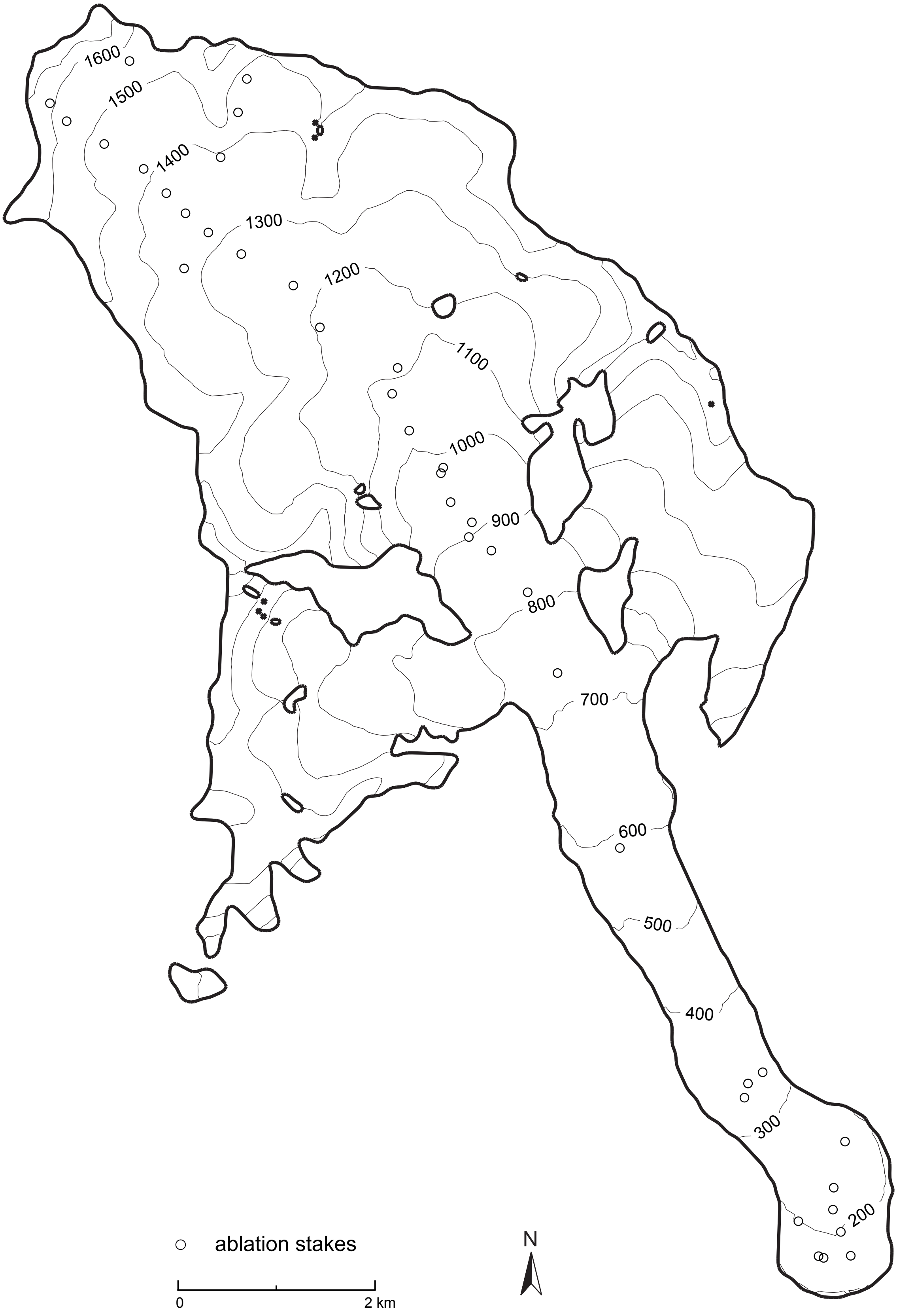
COORDINATES: 79.45° N / 90.67° W

Aerial view of White Glacier taken on 2 July 2008. Photo by J. Alean.

White Glacier is a valley glacier in the Expedition Fiord area of Axel Heiberg Island, Nunavut. It extends in elevation from 1782 m to 85 m a.s.l. and at present occupies 39.4 km^2, having shrunk by gradual retreat of its terminus from an extent of 40.2 km^2 in 1960. Sea-level air temperature in the Expedition Fiord area averages about –20 °C, but the glacier is known to have a bed which is partly unfrozen, at least beneath the valley tongue; ice thickness is typically 200 m, but reaches or exceeds 400 m locally. Annual precipitation at sea level is very low, about 100 mm, although annual accumulation at higher altitudes reaches a few hundred mm. The annual ablation rate at the terminus of White Glacier ranges between –1000 and –4500 mm a^{-1} w.e., although values between –2000 and –4000 mm/a w.e. are more typical. There is now evidence that the retreat of the terminus, previously about –5 m a^{-1}, is decelerating. White Glacier's larger neighbour, Thompson Glacier (384 km^2), has been advancing in a state of „slow surge" since the time of the earliest photographs in 1948, but recent measurements of its terminus show that it has now begun a slow retreat. The terminuses of the two glaciers have been in contact since at least 1948, but, although the two terminuses remain distinguishable, White Glacier has become a tributary of Thompson Glacier.

The cumulative mass balance of White Glacier from 1959/60 to 2010/11, with due allowance for three missing years, is –9850 mm w.e. The mass balance rate for 2009/10, at –188 mm a^{-1} w.e., was indistinguishable from the long-term mean of the measurements (–192 mm a^{-1} w.e.). Uncertainties are in the order of ± 200 to 250 mm w.e. The balance rate for 2010/11, –983 mm a^{-1} w.e., was the most negative measurement during the entire period of record. 2010/11 was the second balance year in the history of the measurement programme, after 2006/07, for which missing-stake corrections were necessary. The average mass balance rate of the decade 1999/2000 to 2008/09 was the most negative of the five decades over which the measurement record now extends. The mass balance normal for 1959/60 to 1990/91, an average of 29 annual measurements, was –95 mm a^{-1} w.e., slightly but significantly negative.

3.5.1 Topography and observation network



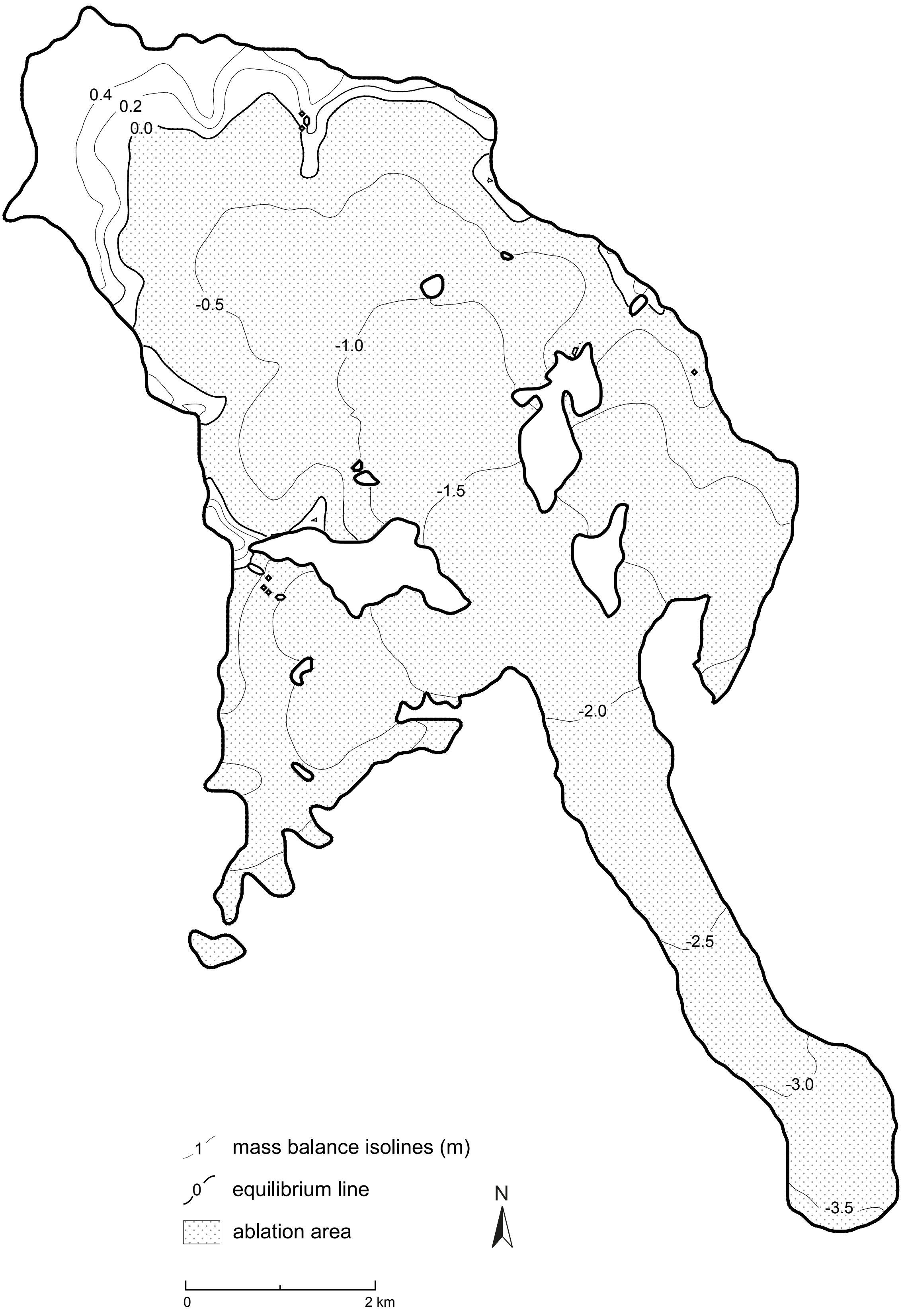
White (CANADA)

3.5.2 Mass balance maps 2009/10 and 2010/11

2009/10

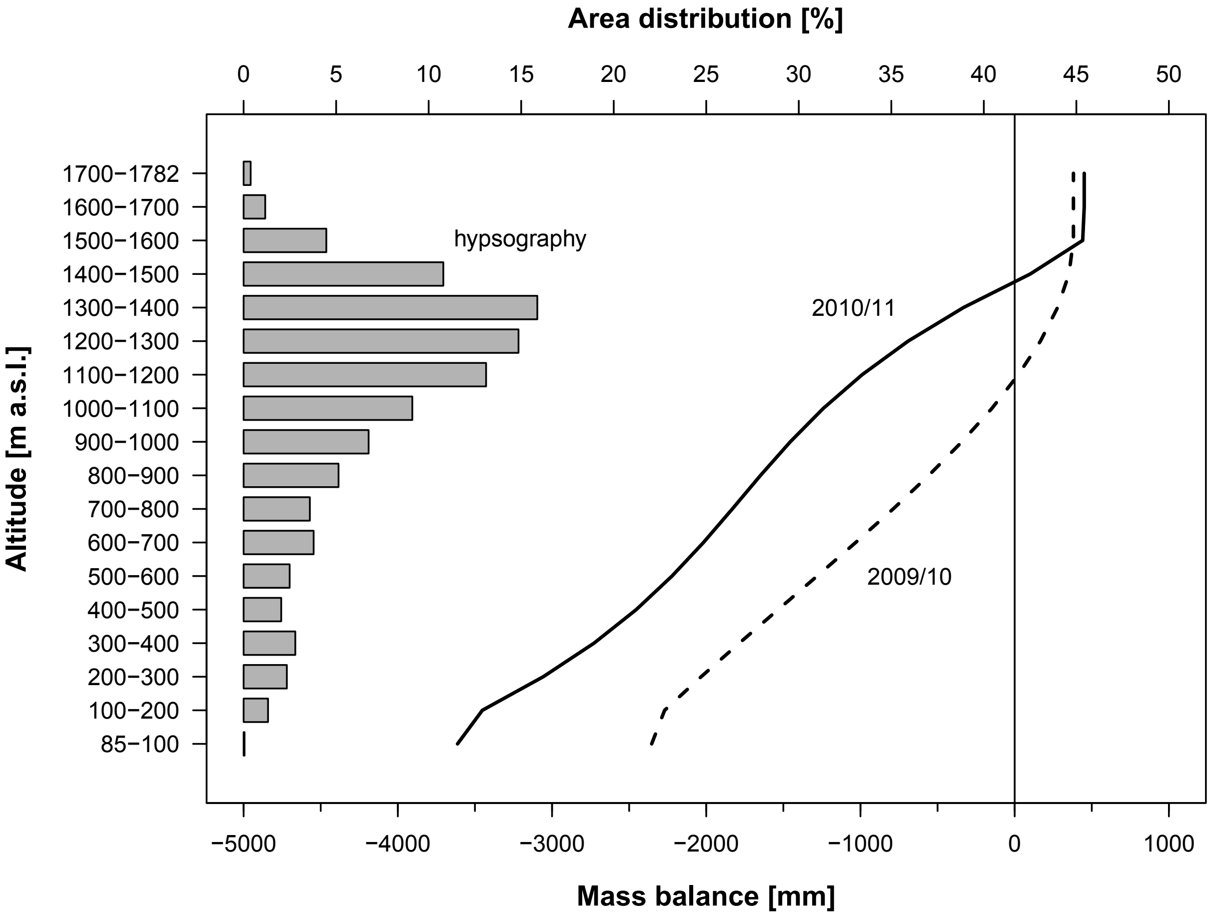
White (CANADA)

2010/11

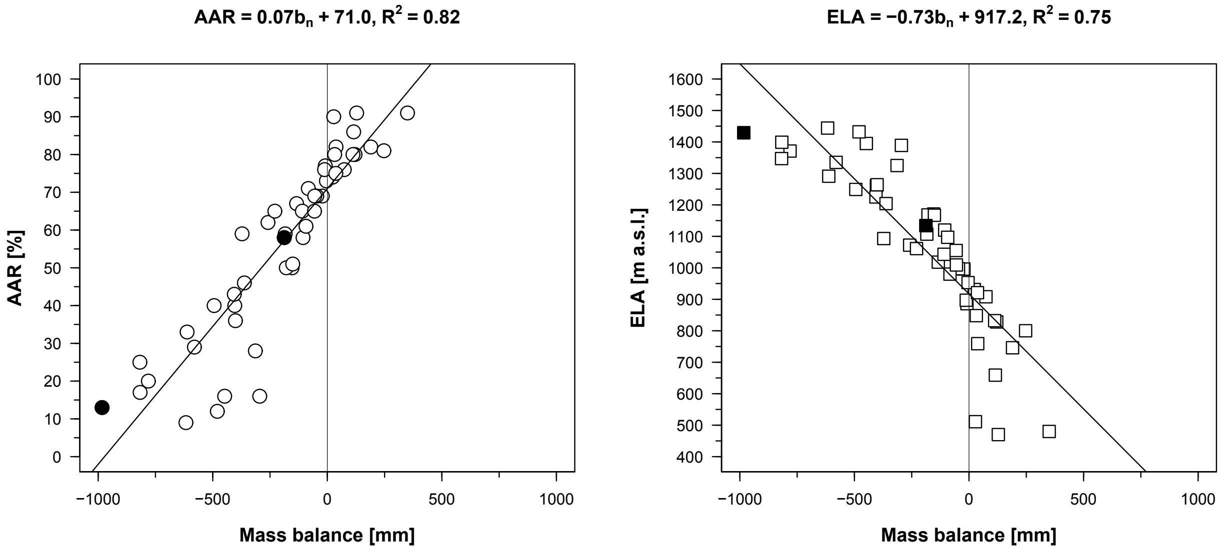


White (CANADA)

3.5.3 Mass balance versus altitude (2009/10 and 2010/11)



3.5.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period



White (CANADA)

3.6 URUMQI GLACIER NO. 1 (CHINA/TIEN SHAN)

COORDINATES: 43.08° N / 86.82° E

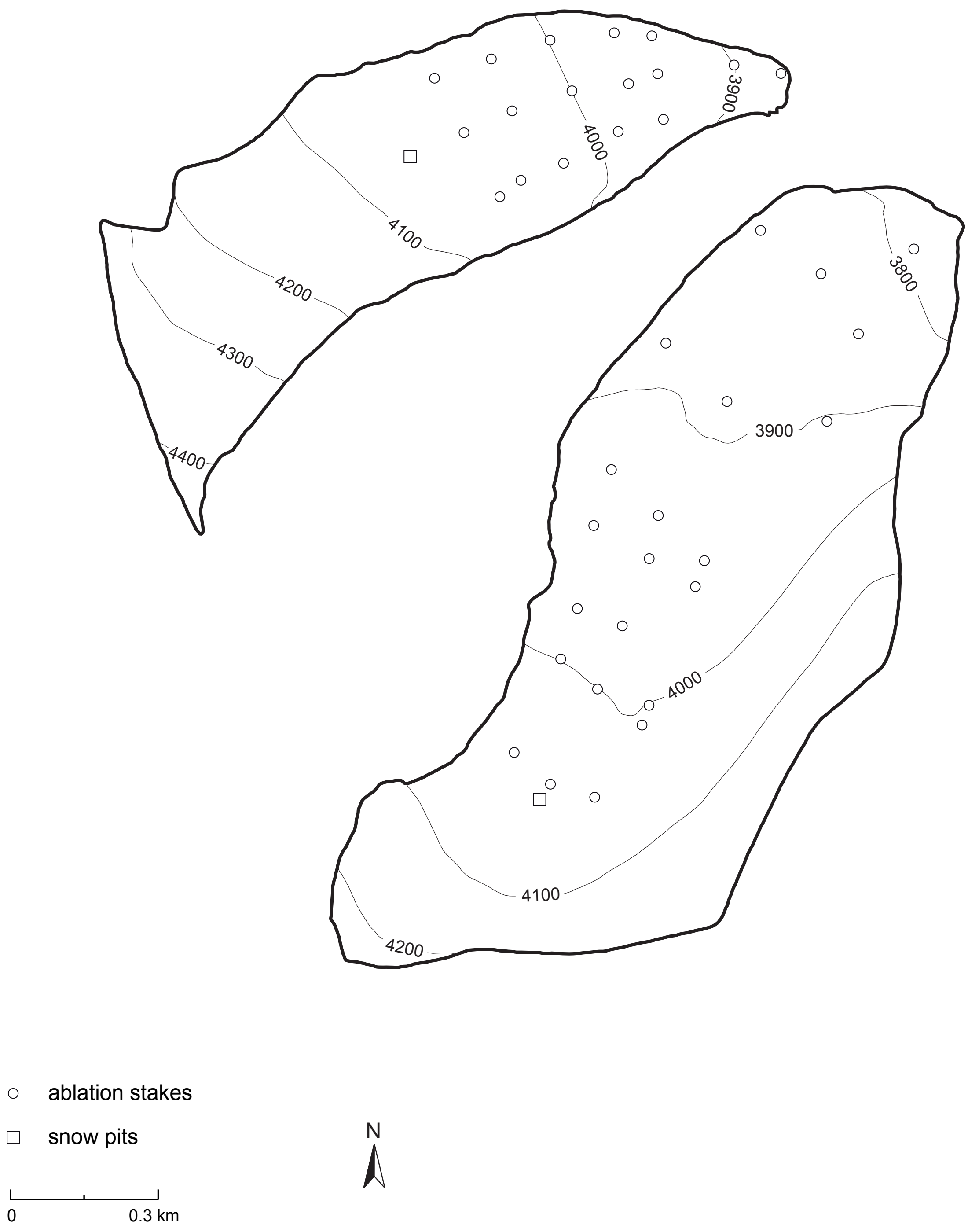
Photo taken by Zhongqin Li, 19 August 2012.

Urumqi Glacier No. 1 has been in constant recession since observations first began in 1959. Due to the retreat, the two branches of the former glacier have become separated into two small glaciers that called the East and West Branch of Glacier No. 1. According to the latest survey in September 2009, the East Branch has a total area of 1.068 km^2, the highest and lowest points are at 4267 m and 3743 m a.s.l. The West Branch has a total area of 0.578 km^2, with the highest and lowest points at 4484 m and 3845 m a.s.l. As a result of the survey, a 1:5000 topographic map of the glacier and its forefield is available for relevant analysis. Radio-echo sounding measurements were carried out on the glaciers in 1980, 2001 and 2006, respectively. According to the latest measurement in 2006, the maximum and mean thicknesses of the glacier are 130.0 ± 5 m and 39.4 ± 5 m, respectively.

The predominantly cold glacier is surrounded by continuous permafrost. Accumulation and ablation both primarily take place during the warm season and the formation of superimposed ice on this continental-type glacier is important. In the 2010/11 mass balance year, the precipitation at the nearby meteorological station located at 3539 m a.s.l. (Daxigou Meteorological Station; DMS) is 466 mm and 500 to 700 mm at the ELA_0 of the glacier. Mean annual air temperature at DMS is –4.2 °C.

The mass balances of both branches of Urumqi Glacier No. 1 were negative in 2009/10 and 2010/11. In 2009/10, the mass balance was –1441 mm w.e. for the East Branch, –1116 mm w.e. for the West Branch, and –1327 mm w.e. for the entire glacier. In 2010/11, the mass balance was –1103 mm w.e. for the East Branch, and –653 mm w.e. for the West Branch. The calculated mean for the entire glacier was –945 mm w.e.

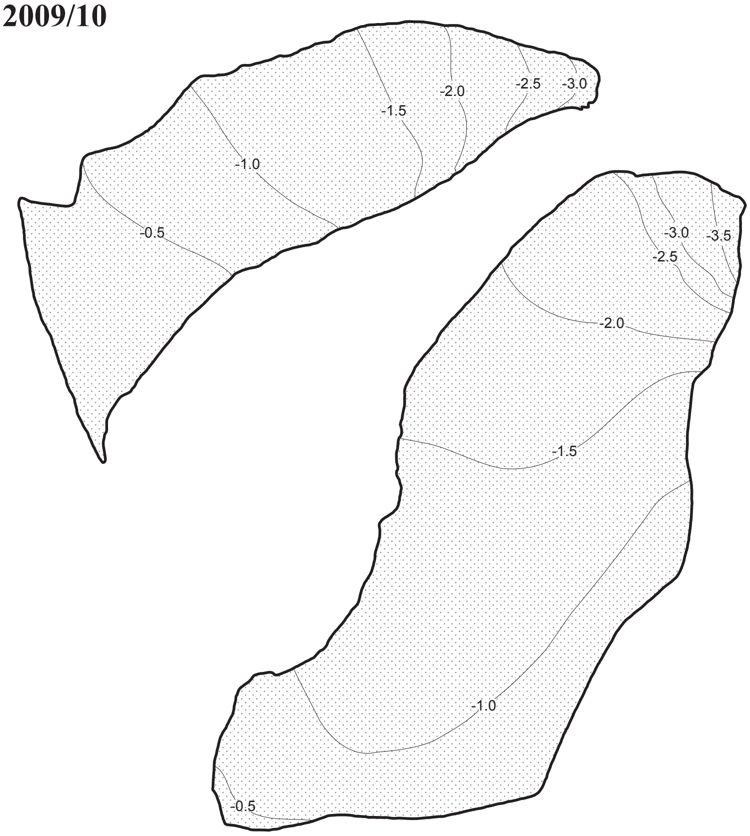
3.6.1 Topography and observation network



Urumqi Glacier No. 1 (CHINA)

3.6.2 Mass balance maps 2009/10 and 2010/11

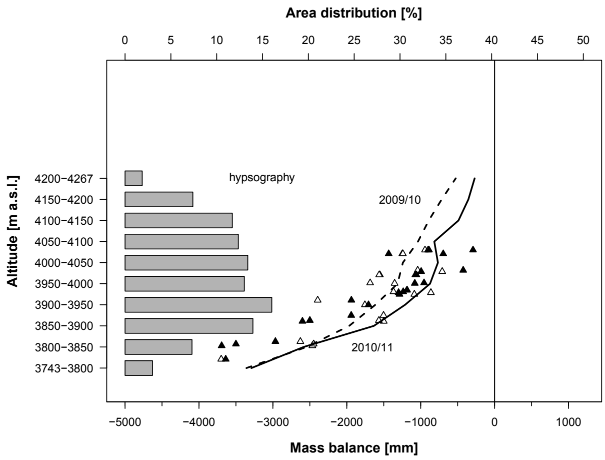
2009/10



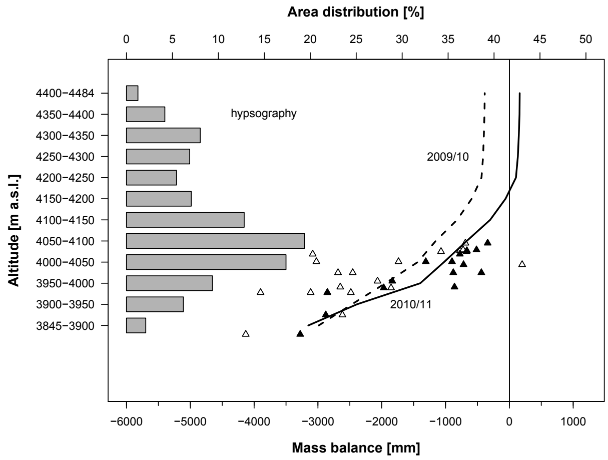
2010/11

Urumqi Glacier No. 1 (CHINA)

3.6.3 Mass balance versus altitude (2009/10 and 2010/11) of the two branches

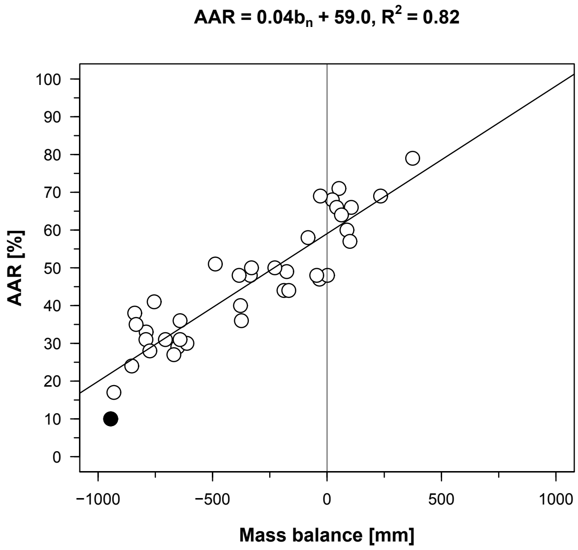


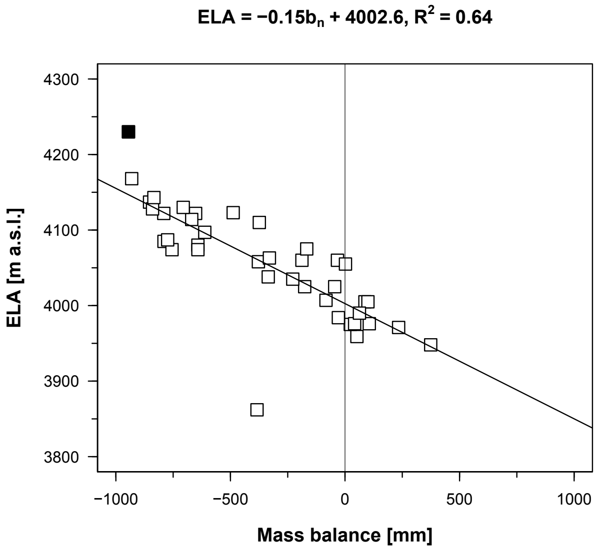
Urumqi Glacier No. 1 East Branch



Urumqi Glacier No. 1 West Branch

3.6.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period for the entire glacier





Urumqi Glacier No. 1 (CHINA)

3.7 CONEJERAS (COLOMBIA/CORDILLERA CENTRAL)

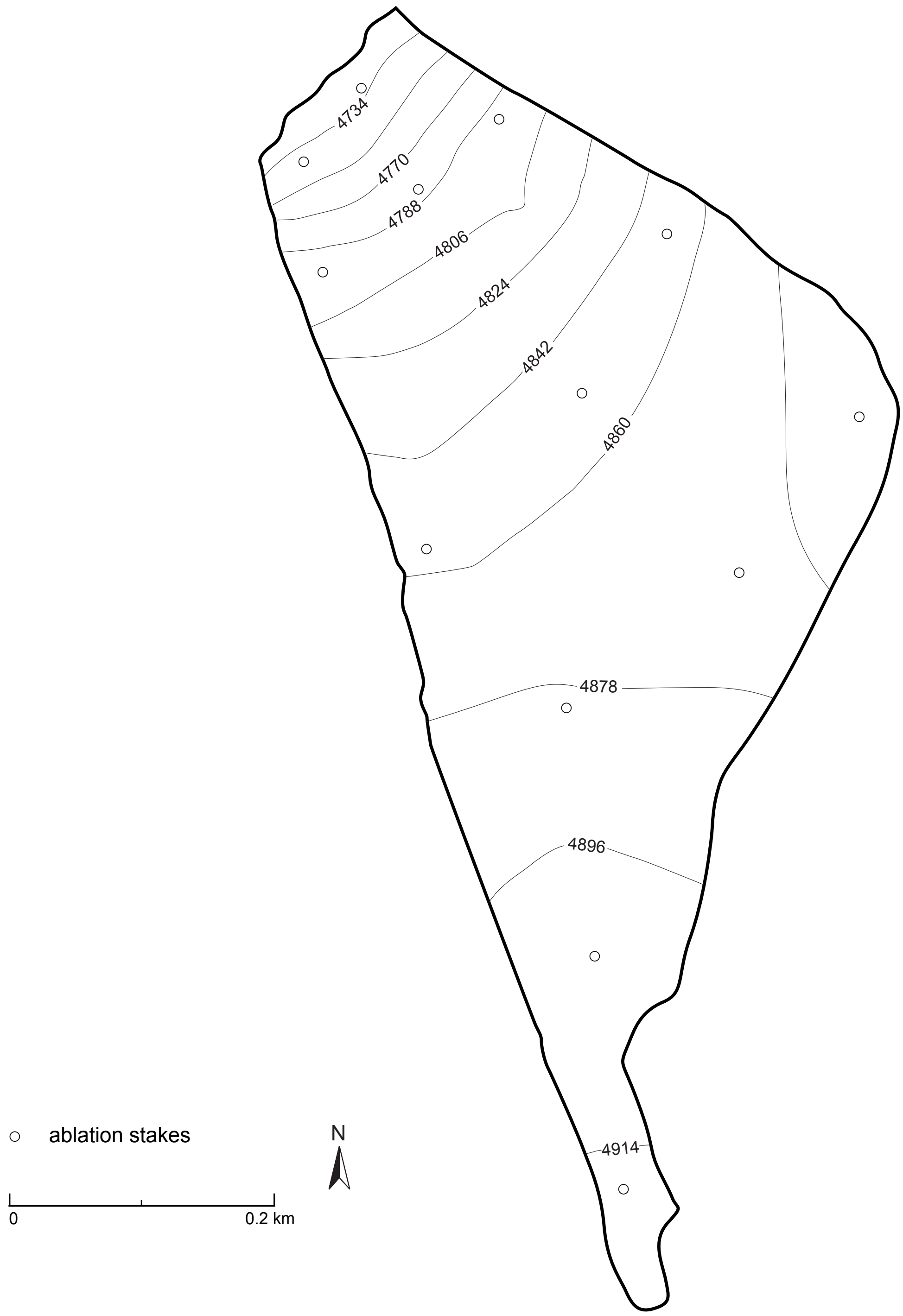
COORDINATES: 4.82° N / 75.37° W

Photo taken by J. L. Ceballos, 15 March 2011.

Santa Isabel is a small ice cap (1.8 km^2) located on a volcanic lava dome in the northern Andes. Along with the glacier volcano Nevado del Ruiz, the glacier volcano Nevado del Tolima and the surrounding páramo ecosystem and Andean forests, Santa Isabel forms a part of the National Park Los Nevados, situated in an important coffee-producing region of Colombia. The studied glacier called „Conejeras" (0.21 km^2) has a maximum of 4958 m a.s.l. and a minimum elevation of 4715 m a.s.l., and is located at Santa Isabel's northwest side. Conejeras' mass balance has been calculated monthly by the direct glaciological method since 2006 (field measurements using stakes); these mass balance calculations have also been complemented with data from meteorological and hydrological stations, extending downvalley to 2700 m a.s.l.

Since 2006, Conejeras Glacier shows a negative mass balance with a peak during the El Niño event in 2009/10. After that, during the La Niña event in 2010/11, the glacier did not show any particular mass gain, although the mass balance was less negative. Overall, the glacier has been in a permanent state of negative mass balance (cumulative mass balance 2006–2011: –12.5 m w.e). The ELA was located at 4916 m a.s.l. (AAR = < 1 %) in 2009/10 and at 4831 m a.s.l. (AAR = 4 %) in 2010/11, respectively. The glacier reacts fast to atmospheric changes and its dynamics are deeply influenced by climatic variability generated by the Intertropical Convergence Zone (ITCZ) and the El Niño-Southern Oscillation (ENSO). Weather patterns in these mountains lead to an annual average precipitation of 1000 mm. The relative humidity is 90 % on average, and the mean temperature ranges between –2 ºC and 4 ºC. Mean solar radiation is 400 W m^{-2}, however, it can reach up to 1100 W m^{-2}.

3.7.1 Topography and observation network



Conejeras (COLOMBIA)

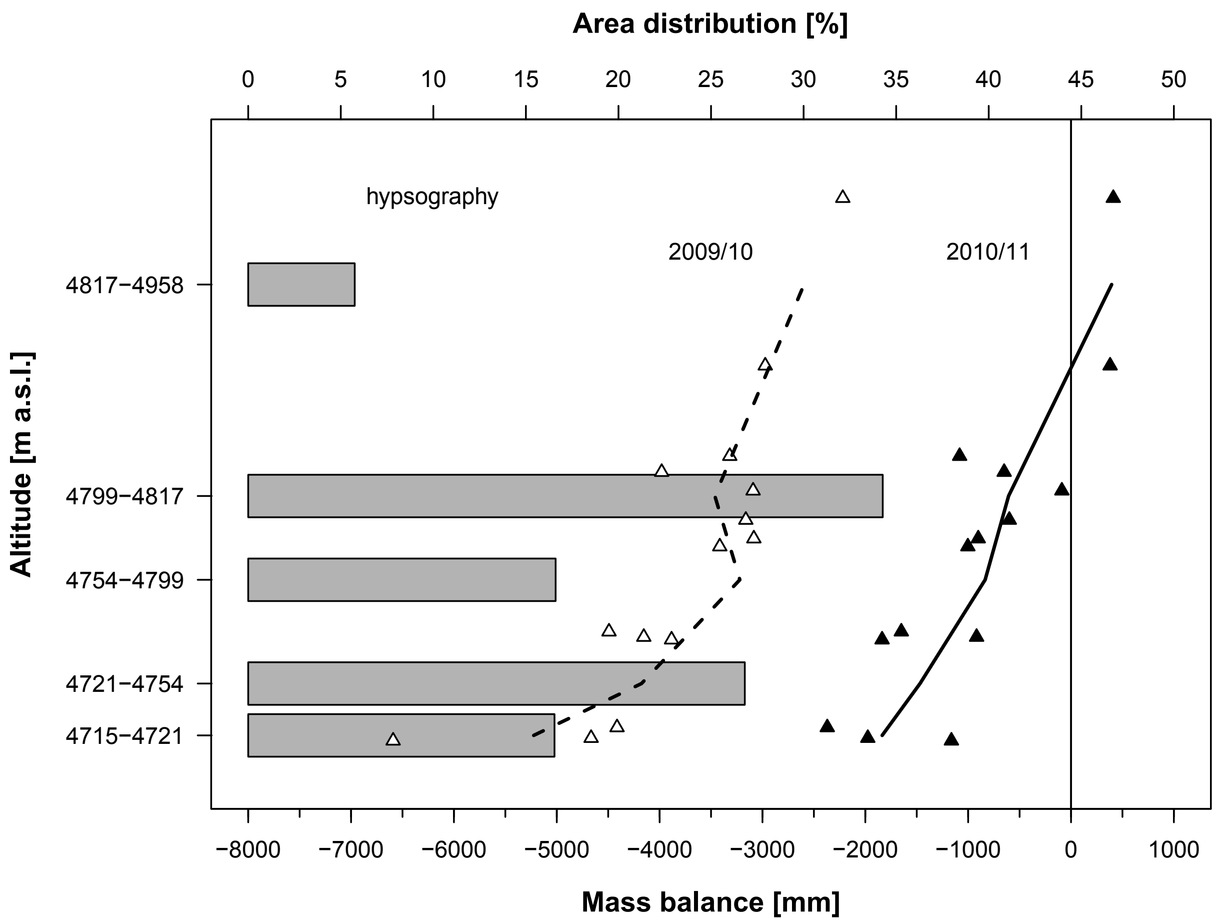
3.7.2 Mass balance maps 2009/10 and 2010/11

2009/10

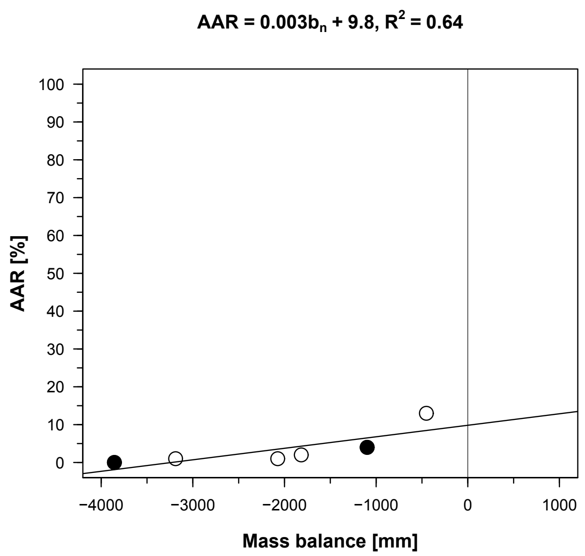
2010/11

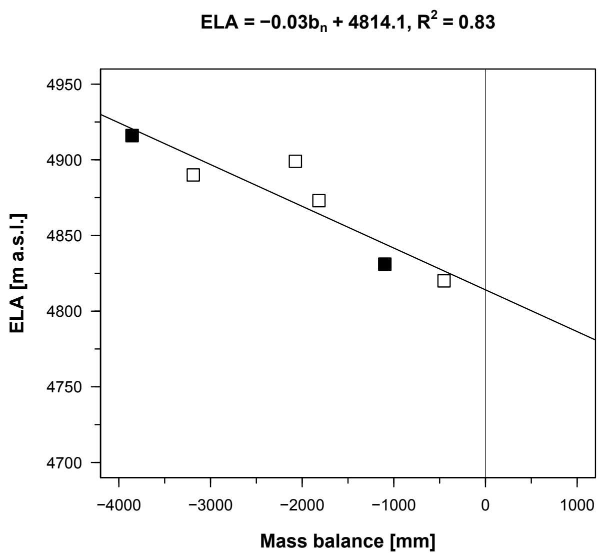
Conejeras (COLOMBIA)

3.7.3 Mass balance versus altitude (2009/10 and 2010/11)



3.7.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period





3.8 FREYA (GREENLAND/NORTHEAST GREENLAND)

COORDINATES: 74.38° N / 20.82° W

Photo taken by B. Hynek, 26 August 2009.

Freya (Fröya) Glacier is a 6 km long valley glacier situated on Clavering Island 10 km southeast of the Zackenberg research station at the north-eastern coast of Greenland. Its surface area is 5.6 km^2 (1987), extending from 1250 m to 330 m a.s.l. and mainly oriented to NW with two separate accumulation areas with a NE and NW aspect. The thickest ice found during a GPR survey in May 2008 is 200 m, located at the confluence of the two accumulation areas. GPR data suggest that Freya Glacier is a polythermal glacier surrounded by continuous permafrost, with temperate ice in a limited area only, at the ELA near the bottom of the glacier. Mean values (1996–2005) of annual temperature and precipitation at Zackenberg station (38 m a.s.l.) are –9.2 °C and 230 mm.

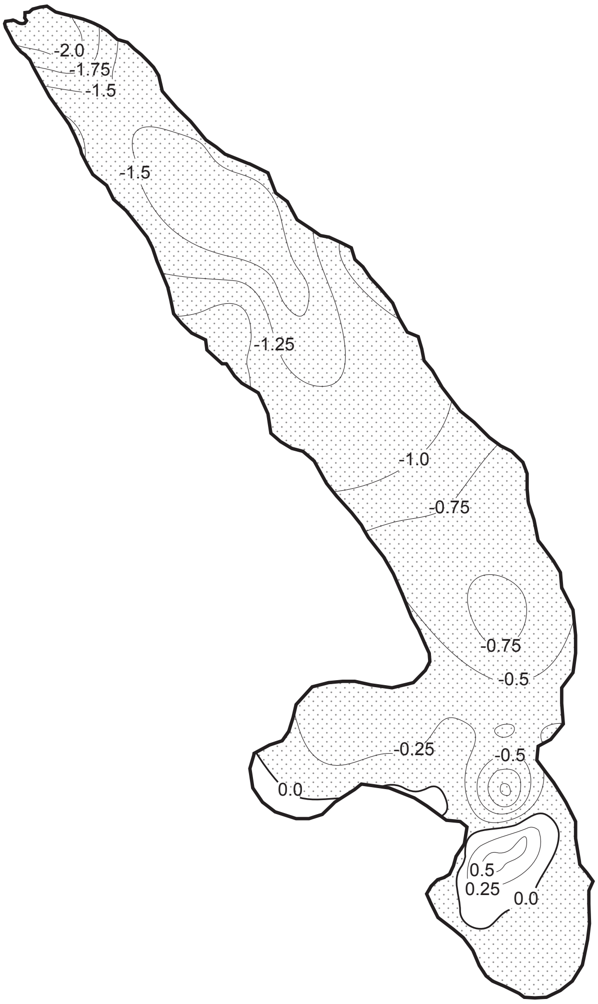
Mass balance fieldwork was carried out on the 20.–21.8.2010 and 21.–24.8.2011. The monitoring network was extended in 2011 by an automatic weather station on the upper part of the glacier. The annual surface mass balances for 2009/10 and 2010/11 were both negative: –806 mm w.e. and –934 mm w.e., respectively. Although there exist limited accumulation areas, the ELA lies above the uppermost part of the glacier in both years. Mean annual temperatures for the two mass balance periods at the nearby Zackenberg station equaled –9.9 °C and –8.5 °C, respectively. In 2011, mean summer temperature (JJA) were 0.4 °C higher compared to 2010 (4.2 °C and 4.6 °C, respectively).

3.8.1 Topography and observation network

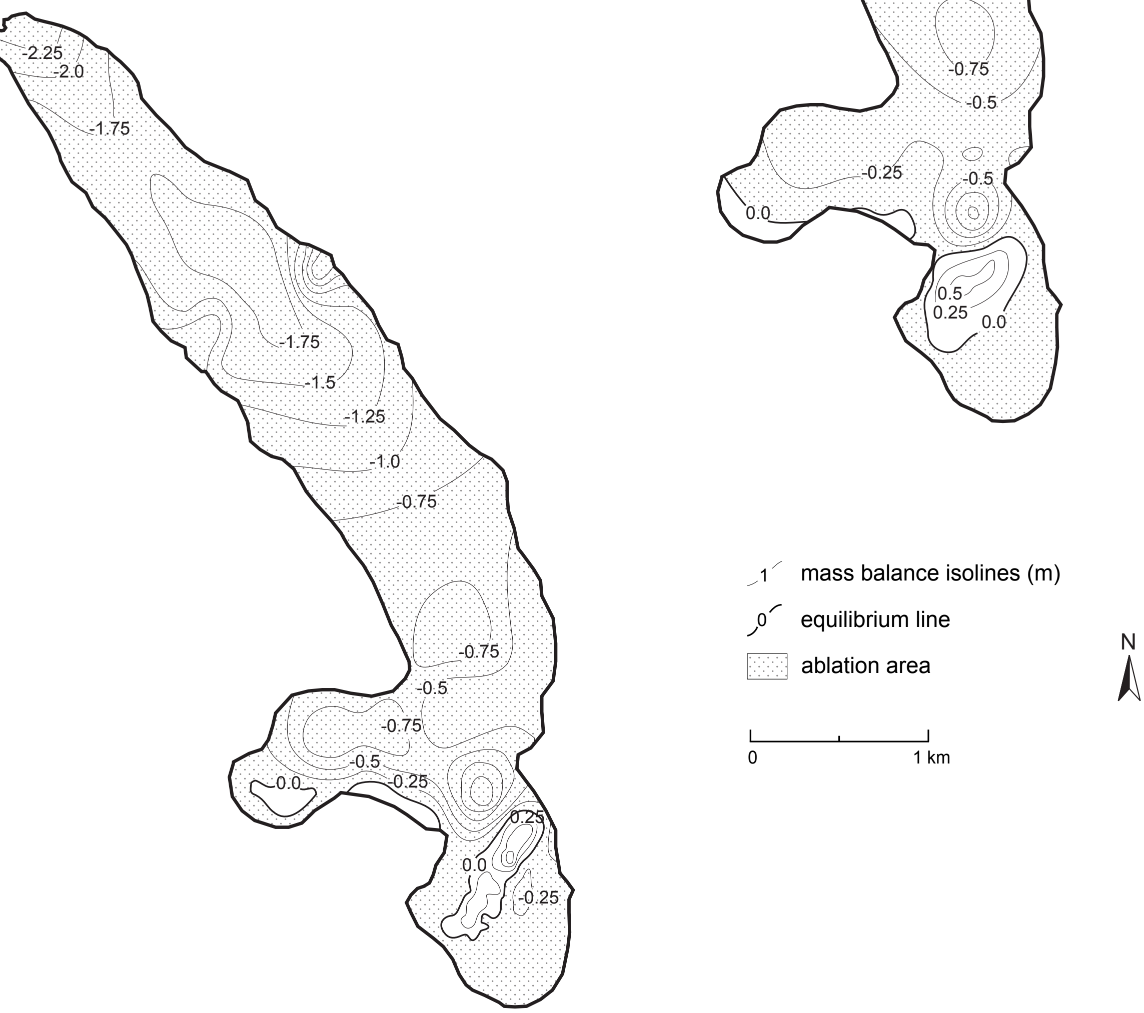
Freya (GREENLAND)

3.8.2 Mass balance maps 2009/10 and 2010/11

2009/10

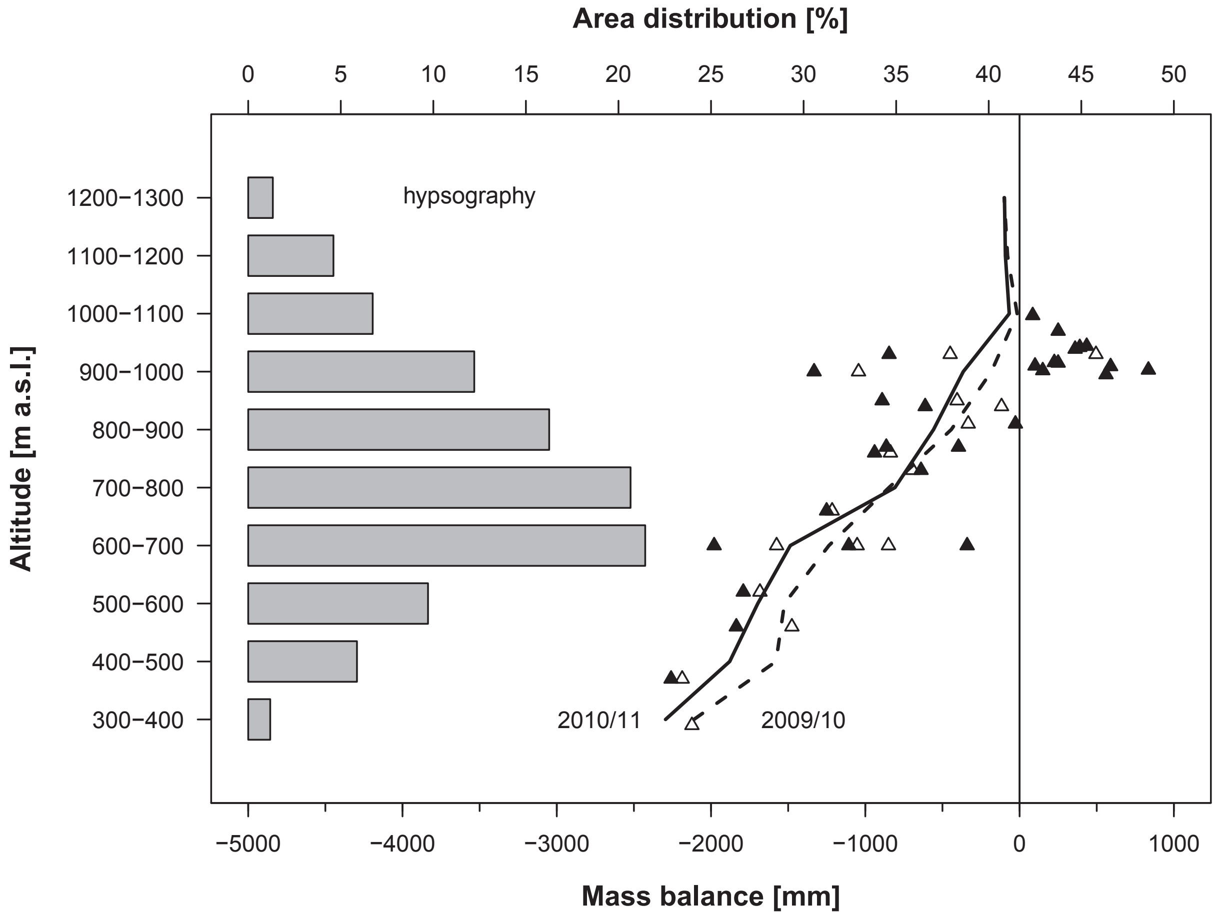


2010/11

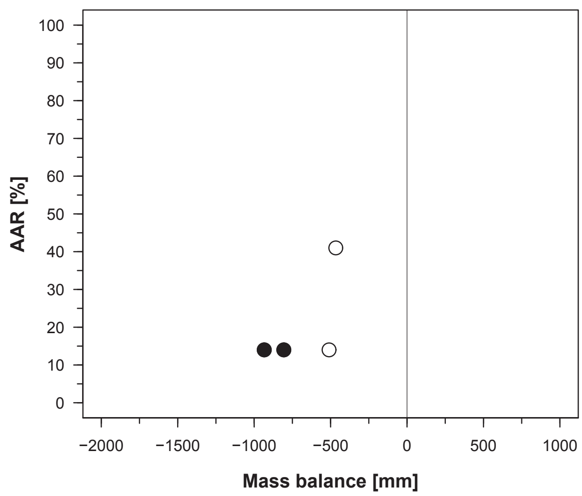


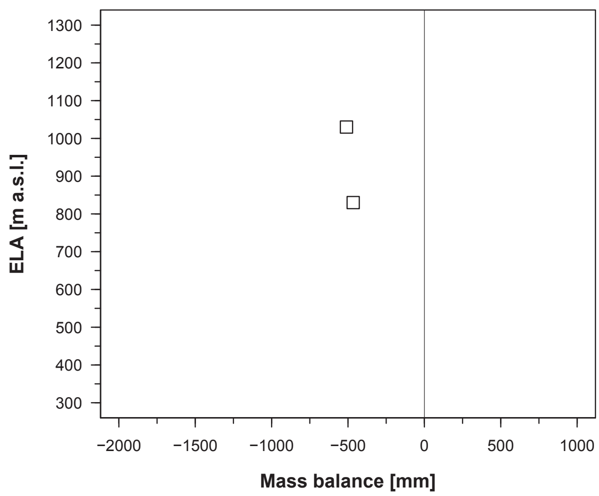
Freya (GREENLAND)

3.8.3 Mass balance versus altitude (2009/10 and 2010/11)



3.8.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period

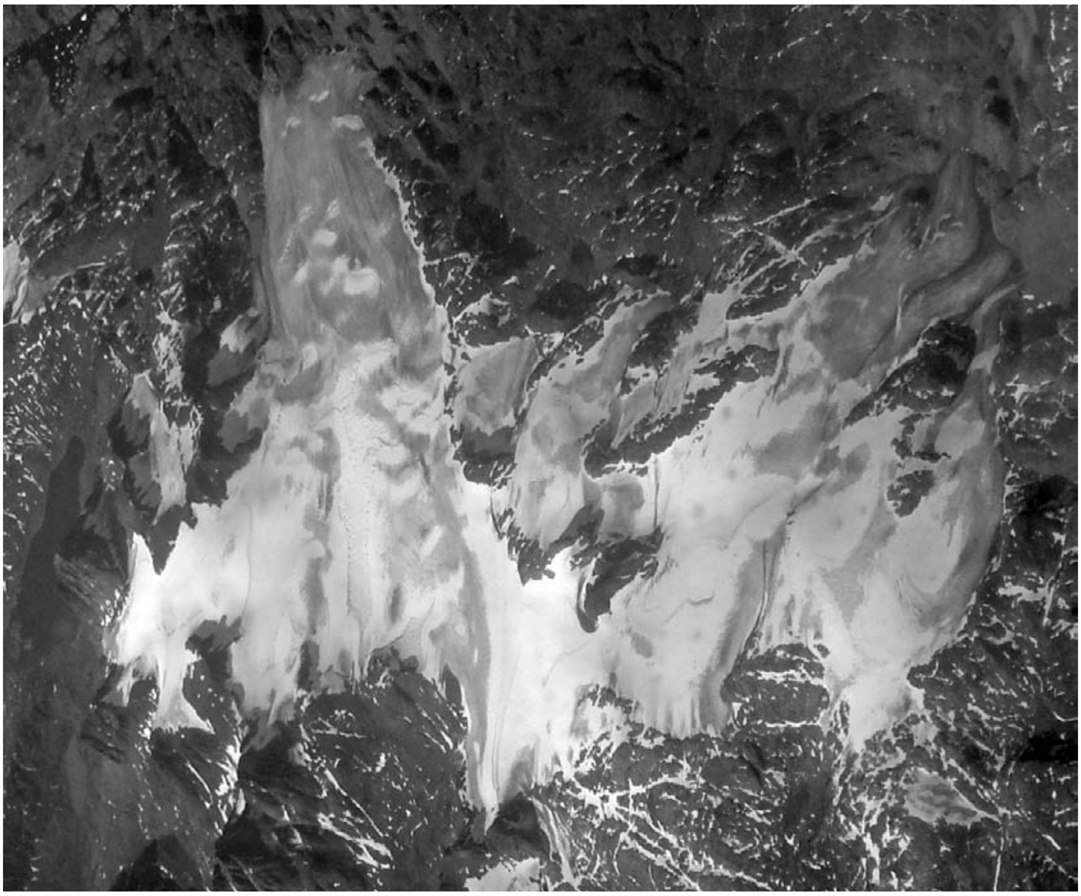




Freya (GREENLAND)

3.9 MITTIVAKKAT (GREENLAND/SOUTHEAST GREENLAND)

COORDINATES: 65.67° N / 37.83° W

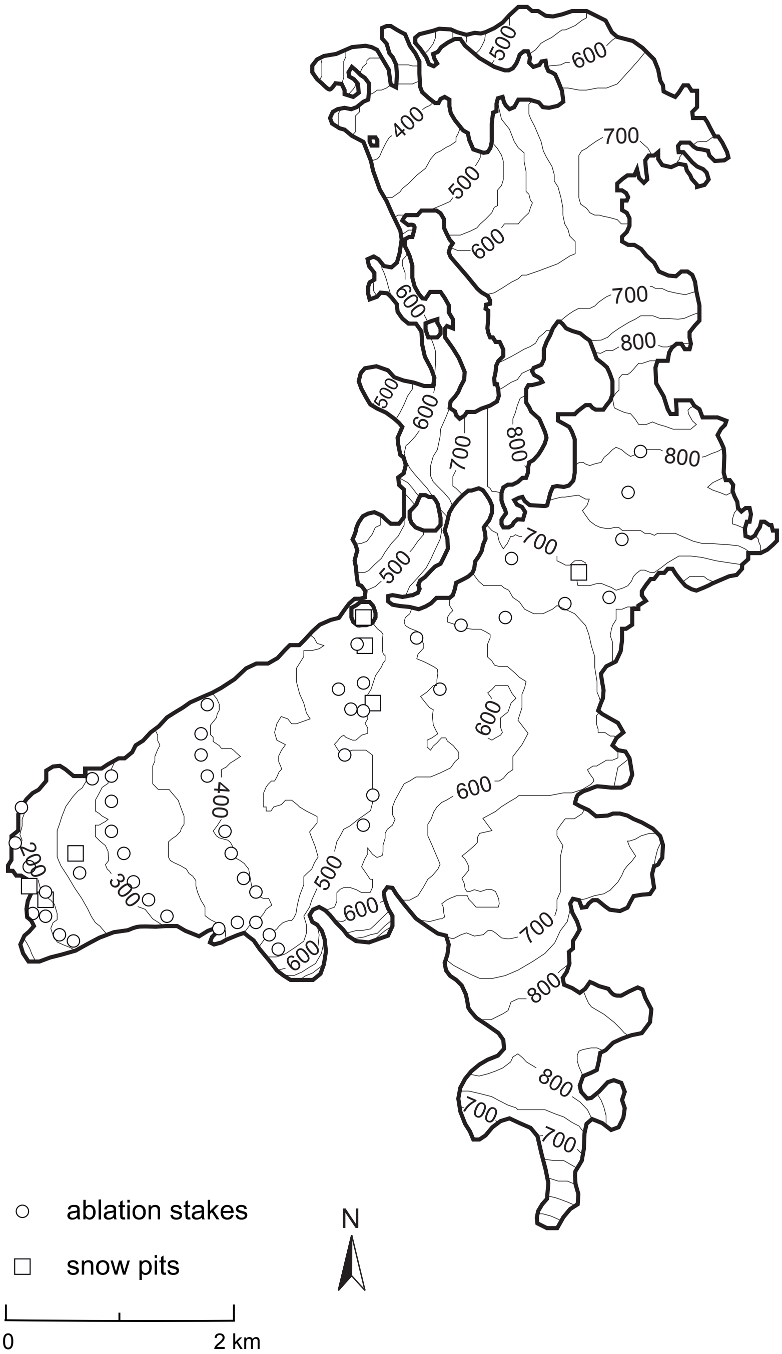


Aerial view looking west at Mittivakkat Gletscher on 12 July 2007, photo by N. T. Knudsen.

Mittivakkat Gletscher is located in the Ammassalik region, south-eastern Greenland and covers 26.2 km² (in 2011), and is the only glacier in Greenland peripheral to the Greenland Ice Sheet for which there exist long-term observations of both glacier front variations (since the maximum Little Ice Age (LIA) extension around 1900) and surface mass balance (since 1995; cf. S. H. Mernild et al., J. Glaciol. 59, 649–659 & 660–670, 2013). The glacier terminus (at the centre line) retreated about 22 m in 2011, which is 12 m less than the observed record of 34 m in 2010, and approximately 1600 m in total since the maximum LIA extent (equivalent to 14 m a^{-1}). Since the LIA the Mittivakkat Gletscher has been almost continuously retreating, and within the last three decades the area diminished from 31.9 km² (1986) to 26.2 km² (2011), in total 18 %, following the overall trend for the Ammassalik region.

Mittivakkat Gletscher is a temperate valley glacier with isothermal conditions close to 0 °C, apart from the upper few metres, caused by the seasonal shifts in temperature. The mean annual mass balance was –970 mm w.e. a^{-1} (1995/96 to 2010/11), winter balance +1180 mm w.e. a^{-1}, and summer balance –1940 mm w.e. a^{-1}. The annual mass balance loss has been increasing (significant, $p < 0.01$) by 96 mm w.e. a^{-1}, the winter balance (significant, $p < 0.01$) by 28 mm w.e. a^{-1}, and the summer balance (insignificant) by 10 mm w.e. a^{-1}. The total 2010/11 mass balance was record-setting at –2450 mm w.e., which is 290 mm w.e. more negative than the observed loss in 2009/10 and significantly greater than the 16-year average loss. The mean AAR of all observation years is below 20 %, indicating that Mittivakkat Gletscher is significantly out of balance with the present climate, and will lose at least 40 % of its current area, even in the absence of further of atmospheric warming.

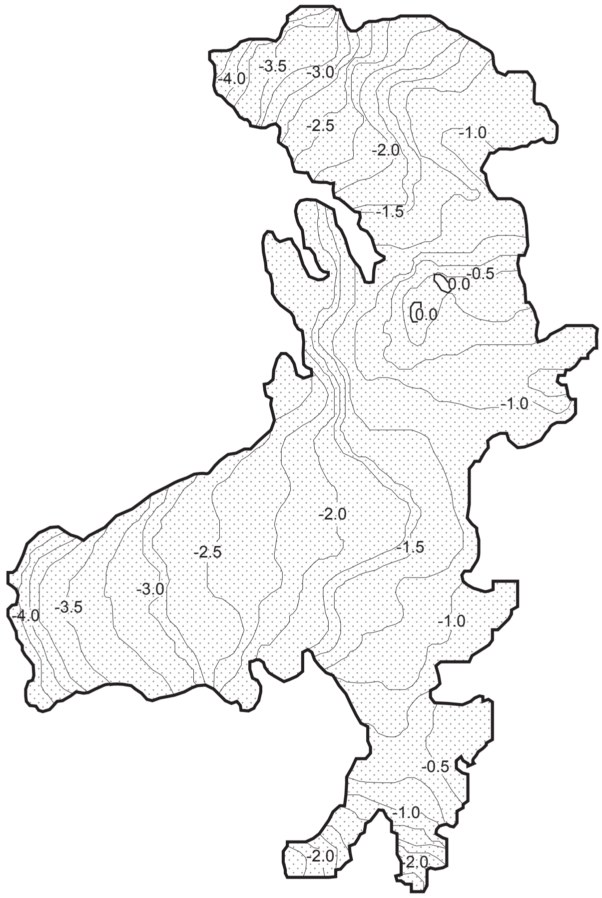
3.9.1 Topography and observation network



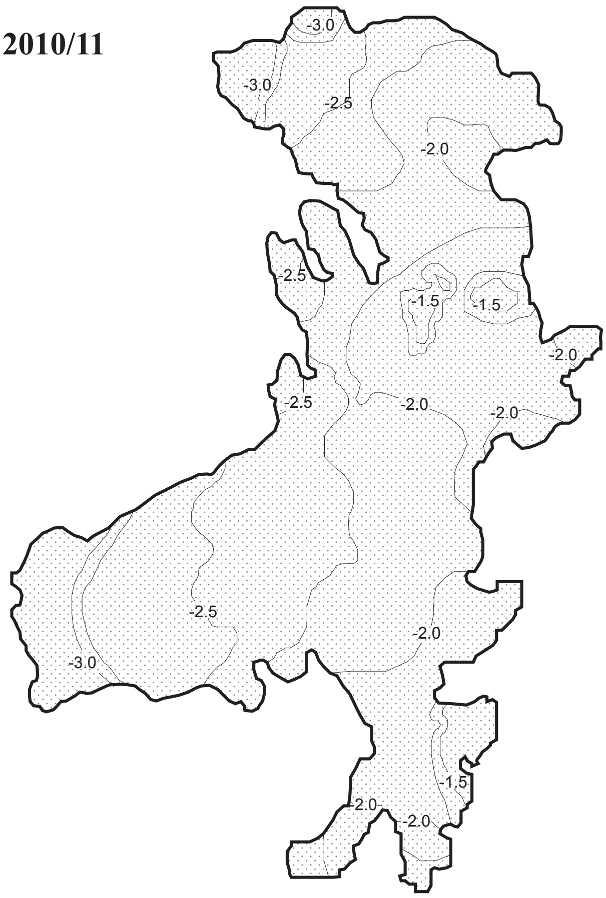
Mittivakkat (GREENLAND)

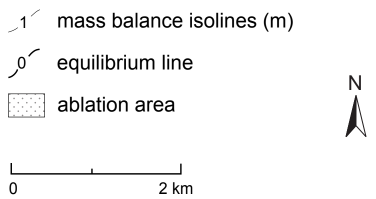
3.9.2 Mass balance maps 2009/10 and 2010/11

2009/10



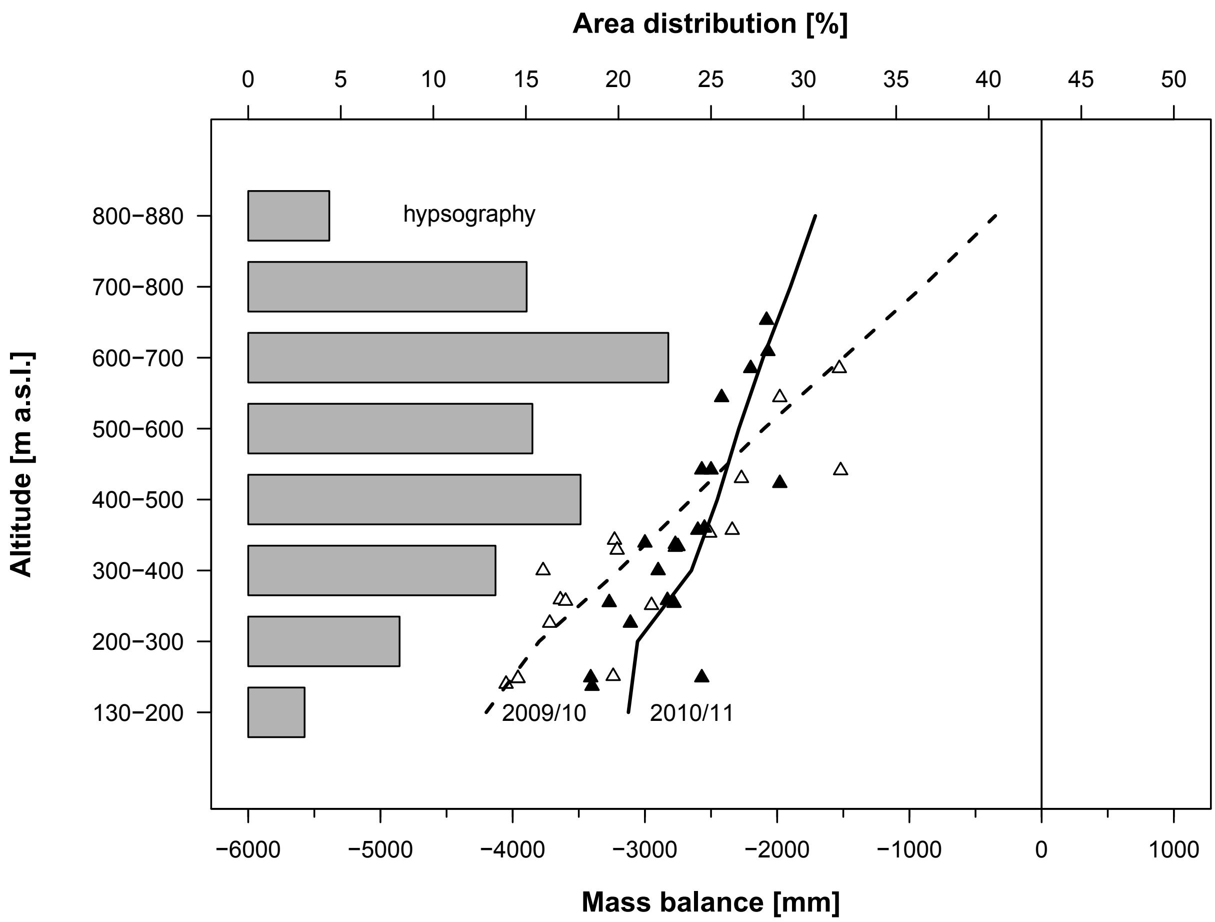
2010/11



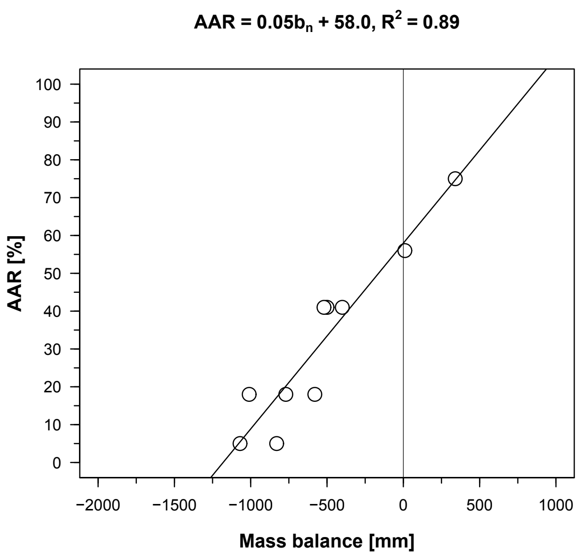


Mittivakkat (GREENLAND)

3.9.3 Mass balance versus altitude (2009/10 and 2010/11)



3.9.4 Accumulation area ratio (AAR) versus specific mass balance for the whole observation period



Mittivakkat (GREENLAND)

3.10 CARESÈR (ITALY/CENTRAL ALPS)

COORDINATES: 46.45° N / 10.70° E

Aerial view of Caresèr Glacier taken on 21 September 2010. Photo by G. Tognoni.

Caresèr Glacier is located in the Ortles-Cevedale group (Eastern European Alps, Italy). It occupies an area of 1.9 km^2 and extends from 3278 to 2880 m a.s.l. The glacier is exposed mainly to the south and is fairly flat. 72 % of the glacier area lies between 2900 and 3100 m a.s.l. and the median altitude is 3079 m a.s.l. The mean annual air temperature at this elevation is about –3 to –4 °C and annual precipitation averages 1450 mm. The mass balance investigations on Caresèr Glacier began in 1967. The mass balance was close to equilibrium until 1980, but since then is has become increasingly negative. In the last thirty years the ELA was almost every year above the maximum altitude of the glacier, which became inactive. The mean value of the annual mass balance was –1195 mm w.e. from 1981 to 2001, but decreased to –1884 mm w.e. from 2002 to 2011. This was a result of both warmer ablation seasons and positive feedbacks (decreasing albedo, surface lowering, increased thermal emission from the growing patches of ice-free terrain). The strongly negative mass balances led to huge morphological changes in the 2000s due to widespread bedrock emersion, which is causing the disintegration of the parent glacier.

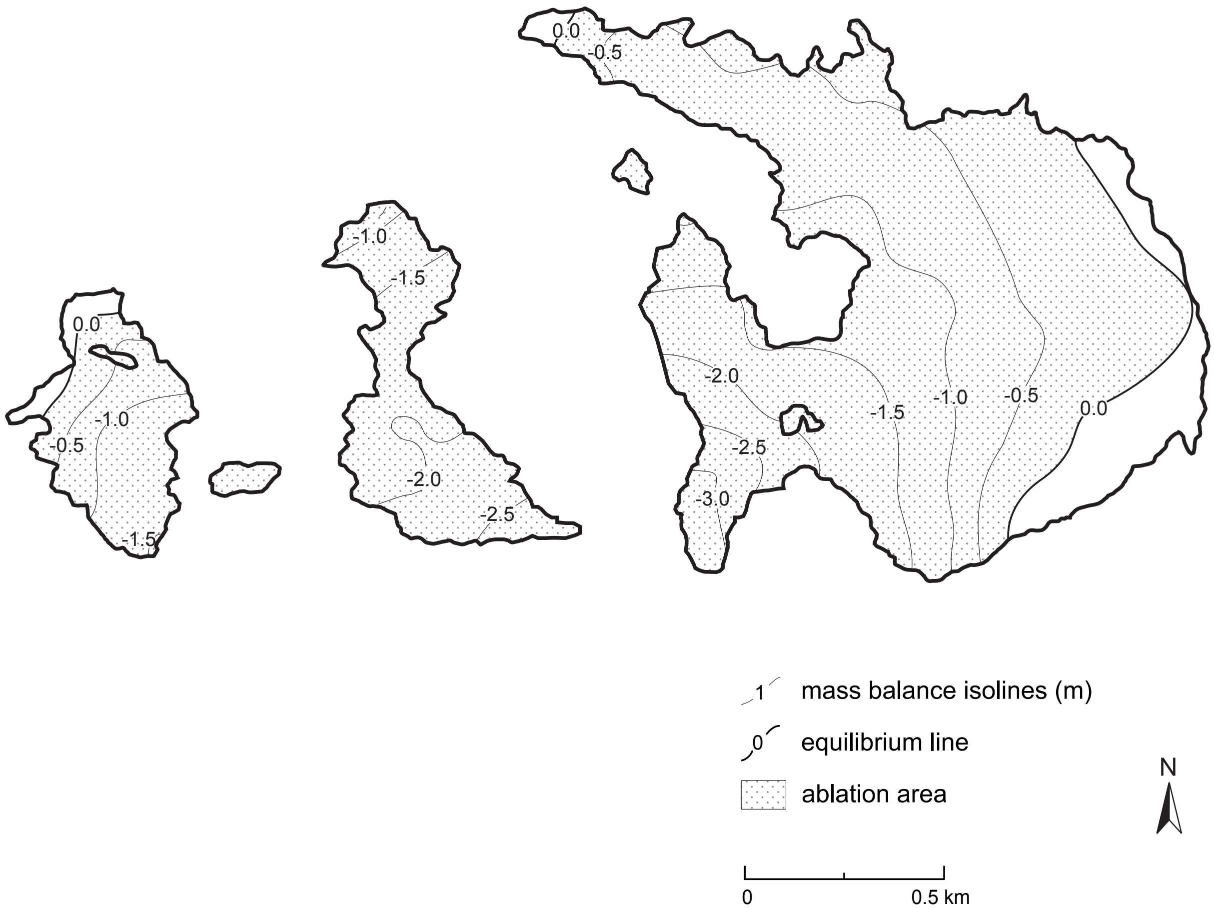
During the hydrological years 2009/10 and 2010/11 the mass balance of Caresèr Glacier was negative, at –962 mm and –1922 mm w.e., respectively. The mass balance for the year 2009/10 was the least negative since 2001, thanks to fairly good snow accumulation during winter (10 % above the long-term mean) and to a less warm ablation season. Conversely, precipitation was scarce in the 2010/11 accumulation season (10 % below the long-term mean) and the ablation season was unusually long.

3.10.1 Topography and observation network

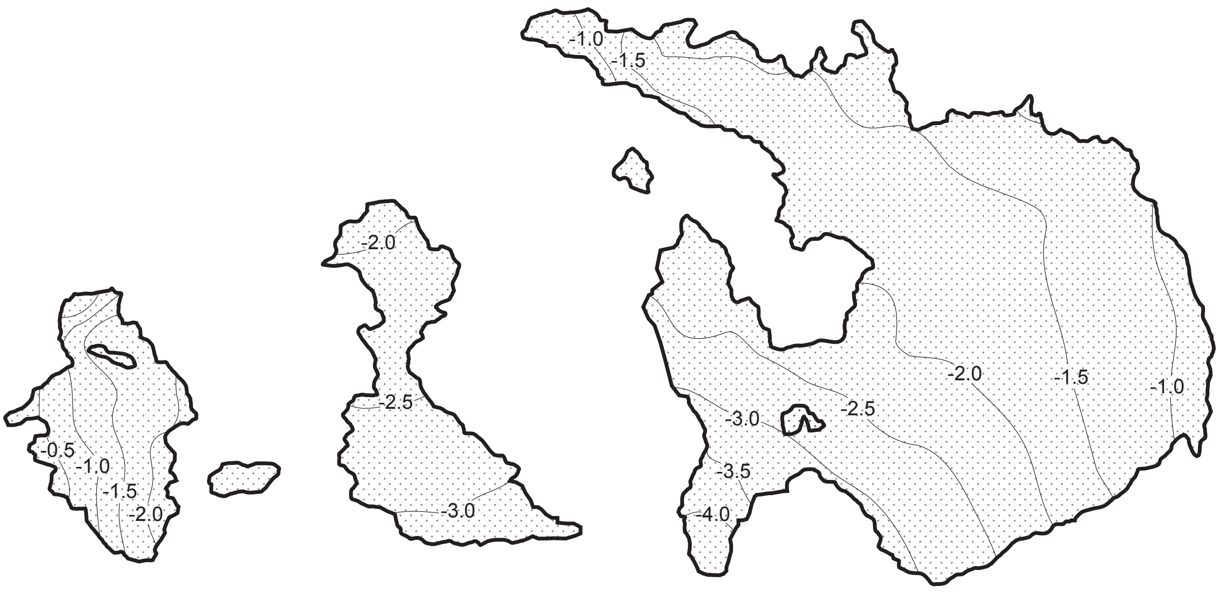
Caresèr (ITALY)

3.10.2 Mass balance maps 2009/10 and 2010/11

2009/10

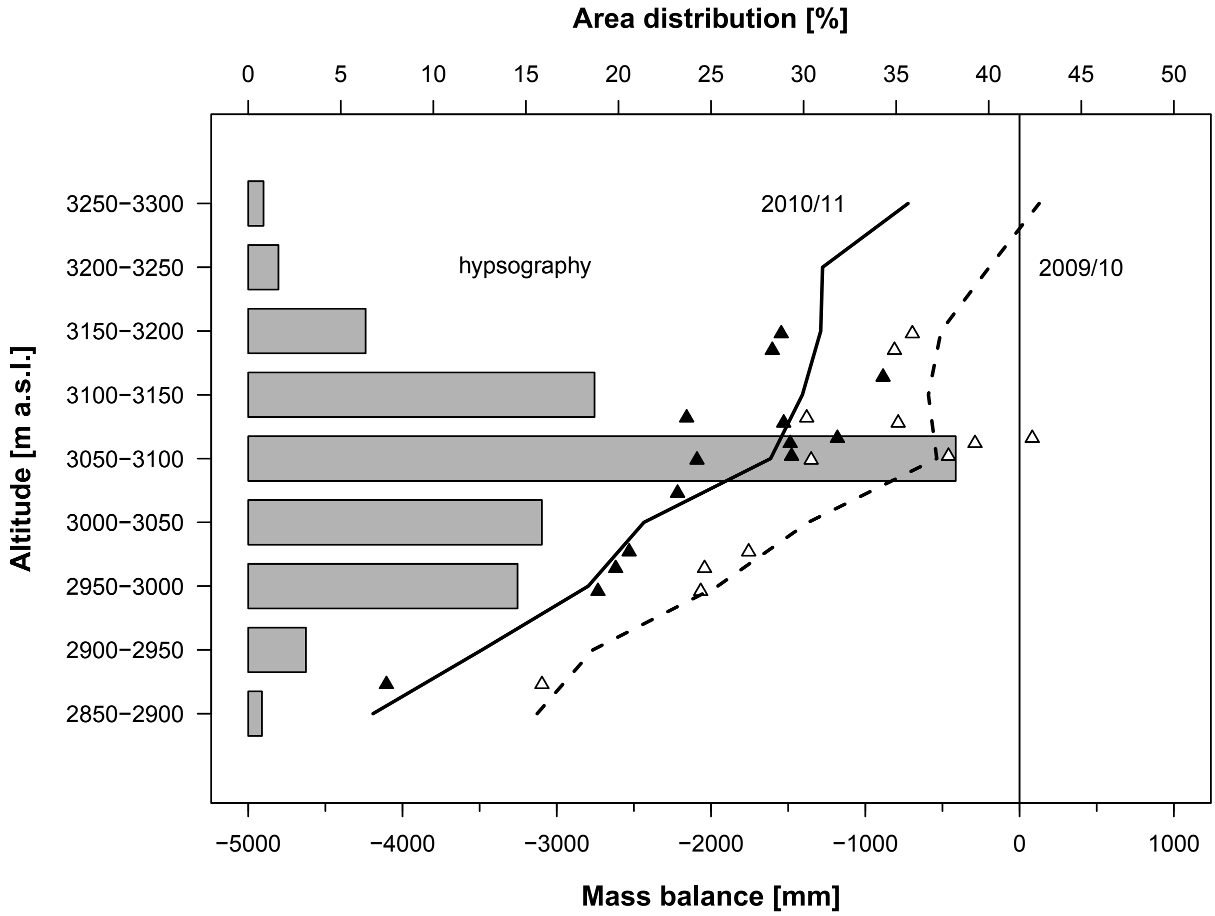


2010/11

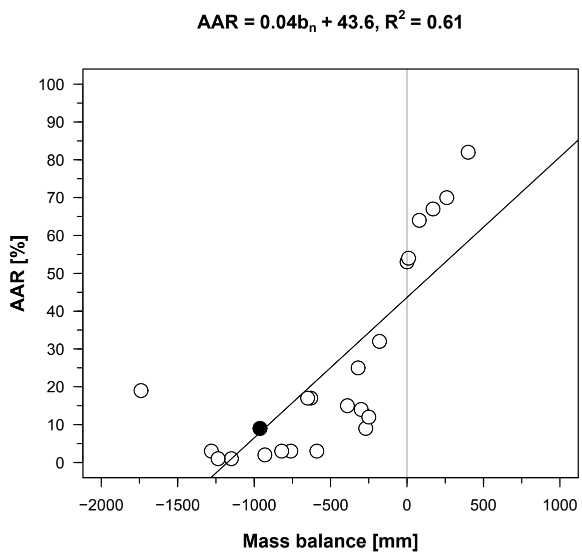


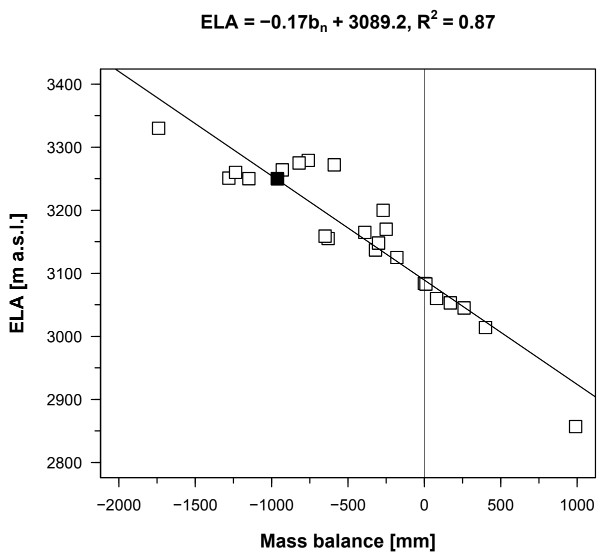
Caresèr (ITALY)

3.10.3 Mass balance versus altitude (2009/10 and 2010/11) for the entire glacier



3.10.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period





Caresèr (ITALY)

3.11 TSENTRALNIY TUYUKSUYSKIY (KAZAKHSTAN/TIEN SHAN)

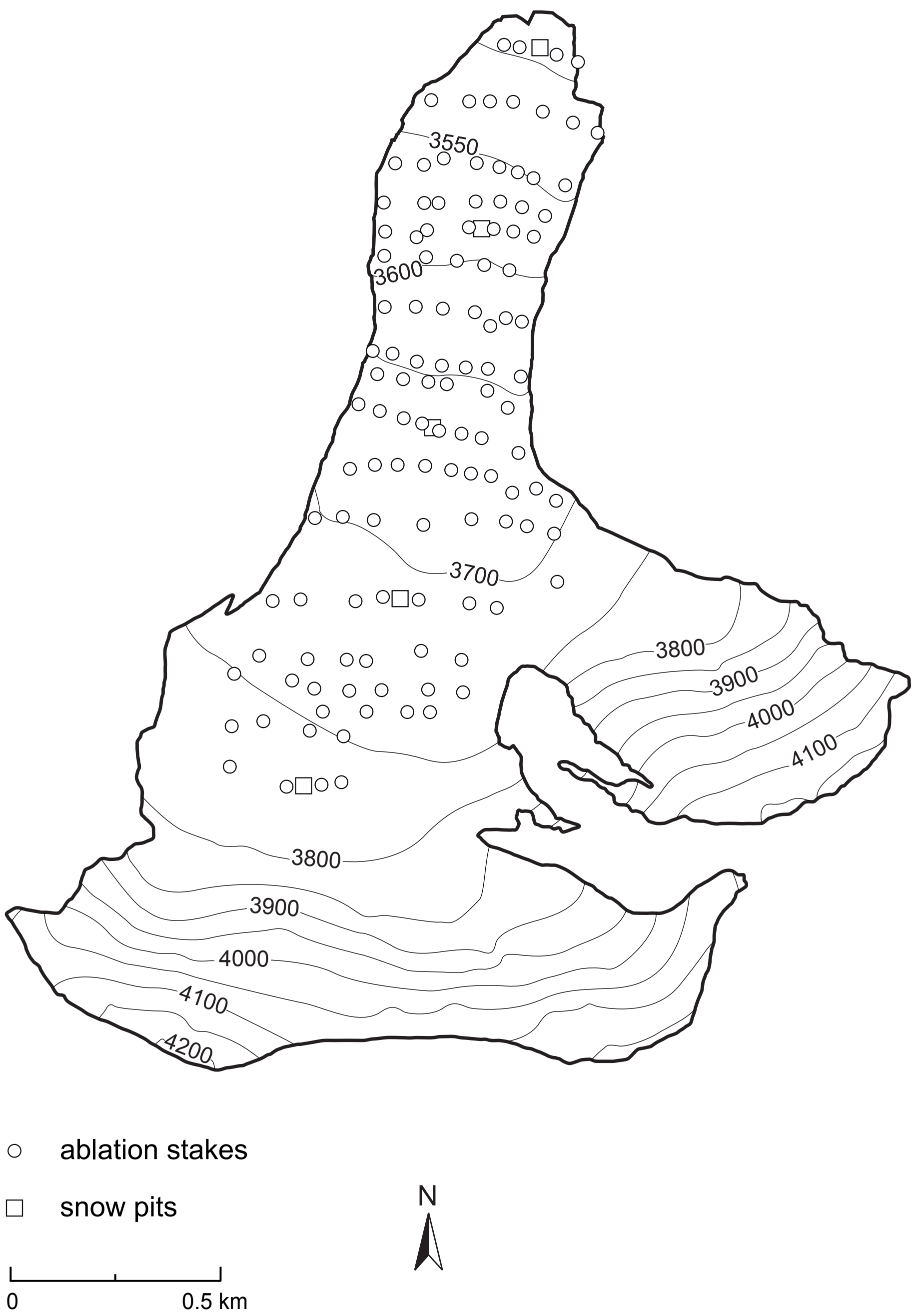
COORDINATES: 43.05° N / 77.08° E

Photo taken by V. P. Blagoveshchenskiy, 2011.

This valley glacier in the Zailiyskiy Alatau Range of Kazakh Tien Shan is also called the Tuyuksu Glacier. It extends from 4219 m to 3467 m a.s.l. and has a surface area of 2.313 km^2 (2011) with exposure to the north. Mean annual air temperature at the equilibrium line of the glacier in 2010 (around 3762 m a.s.l.) was –6 °C for balanced conditions, and –5 to –6 °C in 2011 (ELA around 3800 m a.s.l.). Average annual precipitation as measured with 13 precipitation gauges for the balance year 2009/10 was equal to 1437 mm. For the balance year 2010/11, it amounted to 995 mm (14 precipitation gauges). The summer precipitation equaled 47 % of the annual sum in 2010/11. The glacier is considered to be cold to polythermal and surrounded by continuous permafrost.

Annual precipitation at the meteorological station Tuyuksu (3450 m a.s.l.) equaled 1342 mm (of which 768 mm winter precipitation, and 574 mm summer precipitation) in 2009/10, which is 366 mm more than the mean for the period 1972–2010; air temperatures from June to August (June to September) 2010 were 0.2 °C (0.3 °C) higher. As a result of these conditions the glacier mass balance in 2009/10 was +30 mm w.e. Summer air temperature (June to August) in 2011 were 0.6 °C higher than the average for the 1972–2011 period, while precipitation was 34 mm less. As a result of these conditions the glacier mass balance in 2010/11 was –313 mm w.e.

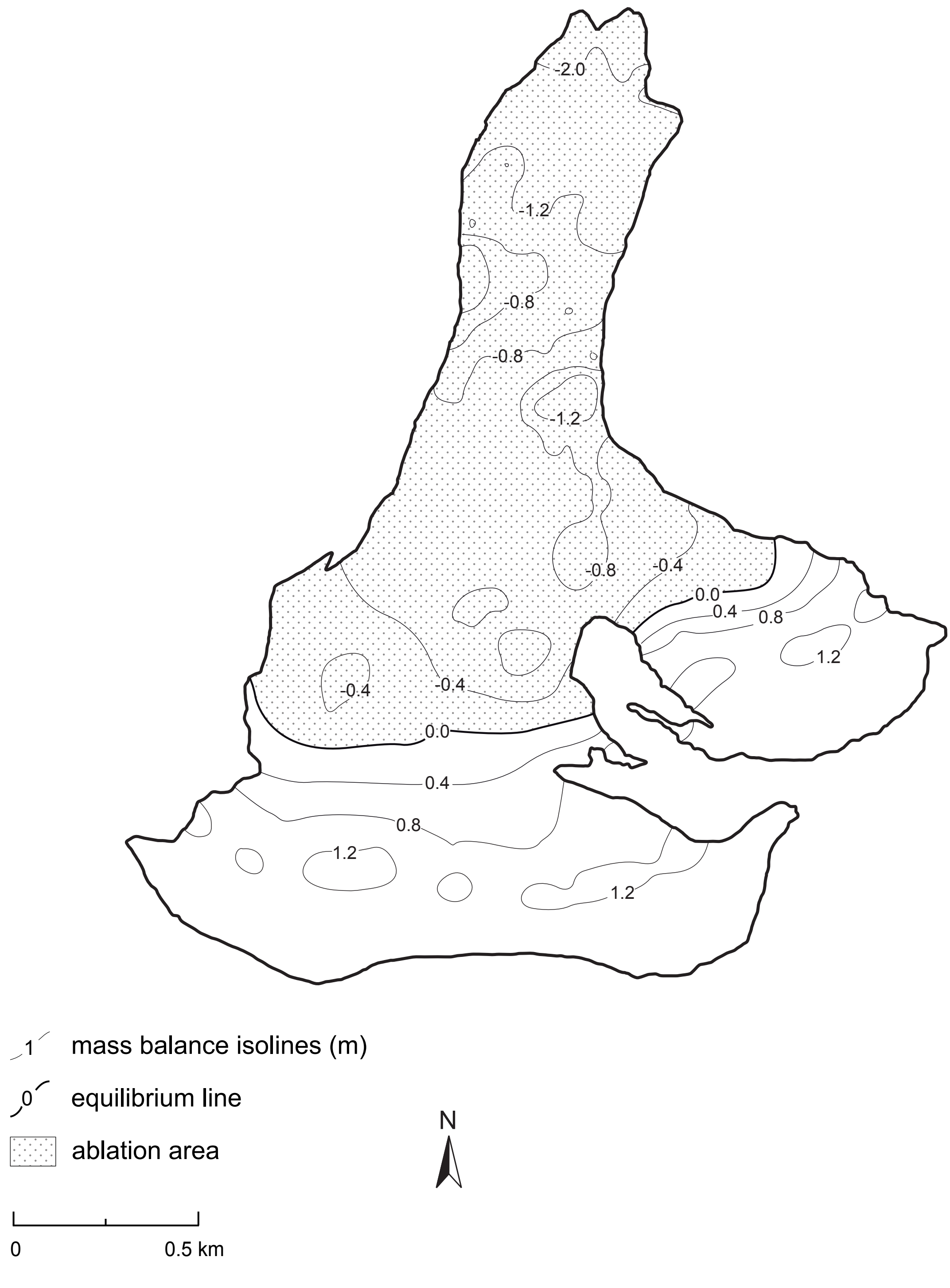
3.11.1 Topography and observation network



Tsentralniy Tuyuksuyskiy (KAZAKHSTAN)

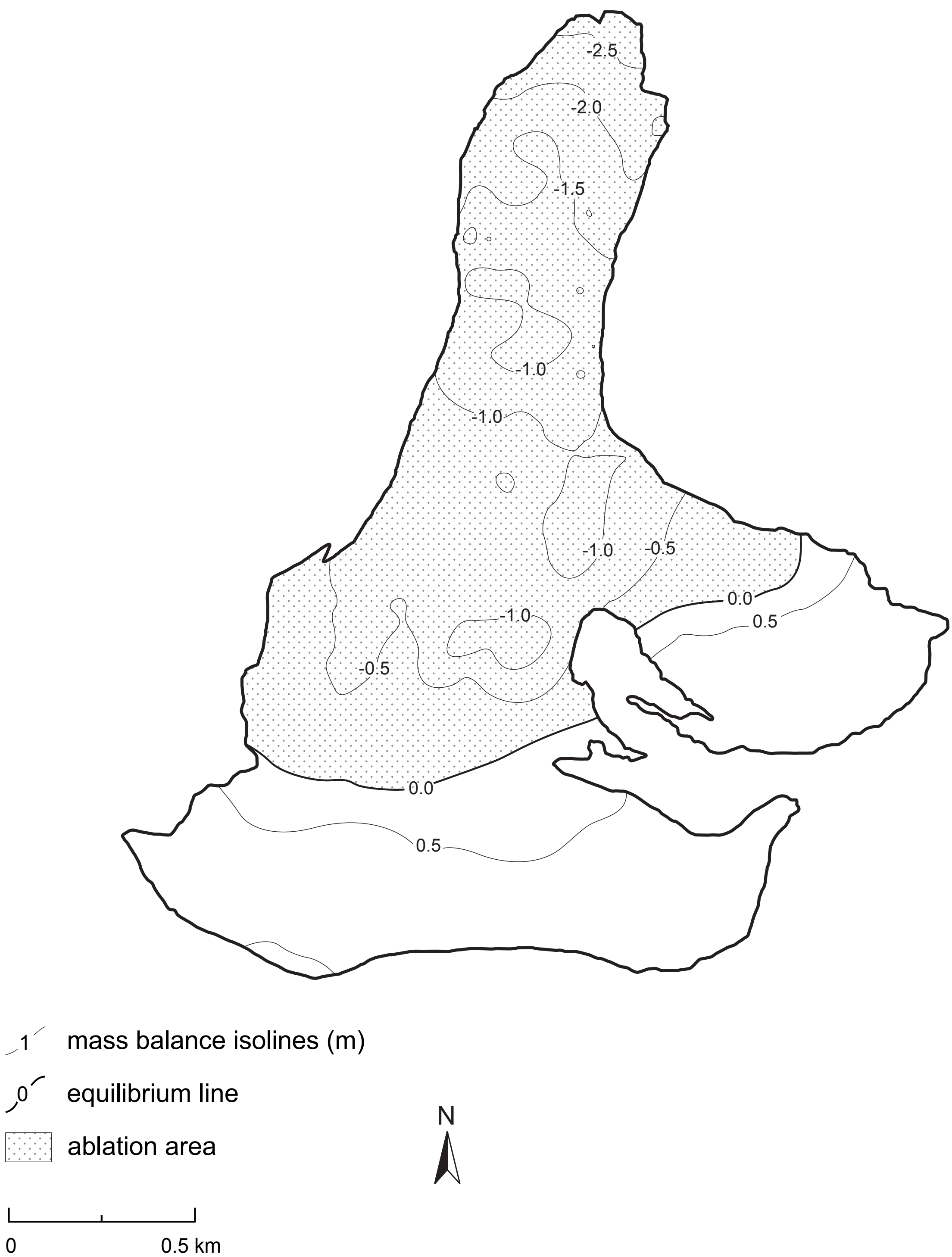
3.11.2 Mass balance maps 2009/10 and 2010/11

2009/10



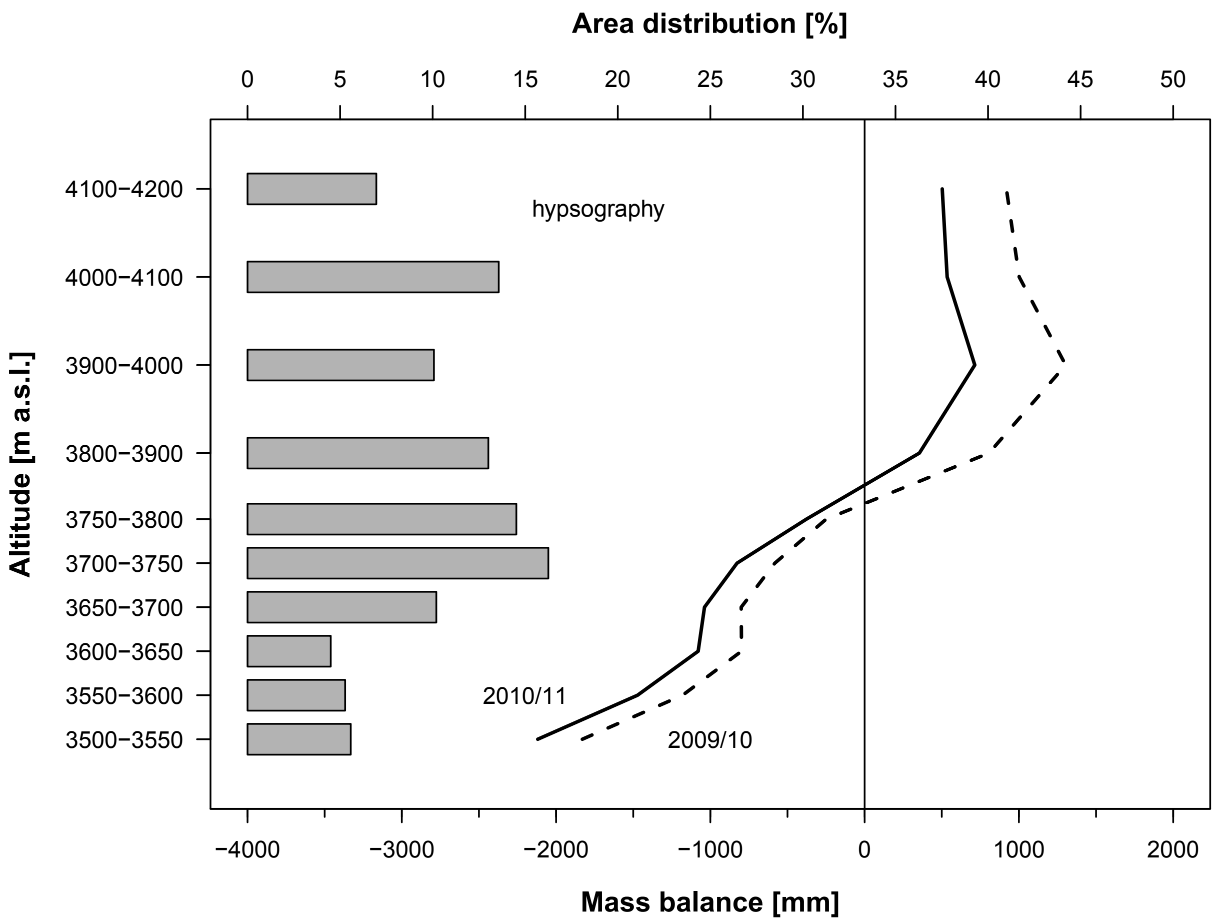
Tsentralniy Tuyuksuyskiy (KAZAKHSTAN)

2010/11

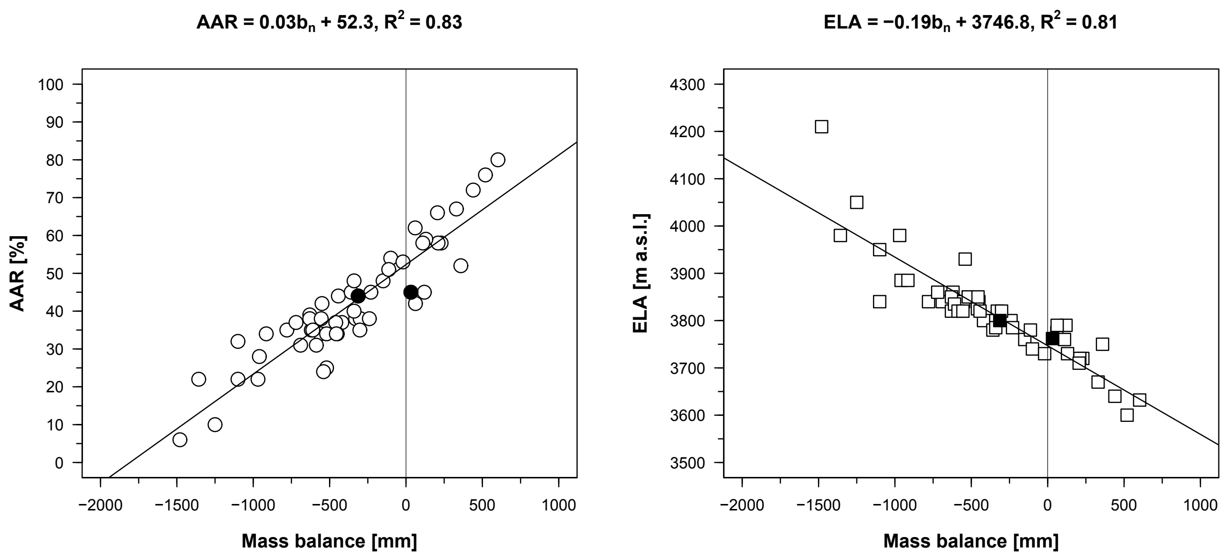


Tsentralniy Tuyuksuyskiy (KAZAKHSTAN)

3.11.3 Mass balance versus altitude (2009/10 and 2010/11)



3.11.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period



Tsentralniy Tuyuksuyskiy (KAZAKHSTAN)

3.12 GOLUBIN (KYRGYZSTAN/TIEN SHAN)

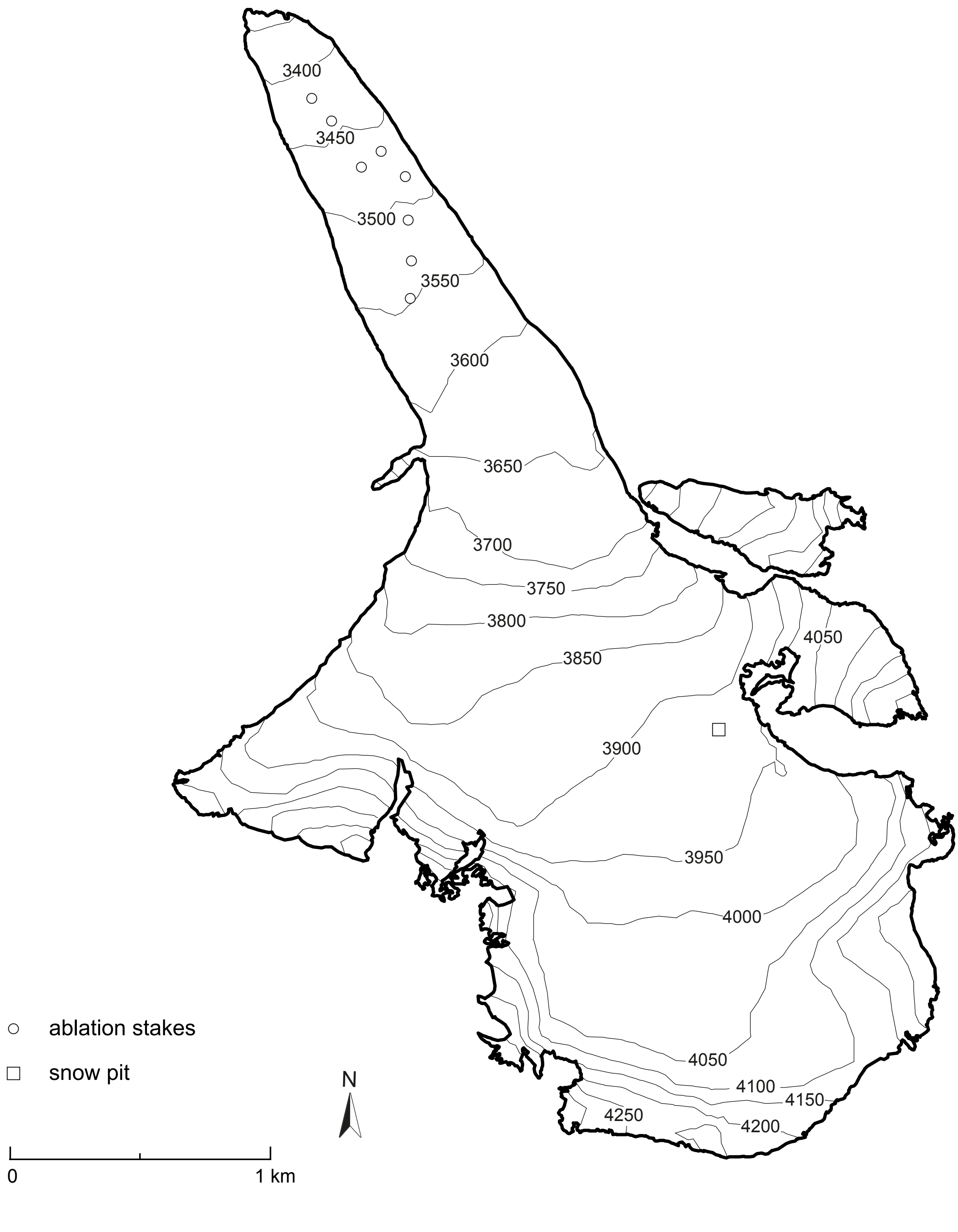
COORDINATES: 42.46° N / 74.50° E

Golubin Glacier, photo taken by M. Hoelzle, 2012.

Golubin Glacier is situated in the Ala Archa valley in the Northern Tien Shan. Today the glacier covers an area of 5.5 km^2 and spans an altitudinal range between 4400 and 3300 m a.s.l. The glacier, which can be classified as continental-type, has a northern aspect in the accumulation area, and a northwestern aspect in the ablation area. The climate shows low amounts of annual precipitation, especially during winter. The temperature amplitudes are high, with low temperatures in winter and high temperatures during the summer season. Glaciological investigations began in 1958 and continued until 1994 when the mass balance programme was stopped. Between 1958 and 1973, the mass balance was predominantly positive and then negative afterwards (V. B. Aizen, Mater. Glyatsiol. Issled. 62, 119–126, 1988). The glacier front retreated from 1981 to 2003 more than 250 m (V. B. Aizen et al., Ann. Glaciol. 43, 202–213, 2006). The mass balance monitoring was re-established in 2010 thanks to the joint efforts of the Central Asian Institute of Applied Geosciences (CAIAG), the Geoforschungszentrum Potsdam (GFZ) and the University of Fribourg (UniFR) as part of the Central Asian Water (CAWa) and Capacity Building and Twinning of Climate Observation Systems (CATCOS) projects.

A mass balance of +70 mm w.e. was calculated in the 2010/11 investigation period. However, the stake readings taken already on the 8th of August 2011 very likely led to a too positive mass balance result, as the ablation season lasts at least one or two months longer. The ELA in 2011 was situated at 3850 m a.s.l., and an AAR of 65 % was determined.

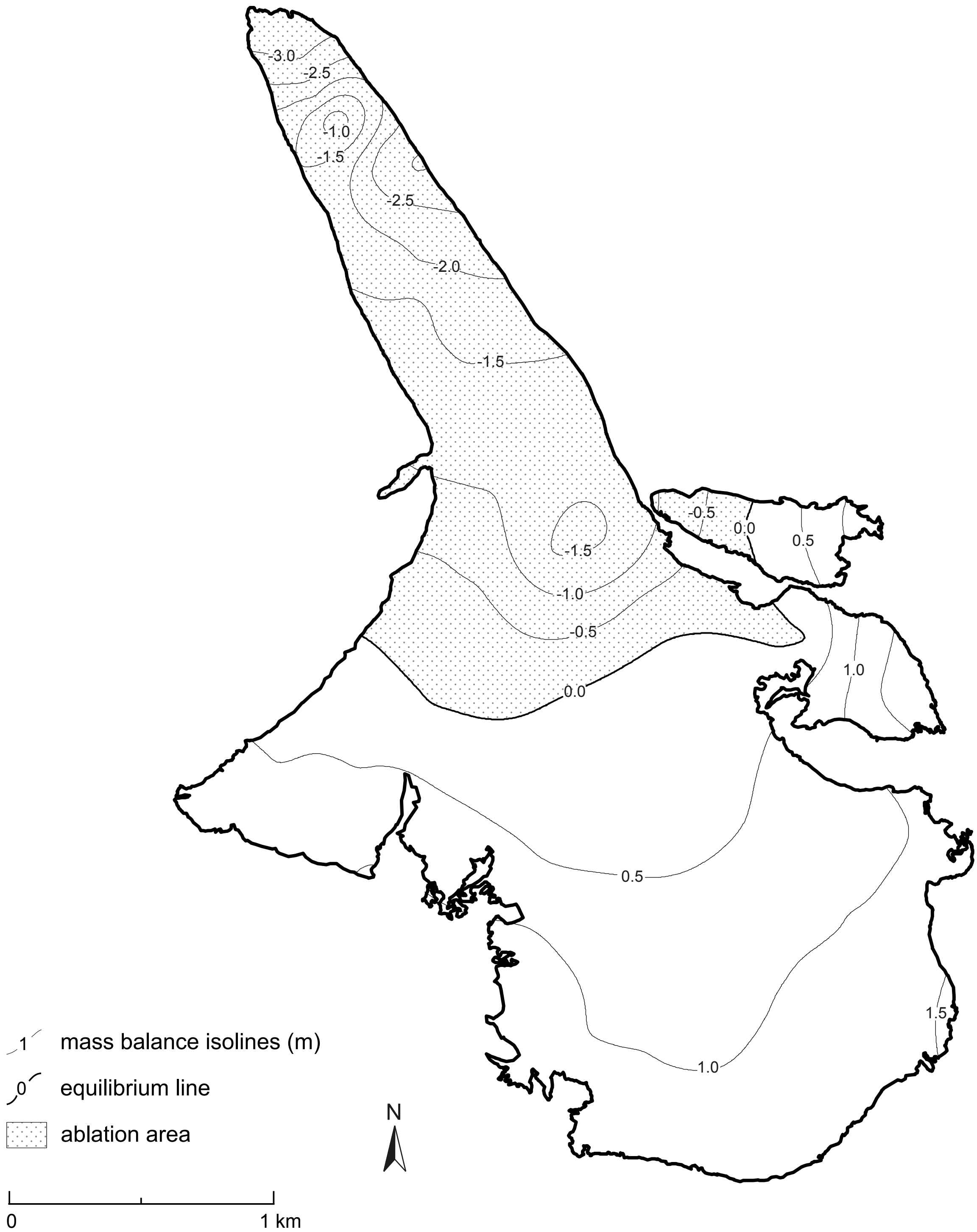
3.12.1 Topography and observation network



Golubin (KYRGYZSTAN)

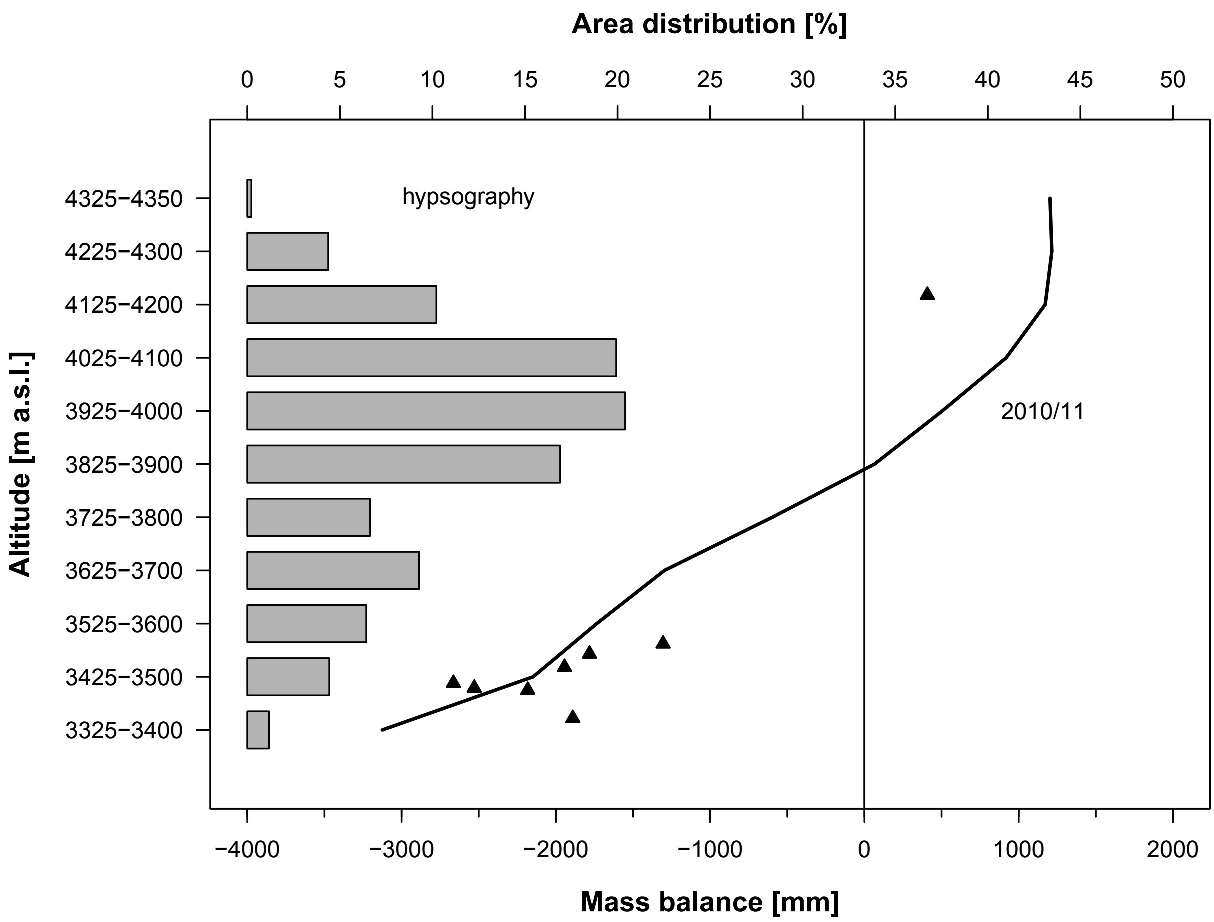
3.12.2 Mass balance map 2010/11

2010/11

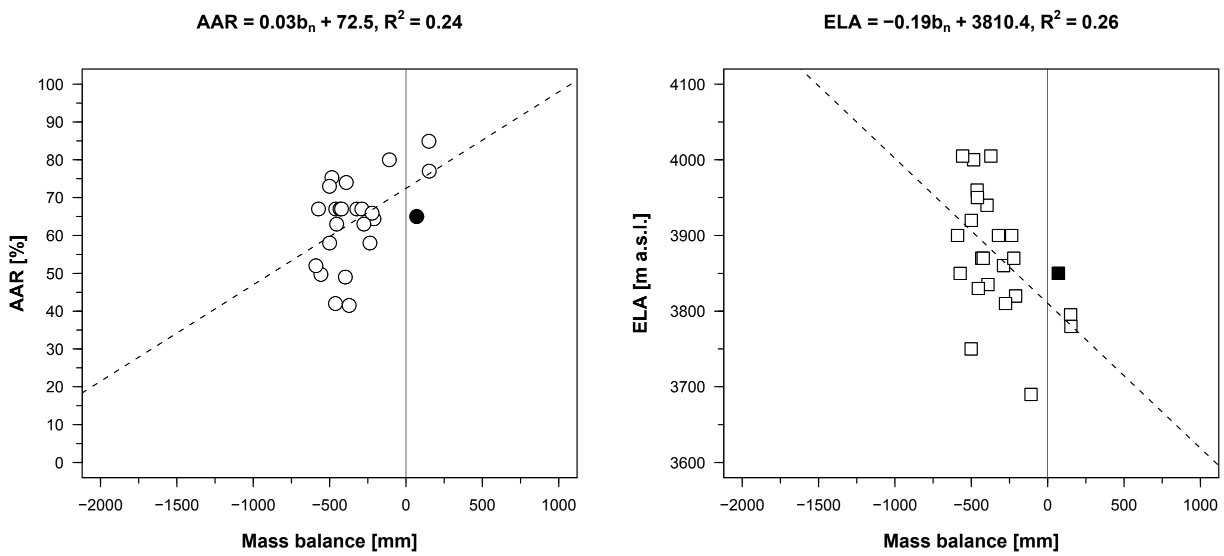


Golubin (KYRGYZSTAN)

3.12.3 Mass balance versus altitude (2010/11)



3.12.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period



Golubin (KYRGYZSTAN)

3.13 WALDEMARBREEN (NORWAY/SPITSBERGEN)

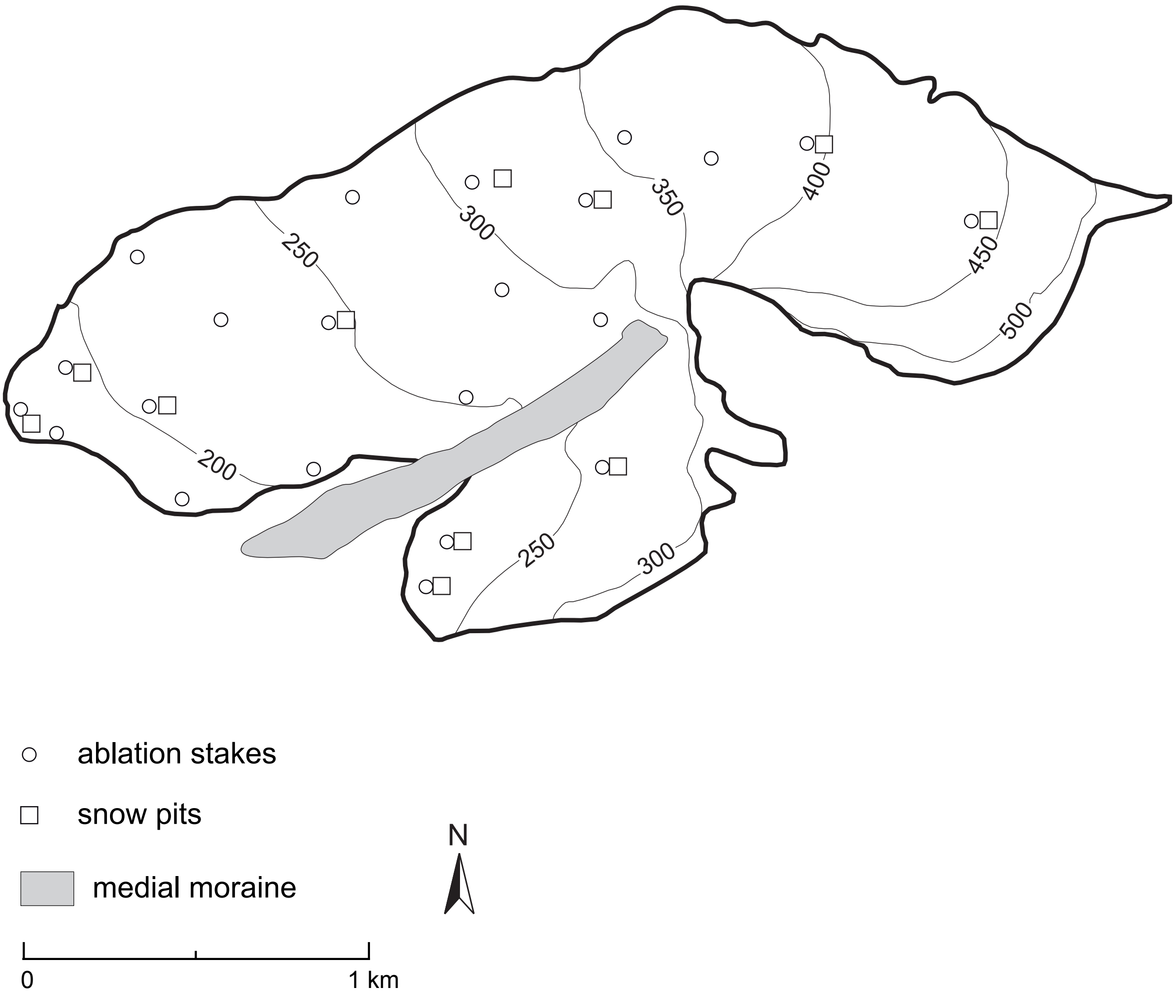
COORDINATES: 78.67° N / 12.00° E

Photo taken by I. Sobota in the summer of 2011.

Waldemarbreen is located in the northern part of the Oscar II Land, north-western Spitsbergen, and flows downvalley to the Kaffiøyra plane. Kaffiøyra is a coastal lowland situated on the Forlandsundet. The glacier is composed of two parts separated by a 1600 m long medial moraine. It occupies an area of about 2.5 km^2 and extends from 500 m to 150 m a.s.l. with a general exposure to the west. Mean annual air temperature in this area is about –4 to –5 °C and annual precipitation is generally 300–400 mm. Since the 19^{th} century the surface area of the glaciers in the Kaffiøyra region has decreased by more than 40 %. Recently, Waldemarbreen has been retreating. Mass balance investigations have been conducted since 1995. Detailed glaciological research methods and geodetic surveys are described by I. Sobota and K. R. Lankauf (Bull. Geogr. 3, 27–45, 2010), and I. Sobota (Recent changes of cryosphere of north-western Spitsbergen based on Kaffiøyra region. Wydawnictwo UMK, Toruń, 450 pp., 2013, in Polish).

The balance in 2009/10 showed a mass loss of –577 mm w.e. The corresponding ELA was 399 m a.s.l., with an AAR of 18 %. In 2010/11 the mass balance was –1239 mm w.e. The ELA was 518 m a.s.l., with an AAR of 1 %. The mean value of the mass balance for the period 1995–2011 was –614 mm w.e.

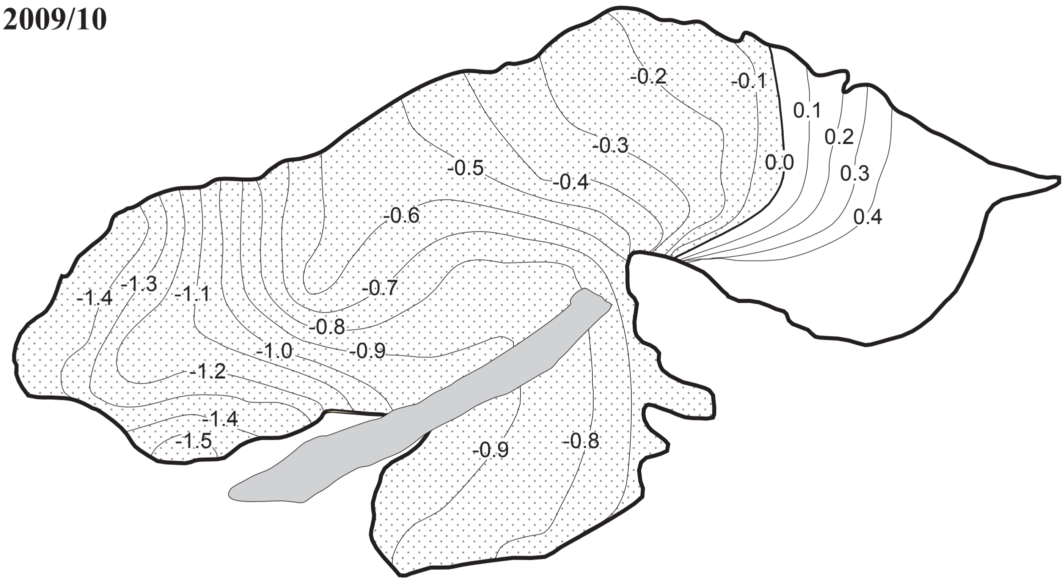
3.13.1 Topography and observation network



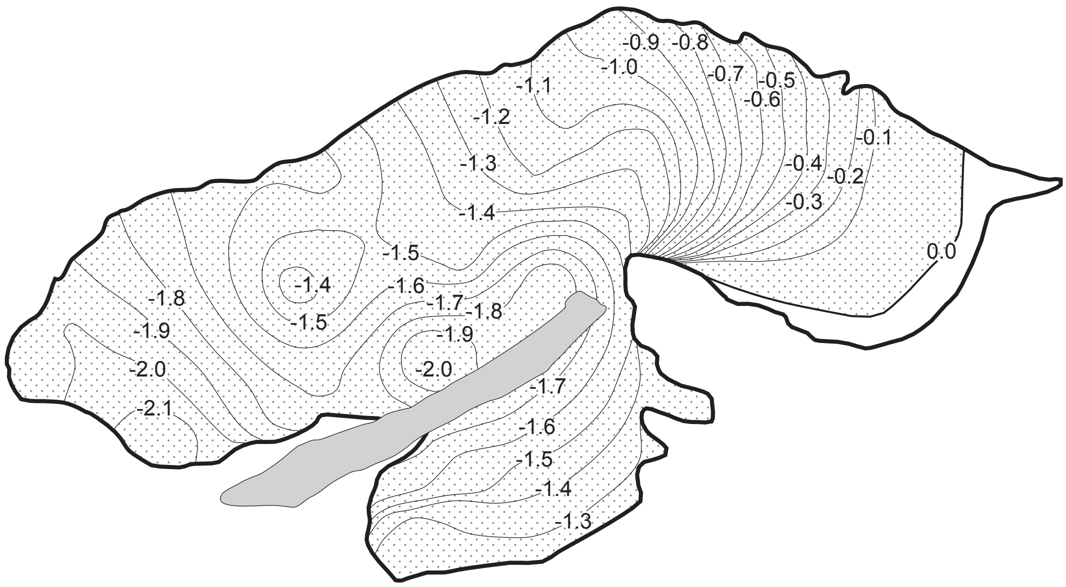
Waldemarbreen (NORWAY)

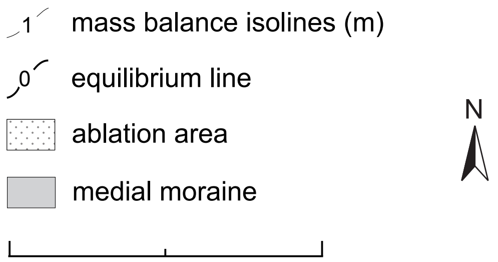
3.13.2 Mass balance maps 2009/10 and 2010/11

2009/10



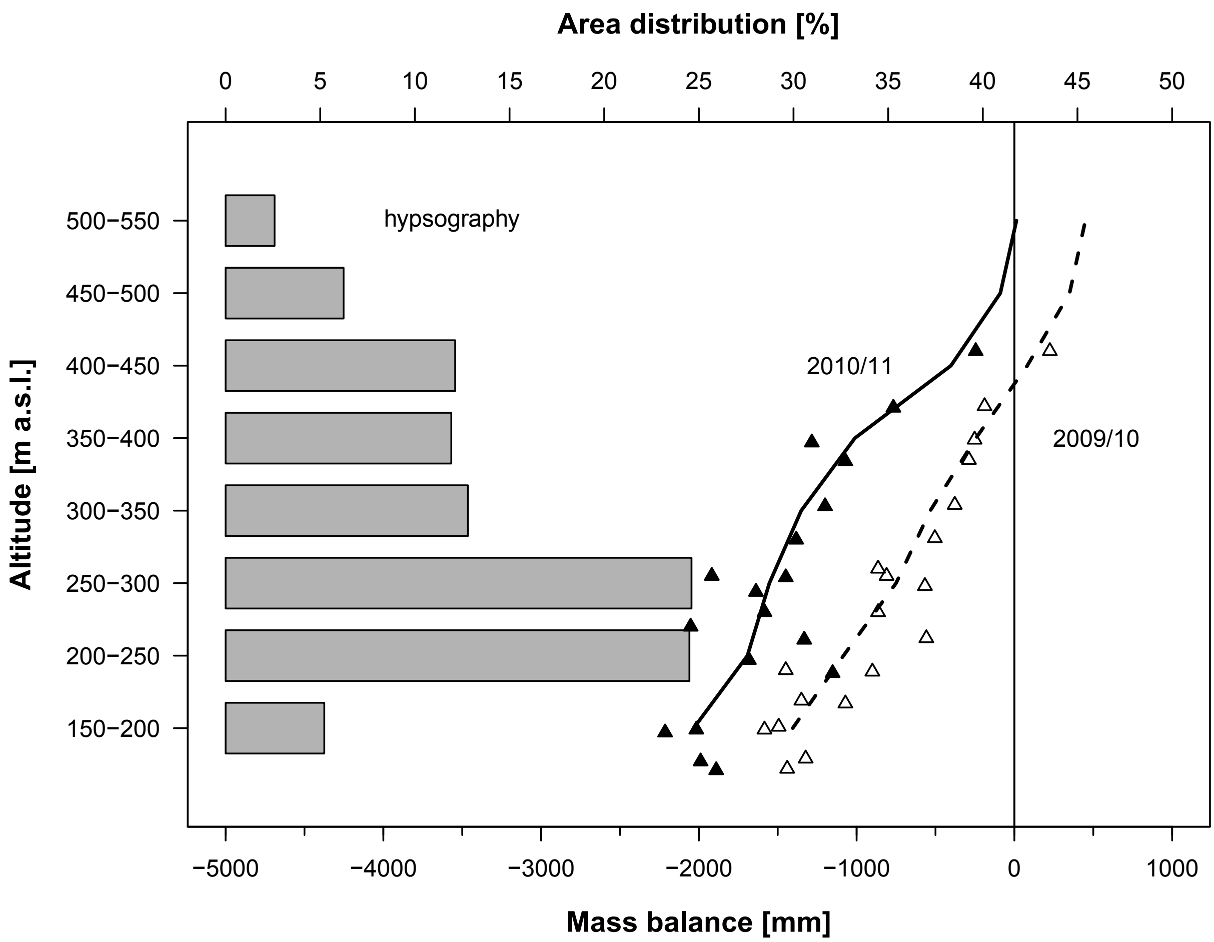
2010/11



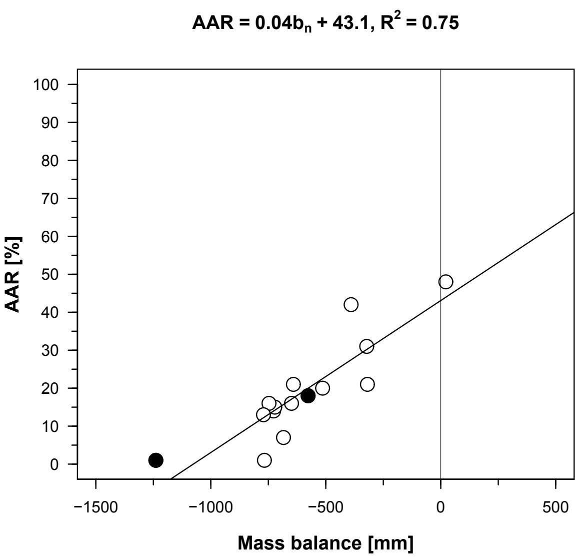


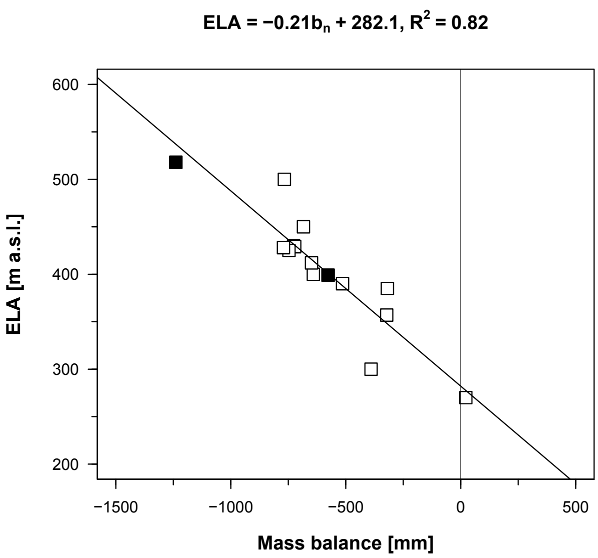
Waldemarbreen (NORWAY)

3.13.3 Mass balance versus altitude (2009/10 and 2010/11)



3.13.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period

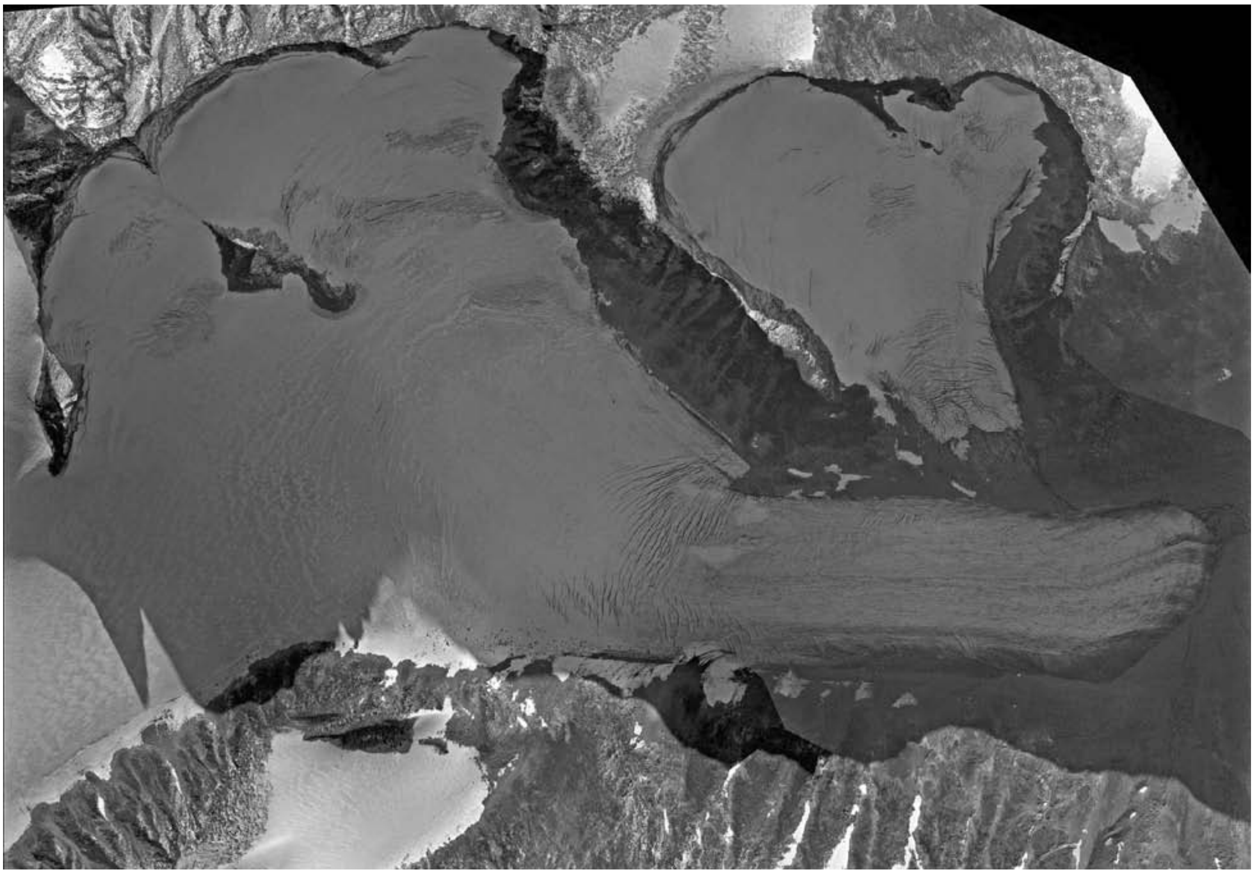




Waldemarbreen (NORWAY)

3.14 HELLSTUGUBREEN (NORWAY/CENTRAL NORWAY)

COORDINATES: 61.57° N / 8.43° E

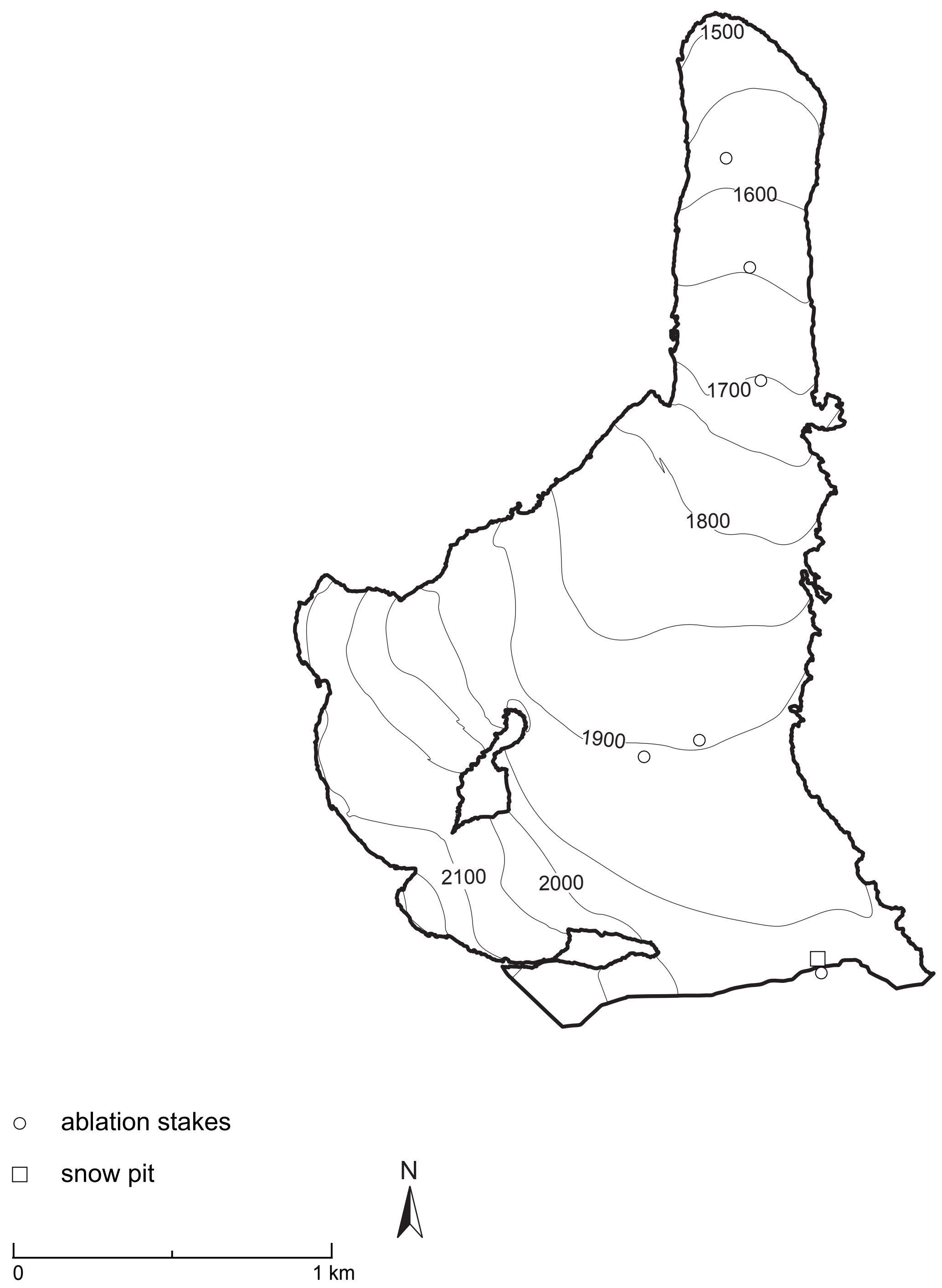


In the past, Hellstugubreen was connected with the small glacier at the top right, but the glaciers detached in the 1960s. Orthophoto taken 14 September 2009 by Blom Geomatics AS. Data source: NVE.

Hellstugubreen (now written with the ending „–an" on official maps, i.e. Hellstugubrean) is a north-facing valley glacier situated in central Jotunheimen, the highest mountain massif in mainland Norway. The glacier borders the Vestre Memurubre glacier. Hellstugubreen ranges in elevation from 2229 to 1482 m a.s.l. and has an area of 2.9 km^2 (map survey of 2009). The glacier is part of an east-west mass balance transect in southern Norway where mass turnover is largest near the western coast and decreases towards the drier interior. Hellstugubreen is in this respect considered a continental glacier, with a smaller mass balance turnover and less winter precipitation than glaciers situated further west. Annual mass balance measurements began in 1961/62, and 2009/10 and 2010/11 were the 49th and 50th year of continuous measurements at Hellstugubreen, respectively. The glacier has been mapped repeatedly; the most recent map is made by laserscanning and is from 2009.

The mass balance of Hellstugubreen was negative in 2009/10, –1340 ± 300 mm w.e. The mass balance was even more negative in 2010/11, –2040 ± 300 mm w.e., the second largest deficit measured at Hellstugubreen. The cumulative mass balance since 1961/62 is –21 m w.e., the mean annual balance over the 50 years of measurements was –420 mm w.e. The large deficit in the two years caused the melt-out of several stakes, and thus ablation measurements are based on fewer stakes for these two years. The ELA was above the highest stake at 1960 m a.s.l. in both years and is estimated from the measurements to be above the highest point at 2229 m a.s.l. corresponding to an AAR of 0 % in both years.

3.14.1 Topography and observation network

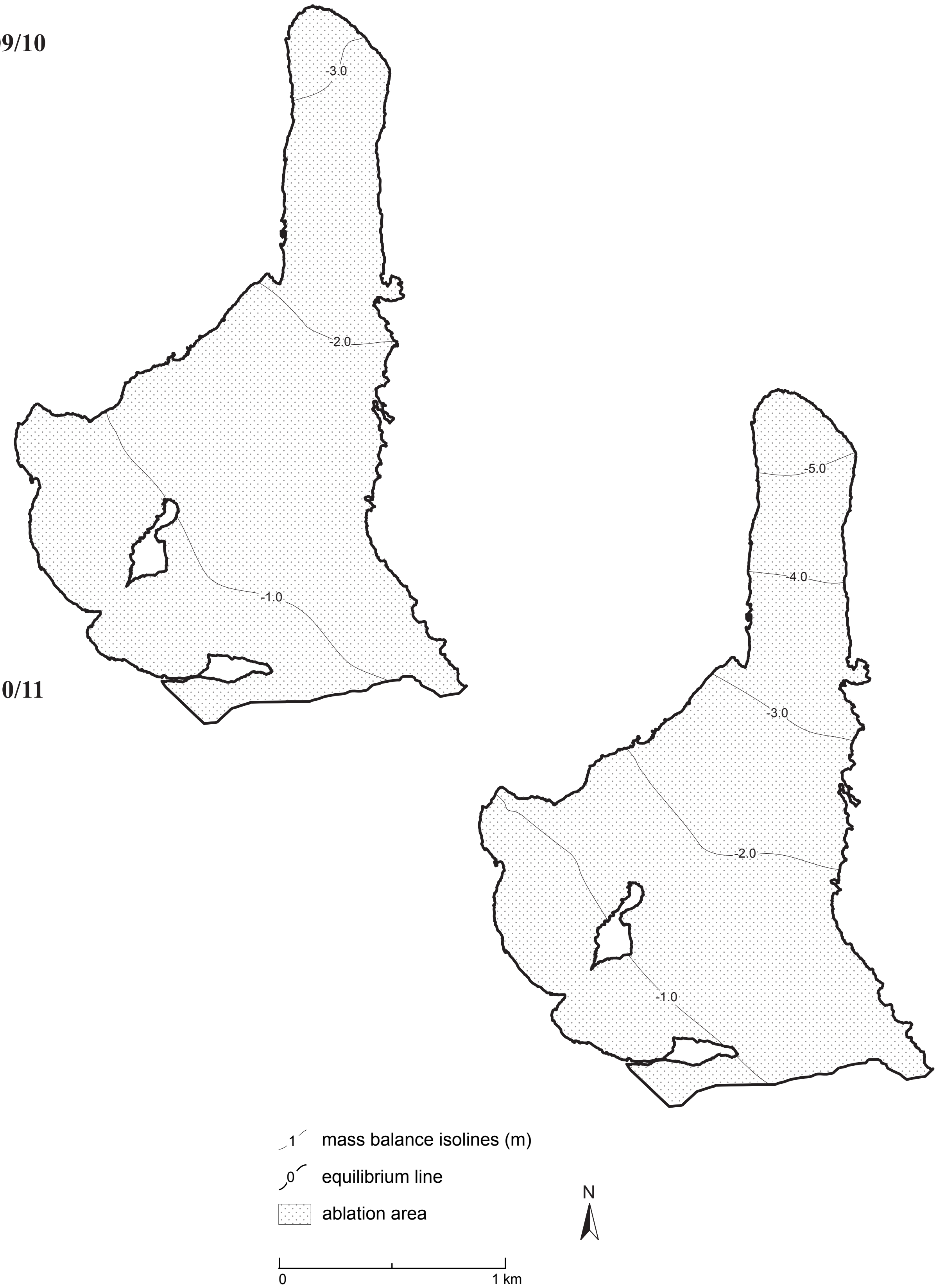


Hellstugubreen (NORWAY)

3.14.2 Mass balance maps 2009/10 and 2010/11

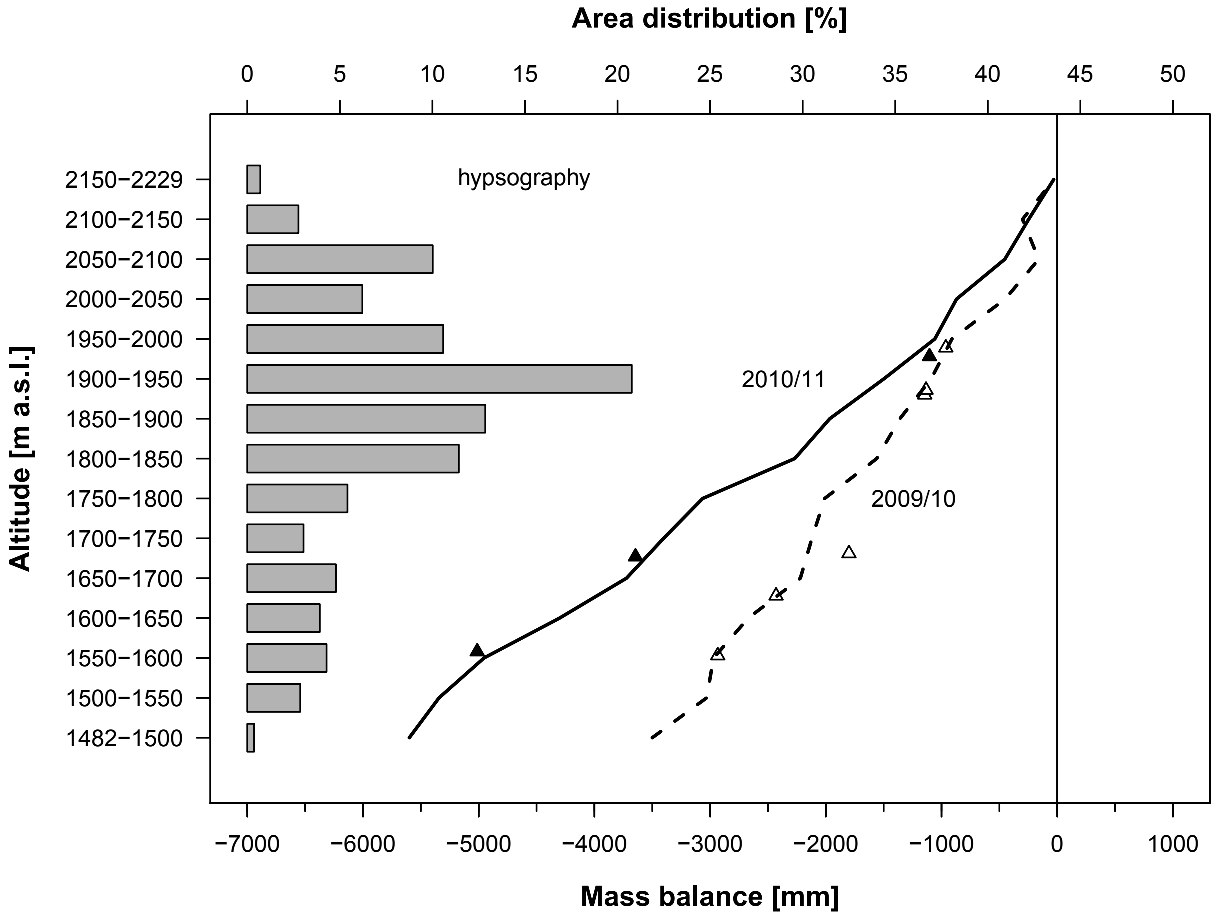
2009/10

2010/11

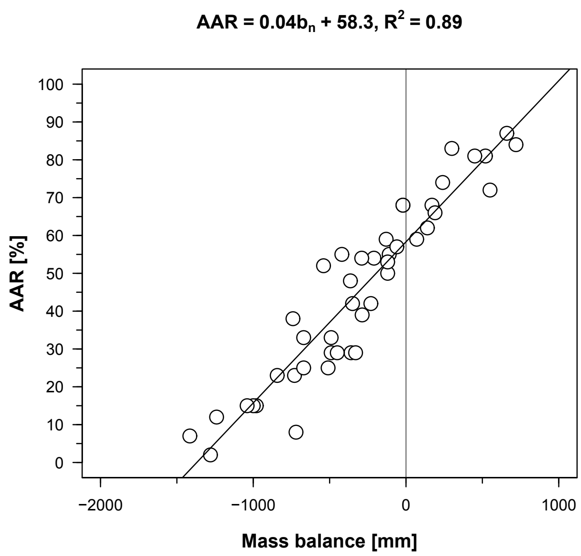


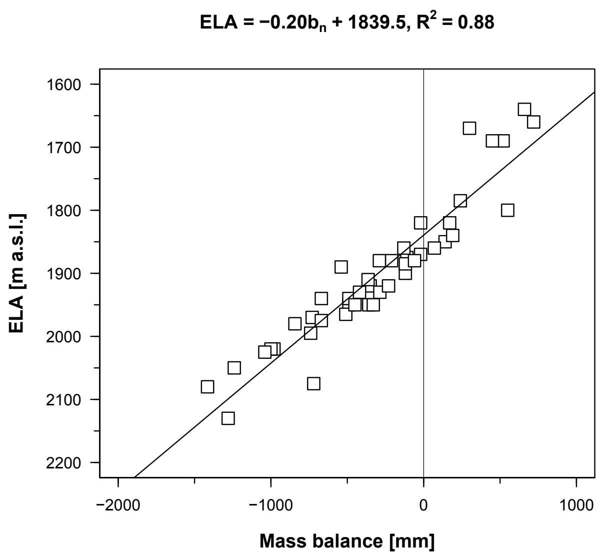
Hellstugubreen (NORWAY)

3.14.3 Mass balance versus altitude (2009/10 and 2010/11)



3.14.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period

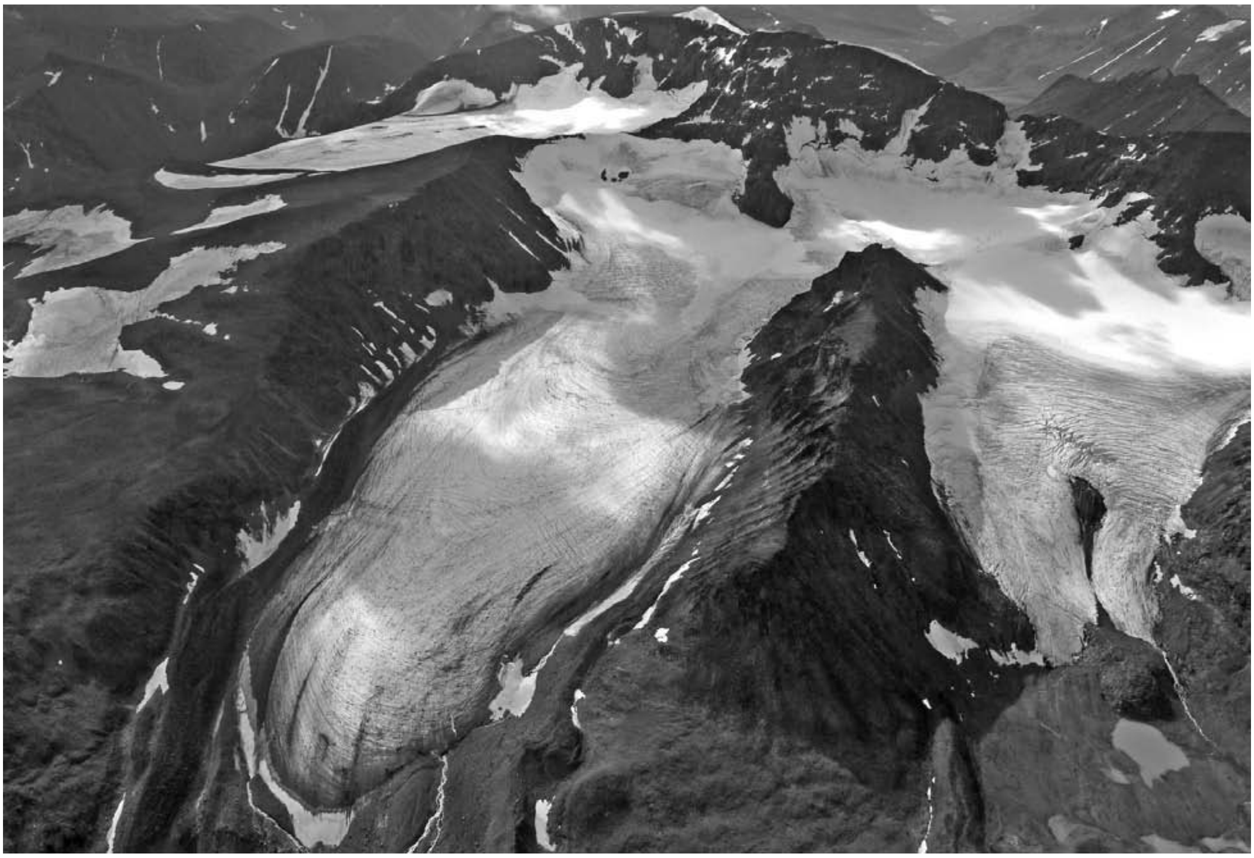




Hellstugubreen (NORWAY)

3.15 STORGLACIÄREN (SWEDEN/NORTHERN SWEDEN)

COORDINATES: 67.90° N / 18.57° E

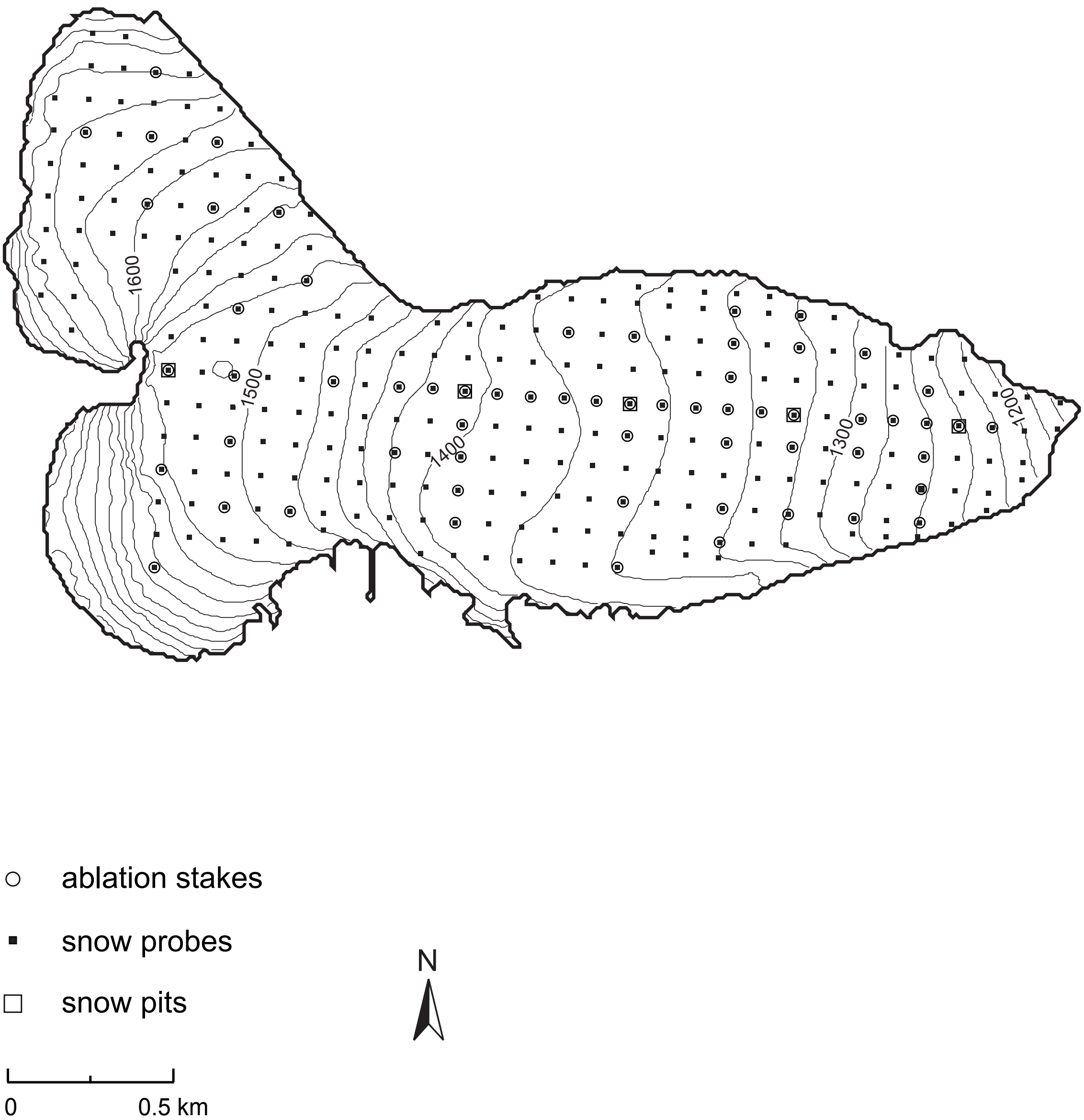


Aerial view of Storglaciären (left) and Isfallsglaciären (right) taken by P. Holmlund, 8 August 2010.

Storglaciären in the Kebnekaise Mountains of northern Sweden is a small valley glacier with a divided accumulation area and a smooth longitudinal profile. It is exposed to the east, maximum and minimum elevations are 1750 m and 1130 m a.s.l., surface area is 3.12 km^2, and average thickness is 95 m (with a maximum thickness of 250 m). Mean annual air temperature at the equilibrium line of the glacier (around 1450 m a.s.l. for balanced conditions) is about −6 °C. Approximately 85 % of the glacier is temperate with a cold surface layer in its lower part (ablation area), and its tongue lying in discontinuous permafrost. Average annual precipitation is about 1000 mm at the nearby Tarfala Research Station.

The mass balance in 2009/10 was negative (−690 mm w.e.) with an ELA at 1570 m a.s.l. and an AAR of 28 %. In 2010/11, the mass balance was also negative (−1060 mm w.e.), which was reflected in the ELA at 1585 m a.s.l. and the AAR of 25 %. Aerial photographs and corresponding glaciological maps are available for the years 1949/59/69/80/90/99. Recently, diapositives of the original photographs were reprocessed using uniform photogrammetric methods. A comparison of the glaciological mass balance with these new volume changes showed that the mean annual differences between glaciological and volumetric mass balance are less than the uncertainty of the in-situ stake reading and, hence, do not require an adjustment of the glaciological data series (cf. T. Koblet et al., Cryosphere 4, 333−343, 2010; M. Zemp et al., Cryosphere 4, 345−357, 2010).

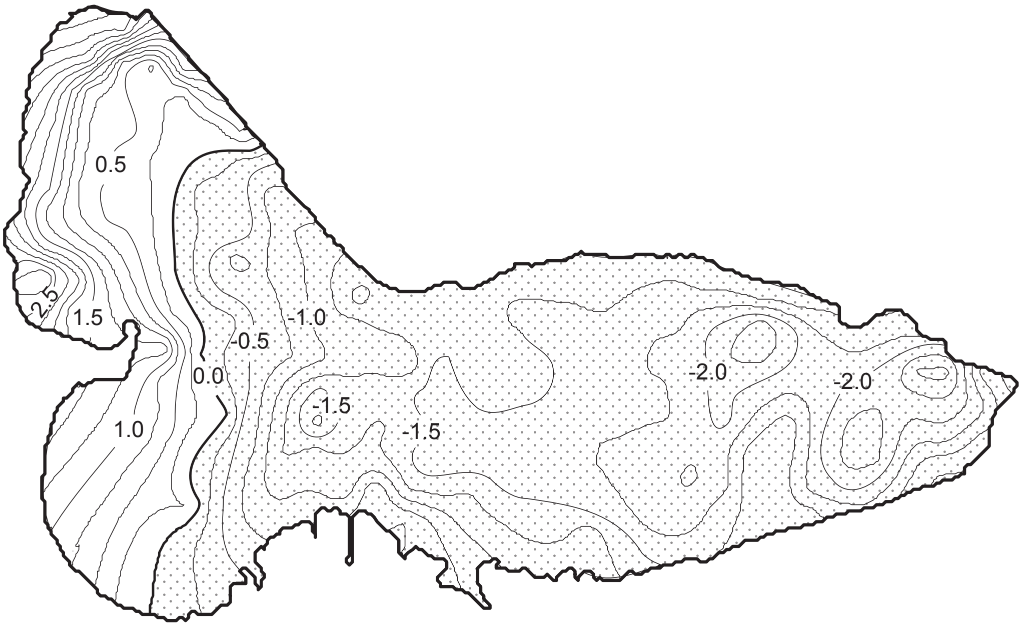
3.15.1 Topography and observation network



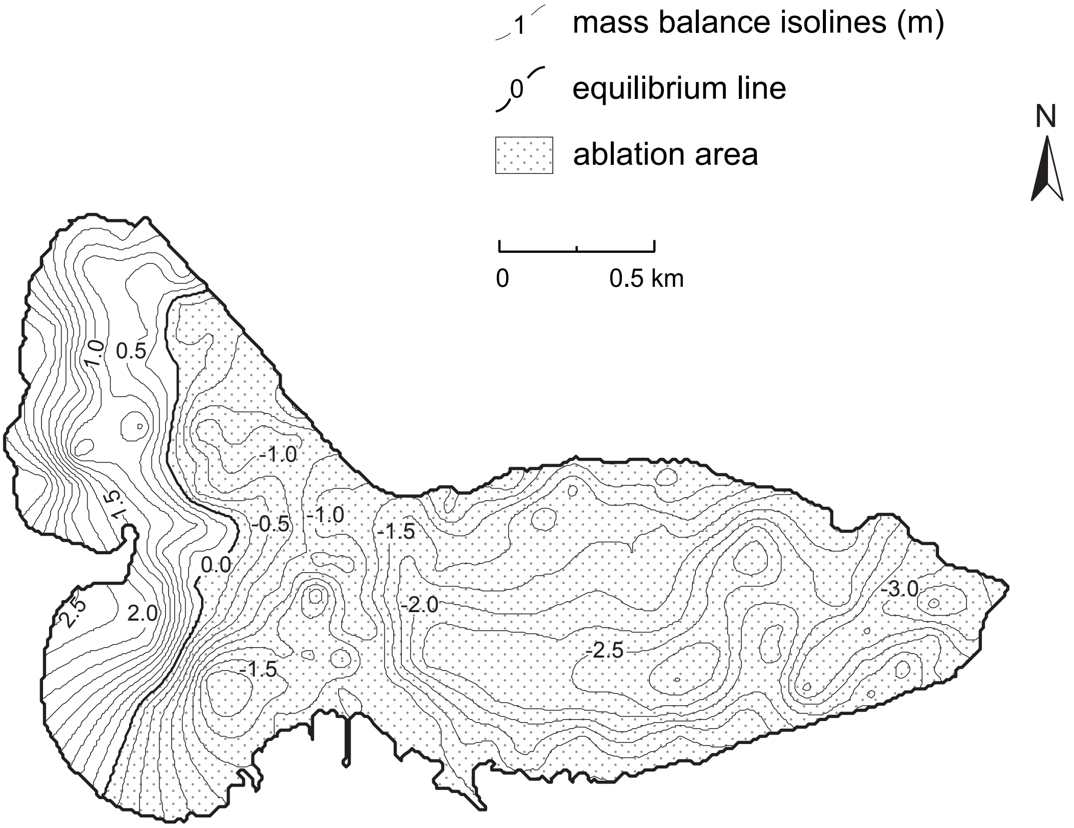
Storglaciären (SWEDEN)

3.15.2 Mass balance maps 2009/10 and 2010/11

2009/10

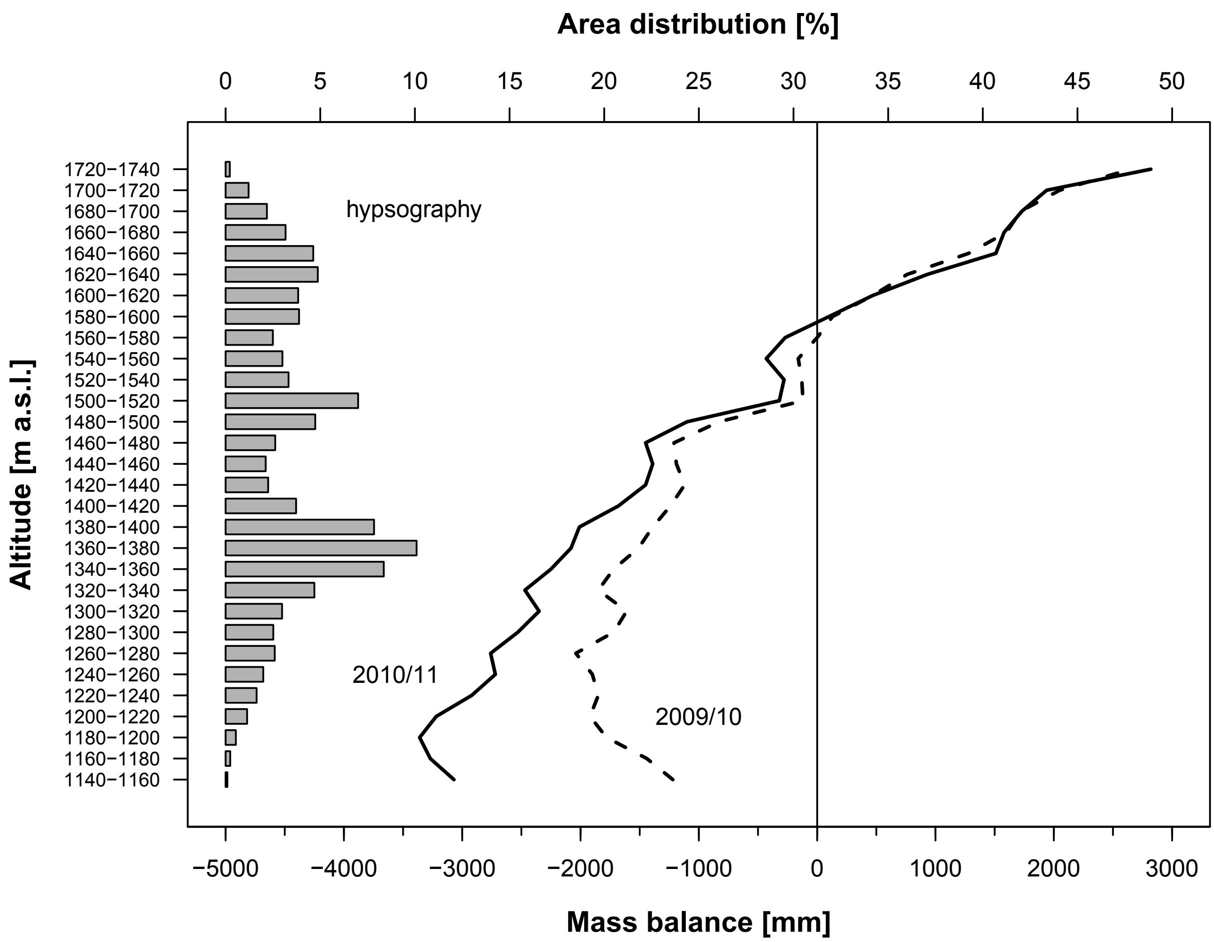


2010/11

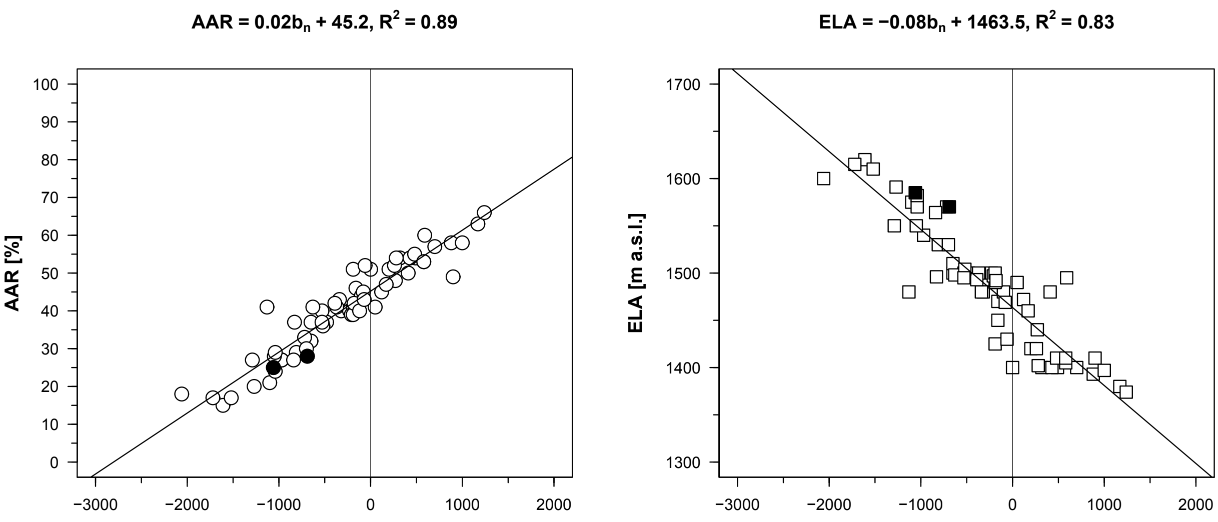


Storglaciären (SWEDEN)

3.15.3 Mass balance versus altitude (2009/10 and 2010/11)



3.15.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period



Storglaciären (SWEDEN)

3.16 GULKANA (USA/ALASKA RANGE)

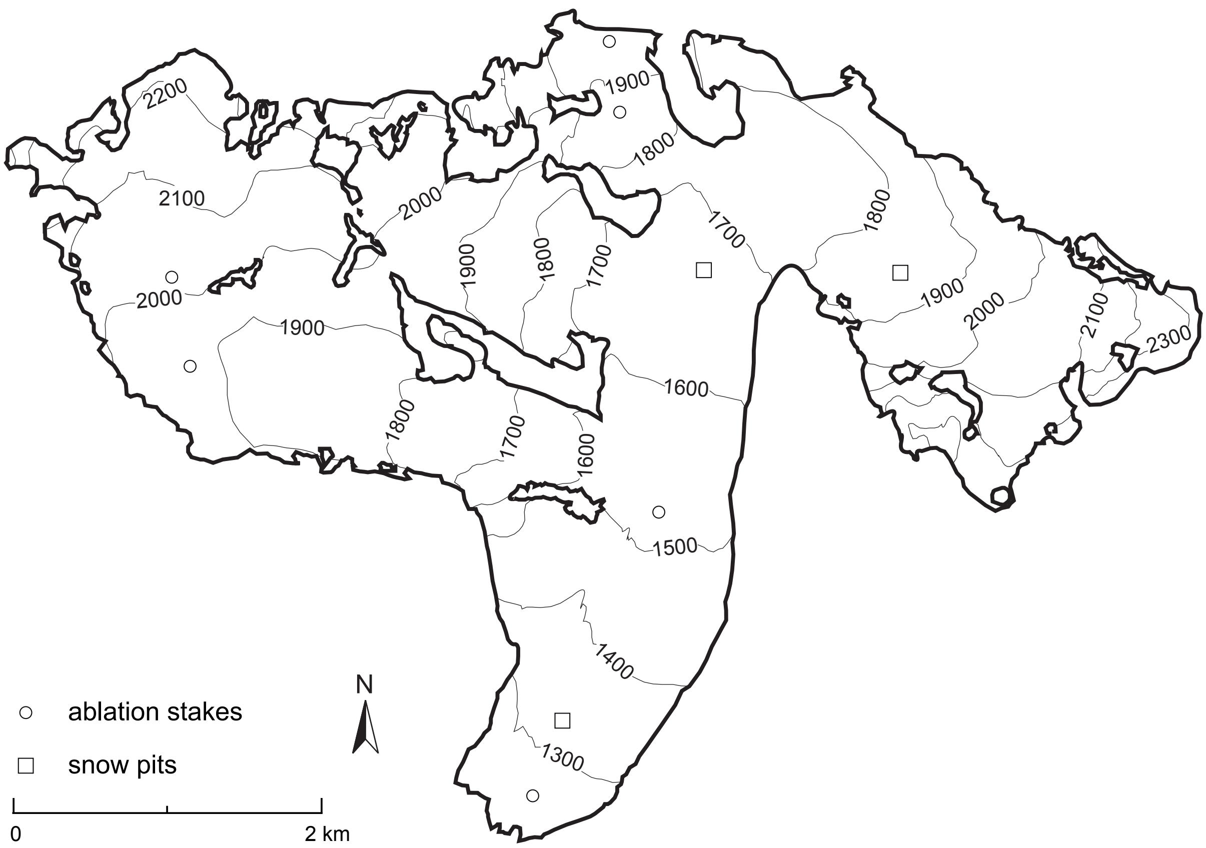
COORDINATES: 63.25° N / 145.42° W

Oblique aerial view looking southwest at Gulkana Glacier on 17 August 2007 derived from vertical photography by Aero-Metric, Inc.

Gulkana Glacier is a 7.5 km long, multi-branched valley glacier located in a continental climate regime on the south flank of the eastern Alaska Range in central Alaska. The accumulation area consists of four adjacent cirques with east, south, and west exposures that reach altitudes as high as 2470 m a.s.l. The ablation area has a south-southwestward orientation with a terminus at about 1160 m a.s.l. The near terminus area is lightly covered with rock debris. The mass balance has been measured seasonally using glaciological methods since 1965/66. Geodetic surveys were made in 1974, 1993, and 2009. Glacier area diminished in size from an estimated 19.59 km^2 in 1965 to measured values of 18.61 km^2, 18.16 km^2, and 16.88 km^2 in 1974, 1993, and 2009, respectively, and to an estimated value of 16.73 km^2 in 2011, for a 13 % loss in area since the start of the mass balance measurements. Ice thickness was about 270 m at 1680 m altitude (a little below the ELA) in the mid-1970s and has thinned by about 20 m to a thickness of 250 m. Ice thickness in the lower ablation zone thinned by almost 65 m over the same period from about 150 m thick to 85 m.

The mean annual air temperature at the long-term ELA of 1770 m a.s.l. is −5.0 °C, as estimated from the Gulkana weather station at 1480 m altitude on a lateral moraine adjacent to the glacier. Annual average precipitation on the glacier is about 1600 mm, as estimated from the same weather station after taking into account an estimated precipitation catch efficiency of 60 %. In 2009/10 the mean air temperature was 1.1 °C above the long-term mean; in 2010/11 it was 0.4 °C below the long-term mean. The specific mass balance was −1630 mm w.e. in 2009/10 and −1290 mm w.e. in 2010/11, compared to the long-term average of −490 mm w.e. These balance deviations from the norm are explained by winter precipitation of about 20 % below normal in both years and by a slightly warmer than normal summer in 2009/10.

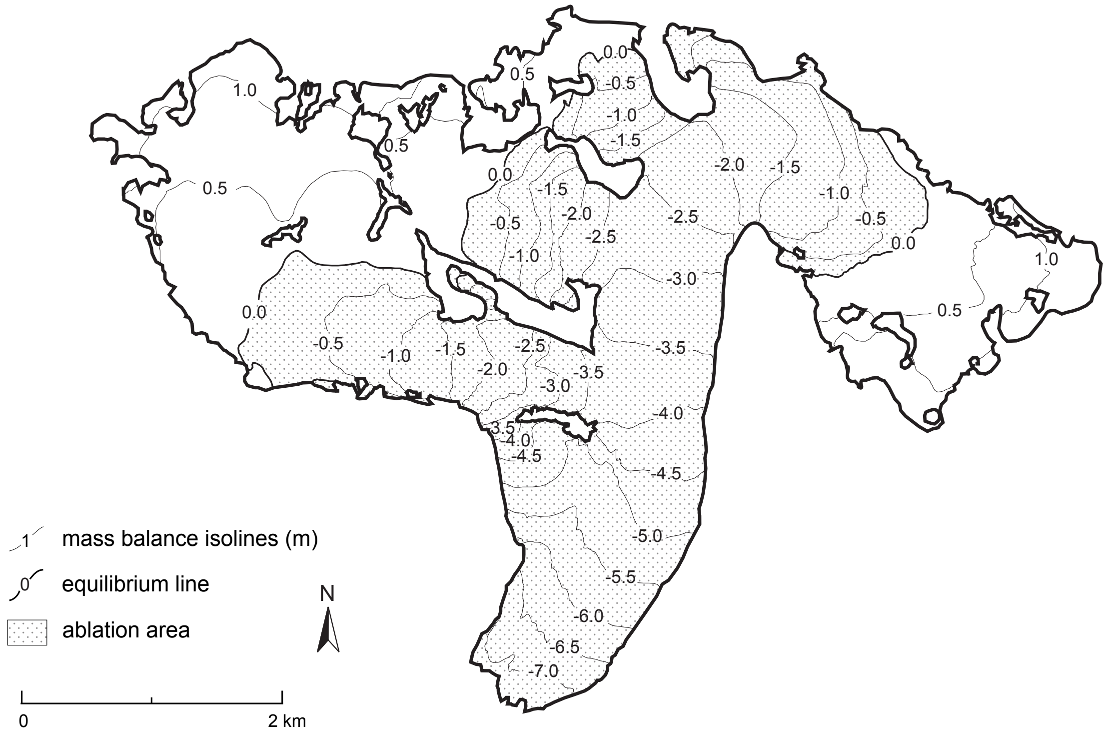
3.16.1 Topography and observation network



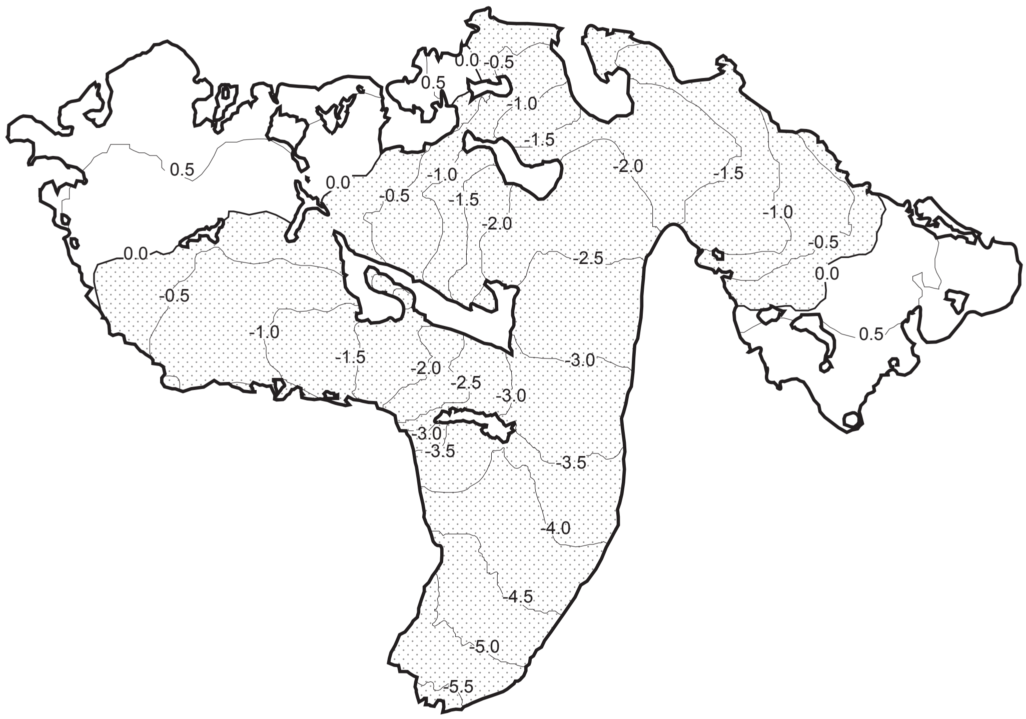
Gulkana (USA)

3.16.2 Mass balance maps 2009/10 and 2010/11

2009/10

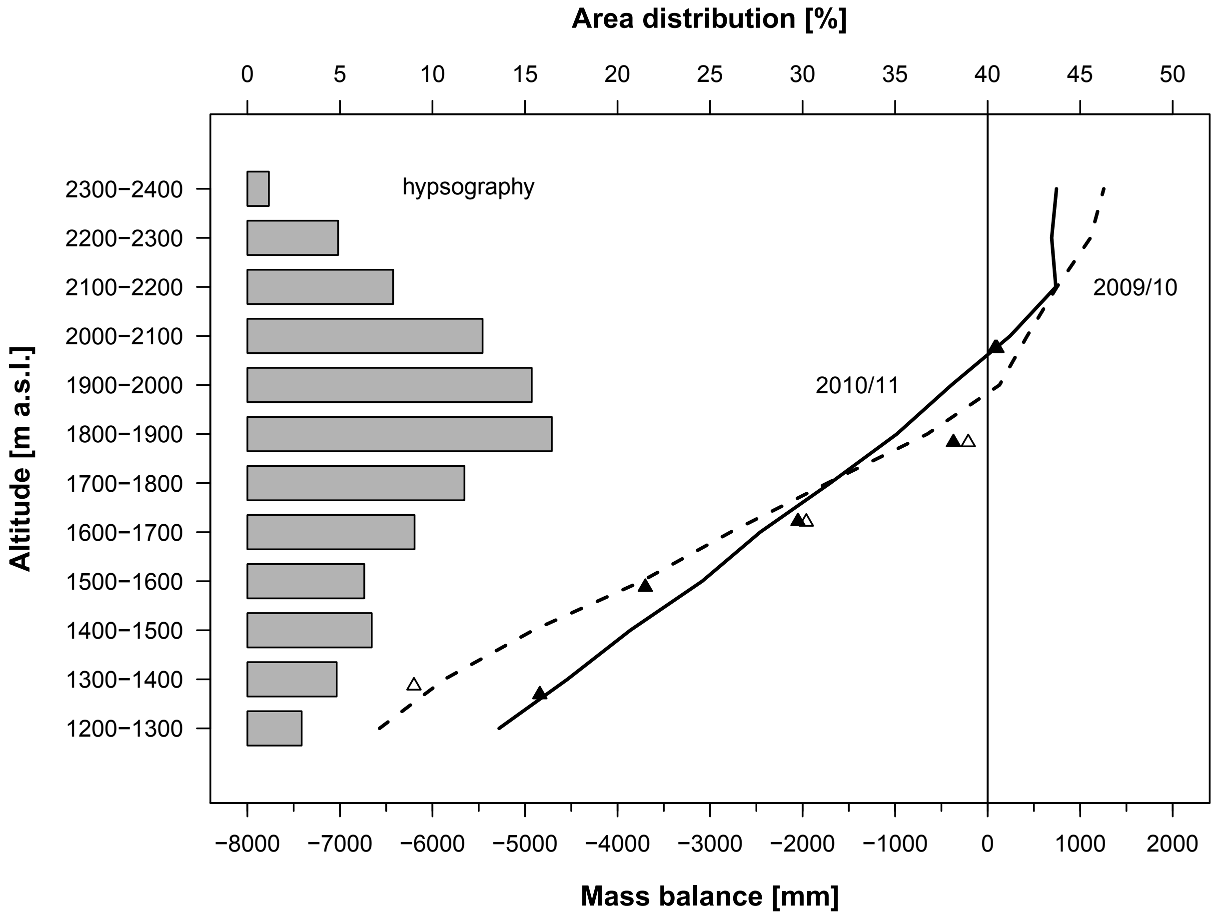


2010/11

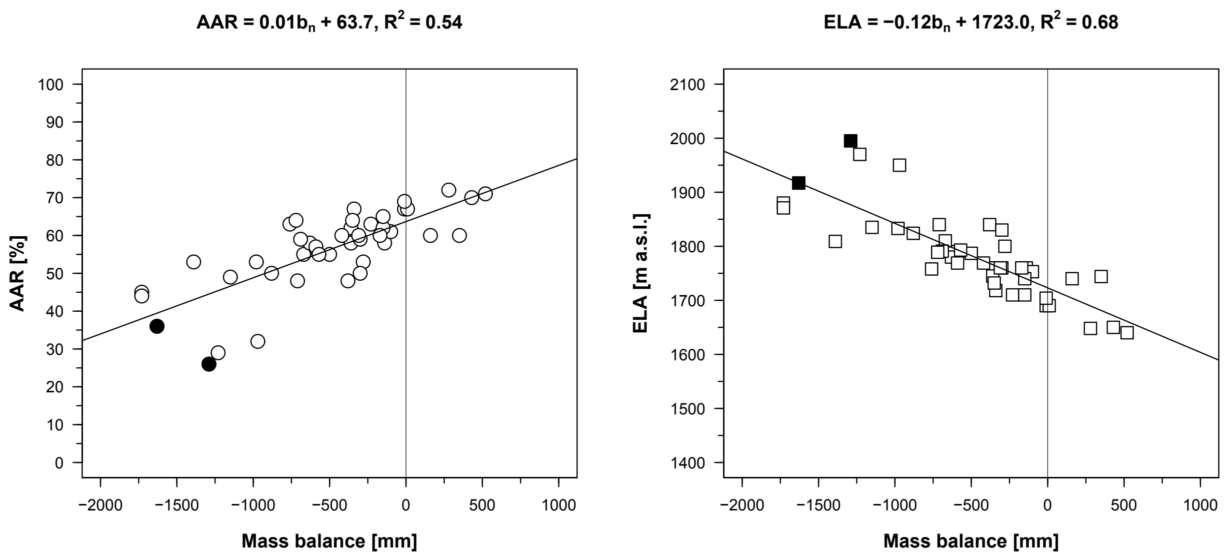


Gulkana (USA)

3.16.3 Mass balance versus altitude (2009/10 and 2010/11)



3.16.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period



Gulkana (USA)

3.17 LEMON CREEK (USA/COAST MOUNTAINS)

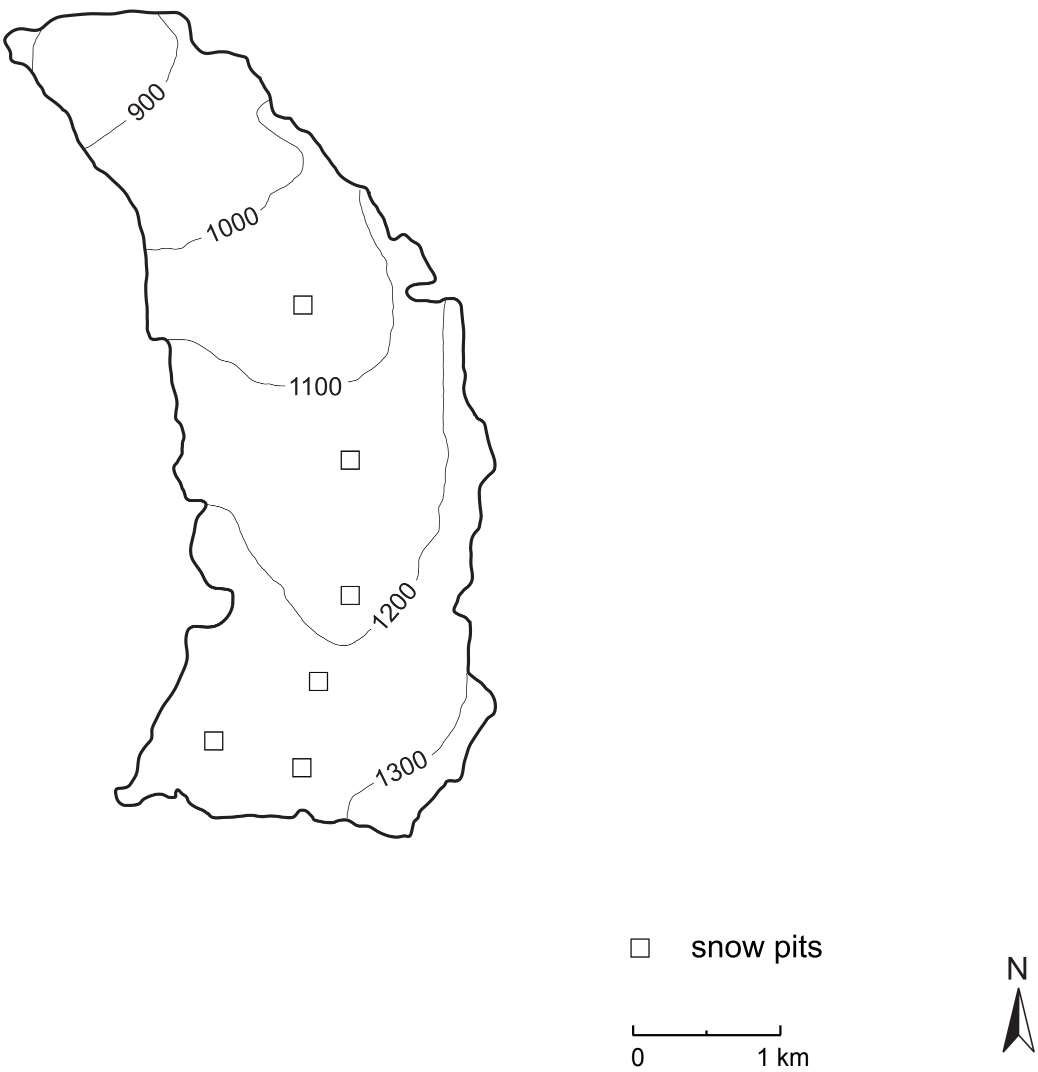
COORDINATES: 58.38° N / 134.36° W

Photo taken L. Bernier, 17 September 2007.

This temperate valley glacier is part of the Juneau Icefield in the Coast Range of southeast Alaska. The equilibrium line is at 1020 m a.s.l. The glacier extends from 1400 to 820 m a.s.l. and has a surface area of 11.6 km^2. The terminus of the glacier is currently steep and continuing a long-term retreat averaging 10–13 m a^{-1} from 1998–2011. Mass balance measurements were initiated on this glacier in 1952/53 and have been conducted continuously since. A combined fixed date/stratigraphic method is employed, and only annual mass balance is determined. Geodetic mapping was completed in 1989 and University of Alaska-Fairbanks laser altimetry surface elevation surveys from 1995, 2000 and 2007 provide validation for the record. The cumulative mass balance record of –12.7 m w.e. (–13.9 m of ice thickness) from 1957–1989 compares well to the thinning identified from geodetic methods of 1957–1989 of –13.2 m w.e. The cumulative mass balance record of –17.1 m w.e. (–19.0 m of ice thickness) from 1957–1995 compares favourably to an observed ice thickness of –16.4 m using laser altimetry compared to USGS maps. Further airborne surface profiling by the University of Alaska-Fairbanks noted an additional –12.9 m surface elevation change 1995–2007, compared to 10.4 m thickness loss from surface mass balance data from 1994–2007. The error in both geodetic programmes is less than 1.5 m.

Accumulation season precipitation October–April was 2270 mm and 2550 mm in 2010 and 2011, respectively, at the Long Lake SNOTEL site 35 km from the glacier, which is close to average. During July and August, the primary ablation period on the Lemon Creek Glacier, temperature at Camp 17 adjacent to the glacier averaged 6.8 °C in 2010 and 6.5 °C in 2011, both above average. The mass balance was negative both years, –580 mm w.e. in 2009/10 with an ELA of 1085 m a.s.l., and –720 mm w.e. with an ELA of 1100 m a.s.l. in 2010/11. Landsat images from 18 September 2010 and 12 September 2011 were used to estimate the ELA from end-of-summer snowlines.

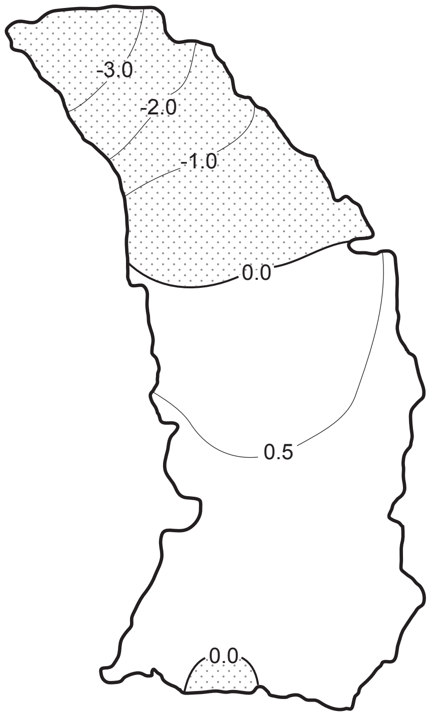
3.17.1 Topography and observation network



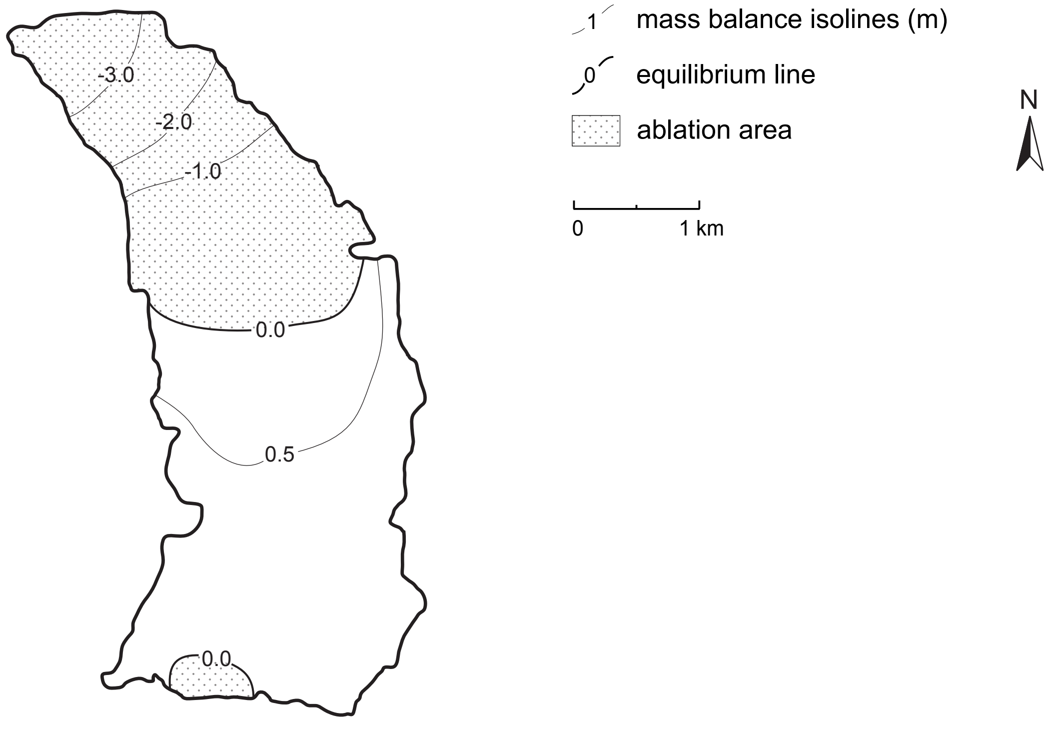
Lemon Creek (USA)

3.17.2 Mass balance maps 2009/10 and 2010/11

2009/10

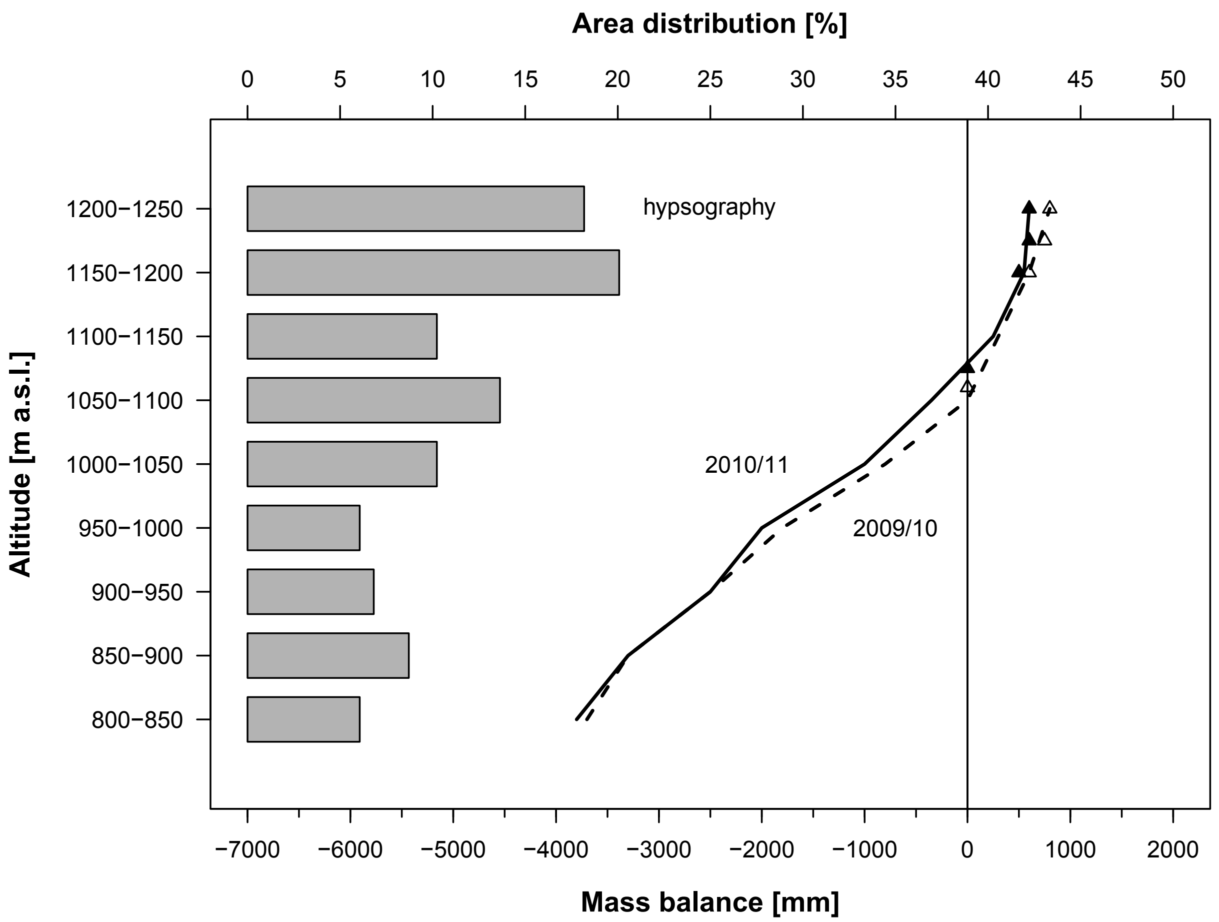


2010/11

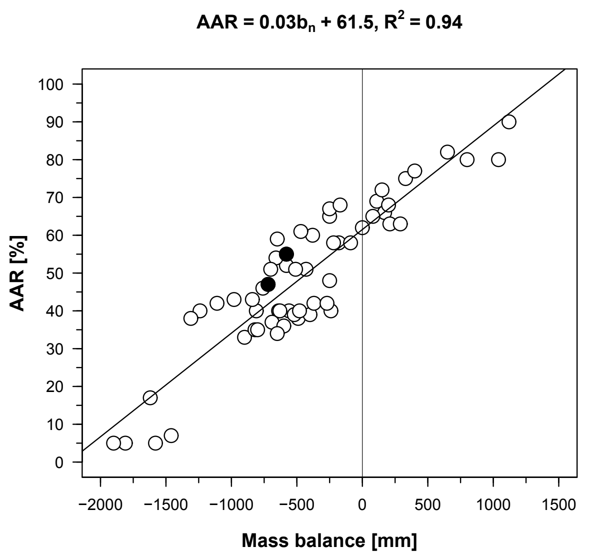


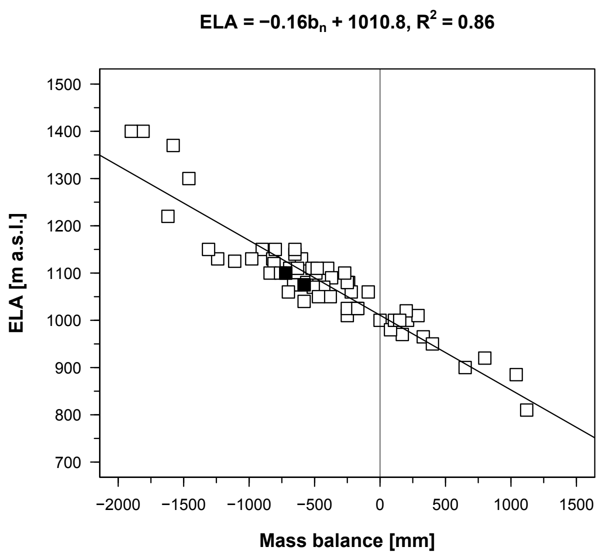
Lemon Creek (USA)

3.17.3 Mass balance versus altitude (2009/10 and 2010/11)



3.17.4 Accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for the whole observation period





Lemon Creek (USA)

4 FINAL REMARKS

Pioneer surveys of accumulation and ablation of snow, firn and ice at isolated points date back to the end of the 19th century and beginning of the 20th century in Switzerland (Mercanton 1916). In the 1920s and 1930s, short-term observations (up to one year) were carried out at various glaciers in Nordic countries. Continuous, modern series of annual/seasonal measurements of glacier-wide mass balance were started in the late 1940s in Sweden, Norway, and in western North America, followed by a growing number of glaciers in the European Alps, North America and other glacierized regions. In the meantime, glacier mass balance measurements have been carried out on more than 300 glaciers worldwide (Dyurgerov 2010, Kaser et al. 2006, Zemp et al. 2009), of which about 260 series are available from the World Glacier Monitoring Service.

Climate (change)-related trend analysis is, in the ideal case, based on long-term measurement series. Continuous glacier mass balance records for the period 1980−2011 are now available for a set of 37 'reference' glaciers in ten mountain ranges (cf. Zemp et al. 2009). These glaciers have well-documented and independently calibrated, long-term mass balance programmes based on the direct glaciological method (cf. Østrem and Brugman 1991) and are not dominated by non-climatic drivers such as calving or surge dynamics. Corresponding results from this sample of glaciers in North and South America and Eurasia are summarized in Table 4.1.

Table 4.1: Summarized mass balance data. A statistical overview of the mass balance results of 34 'reference' glaciers is given for the two recent reporting periods 2010 and 2011 (upper table) in comparison with corresponding values averaged for the decades 1980–1989, 1990–1999 and 2000–2009 (lower table; up to 37 glaciers). All balance values in mm w.e. per year.

	2009/10		2010/11	
mean specific (annual) mass balance	− 782 mm		− 1158 mm	
standard deviation	586 mm		958 mm	
minimum value	− 2110 mm	Echaurren Norte	− 4153 mm	Sarennes
maximum value	+ 80 mm	Place	+ 1210 mm	South Cascade
range	2190 mm		5363 mm	
positive balances	9 %		9 %	
mean AAR	26 %		19 %	

decadal averages of:	1980–1989	1990–1999	2000–2009
mean specific (annual) mass balance	− 223 mm	− 439 mm	− 668 mm
standard deviation	769 mm	885 mm	891 mm
minimum	− 1862 mm	− 2559 mm	− 2760 mm
maximum	+ 1966 mm	+ 1567 mm	+ 1159 mm
range	3828 mm	4126 mm	3919 mm
positive balances	33 %	26 %	20 %
mean AAR	49 %	45 %	38 %

Taking the two years of this reporting period together, the mean mass balance was −970 mm w.e. per year. This is more negative than the mean mass balance for the first decade of the 21st century (2000−2009: −668 mm w.e. per year) and continues the trend to more negative annual balances of the past three decades. Since the turn of the century, the maximum loss of the 1980−1999 time period (−824 mm w.e. per year in 1998) has been exceeded four times (in 2003, 2006, 2010, and 2011), the percentage of positive glacier mass balances decreased from 33 % in the 1980s to below 20 %, and there have been no more years with a positive mean balance for almost three decades. The melt rate and cumulative loss in glacier thickness continues to be extraordinary. Furthermore, the analyses of mean AAR values show that the glaciers are in strong and increasing imbalance with the climate and, hence, will continue to lose mass even without further warming (e.g., Mernild et al. 2013).

The mean of the 37 glaciers included in the analysis is influenced by the large proportion of Alpine and Scandinavian glaciers. A mean value is therefore also calculated using only one single value (averaged) for each of the ten mountain ranges concerned (Table 4.2). Furthermore, a mean was calculated for all mass balances available, independent of record length. Figure 4.1 shows the number of reported observation series as well as annual and cumulative results for all three means. In their general trend and magnitude, all three averages rather closely relate to each other and are in good agreement with the results from a moving-sample averaging of all available data (cf. Kaser et al. 2006, Zemp et al. 2009). The global average cumulative mass balance indicates a strong mass loss in the first decade after the start of measurements in 1946 (though based on few observation series only), slowing down in the second decade (1956–1965; based on observations above

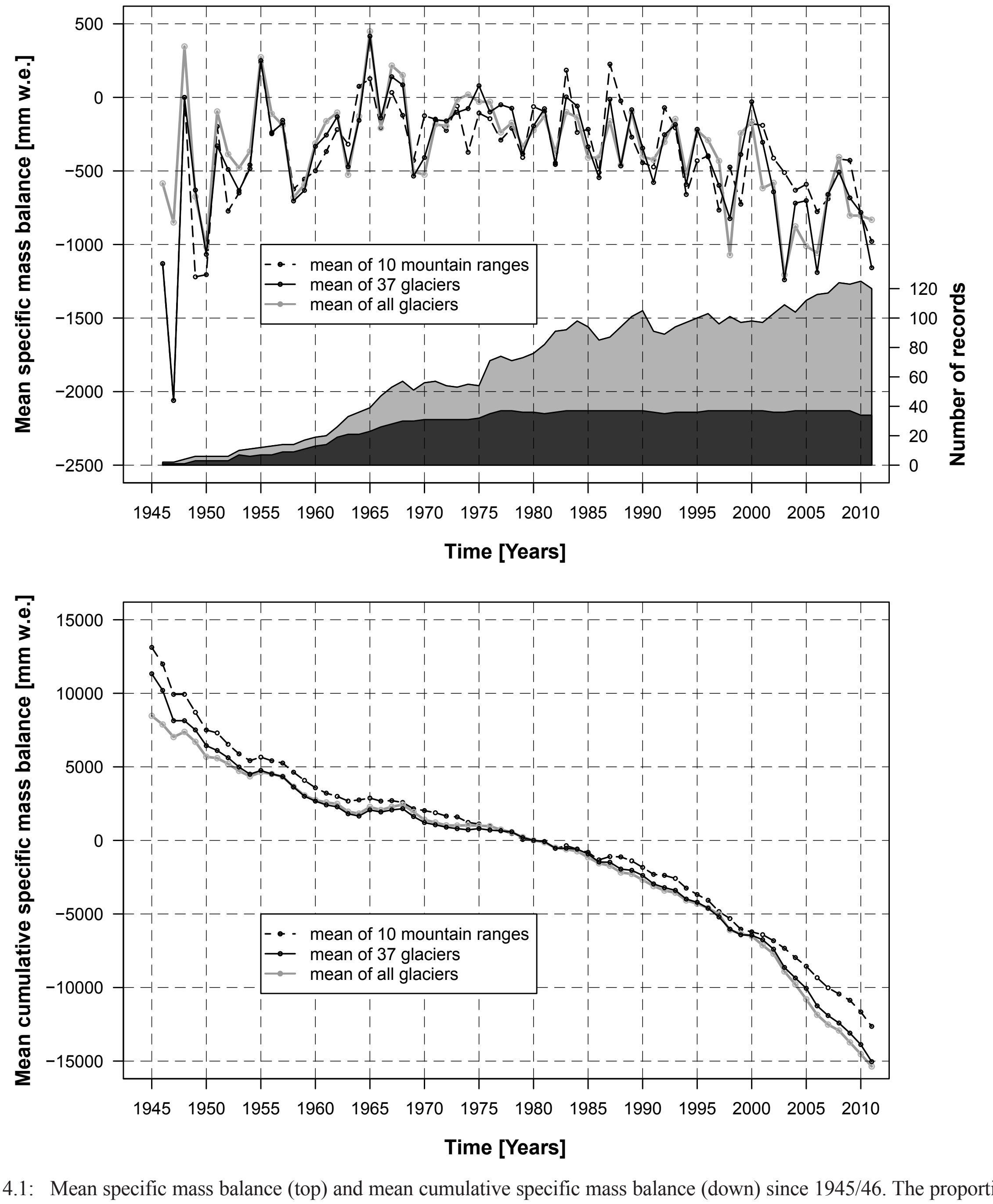


Figure 4.1: Mean specific mass balance (top) and mean cumulative specific mass balance (down) since 1945/46. The proportion of the 37 'reference' glaciers is also given (top; number of 'reference' glaciers in dark grey).

Table 4.2: Mass balance data for 37 glaciers in 10 mountain regions 1980–2011.

Year	Alaska	Pacific Coast Ranges	Andes	Canadian High Arctic	Svalbard	Scandinavia	Alps	Caucasus	Altai	Tien Shan	Mean
1980	+1105	−747	+300	−31	−475	−1055	+441	+380	−10	−482	−57
1981	+1575	−968	+360	−158	−505	+195	−43	−910	−213	−271	−94
1982	−235	−401	−2420	+32	−10	−185	−841	+420	−460	−338	−444
1983	−200	−686	+3700	−76	−220	+756	−434	−970	+197	−220	+185
1984	−335	−273	−1240	+48	−705	+194	+111	+210	+307	−666	−235
1985	+620	−1058	+340	−50	−515	−436	−312	−380	+200	−581	−217
1986	−45	−847	−1700	+58	−265	−249	−1031	−500	+73	−594	−510
1987	+590	−1031	+950	−251	+230	+925	−614	+1540	+183	−258	+226
1988	+355	−668	+2300	−126	−505	−1216	−604	+520	+333	−626	−24
1989	−1055	−1090	−1260	+83	−345	+1878	−889	+40	+117	−177	−270
1990	−1400	−938	−1300	−275	−585	+1195	−1128	+340	+107	−454	−444
1991	−5	−951	−860	−210	+115	+80	−1209	−310	−480	−903	−473
1992	−250	−1564	+1740	−63	−120	+1161	−1198	−130	−127	−108	−66
1993	−1215	−1609	−290	−377	−955	+1174	−517	+1100	+227	+286	−218
1994	−715	−1510	−1860	−182	−140	+172	−886	−840	−240	−410	−661
1995	−1360	−1250	−950	−150	−785	+589	+6	+40	+60	−408	−421
1996	−900	−272	−1180	+49	−75	−642	−448	−150	−140	−207	−397
1997	−1760	−792	−2530	−43	−570	−524	−423	+270	−123	−1160	−766
1998	+55	−2166	+2400	−202	−725	+221	−1640	−1000	−1110	−574	−474
1999	−915	+604	−4280	−354	−350	−122	−661	−560	−113	−510	−726
2000	+330	+416	−750	−404	−25	+988	−748	−1140	−230	−222	−179
2001	−180	−690	+1790	−233	−404	−787	+113	−620	−190	−698	−190
2002	−760	−81	−220	+30	−547	−1141	−916	+430	−357	−568	−413
2003	−320	−1591	+1900	−258	−841	−1392	−2510	+280	−363	−12	−511
2004	−2355	−1411	−550	+121	−1058	−161	−1066	+730	−210	−346	−631
2005	−1245	−1558	−780	−418	−860	+309	−1422	+390	+87	−414	−591
2006	−585	−1612	+480	−114	−606	−2025	−1441	−800	−197	−872	−777
2007	−1085	−456	−130	−543	−354	+405	−1627	−2010	−313	−778	−689
2008	+350	−502	−540	−700	−68	+408	−1286	+100	−800	−1144	−418
2009	−1250	−1118	+80	−593	−195	−132	−1561	−120	+480	+134	−428
2010	−800	−368	−2110	−331	−320	−1188	−800	−600	—	−648	−796
2011	−1250	+180	−1270	−992	−962	−1209	−2001	−680	—	−629	−979
Mean	−476	−844	−309	−210	−430	−57	−862	−154	−110	−464	−397

Alaska	Gulkana, Wolverine
Pacific Coast Ranges	Place, South Cascade, Helm, Lemon Creek, Peyto
Andes	Echaurren Norte
Canadian High Arctic	Devon Ice Cap NW, Meighen Ice Cap, White
Svalbard	Austre Brøggerbreen, Midtre Lovénbreen
Scandinavia	Engabreen, Ålfotbreen, Nigardsbreen, Gråsubreen, Storbreen, Hellstugubreen, Rembesdalsskåka, Storglaciären
Alps	Saint Sorlin, Sarennes, Argentière, Silvretta, Gries, Stubacher Sonnblickkees, Vernagtferner, Kesselwandferner, Hintereisferner, Caresèr
Caucasus	Djankuat
Altai	Vodopadniy (No. 125), Maliy Aktru, Leviy Aktru
Tien Shan	Ts. Tuyuksuyskiy, Urumqi Glacier No. 1

30° N only), followed by a moderate ice loss between 1966 and 1985 (with data from the Southern Hemisphere only since 1976) and a subsequent acceleration of mass loss until the present (2009).

With their dynamic response to changes in climatic conditions – growth/reduction in area mainly through the advance/retreat of glacier tongues – glaciers readjust their extent to equilibrium conditions of ice geometry with a zero mass balance. Recorded mass balances document the degree of imbalance between glaciers and climate due to the delay in dynamic response caused by the characteristics of ice flow (deformation and sliding); over longer time intervals they depend on the rate of climatic forcing. With constant climatic conditions (no forcing), balances would tend towards and finally become zero. Long-term non-zero balances are, therefore, an expression of ongoing climate change and sustained forcing. Trends towards increasing non-zero balances are caused by accelerated forcing. In the same way, comparison between present-day and past values of mass balance must take the changes of glacier area into account, which have occurred in the meantime (Elsberg et al. 2001). Many of the relatively small glaciers, measured within the framework of the present mass balance observation network, have lost large percentages of their area during the past decades. The recent increase in the rates of ice loss over diminishing glacier surface areas, as compared with earlier losses related to larger surface areas, becomes even more pronounced and leaves no doubt about the accelerating change in climatic conditions, even if a part of the observed acceleration trend is likely to be caused by positive feedback processes.

Further analysis requires detailed consideration of aspects such as glacier sensitivity and the mentioned feedback mechanisms. The balance values and curves of cumulative mass balances reported for the individual glaciers (Chapter 2) not only reflect regional climatic variability but also mark differences in the sensitivity of the observed glaciers. This sensitivity has a (local) topographic component: the hypsographic distribution of glacier area with altitude and a (regional) climatic component: the change in mass balance with altitude or the mass balance gradient. The latter component tends to increase with rising humidity and leads to stronger and often faster reactions by maritime rather than by more continental glaciers. For the same reason, the mean balance values calculated above are predominantly influenced by maritime glaciers rather than by continental ones. Maritime glaciers are those found in the coastal mountains of Norway or USA/Alaska, where effects from changes in precipitation may predominate over the influence of atmospheric warming. The modern tool of differencing repeat digital elevation models (DEMs) provides excellent possibilities for assessing how representative long time series of local mass balance measurements are with respect to large glacier samples (Paul and Haeberli 2008) and to analyze spatial patterns of glacier thickness/volume changes in entire mountain ranges: DEM differencing, for instance, revealed that average thickness losses in southern Alaska (Larsen et al. 2007) are far higher than the averages reported here from in-situ observations on various continents.

Rising snowlines and cumulative mass losses lead to changes in the average albedo and to a continued surface lowering. Such effects cause pronounced positive feedbacks with respect to radiative and sensible heat fluxes. Albedo changes are especially effective in enhancing melt rates and can also be caused by input of dust (Oerlemans et al. 2009). The cumulative length change of glaciers is the result of all effects combined, and constitutes the key to a global intercomparison of decadal to secular mass losses. Surface lowering, thickness loss and the resulting reduction in driving stress and flow, however, increasingly replace processes of tongue retreat with processes of downwasting, disintegration or even collapse of entire glaciers. Moreover, the thickness of most glaciers regularly observed for their mass balance is measured in (a few) tens of metres. From the measured mass losses and thickness reductions, it is evident that several network glaciers with important long-term observations may not survive for many more decades. A special challenge therefore consists in developing a strategy for ensuring the continuity of adequate mass balance observations under such extreme conditions (Zemp et al. 2009). As an example, new mass balance measurements were initiated on the still quite large Findelen Glacier (Swiss Alps), which is likely to continue existing for several decades into the future.

Key tasks for the future of glacier mass balance monitoring include the continuation of (long-term) measurement series, the extension of the presently available dataset, especially in under-represented regions, the quantitative assessment of uncertainties relating to available measurements (cf. Zemp et al. 2013), and their representativeness for changes in corresponding mountain ranges. The latter requires a well-considered integration of in-situ measurements, remotely sensed observations (e.g., Gardner et al. 2013), and numerical modelling (e.g., Huss 2012) taking into account the related spatial and temporal scales.

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