The Geography of Glaciers

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Roger J. Braithwaite
School of Environment and Development (SED)
University of Manchester
Manchester M13 9PL, UK

INTRODUCTION (Lecture 1 Slides 1-7)

Firstly, I should start by apologizing for giving so many references to myself. However, there are two points to be made here: (1) I give copious references to the work of others in my papers, including many references to classic work in the 19th Century, and (2) I can freely distribute PDF's of my own papers. You can therefore get a good historic background to several developments in glaciology by reading my papers!

Secondly, I should say that I hope that this outline will correctly follow the new *Glossary of Glacier Mass Balance and Related Terms* from Cogley and others (2010).

Why do we need *The Geography of Glaciers*, or should it be *A Geography of Glaciers*? What would it look like? Is it anything more than a geo-referenced list of glacier names/numbers with locations and areas, and some index of their activity?

Braithwaite and Raper (2002) discuss the effects of glaciers on global sea level rise (SLR). According to their equations, SLR is a sum of contributions from R different glacier regions:

$$SLR = -(1/A0) \sum_{r=1}^{r=R} S_r.\underline{b}_r \qquad (1)$$

The temperature-sensitivity of SLR is given by:

$$\Delta SLR/\Delta T_G = -1000 \sum_{r=1}^{r=R} (S_r/A_O).(\Delta b_n/\Delta T_r) \qquad (2)$$

Where S_r and b_r is the glacier area and mean mass balance in the *r*-th region, ΔT_G is the change in global temperature, A_O is the total area of oceans on the earth, and $\Delta b_n/\Delta T_r$ is the temperature sensitivity of mass balance.

A simple sensitivity study by Braithwaite and Raper (2002) shows that we can expect a SLR of the order of 0.6-0.8 mm a^{-1} K^{-1} for a constant temperature-sensitivity of mass balance of -0.4 m w.e. a^{-1} K^{-1} for all the glaciers on earth (~ 0.7×10^6 km^2).

Of course, the temperature-sensitivity varies between regions but such simple sensitivity studies have their place. One attribute of *A/the Geography of Glaciers* would be a list of temperature-sensitivity for mass balance in all the different glacier regions.

The concept of temperature-sensitivity of mass balance was first popularized by Oerlemans and Fortuin (1992) and has been further developed by Laumann and Reeh (1993), Jóhannesson and others (1995), Jóhannesson (1997), Braithwaite and Zhang (1999a), Braithwaite and others (2003), de Woul and Hock (2005) and Braithwaite and Raper (2007) to just mention a few.

GLACIERS AND TOPOGRAPHY (Lecture 1 Slides 8-13)

Let us start by considering the conditions for forming a glacier. You need: (1) topography on which the glacier can lie, (2) low enough temperatures at high altitudes to allow snow to form, (3) a path down which the glacier can flow to lower altitude, and (4) high enough temperatures at low elevation to melt all the ice flow from higher altitudes. Please note that the terms "high" and "low" are relative. Also, you should note that we are only talking about glaciers with significant melt, i.e. not the glaciers of the Dry Valleys in Antarctica.

If we look at the global distribution of glaciers together with global topography we can see the clear topographic control on glaciers insofar as they are found in mountain ranges. Glaciers in the Arctic are generally found at a 100's of meters while glaciers can only exist in temperate and tropical areas at altitudes of 1,000'of meters. The topographic control on glaciers is also clear when we look at the remains of former glaciers.

CENTRAL IMPORTANCE OF ELA (Lecture 1 Slides 14-22)

Glacier mass balance is generally positive in the higher parts of a glacier and negative in the lower parts. The altitude where mass balance is zero is termed the equilibrium line altitude (ELA). The ELA is of key importance if you want to compare different glaciers, for example in different regions, or to compare a glacier in one state with the same glacier in a different state, i.e. in different years or in different geological epochs. Braithwaite (2008) notes that the *terminology* of ELA only dates back to the 1950's while the ELA *concept* can trace its ancestry back to the snowline concept first studied in the 18th Century. This means that we can use lots of old ideas when discussing modern ELA.

The glaciation level is a concept related to the ELA. Using a topographic map, possibly supplemented by aerial photographs, you can trace the altitude where glacier exist. Østrem and others (1981) have done this southern Alaska. This work is interesting because it illustrates some important concepts for *A/The Geography of Glaciers*. The glaciation rises rapidly as one goes inland from the coast. Østrem and others (1981) estimate the precipitation and temperature at the glaciation level. The winter precipitation and summer temperature both decline as one proceeds inland. This may seem counter-intuitive as summer temperature should generally rise as one goes inland but the point here is that we are following the glaciation limit.

The work of Østrem and others (1981) is a nice illustration of the maritime/continental effect which a key control on glacier geography.

ELA has a dual nature. It is a <u>variable</u> that we can measure from year to year, and correlate with year-to-year fluctuations of climate. ELA is also a <u>parameter</u> as it can be a constant in a certain case and different in another case. So the mean ELA for a 30-year period of record is a parameter as is the balanced-budget ELA, i.e. the ELA value that gives zero mean specific balance for the whole glacier.

INTERNATIONAL DATASETS (Lecture 1 Slides 23-24)

Measured mass balance data for several hundred glaciers are available from the World Glacier Monitoring Service (WGMS), formerly the Permanent Service for the Fluctuation of Glaciers (PSFG).

Data from the World Glacier Inventory (http://nsidc.org/data/glacier_inventory/browse.html) are available for about 130,000 glaciers in many regions. The data consist of topographic parameters like area and length, and various altitudes including minimum and maximum altitude, sometimes median altitude, and occasionally estimates of snowline in a particular area. The WGI data generally refer to conditions in the mid- to late-20th Century and are incomplete in coverage. Most of Eurasia is covered by the WGI including the very large ice areas of the FSU (Former Soviet Union) and China while there are huge gaps in the western hemisphere.

MASS BALANCE AND ELA (Lecture 2 Slides 1-4)

We start by assuming that the mean specific balance of the whole glacier is correlated with the ELA;

$$\underline{b}_t \quad = \quad \beta \,.\, (ELA_t - ELA_0) \qquad (3)$$

Where $\underline{b}_t$ is mean specific balance for year t, ELA_t is ELA for year t, ELA_0 is balanced budget ELA when mean specific balance is zero, and β is an empirical factor for each glacier. We then assume that the specific balance on the glacier is a linear function of altitude near to the ELA:

$$b_{it} \quad = \quad k \,.\, (h_i - ELA_t) \qquad (4)$$

Where b_{it} is specific balance at altitude h_i in year t, and k is balance gradient near the ELA. We recall the definition of mean specific balance as the area-weighted average of specific balances on the glacier:

$$\underline{b}_t \quad = \quad (1 / A)\, \Sigma\, A_i \,.\, b_{it} \qquad (5)$$

Where A_i is area around altitude h_i and A is total area

$$\underline{b}_t \quad = \quad - k \,.\, (ELA_t - h_{mn}) \qquad (6)$$

Where h_{mn} is the area-weighted mean altitude of the glacier. Comparing equations (3) and (6) we find that:

$$k \quad = \quad - \beta \qquad (7)$$

and

$$ELA_0 \quad = \quad h_{mn} \qquad (8)$$

The balance gradient for Hintereisferner is c. 0.5 m w.e./100 m altitude. The supposed equality of balanced-budget ELA and mean altitude was first stated by L. Kurowski in the late 19th Century if we allow for changes in terminology

INDIRECT ESTIMATATION OF ELA (Slides 5-11)

According to the above model, the balanced-budget ELA is approximately equal to the area-weighted mean altitude h_{mn} if the specific balance is a linear function of altitude, i.e. the vertical gradient of mass balance is constant. If we assume, further that the altitude-area distribution of the glacier is symmetrical, we can infer that mean altitude h_{mn} is equal to median altitude h_{med}, which is the altitude that divides the glacier area into two equal halves. That is to say that the median altitude h_{med} has an accumulation-area ratio AAR of 0.5.

Results from many glaciers show that mass balance gradient is generally not constant (Braithwaite and Raper, 2009). For most glaciers the mass balance curve flattens out in the accumulation area so a proportionally larger accumulation area is needed to produce a balanced-budget, i.e. an AAR rather larger than 0.5. For example, AAR = 0.67 has been suggested for alpine glaciers.

In the lecture I will show several graphs of year-to-year variations in ELA for Hinteisferner in comparison with parameters like ELA_0, H_{50}, H_{67} and H_{mn}.

I then discuss in detail the correlation of ELA and annual balance for as many glaciers as I could find data for (Braithwaite and Raper, 2009).

CLIMATE AT ELA (Lecture 2 Slides 11-23)

Ohmura and others (1992) is seminal work on the climate at the ELA, which Braithwaite (2008) extends to include the degree-day model.

Estimation of temperature at the ELA as done by Ohmura and others (1992) and Braithwaite (2008) depends upon being to extrapolate temperature data from low-lying stations to the ELA. In the lecture, I show a number of slides to support the idea that we can accurately extrapolate temperatures in this way, using 1961-1990 mean temperatures from many stations in Switzerland. Although air temperature depends linearly on altitude, the lapse rate varies somewhat through the year, with highest values April-June (unpublished)

In addition to temperature lapse rate we also have to take account of the “glacier cooling effect” for which there is some empirical evidence (unpublished).

Braithwaite (2008) applies the degree-day model to the same data as used by Ohmura and others (1992) and shows there is no single curve relating annual accumulation to summer mean temperature: rather there is a family of curves depending upon the annual temperature range at the glacier in question.

VARIATIONS IN MASS BALANCE (Lecture 3 Slides 1-18)

I first start by discussion variations in observed mass balance, mainly from Braithwaite (2005 & 2009). In particular, I show that mass balance variability depends upon the climatic setting. This, in turn, is expressed by the maritime/continental aspect of the glacier location as given by a graph of annual precipitation versus annual temperature range.

There is a clear bias in observed mass balance data (Braithwaite, 2009) in that measured glaciers have generally higher precipitation than the global norm. This effect appears to be unknown to the WGMS and one has to be skeptical about the annual summary of mass balance measurements shown on their website (http://www.geo.uzh.ch/microsite/wgms).

I then discuss variations in modeled mass balance, mainly based upon the degree-day model using air temperature data extrapolated to the ELA (Braithwaite and Raper, 2007). The degree-day model is "tuned" to fit observed mass balance data and is then "tweaked" to assess mass balance sensitivity to climate. This approach was pioneered by Oerlemans and Fortuin (1992).

I only discuss the sensitivity of mass balance to a constant temperature change throughout the whole year as this demonstrates the principles of the approach. There are other sensitivities that have been used, for example the sensitivity to a 10% change in annual precipitation, or the sensitivity to changes in only summer temperature.

It is striking that the temperature-sensitivity of the degree-day model (Braithwaite and others, 2003) is remarkably similar to the temperature sensitivity of the energy balance model of Oerlemans and Fortuin (1992). This is shown in my slide number 11. Although the Oerlemans and Fortuin (1992) model is described as an energy balance model it does also contain a temperature-dependant term for which the authors give no justification. This similarity of the degree-day and energy balance models appears to be due to this choice of coefficient.

The models of Braithwaite and others (2003) and Oerlemans and Fortuin (1992) agree in stating that mass balance sensitivity depends in some way on precipitation, e.g. as expressed by the maritime/continental setting of the glacier (slide 12). One can relate the effect shown in slide 12 (models) that that shown in slide 4 (observations). In the real world, the temperature is fluctuating from year-to-year generating a mass-balance series with greater or lesser variability (standard deviation) depending upon the magnitude of temperature-sensitivity of mass balance.

In the last few slides I show some degree-day model results on mass balance at the ELA in several widely varying regions (Braithwaite and Raper, 2007). Accumulation at the ELA varies by a factor of about 20 between Axel Heiberg Island (Arctic Canada) and New Zealand, while Scandinavia (north and South) and the Alps have similar conditions. Similarly, temperature-sensitivity varies greatly between Axel Heiberg Island and New Zealand with roughly similar conditions in Scandinavia (north and south), the Alps and the Caucasus.

To put these results into a local context (slide 18) we would expect high accumulation and high temperature-sensitivity of mass balance around the Gulf of Alaska (a high precipitation region) and relatively low accumulation and sensitivity across the Canadian Arctic (a low precipitation region). The popular construct of Alaska is "northern" but would prefer to call it "wet".

OUTLOOK

I confess that I had hoped to be further along with my great project *A/The Geography of Glaciers*. The thing that set me back by several months was the release of new version of the World Glacier Inventory in early 2012. I had made great progress assimilating the old WGI with the glacier cover shown by *Digital Chart of the World* and with a 0.5 degree digital climatology but I had to go right back to scratch with the new WGI.

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