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)

and the International Hydrological Programme (IHP, UNESCO)

Compiled by

the World Glacier Monitoring Service (WGMS)

ICSU (WDS) – IUGG (IACS) – UNEP – UNESCO – WMO

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Edited by

Michael Zemp, Samuel U. Nussbaumer, Kathrin Naegeli, Isabelle Gärtnер-Roer,
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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, therefore, 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 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 firm 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 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, 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 ICSU/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 1985–1990 (Vol. 6, W. Haeberli and M. Hoelzle)
- World Glacier Inventory – Status 1988 (W. Haeberli, H. Bösch, K. Scherler, G. Østrem and C. C. Wallén)
TABLE OF CONTENTS

1 INTRODUCTION 1
  1.1 GENERAL INFORMATION ON THE OBSERVED GLACIERS 1
  1.2 GLOBAL OVERVIEW MAP 5

2 BASIC INFORMATION 6
  2.1 SUMMARY TABLE (MASS BALANCE, ELA, ELA<sub>o</sub>, AAR, AAR<sub>o</sub>) 6
  2.2 CUMULATIVE SPECIFIC MASS BALANCE GRAPHS 10

3 DETAILED INFORMATION 16
  3.1 BAHÍA DEL DIABLO (ANTARCTICA/ANTARCTIC PENINSULA) 17
  3.2 MARTIAL ESTE (ARGENTINA/ANDES FUEGUINOS) 21
  3.3 HINTEREISFERNER (AUSTRIA/EASTERN ALPS) 25
  3.4 ZONGO (BOLIVIA/TROPICAL ANDES) 29
  3.5 WHITE (CANADA/HIGH ARCTIC) 33
  3.6 URUMQI GLACIER NO. 1 (CHINA/TIEN SHAN) 38
  3.7 CONEJERAS (COLOMBIA/CORDILLERA CENTRAL) 42
  3.8 FREYA (GREENLAND/NORTHEAST GREENLAND) 46
  3.9 MITTVAKKAT (GREENLAND/SOUTHEAST GREENLAND) 50
  3.10 CARESÈR (ITALY/CENTRAL ALPS) 54
  3.11 TSENTRALNIY TUYUKSUYSKIY (KAZAKHSTAN/TIEN SHAN) 58
  3.12 GOLUBIN (KYRGYZSTAN/TIEN SHAN) 63
  3.13 WALDEMARBREEN (NORWAY/SPITSBERGEN) 67
  3.14 HELLSTUGUBREEN (NORWAY/WESTERN NORWAY) 71
  3.15 STORGLACIÄREN (SWEDEN/NORTHERN SWEDEN) 75
  3.16 GULKANA (USA/ALASKA RANGE) 79
  3.17 LEMON CREEK (USA/COAST MOUNTAINS) 83

4 FINAL REMARKS 87

5 ACKNOWLEDGEMENTS AND REFERENCES 91

6 PRINCIPAL INVESTIGATORS AND NATIONAL CORRESPONDENTS 92
  6.1 PRINCIPAL INVESTIGATORS 92
  6.2 NATIONAL CORRESPONDENTS OF WGMS 102
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.

<table>
<thead>
<tr>
<th>No.</th>
<th>Glacier name 1)</th>
<th>1st/last survey 2)</th>
<th>Country</th>
<th>Location</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bahía del Diablo</td>
<td>2000/2011</td>
<td>Antarctica</td>
<td>Antarctic Peninsula</td>
<td>63.82° S 57.43° W</td>
</tr>
<tr>
<td>2</td>
<td>Hudson</td>
<td>2002/2011</td>
<td>Antarctica</td>
<td>Antarctic Peninsula</td>
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</tr>
<tr>
<td>3</td>
<td>Johnsons</td>
<td>2002/2011</td>
<td>Antarctica</td>
<td>Antarctic Peninsula</td>
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<tr>
<td>4</td>
<td>Brown Superior</td>
<td>2010/2011</td>
<td>Argentina</td>
<td>Andes Centrales</td>
<td>29.98° S 69.64° W</td>
</tr>
<tr>
<td>5</td>
<td>Concon Norte</td>
<td>2010/2011</td>
<td>Argentina</td>
<td>Andes Centrales</td>
<td>29.98° S 69.64° W</td>
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<td>6</td>
<td>Los Amarillos</td>
<td>2010/2011</td>
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<td>Andes Centrales</td>
<td>29.30° S 69.99° W</td>
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<td>7</td>
<td>Piloto Este</td>
<td>2001/2011</td>
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<td>Andes Fueguinos</td>
<td>54.78° S 68.40° W</td>
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<td>Filleckkees</td>
<td>1964/1980</td>
<td>Austria</td>
<td>Eastern Alps</td>
<td>47.13° N 12.60° E</td>
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<td>10</td>
<td>Goldbergkees</td>
<td>1989/2011</td>
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<td>11</td>
<td>Hintereisferner</td>
<td>1953/2011</td>
<td>Austria</td>
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<td>13</td>
<td>Kesselwandferner</td>
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<td>14</td>
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<td>42</td>
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<td>52</td>
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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 Carsèr split into three parts: Carsèr occidentale, Carsèr orientale (2005) and Carsèr centrale (2009).
⁶ Perennial snowfield or glacieret.
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 ELAs and AARs 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 AARs and ELAs 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, ELA0, AAR, AAR0)

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<th>b11 [mm w.e.]</th>
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<th>ELA11 [m a.s.l.]</th>
<th>ELA0 [m a.s.l.]</th>
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2 Basic Information

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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.

* Mass balance is determined by correlating observed ELA/AAR and mass balance using direct mass balance series from 1963/64 to 1979/80.
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 AAR0 and ELA0 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 km², 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 °C, 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 °C. 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

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 km². The Martial Este Glacier has a surface area of 0.1 km² 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 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)

![Area distribution graph]

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

![Graphs of AAR and ELA]

Martial Este (ARGENTINA)
3.3 HINTEREISFERNER (AUSTRIA/EASTERN ALPS)

COORDINATES: 46.80° N / 10.77° E

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 Langtaufenerjochferner in 2000. The glacier area decreased from 10.24 km² in 1953 to 6.88 km² 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 firm 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. Gletscherkd. 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 lasercan DEM of October 2001. In addition to the annual geodetic surveys carried out by H. Schneider, several airborne lasercan 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

![Graph showing mass balance versus altitude with area distribution and hypsography]

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

\[ \text{AAR} = 0.03b_n + 66.0, \ R^2 = 0.92 \]

\[ \text{ELA} = -0.23b_n + 2921.0, \ R^2 = 0.91 \]

**Hintereisferner (AUSTRIA)**
3.4 ZONGO (BOLIVIA/TROPICAL ANDES)

COORDINATES: 16.25° S / 68.17° W

The Zongo Glacier is a temperate glacier covering an area of 1.9 km² (in 2011) over a catchment area of 3.3 km². 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
3.4.3 Mass balance versus altitude (2009/10 and 2010/11)

![Graph showing mass balance versus altitude with data for 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

![Graphs showing AAR and ELA calculations with regression lines.]

Zongo (BOLIVIA)
3.5 WHITE (CANADA/HIGH ARCTIC)

COORDINATES:  79.45° N / 90.67° W


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 km², having shrunk by gradual retreat of its terminus from an extent of 40.2 km² 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 km²), 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
3.5.2 Mass balance maps 2009/10 and 2010/11

2009/10

White (CANADA)

2010/11

White (CANADA)

mass balance isolines (m)
equilibrium line
ablation area

0 2 km
3 Detailed Information

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

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 km², 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 km², 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 ELAo 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

Santa Isabel is a small ice cap (1.8 km²) 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 km²) 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
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)

![Graph showing mass balance versus altitude for Conejeras (COLOMBIA).](image)

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

![Graph showing AAR and ELA versus mass balance.](image)

Conejeras (COLOMBIA)
3.8 FREYA (GREENLAND/NORTHEAST GREENLAND)

COORDINATES: 74.38° N / 20.82° W

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 km² (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)

![Area distribution graph showing mass balance versus altitude for Freya (GREENLAND)]

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

![Graphs showing accumulation area ratio (AAR) and equilibrium line altitude (ELA) versus specific mass balance for Freya (GREENLAND)]
3.9 MITTIVAKKAT (GREENLAND/SOUTHEAST GREENLAND)

COORDINATES: 65.67° N / 37.83° W

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)

![Graph showing mass balance versus altitude]

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

![Graph showing accumulation area ratio (AAR) versus specific mass balance]

Mittivakkat (GREENLAND)
3.10 CARESÈR (ITALY/CENTRAL ALPS)

COORDINATES: 46.45° N / 10.70° E

Caresèr Glacier is located in the Ortles-Cevedale group (Eastern European Alps, Italy). It occupies an area of 1.9 km² 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 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
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
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 km² (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
3.11.2 Mass balance maps 2009/10 and 2010/11

2009/10

Tsentralniy Tuyuksuyskiy (KAZAKHSTAN)
2010/11

mass balance isolines (m)
equilibrium line
ablation area

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

![Graph showing mass balance versus altitude for the whole observation period]

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

\[
\text{AAR} = 0.03b_n + 52.3, \quad R^2 = 0.83
\]

\[
\text{ELA} = -0.19b_n + 3746.8, \quad R^2 = 0.81
\]
3.12 GOLUBIN (KYRGYZSTAN/TIEN SHAN)

COORDINATES: 42.46° N / 74.50° E

Golubin Glacier is situated in the Ala Archa valley in the Northern Tien Shan. Today the glacier covers an area of 5.5 km² 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

Golubin (KYRGYZSTAN)
3.12.3 Mass balance versus altitude (2010/11)

![Hypsography](image1)

Mass balance versus altitude (2010/11)

<table>
<thead>
<tr>
<th>Altitude [m a.s.l.]</th>
<th>Area distribution [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3325−3400</td>
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</tr>
<tr>
<td>3425−3500</td>
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<td>3525−3600</td>
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<td>3625−3700</td>
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<td>4125−4200</td>
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<tr>
<td>4225−4300</td>
<td></td>
</tr>
<tr>
<td>4325−4350</td>
<td></td>
</tr>
</tbody>
</table>

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

![AAR and ELA](image2)

- **AAR** = 0.03bn + 72.5, \( R^2 = 0.24 \)
- **ELA** = −0.19bn + 3810.4, \( R^2 = 0.26 \)

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 km² 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 19th 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

mass balance isolines (m)
equilibrium line
ablation area
medial moraine

0 1 km

Waldemarbreen (NORWAY)

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  HELSTUGUBREEN (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 km² (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)**

![Graph showing mass balance versus altitude](image)

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

\[ \text{AAR} = 0.04b_n + 58.3, R^2 = 0.89 \]

\[ \text{ELA} = -0.20b_n + 1839.5, R^2 = 0.88 \]

**Hellstugubreen (NORWAY)**
3.15 STORGLACIÄREN (SWEDEN/NORTHERN SWEDEN)

COORDINATES: 67.90° N / 18.57° E

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 km², 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)

![Graph of mass balance versus altitude](image)

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

![Graph of AAR and ELA](image)

**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 km² in 1965 to measured values of 18.61 km², 18.16 km², and 16.88 km² in 1974, 1993, and 2009, respectively, and to an estimated value of 16.73 km² 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**

![Mass balance map 2009/10](image)

**2010/11**

![Mass balance map 2010/11](image)
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

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 km². 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

![Topography and observation network diagram](image_url)
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)

![Graph showing mass balance versus altitude]

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

![Graph showing AAR and ELA versus mass balance]

**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.

<table>
<thead>
<tr>
<th></th>
<th>2009/10</th>
<th>2010/11</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean specific (annual) mass balance</td>
<td>−782 mm</td>
<td>−1158 mm</td>
</tr>
<tr>
<td>standard deviation</td>
<td>586 mm</td>
<td>958 mm</td>
</tr>
<tr>
<td>minimum value</td>
<td>−2110 mm</td>
<td>Echaurren Norte −4153 mm</td>
</tr>
<tr>
<td>maximum value</td>
<td>+80 mm</td>
<td>Place +1210 mm</td>
</tr>
<tr>
<td>range</td>
<td>2190 mm</td>
<td>5363 mm</td>
</tr>
<tr>
<td>positive balances</td>
<td>9 %</td>
<td>9 %</td>
</tr>
<tr>
<td>mean AAR</td>
<td>26 %</td>
<td>19 %</td>
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</table>

<table>
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<tr>
<th></th>
<th></th>
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<tr>
<td>mean specific (annual) mass balance</td>
<td>−223 mm</td>
<td>−439 mm</td>
<td>−668 mm</td>
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<tr>
<td>standard deviation</td>
<td>769 mm</td>
<td>885 mm</td>
<td>891 mm</td>
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<tr>
<td>minimum</td>
<td>−1862 mm</td>
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<td>maximum</td>
<td>+1966 mm</td>
<td>+1567 mm</td>
<td>+1159 mm</td>
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<td>4126 mm</td>
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<td>positive balances</td>
<td>33 %</td>
<td>26 %</td>
<td>20 %</td>
</tr>
<tr>
<td>mean AAR</td>
<td>49 %</td>
<td>45 %</td>
<td>38 %</td>
</tr>
</tbody>
</table>

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...
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.

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Alaska</th>
<th>Pacific Coast Ranges</th>
<th>Andes</th>
<th>Canadian High Arctic</th>
<th>Svalbard</th>
<th>Scandinavia</th>
<th>Alps</th>
<th>Caucasus</th>
<th>Altai</th>
<th>Tien Shan</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>+1105</td>
<td>−747</td>
<td>+300</td>
<td>−31</td>
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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.
ACKNOWLEDGEMENTS AND REFERENCES

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REFERENCES


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