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Document Version
Accepted author manuscript

Citation for published version (APA):
Braithwaite, R. J. (2011). Degree-days. In V. P. Singh, P. Singh, & U. K. Haritashya (Eds.), *Encyclopedia of snow, ice and glaciers* (pp. 196-199). (Encyclopedia of Earth Sciences Series). Springer Nature.

Published in:
Encyclopedia of snow, ice and glaciers

Degree-days

Roger J. Braithwaite
Geography Programme
School of Environment and Development
University of Manchester
Manchester M13 9PL, U.K.
E-mail: r.braithwaite@manchester.ac.uk
Tel: +44 161275 3653

Synonyms

Degree-day methods
Degree-day factor
Degree-day total or positive degree-day sum

Definitions

Degree-day methods. The melting of snow and ice is assumed to be related to air temperature as long as air temperature is above a critical threshold, usually close to the melting point of ice. In particular, the amount of snow or ice melted at a certain place, during a certain period, is assumed proportional to the sum of positive temperatures (on the Celsius scale) at the same place and in the same period. The amount of melt is linked to this *positive degree-day sum* by the *degree-day factor*. In the present article, *air temperature* refers to conventional measurements made c. 2 m above the snow or ice surface, or extrapolated from a similar station in the same region.

The melting of snow and ice and air temperature

By the end of the 19th Century, the general importance of air temperature for the melting of snow and ice was widely recognized (Hann, 1903) although few data were then available. Finsterwalder and Schunk (p. 82, 1887) assume "in the absence of direct observations" that ice ablation on a glacier depends on the length of the snow-free period and on the average temperature above the freezing point during that period. The product of these two factors is clearly related to our degree-day sum. Finsterwalder and Schunk (1887) made no connection but temperature sums above some critical threshold were already widely used in discussion of temperature control of vegetation (Hann, 1903).

The full history of degree-day methods in hydrology remains to be written but the relation between snowmelt runoff and degree-day sums was already well known to Wilson (1941) who tried to explain it in thermodynamic terms. Early workers appear to have compared snowmelt runoff from a whole basin with the degree-day sum at a particular site so the numerical value of any factor linking the two variables has no general significance and is not usually published. The degree-day approach is still widely used for estimating runoff from melting snow although, significantly, De Walle and Rango (2008) do not include values of the degree-day factor in their detailed table of Snow Runoff Model (SRM) applications and results for 112 case studies. The TS-variable developed by Hoinkes and Steinacker (1975) is also based on the degree-day concept and gives a reasonably high correlation with annual mass balance series but, again, the numerical value of the factor linking the TS-variable to the annual balance is not given.

Zingg (1951), de Quervain (1979) and Kuusisto (1984) estimate degree-day factors for seasonal snow by comparing data from snow stakes with air temperature data at the same site, and their degree-day factors can therefore be compared, see Hock (2003).

The key role of air temperature in variations of glacier mass balance may seem obvious to us today but Hoinkes (1955) explicitly downplayed the role of air temperature in controlling glacier melt. Slater (1927) may have been the first worker to measure ablation and air temperature at the same location. Leaving aside the crudity of his instruments, his result is equivalent to a degree-day factor for melting ice of 9.1 mm d^{-1} K^{-1}. From various glaciers in the former Soviet Union, Krenke and Khodakov (1966) suggest degree-day factors of 4.5 and 7 mm d^{-1} K^{-1} for snow and ice respectively. Orheim (1970) also calculated degree-day factors for melting ice over two years on a Norwegian glacier and found values of 6.1 and 6.5 mm d^{-1} K^{-1}, which are not included in Hock (2003).

The measurement of daily melt on glaciers by Müller and Keeler (1969) in parallel with meteorological measurements was a significant development and allowed Braithwaite (1981) to model daily ablation in terms of air temperature and energy balance. He obtained an average degree-day factor of 6.3±1.1 mm d^{-1} K^{-1} for the four series studied, equivalent to a total of 123 days of record. Daily measurements of ice melt were made over a number of summer seasons (1979-86) at two sites on the Greenland ice-sheet margin at Nordbogletscher (415 days) and Qamanârssûp sermia (512 days) (Braithwaite, 1995).

Variations in degree-day factors

There are substantial variations between degree-day factors at various sites on glaciers. For example, see extensive tables and discussion in Braithwaite (1995), Braithwaite and Zhang (2000), Hock (2003 and 2005), and especially some previously unpublished values from the high mountains of China in Zhang *et al.* (2006). These results are mainly based on melt data from stakes on glaciers but Braithwaite (2008) has also used a simple model to assess degree-day factor at the equilibrium line altitude (ELA) of 66 glaciers.

Degree-day factors are generally lower for snow and higher for ice (Table 1). Monthly estimates of degree-day factors for melting ice at Nordbogletscher and Qamanârssûp sermia (Braithwaite, 1995) describe time variations in degree-day factor. Similarly, time variations are illustrated by a 28-year series of snow melt data from Weissfluhjoch, Switzerland (de Quervain, 1979). Degree-day factors listed by Hock (2003) for both ice (32 sites) and snow (18 sites) illustrate variations between different locations and periods. Results from Braithwaite (2008) reflect different locations (66 glaciers) but also different methods based on either winter balance or "winter balance plus summer precipitation" from Ohmura *et al.* (1992).

From Table 1 it is clear that degree-day factors for ice and snow are not precise single values, even at the same place. Variations in degree-day factor in Table 1 are denoted by standard deviations but field data (Krenke and Khodakov, 1966) and analysis of the energy balance (Braithwaite, 1995) both suggest that very high degree-day factors for ice should only occur at low temperatures and not at random. The generally lower degree-day factor for melting snow compared with ice is mainly due to higher albedo which reduces the energy available for melting (Braithwaite, 1995), while time variations at the same locations presumably reflect differing weather conditions as expressed by variations in the surface energy balance.

Insofar as we can expect the different terms in the energy balance to vary geographically and temporally (Braithwaite, 1995 and Guðmundsson et al. 2009), we may expect some systematic variations in degree-day factor and there is some evidence for this. Zhang et al. (2006) claims a clear geographic variation in degree-day factor for ice from low values (2 to 3 mm d^{-1} K^{-1}) in the relatively continental Tien Shan in NW China to high values (15 mm d^{-1} K^{-1}) in the relatively maritime mountains of south China. Fausto et al (2009) have suggested different degree-day factors for ice over colder and warmer parts of the Greenland ice sheet, i.e. 15 and 7 mm d^{-1} K^{-1} respectively. Huss and Bauder (2009) claim to detect multi-year variations in glacier-averaged degree-day factor for Swiss glaciers (roughly equal to the degree-day factor for snow?) which they explain in terms of secular variations in global radiation.

Estimation of degree-day sums

The calculation of degree-day totals from raw temperature data is a trivial one of summing all the positive temperatures in a time series and a computer can do this easily. However, it would be very laborious to find and store long series of daily, or better sub-daily, temperature data if all we want to do is to calculate monthly or annual sums. Braithwaite (1985) therefore suggested that monthly degree-day totals can be calculated from monthly mean temperature by assuming that temperature is normally distributed within the month with standard deviations of about ±2 to ±4 K. The advantage of this approach is that monthly mean temperatures are now more widely available in digital form for individual climate stations, or for cells in a gridded climatology like that of New *et al*. (1999).

Reeh (1991) extended the approach of Braithwaite (1985) by noting that monthly mean temperatures can be approximated by a sine curve around the annual mean temperature if the annual temperature range is prescribed. Temperatures at any particular time are then assumed to be Normally distributed around the sine curve. Carlov and Greve (2005) revisit the calculations of Braithwaite (1985) and Reeh (1991) and propose a much more efficient algorithm suitable for the many repeated calculations needed for long-term simulations of the Greenland ice sheet.

Degree-day models

A degree-day model is one where snow and ice melt are calculated according to the degree-day method, for example as opposed to the energy-balance model, although extra procedures are needed to account for snow accumulation and refreezing of melt water. According to Hock (2003), degree-day models are widely used for four reasons: (1) wide availability of air temperature data, (2) relatively easy interpolation and forecasting possibilities for air temperature, (3) generally good model performance despite their simplicity and (4) computational simplicity.

The reported success of the degree-day approach to ice and snow melt at two sites in Greenland (Braithwaite and Olesen, 1989) inspired Reeh (1991) to further develop the model and test it with the limited amount of data from other sites in Greenland. Huybrechts *et al.* (1991) then used the degree-day model to calculate mass balance forcing for their model of ice dynamics for the whole Greenland ice sheet, assuming degree-day factors of 3 and 8 mm d^{-1} K^{-1} for snow and ice respectively. Many of the current models of Greenland mass balance follow Huybrechts *et al.* (1991).

Laumann and Reeh (1993), Jóhannesson *et al.* (1995), Jóhannesson (1997), Marshall and Clarke (1999), Braithwaite and Zhang (2000), Braithwaite et al. (2002), De Woul and Hock (2005), Raper and Braithwaite (2006), Anderson et al. (2006), Braithwaite and Raper (2007), Liu et al. (2009), Shea *et al*. (2009), Hughes and Braithwaite (2008) and Rasmussen and Wenger (2009) use different variants of the degree-day model to calculate mass-balances of glaciers outside Greenland. The relevant degree-day factors are either found by tuning models onto field data or are prescribed. In general, modelled accumulation depends upon the degree-day factor for snow, and mass-balance sensitivity depends upon the degree-factor for ice (Braithwaite and Raper, 2007). Balance gradients near the ELA depend on both degree-day factors with higher gradient in the upper ablation area and lower gradient in the lower accumulation area (Braithwaite and Raper, 2007). This predicted nonlinearity of the balance gradient is in reasonable agreement with observations (Furbish and Andrews, 1984: Rea, 2009).

Many workers use a simpler approach than the degree-day model whereby glacier melt is assumed to be a function of summer mean temperature. With appropriate choice of averaging period, e.g. June-August, May-September or May-October, the summer mean temperature mainly represents the effects of above-freezing temperatures. For example, Krenke and Khodakov (1966) assume a power-law relation between melt and summer mean temperature and their equation was used in constructing the *World Atlas of Snow and Ice Resources* (Kotlyakov *et al*., 1997).

Other workers follow Ahlmann (1924) in using an exponential relation to link melt to summer mean temperature (Nesje and Dahl, 2000). As the degree-day model predicts a family of curves linking melt to summer mean temperature (Reeh, 1991: Braithwaite, 2008) these different approaches are not in serious conflict as long as it is accepted that there can be no single curve linking melt to summer mean temperature.

Summary and outlook

There is generally a relation between the melting of snow and ice and air temperature which can be modelled using degree-day methods. No doubt the relative merits of degree-day and energy-balance methods will continue to be discussed but more climate data from glaciers in different climatic regions should be collected using modern data loggers that can be left unattended for long periods. At the same time, running degree-day and energy models in parallel may also be a fruitful line for future work in trying to understand the possible variations in degree-day factor. In particular, the role of sublimation in the energy balance of very high mountains in the Andes and High Asia deserves further study as does the effect of debris cover.

Roger J. Braithwaite

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Table 1. Mean and standard deviation of degree-day factors for melting ice or snow (from Braithwaite, 2008).

Location	Type	Degree-day factor mm d^{-1} K^{-1}		
		Mean	St. devn.	Sample
Nordbogletscher Braithwaite (1995)	Glacier ice	6.9	±1.1	Nearly daily data for 14 months
Qamanârssûp sermia Braithwaite, 1995)	Glacier ice	7.8	±1.0	Nearly daily data for 21 months
Hock (2003)	Glacier ice	8.9	± 3.7	32 sites
Weissfluhjoch, Switzerland De Quervain (1979)	Seasonal snow on land	4.2	±1.0	28 melt seasons
Hock (2003)	Snow on glaciers	5.1	± 2.2	18 sites
Braithwaite (2008) using data from Ohmura *et al*. (1992)				
(1) Winter balance	Snow at ELA	3.5	±1.4	66 glaciers
(2) Winter balance plus summer precipitation	Snow at ELA	4.6	±1.4	66 glaciers
(1) and (2) Combined	Snow at ELA	4.1	±1.5	2 × 66 glaciers