Chapter 7
Snow and ice

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Throughout the solar system there are different types of large ice bodies, not only water ice but also ice made up of ammonia, carbon dioxide and other substances that are gases or liquids at conditions typical for the earth's surface, but may freeze solid at much lower temperatures. The planets between the Sun and Earth (Venus and Mercury) are too warm for ice to build up. Mars has a big polar icecap composed of water and carbon dioxide ice; this ice cap grows and shrinks with the seasons, similar to the seasons on earth with different amounts of solar radiation received at the earth's surface in winter and summer. The surface layers of Jupiter and Saturn are composed of different types of ices and one of Jupiter's moons, Europa, actually has an ice crust of several tens to possibly hundreds of kilometers in thickness which is in many ways similar to ice features visible on earth; even our moon may have some ice present within the upper soil layers.

On earth, we find glaciers and ice-sheets on every continent (if New Zealand as taken as a part of the Australian continent). Roughly 10 % of the total land surface is covered by glaciers or ice sheets, and sea ice covers roughly 10 % of the world's ocean surface.

Polar sea ice is one of the most variable features of the Earth's climate, changing considerably from summer to winter and from one year to another. At any given time, global sea ice covers an area approximately the size of the North American continent. The presence of the ice restricts the transfer of heat between the ocean and the atmosphere. The ice also restricts evaporation into the atmosphere and affects the circulation of the ocean.

If we take into account the distribution of ice sheets during previous glaciations, glaciers have at some point in time covered an even larger fraction of the earth's surface; as a result, a significant fraction of the landscapes on earth are influenced by glacial action. Glaciers are also an important part of the hydrological cycle, see Table 1.1 which lists the distribution of water on earth.

Definition 7.1. Cryosphere is the region where ice can form.

On Earth it ranges from about 600-800 m depth (where ice formation is limited by heat), to 6-18 km height where moisture is too low.

7.1 Glacier mass balance

The mass balance of glaciers refers to the inventory of how much the glacier gains (accumulation, c) and how much it loses (ablation, a) during the year. By measuring all accumulation and ablation at several points on the glacier, we can construct a net balance, income (accumulation) minus expenses (ablation), at those locations. If we do this at several elevations we can construct a mass balance curve as a function of elevation. But to know whether the whole glacier is gaining or loosing mass we need to account for the area distribution with height. If most of the glacier resides above 300 m a.s.l., and only a small outlet glacier reaches sea level, the glacier can be gaining even if the ablation below 300 m is greater than the accumulation above 300 m. Below we define these terms and show examples.

Equilibrium Line Altitude (ELA)

The balance b at a point on the glacier is difference between accumulation and ablation,

$$b = c - a, \tag{7.1}$$

where c is accumulation, and a is ablation. Therefore, for the annual net balance b_n,

$$b_n = net\,balance, \quad where \begin{cases} b > 0, & in\,the\,accumulation\,area, \\ b < 0, & in\,ablation\,area. \end{cases} \tag{7.2}$$

Figure 7.1 shows a schematic of how we determine the ELA. The area above

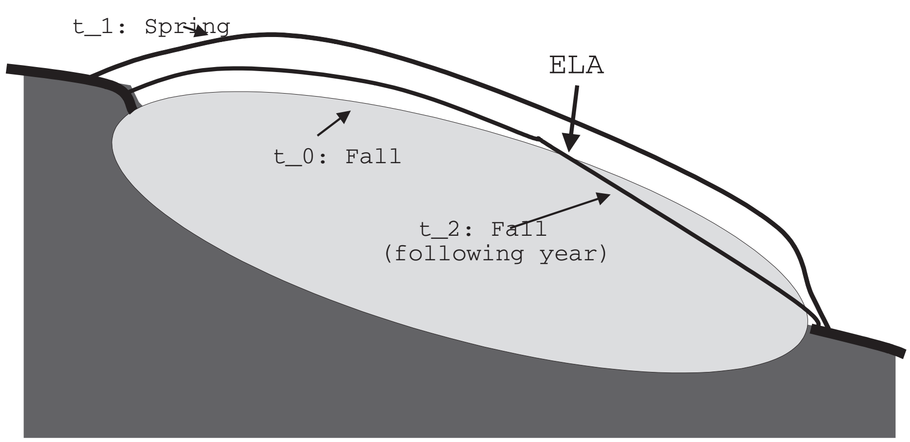

Fig. 7.1 Equilibrium Line Altitude (ELA). The surface at fall t_0, after the winter accumulation in spring t_1 and the following fall t_2.

ELA is the accumulation area, and the area below the ELA is the ablation area, thus we have the following definition of the ELA:

Definition 7.2. Equilibrium Line Altitude, ELA, is the elevation across the glacier where the annual net balance is zero, $b_n = 0$.

Measuring mass balance

In spring the winter balance at a point is measured,

$$b_w = c_w - a_w. \tag{7.3}$$

The following fall the summer ablation balance is measured,

$$b_s = c_s - a_s. \tag{7.4}$$

Then the net balance is,

$$b_n = b_w + b_s. \tag{7.5}$$

Figure 7.2 shows the summer-, winter-, and net-balance for Tungnárjökull in 2004.

Point measurements of mass balance

In spring stakes, poles or wires, are set out. It is common to do measurements along the center-flow line of a glacier. Finding the surface from last year is easy in the ablation area, since all ice underneath. In the accumulation zone it is necessary to find last years layer. To do that we can look for dust, isotope signals, ice layer, ... This is called stratigraphic method.

Since the density of the snowpack varies with depth, we need to convert the measured snow thickness to equivalent water (or ice) thickness,

$$h_{water} = \frac{\rho_{snow}}{\rho_{water}} h_{snow}. \tag{7.6}$$

The density profile is constructed from snow from snow pits, or snow cores. Table 7.1 shows the typical densities of snow and ice.

The following fall we get a measure of the ablation (Figure 7.4). Note that the density profile must be measured again in the accumulation zone, since summer melt will alter the snowpack.

Now assuming that the point measurements are representative of a larger area, commonly the surface area of the glacier covering the height span half way to the next measurement points, we get

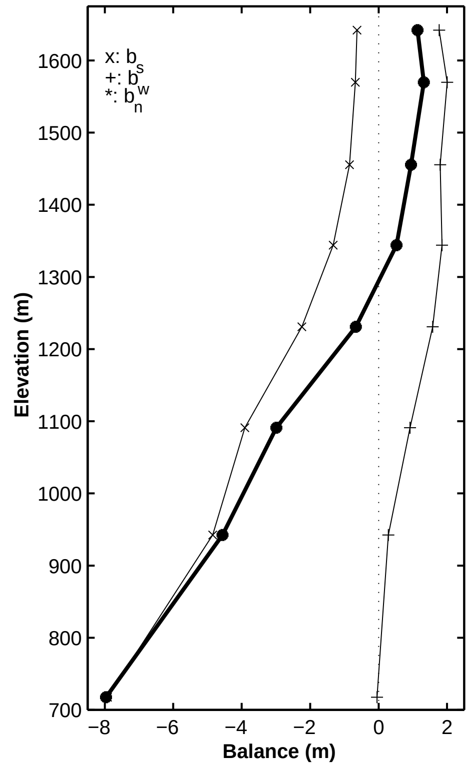

Fig. 7.2 Balance data from Tungnárjökull, 2004. Plot of summer- (b_s), winter- (b_w) and net-balance (b_n) with elevation for the year 2004. Data from Helgi Björnsson and Finnur Pálsson.

Table 7.1 Typical densities

	kg m^{-3}
New snow	50 - 70
Damp new snow	100 - 200
Settled snow	200 - 300
Depth hoar	100 - 300
Wind packed snow	350 - 400
Firn	400 - 830
Very wet snow and firn	700 - 800
Glacier ice	830 - 917

$$B_n = \int b_n dS_c + \int b_n dS_a, \qquad (7.7)$$

where S_a is the ablation area and S_c the accumulation area. If $B_n = 0$ the glacier is in balance, if $B_n < 0$ it is shrinking, and if $B_n > 0$ it is growing.

Knowing the balance (b_n) and area (S) at several heights, it is possible to calculate B_n, and plot as a function of height, see Figure 7.3.

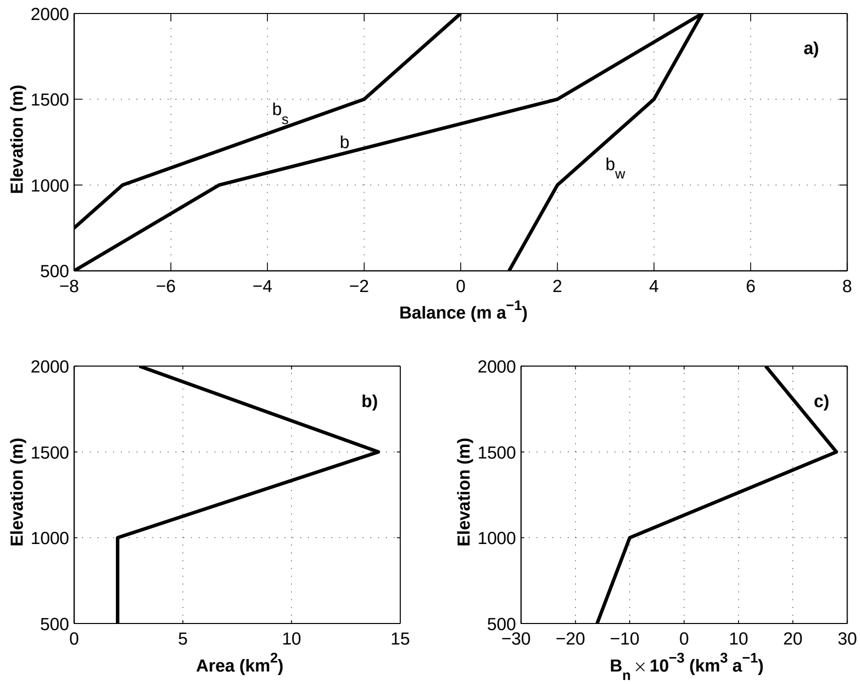

Fig. 7.3 Mass balance data. a) Plot of summer- (b_s), winter- (b_w) and net-balance (b) with height, b) area distribution with height, and c) area weighted balance B_n.

Other measurement methods

In some cases it may be possible to calculate each term in the mass balance.

For the large ice sheets the pattern of accumulation is fairly well known. In Greenland the accumulation ranges from 100 mm/a in the N-center to 1500 mm/a in the S-E, with an average accumulation of 300 mm/a. In Antarctica the accumulation ranges from 20-700 mm/a, with an average of 143 mm/a.

The negative terms in the mass balance of the large ice sheets are a) calving, b) surface melt, c) basal melting, and d) melting under water; in Antarctica. It is difficult to measure the melting under water. The surface melt term is small in Antarctica. To calculate the calving rate the area of ice-bergs is estimated and also of thickness. But we have to know how long they survive to know the rate.

Another method when there is not significant melting is to simply estimate the inflow (accumulation) and outflow through a perimeter (or grounding line).

For smaller glacier a method called the hydrological method is sometimes applicable. It determines only the net balance of the whole glacier,

$$B_n = P - R - E, \tag{7.8}$$

where R is the measured drainage, P is the measured total precipitation, and E is the measured or estimated evaporation (usually small).

Comparing maps can sometimes be used to estimate changes in balance along flow lines. There we have to consider the flow,

$$\frac{\partial h}{\partial t} = b - \frac{\partial q}{\partial x},$$

where h is the surface elevation, b is the balance, and q is the ice flux.

Remote sensing is also very useful. It can be used to map the firn-ice transition, track elevation changes, and calculate the flux out of a perimeter.

In Iceland the accumulation on Vatnajökull is 4-5 m water equivalent. The ablation ranges from 10.0 m at 100 m.a.s.l, through 6.0 m at 700 m.a.s.l, to 0.5 m at $\sim$1400 m.a.s.l. Figure 7.4 shows an example of summer ablation on Mýrdalsjökull, S-Iceland.

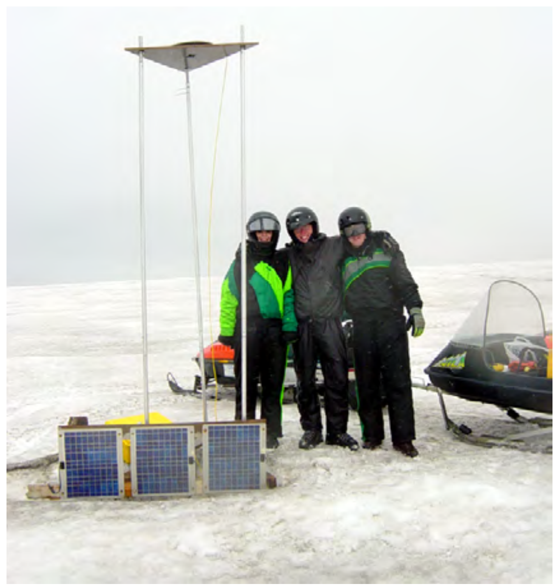

Fig. 7.4 Ablation at Mýrdalsjökull, S-Iceland. The triangular platform was 20 cm above the surface in late April. When this picture was taken, in late June, it stood 3 m above the surface. Picture Throstur Thorsteinsson, 2003.

7.2 Problems

Massbalance Problems

7.1. a) Find the ELA from the data in Figure 7.5. Also, b) find B_n; c) is the glacier growing or shrinking?

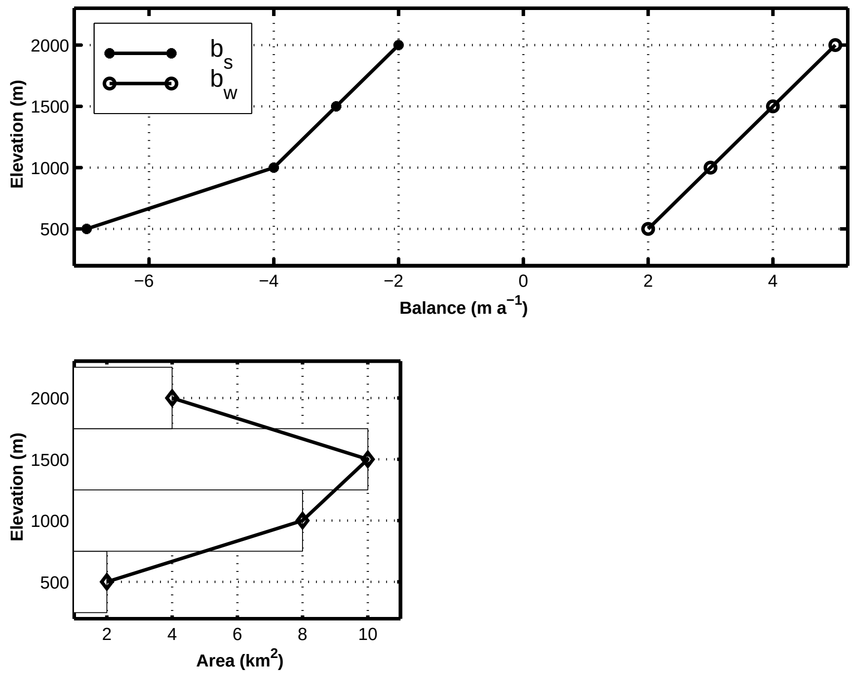

Fig. 7.5 Plot of area distribution with height, and summer and winter balance.

7.2. Imagine we have 10 point measurements as a function of elevation for a glacier covering a mountain top. All the measurements are done along a flow line on the W-side. How representative for the whole glacier would you expect the profile to be? (What are the potential problems?)
Consider the following density profile,

z (m)	ρ **(kg m^{-3})**
0	100
50	500
100	900
120	917

Find the water equivalent accumulation.

7.3. Find the balance b and plot as a function of height for Tungnarjkull 2004,

h (m)	b_w	b_s
717.49	-0.045	-7.920
942.33	0.286	-4.849
1091.09	0.918	-3.906
1230.88	1.578	-2.244
1344.09	1.853	-1.328
1455.39	1.799	-0.851
1569.66	2.001	-0.681
1642.08	1.769	-0.633

7.4. Given the following measurements,

h (m)	**A** (km^2)	b_w (ma^{-1})	b_s (ma^{-1})
500	2	1	-9
1000	2	2	-7
1500	14	4	-2
2000	3	5	0

a) Find the ELA. First calculate b_n, then find the ELA from a plot or calculate it.
b) Find the volume change for the glacier, B_n. Is the glacier growing, steady state, or shrinking?
c) Plot h vs. b_n, h vs. A, and h vs. B_n.

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