GEOGRAPHY OF GLACIERS 2

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EQUILIBRIUM LINE ALTITUDE (ELA)

- ELA (variable) is part of the annual balance
- Can estimate ELA (parameter) from glacier topography
- ELA (parameter) is a “standard altitude” for a glacier
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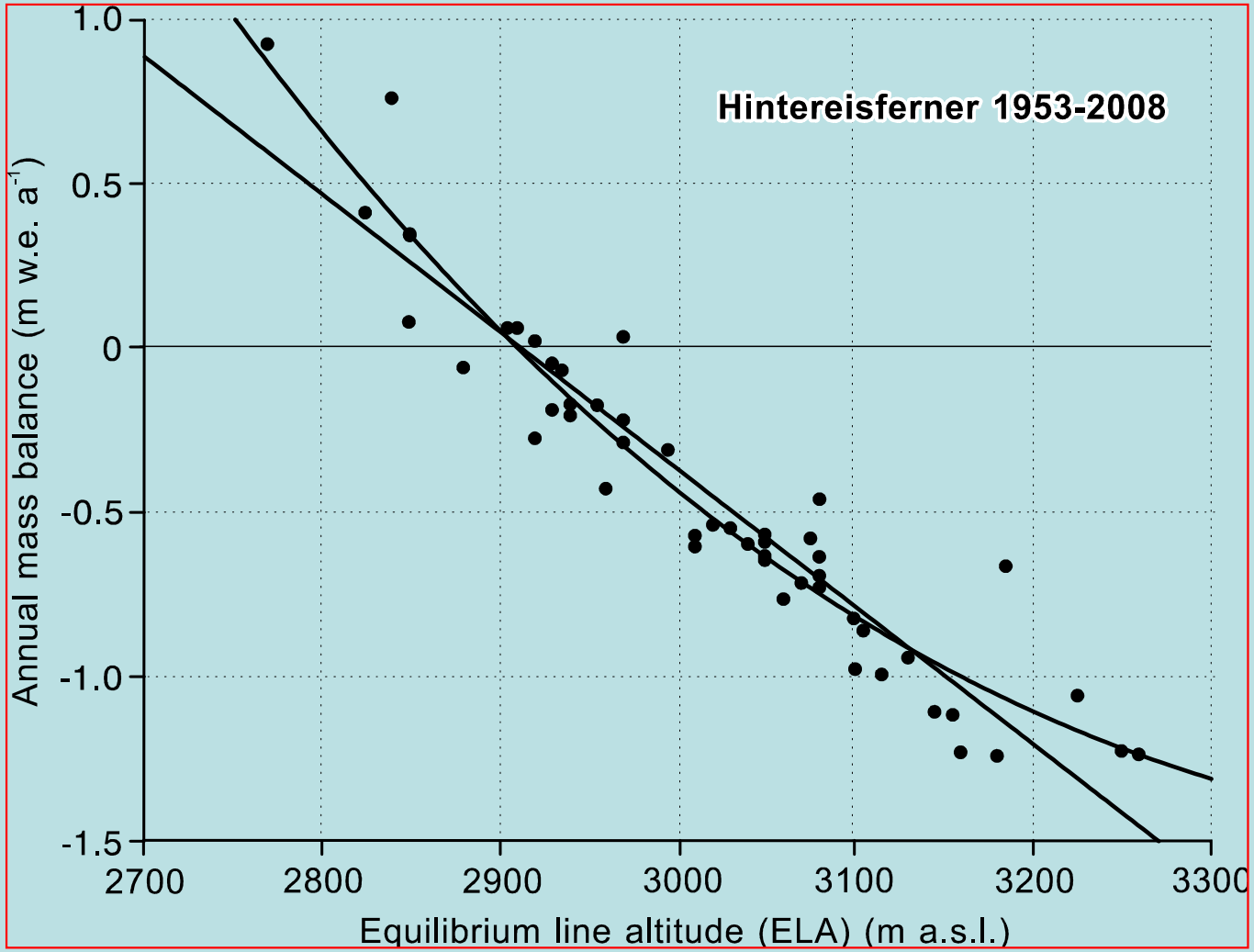
- Estimate ablation/accumulation at the ELA from air temperature
- Degree-day model

CORRELATION OF ELA AND ANNUAL BALANCE FOR HINTEREISFERNER



- Hintereisferner
- Year-to-year fluctuations are correlated
- Approximately linear relation
- Balance-budget ELA when balance = 0

SIMPLE MODEL

(Braithwaite & Raper, 2009)

- $\underline{b}_t = \beta \,.\, (ELA_t - ELA_0)$ (1)

Where $\underline{b}_t$ is mean specific balance for year t, ELA_t is ELA for year t, ELA_0 is balanced budget ELA, and β is empirical factor for each glacier

- $b_{it} = k \,.\, (h_i - ELA_t)$ (2)

Where b_{it} is specific balance at altitude h_i in year t, and k is balance gradient near the ELA

- $\underline{b}_t = (1 / A)\, \Sigma\, A_i \,.\, b_{it}$ (3)

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

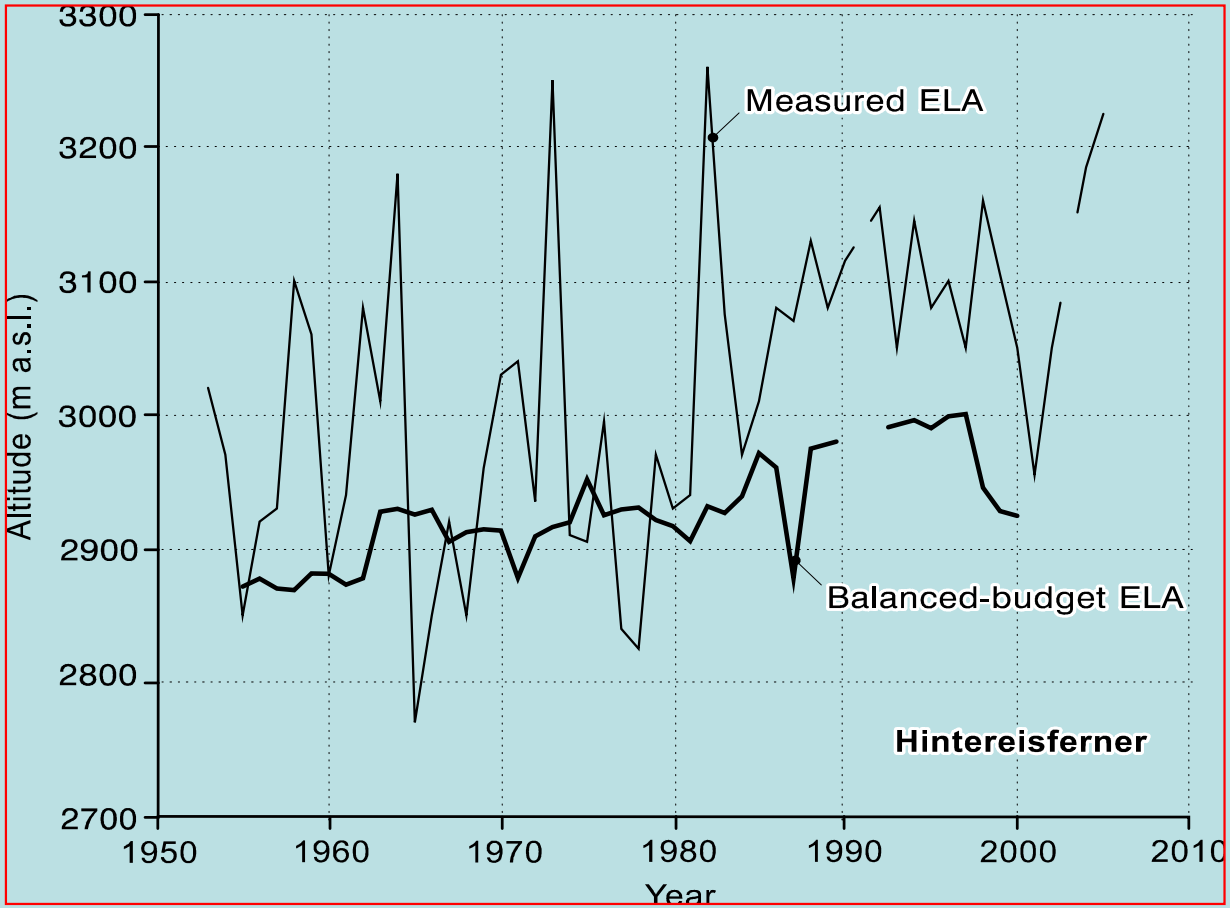
- $\underline{b}_t = - k \,.\, (ELA_t - h_{mn})$ (4)

Where h_{mn} is the area-weighted mean altitude of the glacier

- $k = - \beta$ (5)

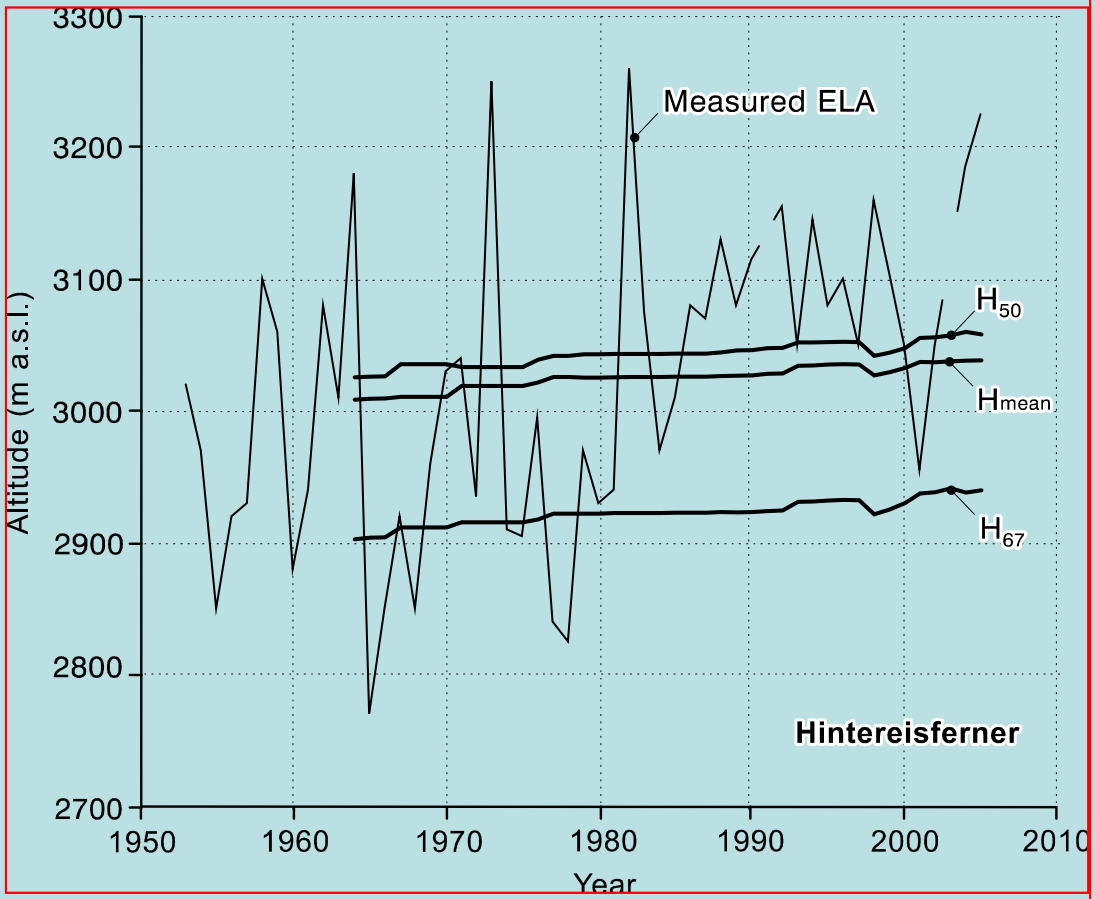
Balance gradient for Hintereisferner is c. 0.5 m w.e./100 m altitude. Equality of balanced-budget ELA and mean altitude first stated by Kurowski (1891) if we allow for changes in terminology

VARIABLE AND PARAMETER



- Hintereisferner has long MB record
- Calculate balanced-budget ELA for overlapping 5-year chunks of data
- Balance budget ELA varies but varies much less than ELA

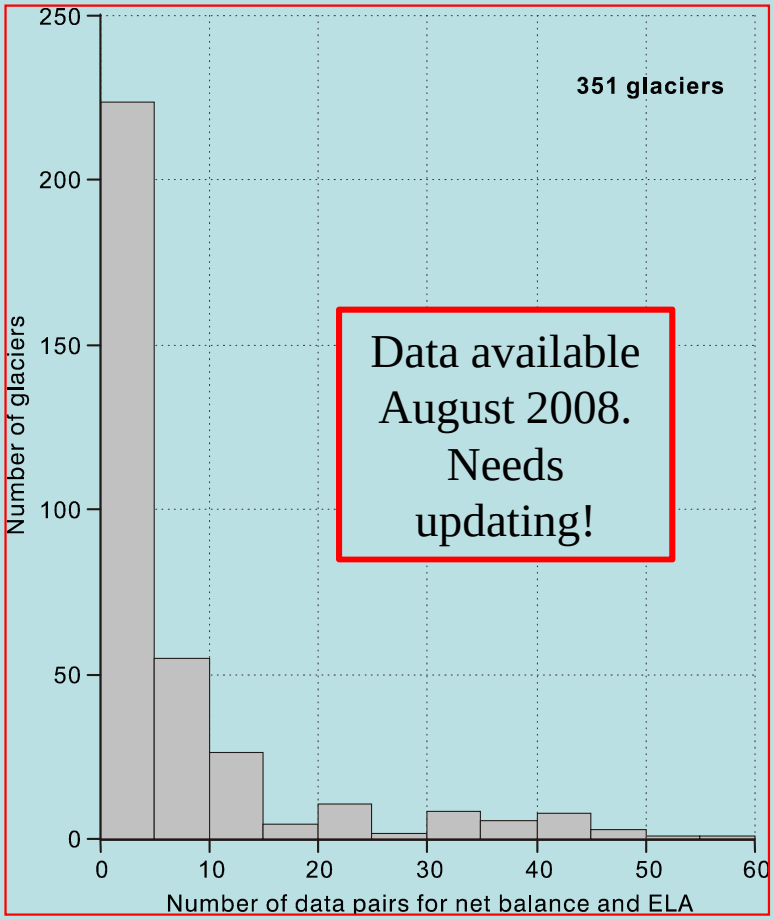
EXTENDING THE KUROWSKI MODEL



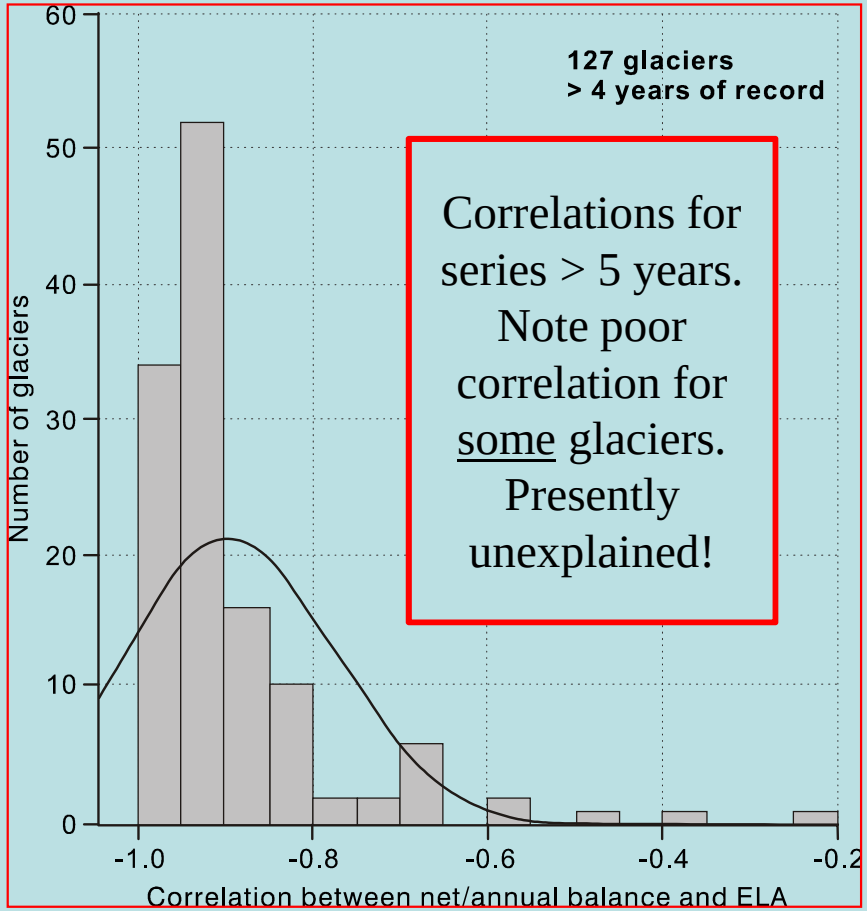
- If area altitude distribution is symmetric around mean altitude h_{mn}
- Median altitude $h_{med} = h_{mn}$
- Accumulation area ratio (AAR) = 0.5 for h_{med}
- AAR = 0.5 often assumed for balanced-budget ELA
- Balance gradient is not constant, suggesting that AAR > 0.5
- AAR = 0.67 suggested for alpine glaciers

CORRELATION OF ELA AND ANNUAL BALANCE FOR OTHER GLACIERS

(Braithwaite & Raper, 2009)



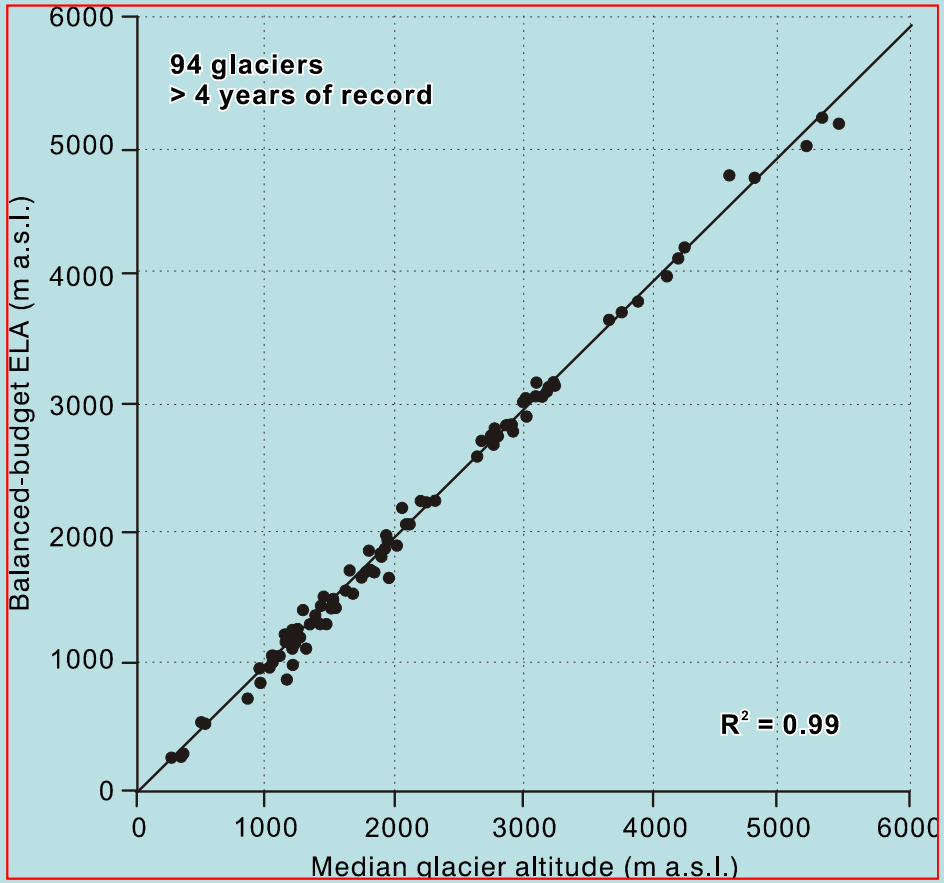
Data available August 2008. Needs updating!

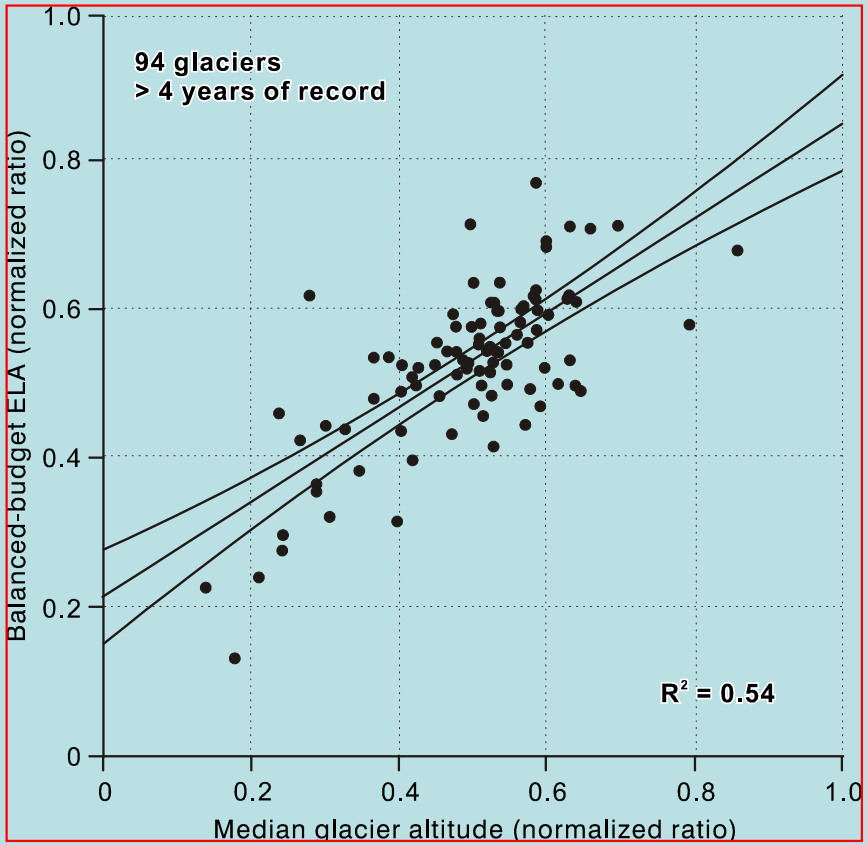


Correlations for series > 5 years. Note poor correlation for <u>some</u> glaciers. Presently unexplained!

BALANCED-BUDGET ELA AND MEDIAN ALTITUDE

(Braithwaite & Raper, 2009)





High correlation (on left) is forced by geographical variations
Lower correlations with normalized data

ESTIMATION OF BALANCED-BUDGET ELA

(Braithwaite & Raper, 2009)

Method	**Mean error**	**STD error**
Median altitude (94 glaciers)	-38 m	± 82 m
Mid-point altitude (94 glaciers)	-27 m	± 125 m

- Estimate balanced-budget ELA from median altitude h_{med} with error of c. ± 80 m
- If you don't know the median altitude, you can use the mid-point altitude $(h_{max} – h_{min})/2$ with a greater error of c. ± 130 m

NUMBERS

(Braithwaite & Raper, 2009)

Graphs 7-9 based on August 2008 dataset and can be updated anytime. In August 2008:

- MB data available for 351 glaciers
- 127 glaciers had > 4 years of MB-ELA record to calculate ELA_0
- 116 out of 127 glaciers had MB-ELA correlation < -0.71 to calculate <u>reliable</u> ELA_0
- 94 out of 116 glaciers had data h_{med} to <u>compare with</u> ELA_0

An update to 2010 will probably increase these numbers a little

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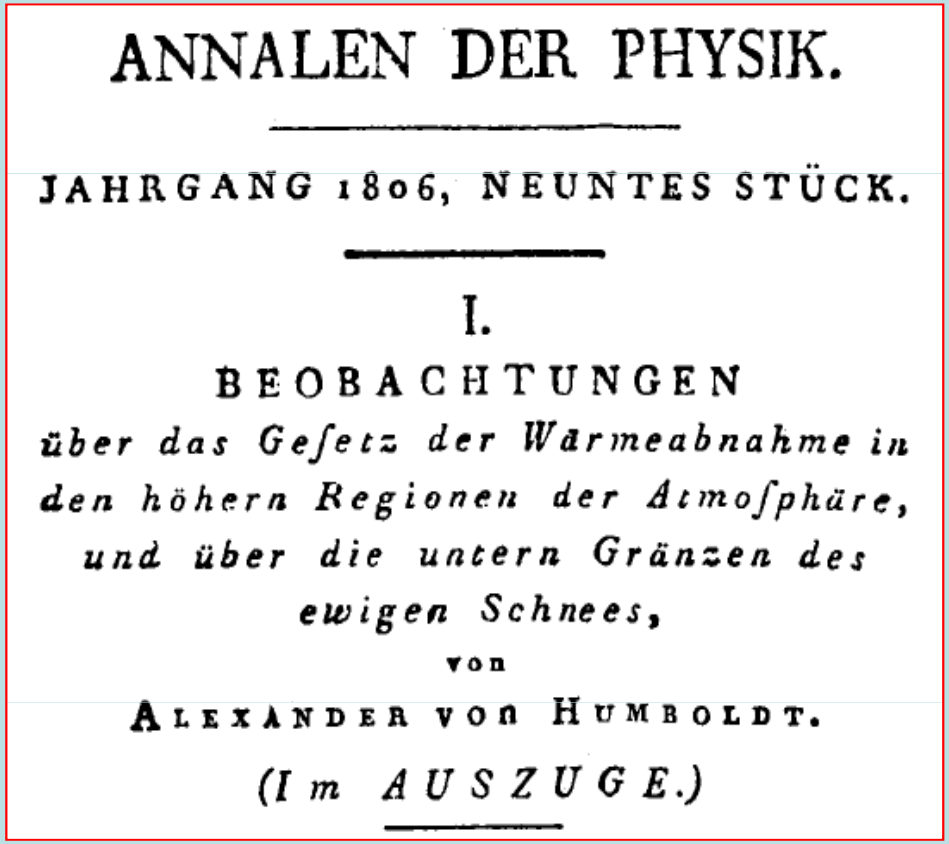
TEMPERATURE LAPSE RATE


ANNALEN DER PHYSIK.

JAHRGANG 1806, NEUNTES STÜCK.

I.

BEOBACHTUNGEN

über das Gesetz der Wärmeabnahme in den höhern Regionen der Atmosphäre, und über die untern Gränzen des ewigen Schnees,

von

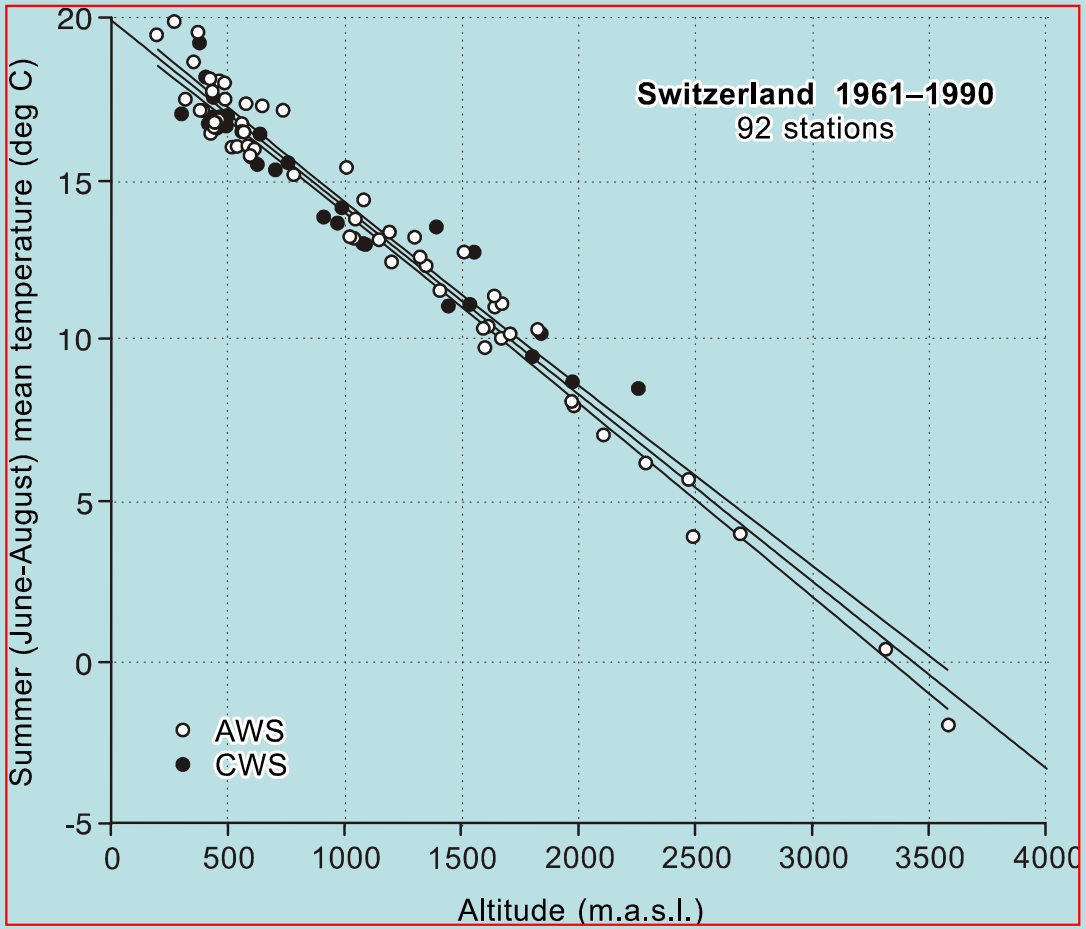
ALEXANDER VON HUMBOLDT.

(Im AUSZUGE.)

- ELA (a.k.a. snow line) and temperature lapse rate (TLR) have been linked for a long time
- TLR varies with season and latitude
- Models often use constant lapse rate of c. 0.6 K/100 m

TLR IN SWITZERLAND

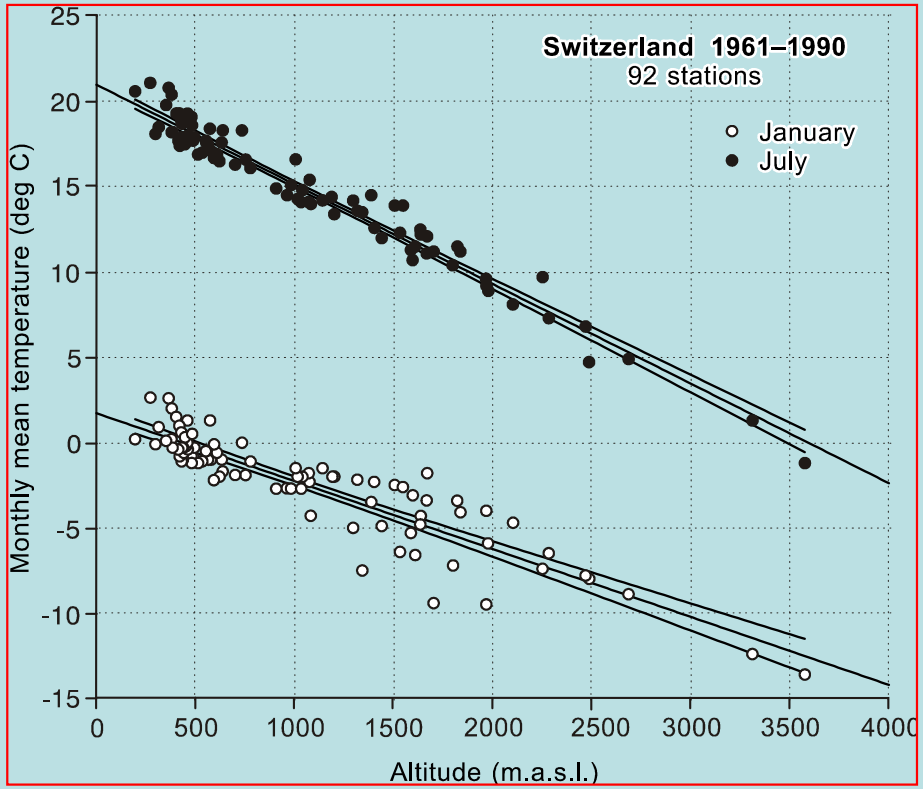
(Braithwaite, unpublished)



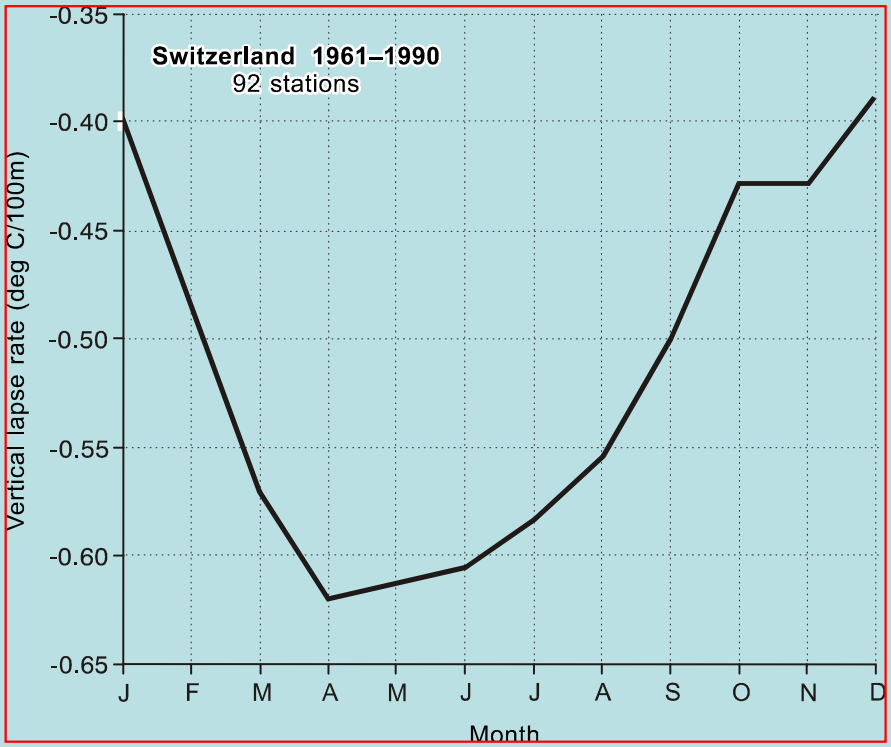
- Meteoswiss have published climatic norms for 1961-1990 for many stations
- We can plot summer (June-August) mean temperature versus altitude
- Strong linear correlation over large height range

SEASONAL VARIATION IN TLR

(Braithwaite, unpublished)



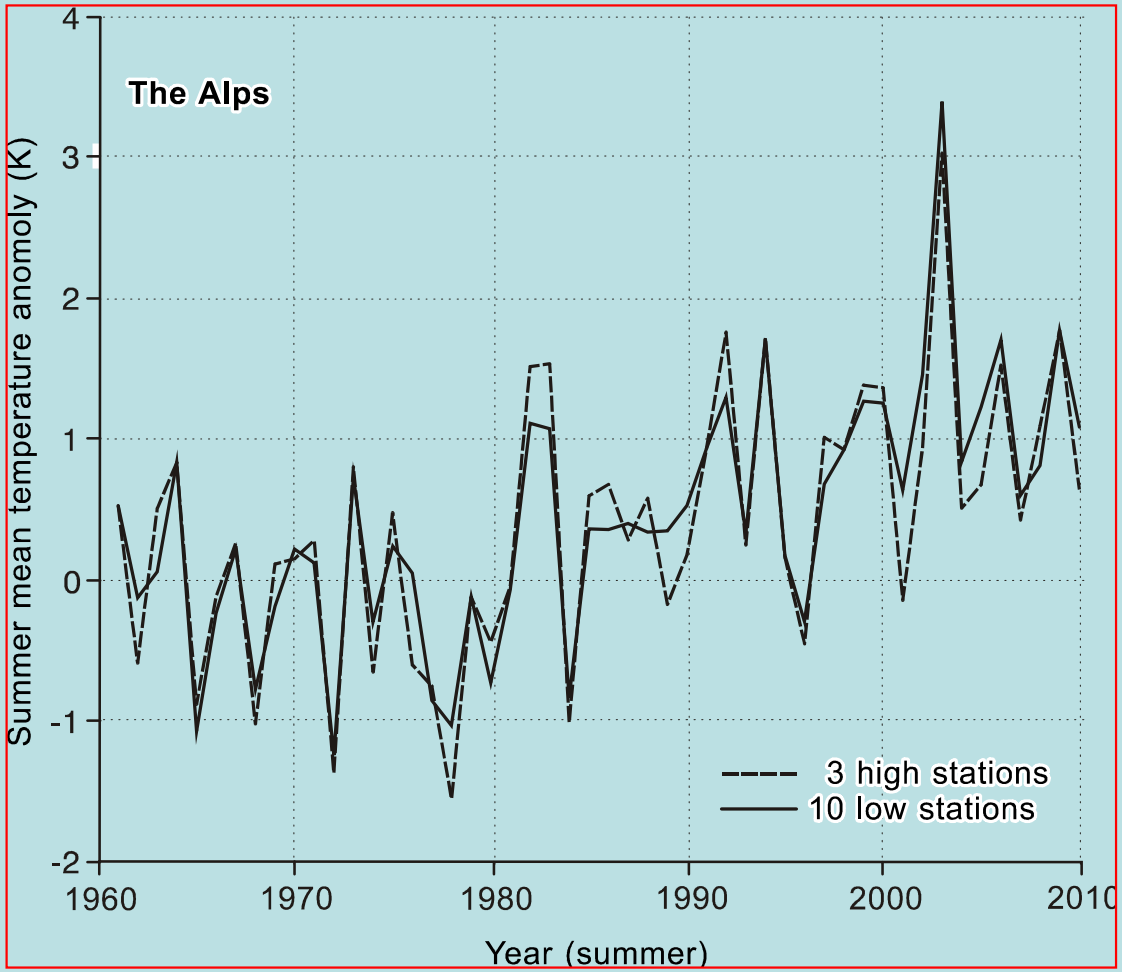
TLR for June-August somewhat less than 0.6 deg/100 m



Use regression lines for each month to calculate monthly TLR

TEMPERATURE ANOMALIES

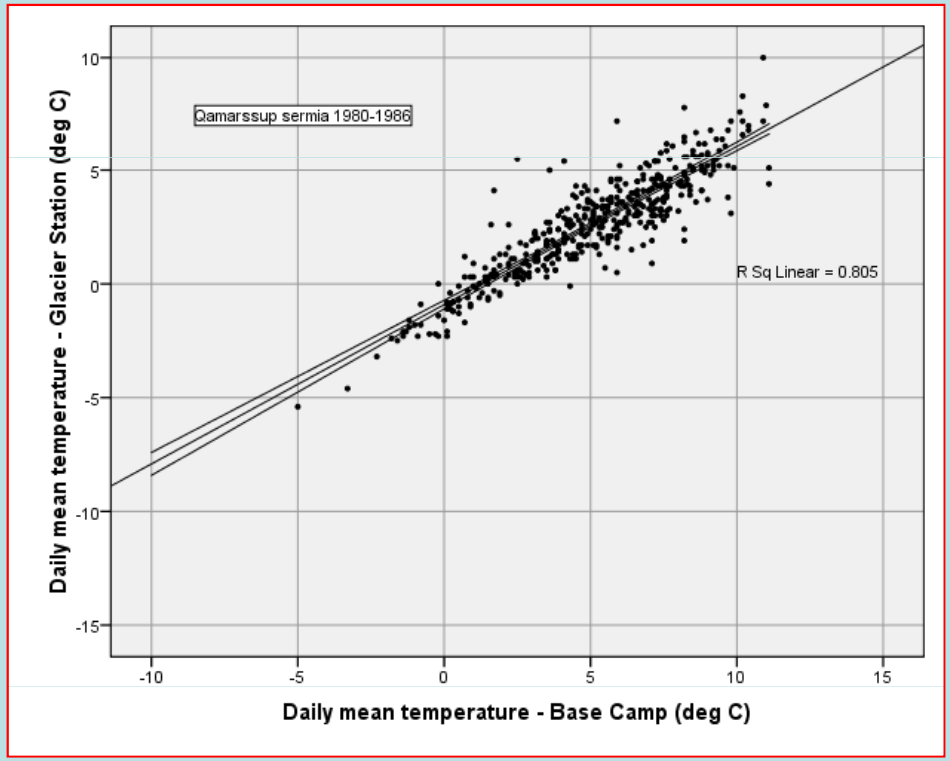
(Braithwaite, unpublished)



- Low and high stations in and around the Alps have remarkably similar patterns
- Suggests that TLR may not be much affected by climate change
- This point is worth watching!

GLACIER COOLING EFFECT - 1

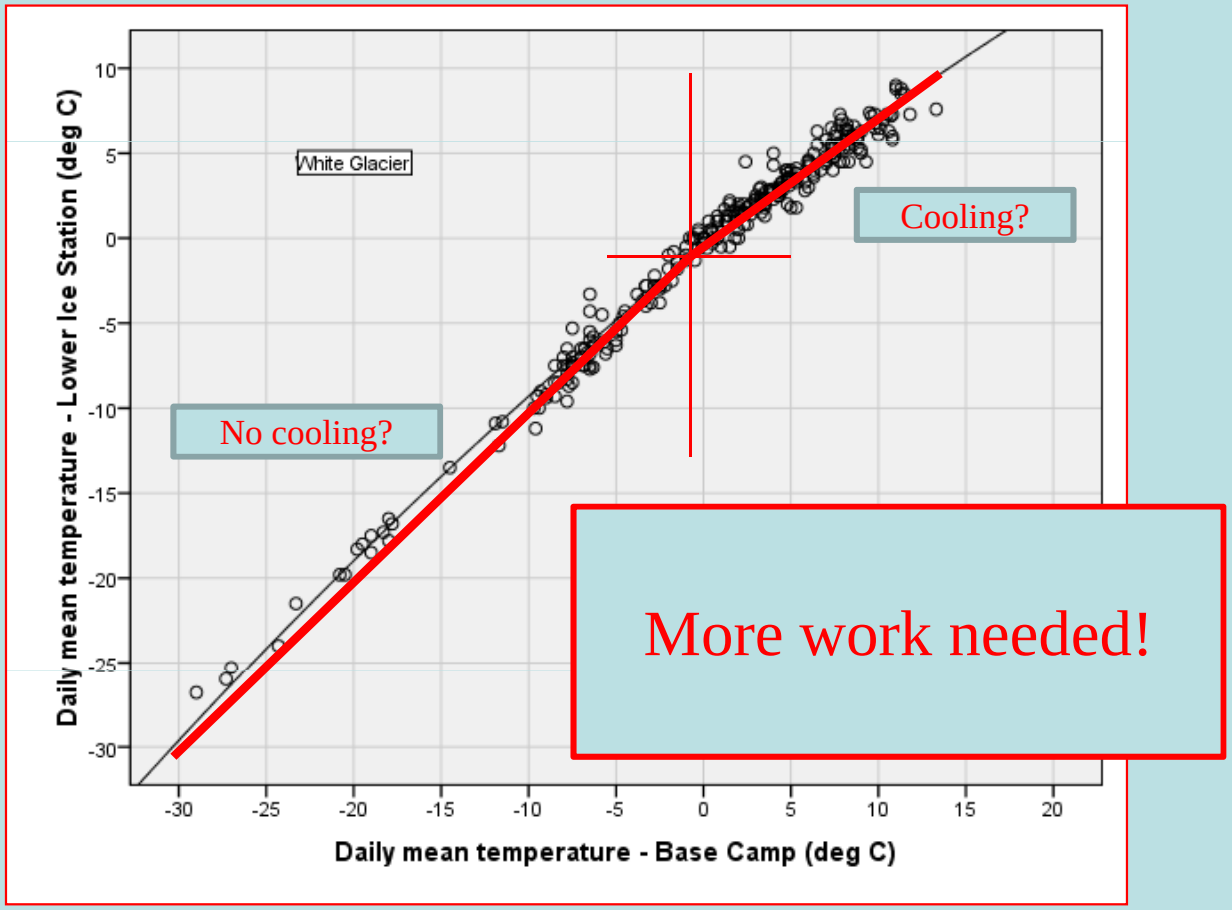
(Braithwaite, unpublished unsolved problem)



Very similar (but not same?) cooling effect at these two Greenland glaciers
Under climate change, glacier temperature will not rise as quickly as regional temperature

GLACIER COOLING EFFECT - 2

(Braithwaite, unpublished unsolved problem)



- Could there be a change of slope?
- For low temperatures glacier surface will be same temperature as snow-free ground
- For higher temperatures glacier surface will be fixed at 0 C

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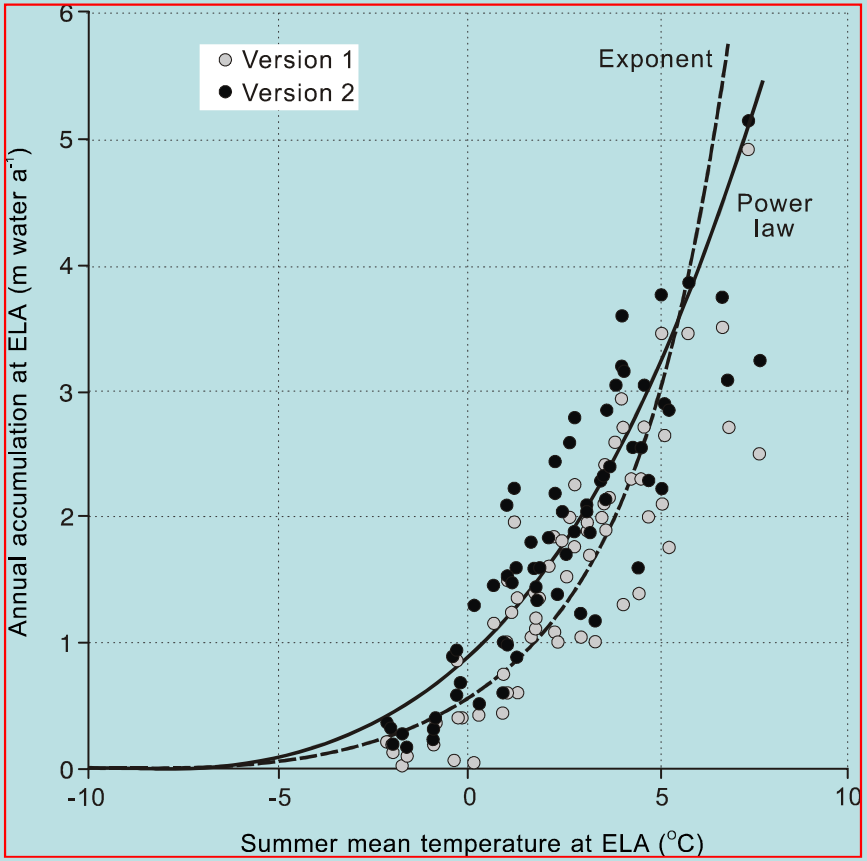
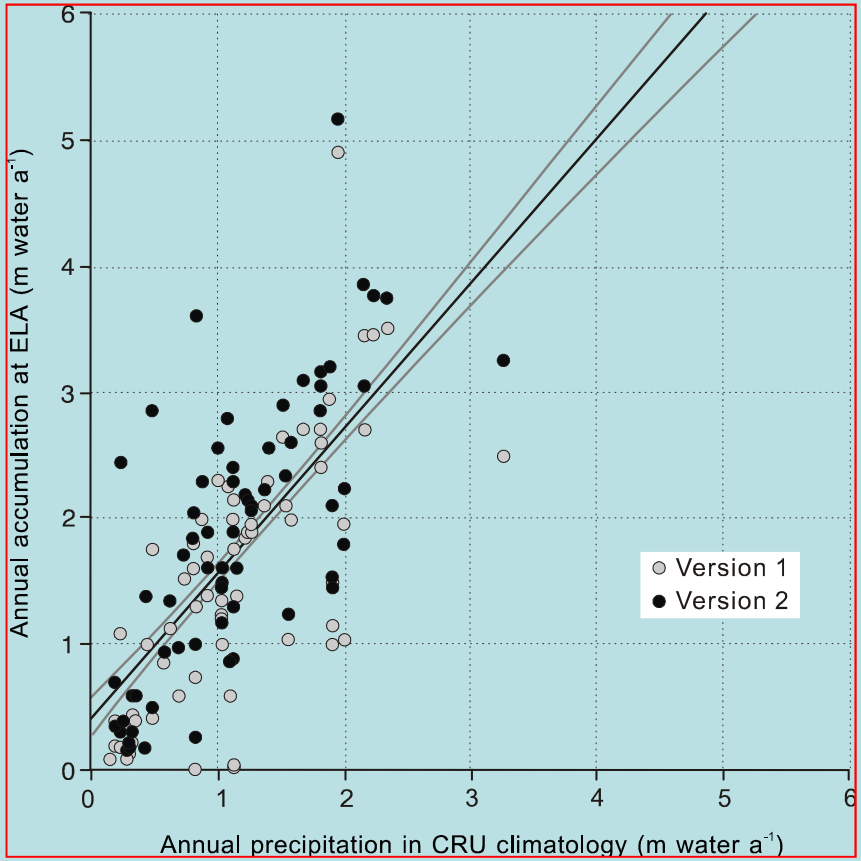
CLIMATE AT ELA

(Ohmura et al. 1992 and Braithwaite, 2008)



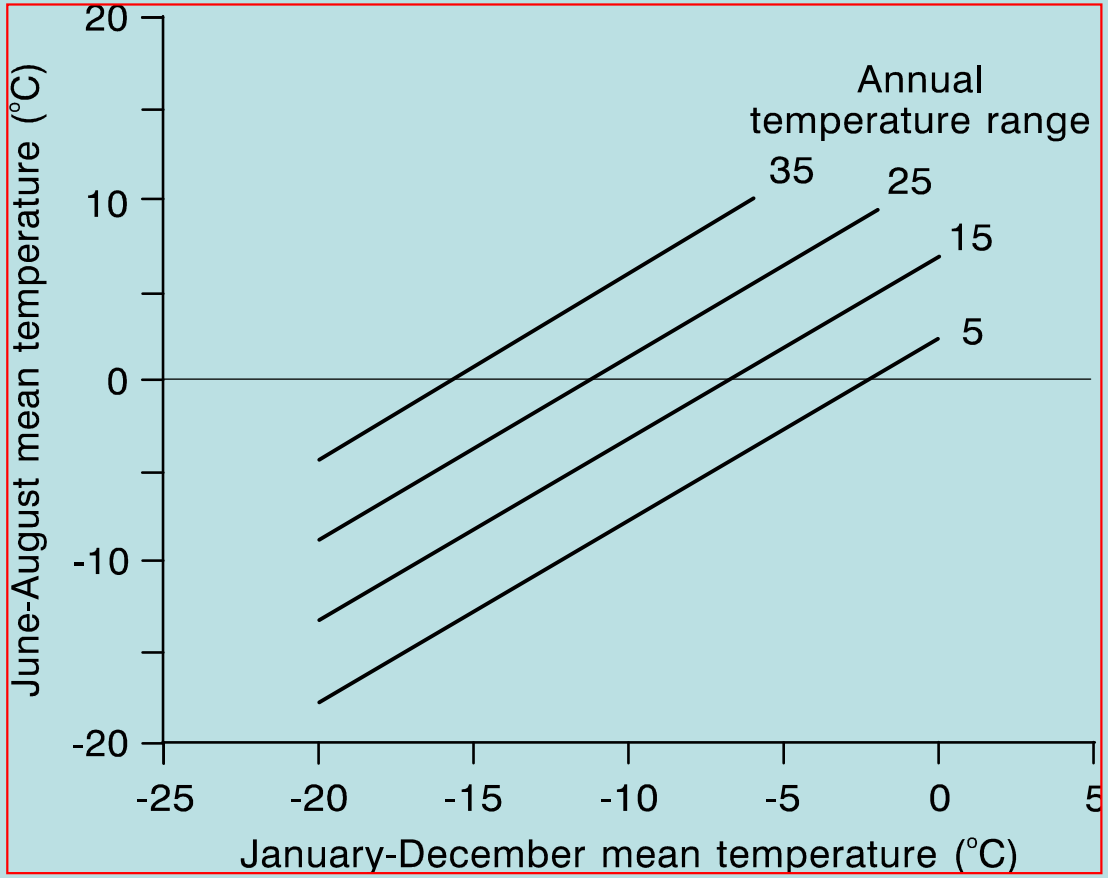


Ohmura et al (1992) gives winter balance and "winter balance + summer precipitation". Braithwaite (2008) interprets these as low (Version 1) and high (Version 2) estimates of annual accumulation (unmeasurable)

CLIMATE AT ELA

The logic, going back to Ahlmann (1922), is that (1) snowmelt is a nonlinear function of summer temperature, (2) snowmelt = snow accumulation at ELA, (3) snow accumulation is nonlinear function of summer temperature. Exponent and power law relations have been proposed.

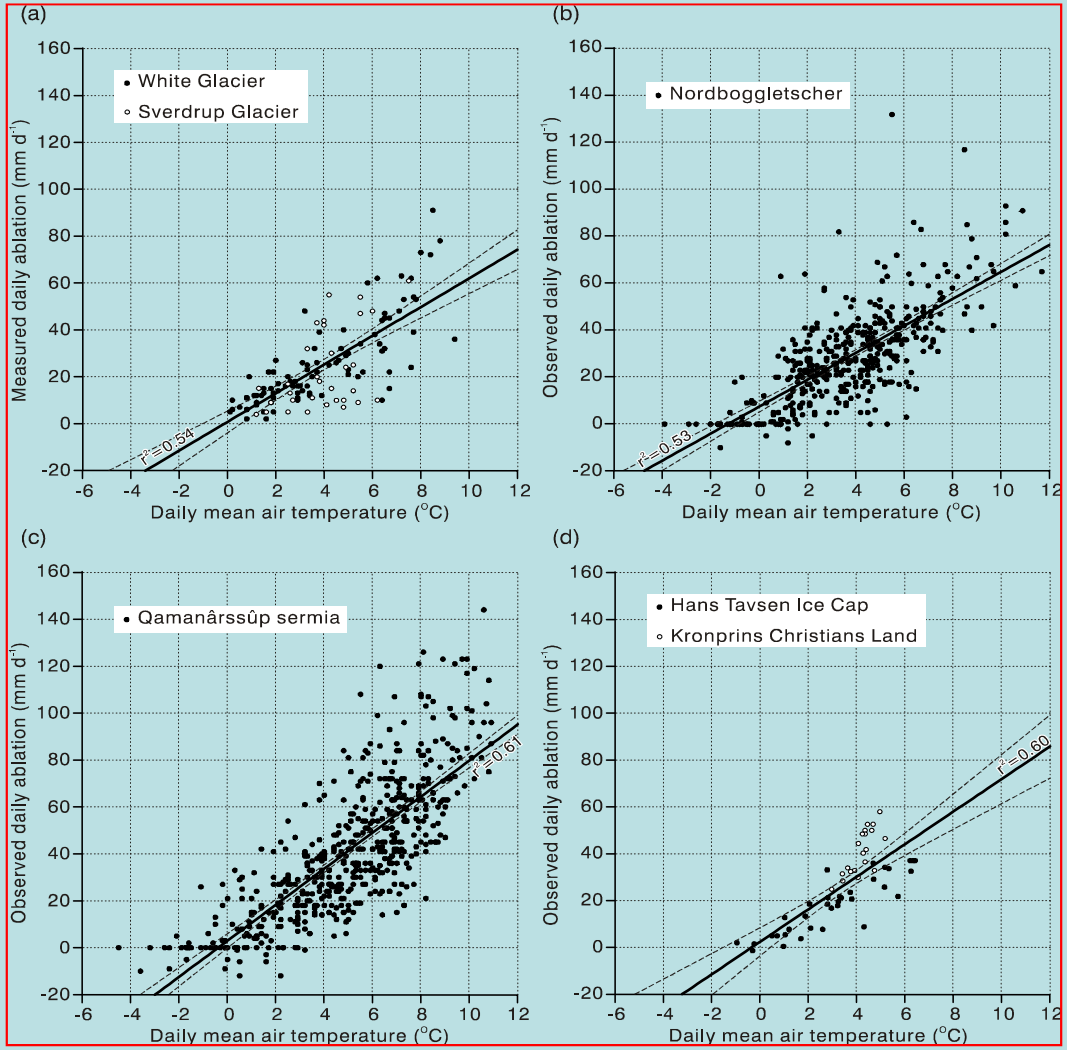
MEAN TEMPERATURE AT ELA

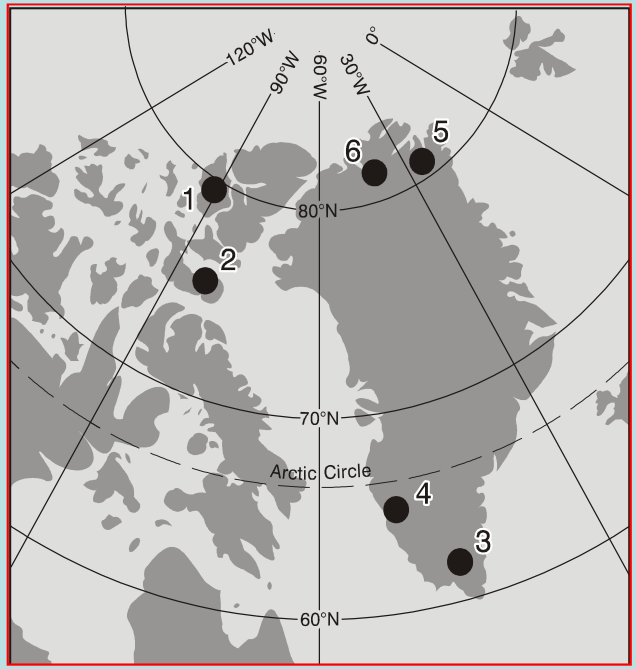


- Ohmura et al (1992) gives summer (June-August) mean temperature at ELA
- If monthly temperatures at ELA follow sine wave (of known range) we can calculate monthly temperatures
- Get temperature amplitude from CRU gridded climatology

ICE ABLATION AND TEMPERATURE

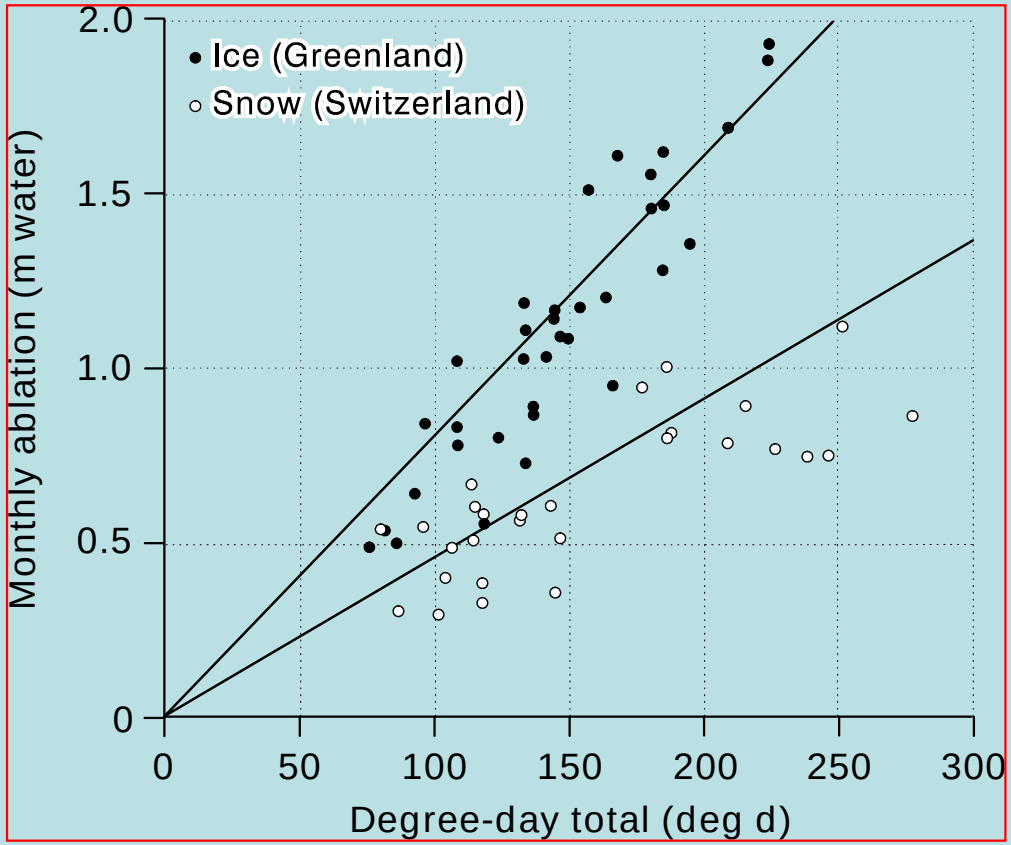
(Braithwaite, 1981, 1996 & 2011)

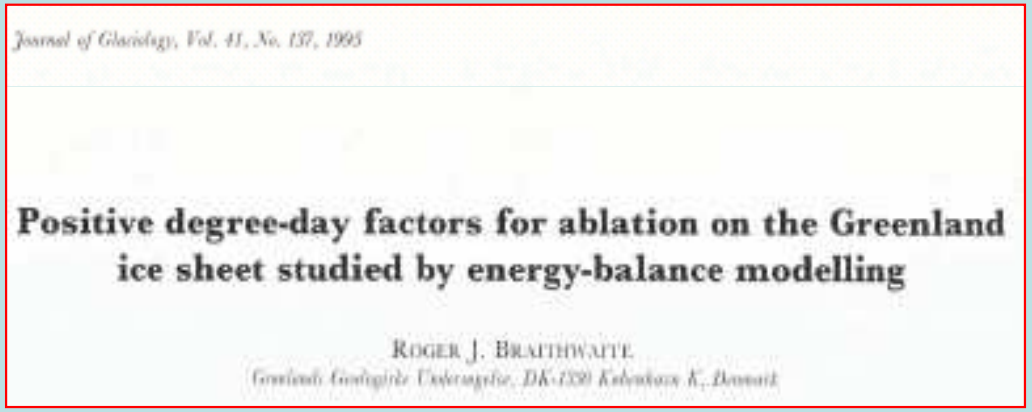




Well-constrained relationship between ice ablation and air temperature from Arctic & Greenland

DEGREE-DAY MODEL

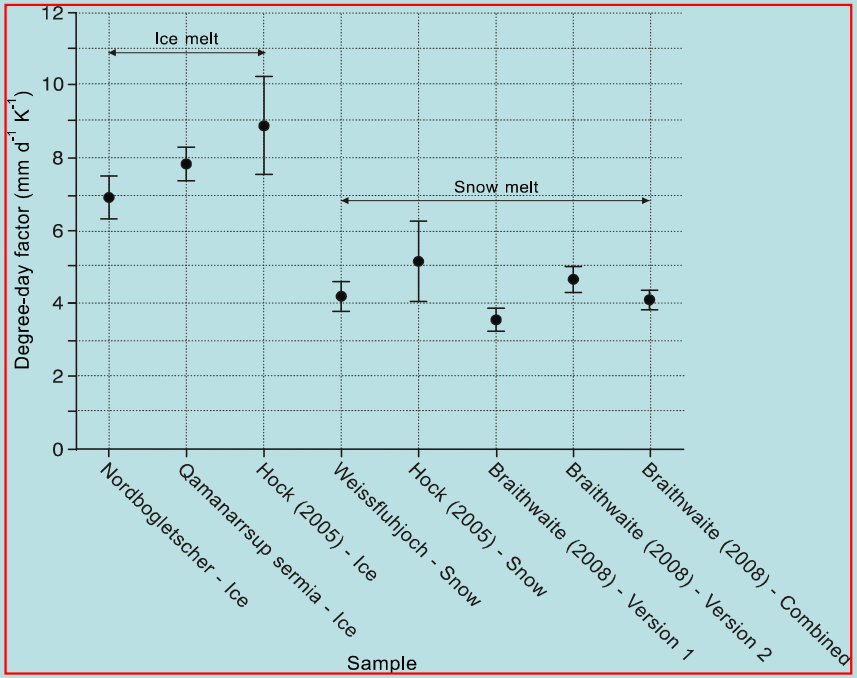



Journal of Glaciology, Vol. 41, No. 137, 1995

Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling

ROGER J. BRAITHWAITE

Greenland Geologiske Undersøgelse, DK-1350 København K, Denmark



Degree-day model well justified by energy-balance

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Band 20 (1984), S. 1—8

ZEITSCHRIFT FÜR GLETSCHERKUNDE UND GLAZIALGEOLOGIE

CALCULATION OF DEGREE-DAYS FOR GLACIER-CLIMATE RESEARCH

By ROGER J. BRAITHWAITE, Copenhagen

The degree-day sum for a period of N days is given by:

$$Y = \frac{1}{M} \sum_{m=1}^{m=M} \sum_{n=1}^{n=N} \alpha_{nm} T_{nm} \qquad (1)$$

where α_{nm} has either a value of unity or zero according to:

$$\alpha_{nm} = 1.0 \text{ if } T_{nm} \geqslant 0^\circ \text{ C}$$
$$= 0.0 \text{ if } T_{nm} < 0^\circ \text{ C} \qquad (2)$$

T_{nm} is the temperature at the mth observation on the nth day and M is the number of observations in the day.

If the temperature is assumed to constitute a stationary random series, the time-summation in Equation (1) can be replaced by an ensemble-summation as follows:

$$Y = N \sum_{k=0}^{k=K} f(T_k) T_k \qquad (3)$$

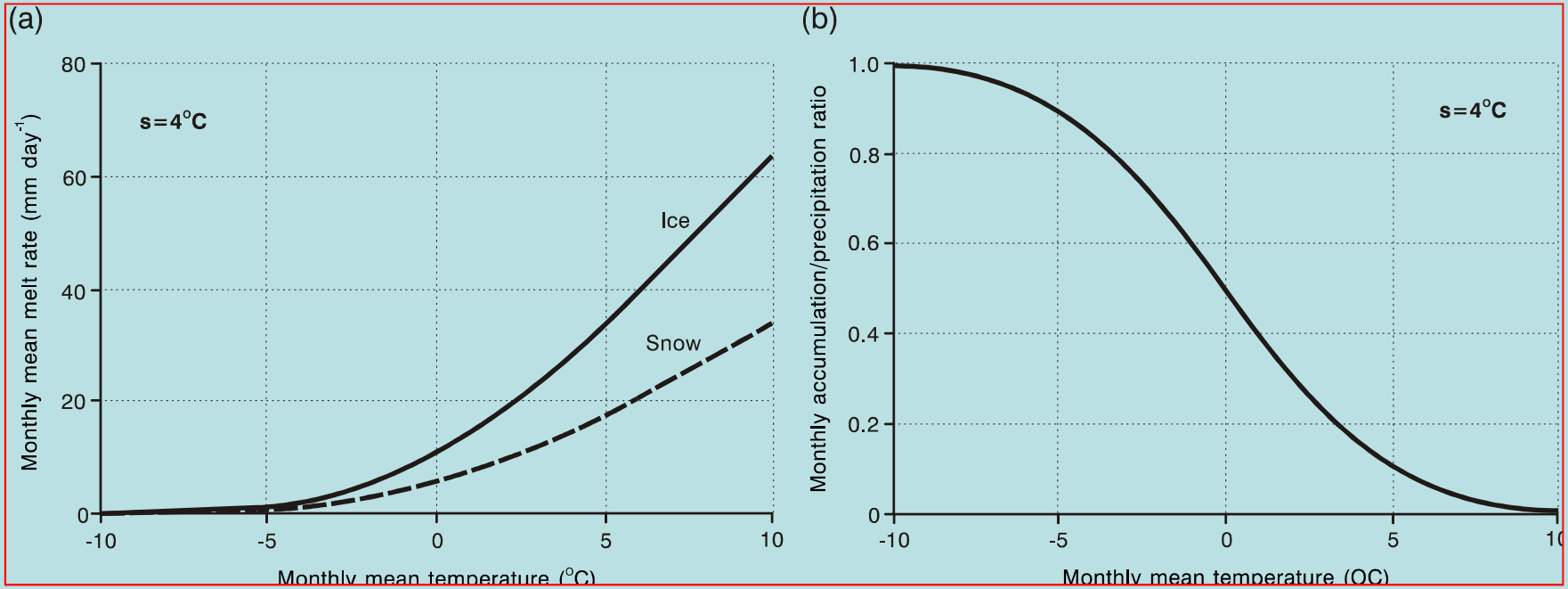
where:

$$T_k = T_0 + k \Delta T \qquad (4)$$

and $f(T_k)$ is the probability that the temperature lies in an interval of width ΔT centred on T_k and K is the value of k such that $f(T_k)$ becomes zero. T_0 is zero for the computation of positive degree-days.

- Strictly, degree-day totals are calculated from daily temperature data
- Can calculate degree-day totals from monthly data using probability model
- Assume monthly temperatures are normally distributed with specified standard deviation

MONTHLY MELT AND ACCUMULATION

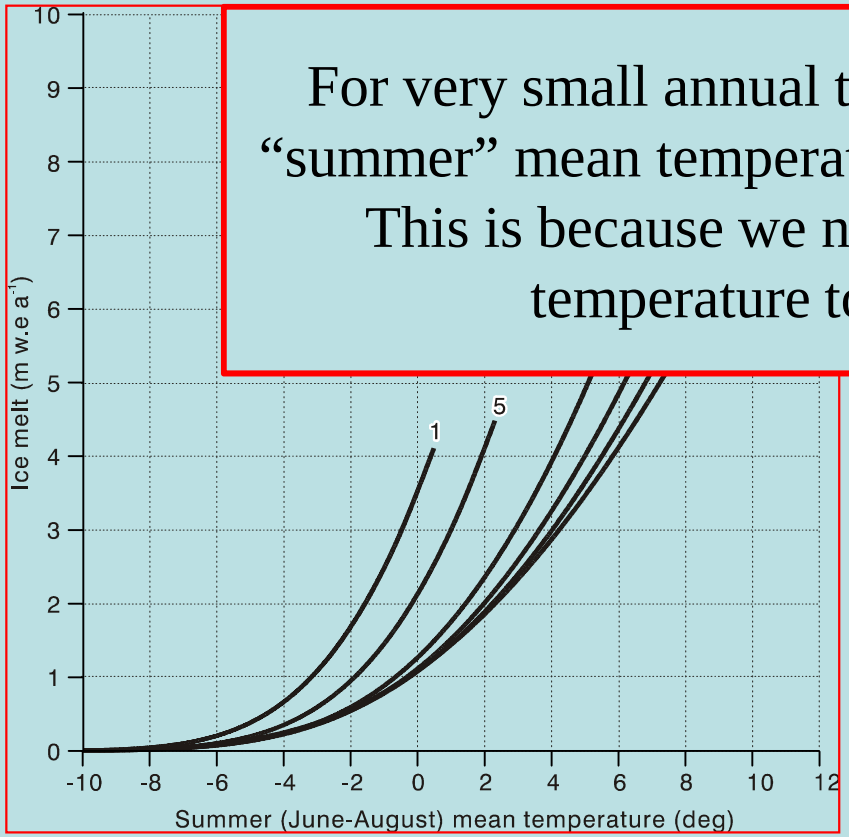


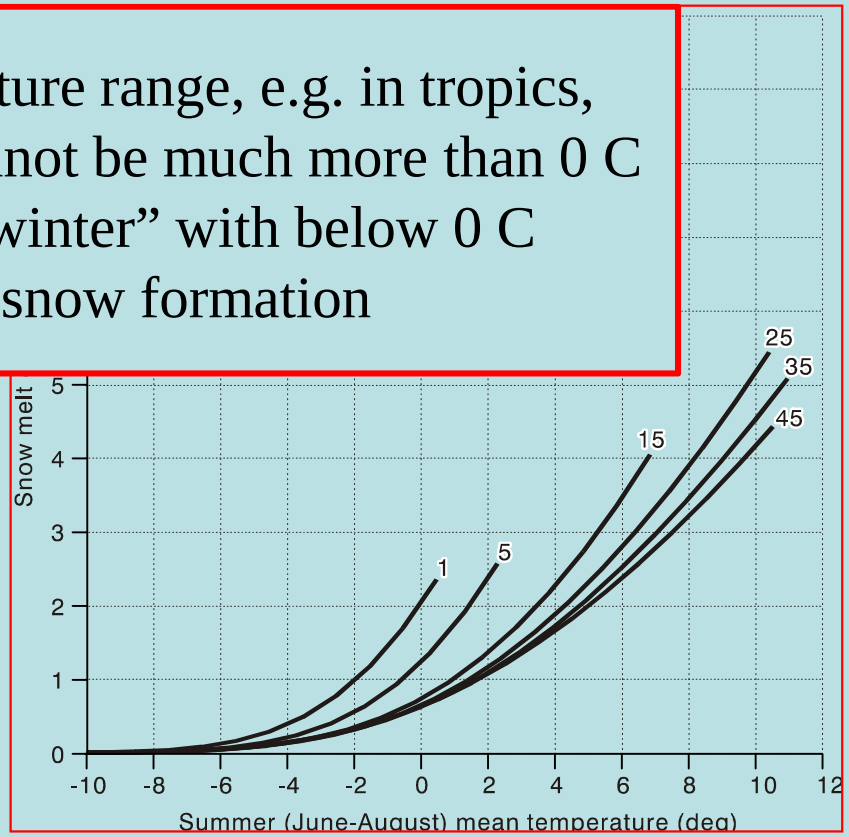
Use Braithwaite (1985) model to calculate monthly melt and monthly accumulation

DEGREE-DAY MODEL

Reeh (1991) modified Braithwaite (1985) model by assuming monthly temperature follows sine wave

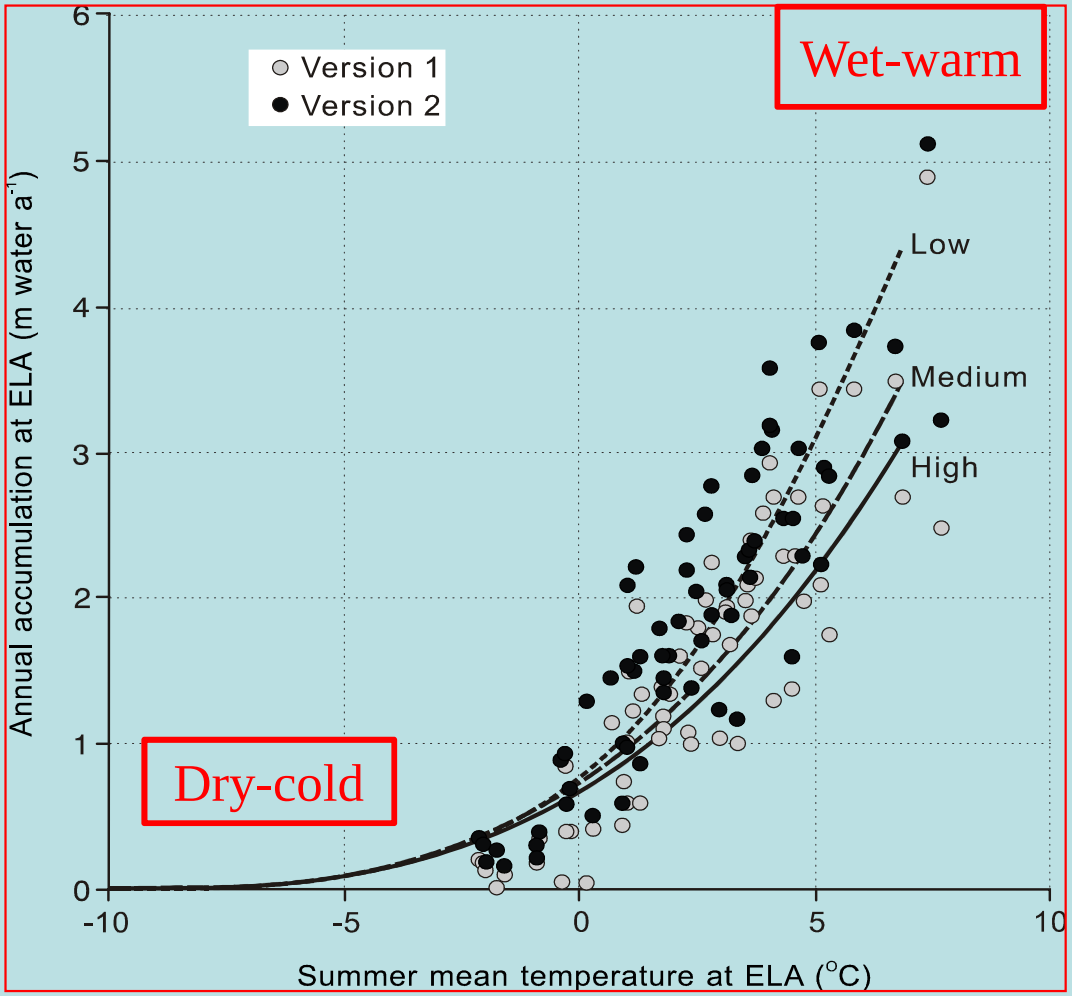
For very small annual temperature range, e.g. in tropics, “summer” mean temperature cannot be much more than 0 C
This is because we need a “winter” with below 0 C temperature to allow snow formation





CLIMATE AT ELA AGAIN

(Ohmura et al. 1992 and Braithwaite, 2008)



- We can now "explain" the accumulation-temperature relation
- Different curves for different annual temperature range


So now you know why accumulation at ELA depends on temperature