What is mass balance?

Regine Hock

Glacier summer school 2018, McCarthy, Alaska
• Terminology, Definitions, Units
• Conventional and reference surface mass balance
• Firn line, snow line, ELA
• Glacier runoff
• Global mass changes
PART I
Terminology
Background

General reference for mass-balance terminology has been Anonymous, 1969, J. Glaciology 8(52).

In practice diverging and inconsistent and confusing use of terminology

New methods, e.g. remote sensing, require update

Working group (2008-2012) by International Association of Cryospheric Sciences (IACS)

Aims to update and revise Anonymous (1969) and to provide a consistent terminology for all glaciers (i.e. mountain glaciers, ice caps and ice sheets)


Can be downloaded from: http://www.cryosphericsciences.org/mass_balance_glossary/massbalanceglossary
Glacier mass balance

Mass balance is the change in the mass of a glacier, or part of the glacier, over a stated span of time:

\[ \Delta M = \int_{t_i}^{t} \dot{M} \, dt \]

= mass budget

‘mass imbalance’

Accumulation area: acc > abl

Ablation area: acc < abl

Equilibrium line: acc = abl

Firn line

Long-term ELA

Net gain of mass

Net loss of mass

\textbf{SPACE:} study volume needs to be defined

\textbf{mass balance is often quoted for volumes other than that of the whole glacier, for example a column of unit cross section}

\textbf{important to report the domain!}

\textbf{TIME:} the time period (esp important for comparison with model results)

\textbf{mass change can be studied over any period}

\textbf{often done over a year or winter/summer seasons} \rightarrow \textbf{Annual mass balance (formerly ‘Net’)}
\[ \Delta m = c + a = \int_{t_1}^{t} (c + a) \, dt \]

**ACCUMULATION, \((c, C)\)**
- Snow fall
- Deposition of hoar, freezing rain
- Windborne blowing snow/drifting snow
- Avalanching

**ABLATION \((a, A)\)**
- Melting
- Sublimation
- Loss of windborne blowing snow/drifting snow
- Avalanching
- Calving, submarine melt ...

![Diagram of ice sheets with labels for accumulation and ablation processes.](Image)
Mass balance components:

*It’s more than snowfall and melt*

Total mass budget: sum of climatic balance and frontal ablation

Mass balance components

Precipitation - Surface accumulation

*precipitation includes rain; rain water is not accumulation; water is not considered to be part of the glacier*

Accumulation - Net accumulation

- *Net acc is a balance, acc is not*
Winter balance $\leftrightarrow$ accumulation
Summer balance $\leftrightarrow$ ablation

\[ B_a = B_w + B_s = \text{Acc} + \text{Abl} \]
\[ B_w = \text{Acc}_w \quad B_s = \text{Abl}_w \]

Implications for comparison of field measurements with model results?
C, A can be modeled, but what is measured often is $B_w, B_s$
Mass balance components

**Precipitation - Surface accumulation**

Precipitation includes rain; rain water is not accumulation; water is not considered to be part of the glacier.

**Accumulation - Net accumulation**

Net acc is a balance, acc is not.

**Melt - meltwater runoff**

Melt water may refreeze and does not contribute to meltwater runoff.

**Meltwater runoff - Runoff**

Runoff includes rain water.

---

What is mass balance?

**Mass balance of a column**

[Layers diagram with symbols: \( c_{sfc} \), \( \rho_{\text{snow?}} \), \( \rho_{\text{firm?}} \), \( q_{\text{in}} \), \( q_{\text{out}} \), \( a_i \), \( c_i \), \( c_b \), \( a_b \)]
What is mass balance?
Change of the mass over a stated span of time

Mass balance of a column

\[ \Delta m = c_{sfc} + a_{sfc} + c_i + a_i + c_b + a_b + q_{in} + q_{out} \]

- \( c = \) accumulation
- \( a = \) ablation (is negative)

Layer diagram:
- Surface
- Internal
- Basal

\( \rho_{\text{snow?}} \)
\( \rho_{\text{firn?}} \)

\( q_{in} \)
\( q_{out} \)
Terminology ‘mess’

Mass balance of a column

\[ \Delta m = c_{sfc} + a_{sfc} + c_i + a_i + c_b + a_b + q_{in} + q_{out} \]

Surface, internal, basal flux divergence

Continuity equation

\[ h = \dot{b} - \nabla \cdot Q \]

Thickness change

Mass balance?

SMB?
Mass balance of a column

$c = \text{accumulation}$

$a = \text{ablation}$

$$\Delta m = c_{sfc} + a_{sfc} + c_i + a_i + c_b + a_b + q_{in} + q_{out}$$

What is mass balance?

(Total) mass balance, $\Delta m$

$\dot{h} = b - \nabla Q$
What do you measure with GPS vs with a stake?

\[ \Delta m = c_{sfc} + a_{sfc} + c_i + a_i + c_b + a_b + q_{in} + q_{out} \]

- Surface
- Internal
- Basal
- Flux divergence

Climatic balance
Climatic-basal balance
(Total) mass balance

\[ h = (b \cdot \nabla \dot{Q}) \]
What do you measure with GPS vs with a stake?

\[ \Delta m = c_{sfc} + a_{sfc} + c_i + a_i + c_b + a_b + q_{in} + q_{out} \]

- **GPS** --> total mass balance
  (but partitioning in components unknown)
- **Stake** --> only surface mass balance,
  measurement relative to top of the stake
What do you measure with GPS vs with a stake?

<table>
<thead>
<tr>
<th>Point/part of glacier</th>
<th>Glacier-wide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS</strong> --&gt; total mass balance</td>
<td>• total mass balance --&gt; <em>geodetic balance</em></td>
</tr>
<tr>
<td><strong>Stake</strong> --&gt; only surface mass balance, measurement relative to top of the stake</td>
<td>• total mass balance (for land-terminating non-calving glaciers)</td>
</tr>
</tbody>
</table>

*Interpolating point data over entire glacier*
Why does the geodetic method work?
- Does not need any ice velocity measurements

Over an entire glacier (no ice flowing into another ice mass) the flux divergence is zero, i.e. height changes equal the climatic-basal mass balance (accounting for density); assuming no changes at the glacier bed

\[ \frac{\partial h}{\partial t} = B_N - \frac{\partial q}{\partial x} \]

Does an elevation change at point always indicate a change in mass?

- changes in elevation can occur without changes in mass or visa versa
Mass flux or volumetric flux of ice through a glacier cross-section or “gate”.

The gate can be anywhere on the glacier, but is often at the glacier terminus.

**Calving flux**

- only includes mass loss due to calving
- BUT: >50% of the mass loss at the glacier front can be due to submarine melting (even if grounded)

--- > frontal ablation

- mass loss at the glacier front (includes calving, submarine melting, arial melt/sublimation ...)

**What is ice discharge?**

Mass flux or volumetric flux of ice through a glacier cross-section or “gate”.

The gate can be anywhere on the glacier, but is often at the glacier terminus.
Time systems: Annual mass balance, i.e. balance over (roughly) one year

- stratigraphic system
- fixed-date system
- floating-date system
- combined system
End winter snow probing: What system?
• Stratigraphic system: dates are unknown.
### Time Systems of Annual Measurements of Mass Balance Reported to World Glacier Monitoring System WGMS (Cumulative to 2008)

<table>
<thead>
<tr>
<th>Time System</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>No information provided</td>
<td>1519</td>
</tr>
<tr>
<td>Fixed-date system</td>
<td>917</td>
</tr>
<tr>
<td>Stratigraphic system</td>
<td>931</td>
</tr>
<tr>
<td>Combined system</td>
<td>265</td>
</tr>
<tr>
<td>Other</td>
<td>188</td>
</tr>
</tbody>
</table>

**Total of reported annual measurements** 3820

-> comparing observations with model results problematic if time system not known
What is **specific** mass balance?

1. The mass balance at a specific location?
2. The mass balance of the entire glacier?
3. The mass balance expressed in m w.e.?

**Definition:**

*Mass balance* expressed per unit area, that is, with dimension \([\text{M L}^{-2}]\) or as a rate \([\text{M L}^{-2} \text{T}^{-1}]\) often \(\text{kg m}^{-2}\) or m w.e.

- The prefix “specific” is not necessary. The units make clear whether or not it is specific.
- Specific mass balance may be reported for a point on the surface (if it is a *surface mass balance*), a column of unit cross-section, or a larger volume such as the entire *glacier*.
- Balances reported for a point are always specific.
Mass-balance units

- **Mass** \([M]\) kg, Gt (=10^9 kg, 1 billion tonnes)
- **mass change per unit area** \([M \, L^{-2}]\) --> kg m\(^{-2}\) (specific unit)
- **m or mm water equivalent (w.e.)**: 
  - -> 1 kg of water (density 1000 kg m\(^{-3}\)) has thickness of 1 mm when distributed over 1 m\(^2\)
  - -> kg m\(^{-2}\) and mm are numerically identical
  - -> 1 m w.e. = 1000 kg m\(^{-2}\)/density of water
- **m\(^3\) w.e. or km\(^3\) w.e.** (1 km\(^3\) w.e. = 1 Gt) 
  --> **important to add w.e. or i.e. (ice equiv.)**
- **Sea-level equivalent:**
  - kg m\(^{-2}\) x glacier area /-(density of water x area of the ocean) (362x10\(^6\) km\(^2\))

Often not included:

- **changes in ocean area**; any delay and storage in transport of water in the terrestrial water cycle
- **isostatic adjustment of the land surface, tectonic movements**
- **differentiate between grounded and floating ice** (floating ice does not contribute to sea-level; grounded ice contributes only to a small fraction since the ice already displaces water)
Mass balance time series look different in different units

by Christian Kienholz
PART II
Concept of conventional and reference surface balance

Claridenfirn, Switzerland, 1916
Mass balance as climate indicator?

Stable climate

$B_a = 0$

Steady-state

Step change in climate

$B_a < 0$

Glacier retreat

Stable climate

$B_a = 0$

Steady-state
Glaciers are indicators of climate change? 

• **conventional mass balance**
  
  
  glacier area/hypsometry is updated annually

• **reference surface balance**
  
  
  glacier area/hypsometry is kept constant

---

**Harrison, W., Elsberg, Cox and March, 2005.** Different balances for climatic and hydrological applications. J. Glaciol., page 176.

This paper is in your folder!
### Conventional mass balance

**Time 1** (t1)                      **Time 2** (e.g. 50 yrs later)

**Measurement sites**

\[
B = \frac{1}{A} \int_{t_1}^{t_2} b(h_1) \, dA
\]

**Note area AND surface elevation changes**

**Reference surface mass balance**

**Relevant for hydrological purposes**

\[
B = \frac{1}{A} \int_{t_1}^{t_2} b(h_2) \, dA
\]

**Relevant for climatological purposes**

\[
B = \frac{1}{A} \int_{t_1}^{t_2} b'(h_1) \, dA
\]

\[b = \text{measured point balances}\]

\[b' = \text{measured point balance at t2 on surface at t2 but adjusted to surface at t1}\]
Mass balance as climate indicator?

Stable climate

\[ B_n = 0 \]

Steady-state

Climate change

\[ B_n < 0 \]

Glacier retreat

Stable climate

\[ B_n = 0 \]

Steady-state

Reference surface mass balance does not go to 0
Which balance to use when?

Conventional balance:
Relevant for hydrological/sea level purposes

- kilogramme (kg), or gigatonne (Gt; 1 Gt = 10^{12} kg).
- m^3 w.e. or km^3 w.e.

Reference surface balance:
Relevant for climatological purposes

1 kg m^{-2} = 1 mm of water equivalent, mm w.e. = specific mass balance
Mass-balance feedback: Two opposing effects

Retreat effect

Thinning effect

(Bodvarðsson, 1955)

Ice cap

stabilizing

destabilizing

Increased thinning

Glacier retreat

Increased thinning
Which one is the conventional / reference balance?

PART III
Firn line, equilibrium line, snow line ...
**Snow line**

- Boundary separating snow from ice or firn at any time \( t \)
- Transient - Annual
FIRN
Wetted snow that has survived one summer without being transformed to ice

The set of points on the surface of a glacier delineating the firn area and, at the end of the mass-balance year, separating firn (usually above) from glacier ice (usually below).
FIRN LINE can be seen on radar profiles
Snow line
• Boundary separating snow from ice or firn at any time t
• Transient - Annual

Equilibrium line
• The set of points on the surface of the glacier where the climatic mass balance is zero at a given moment. The equilibrium line separates the accumulation zone from the ablation zone.
• Transient - Annual
Equilibrium line vs. equilibrium line altitude (ELA)

Approximate ELA
ELAs from space: Remote sensing

Landsat image of Vatnajoekull (Iceland)

Where is the firn line, ELA?
Where are the firn line, equilibrium line, snow line relative to each other?

Assuming no superimposed ice

\[ \text{firn} < \text{snow} = \text{EL} \]
if no superimposed ice

\[ \text{firn} = \text{snow} = \text{EL} \]
if no superimposed ice

\[ \text{firn} = \text{snow} = \text{EL} \]
if no superimposed ice

balanced year: Lines are the same only when glacier is in equilibrium (i.e. balance=0 over many years and firn line = long-term EL)

negative mass balance firn line retreats slower

positive mass-balance, remaining snow becomes firn --> all lines are the same
PART IV

‘Sensitivities’

Claridenfirn, Switzerland, 1916
Sensitivities to climate change

The change in mass balance due to a change in a climatic variable such as air temperature or precipitation. Sensitivities to temperature and precipitation are often expressed as changes in response to a 1 K warming or a 10% precipitation increase.

\[ S_x = \frac{\partial \bar{b}_n}{\partial x} \]

- **Static sensitivities** assume constant glacier size and geometry and refer only to the change in mean specific mass balance
- **Dynamic sensitivities** consider the volume and geometry changes following climate change and are thus more realistic
- Sensitivities vary among regions (e.g. maritime climates more sensitive)
### Static mass balance sensitivities using energy balance (EB) or temperature-index (TI) melt models

<table>
<thead>
<tr>
<th>Glaciers</th>
<th>Method</th>
<th>Static mass balance sensitivity T +1 K (m a⁻¹)</th>
<th>Static mass balance sensitivity P +10 % (m a⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Norwegian glaciers</td>
<td>EB</td>
<td>-0.72 to -1.11</td>
<td></td>
<td>Oerlemans (1992)</td>
</tr>
<tr>
<td>12 glaciers</td>
<td>EB</td>
<td>-0.12 to -1.15</td>
<td></td>
<td>Oerlemans and Fortuin (1992)</td>
</tr>
<tr>
<td>12 glaciers</td>
<td>EB</td>
<td>-0.40 (average)</td>
<td></td>
<td>Oerlemans (1993)</td>
</tr>
<tr>
<td>3 Norwegian glaciers</td>
<td>TI</td>
<td>-0.54 to -1.04</td>
<td>+0.14 to +0.39</td>
<td>Laumann and Reeh (1993)</td>
</tr>
<tr>
<td>2 Svalbard glaciers</td>
<td>EB</td>
<td>-0.61 (average)</td>
<td></td>
<td>Fleming et al. (1997)</td>
</tr>
<tr>
<td>2 Icelandic glaciers</td>
<td>TI</td>
<td>-0.6 to -0.9</td>
<td></td>
<td>Jóhannesson (1997)</td>
</tr>
<tr>
<td>12 glaciers</td>
<td>TI, EB</td>
<td>-0.4 to -1.35</td>
<td></td>
<td>Oerlemans et al. (1998)</td>
</tr>
<tr>
<td>37 glaciers</td>
<td>TI</td>
<td>-0.1 to -1.3</td>
<td></td>
<td>Braithwaite and Zhang (1999)</td>
</tr>
<tr>
<td>5 Swiss glaciers</td>
<td>TI</td>
<td>-0.44 to -0.89</td>
<td></td>
<td>Braithwaite and Zhang (2000)</td>
</tr>
<tr>
<td>6 Scandinavian glaciers</td>
<td>TI</td>
<td>-0.68 to -1.13</td>
<td>+0.26 to +0.50</td>
<td>Nesje et al. (2000)</td>
</tr>
<tr>
<td>61 glaciers</td>
<td>TI</td>
<td>-0.13 to -1.22</td>
<td>+0.04 to +0.37</td>
<td>Braithwaite et al. (2002)</td>
</tr>
<tr>
<td>9 Icelandic glaciers</td>
<td>EB</td>
<td>-0.49 to -0.80</td>
<td>+0.27 to +0.35</td>
<td>de Ruyter de Wildt et al. (2003)</td>
</tr>
<tr>
<td>17 glaciers</td>
<td>TI</td>
<td>-0.2 to -1.5</td>
<td></td>
<td>Schneeberger et al. (2003)</td>
</tr>
<tr>
<td>42 Arctic glaciers</td>
<td>TI</td>
<td>-0.20 to -2.01</td>
<td>+0.03 to +0.36</td>
<td>de Woul and Hock (2005)</td>
</tr>
<tr>
<td>12 Scandinavian glaciers</td>
<td>TI</td>
<td>-0.30 to -1.01</td>
<td>+0.16 to +0.41</td>
<td>Rasmussen and Conway (in press)</td>
</tr>
</tbody>
</table>
Mass balance sensitivities

Global mean static mass balance

• -0.39 m a\(^{-1}\) K\(^{-1}\) (Oerlemans, 1993)
• -0.37 m a\(^{-1}\) K\(^{-1}\) (Dyurgerov and Meier, 2000)
• -0.68 m a\(^{-1}\) K\(^{-1}\) (Hock et al., 2009)
What do mass balance sensitivities depend on?

Affected by

- Glacier geometry
- Climate
Annual mass balance sensitivity $[m\ a^{-1}]$ to a $+1\ K$ warming

Regions with high sensitivities due to

- change in rain/snow fraction has a larger effect where precip is higher
- longer ablation season has larger effect on glaciers that extend down to low-lying warmer areas
- greater reduction in precip in maritime regions for a given percentage change in precip

Hock et al., 2009, GRL
Future volume changes using mass balance sensitivities

\[ \Delta M = A_{\text{glacier}} \left( S^T \Delta T + S^P \Delta P \right) \]

\[ S^T = \text{Mass balance sensitivity to } +1 \text{ K warming} \]
\[ S^P = \text{Mass balance sensitivity to } 1\% \text{ precipitation increase} \]
\[ \Delta T = \text{predicted temperature increase} \]
\[ \Delta P = \text{precipitation increase } (\%) \]

Mass balance in specific units

Assumptions:

- Assumption that glacier initially are in steady-state
- Constant sensitivities with time
Seasonal sensitivity characteristic

Sensitivity varies with season

- applies temperature and precipitation perturbations employed individually for each month while leaving the data for the remaining months unchanged.

SSC (Oerlemans & Reichert, 2000):

Monthly perturbations in precipitation or temperature
Seasonal mass balance sensitivities

- applies temperature and precipitation perturbations employed individually for each month while leaving the data for the remaining months unchanged.
PART IV
Global mass balances

Claridenfirn, Switzerland, 1916
Global glacier volume

- Sea-Level Equivalent (SLE): ~66 m
- 58.3 m Antarctica
- 7.4 m Greenland
- 0.5 m mountain glaciers
Ice volume

- Mountain glaciers (1%)
- Greenland (11%)
- Antarctica (88%)

Sea-level contribution

- Glaciers (27%)
- Thermal expansion (39%)
- Greenland (12%)
- Antarctica (9%)
- Land water storage (13%

1992 - 2010, IPCC 2013
Global glacier mass loss (IPCC, 2007)

- based on 3 global estimates (Cogley, 2005; Dyurgerov & Meier, 2005; Ohmura, 2004)
- based on spatial extrapolation of direct mass balance measurements on <200 glaciers
- incomplete glacier inventory

1993-2003: SLE = 0.77 ± 0.22 mm/yr

Kaser et al. 2006, GRL; IPCC 2007
The Randolph Glacier Inventory: a globally complete inventory of glaciers

W. Tad PFEFFER,1 Anthony A. ARENDT,2 Andrew BLISS,2 Tobias BOLCH,3,4 J. Graham COGLEY,5 Alex S. GARDNER,6 Jon-Ove HAGEN,7 Regine HOCK,2,8 Georg KASER,9 Christian KIENHOLZ,2 Evan S. MILES,10 Geir MOHOLDT,11 Nico MÖLG,3 Frank PAUL,3 Valentina RADIC,12 Philipp RASTNER,3 Bruce H. RAUP,13 Justin RICH,2 Martin J. SHARP,14 THE RANDOLPH CONSORTIUM15

- inventoried glacierized area (WGI)
- NOT inventoried glacierized area before 2012
IACS Working group
Division on Glaciers and Ice Sheets

Randolph Glacier Inventory and infrastructure for glacier monitoring
(2014 - 2018)

WG co-chairs:

- Graham Cogley, Trent University, Peterborough, Canada
- Regine Hock, University of Alaska Fairbanks, USA

WG members:

- Etienne Berthier, CNRS-OMP-LEGOS, Toulouse, France
- Andrew Bliss, University of Alaska Fairbanks, USA
- Tobias Bolch, University of Zürich, Switzerland
- Koji Fujita, University of Nagoya, Japan
- Alex Gardner, Clark University, USA
- Matthias Huss, University of Fribourg and ETH Zürich, Switzerland
- Georg Kaser, University of Innsbruck, Austria
- Christian Kienholz, University of Alaska Fairbanks, USA
- Anil Kulkarni, Indian Institute of Science, Bangalore, India
- Shiyin Liu, Cold and Arid Regions Environmental & Engineering Research Institute, Lanzhou, China
- Christian Nuth, University of Colorado, USA

Goal of the Working Group

The Randolph Glacier Inventory (RGI) is a recently-published, globally complete collection of digital outlines of glaciers, excluding the ice sheets. The Working Group aims to maintain and develop the RGI as a resource for global/regional-scale mass-balance assessments and projections and work towards merging the RGI into the Global Land Ice Measure-ments from Space (GLIMS) database.

Scope:

- Background
- Objectives

Relevant publications:

- Measurements from Space towards merging the RGI into the Global Land Ice (GLIMS) database.

Related Working Groups:

- Mass balance terminology
- GLIMS

Deliverables and milestones:

- Deliverables and milestones — back to working groups page

Christopher Nuth, University of Oslo, Norway
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Frank Paul, University of Zürich, Switzerland
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Akiko Sakai, University of Nagoya, Japan
Donghui Shangguan, Cold and Arid Regions Environmental & Engineering Research Institute, Lanzhou, China
Arun Shrestha, International Centre for Integratred Mountain Development, Kathmandu, Nepal
Mass changes 2003 - 2009 (IPCC 2013)

Approach: combine best available estimates for each region with new analyses based on ICESat

Global glacier mass changes 2003 - 2009

All glaciers other than the ice sheets in Greenland and Antarctica

- Largest regional contributors: Arctic Canada, Alaska, Greenland periphery, Southern Andes

- Average thinning rate = 0.4 m yr⁻¹
  Global glacier mass loss = 0.71 ± 0.08 mm SLE yr⁻¹

- 29% of observed global sea-level rise
- Roughly equivalent to ice sheet mass loss

Gardner et al., 2013, Science
Global volume projections 2015 - 2100

RCP2.6

RCP4.5

RCP8.5

Volume (normalized)

-14%

-24%

-20%

-33%

-26%

-48%

multi-GCM mean

individual GCMs

Marzeion et al

Giesen & Oerlemans

Huss & Hock

Bliss & Radic et al.

Slangen et al.

RCP = Representative Concentration Pathways (emission scenarios)
Marzeion et al.
Giesen & Oerlemans
Huss & Hock
Bliss/Radic et al.
Slangen et al.

Volume (normalized)

2100
2020
0
0.6
1

RCP8.5

multi-model mean
individual GCMs
PART V
What is Glacier runoff?

Claridenfirn, Switzerland, 1916
How does runoff change as it becomes warmer?

**Short-term time scale**

**Long-term time scale**

**Period of negative mass balances**

**Balanced mass budget**

How does runoff change as it becomes warmer?

**Short-term time scale**

**Long-term time scale**

**Period of negative mass balances**

**Balanced mass budget**
later peak water in basin with larger glaciers/ice cover %

Huss & Hock, 2018, Nature Climate Change
What is glacier runoff?

1.) All runoff from glacierized area  
   \[ Q = M - R \]  
   - discharge a gauging station would measure  
   - happens always, i.e. also in year where annual net balance is zero  
   - glacier in balance has no effect on annual runoff (but seasonal effects)  
   - relevant for hydrologists

2.) Runoff from glacier net mass loss  
   \[ Q = M - R + P \]  
   - relevant for sea-level  
   - ‘extra’ water from long-term glacier storage

3.) Runoff only from bare ice area  
   \[ Q = M_{\text{ice}} \]

Main conclusion

• Reporting mass balance: always report
  – domain to which the balance refers (and area)
  – time period a balance refers to

• if annual balance is reported report the dates and/or the time system (--> essential to compare to model results)

• report which mass balance component is measured/modelled; use proper terminology

• Elevation change vs mass balance from stake measurements
  a) at a point (NOT equal)
  b) glacier-wide (equal)
Summary

• **Specific mass balance**: mass per area
• **surface mass balance**: strictly speaking only balance at the surface -> climatic balance if internal accumulation included
• **annual balance** instead of previous term **net balance**
• Accumulation is not identical to net accumulation
• **Runoff is not identical to melt or meltwater runoff**
• **Frontal ablation** includes calving flux and submarine melting
• Reporting of **time systems and glacier area** (area-elevation distribution) is crucial
• **Conventional balance** (area, elevation updated) reference surface mass balance (kept constant)