Module 2-AL (January 21, 2015)
Approaches to model glacier mass balances

Learning objectives

You have an overview on different methods to extrapolate point measurements to glacier wide mass balances and you have an idea about the related uncertainties.

You are aware of the two different approaches to model glacier mass balances (complexity, input data, application scale, etc.) and you can address their advantages and shortcomings.

Terms and Concepts

Energy balance, mass balance (point, area, time), specific mass balance, methods to determine mass balance (and their sources of uncertainty), natural/stratigraphic budget year, mass balance gradient, inter- and extrapolation, profile method, contour line method, melt modelling, temperature-index model, degree-day factor, energy balance model

References and Further Reading

Literature

Cogley et al. (2011): Glossary of glacier mass balance

Østrem & Brugman (1991): Glacier mass balance measurements, a manual.

Cogley (2012): An overview on current research on glaciers and their modelling tools

Hoelzle et al. (2005): About different modelling approaches

Hock (2005): Review on processes of glacier melt and their modelling

Hock (2003): Review on temperature-index models

Paul et al. (2008): Overview on mass balance modelling and an energy balance model

Additional Information

Melt of Ice

Ice and snow melt at 0°C, but this does not necessarily mean that melting occur with an air temperature ≥ 0°C. Glacier melting is determined by the energy balance at the glacier surface, where air temperature is only one factor among many. The energy balance is the balance between all positive and negative energy flows to the surface and is controlled by meteorological conditions and physical properties of the glacier surface.

Mass Balance Modelling

The mass balance of a glacier results from climate. If non-climate mechanical processes can be excluded (e.g. surging, kinematic waves, avalanches) the mass balance can be derived from climate records. Depending on the accuracy and availability of climate data a variety of models can be applied. Most models focus on the ablation season using simple degree-day approaches or more sophisticated energy balance methods. To date, all of models have to be calibrated for the glacier in question. Thus, mass balance data are needed, at least in the beginning.

Energy balance methods

Melting can be modelled through calculating the energy balance, i.e. the energy that is available for melting. The energy balance of a temperate glacier can be calculated with the help of the following meteorological data at one level (e.g. 2 m) on the glacier:

- net radiation
- air temperature (--> used to compute the sensible heat flux)
- air humidity (--> used to compute the latent heat flux)
- wind speed (--> used to compute the sensible and latent heat fluxes).

The energy balance components (if not measured directly) can be approximated with the help of appropriate parameterizations, i.e. as functions of variables that control the component and that can be measured simply. This usually includes a simplification of the physical processes.

Instead of net radiation, the different radiation components can be measured separately. In practice, parameterizations are most often used because radiation measurements are expensive and difficult to obtain under the difficult conditions that typically prevail on a glacier. So incoming longwave radiation can, for example, be parameterized with the help of air temperature, humidity, and cloud data. A large number of the parameterizations for the different components of the energy balance have been developed.

Temperature index methods

Energy balance methods are physically based but require input data that are often not available. Therefore, in practice, the temperature index method is usually employed. The method is based upon an empirical relation between melting and air temperature. Despite the fact that it is the energy balance that determines how much can melt, it has been shown that over longer periods (>days/weeks) melting correlates well with air temperature. This is due to the fact that most energy balance components directly or indirectly depend upon air temperature. For example, the turbulent flux, incoming longwave radiation, and rain heat flux are directly a function of air temperature, while the air temperature is in turn indirectly affected by solar radiation. The simplest method is what is known as the **degree-day method**, where melt, M, is proportional to the positive temperature. Daily melt is calculated multiplying a degree-day factor by the positive temperatures. The degree-day factor is the coefficient of proportionality $f = -a/\varphi$ between surface ablation a (which is negative) and the positive degree-day sum φ over any period.

The degree-day factor parameterizes all of the details of the energy balance that results in ablation by melting and possibly sublimation, and is therefore a simplification. It is usually treated as one or more constants; in particular, it is different for snow and for glacier ice, because the ice is generally less reflective than snow. It is usually expressed in mm w.e. K^{-1} d^{-1} or kg $m^{-2}K^{-1}d^{-1}$. Melting is assumed to be zero when the air temperature is ≥ 0ºC. Different variations of the traditional degree day method have been developed.

Advantages and disadvantages of the two MB modelling approaches

The main advantage of temperature-index/degree-day models is the small amount of input data they require, the wide availability of temperature data, the easy interpolating and forecasting and the computational simplicity. Their main disadvantage is that these models are not physically but empirical based, the high variation of degree-day factors from glacier to glacier and therefore the requirement to work on average condition or to restrict it to a specific glacier with a known degree-day factor.

The main advantage of energy balance models is that their strict, process-based physical rules allow their application to large regions and projections are more reliable. Their major disadvantage is the large amount of (meteorological) input data they require, which is often not available, but can be parameterized from other known variables or held constant.

References

Cogley, G. (2012). The Future of the World's Glaciers. In: The Future of the World’s Climate, (edited by Henderson-Sellers, A. and McGuffie, K.), pp. 197–222. Elsevier, Amsterdam.

Cogley, J., Hock, R., Rasmussen, L., Arendt, A., Bauder, A., Braithwaite, R., Jansson, P., Kaser, G., Möller, M., Nicholson, L., and Zemp, M. (2011). Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

Hock, R. (2003). Temperature index melt modelling in mountain areas. Journal of Hydrology,c282 (1–4): 104–115. doi: 10.1016/S0022-1694(03)00257-9.

Hock, R. (2005). Glacier melt: a review of processes and their modelling. Progress in Physical Geography, 29 (3): 362–391. doi: 10.1191/0309133305pp453ra.

Hoelzle, M., Paul, F., Gruber, S., and Frauenfelder, R. (2005). Glaciers and permafrost in mountain areas: Different modeling approaches. In: Global change impacts in mountain biosphere reserves, (edited by UNESCO), pp. 28–39.

Østrem, G. and Brugman, M. (1991). Glacier mass-balance measurements: a manual for field and office work. NHRI Science Report.

Paul, F., Machguth, H., Hoelzle, M., Salzmann, N., and Haeberli, W. (2008). Alpinewide distributed glacier mass balance modelling: a tool for assessing future glacier change? In: Darkening Peaks: Glacier Retreat, Science, and Society, (edited by Orlove, B., Wiegandt, E., and Luckman, B.), pp. 111–125. University of California Press, Berkeley and Los Angeles.