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Glacier distribution and direction in Svalbard, Axel Heiberg Island and throughout the Arctic: General northward tendencies

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Abstract: Arctic glaciers depend on supply of moisture, mostly from the Atlantic. The snowline is remarkably high in northeast Siberia, remote from this source. Because of differential solar radiation receipt, local glaciers have a northward-facing tendency throughout the Arctic. This is weaker than in dry mid-latitudes but low sun angles enhance the effects of shading, compensating for the broader range of aspects (*i.e.* slope directions) illuminated in summer. Statistics from the World Glacier Inventory and other sources show that mass balance differences between slopes of different aspects give both more glaciers, and lower glaciers, facing the favoured direction: usually North. This is clear, for example, for local glaciers (and for all small glaciers) in central Spitsbergen and in Axel Heiberg Island. Wind effects (drifting snow to leeward slopes) are much less important, except in northwest Europe from Norway to Novaya Zemlya which is under the strong influence of westerly winds, greatest in the Polar and Sub-polar Urals. A thorough analysis is provided of aspect data for local glaciers within and near the Arctic Circle, and of variation in glacier mid-altitude with aspect and position. There is consistency between mean glacier aspect (in terms of numbers) and aspect with lowest glaciers, everywhere except in Wrangel Island.

Key words: Arctic, mountain glaciers, aspect, solar radiation, ELA, asymmetric glaciation.

Introduction and background

Aims and objectives. — As yet our knowledge of world glacier distribution is incomplete and quantitative analyses are limited or localised. Many papers are being published on glacier change, but it is not clear how representative are the glaciers studied. Glacier change should be evaluated against a thorough background understanding of glacier distribution. This paper is concerned with variations in the local differences around regional Equilibrium Line Altitudes (ELAs) in the Arctic, differences that give asymmetry to the glaciation of mountain ranges (Evans 1977). The emphasis is on local glaciers – slope, cirque and valley glaciers –

rather than ice sheets and ice caps. There are contrasts between north-facing slopes and south-facing, for which a global model has been developed; and contrasts between windward and leeward slopes, that show greater spatial variation.

The overall aim here is to provide a quantitative understanding of the role of aspect in the spatial and altitudinal distributions of local glaciers throughout the Arctic. Specific objectives are:

– to analyse newly available data sets;
– to analyse World Glacier Inventory (WGI) data on glacier altitude and aspect more thoroughly;
– to reanalyse data for Svalbard and for Axel Heiberg Island, to investigate puzzling inconsistencies in the initial results of Evans and Cox (2005) and Evans (2006a);
– to test the Evans and Cox (2005) global model of local asymmetry of glaciation;
– to set these results in the broader context of Arctic glacier geography; and
– to provide a more coherent picture of how local asymmetry of glaciation varies across the Arctic.

The broad picture. — Glaciers exist in the Arctic wherever precipitation is sufficient. Evans (2007) tabulated Arctic glacier numbers, total areas and ELAs for 22 regions. Except for northern Norway, the whole Arctic is cold enough even at sea level to sustain glaciers, given a moderate snowfall (Filippov *et al.* 1964; Kotlyakov 1997). Thus aridity is the limiting factor, permitting few glaciers to develop in Arctic Siberia and in the western Canadian Arctic Archipelago. Ice-free land exists in northernmost Greenland (to 83.6° N) and Franz Josef Land (to 81.9° N). Even including the Greenland Ice Sheet, more Arctic land is glacier-free than is glacier-covered.

For the present, the Arctic Ocean is mostly covered by sea ice and provides little evaporation: thus it is a very minor moisture source. Most Arctic glacier ice is from snow of Atlantic origin, with moisture-laden winds penetrating northward up the Labrador Sea and Davis Strait, the Greenland Sea and the Barents Sea (Vowinckel and Orvig 1970; Seppälä 2004, ch. 3; McBean *et al.* 2005). Snowlines and ELAs rise in all directions away from these extensions of the Atlantic Ocean. Published data relate mainly to the 1970s and 1980s situations. Around Davis Strait and Baffin Bay, coastal ELAs around 300 m rose inland to 1300 m. In east Greenland, ELA rose inland from 300 to 1200 m (Weidick 1995). In Svalbard (in 1936) it rose from 200–300 m on east and west coasts to 900 m in the centre, but is now higher throughout. In the Russian Arctic, it rose eastward (Grosval'd and Kotlyakov 1969; Dowdeswell and Hambrey 2002; Dowdeswell and Hagen 2004). Lowest regional ELAs rose from 100 m in Franz Josef Land to 300 m in Novaya Zemlya and 350 m in Severnaya Zemlya and across Siberia from 700 m in the Taimyr Peninsula and 950 m in the Putorana Plateau, to 1600 m in the Orulgan (northern Verkhoyansk) Mountains and 1900 m in the Cherskiy Mountains (but each of these has considerable internal variation). Although there are many tidewater glaciers on the Arctic islands, all have ablation zones. Unlike the Antarctic situation, in the Arctic, the ELA nowhere reaches sea level.

Global model of local asymmetry. — Local asymmetry of glaciation relates essentially to glacier balance on different slopes, modulated by topographic lineation. Topography permitting, it is expected that slope aspects with the most positive mass balances will generate more glaciers, and that glaciers with these aspects will have lower ELAs. A global survey of WGI data by Evans and Cox (2005) showed that sun–shade, North–South asymmetry due to different receipts of solar radiation is greatest in mid-latitudes (especially in dry, sunny climates) and declines, as expected, to zero at the Equator and the Poles (Fig. 1). The expectation for the Arctic is that the strength of this asymmetry will decline toward wetter, cloudier climates, as well as toward the Pole. Local slopes affect several components of glacier mass balance, and we expect that there will be both lower glaciers, and more glaciers, facing directions (azimuths, aspects) with more positive mass balances.

Evans (2006a) found that results for glacier numbers and for glacier altitudes were consistent for most regions, including the Brooks Range (Alaska) and Siberian ranges near the Arctic Circle. However, he identified notable anomalies in

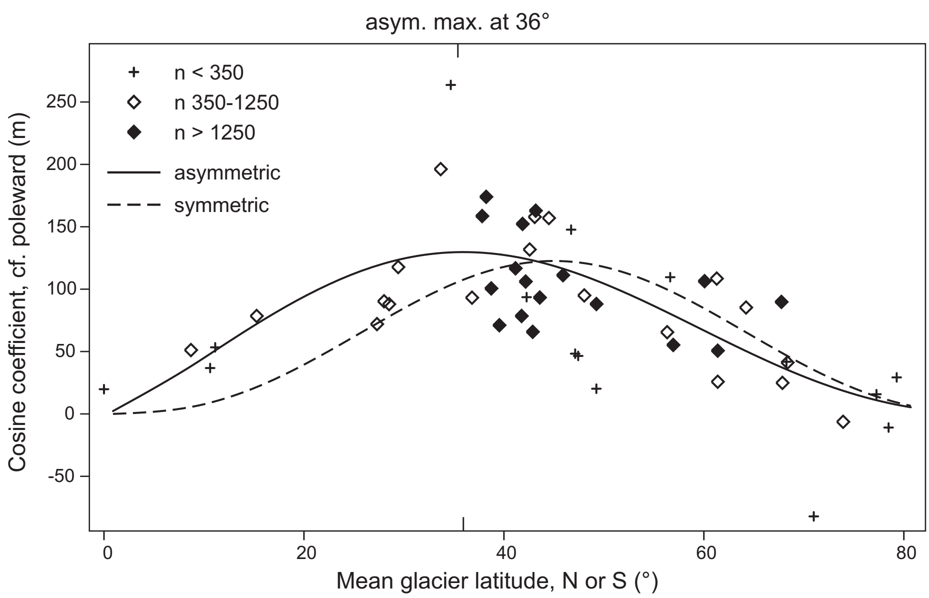

Fig. 1. Latitudinal variation in degree of poleward asymmetry of twentieth-century glaciers, from WGI data, from Evans and Cox (2005). This is expressed by the cosine coefficient for locally lowest glacier altitude: the cosine coefficient is reversed for Southern Hemisphere data. The “symmetric” sine-cosine model has a fixed maximum at 45° (N and S), but the more flexible “asymmetric” sine-cosine model is preferred. It gives a maximum at 36°. The model is fitted by non-linear least squares, with each region weighted by its number of glaciers. Reprinted from the *Journal of Glaciology* with permission of the International Glaciological Society.

four High Arctic data sets (Wrangel Island, Svalbard, Ellesmere Island and Axel Heiberg Island), where the favoured aspect in terms of numbers of glaciers differed from that with the lowest glaciers. These anomalous results require explanation, attempted here. Further analyses of glaciers in Spitsbergen (Svalbard) and Axel Heiberg Island show that these apparent inconsistencies are related to incompleteness of data.

A number of new data sets are available. Although coverage of the Arctic is far from complete, the opportunity is taken here to review both WGI and other information on the aspect and altitude of local glaciers throughout the Arctic, including five glacier regions (Greenland, Baffin Island, N. Scandinavia, the Urals and the Cherskiy Ranges) that straddle the Arctic Circle and extend southward from 66.5 to 64° N. All areas north of the Arctic Circle for which aspect data are available for local glaciers are discussed here (Fig. 2). In terms of regional temperatures and vegetation, a different definition of the Arctic might be more appropriate, but as the effects of aspect work largely through insolation receipt and shading they are especially sensitive to latitude, and thus a latitudinal definition is used here.

It is important to clarify the effects of aspect because the distribution of glaciers, both locally and regionally, provides unique information on climate in mountains (Humlum 2002a). This is needed because weather stations are sparsely distributed in mountain areas, and unrepresentative because they are biased toward valleys and accessible areas. Also, reconstructed former glaciers and glacial features such as cirques give information on palaeoclimate (Mîndrescu *et al.* 2010), especially when combined with other evidence such as dated frost features, fauna, vegetation and aeolian landforms. Thus, we need to be as precise as possible about the relations between glacier distribution, climate and topography. Most interpretations of former glaciers rely exclusively on altitude, but more evidence on present-day variations with aspect is needed so that the palaeoclimatic implications of former glacier distributions can be more fully realised (Williams 1975). As variation of mass balance with aspect is a small effect, compared with variation with altitude and regional location, careful analysis of fairly large data sets is needed. To avoid over-interpreting variations that may be essentially random, statistical confidence intervals on estimated directions are needed throughout.

Local asymmetry must be distinguished from regional asymmetry on scales of tens or hundreds of km, due usually to greater snowfall on the exposed, windward side of major ranges of mountains. Regionally, ELAs are lower on the windward side of a mountain range, whereas locally wind drifts snow to lee slopes and ELAs are lower on the leeward side of each ridge.

Although aspect differentials in solar radiation are less in polar regions than in middle latitudes because even pole-facing slopes are illuminated during 24-hour days, there is some compensation for this once shading is taken into account. Arnold *et al.* (2006; Arnold and Rees 2009) show that even at 81° N, north-facing slopes receive considerably less solar radiation than south-facing. Thus, although there can

Fig. 2. Arctic areas of local (mountain) glaciation discussed here. Only regions with data for glacier aspect are included.

be no such differential at the Poles, as there is no land north of 83.6° N all Arctic land masses and glaciers are affected by differential receipt of solar radiation.

After outlining the several methods employed and the nature of the inventory data used in this paper, the aspect and altitude of local glaciers in each region is analysed, with special attention to Svalbard and Axel Heiberg I., where previous results had shown some inconsistencies. The sequence is essentially eastward, from Svalbard and Scandinavia to Greenland and Axel Heiberg I. The discussion leads on to conclusions concerning local glaciation in the Arctic, followed by more general methodological conclusions on relevant data and statistics.

Methods

Trend surface methods. — The generalization of regional trends in altitude by polynomial trend surfaces representing altitude as a function of easting and northing (x and y) is well established (Andrews *et al.* 1970). Linear trends require only three fitted constants and are appropriate to coastal mountains with steep inland rises in ELA. There is a further tendency, however, for glaciers to be higher in the centre of a mountain range (*e.g.* the Alps: Evans 2006b) and quadratic trends (curvilinear, with six fitted constants) are necessary to allow for a single maximum. More complex patterns pose difficulties, as multi-collinearity (high correlation between terms, between powers of the same variable) may cause instability in higher-order trend surfaces, and high powers cause over-sensitivity to peripheral values: data points must be evenly distributed if outrageous predicted values are to be avoided. Quantile regression will be considered for future trend surface analyses. Finally, although x and y are ideally Cartesian grid coordinates, geographical coordinates are universally available in the WGI and using these within limited areas causes only small distortions. Distortions due to the trend surfaces over-generalising spatial variation are expected to be greater.

Circular statistics. — Aspect (slope direction) requires more specialised methods, of circular/directional/periodic statistics. Although needed for a wide range of applications – annual and diurnal cycles, wind directions, slope analysis – methods for directional data receive little or no attention in elementary statistics texts. The terminology – vectors, Fourier regression – is mathematical, but the reality is quite straightforward and can be understood in graphical terms. Vector analysis has been used in dune studies at least since Landsberg (1956), and for glaciers and glacial cirques since Evans (1969).

It bears repeating that conventional linear statistics can produce misleading results. Aspect, and direction in general, are measured on the circle between 0° and 360°, which are identical. The (linear) mean of 10° and 350° is 180°, and the range in linear terms is 340°: both of these results are nonsensical. The vector mean is 0° and the range on the circle is 20°. These are correct but their calculation needs methods and programs other than those for the usual linear descriptive statistics.

Vector methods. — The techniques used here are vector analysis of glacier aspect (azimuth or direction of surface slope, preferably in the accumulation area), and regression of glacier mid-altitude on aspect. In vector analysis, each glacier aspect is treated as a unit vector and resolved into sine and cosine components, which are summed separately. The arctangent of the cosine sum over the sine sum is the direction of the resultant vector, giving the vector mean – the true mean – of the data. Users should check that their computer algorithms take quadrants into account, and whether they work in radians or degrees. The length of the resultant vector, obtained by Pythagoras' Theorem, gives the magnitude of the tendency to that direction. It cannot exceed the total of the input unit vectors. Dividing the resultant length by the total gives a dimensionless strength of this tendency, vector strength (vs) varying from 0 to 100%.

The same results can be obtained graphically, by plotting the unit aspect directions cumulatively. Joining the start point to the end point gives the resultant vector. Neater diagrams are obtained by starting opposite the vector mean, as below.

Two significance tests are used here. Rayleigh's tests for a net tendency, a single preferred direction rather than a random set, *i.e.* for the significance of the resultant vector. Kuiper's tests for any deviation from a uniform distribution on the circle, *i.e.* for multimodality as well as unimodality, and thus tends to give a lower p value. As most of the resultants considered here are significant at the 0.05 (5%) level, more emphasis is placed on the 95% confidence interval around the vector mean.

Circular regression. — Vector analysis gives favoured aspect in terms of glacier numbers (Evans 1977); regression, in terms of glacier altitudes. There is an expectation that the two should be consistent, *i.e.* that the 95% confidence intervals on favoured aspect should overlap (Evans 2006a). The regression cannot be linear: for regression on the circle, a "Fourier regression" on sine and cosine of aspect (azimuth) (Evans and Cox 2005) is appropriate. This is also known as circular, periodic, harmonic or trigonometric regression. Fuller discussion and justification of these techniques is given in the latter two papers and in Cox (2006).

Here first-order Fourier regressions are used, with one maximum and one minimum on the circle, because they are appropriate to the hypothesis of climatic control of glacier aspect and altitude. The cosine term expresses north-south differences; the sine term expresses east-west differences. Higher-order terms, with the possibility of several maxima on the circle, give closer fits but are not appropriate here. For oriented data, *e.g.* NW-SE joint sets, a second-order regression with two maxima would be appropriate. Regressions on sine and cosine ensure that predictions for 360° are identical to those for 0°, and give a smooth variation of predicted altitude with aspect. The predicted amplitude of variation between most and least favoured aspects is given by the square root of the sum of the squared cosine and sine coefficients.

As spatial variation is usually much greater than variation with aspect (Evans 2006a, 2006b) it cannot be ignored. There are at least three ways of allowing for this. For each (small) range, altitude can be related to the average altitude as in Evans and Cox (2010), before combining different ranges. In a fuller analysis of variance, a qualitative term for position (mountain range) can be included, as in Evans (2006b). Finally, the linear or quadratic trend surface can be combined with the Fourier terms in a multiple regression, as in Evans and Cox (2005) and most of the examples here.

Graphs. — Aspects can be plotted as standard histograms, where some repetition is desirable so that the shape is not affected by the arbitrary truncation at 0° = 360° or elsewhere; as histograms on a circle, as in Evans and Cox (2010); or as cumulated vector plots. The latter are used throughout this paper. Starting opposite the vector means, vectors proportional in length to the number of glaciers are plotted in compass order. The start point is joined to the endpoint by a thick line, the vector resultant. Vector plots emphasise the general tendency of the data, which is especially useful for unimodal distributions, whereas histograms emphasise detail.

The plots of altitude against aspect are devised to solve the problem of overplotting when large data sets have discretised values: in WGI, there are only 16 possible values of aspect. Using Stata code written by Dr. N.J. Cox, altitudes for each value of aspect become a vertical histogram, but one which is centred on and symmetrical about the precise aspect value. Thus, the number of data points (squares) is clear and there are no hidden data points. Mid-altitudes are plotted uncorrected for position in these graphs, and much of the considerable scatter visible is due to position: the effects of aspect are relatively subtle.

Glacier characteristics

Altitude. — This study starts from the data available in the WGI (Haeberli *et al.* 1989, 1998; NSIDC 1999) as analysed by Evans and Cox (2005) and Evans (2006a). This is supplemented by more recent sources, and where necessary by other sources.

Since in the WGI many more glaciers are given lowest and highest altitudes than have true ELAs, it is necessary to use these and average them to give mid-range altitude (mid-altitude) as the most representative altitude characteristic available. Evans and Cox (2005) justified the value of mid- altitude as a surrogate for long-term ELA. Svoboda and Paul (2009, fig. 7b) provide further support for use of mid-altitude by illustrating its correlation of +0.97 with glacier mean altitude from a DEM. A complication in polar regions is that calving of tidewater glaciers amounts to premature termination, a truncation of the ablation area, so that the mid-altitude is expected to be higher relative to the ELA than for land-terminating glaciers. Obviously, this difference increases as the proportion of ablation by calving increases. As the relation of ELA to aspect is the effect of greatest interest, the use of mid-altitude as a surrogate should be confined to land-terminating glaciers, or to glaciers with similar proportions of calving.

Aspect. — The existence of glaciers requires an accumulation area, where accumulation exceeds ablation. Thus the slope climate (mesoclimate) in this area is of fundamental importance, and the preferred measure of glacier aspect is for the accumulation area. Aspect of the ablation area also has some influence, but it is more likely to be influenced by pre-existing valleys: thus it tends to show a little more dispersion than accumulation area aspect, and to relate less strongly to climate. Nevertheless, the two aspects are highly correlated, and usually identical for small glaciers (*e.g.* cirque glaciers).

A further problem, where large glaciers are present, is that they normally have several sources with different aspects which are commonly averaged to give one aspect, as in the WGI. This prevents each glacier source (cirque) receiving equal weight. It cannot be compensated simply by giving greater weight to larger glaciers because averaging has eliminated much of the source aspect dispersion. Evans and Cox (2010) explore one solution, by recording the aspect of each glacier source cirque.

Note that three different variables, latitude, gradient and aspect, are all expressed in degrees. To reduce confusion, mean aspects are always given as three digits, *e.g.* 045° for northeast.

Glacier types. — It is more difficult to analyse local glacial asymmetry where glaciation is extensive or covers areas of low relief, as on many Arctic islands. Ice sheets and large icecaps may show regional asymmetry, but low gradients in the accumulation areas reduce the effects of variations in climate with slope aspect. Thus, it is desirable to focus on local glaciers, or on glacier units with high slope gradients in their accumulation areas. In the WGI, local glaciers are coded as classes 5 (valley), 6 (mountain) and 7 (glacieret).

Restriction to local glaciers is not always appropriate as there are transitions from icecaps with distinct outlet glaciers, through ice fields and transection glaciers with considerable coalescence between accumulation areas, to discrete local glaciers. In some areas, there may be local glaciers on one side of a range and ice fields on the other, so focussing on one type of glacier may omit complementary glaciers on opposing aspects and give a misleading picture. Hence, some analyses refer to "all glaciers", or to those below a size threshold, as well as to "local glaciers".

A further reason for considering some glaciers outside the three WGI local classes is that some ice caps (class 4) are as small as cirque glaciers and may have preferred aspects. For example, around 68° N on Baffin I. "the ice caps all tend to lie on the northern slopes of hills" (Andrews and Miller 1972, fig. 3). It is always necessary to exclude rock glaciers (class 9), because of their different origins and their very different degrees of inclusion in the WGI for different countries.

Regional overviews

Svalbard

In Svalbard, the most accessible of High Arctic regions, late twentieth-century ELA rose from around 200 or 300 m near the coasts to over 800 m in some interior regions (Liestol 1993; Hagen *et al.* 2003). This shows that moisture from both western (Greenland Sea), eastern (Barents Sea) and southern sources is important in providing snow. Cold temperatures from the East Spitsbergen current also help give more extensive glaciation in eastern Spitsbergen (Wieslaw Ziaja, personal communication June 2010). The WGI (*cf.* Hagen *et al.* 1993) lists 894 glaciers with their latitude, longitude and area. Only 406 glaciers are given a classification, which is important here as Svalbard has a mixture of many types of glacier and ice-

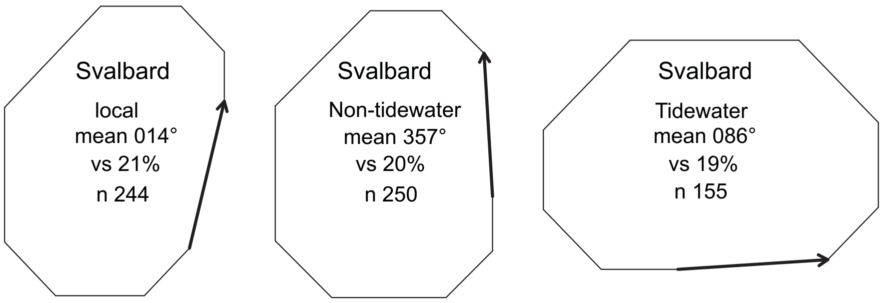

Fig. 3. Cumulated vector plots of Svalbard glaciers from WGI data; vs = vector strength.

caps and outlet glaciers need to be separated from local glaciers. The WGI classifies 237 as valley glaciers, none as mountain glaciers, and four as "glacierets" (but these range in size from 6.3 to 8 km^2).

Evans and Cox (2005) analysed these 241 local glaciers, for which the vector mean is 014° ± 17° with a strength of 21% (Fig. 3 includes three icefields). Allowing for a quadratic spatial trend, mid-altitude is predicted to be lowest at an azimuth of 109° ± 46°, an eastward tendency that is significant only when position is included in the regression. The inconsistency between the two approaches was puzzling, and the latter result was anomalous in the trend of north-south contrasts with latitude (Fig. 1). It could be explained if strong winds from between west and north were sustaining leeward glaciers, but this would affect glacier numbers and the vector mean as well; and it has not been observed. The "non-local" glaciers have no significant resultant vector, and their lowest altitude is weakly eastward. The 155 tidewater glaciers (Błaszczyk *et al.* 2009) (half of which are "local") have an eastward resultant (086° ± 34°, strength 19%: Fig. 3). The 250 non-tidewater glaciers are similar to local glaciers, with a mean of 357° ± 26° and a strength of 20%. A modified data set from Hester Jiskoot (personal communication 2004; *cf.* Jiskoot *et al.* 2000) led to similar results.

Table 1 gives vector results for a division of the Svalbard Archipelago into five regions. S is south of Bellsund and Van Mijenfjorden, C is from there to Isfjorden,

Table 1

Vector analysis of numbers of glaciers for five regional divisions of Svalbard. All glaciers with aspect data are included.

Region	*n*	Mean ± 95% band (°)	Strength (%)	Significance (*p*)	
				Rayleigh	Kuiper
S	73	006.1 ± 76.1	17	0.131	0.002
C	69	020.9 ± 41.0	24	0.018	0.000
NW	94	029.4 ± 74.0	15	0.132	0.003
E	79	088.2 ± 38.4	24	0.012	0.000
NE	90	331.4 ...	15	0.147	0.001

NW is west of Woodfjorden and Ekmanfjorden, NE is around Wijdefjorden, and E covers the eastern islands and Olav V Land, with large icecaps. All of the aspect distributions are "non-uniform" by the broad Kuiper significance test, but confidence intervals are wide even when all glaciers are included, and only C (to north-north-east) and E (to east) have significantly favoured directions by the Rayleigh test.

Regressions of altitude on aspect are insignificant except for the southern region (S). Here, eastward aspects are favoured, with glaciers 180 m (mid-altitude) or 140 m (snowline altitude) lower facing 100° than facing 280° (Fig. 4).

The reason for these inconsistent or insignificant results rests in the incompleteness of the WGI data. The average length (8861 m) of Svalbard local glaciers was more than twice that in any of the other 51 regions for which WGI data were analysed, and the average gradient (5.8°) was less than half (Evans 2006a, table 2). Inspection of images of Svalbard glaciers confirms the impression that they are gentler than those of high mountain areas such as the Alps or Himalaya. However, the WGI-based results overstate the contrast. Fuller information on the Svalbard inventory is available in Hagen *et al.* (1993), where it is stated that only glaciers exceeding 1 km^2 in area are listed separately; aspects and altitudes are not given for most glaciers with areas below 5 km^2. This contrasts with most regions in the WGI, for which glaciers down to 0.1 or even 0.01 km^2 were inventoried. There are many more than 241 local glaciers in Svalbard, and the omission of small glaciers loses those which are steeper and show the effects of aspect more clearly.

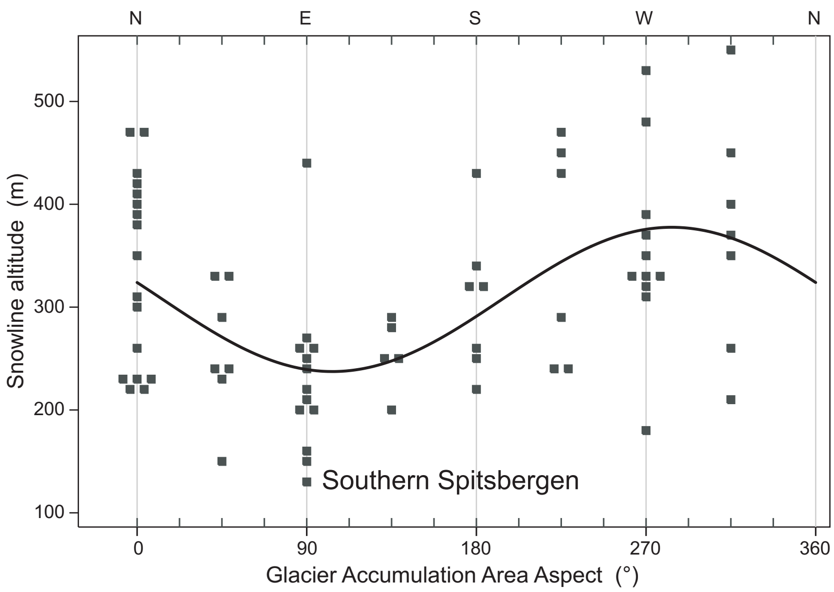

Fig. 4. Variation of snowline altitude with aspect for all glaciers in Spitsbergen south of Van Mijenfjorden: all those with relevant data are >5 km^2. Snowline is lowest at 104° ± 23°: Snowline altitude = 308 + 16 cos(aspect) – 68 sin(aspect) R^2 = 24%, *rmse* = 84 m, p <0.0001, n = 73. Each square is one glacier.

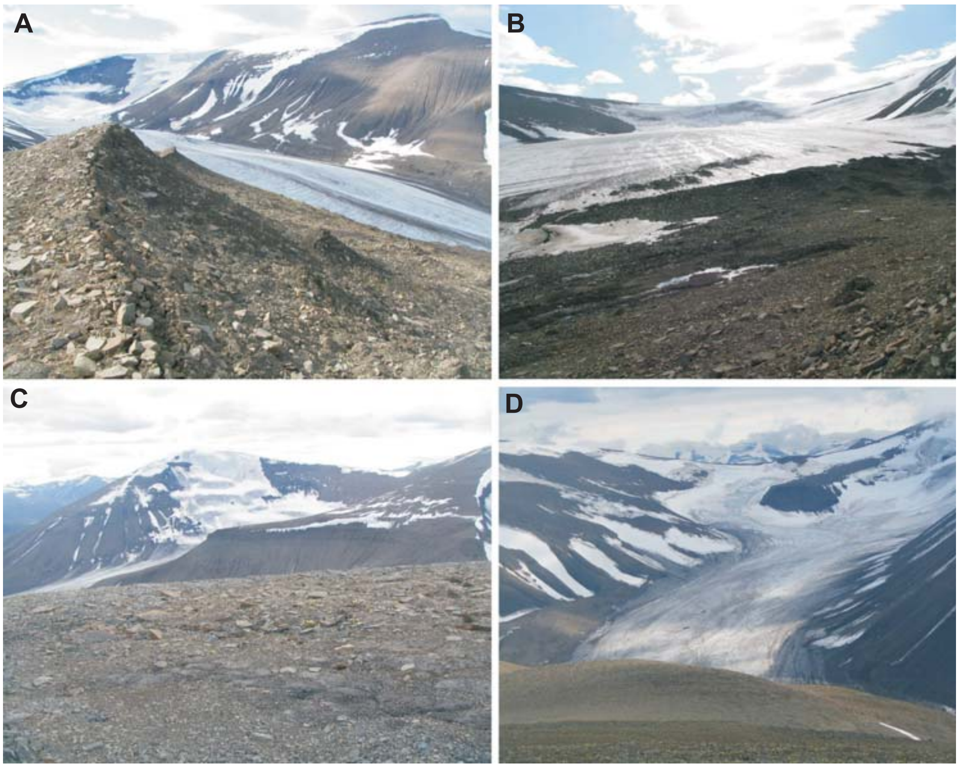

Fig. 5. Glaciers near Longyearbyen, 15 August 2007. Longyearbreen (**A**), Larsbreen (**B**), Dryadbreen (**C**), and Bogerbreen (**D**). Longyearbreen faces ENE, the other three face NNE.

To overcome this problem, Evans and Cox (2010) generated a small inventory for Nordenskiöld Land, the main area of local glaciation in Svalbard, in central Spitsbergen (Fig. 5) (Etzelmüller *et al.* 2000; Humlum 2002b; Ziaja 2002, 2005; Ziaja and Pipała 2007). In an area 75 km × 35 km, there are four mountain blocks separated by valleys and low passes. In combination, these contain 205 sources of glaciers with an average gradient of 16° and length of 1.72 km. The largest (Tavlebreen) has a length of 6 km and an area of 11 km^2.

These have a vector mean aspect of 011° ± 8° (Fig. 6) and are taken as more representative of local glaciers in Svalbard. A combined regression on aspect, allowing for the mean mid-altitude within each of the four mountain blocks, gives lowest glaciers facing 042° ± 41°, with $p = 0.027$ but an R^2 of only 3%. Taking the lowest altitude for each glacier, however, gives a stronger relation with an R^2 of 15% (p <0.0001) and lowest glaciers facing 026° ± 15°. Both of these confidence intervals include the vector mean, so the results are clearly consistent and north-northeast is the favoured aspect – as in many other parts of the world (Evans 1977). To establish this, it was necessary to focus on small, land-terminating glaciers.

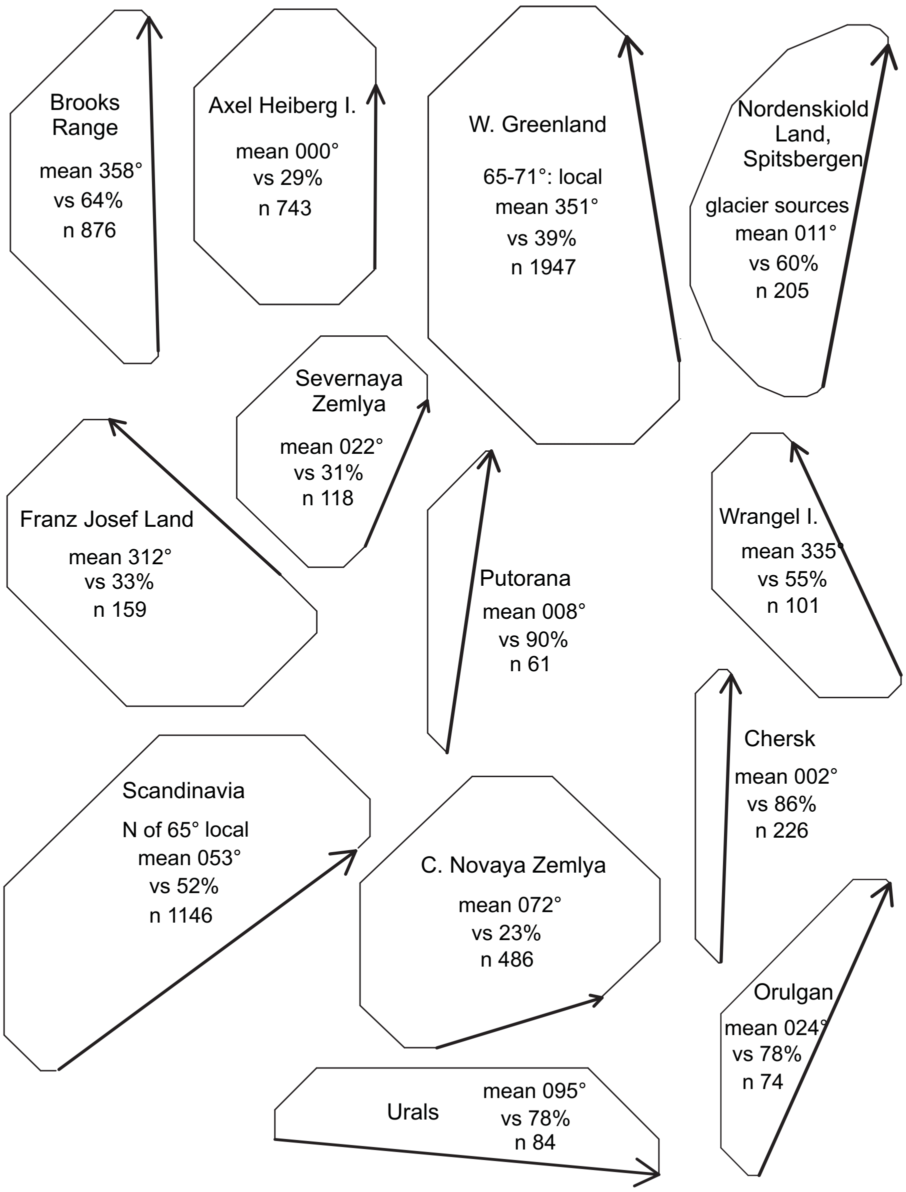

Fig. 6. Cumulated vector plots for Arctic data sets; vs = vector strength.

Jan Mayen. — All 20 glaciers on Jan Mayen Island (8° W, 71° N) are on the volcano Beerenberg (altitude 2277 m), covering all aspects. The ELA estimates given in Hagen *et al.* (1993) show a simple pattern of variation with aspect: north-facing glaciers are 288 m lower than south-facing (Fig. 7). Scatter is low and the relation is highly significant, although on the other hand the variation of median altitude with aspect is not significant.

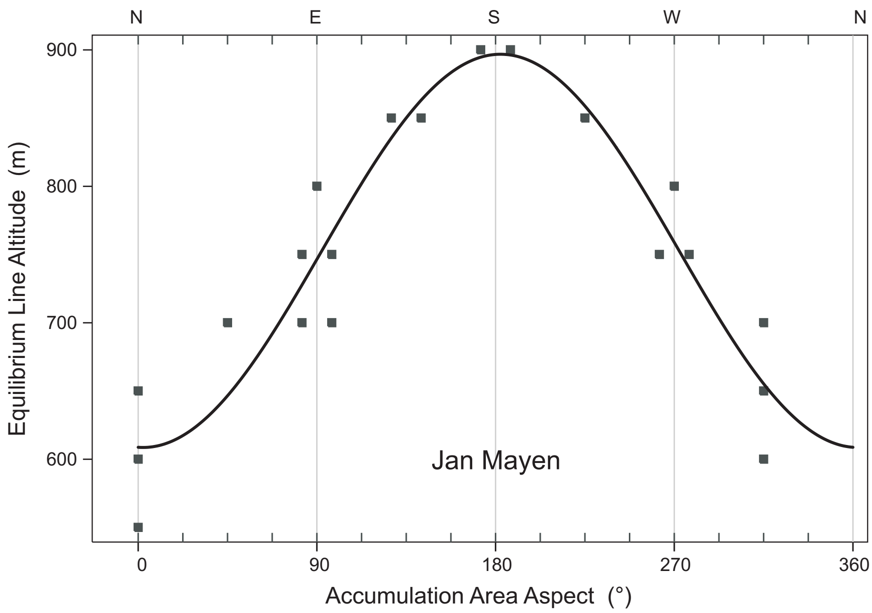

Fig. 7. Variation of ELA with aspect for glaciers on the volcano Beerenberg, Jan Mayen Island, N. Atlantic (data from Hagen *et al.* 1993). Glaciers are lowest facing 003° ± 9°: ELA = 753 – 144 cos(aspect) – 6 sin(aspect) R^2 = 87%, *rmse* = 36 m, p <0.0001, n = 20.

Other Eurasia

Northern Scandinavia. — In mainland Scandinavia (Norden) there are no glaciers between 63.2° and 65.1° N, so the region of "Arctic" glaciers is extended from 70.5° down to 65° N. In northern Norway, there are numerous summits over 1500 m. In Sweden, mountains rise to 2111 m (Kebnekaise), compensating for lower precipitation on that lee slope. Apart from its latitudes, Northern Scandinavia is the least Arctic of all regions considered here, because the strong influence of the North Atlantic Drift makes this the warmest region on the Arctic Circle. Nevertheless, it contains many polythermal glaciers, especially in Sweden (Holmlund 1998).

Overall, the 1483 glaciers have a vector mean of 053° ± 4° and strength of 45%; the resultant is highly significant (p<0.001). Coastal regions in Norway have vector means of northeast even if relief is high. Where ridges are sharp, advected heat from the Atlantic giving greater melt on windward slopes may be more important than drifting of snow to leeward. However, the 243 glaciers in Swedish ranges from Sarek to Abisko (data from Østrem *et al.* 1973) give a vector mean of 071° ± 9°, with a strength of 46%.There are more high plateau areas on the Swedish side, and the snow is drier, so drifting of snow to leeward slopes by westerly winds is of greater importance.

328 glaciers are classified as icefield, icecap or outlet glaciers, and 9 as uncertain. The remaining 1146 have the same vector mean as the total, but vector

strength is increased to 52%. The regression of middle altitude on aspect gives lowest local glaciers facing due North (± 27°):

Mid-altitude = 1185 – 55.1 cos(aspect) + 0.2 sin(aspect)

but accounts for only 2% of variance (*rmse* 246 m). Allowing for the linear trend in geographical coordinates accounts for 54% but reduces the aspect effect:

Mid-altitude = 22159 – 24.9 cos(aspect) – 17.4 sin(aspect) – 348.95 latitude + 157.46 longitude (*rmse* = 169 m, p <0.0001, n = 1146)

This predicts lowest glaciers facing 035° ± 30°, with lower glaciers to the north and west, *i.e.* towards the Atlantic coast. Although the aspect effect is weak, presumably because of cloudiness especially near the coast, glaciers facing northeast are both lower and more numerous. The effect of aspect on altitude is negligible for the 136 glacierets and is weaker for the 145 valley glaciers than for the 865 mountain glaciers. For all 1483 glaciers, the cosine coefficient is reduced to -17.3 m, *i.e.* only a 34.6 m difference between north- and south-facing glaciers, and the lowest glaciers face 045° ± 32°.

The WGI also includes four tiny glaciers in the Kola Peninsula, around 34° E and 68.4° N in the Khibiny Mountains south of Murmansk. They are 2 or 3 ha in area and 200 to 400 m long, with middle altitudes of 935 to 1065 m: two face North and two face West. The Khibiny receive heavy snowfalls and avalanches are important (Shahgedanova *et al.* 2002).

Urals. — Glaciers in the Polar and Sub-polar Urals, from 64.8° to 68.2° N, are small and wasting rapidly. Glazovskiy *et al.* (2005) describe late-20th century losses in nine glaciers with areas of 0.1 to 0.9 km^2. Kononov *et al.* (2005) related the mass balance of the IGAN and Obruchev Glaciers to summer temperature and winter precipitation. However, it has long been established (Dolgushin 1961) that without drifting of snow by strong westerly winds there would be no glaciers here. Accumulation (mean winter balance) on the Obruchev Glacier is five times winter precipitation nearby (Mangerud *et al.* 2008, table 3) and the Ural glaciers are well-shaded in cirques: precipitation is concentrated by the avalanching of wind-blown snow. Thus the vector mean of the 84 glaciers in the WGI is 095° ± 3°, with a strength of 78%. As there are no glaciers facing west, northwest or southwest, regressions on aspect are insignificant. Nevertheless, they predict lowest glaciers facing 099°, or 109° when the linear trend is included, and these directions are consistent with that favoured by glacier numbers. The direction rather south of east not only confirms Dolgushin's view on the importance of wind, but shows that the net effective wind that drifts snow comes from some point north of west.

Novaya Zemlya. — Novaya Zemlya is two long islands trending generally southwest-northeast, north of the Urals. Regionally, ELAs are lower on the northwest side. Out of a total 685 glaciers, Novaya Zemlya has 395 valley glaciers, 158 mountain glaciers and 27 glacierets, giving 580 local glaciers, 574 of which have the aspect and altitude data for analysis of local asymmetry. The vector mean of these local glaciers is 062° ± 15°, and of all 639 glaciers (with such data) is 050° ± 14°: vector strength is 23% in both cases. Novaya Zemlya has extra glaciers facing northeast and southeast, giving this significant eastward component. The direction of minimum mid-altitude as predicted from the regression on latitude, longitude, sine and cosine of aspect is 098° ± 18°.

In this moderate relief (highest point 1342 m), the effects of wind from westerly directions seem to operate mainly through drifting snow to lee slopes. The effect of wind increases southward. In Novaya Zemlya north of 75° N, the 73 local glaciers have a mean aspect of 013° ± 24°. The 231 south of 73.6° N have a mean of 087° ± 26°, and the 276 between have 063° ± 20°. Vector strengths are 39%, 22% and 24%, respectively. Alternatively taking glaciers less than 10 km^2 in area, the means are 003° in the north, 079° in the south and 052° in the middle, with comparable numbers of glaciers.

There is a contrast between the northern part of Novaya Zemlya, dominated by an elongated icecap, the central part with many local glaciers, and the part south of 72.8° N which has no glaciers. All outlet glaciers (Sharov 2005) and all but five of the smaller icecaps are north of 74.65° N, and this northern region gave the discrepancy between a vector mean of 018° ± 26° and lowest glaciers (insignificantly) facing 133° ± 50° for the 93 local glaciers, noted in Evans and Cox (2010). The local glaciers there are mainly in the west, but with smaller groups in the north and the southeast, peripheral to the main icecap. This distribution is biased by the main icecap occupying most of the island, preventing local glacier formation on some aspects. The local glaciers should not be separated from the icecaps and outlet glaciers here, but even when these are included the discrepancy is little changed.

Further analysis concentrates on the area south of 74.65° N, with 569 local glaciers and 5 small icecaps. The “icecaps” are described as ice aprons: they are 0.7 to 7.2 km^2 in area, 1.4 to 3 km long and 300 to 550 m in height range, with middle altitudes between 475 and 645 m. Thus, they can be included with the local glaciers. The vector mean of the 574 glaciers south of 74.65° N is 072° ± 17°, again suggesting a strong westerly wind effect. In the simpler regression, lowest glaciers face 081° ± 22° (Fig. 8). Taking position into account, the cosine and longitude terms are insignificant and the lowest glaciers face 091° ± 19°:

$$\text{Mid-altitude} = 8384 + 1\cos(\text{aspect}) - 42\sin(\text{aspect}) - 115.21\ \text{latitude} + 11.69\ \text{longitude}\ (R^2 = 16\%,\ rmse = 116\ \text{m},\ p < 0.0001,\ n = 486)$$

All three favoured directions are thus mutually consistent. The anomalous result for northern Novaya Zemlya is attributed to the uneven distribution of local glaciers.

The northwest-southeast regional contrast in Novaya Zemlya is manifest also in the distribution of the 32 surge-type glaciers. 27 are on the northwest side of the

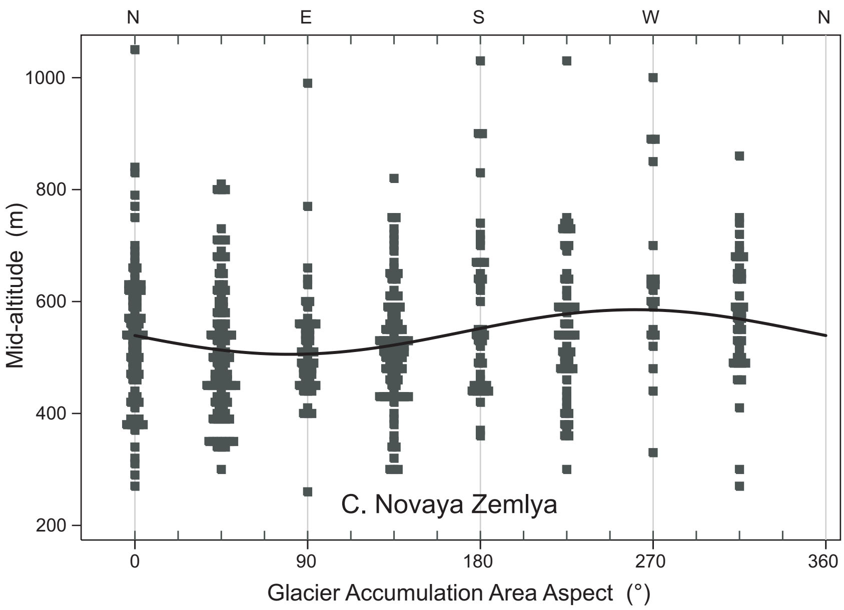

Fig. 8. Variation of mid-altitude with aspect for all glaciers in central Novaya Zemlya, 72.8° to 74.65° N. Glaciers are lowest facing 081° ± 22°: Mid-altitude = 546 – 6 cos(aspect) – 39 sin(aspect); R^2 = 4%, *rmse* = 124 m, p = 0.0001, n = 486.

islands and only 5 on the southeast. These are not local glaciers, however, all are north of 74.25° N, have lengths >7 km, areas >19 km^2 and gradients <5.4°; all are outlet glaciers of large icecaps (Grant *et al.* 2009). Thus the surge-type glaciers require both considerable size and the greater inputs of the windward slope.

Franz Josef Land and Severnaya Zemlya. — Krenke (1997) points out that because winter storm tracks along the Arctic Front follow the Norwegian and Barents Seas, passing south of Svalbard and Franz Josef Land, the most thorough glacier cover is in the southeast parts of these archipelagos, as it is in Iceland. Because Norway and Novaya Zemlya lie south of these tracks, they have heavier snowfall and their glaciers are regionally lower in the northwest. Table 2 shows that several archipelagos in the Arctic for which WGI data are available show weak but significant asymmetry of glacier numbers, mainly northward.

Franz Josef Land (79.8° to 81.9° N) has 995 glacier units, but most of them are outlet glaciers and sectors of ice caps and thus unsuitable for analyses related to slope climates. The eleven main islands are 71 to 95% ice-covered (Krenke and Slupetzky 1997) and 60% of the coastline is glacier ice (Sharov 2005). Thus the archipelago is the most Antarctic-like part of the Arctic, but with a lot of cloud (average 76% cover) and 300 mm precipitation (on Hayes Island, but up to 450 mm on the ice caps: Krenke 1997), like the Antarctic Peninsula. The maximum altitude is 620 m. The ice is largely "cold", but the outlet glaciers flow at up to 60 m a^{-1} with great seasonal variations, showing basal sliding.

Table 2

Vector analyses for numbers of local glaciers, extended from Evans and Cox (2005), compared with analyses for all glaciers. Mean and 95% confidence limits are in degrees. All these analyses give resultant vectors of accumulation area aspect significant at the 0.001 level by Rayleigh's test, and are significantly different from uniform distributions by Kuiper's more general test, also at the 0.001 level.

Region		*n*	Mean ± 95% band (°)	Strength (%)
Svalbard	local	241	013.6 ± 23.9	21
	all	405	027.0 ± 28.4	14
Franz Josef Land	local	159	312.3 ± 17.0	33
	all	995	357.1 ± 5.1	40
Severnaya Zemlya	local	118	022.4 ± 24.0	31
	all	289	015.4 ± 10.4	40
Novaya Zemlya	local	580	062.9 ± 15.0	23
	all	685	046.1 ± 14.0	23
Axel Heiberg	local	289	254 (insignificant)	
	all	526	331.2 ± 57.4	6
Wrangel I.	local = all	101	335.7 ± 13.2	55

Local glaciers are only 16% of all glaciers recorded in the WGI for Franz Josef Land. There are 153 glacierets and 6 other local glaciers, yet all but 7 lack either lowest or (mainly) highest altitude in the Inventory. They are scattered throughout the archipelago, around the peripheries of ice caps, and many are probably remnants from the downwasting of ice caps: the estimated 1930–1959 lowering of ice surfaces in Franz Josef Land is 8 m (Krenke and Slupetsky 1997). Nevertheless, vector analyses of these supposedly local glaciers show highly significant asymmetry, tending to 312° ± 17° with a vector strength of 33%. This is a leeward tendency in accordance with Krenke and Slupetsky's (1997) emphasis on the importance of moisture brought from the Barents Sea by southeast winds.

Although these local glaciers favour northwestward aspects, the total data set favours northward. This is the only area in Table 2 where the confidence limits for all glaciers do not overlap those for local glaciers. It is a little surprising that in Franz Josef Land and Severnaya Zemlya vector strengths are greater for all glaciers than for local glaciers. This is attributed to the problems of coverage noted below.

East of Franz Josef Land in Severnaya Zemlya (79° N, north of western Siberia) highest altitude is again normally missing, and altitude regressions cannot be calculated from WGI data. But these islands receive moisture from the southwest (Barents Sea, via Saint Anna Strait) rather than the east, and the vector mean for the 118 local glaciers is 022° ± 24°, with vector strength of 31%. This suggests a slight wind modification of the general northward tendency.

Ushakov Island and Victory Island are covered by icecaps, with no local glaciers.

Northwest Siberia (mainland). — Although no WGI data are available on-line for the Byrranga Mountains on the Taymyr Peninsula, Glazovskiy (1996) mentions

96 slope, cirque and valley glaciers, with the largest (Neozhidanny) being 4.3 km^2 in area: more than ten disappeared, 1960–77. ELA is 850 m, at which mean annual air temperature is -2.9°, and accumulation is 330 mm (Glazovsky 2003). As in the Urals, wind drifting of snow is important, but 30 of the 31 km^2 were in the ablation zone (in the 1980s): the rest was superimposed ice, with no firn zone. The glaciers are in the northeastern part of the Mountains (Pospelova *et al.* 2004): annual precipitation is 400 to 500 mm and glacier area reduced between 1960 and 1977, to 30.5 km^2. Glaciers are visible on Google Earth around 107.7° E, 75.9° N.

The Putorana massif in northwest Siberia is the most humid part of the Russian Arctic (Filippov *et al.* 1964). The Putorana was poorly covered in the WGI, where 22 glaciers were identified. A recent resurvey using Landsat images as well as fieldwork identified 61 glaciers between 0.02 and 0.3 km^2 in area (Sarana 2005), in the northwest quarter of the Plateau which is dissected by deep glacial troughs. Seven of the WGI glaciers were excluded, downgraded to snowpatches: Sarana also mapped many further snowpatches. The glaciers are beside summits from 633 to 1591 m in altitude. Interestingly, no glaciers are recorded farther east where the Plateau reaches its maximum height of 1701 m. Their existence requires the shade of steep slopes in more dissected areas. Most glaciers are in cirques around tributary troughs.

The mean aspect of these glaciers is 008° ± 7° with a strength of 90% (Fig. 6). There are 40 facing north, 15 northeast, 5 northwest and 1 east. The lack of southerly-facing glaciers makes the north-south term in Fourier regressions insignificant; so is the east-west term once position is taken into account. Lowest glaciers are then predicted to face 345° ± 48°. Although this is consistent with mean aspect, it arises simply because the average mid-altitude for (5) northwest-facing glaciers is 682 m, while that for northeast-facing is 907 m. Mid-altitude rises eastward:

$$\text{Mid-altitude} = -11048 + 131.22 \text{ longitude } (R^2 = 50\%,\ rmse = 122 \text{ m},\ n = 61).$$

This reflects the eastward rise in the altitudes of the mountains supporting the glaciers. Mountain altitude rises eastward at 178 m per degree, the top altitude of glaciers rises at 136 m, mid-altitude by 131 m and bottom altitude by 126 m per degree. R^2 values are 74, 50, 50 and 49% respectively. Latitude does not add significantly to these trends. The lowest glacier (460 to 400 m) is the westmost.

Northeast Siberia (mainland). — The physical geography of Siberian mountains including Putorana is summarised by Shahgedanova *et al.* (2002), who give references to the literature in Russian, and by Suslov (1961). On the Russian mainland, the importance of westerly winds for mass balance and glacier aspect steadily decreases eastward from the Urals through the Putorana and Orulgan to the Cherskiy Ranges. East of the Lena River, the Orulgan Mountains – the northern part of the Verkhoyansk Ranges – have 74 WGI glaciers between 67.4° and 69.1° N. They are up to 3.5 km long and 2.8 km^2 in area, with vertical extents of up to 530 m. Mid-altitude varies from 1580 to 2175 m. They are lower to the north, but also to the west as atmospheric moisture comes mainly from that direction:

Mid-altitude = 5872 – 41.8 cos(aspect) – 12.7 sin(aspect) – 208 latitude + 80 longitude (R^2 = 55%, *rmse* 83 m, n = 71).

This predicts lowest glaciers at 017° ± 46°. Although the aspect terms are insignificant, this is consistent with the vector mean of 024° ± 9°. There is some influence from westerly winds, but the poleward tendency due to shade from solar radiation is dominant.

Farther east, the Cherskiy Ranges straddle the Arctic Circle around the Indigirka River from 67.7° to 64.6° N. They are near the Northern Hemisphere pole of winter cold and have the most continental climate. Including the Moma Range, they are from 138° to 149° E, and seem to be influenced by both Pacific and Atlantic moisture and air masses. Predicted ELA varies from 2200 to 2700 m and rises southward and westward (Ananicheva and Krenke 2005; Ananicheva *et al.* 2006). Actual glacier mid-altitudes are 1800 to 2650 m (mean 2176 m). Because of the low precipitation, these are the highest ELAs in the Arctic. Deep temperature inversions mean that only the high mountains receive moisture from the west in winter, and this is less than in other seasons (Shahgedanova *et al.* 2002).

By 1944, recession from Little Ice Age (LIA) moraines was limited (Solomina and Filatov 1998). Solomina (2000) attributed the relatively low losses to low mass balance turnover in the severe continental climate. Limited recession was confirmed from 2001-satellite-based mapping of 80 glaciers and their moraines in the Buordakh massif (65.2° N) by Gurney *et al.* (2008), who found that 39% of glaciers were stable and areal recession was only 17% since the LIA . These 80 glaciers (with areas > 0.1 km^2) face mainly northward. Analyses in Evans and Cox (2005) and Evans (2006a) combined the Cherskiy ("Chersk") with the Suntar-Khayata Range, but as the glaciers in the latter are well outside the Arctic (from 62.8° to 61.6° N), and there is a gap of 1.8° latitude, they are excluded here.

The great majority of the 226 Cherskiy glaciers in WGI face north: the vector mean is 002° ± 3°, with a strength of 86%. However, there are some south-facing glaciers, and the altitude regressions are significant:

Mid-altitude = 2293 – 136 cos(aspect) + 3 sin(aspect)
(R^2 = 11%, *rmse* = 126 m) (Fig. 9)

Mid-altitude = 10654 – 100 cos(aspect) + 9 sin(aspect) – 118 latitude – 4 longitude (R^2 = 32%, *rmse* = 110 m).

With the linear trend, lowest glaciers are predicted at 355° ± 23° and the north-south contrast is a clear 199 m. The quadratic trend increases R^2 to 44% but has little effect on the aspect terms. Regionally, mid-altitude falls northward at 118 m per degree, but variation with longitude is insignificant, confirming the minimal net effect of wind here.

In mainland Chukotka, the easternmost region of Siberia, moisture is derived from the North Pacific and the Chukchi Sea. Sedov (1992, 1997) described steep,

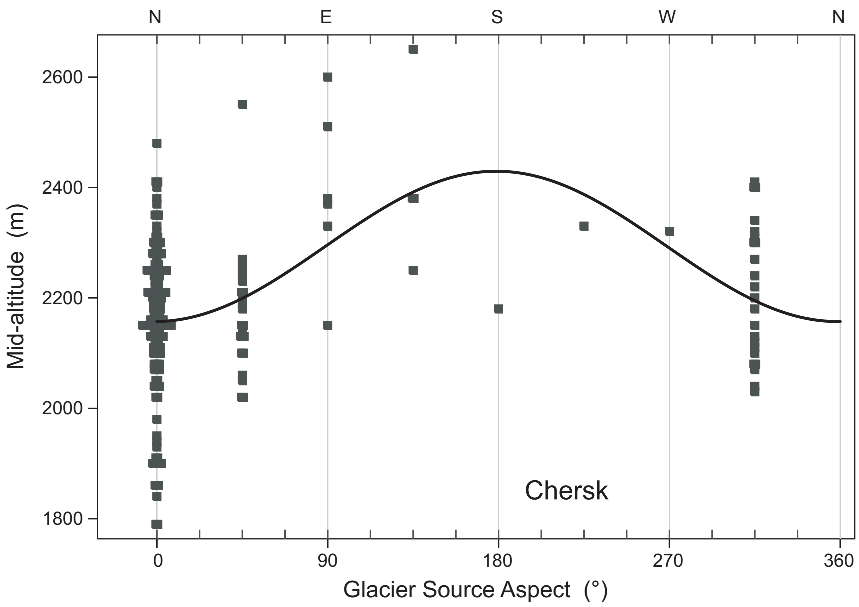

Fig. 9. Variation of mid-altitude with aspect for glaciers in the Cherskiy Ranges, northeast Siberia. Glaciers are lowest facing 359° ± 19°: Mid-altitude = 2293 – 136 cos(aspect) – 3 sin(aspect); R^2 = 11%, *rmse* = 126 m, p <0.0001, n = 226.

debris-covered cirque glaciers "in a stage of degradation" in the Tenianyy (Tenkianiy) Range. Omitted from the on-line WGI, these have equilibrium lines around 500 m and about 1900 kg/m² annual accumulation. There are also small glaciers in the Pekulney Range, around 175° E, 66.2° N, and together with those on the Chukotka Plateau and Ekiataps Range (*e.g.* a north-facing glacier at 179.2° E, 68.66° N, with an 820 m ELA) the total area is 17.1 km² (Sedov 1997).

Wrangel Island, Russian Far East. — Also in Chukotka, all 101 glaciers in the WGI for Wrangel I. (71° N) are local, and from 0.1 to 1.2 km long. Their vector mean is 335° ± 13° (strength 55%) but they are lowest when facing southeast: 143° ± 34°. Disregarding position, the 70 glaciers facing north, NW or NE average 465 m in mid-altitude; the 9 facing south, SE or SW average 292 m. Although small, the numbers are sufficient to provide significant Fourier coefficients and it must be admitted that on Wrangel glacier numbers and altitudes reflect aspect in different ways. Linear trends of altitude with position seem insufficient here to allow for the regional effects of moisture brought from southerly sources:

Mid-altitude = 8722 + 82.1 cos(aspect) – 60.7 sin(aspect) – 1111 latitude + 394 longitudeW (R^2 = 22%).

Compared with the other regions in Table 2, Wrangel glaciers are unusually small. Their mean length is only 162 m, whereas the others are over 700 m. Their mean height range is only 55 m, whereas all others exceed 250 m. The glaciers are in the higher, south-central part of the island around 179° W, but five start as low as 150 to 240 m and these have height ranges of only 20 to 40 m. Nine of the twelve longest glaciers (300 to 1200 m long) start above 500 m, around 71.125° N and near the highest peak, Mount Sovetskaya (1096 m). Of the 101, 41 are classified as glacierets, 57 as mountain glaciers and 3 as valley glaciers. All are described as niche or cirque glaciers, but further information is needed on their true nature. Surprisingly, Gualtieri *et al.* (2003, page 400) assert that "No modern glaciers exist today on WI [Wrangel I.], but perennial snowfields occur in the highest mountain passes". They give the mean annual temperature of Wrangel I. as -12° C and precipitation as 104 mm, while another source gives 275 mm.

In the WGI, 15 glaciers are listed for the De Long Islands, around 77° N and from 148° to 158° E, west of Wrangel I. but far east of Severnaya Zemlya. There are three icecaps and five outlet glaciers on the western islands, and five glacierets, one icecap and one outlet glacier on the eastern. The glacierets are between 0.4 and 2.5 km long and 0.1 to 1.2 km^2 in area, with low height ranges and mid-altitudes between 25 and 285 m. Their mean direction of 344° ± 53° is insignificant despite a vector strength of 71%.

Other North America

Brooks Range. — In northern Alaska, glaciers are scattered through the Brooks Range from 143.2° to 156.5° W and from 67.2° to 69.4° N. The regional ELA rises from 1500 m in the west of the southern slope, to 2100 m in the east of the northern slope near the Yukon border (Porter *et al.* 1983). Glacier mid-altitude similarly rises northward and eastward:

Mid-altitude = -11653 + 221.4 latitude – 11.6 longitudeW
(R^2 = 58%, *rmse* = 141 m).

This shows that Brooks Range moisture comes essentially from the Pacific, and as remoteness from that source increases ELA rises almost as high as in the Cherskiy Ranges. In the far northeast around Mount Chamberlain (2749 m; 144.9° W), Arctic Ocean moisture causes a small lowering of ELA.

Excluding 39 rock glaciers, the WGI gives altitudes and aspect for 876 glaciers in the Brooks Range. These have a vector strength of 64% with a mean at 358° ± 4°, and lowest glaciers facing 025° ± 20°, including the trend with position (Evans 2006a). For three divisions (west of 152° W, central, and east of 147.7° W), vector means are within an 11° range and vector strengths are high. Lowest altitudes, however, have no significantly favoured aspect in either the western or the central divisions. The overall result comes essentially from glaciers in the eastern division, where 017° ± 15° is lowest:

Mid-altitude = 15209 – 68 cos(aspect) – 21 sin(aspect) – 49.1 latitude – 68.0 longitudeW (R^2 = 32%, *rmse* = 115 m, p <0.0001, n = 350).

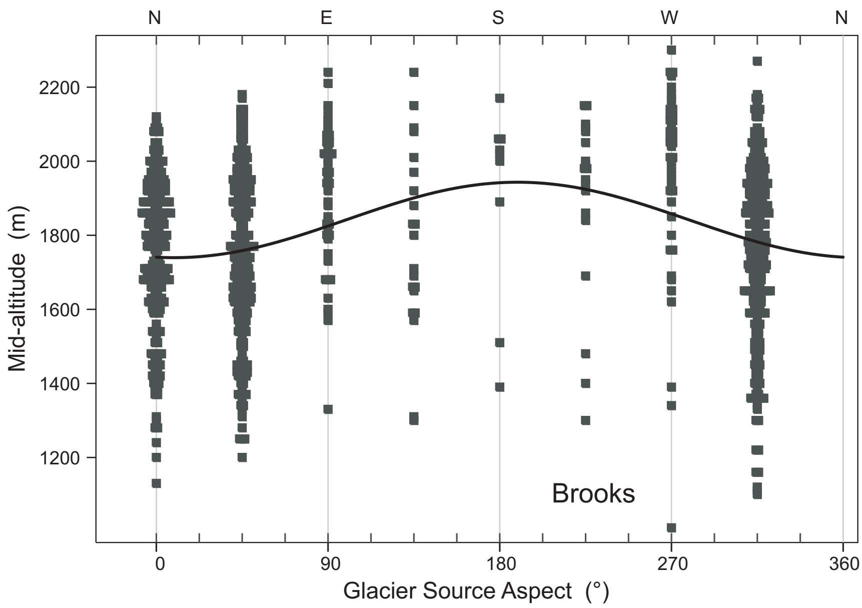

Fig. 10. Variation of mid-altitude with aspect for glaciers in the Brooks Range, Alaska, east of 147.7° W. Glaciers are lowest facing 009° ± 13°: Mid-altitude = 1996 – 92 cos(aspect) – 15 sin(aspect); R^2 = 11%, *rmse* = 131 m, p <0.0001, n = 350.

Figure 10 shows this relationship. Without allowing for position, glaciers facing 009° ± 13° are lowest. Thus although there are some differences between the divisions of the Brooks Range, it is clear that a northward aspect is favoured both in the eastern division and overall. Also the ninefold WGI regional division gives significant vector means, all between 349° and 008°. A different approach by Wendler (1969) based on grid squares gave a mean of 008° and vector strength of 59% for glaciers in part of the Brooks Range.

Baffin Island. — Glaciers extend along the raised northeast side of Baffin I. from 62.0 to 73.8° N (Andrews 2002), fed by moisture from Davis Strait. In the Arctic sector, ELA rises (Andrews and Miller 1972) from 900–1000 m in the southeast corner of Baffin I. to over 1200 m in the interior, and falls to 750 m in the northern part of Bylot Island (Williams 1978). Svoboda and Paul (2009, table 1) analysed data for 662 glaciers, around 66–67° N in the eastern Cumberland Peninsula of Baffin I. Northward tendencies were dominant for glacier numbers, and even more so for glacier area. North-facing glaciers have mean altitudes about 200 m lower than south-facing. This is consistent with the results of Andrews *et al.* (1970) for 48 cirque glaciers in the Okoa Bay area, 67.5–68° N. These have a vector strength of 68% around a vector mean of 011° ± 15°: none face between 150° and 308°. Cirques with glaciers have floors some 190 m above the empty cirques facing southeast to southwest (Andrews *et al.* 1970, figs 3 and 11). The 165 outlet glaciers of the adjacent Home Bay area (68–69° N) also have a tendency just east of north.

Williams (1975, fig. 4) showed that on the Okoa Bay map sheet there are five north-facing glaciers in cirques with headwall-floor junction altitudes around 700 m, and higher north-facing cirques have glaciers. On the other hand, no south-facing cirques have glaciers even though four of them are as high as 1300 m. Although Williams calculates similar north-south contrasts of 600 m from two model simulations, this contrast seems excessive and is probably due to the conflation of local contrasts with the 300 m variation in ELA across the map sheet. In other words, the altitudes should be related to the regional trend as above, as well as to local aspect.

Dowdeswell *et al.* (2007) inventoried the glaciers of Bylot Island, just offshore from northern Baffin I., but did not discuss aspect.

Greenland. — In general, ELA and Glaciation Level rise away from each coast of Greenland (Humlum 1985). Taken as 200 m below Glaciation Level, the ELA in east Greenland rises from about 300 m along the outer coast to 1300 m in numerous inland areas fringing the Ice Sheet (Weidick 1995). In west Greenland, it is from about 600 m near the coast, and in the north, from about 300 m. This is considerably lower than near the facing coast of Baffin I., across Davis Strait. Inventories with aspect data are not currently available for most of Greenland, which is estimated to have 70,000 glaciers around the fringes of the Ice Sheet (Weidick and Morris, in Haeberli *et al.* 1998). These include many near the east coast and in the far north. Weng (1995) estimated that the 301 local glaciers and ice caps shown on 1: 2,500,000 maps cover 48,600 km^2.

A non-WGI inventory of 5299 glaciers covers West Greenland between 59.8° and 71.2° N (Weidick *et al.* 1992). Accumulation area aspects are not included, but ablation area aspect is given for 5144 glaciers of which 3756 are classified as local. Given the correlation between accumulation and ablation area aspects noted elsewhere for local glaciers, ablation aspects are used here. The southern part of this extensive region is well outside the Arctic, and there are gaps with few glaciers between 64.6° and 65.1° N, also 62.0–62.4°, 66.7–67.0° and 67.4–69.2° N. Thus Evans and Cox (2005) used the former gap and divided the data at 64.8°: as the next gap to the north starts at 66.7°, the same division is appropriate for this Arctic study and only glaciers north of 64.8° N are considered. There are 1947 such local glaciers with aspect (Fig. 6), of which 1775 also have altitude variables.

The vector mean of these local glaciers (between 64.8° and 71.2° N) is 349° ± 5° for those with altitude (Fig. 6), and 004° ± 11° for those without: these confidence intervals overlap at 353°. Figure 11 shows that the lowest glaciers face north-northwest: 332.4° ± 12.7° when aspect alone is considered, and 353.9° ± 12.4° when position is included in the regression. Overall, then, these directions are just about consistent. The amplitudes of variation between these and opposed aspects are 185 m and 181 m respectively.

Further division of this data set is feasible using the gaps at 66.7° and 69.2° N, and subdividing the southern area at 51.7° W and the northern at 52.15° W to give

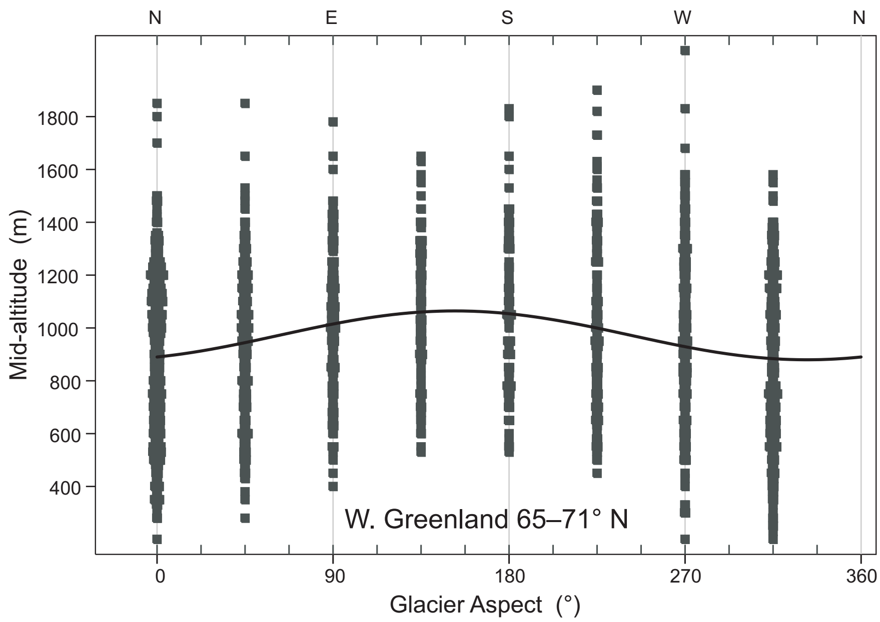

Fig. 11. Variation of mid-altitude with ablation area aspect for local glaciers in West Greenland between 65° and 71° N. Glaciers are lowest facing 332° ± 13°: Mid-altitude = 972 – 82 cos(aspect) + 43 sin(aspect); R^2 = 4%, *rmse* = 293 m, p <0.0001, n = 1775.

five regions with local glaciers. Table 3 gives the results of vector analyses for these and shows strong northward or north-northwestward tendencies for each region, confirming the overall result. Table 4 permits comparison of regression coefficients for aspect, for linear trend, and for both together. Note that the large base coefficients for latitude and longitude arise because the origin (0,0), is a long way from this study area. While aspect regressions are insignificant for three regions, cosine coefficients are consistent and significant except for the fifth region (where they are positive). Westward tendencies are weak. The sine coefficients are insignificant at $p = 0.05$. Tendencies to be lower on northward aspects are strongest for Disko – W. Nuussuaq and Sukkertoppen – S. Isortoq, where north-facing glaciers are 230 m lower than south-facing. Aspect effects are weaker nearer the Ice Sheet. The regional results essentially replicate the conclusion that there is a clearly favoured aspect in Arctic West Greenland, and it is toward north-northwest.

A separate inventory for Disko Island provided by Jacob Yde (personal communication 2006) gives a vector mean of 006° ± 16° and strength of 32%, for 227 glaciers, but no significant aspect effects on altitude.

Regionally (from the third equation of each set in Table 4), glaciers are higher in the north and east, reflecting the importance of moisture sources from the southwest rather than any northward reduction in temperature over the six degrees of latitude. Within each region glaciers are also higher in the north; in the seaward (western) regions glaciers are higher in the east, but in the two landward regions (the second and

Table 3

Vector analyses for local glaciers in West Greenland between 64.8° and 71.2° N (which have altitude variables). All are highly significant ($p < 0.001$ by both Rayleigh and Kuiper tests).

Region	*n*	Mean (°)	Strength (%)	95% limits (°)	
Disko and W. Nuussuaq	662	350.3	36.0	341.8	358.7
E. Nuussuaq	119	004.3	36.0	344.6	024.1
Nordre Isortoq	113	355.1	50.9	342.4	007.7
Sukkertoppen and S. Isortoq	626	327.1	35.6	319.0	335.1
Amitsuloq and Majorqaq	255	015.1	57.7	008.5	021.7
65–71° N Total	1775	349.4	38.1	344.7	354.0

Table 4

Regression coefficients for mid-altitude (m) in West Greenland between 64.8° and 71.2° N, as a function of aspect and location. For each subset of local glaciers, the results of three regressions are given: aspect, without location; aspect with a linear spatial trend; and linear spatial trend alone.

Coefficient for:	Base	Cosine	Sine	Lat	LongW	R^2 (%)	*rmse* (m)	*p*
Disko and W. Nuussuaq $n = 662$	969	-116	+5			4.3	333	<0.0001
	-35978	-115	+3	+620.92	-120.91	70.9	184	<0.0001
	-35812			+619.46	-122.86	66.3	198	<0.0001
E. Nuussuaq $n = 119$	985	-43	+6			0.3	194	0.31
	-31564	-80	+18	+382.74	+109.19	39.1	152	<0.0001
	-28785			+327.61	+130.00	33.3	159	<0.0001
Nordre Isortoq $n = 113$	1055	-53	+32			1.4	212	0.17
	-12492	-66	+8	+566.47	-462.46	62.5	131	<0.0001
	-8684			+510.50	-464.00	59.5	136	<0.0001
Sukkertoppen and S. Isortoq $n = 626$	916	-135	+53			10.4	289	<0.0001
	-27255	-116	+6	+777.31	-438.91	65.0	180	<0.0001
	-23564			+773.14	-504.19	59.0	195	<0.0001
Amitsuloq and Majorqaq $n = 255$	(aspect regression is insignificant at $p = 0.10$)							
	(regression with aspect is insignificant at $p = 0.10$)							
	-11099			+118.20	+86.75	17.9	107	<0.0001
65–71° N Total $n = 1775$	972	-82	+43			3.8	293	<0.0001
	3318	-90	+10	+44.47	-101.73	18.7	269	<0.0001
	3202			+44.20	-99.82	15.0	275	<0.0001

fifth) glaciers are lower in the east as the Ice Sheet is approached. This is shown also in Humlum's (1986) glaciation level maps of the area around Disko Island.

New data recently provided by Frank Paul (personal communication December 2010) cover the area immediately to the north in West Greenland, from 71.4° to 73.2° N. This has 1646 glaciers between 0.01 and 48.3 km² in area, 1073 of which have aspect data; all of these have altitude data also. The vector mean direction is 340° ± 5°, with a 44% strength. There is again a suspicion of westward bias because some west-facing slopes are included without corresponding east-facing, but this can be tested by separating the area into eight regions, six of which cover complete mountain ranges between valleys or fjords.

The two inner regions, affected by possible bias but also by katabatic winds off the ice sheet, have 245 glaciers with a mean of 307° ± 24° and a strength of only 21%. Two intermediate regions, the two main Svartenhuuk Peninsula ranges and the island with Nuugaatsiaq, have 372 glaciers with a combined mean of 344° ± 17° and a strength of 26%. The combination of four outer-coastal regions, covering the whole latitude range, various islands and the mountains around Umiarfik Fjord, has 456 glaciers with a mean of 344° ± 4° and a great strength, 74%, showing a very consistent north-northwest tendency. Regional means are between 335° and 358°, strengths 73 to 84%.

For predictions of mid-altitude, the (negative) cosine term greatly exceeds the (usually positive) sine term in all regressions, confirming a favoured direction a little west of north. For all 1073 glaciers, aspect alone accounts for (R^2) 25%; with position it covers 61% but its coefficients are halved:

Mid- altitude = -12940 – 124 cos(aspect) + 14 sin(aspect) + 1.236 N + 6.847 E, where N and E are UTM northing and easting in km and *rmse* = 196 m.

Lowest glaciers are predicted to face 354° ± 8°. The cosine term is consistent over the three divisions, but in the outer division ($n = 456$) the sine term is negative and significant, so that the lowest glaciers face east of north ($R^2 = 44\%$, *rmse* = 131 m, lowest glaciers face 012° ± 11°):

Mid-altitude = -16473 – 130 cos(aspect) – 27 sin(aspect) + 1.553 N + 8.607 E'

These highly significant ($p < 0.0001$) regressions support the earlier conclusion that northward tendencies are general among the local glaciers of West Greenland, and there is a weaker westward tendency strengthened by proximity to the ice sheet. This applies to glacier altitudes as well as glacier numbers. Comparison of cosine coefficients with those in Table 4 shows that the north v. south effect is stronger north of 71.4° than south of 71.2° N in West Greenland.

Ellesmere Island. — Miller *et al.* (1975, fig. 2) map ELA and Glaciation Level in Ellesmere Island (see also Koerner 1989, 2005). ELA varies from 400 m near the southeast coast to 800–1200 m in five interior massifs, and falls to 200 m on the northwest coast including the northern tip of Axel Heiberg Island. Although Ellesmere Island ice cover consists mainly of icecaps (Ó Cofaigh *et al.* 2003), there are also numerous local glaciers. Southeast Ellesmere Island has an Inventory of 780 glaciers, but only 330 of these are local glaciers, of which only 80 have accumulation area aspects. The latter have a significant southward resultant of 185° ± 40°, but no significant altitude variation (Evans and Cox 2005). The resultant is anomalous, and is not supported by analysis of altitudes. The data set, however, does not match the requirements for analysis of asymmetry (local or regional). Mapping the glacier centroids showed them to be confined to the south-east coast, around the fjords of Makinson Inlet, Talbot Inlet and Buchanan Bay. Even the glacierets are distributed linearly along the coasts. A useful analysis thus awaits fuller data for Ellesmere Island.

Axel Heiberg Island, Canada

Glaciers are found between 78.3° and 81.4° N and 88.0° and 96.6° W on Axel Heiberg Island, immediately west of the larger Ellesmere Island. It has several mountains over 1500 m; the highest, with a thin ice cover, is over 2130 m. Although there are large Ice Caps (Müller, formerly McGill, and Steacie), most glaciers are topographically constrained. As only three glaciers reach tidewater (a long way below their ELAs), mid-altitude can be taken as a surrogate for ELA. Different types of glacier are intimately mixed over Axel Heiberg I., but there are some regional concentrations (Fig. 12). The way asymmetry varies between types of glacier may thus interact with the regional variations to bias the relation of altitude to aspect. There are more glacierets in the west and north, more valley glaciers in the south, and more outlet glaciers in the east.

Axel Heiberg I. was the subject of a major trial of methodology for the World Glacier Inventory. Ommanney (1969; Ommanney *et al.* 1969) provided a spatially complete Inventory with few missing data. However, this is an area with coalescent ice masses, and accumulation area aspects are given for only 526 of the 1091 glaciers; initial analyses (Evans and Cox 2005) were thus based on the 289 of these classified as local (valley, mountain or glacieret, WGI codes 5, 6 and 7). These local glaciers are concentrated in the north and west (Fig. 12), including all the glaciers north of 80.7° N and all but one of those west of 95.2° W.

Ablation area aspect data are available for 1041 glaciers on Axel Heiberg I., including all but 10 of those lacking accumulation area aspect: 691 of the former are classified as local. Vector means are 357° ± 10° for all and 003° ± 10° for local glaciers, with strengths of 25% and 28%, respectively. These compare with mean accumulation area aspects of 331° ± 57° (insignificant, $p \approx 0.06$; $n = 526$ for all) and 254° (completely insignificant; $n = 289$).

For 476 glaciers both aspects are given: 76% have the same accumulation and ablation aspect, on the eight-class azimuth scale. The circular (not linear) correlation is +0.77, and is almost the same for the 252 local glaciers, and for the non-local ones. Thus, it is justifiable to combine the two aspect variables for further Axel Heiberg analyses, using ablation aspect where accumulation aspect is not available; distortions will be less for smaller glaciers and for those with straighter centre-lines. This gives “mixed aspect” for 1041 glaciers, a nearly complete coverage, with a vector mean of 357° ± 10° and strength 23%. Of these, the 728 local glaciers have a mean of 002° ± 12° and strength 24%. Given the consistency of these vector analyses, the latter is taken as the best representation of aspect tendencies in terms of numbers of glaciers. Glacierets have stronger tendencies than “mountain gla-

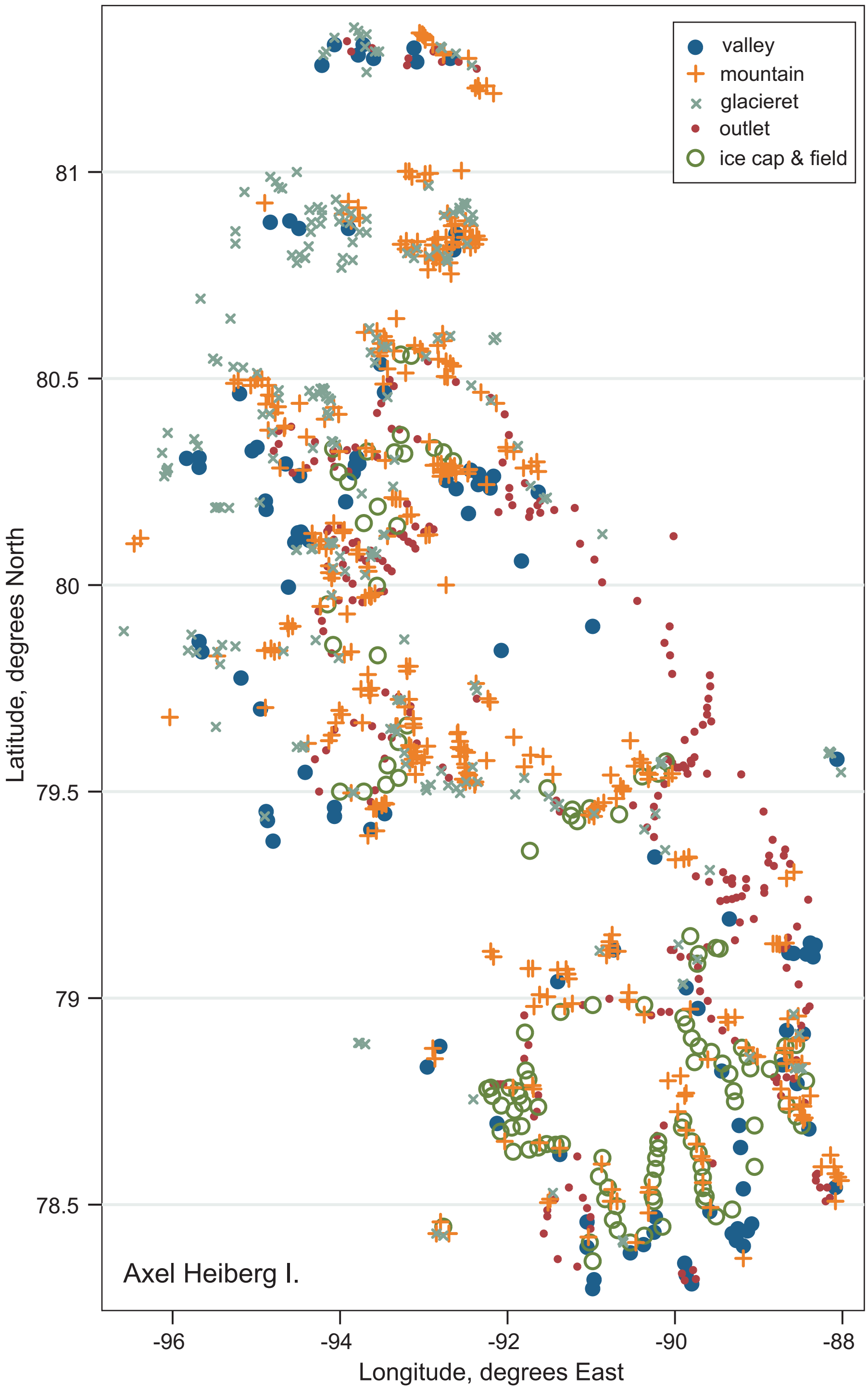

Fig. 12. Glaciers on Axel Heiberg Island with aspect data: distribution of different types (WGI classes).

ciers" (vector strength 40% *versus* 26%), but similar mean directions: results are insignificant for "valley glaciers" but northward for ice fields and NNW for ice caps and outlet glaciers. There is a clear northward tendency in Axel Heiberg glaciers, although not a strong one.

Local glaciers should be smaller and steeper than ice caps, icefields and outlet glaciers, but size statistics for the different classes of glacier showed surprisingly large overlaps. Therefore further analyses were performed for subsets defined by length, area or gradient and ignoring WGI class. Vector strength was greatest (38%) for the 124 glaciers below 0.2 km^2 in area but mean directions were consistent for different bins (bands, classes) of area, up to 3 km^2, with north always falling within the confidence interval. Results were insignificant for larger glaciers. The 744 glaciers smaller than 3 km^2 had a vector mean of 000° ± 10° and a strength of 29% (Fig. 6).

Strength rose to 35% for the 91 glaciers less than 0.5 km long, and there was no significant vector mean for those longer than 4 km. The 812 glaciers shorter than 4 km had a mean of 001° ± 10°, strength 28%. In terms of gradient, strength is 26% for the 602 steeper than 9°, and the mean is 359° ± 12°. Again for gradient, as for area and length, north fell within the confidence interval for any band (bin) analysed. Significant means were always between 345° and 029°. The prevalence of north-south asymmetry in numbers of glaciers is consistent across different glacier areas, lengths and gradients, with northward aspects being favoured.

Subdividing finally by latitude, glaciers in the north of the Island tend NNE, those in the centre (79.23° to 80.75° N) tend NNW, and those in the south tend northward but weakly and insignificantly so.

As Axel Heiberg I. is 370 km × 198 km, it is necessary to consider spatial variations in glacier altitude (Fig. 13) before aspect effects on altitude. These are ap-

(0)	**200** *(26)*	**440** *(21)*	*(0)*
165 *(6)*	**579** *(181)*	**811** *(147)*	*(0)*
359 *(3)*	**694** *(185)*	**919** *(122)*	**990** *(1)*
(0)	**368** *(3)*	**729** *(168)*	**876** *(166)*
(0)	*(0)*	**546** *(5)*	**958** *(59)*

Fig. 13. Mean ELA altitudes (m) per UTM 100 km grid square on Axel Heiberg Island, from data in Ommanney (1969). Numbers of glaciers involved are given in brackets.

proximated by regressing mid-altitude on latitude and longitude (deviations from their mean values). The linear spatial trend is for glaciers to be lower in the west (a difference of 1102 m is predicted), and insignificantly lower in the north (a difference of 37 m): R^2 is 27%, for all 1083 glaciers. Extending the regression with terms in latitude and longitude squared, the quadratic trend is much stronger (68%), especially in a north-south direction, and predicted mid-altitudes vary by 930 m. This is consistent with the maps of ELA and Glaciation Level in Miller *et al.* (1975). ELA is high in the east and low in the west, falling from 1200 m in the centre to 400 m in the northwest. Glaciation Levels are 100 to 200 m higher. Miller *et al.* (1975) used the same 1:250,000 maps as Ommanney, so their results are expected to be compatible with the WGI. It should be noted that (in middle latitudes) use of more detailed maps and air photos often detects many more small glaciers and lowers the estimated Glaciation Level (Evans 1990).

The nearest full weather station is just to the east at Eureka (78° N 86° W, 10 m altitude), in an area of high ELA on Ellesmere I. Temperature averages +5.7° in July and -38.4° in February; there are no data for diurnal variations in cloudiness. Snow can fall at Eureka in any month, but the maximum is from August to November (September 110 mm); snow cover is deepest in April (Environment Canada, 2004). In August and September, winds from the southeast are most frequent, with maximum gusts coming from the south. In October and November, east winds are most frequent, with maximum gusts from northwest or east. Over the year, southeast winds are most frequent and have maximum hourly speeds, but maximum gusts are from the east. Nevertheless, the spatial patterns mapped by Miller *et al.* (1975) clearly require that snow is brought to most of Axel Heiberg I. from the west, from the Arctic Ocean rather than from Baffin Bay. ELA and Glaciation Level fall steeply to the west coast, are relatively flat in the centre-east, and (by interpolation) fall gently northward around Eureka. Ommanney (1969, p. 34) notes that precipitation comes with cyclonic disturbances from the west and southwest, and not from the east.

Both Axel Heiberg and Ellesmere I. are polar deserts (Lotz and Sagar 1963), and form one of the driest parts of the Arctic throughout the year (Serreze and Barry 2005, fig. 6.3). Hence, Cogley *et al.* (1995, 1996) observed an average 1960–1991 ELA of 970 m for the White Glacier, a little southeast of the centre of the Island, with the balance ELA at 862 m. Annual mass balance varied from +0.3 m around 1650 m altitude to -1.8 m around 150 m (Cogley and Adams 1998).

Table 5 gives coefficients for regressions of mid-altitude on aspect and position, combined. The first row is read as:

Middle altitude = 750 – 115 cos(aspect) + 8 sin(aspect) metres and implies that, disregarding location, the lowest glaciers face 356° ± 12° and are 231 m lower than those on the opposite aspect (176°). The second equation (row), allowing for the linear trend in altitude across the Island, gives lowest glaciers at 006° ± 19°. Finally the quadratic trend, much stronger than the linear, gives lowest glaciers at

Table 5

Regression coefficients for mid-altitude (m) on Axel Heiberg Island, as a function of aspect and location. For each subset of glaciers, the results of three regressions are given: aspect, without location; aspect and a linear spatial trend; aspect and a quadratic spatial trend: each set of controls is a subset of the following one. *rmse* (root mean square error of estimate) values should be compared with the standard deviations (st dev) of each set.

Coefficient	Base	Cosine	Sine	Lat	Long	Lat^2	$Long^2$	R^2 (%)	*rmse* (m)	lowest at
727 local glaciers, st dev 249 m:										
aspect	750	-115	+8					10	237	356° ± 12°
linear	754	-68	-4	-2	+63			31	207	006° ± 19°
quadratic	968	-32	+11	+52	+103	-238	-16	66	145	341° ± 26°
743 glaciers less than 3 km^2, st dev 266 m:										
aspect	761	-121	+16					9	254	353° ± 13°
linear	765	-76	+12	-21	+60			32	219	351° ± 18°
quadratic	986	-34	+10	+54	+103	-253	-16	70	146	343° ± 25°
811 glaciers less than 4 km long, st dev 261 m:										
aspect	758	-116	+13					9	249	354° ± 12°
linear	758	-72	+6	-5	+61			31	217	355° ± 18°
quadratic	979	-36	+15	+54	+103	-247	-17	69	144	338° ± 22°
All 1083 glaciers, st dev 250 m:										
aspect	766	-90	+13					6	242	352° ± 13°
linear	756	-50	-7	+22	+66			28	211	008° ± 21°
quadratic	970	-23	+4	+48	+99	-238	-17	68	142	349° ± 30°

341° ± 26°. The overlapping confidence intervals show that all three results are consistent with due north being the most favoured aspect – as for glacier numbers. Figure 14 corresponds to the fourth equation in Table 5, and shows a difference of 244 m in the altitudes predicted for most favoured and opposite aspects.

These results confirm that regional variation in altitude considerably exceeds local variation with aspect. In each equation, the cosine term (north *versus* south: see Evans and Cox 2005) is significant and the sine term (east *versus* west) is not. Taking location into account reduces the magnitude of the cosine coefficient. Probably, the most useful version to take is that allowing for the quadratic trend, giving cosine coefficients around -32 m, *i.e.* north: south contrasts of 64 m in glacier altitude for local glaciers, and a little more for glaciers shorter than 4 km. The aspect of lowest predicted altitude is remarkably consistent, a little west of north, approaching north-northwest (= 337.5°) for each of the first three data sets (*i.e.* for small glaciers), allowing for the quadratic trend. This is consistent also with the strongly northward vector analyses (Fig. 6) and suggests little net wind effect on the variation of glacier balance with aspect. On Axel Heiberg Island, northward slopes are clearly favoured for glacier accumulation, with glaciers reaching lower altitudes as well as being more numerous.

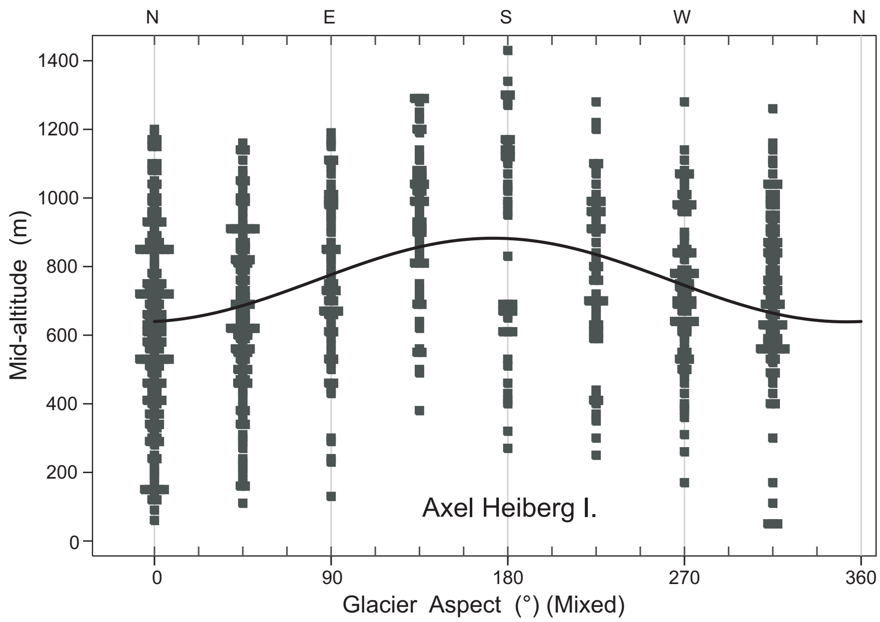

Fig. 14. Variation of mid-altitude with mixed aspect for glaciers in Axel Heiberg Island <3 km^2 in area. Glaciers are lowest facing 353° ± 13°: Mid-altitude = 761 – 121 cos(aspect) + 16 sin(aspect); R^2 = 9%, *rmse* = 254 m, p <0.0001, n = 743.

Most small-scale maps, *e.g.* Miller *et al.* (1975, fig. 2), imply that Axel Heiberg Island is like Ellesmere Island in being covered by large icefields or ice caps. More detailed images, including those available on Google Earth, show the strong topographic influence and the numerous valley and cirque glaciers. This suggests that when fuller inventories are available for Ellesmere Island, aspect tendencies similar to those in Axel Heiberg Island may be detected.

Regional data evaluation

Local slopes affect several components of glacier mass balance, and as expected there are normally both lower glaciers, and more glaciers, facing directions (azimuths, aspects) with more positive mass balances. The analysis here of glacier aspect and its relation to altitude across the Arctic is as comprehensive as is possible from currently available data.

The consistency of glacier numbers and glacier altitudes in having similar favoured aspects is a universal rule that can be overcome only by extremely unusual topographic effects. In northern Novaya Zemlya, difficulty arises from the patchy distribution of local glaciers around an extensive ice cap. For the small glaciers of Wrangel I., the lower southeast-facing glaciers require further investigation; glacier numbers tend north-northwest. This remains a deviation from the asymmetric sine-cosine model of the strength of poleward tendency (Fig. 1) of Evans and Cox (2005), but the other deviations have been accounted for.

The incompleteness of data remains a constraint on provision of a truly comprehensive view of Arctic local glaciation. The WGI has large gaps in spatial coverage of local glaciers in the Arctic. It gives data for only half of the 22 regions tabulated by Evans (2007). Although more data are becoming available, large blanks remain for the peripheral regions of Greenland. Eastern and northern Greenland have the biggest gaps, followed by Ellesmere I., northern Baffin I. and some other Canadian islands (see also Cogley 2009). The work of Sarana (2005) shows that Soviet inventories from the 1970s need revision (and not just updating) for glaciers below 1 km^2 in area. The analyses in this paper need only aspect and highest and lowest altitudes for each glacier, yet the latter are often incomplete in the WGI. There is hope that the GLIMS project (Raup *et al.* 2007; Frank Paul, personal communication March 2010) will soon provide near-complete coverage.

Three statistical points, important in many environmental studies, are illustrated here. First, the sampling basis and spatial coverage of data can bias results. Second, as the range of altitudes varies between regions, often simply because of the spatial extent of regions, R^2 should not be used as the only measure of the goodness of fit and validity of statistical models: *rmse* retains the original units (here metres) and is the most comparable measure of residual, unexplained error. Third, it is valuable to consider not only the statistical significance of results, but also the confidence intervals on important statistics. Only thus can consistency between aspect results be discussed.

Conclusions

Table 6 brings together regressions predicting mid-altitude, the surrogate for ELA, from aspect and position (linear trends, for comparability), with some rounding. Five of the eight regions (Orulgan, Cherskiy, Brooks, Axel Heiberg and W. Greenland) have lowest glaciers facing north (between 350° and 017°); N. Scandinavia gives 035° and southern Novaya Zemlya 091°, as the influence of west winds increases. Finally, the small glaciers and glacierets on Wrangel I. are lowest when facing southeast, 143°. It is doubtful if this can be attributed to winds from northwest. The large latitude and longitude coefficients for Wrangel I. relate to the small area covered and its distance from the origin of geographical coordinates. The latter two regions, with the most discrepant favoured directions, also have low fits in terms of R^2. *Rmse* values are lower for smaller regions. Central Spitsbergen too has lower glaciers facing north-northeast, and on Jan Mayen ELA is lower on north-facing glaciers.

Figure 6 shows that northward tendencies are even more widespread in vector analysis of glacier numbers. These provide significant results for smaller samples,

Table 6

Regression coefficients for mid-altitude (m) as a function of aspect and location (linear trend).

Coefficient	Base	Cosine	Sine	Lat	Long	R^2 (%)	*rmse* (m)	*n*	lowest at
N. Scandinavia >65° N	22159	-25	-17	-349	+157 E	58	169	1146	035° ± 30°
Nov. Zem. <74.65° N	8384	+1	-42	-115	+12 E	16	116	486	091° ± 19°
Orulgan	5872	-42	-13	-208	+80 E	55	3	71	017° ± 46°
Cherskiy	10654	-100	+9	-118	-4 E	32	110	226	355° ± 23°
Wrangel I.	8722	+82	-61	-1111	+394 W	22	156	101	143° ± 34°
Brooks, E. of 147.7° W	15209	-68	-21	-49	-68 W	32	115	350	017° ± 15°
Axel Heiberg >3 km^2	765	-76	+12	-21	+60 W	32	219	743	351° ± 18°
W. Greenland 65–71° N	3318	-90	+10	+44	-102 W	19	269	1775	354° ± 12°

where Fourier regressions do not. Thus, northern Novaya Zemlya, Severnaya Zemlya, the Putorana, and even Wrangel I. can be added to the list of regions showing northward tendencies, which are confirmed for the five listed above and for central Spitsbergen. Franz Jozef Land favours northwest, central Novaya Zemlya east-northeast, and the Urals east. Andrews *et al.* (1970) and Svoboda and Paul (2009) demonstrate clear northward tendencies for both glacier numbers and lowest altitudes in Baffin I. Remaining regions include Chukotka and the Byrranga Mountains, with inadequate data for aspect.

The varied nature, incompleteness and scattered distribution of inventory data make it difficult to establish patterns in the degree of local asymmetry across the Arctic. This hinders testing of the global model, but some consistent patterns do emerge. Contrary to some initial results, northward tendencies are found in glacier aspects and altitudes throughout the High Arctic. Apparent anomalies in Svalbard and Ellesmere I. are shown to result from data being incomplete either in spatial coverage or in failing to cover small, steep glaciers, for which the effects of slope climates are greatest. Northward tendencies are also present in the Low Arctic except for the Urals and southern Novaya Zemlya, where strong westerly winds dominate and produce leeward glaciers. In the adjacent areas of northern Scandinavia and northern Novaya Zemlya, northward and eastward tendencies are roughly balanced, giving northeast-facing glaciers. Mîndrescu *et al.* (2010, table 3) show how wind and solar radiation effects of different relative strengths may combine to give vector mean resultant glacier aspect.

It is clear that solar radiation is the main factor in ablation on Arctic glaciers and that differential receipts on sloping glacier surfaces are sufficient to give more and lower glaciers on northward aspects. North-south contrasts are less than in continental mid-latitude climates, but are found throughout the Arctic, even around 80° N. There is some reduction toward the North Pole, but the absence of glaciers (or land) north of 83.6° N means that symmetrical local glaciation is not found. Northward tendencies are general (Fig. 6). Wind effects are much less important than solar radiation effects on local glaciers in the High Arctic and east Siberian Arctic, and in North America and Greenland, but wind has increasing effects as we move south in Novaya Zemlya and into mainland Europe (northern Scandinavia and the Urals). Only in the Urals, wind effects do overcome radiation effects to give glaciers facing south of east on average, but the confidence interval does extend north of east. In parts of Novaya Zemlya, a similar situation affects the aspect of lowest glaciers.

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References

ANANICHEVA M.D. and KRENKE A.N. 2005. Evolution of climatic snowline and Equilibrium Line Altitudes in the North-eastern Siberia mountains (20th century). *Ice and Climate News* 6: 3–6.

ANANICHEVA M.D., KAPUSTYN G.A. and KOREYSHA M.M. 2006. The state of glaciers in the Suntar-Khayata and Cherskiy mountains from data in the Katalog Lednikov SSSR and satellite images from 2001–2003. *Materialy Glyatsiologicheskikh Issledovanniy* 101: 163–168 (in Russian).

ANDREWS J.T. 2002. Glaciers of Baffin Island. *In*: R.S. Williams and J.G. Ferrigno (eds) Satellite Image Atlas of Glaciers of the World. *U.S. Geological Survey Professional Paper* 1386-J: 165–198.

ANDREWS J.T. and MILLER G.H. 1972. Quaternary history of Northern. Cumberland Peninsula, Baffin I., N.W.T., Canada: Part IV: Maps of the present glaciation limits and lowest ELA for N. & S. Baffin I. *Arctic & Alpine Research* 4 (1): 45–59.

ANDREWS J.T., BARRY R.G. and DRAPIER L. 1970. An inventory of the present and past glacierization of Home Bay and Okoa Bay, east Baffin Island, N.W.T., Canada, and some climatic and palaeoclimatic considerations. *Journal of Glaciology* 9 (57): 337–362.

ARNOLD N.S. and REES W.G. 2009. Effects of digital elevation model spatial resolution on distributed calculations of solar radiation loading on a High Arctic glacier. *Journal of Glaciology* 55 (194): 973–984.

ARNOLD N.S., REES W.G., HODSON A.J. and KOHLER J. 2006. Topographic controls on the surface energy balance of a high Arctic valley glacier. *Journal of Geophysical Research* 111(F2), F02011 (10.1029/2005JF000426).

BŁASZCZYK M., JANIA J.A. and HAGEN J.O. 2009. Tidewater glaciers of Svalbard: Recent changes and estimates of calving fluxes. *Polish Polar Research* 30 (2): 85–142.

COGLEY J.G. 2009. A more complete version of the World Glacier Inventory. *Annals of Glaciology* 50 (53): 32–38.

COGLEY J.G. and ADAMS W.P. 1998. Mass balance of glaciers other than the ice sheets. *Journal of Glaciology* 44 (147): 315–325.

COGLEY J.G., ADAMS W.P., ECCLESTONE M.A., JUNG-ROTHENHÄUSLER F. and OMMANNEY C.S.L. 1995. Mass balance of Axel Heiberg glaciers, 1960–1991: A reassessment and discussion. Environment Canada, Saskastoon, Saskatchewan. *National Hydrology Research Institute (NHRI) Science Report* 6: 168 pp.

COGLEY J.G., ADAMS W.P., ECCLESTONE M.A., JUNG-ROTHENHÄUSLER F. and OMMANNEY C.S.L. 1996. Mass balance of White Glacier, Axel Heiberg Island, N.W.T., Canada, 1960–1991. *Journal of Glaciology* 42 (142): 548–563.

COX N.J. 2006. In praise of trigonometric predictors. *Stata Journal* 6 (4): 561–579.

DOLGUSHIN L.D. 1961. Main features of the modern glaciation of the Urals. Union Geodésique et Géophysique Internationale, Association Internationale d'Hydrologie Scientifique, Commission des Neiges et Glaces. Assemblée Générale de Helsinki, 25.7–6.8 1960. Gentbrugge, *Publication de l'Association Internationale d'Hydrologie Scientifique* 54 : 335–347.

DOWDESWELL J.A. and HAGEN J.O. 2004. Arctic glaciers and ice caps. *In*: J.L. Bamber and A.J. Payne (eds) *Mass balance of the cryosphere*. Cambridge University Press: 527–557.

DOWDESWELL J.A. and HAMBREY M. 2002. *Islands of the Arctic*. Chapter 4: Glaciers. Cambridge University Press: 82–113.

DOWDESWELL E.K., DOWDESWELL J.A. and CAWKWELL F. 2007. On the glaciers of Bylot Island, Nunavut, Arctic Canada. *Arctic, Antarctic and Alpine Research* 39 (3): 402–411.

ENVIRONMENT CANADA 2004. www.weatheroffice.ec.gc.ca/climate-normals. Accessed 27 April 2008.

ETZELMÜLLER B., ODEGARD R. S., VATNE G., MYSTERUD R.S., TONNING T. and SOLLID J.L. 2000. Glacier characteristic and sediment transfer systems of Longyearbreen and Larsbreen, western Spitsbergen. *Norsk Geografisk Tidsskrift* 54 (4): 157–168.

EVANS I.S. 1969. The geomorphology and morphometry of glaciated mountains. *In*: R.J. Chorley (ed.) *Water, Earth and Man.* Methuen, London: 369–380.

EVANS I.S. 1977. World-wide variations in the direction and concentration of cirque and glacier aspects. *Geografiska Annaler A* 59: 151–175.

EVANS I.S. 1990. Climatic effects on glacier distribution across the southern Coast Mountains, B.C., Canada. *Annals of Glaciology* 14 ("Ice & Climate"): 58–64.

EVANS I.S. 2006a. Local aspect asymmetry of mountain glaciation: A global survey of consistency of favoured directions for glacier numbers and altitudes. *Geomorphology* 73: 166–184.

EVANS I.S. 2006b. Glacier distribution in the Alps: statistical modelling of altitude and aspect. *Geografiska Annaler* 88 A (2): 115–133.

EVANS I.S. 2007. Glacier distribution and direction in the Arctic: the unusual nature of Svalbard. *Landform Analysis* 5: 21–24. Association of Polish Geomorphologists, Poznań. [Extended Abstract, IAG Conference.]

EVANS I.S. and COX N.J. 2005. Global variations of local asymmetry in glacier altitude: separation of north-south and east-west components. *Journal of Glaciology* 51 (174): 469–482.

EVANS I.S. and COX N.J. 2010. Climatogenic north-south asymmetry of local glaciers in Spitsbergen and other parts of the Arctic. *Annals of Glaciology* 51(55): 16–22.

FILIPPOV Yu.V., SERDEROVA G.M. and GERASIMOV I.P. (eds) 1964. *Fiziko-geograficheskiy Atlas Mira*. Akademiya Nauk SSSR, Moskva: 298 pp.

GLAZOVSKIY A.F. 1996. Russian Arctic. Section 2.7. *In*: J. Jania and J.O. Hagen (eds) Mass balance of Arctic glaciers. *International Arctic Science Committee Report* 5. University of Silesia Faculty of Earth Sciences.

GLAZOVSKY A.F. 2003. Glacier changes in the Russian Arctic. *In*: *Papers and Recommendations: Snow Watch 2002 Workshop and Assessing Global Glacier Recession, Glaciological Data Report GD-32*, Boulder, CO: NSIDC/WDC for Glaciology: 78–82.

GLAZOVSKIY A.F., NOSENKO G.A. and TSVETKOV D.G. 2005. Glaciers of the Urals: current state and prospective evolution. *Materialy Glyatsiologicheskikh Issledovanniy* 98: 207–213 (in Russian).

GRANT K.L., STOKES C.R. and EVANS I.S. 2009. Identification and characteristics of surge-type glaciers on Novaya Zemlya, Russian Arctic. *Journal of Glaciology* 55 (194): 960–972.

GROSVAL'D M.G. and KOTLYAKOV V.M. 1969. Present-day glaciers in the USSR and some data on their mass balance. *Journal of Glaciology* 8 (52): 9–22.

GUALTIERI L., VARTANYAN S., BRIGHAM-GRETTE J. and ANDERSON P.M. 2003. Pleistocene raised marine deposits on Wrangel Island, northeast Siberia and implications for the presence of an East Siberian ice sheet. *Quaternary Research* 59: 399–410.

GURNEY S.D., POPOVNIN V.V., SHAHGEDANOVA M. and STOKES C.R. 2008. A glacier inventory for the Buordakh Massif, Cherskiy Range, North East Siberia, and evidence for recent glacier recession. *Arctic, Antarctic and Alpine Research* 40 (1): 81–88.

HAEBERLI W., BOSCH H., SCHERLER K., ØSTREM G. and WALLÉN, C.C. (eds) 1989. *World Glacier Inventory: status 1988.* IAHS(ICSI)-UNEP-UNESCO: 368+22 pp.

HAEBERLI W., HOEZLE M. and SUTER S. (eds) 1998. Into the second century of worldwide glacier monitoring – prospects and strategies. Paris: Unesco, for IHP & GEMS. *UNESCO Studies & reports in Hydrology* 56: 227 pp.

HAGEN J.O., LIESTØL O., ROLAND E. and JØRGENSEN T. 1993. Glacier Atlas of Svalbard and Jan Mayen. *Norsk Polarinstitutt Meddelelser* 129: 141 pp. and 17 maps.

HAGEN J.O., MELVOLD K., PINGLOT F. and DOWDESWELL J.A. 2003. On the net mass balance of the glaciers and ice caps in Svalbard, Norwegian Arctic. *Arctic, Antarctic & Alpine Research* 35: 264–270.

HOLMLUND P. 1998. Glacier mass balance and ice-core records from northern Sweden. *Ambio* 27 (4): 266–269.

HUMLUM O. 1985. The glaciation level in West Greenland. *Arctic & Alpine Research* 17: 311–319.

HUMLUM O. 1986. Mapping of glaciation levels: comments on the effect of sampling area size. *Arctic & Alpine Research* 18 (4): 407–414.

HUMLUM O. 2002a. Modelling late 20th-century precipitation in Nordenskiöld Land, Svalbard, by geomorphic means. *Norsk Geografisk Tidsskrift* 56: 96–103.

HUMLUM O. 2002b. Discussion of "Glacier recession in Sorkappland and central Nordenskiöld Land, Spitsbergen, Svalbard, during the 20th century" by Wieslaw Ziaja. *Arctic, Antarctic and Alpine Research* 34 (2): 226–227.

JISKOOT H., MURRAY T. and BOYLE P. 2000. Controls on the distribution of surge-type glaciers in Svalbard. *Journal of Glaciology* 46: 412–422.

KOERNER R.M. 1989. Queen Elizabeth Is. glaciers. *In*: R.J. Fulton (ed.) *Quaternary Geology of Canada & Greenland.* Geology of Canada no. 1, Canadian Government Publishing Centre, Ottawa: 464–473.

KOERNER R.M. 2005. Mass balance of glaciers in the Queen Elizabeth Islands, Nunavut, Canada. *Annals of Glaciology* 42: 417–423.

KONONOV Yu.M., ANANICHEVA M.D. and WILLIS I.C. 2005. High-resolution reconstruction of Polar Ural glacier mass balance for the last millennium. *Annals of Glaciology* 42: 163–170.

KOTLYAKOV V.M. (ed.) 1997. *World atlas of snow and ice resources*, vol. 1. Russian Academy of Sciences, Moskva; 400 pp.

KRENKE A.N. 1997. The climate of Franz Josef Land. *In*: R. Kostka (ed.) The Franz Josef Land Archipelago – remote sensing and cartography. *Petermanns Geographische Mitteilungen Ergänzungsheft* 293: 34–40.

KRENKE A.N. and SLUPETZKY H. 1997. The glaciers of Franz Josef Land. *In*: R. Kostka (ed.) The Franz Josef Land Archipelago – remote sensing and cartography. *Petermanns Geographische Mitteilungen Ergänzungsheft* 293: 41–46.

LANDSBERG S.Y. 1956. The orientation of dunes in Britain and Denmark in relation to wind. *Geographical Journal* 122 (2): 176–189.

LIESTØL O. 1993. Glaciers of Europe-Glaciers of Svalbard, Norway. *USGS Professional Paper* 1386-E-5, *Satellite Image Atlas of Glaciers of the World*: E127–E151.

LOTZ J.R. and SAGAR R.B. 1963. Northern Ellesmere Island – an Arctic desert. *Geografiska Annaler A* 44: 366–377.

MANGERUD J., GOSSE J., MATIOUCHKOVC A. and DOLVIK T. 2008. Glaciers in the Polar Urals, Russia, were not much larger during the Last Global Glacial Maximum than today. *Quaternary Science Reviews* 27 (9–10): 1047–1057.

MCBEAN G., ALEKSEEV G., CHEN D., FØRLAND E., FYFE J., GROISMAN P. Y., KING R., MELLING H., VOSE R. and WHITFIELD P. H. 2005: *Arctic Climate: Past and Present. Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge: 22–60.

MILLER G.H., BRADLEY R.S. and ANDREWS J.T. 1975. The glaciation level and lowest equilibrium line altitude in the High Canadian Arctic: maps and climatic interpretation. *Arctic and Alpine Research* 7 (2): 155–168.

MÎNDRESCU M., EVANS I.S. and COX N.J. 2010. Climatic implications of cirque distribution in the Romanian Carpathians: palaeowind directions during glacial periods. *Journal of Quaternary Research* 25 (6): 875–888.

NSIDC (National Snow and Ice Data Center) 1999, updated 2005. *World Glacier Inventory*. Boulder, CO, World Glacier Monitoring Service. National Snow and Ice Data Center/World Data Center for Glaciology. CD-ROM

Ó COFAIGH C., EVANS D.J.A. and ENGLAND J. 2003. Ice-marginal terrestrial landsystems: sub-polar glacier margins of the Canadian and Greenland High Arctic. *In*: D.J.A. Evans (ed.) *Glacial landsystems*. Arnold, London: 44–64.

OMMANNEY C.S.L. 1969. A study in glacier inventory: the ice masses of Axel Heiberg Island, Canadian Arctic Archipelago. *Axel Heiberg Island Research Reports: Glaciology*, No. 3. McGill University, Montreal: 105 pp. + maps.

OMMANNEY C.S.L., GOODMAN R.H. and MÜLLER F. 1969. Computer analysis of a glacier inventory of Axel Heiberg Island: Canadian Arctic Archipelago. *Bulletin of the International Association of Scientific Hydrology* 14 (1): 19–28.

ØSTREM G., HAAKENSEN N. and MELANDER O. 1973. Atlas over Breer i Nord-Skandinavia. *Norges Vassdrags og Elektrisitetsvesen, Hydrologisk avdeling, Meddelelser* 22: 315 pp.

PORTER S.C., PIERCE K.L. and HAMILTON T.D. 1983. Late Wisconsin Mountain glaciation in the Western United States. *In*: H.E. Wright, Jr. and S.C. Porter (eds) *Late Quaternary Environments of the United States*, vol. 1. University of Minnesota Press, Minneapolis: 71–111.

POSPELOVA E.B., POSPELOV I.N., ZHULIDOV A.V., ROBARTS R.D., ZHULIDOVA O.V., ZHULIDOV D.A. and GURTOVAYA T.Yu. 2004. Biogeography of the Byrranga Mountains, Taymyr Peninsula, Russian Arctic. *Polar Record* 40 (215): 327–344.

RAUP B., RACOVITEANU A., KHALSA S.J.S., HELM C., ARMSTRONG R. and ARNAUD Y. 2007. The GLIMS geospatial glacier database: A new tool for studying glacier change. *Global and Planetary Change* 56 (1–2): 101–110.

SARANA V.A. 2005. Glaciers of the Putorana Plateau. *Materialy Glyatsiologicheskikh Issledovanniy* 98: 19–29 (in Russian).

SEDOV R. V. 1992. Cirques and glaciers in the Tenianyy range, Chukotka. *Polar Geography* 16 (1): 58– 64.

SEDOV R.V. 1997. Glaciers of the Chukotka. *Materialy Glyatsiologicheskikh Issledovaniy* 82: 213–217 (in Russian).

SEPPÄLÄ M. 2004. *Wind as a geomorphic agent in cold climates*. Cambridge University Press: 358 pp.
SERREZE M.C. and BARRY R.G. 2005. *The Arctic climate system.* Cambridge University Press: 385 pp.
SHAHGEDANOVA M., PEROV V. and MUDROV Y. 2002. The mountains of northern Russia. *In*: M. Shahgedanova, (ed.) *The physical geography of Northern Eurasia.* Oxford University Press: 284–313.
SHAROV A.I. 2005. Studying changes of ice coasts in the European Arctic. *Geo-Mar Letters* 25: 153–166.
SOLOMINA O.N. 2000. Retreat of mountain glaciers of northern Eurasia since the Little Ice Age maximum. *Annals of Glaciology* 31: 26–30.
SOLOMINA O. N. and FILATOV Ye.S. 1998. Changes in mountain glaciers in Northeast Russia from the Little Ice Age to the Mid-20th Century. *Polar Geography* 22 (1): 65–78.
SUSLOV S.P. 1961. *The physical geography of Asiatic Russia*. W.H. Freeman, San Francisco: 594 pp.
SVOBODA F. and PAUL F. 2009. A new glacier inventory on southern Baffin Island, Canada, from ASTER data: II. Data analysis, glacier change and applications. *Annals of Glaciology* 50 (53): 22–31.
VOWINCKEL E. and ORVIG S. 1970. The climate of the north polar basin. *In*: S. Orvig (ed.) Climates of the Polar Regions. *World Survey of Climatology* 14: 129–252.
WEIDICK A. 1995. Greenland. *In*: R.S. Williams and J.G. Ferrigno (eds) Satellite Image Atlas of Glaciers of the World. *U.S. Geological Survey Professional Paper* 1386-C.
WEIDICK A., BEGGILD C.E. and KNUDSEN N.T. 1992. Glacier inventory and atlas of West Greenland. *Grønlands Geologiske Undersøgelse, Rapport* 158: 1–194.
WENDLER G. 1969. Characteristics of the glaciation of the Brooks Range, Alaska. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B* 18 (1): 85–92.
WENG W.L. 1995. Letter to the editor. *Arctic* 48: 206.
WILLIAMS L.D. 1975. The variation of corrie elevation and ELA with aspect in eastern Baffin I., N.W.T., Canada. *Arctic and Alpine Research* 7 (2): 169–181.
WILLIAMS L.D. 1978. The Little Ice Age Glaciation Level on Baffin Island, Arctic Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 25: 199–207.
ZIAJA W. 2002. Reply to Humlum's discussion of "Glacier recession in Sorkappland and central Nordenskiöld Land, Spitsbergen, Svalbard, during the 20th century" by Wieslaw Ziaja. *Arctic, Antarctic and Alpine Research* 34 (2): 227–229.
ZIAJA W. 2005. Response of the Nordenskiöld Land (Spitsbergen) glaciers Grumantbreen, Håbergbreen and Dryadbreen to the climate warming after the Little Ice Age. *Annals of Glaciology* 42: 189–194.
ZIAJA W. and PIPAŁA R. 2007. Glacial recession 2001–2006 and its landscape effects in the Lindströmfjellet–Håbergnuten mountain ridge, Nordenskiöld Land, Spitsbergen. *Polish Polar Research* 28 (4): 237–247.

For further references to the extensive Russian-language literature see Shahgedanova *et al.* (2002) and Kotlyakov (1997).

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