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Map-based methods for estimating glacier equilibrium-line altitudes

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ABSTRACT. We examine the validity of two methods for estimating glacier equilibrium-line altitudes (ELAs) from topographic maps. The ELA determined by contour inflection (the kinematic ELA) and the mean elevation of the glacier correlate extremely well with the ELA determined from mass-balance data (observed ELA). However, the range in glacier elevations above sea level is much larger than the variation in ELA, making this correlation unhelpful. The data were normalized and a reasonable correlation ($r^2 = 0.59$) was found between observed and kinematic ELA. The average of the normalized kinematic ELAs was consistently located down-glacier from the observed ELA, consistent with theory. The normalized mean elevation of the glacier exhibited no correlation and suggests that the toe–headwall altitude ratio is not a good approximation for the ELA. Kinematic waves had no effect on the position of the kinematic ELA. Therefore, topographic maps of glacier surfaces can be used to infer the position of the ELA and provide a method for estimating past ELAs from historic topographic maps.

INTRODUCTION

Field measurements of glacier mass change (e.g. Kasser, 1967, 1973; Müller, 1977; Haeberli, 1985; Haeberli and Müller, 1988; Østrem and others, 1991; Haeberli and Hoelzle, 1993; Haeberli and others, 1998; Krimmel, 1999) are used to understand the response of glaciers to climatic variations (e.g. Holmlund, 1996; Dyurgerov and Meier, 2000; McCabe and others, 2000). It is also important to understand the contribution of glacier melt to regional stream-flow variations (e.g. Meier, 1969; Braithwaite and Olesen, 1988) and to global sea-level change (Meier, 1984; Oerlemans and Fortuin, 1992; Dyurgerov and Meier, 1997). However, mass-balance studies are time-intensive and can be applied to only a small fraction of the glaciers in any given region. Unfortunately, methods to rapidly assess regional glacier change have been elusive. Monitoring changes in terminus position is an attractive method because glacier termini are clearly visible and easily monitored by aerial and ground-based photographic surveys (Gilbert, 1904; LaChapelle, 1962; Veatch, 1969; Aniya, 1988) and by satellite imagery (Williams and Ferrigno, 1993; Duncan and others, 1998; Paul, 2002). Inferring climate change or glacier mass change can be difficult because one must separate the dynamic response of the glacier from the changes in glacier mass (Nye, 1962). Recent advances in understanding the time-scale of glacier responses to climate change (Jóhannesson and others, 1989) have increased our capability to interpret the lag time between climate variation and terminus response. However, to track climate change through changes in terminus position is still problematic because of kinematic waves (Nye, 1965; Van de Wal and Oerlemans, 1995). To apply time-scale response methods also requires estimates of glacier thickness and some knowledge of mass change at the terminus, which are unknown for most glaciers.

One appealing alternative to measuring terminus position is to find the equilibrium-line altitude (ELA). The position of the ELA is controlled entirely by climatic processes (Kuhn, 1981; Ohmura and others, 1992; Seltzer, 1994; Fountain and others, 1999). Up-glacier from this "line", the accumulation zone gains more mass annually than it loses. Down-glacier, in the ablation zone, the glacier loses more mass than it gains. At the ELA, the annual mass change is zero (Paterson, 1994). The most accurate method to determine the ELA is by field measurements (e.g. Østrem and Brugman, 1991). One approach is to contour the point measurements of mass balance on a map to determine the glacier's ELA for that year. Such field methods are slow and expensive and therefore are only applied to a few glaciers. These constraints have led to a variety of remote monitoring techniques to find the position of a glacier's ELA. Assuming that the snowline at the end of the summer is a good approximation of the ELA, then aerial and ground-based photography are attractive methods to monitor inferred changes in ELA (LaChapelle, 1962). This method is difficult in practice because the timing of the photography is critical. Observations have to be collected just prior to the start of the accumulation season, and early snowfall or late warming events may require repeated imaging. Also, poor weather, common to mountainous regions, can delay image acquisition for weeks. This method cannot easily be applied to environments where accumulation and ablation seasons do not neatly fit into the climatic seasons of winter and summer, respectively. In the dry valleys of Antarctica, for example, snowfall occurs year-round on all surfaces and distinct accumulation/ablation seasons do not exist (Fountain and others, 1998). In the Hima-

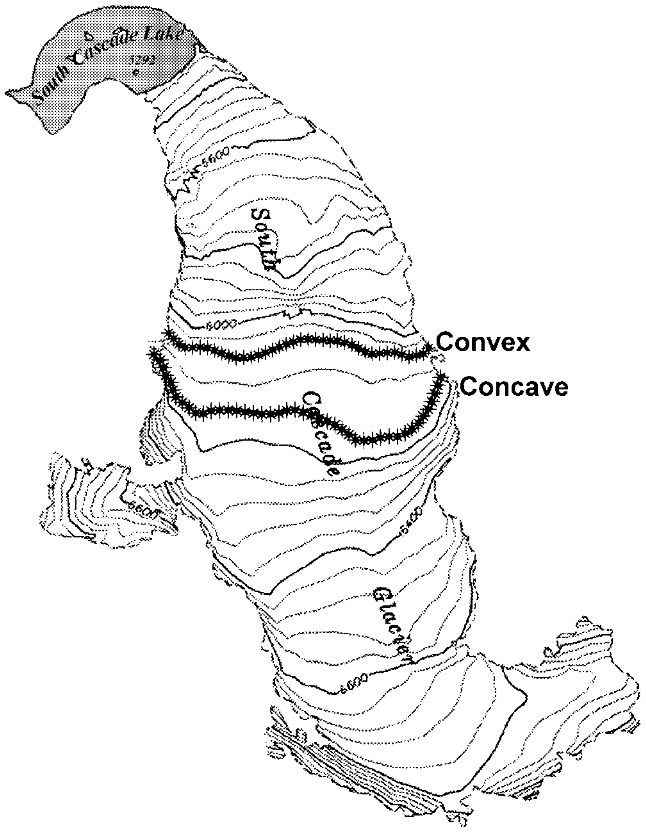

Fig. 1. Contour map of South Cascade Glacier, Washington, U.S.A., from the United States Geologic Survey Dome Peak 7.5′ quadrangle. According to the map, the glacier was field-checked in 1965.

laya, the accumulation and ablation seasons occur simultaneously during the monsoonal season (Ageta and Higuchi, 1984), and in the equatorial regions multiple seasons of accumulation and ablation exist (Kaser, 1999).

An alternative method for determining ELA is based on the inflection of elevation contour lines on a topographic map of a glacier (Østrem, 1966; Porter, 1975). This method was first introduced by Hess (1904) to determine firn-line locations, and in the European scientific literature it is sometimes referred to as the "Hess method". The accumulation zone of the glacier is bowl-shaped, because snow accumulating on the margins of the glacier advects toward the center. Below the ELA, in the ablation zone, the contour lines are convex, because mass is lost from all sides and ice is advected away from the glacier center towards the margins. The transition or inflection from a concave to convex contour is a relatively flat surface that should be close to the location of the long-term average ELA (Fig. 1). If this is true, then the topography of the glacier surface can be used to infer the average location of the ELA. Because the ELA position determined by the contour method results in part from glacier motion, we term this ELA the "kinematic ELA" to distinguish it from the year-to-year ELA determined by observations of glacier surface mass changes, or "observed ELA".

This paper examines the correspondence between the kinematic and observed ELA. To our knowledge, the "kinematic" ("Hess") method has not been empirically tested in this way. If these two values correspond, historical maps of glaciers can be used to estimate ELA change since the turn of the 20th century, when reliable topographic maps of alpine regions became available, and modern maps can be used to estimate ELAs for glaciers on which mass-balance studies are not performed. We also evaluate the correlation between ELA and mean glacier elevation. The normalized form of mean glacier elevation, which we use, is similar to the toe–headwall altitude ratio (THAR), a procedure for estimating ELA in the glacial geologic literature (Meierding, 1982; Hawkins, 1985; Torsnes and others, 1993).

Table 1. The glaciers used in this study

Glacier	*Country*	*Latitude*	*Area in 1995* km^2	*Years of ELA records*
Peyto	Canada	51.40° N	13.35	25
White	Canada	79.27° N	38.9	19
Gulkana	U.S.A.	63.15° N	19.3	15
South Cascade	U.S.A.	48.22° N	2.5	25
Blue	U.S.A.	47.49° N	5.5	8
Wolverine	U.S.A.	60.24° N	17.24	15
Rabots glaciär	Sweden	67.54° N	3.9	10
Storglaciären	Sweden	67.54° N	3.1	25
Hansbreen	Norway	77.05° N	1.84	10
Hellstugbreen	Norway	61.34° N	3.13	23
Ålfotbreen	Norway	61.45° N	4.82	23
Nigardsbreen	Norway	61.43° N	48.2	23
Hintereisferner	Austria	46.48° N	8.72	25
Langtalferner	Austria	46.48° N	3.52	5
Kesselwandferner	Austria	46.50° N	4.29	25
Sonnblickkees	Austria	47.08° N	1.5	10
Vernagtferner	Austria	46.53° N	9.18	25
Limmern	Switzerland	46.49° N	2.62	15
Plattalva	Switzerland	46.50° N	0.81	8
Gries	Switzerland	46.26° N	6.25	25
Silvretta	Switzerland	46.51° N	3.25	25
Ürümqi No. 1	China	43.05° N	1.84	32
Hofsjökull ice cap				
north: Sátujökull	Iceland	64.57° N	90.6	8
east: Þjórsárjökull	Iceland	64.48° N	250	9
southwest: Blágnípujökull	Iceland	64.43° N	51	8
Lewis	Kenya	0.09° S	0.24	15
Abramov	CIS/U.S.S.R.	39.38° N	26.21	10
Davidov	CIS/U.S.S.R.		11.43	2
Golubina	CIS/U.S.S.R.	42.28° N	5.75	15
Igly Tuyuksu	CIS/U.S.S.R.	43.0° N	1.72	5
Karabatkak	CIS/U.S.S.R.	42.06° N	4.19	10
Mametova	CIS/U.S.S.R.	43.0° N	0.35	3
Mayakovskogo	CIS/U.S.S.R.	43.0° N	0.18	3
Molodezhniy	CIS/U.S.S.R.	43.0° N	1.43	5
Ordzhonikidze	CIS/U.S.S.R.	43.0° N	0.31	5
Sary-Tor	CIS/U.S.S.R.		3.61	3
Shumskiy	CIS/U.S.S.R.	45.05° N	2.81	5
Suyok-Zapadniy	CIS/U.S.S.R.	41.47° N	1.25	5
Tuyuksu	CIS/U.S.S.R.	43.03° N	2.72	5
Visyachiy 1	CIS/U.S.S.R.	43.0° N	0.29	5

Note: The data are from Kasser (1967, 1973); Müller (1977); Haeberli (1985); Haeberli and Müller (1988); Haeberli and Hoelzle (1993); Haeberli and others (1998).

METHODS

We collected topographic maps of glaciers for which observed ELAs have been recorded by the World Glacier Monitoring Service (WGMS). The 40 glaciers we examined are listed in Table 1. Our dataset is biased towards glaciers in the Northern Hemisphere, but that should not change our results. We selected the contour that best represented the inflection between the regions of surface concavity (accumu-

Table 2. The data used in this study

Glacier	*Map date*	*Mean elevation*	*Kinematic ELA*	*Same-year observed ELA*	*Mean observed ELA*	*Maximum observed ELA*	*Minimum observed ELA*
		m a.s.l.	m a.s.l.	m a.s.l.	m a.s.l.	m a.s.l.	m a.s.l.
Peyto	1966	2660	2360	2610	2685	2800	2550
White	1958	930	875		944	1200	630
Blue	1983	1808	1800		1755	1910	1625
Gulkana	1966	1813	1600	1800	1788	2000	1640
South Cascade	1965	1882	1900	1880	1986	2250	1770
Wolverine	1966	1050	1050	1250	1180	1470	906
Rabots glaciär	1987	1385	1530	1540	1434	1840	1278
Storglaciären	1990	1430	1410	1495	1478	1610	1374
Ålfotbreen	1988	1130	1100	1030	1137	1550	870
Hans	1990	300	320	370	331	400	240
Hellstugbreen	1980	1800	1750	2050	1879	2130	1650
Nigardsbreen	1984	1153	1450	1500	1518	1850	1170
Hintereisferner	1979	3068	2900	2970	3021	3260	2825
Langtalferner	1971	2933	2860		2864	2975	2795
Kesselwandferner	1971	3098	3065	3090	3119	3250	3040
Sonnblickkees	1990	2775	2670	2855	2844	2975	2715
Vernagtferner	1990	3175	3120	3283	3147	3650	2935
Limmern	1977	2845	2500	2555	2705	2980	2302
Plattalva	1977	2770	2900	2620	2821	2940	2620
Gries	1979	2880	2980	3070	2929	3410	2510
Silvretta	1973	2801	2100	2575	2730	2905	2505
Ürümqi No. 1	1980	4111	3900	4038	4048	4160	3948
Hofsjökull ice cap							
north: Sátujökull	1983	1338	1350		1287	1485	1160
east: Þjórsárjökull	1983	1220	975		1134	1370	1000
southwest: Blágnípujökull	1983	1250	1375		1287	1410	1190
Lewis	1993	4785	4840	4790	4934	5000	4700
Abramov	1986	4290	3980	4130	4216	4470	4110
Davidov	1987	4350	4020		4415	4620	4210
Golubina		3844	3550		3855	4150	3750
Igly Tuyuksu	1958	3805	3610		3879	4200	3725
Karabatkak	1947	4040	3620		3892	4000	3750
Mametova		3865	3730		3934		
Mayakovskogo		3835	3710		4033	4100	4000
Molodezhniy	1958	3795	3560		3873	4147	3750
Ordzhonikidze		3785	3520		3884	4100	3800
Sary-Tor	1987	4320	4120	4340	4297	4340	4260
Shumskiy	1966	3785	3425	3676	3678	3716	3615
Suyok-Zapadniy		4197	4160		4300	4300	4300
Tuyuksu	1958	3817	3640		3837	4220	3632
Visyachiy 1		3735	3680		3744	3750	3725

Note: The "same-year observed ELA" is that ELA observed in the field the same year the map was prepared.

lation zone) and convexity (ablation zone). The altitude represented by this contour is defined as the kinematic ELA. In some cases it is difficult to determine the specific contour defining the inflection of the glacier surface because the contour line itself may contain concave and convex segments. In these situations the line that shared the most symmetrical distribution of concavity and convexity was selected. The error of the selection of the contour line is, at minimum, the error of the contour map, typically half of the contour interval. In those cases where several adjacent contour lines seemed suitable, we chose the average. The date of the glacier surface depicted was determined from either the date of photography used to make the map or the date the surface was surveyed. If a "field check" was performed on the glacier, the map's date was set to that of the fieldwork. Information on the date of aerial photography or field checking is typically included in the map legend.

The highest and lowest elevations of each glacier were recorded from the maps and checked against values reported to the WGMS. We used them to calculate the mean elevation of each glacier (maximum elevation plus minimum elevation divided by two). This is not the area-weighted mean discussed by Braithwaite and Müller (1980), rather it corresponds to their "E_{CR}". Kurowski (1891) introduced this method of estimating a glacier's firn line, and Porter (1975) suggested the mean elevation of a glacier is a good estimate of the ELA, but neither author presents data to support this assertion.

ELA data were obtained from the WGMS reports (Kasser, 1967, 1973; Müller, 1977; Haeberli, 1985; Haeberli and Müller, 1988; Haeberli and Hoelzle, 1993; Haeberli and others, 1998). We averaged the observed ELAs reported for the years 1965–95, and compared this average with the kinematic ELA for a date within this time period. We did not calculate steady-state ELAs because most glaciers are not in a steady state. We chose to average the whole record, rather than select a smaller time interval, both because the kinematic ELA results from long-term climate trends and because we did not want abnormally high or low ELAs to bias the average. Typically, the maps were prepared at the beginning of the mass-balance program and

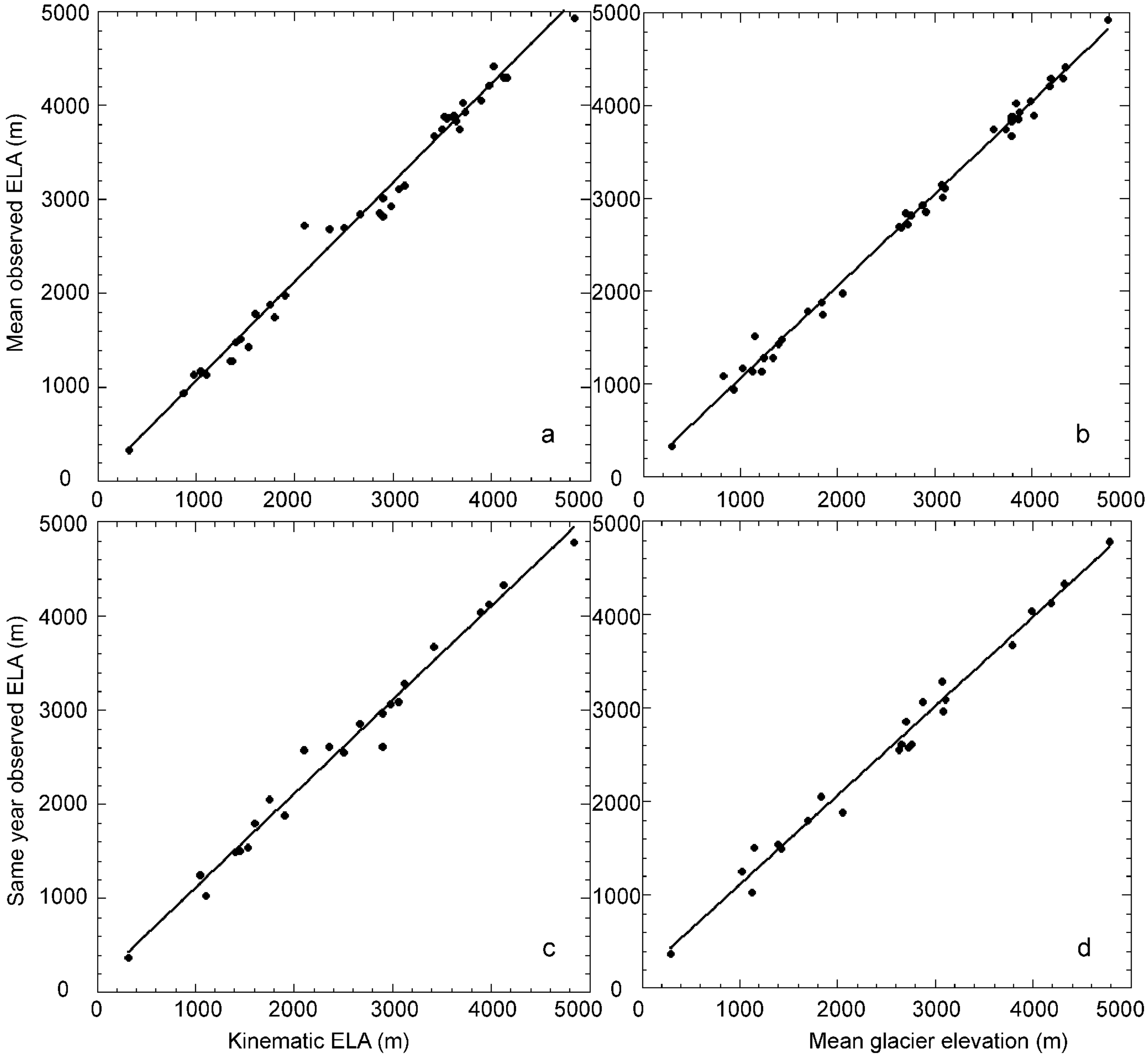

Fig. 2. Relations between the observed ELA and the kinematic ELA and mean elevation: (a) kinematic ELA vs mean observed ELA; (b) mean glacier elevation vs mean observed ELA; (c) kinematic ELA vs same-year observed ELA; (d) mean glacier elevation vs same-year observed ELA.

precluded averaging the observed ELA record for the years preceding the map date, as might be suggested by response-time theories (Jóhannesson and others, 1989).

RESULTS

Table 2 summarizes the results of our kinematic ELA estimates and the observed ELAs and mean elevation. The correlation between the kinematic and observed ELAs is very good (Fig. 2a), with a correlation coefficient, r^2, of 0.99 (Table 3). The slope of the least-squares fit is 1.05, only slightly steeper than a one-to-one ratio. The intercept of the equation is +10.8 m, indicating the observed ELA is a bit higher than the kinematic ELA. The relation between mean glacier altitude and observed ELA (Fig. 2b) is similar to Figure 2a, with a slope slightly smaller (0.99) and a larger intercept, 46 m, with the observed ELA higher than the mean altitude. Correlations were also calculated between the observed ELA for only that year in which the map was made, and the kinematic ELA and mean altitude (Fig. 2c and d). Results were similar to those of the previous findings, but with lower correlation coefficients and larger intercepts, as one might expect from the year-to-year variability of the observed ELA relative to the mean ELA.

The correlation between kinematic and observed ELAs should be good, since the two values are constrained to the altitude range of each glacier, while the range itself varies greatly among the glaciers. Our sample is also dominated by relatively small alpine glaciers, on which many mass-balance studies are based. To remove the spurious correlation induced by the wide range of altitudes, we normalized the data by the altitude range of the glacier,

$$E_i = \frac{\mathrm{ELA}_i - z_0}{z_\mathrm{m} - z_0} \qquad (1)$$

where E is the normalized value, subscript i indicates either the kinematic (k) or observed values (o), ELA is observed or kinematic ELA, z_0 is the minimum glacier altitude, and, z_m is the maximum glacier altitude. The normalization limits the altitude of each ELA to a range of 0–1. The mean elevation

Table 3. Regression equations for the studied ELA relationships corresponding to Figures 2 and 3

Relation	*Regression equation*	R^2	*rms*
Kinematic ELA vs same-year observed ELA	$e_o = 78 + 1.003e_k$	0.99	150.4
Mean elevation vs same-year observed ELA	$e_o = 156 + 0.953z_m$	0.99	132.8
Kinematic ELA vs mean observed ELA	$e_o = 10.748 + 1.051e_k$	0.99	137.8
Mean elevation vs mean observed ELA	$e_o = 46.81 + 0.99z_m$	0.99	94.2
Normalized ELA(k) vs ELA(o) relationship	$E_o = 0.466 + 0.214E_k$	0.10	0.11
Normalized long-record glaciers E(k) vs E(o)	$E_o = 0.254 + 0.701E_k$	0.59	0.08
Normalized Z_m vs ELA(o) relationship			0.13
Normalized long-record glaciers Z_m vs E(o)			0.14

Notes: e_o is the observed ELA, e_k is the kinematic ELA, and z_m is the mean elevation of the glacier. The normalized values are represented by E. R^2 is the correlation coefficient. rms is the root-mean-squared error between the observed ELA and that predicted by the regression equation.

for all glaciers becomes 0.5. Averages of the normalized data showed that the kinematic ELA was about 20% lower than the observed ELA. An F test on the normalized data showed that the kinematic and observed ELAs were not statistically different. The mean elevation data cannot be analyzed in the same way against the observed ELAs, as this would compare a single point (0.5) with a variable dataset. As can be seen in Figure 3c and d, there is no correlation between the normalized mean elevation and normalized observed ELA.

The relation between the normalized observed and kinematic ELA was poor (Fig. 3a; $r^2 = 0.1$). Concerned that short time series of ELAs could bias the relation, we replotted our data after removing all glaciers with observation records of <15 years. The results for these long-record glaciers are much better (Fig. 3b; Table 3: $r^2 = 0.59$).

Glaciers with kinematic waves produce large variations in terminus position that might strongly affect the application of the proposed method. We compared the kinematic ELA with the mean glacier elevation for a series of 12 maps of Nisqually Glacier, Mount Rainier, Washington, dating from 1913 to 1994. Nisqually Glacier is well known for its kinematic waves (Meier, 1962), but its mass balance has never been measured due to the difficulty of the glacier terrain. Our results show that the mean elevation is far more variable than the kinematic ELA (Fig. 4). The change in kinematic ELA is coincident with extensive glacier retreat from 1913 to 1940 (T. Nylen, 2003). Since 1940 the ELA has been relatively stable and, relative to the errors in the method, the ELA can be considered constant. We believe the pre-1940 rise in ELA is real and is perhaps an artifact of the Little Ice Age in this region. After 1940, the variation in the mean elevation is large compared to the kinematic ELA and is a result of kinematic waves which temporarily lengthen the glacier. In addition, defining the terminus of such glaciers is problematic because of the large portions of "dead" ice that accompany large advances from the kinematic waves (T. Nylen, unpublished information).

DISCUSSION

The correlation between the kinematic and observed ELA is good, but we were initially puzzled by the offset (20% of the total glacier elevation in Fig. 3b) between the normalized kinematic and observed ELAs. Hooke (1998) points out that an offset should be expected because glaciers move down slopes. For a steady-state glacier, the net balance (b_n) is directly related to the emergence (vertical) velocity (w_s) at the surface. For a point on a surface with slope α and horizontal velocity u_s,

$$b_n = -w_s + u_s \tan\alpha \,. \qquad (2)$$

At the observed ELA, $b_n = 0$, and since u_s is positive and the slope is negative, the emergence velocity w_s is negative, or into the glacier. Thus, at the observed ELA, mass is being advected into the glacier and the kinematic ELA of zero emergence velocity is located down-glacier. Alternatively, where w_s is equal to zero (kinematic ELA), the balance is negative, placing the kinematic ELA lower on the glacier than the observed ELA, in the ablation zone, as shown by our results. Another possible cause of this offset is that the map was made before field observations were collected and the ELA has risen in elevation since that time.

The mean elevation of a glacier correlates well with the observed ELA (Fig. 2b and d) when elevations above sea level are used. This is spurious because the relation is biased by the large range in glacier elevations. Moreover, as previously described, the normalized ELA shows great scatter about the normalized mean elevation, fixed at 0.5 (Fig. 3c and d). Normalized mean elevation is similar to the THAR method (Meierding, 1982; Hawkins, 1985; Torsnes and others, 1993). The THAR method is used principally in glacial geology to determine a former glacier's ELA based on valley morphology. The difference in elevation between the former glacier's terminus, or toe, (usually determined from moraine location) and the elevation of the former glacier's headwall is multiplied by the THAR to estimate the elevation of the former equilibrium line relative to the terminus. A THAR of 0.4 means that the ELA is 40% of the glacier's elevation range higher than the terminus. Both Meierding (1982) and Torsnes and others (1993) compared the THAR of 0.4 with the accumulation–area ratio (AAR) of 0.6, an equilibrium value for "normal" alpine glaciers (Meier and Post, 1962), and found a good correlation.

For the small mountain glaciers used in this study we do not observe a constant THAR, as the normalized ELA is quite variable from glacier to glacier. This brings into question the validity of the THAR method for small alpine glaciers. However, it may be useful in the broadest of contexts because the average of the normalized observed ELAs is 0.55, close to the normalized value of glacier elevation (THAR) of 0.5.

A strong word of caution: our methods to estimate the ELA from maps or average glacier altitude and THAR apply only to alpine glaciers that terminate "normally" on dry land. Like the application of the AAR, these two methods do not apply to glaciers that terminate in marine or lacustrine waters or to glaciers that terminate on cliffs. In these situations, the relation between mass balance and altitude is strongly biased by calving at the glacier terminus. The calving flux is largely controlled by processes at or near the terminus and, for marine and lacustrine systems, is

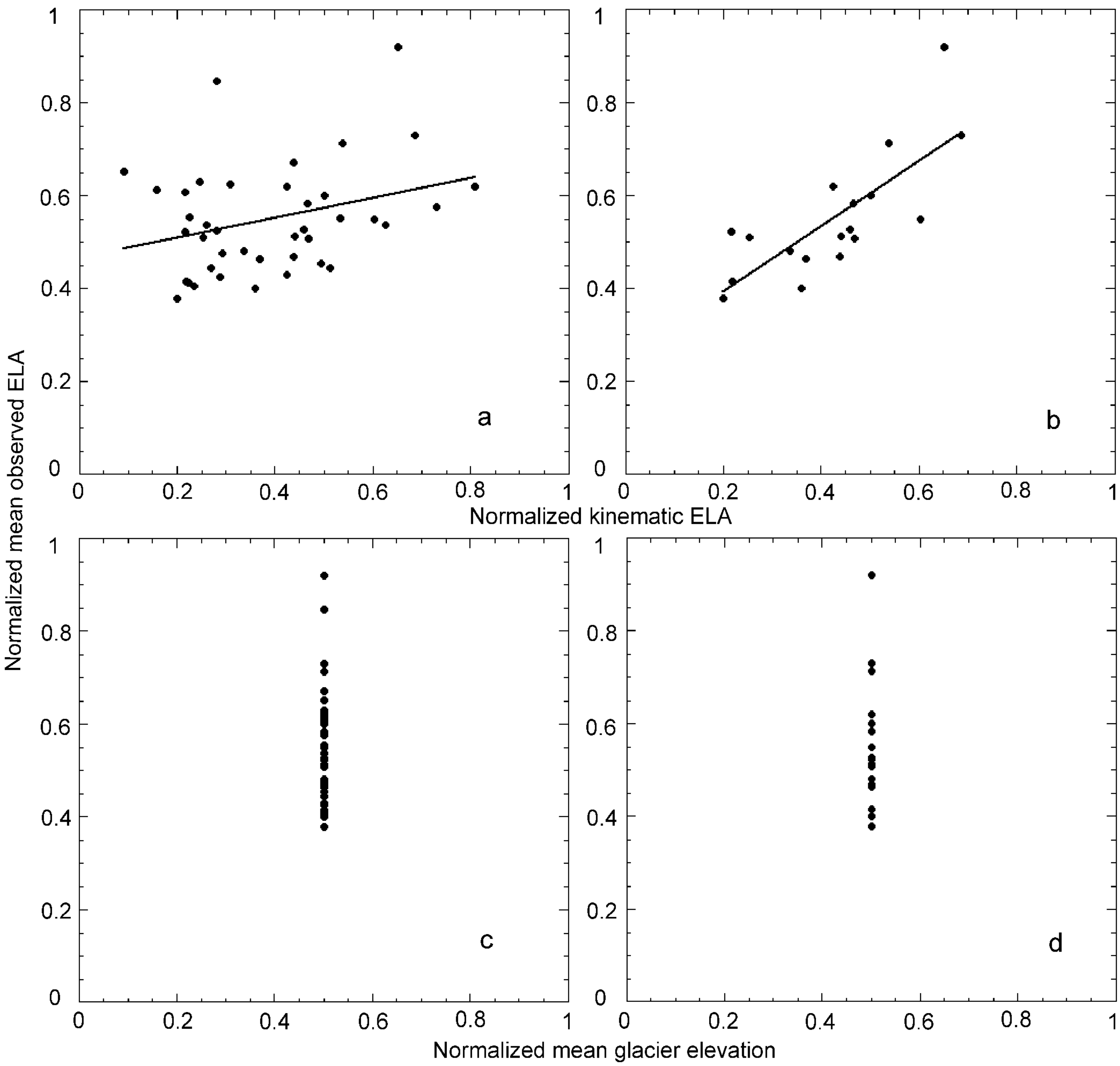

Fig. 3. The relation between the normalized values of the kinematic and mean observed ELAs and the mean elevation and mean observed ELAs: (a) normalized kinematic ELA vs mean observed ELA with all glaciers included; (b) normalized kinematic vs mean observed ELA for glaciers with >15 years of data; (c) normalized mean elevation vs mean observed ELA for all glaciers; (d) normalized mean elevation vs mean observed ELA for glaciers with >15 years of observed ELA data.

largely independent of annual climate (Brown and others, 1982; see papers in Van der Veen, 1997).

For "normal" glaciers the kinematic ELA will provide a reasonable approximation of a glacier's average ELA at far less expense than a traditional mass-balance study. Recent advances in remote-sensing techniques for mapping glacier surfaces (Echelmeyer and others, 1996; Allen, 1998; Favey and others, 1999; Kääb and Funk, 1999; Hubbard and others, 2000) will make the kinematic ELA method even more practical.

CONCLUSIONS

The "kinematic" method of estimating the ELA, by selecting the topographic contour representing the inflection between the concave and convex surfaces on a glacier, is a reasonable approximation for the actual, long-term, ELA acquired through traditional mass-balance studies. The kinematic ELA occurs lower on the glacier than the observed ELA, consistent with theoretical models of glacier flow and with a climate-driven rise in the position of the ELA during the period of observed ELA data collection. Distortions to the glacier surface by kinematic waves do not seem to affect the results of this method. Application of this method is limited to those "normal" alpine glaciers that do not terminate in cliffs or in water.

The mean elevation of a glacier does not provide a reasonable approximation for the observed ELA but may be useful as the most general of indices. The THAR method, an approach common to glacial geological studies, may be applicable in a broad sense but should not be used with individual glaciers. Our work suggests an appropriate THAR for modern alpine glaciers (using the highest elevation on each

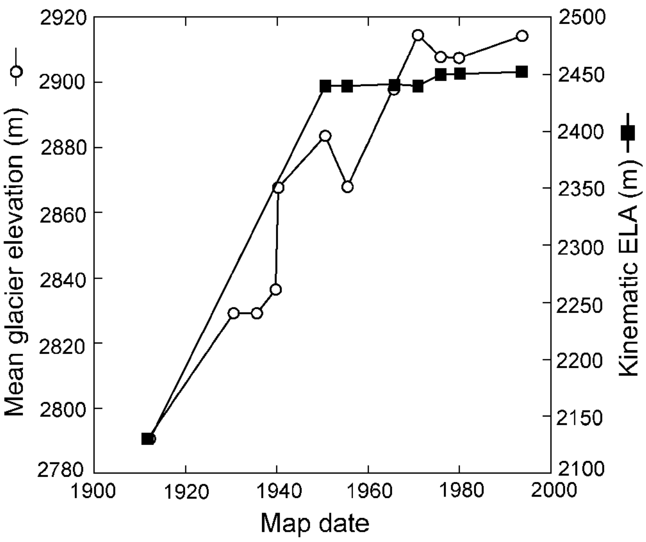

Fig. 4. Estimates of the ELA with time using the mean elevation and topographic methods for Nisqually Glacier which regularly experiences kinematic waves. No kinematic ELA was recorded for the years 1925–45 because the maps from those years only included the ablation area.

glacier as the headwall altitude) is 0.55, much higher than the value of 0.4 commonly used.

These methods allow the examination of the spatial and temporal variation in ELA starting in the early 20th century when reliable topographic maps of alpine regions became available. With increasing access to airborne and satellite imagery, practical application for constructing and revising topographic maps will increase in time. By applying the kinematic method to these topographic maps, we can remotely infer ELAs for many glaciers over large regions and track changes in ELA through time. This will increase our understanding of variations in glacier activity in relation to climatic variations and local topographic settings.

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