

## Microscale spatial variation in the deposition of sea-salt components in snow in Celtic mountains

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### Abstract

In the Scottish and Welsh uplands high winds commonly redistribute snow from exposed to sheltered sites. This results in a high degree of spatial variability in snow mass, depth, density and chemical load, especially for the sea-salts (Na, Cl, Mg). During blowing snow events in the Cairngorm mountains, erosion and redistribution increased the small-scale variability of sea-salt concentrations in snow cover. Post-depositional relocation of snow within a sheltered corrie catchment and an exposed plateau site resulted in ion behaviour which was non-conservative, and an approximate two-fold increase in Na, Cl and Mg concentrations was measured between areas of erosion and deposition. Differences in chemical concentrations were also evident between corrie and plateau, resulting from greater wind transport and drifting at the more exposed site. These results have important implications for the design of effective sampling strategies and the scaling up of snow chemistry measurements to a basin scale. In addition, these findings suggest that the chemical signature of snow covers may provide a useful tool for distinguishing zones of blowing snow convergence and divergence within a landscape.

### Résumé

Dans les hauts pays de l'Ecosse et du Pays de Galles les vents forts redistribuent la neige des sites exposés vers les sites protégés. Cette redistribution donne lieu à une haute variabilité des données spatiales sur la quantité, la profondeur, la densité, et la charge chimique de la neige - particulièrement en ce qui concerne les composants d'origine marine (Na, Cl, Mg). Pendant des périodes de poudrière dans les montagnes Cairngorm, l'érosion et redistribution de la neige ont augmenté la variabilité à petite échelle des concentrations des espèces marines dans le couvert de neige. La redistribution des chutes de neige au sol, soit dans un creux à l'abri du vent soit sur un plateau ouvert au vent, a démontré que les espèces ionique n'étaient pas conservatrices, et que les concentrations de Na, Cl et Mg dans les zones de déposition sont approximativement deux fois celles observées dans les zones d'érosion. De plus, les différences entre les concentrations chimiques des neiges dans le creux par rapport à celles sur le plateau peuvent être le résultat d'un transport et d'entassement de neige plus accentués dans le site exposé. Ces travaux font sortir l'importance de planifier des méthodes d'échantillonnage efficaces et les stratégies fiables d'extrapolation d'échelle des données chimiques sur l'échelle d'un bassin versant. Enfin, ces résultats suggèrent aussi que la composition chimique des couverts de neige peut servir comme un indicateur pour distinguer les zones de convergence et de divergence de neige transportée par le vent dans un terrain quelconque.

### Crynodeb

Yn ucheldiroedd Cymru a'r Alban mae gwyntoedd uchel yn gwasgaru eira o ardaloedd agored i safleoedd cysgodol. O ganlyniad mae yna wahaniaethau gofodol sylweddol yn natur yr eira, ei ddyfnder, dwysedd a llwyth cemegol, yn arbennig halwynau môr (Na, Cl, Mg). Yn ystod cyfnodau pryd y bydd eira yn cael ei chwythu ym mynyddoedd y Cairngorm, mae erydiad ac ail-ddosbarthiad yn cynyddu amrywioldeb crynodiad halwynau môr yn yr eira. Effaith ail-ddosbarthiad eira ôl-ddyddodiadol oddi mewn i dalgylch beiran gysgodol a llwyfandir agored yw newid cymeriad yr ïonau i fod yn anghadwrol ac achosi cynnydd deublyg yng nghrynodiad Na, Cl a Mg rhwng ardaloedd erydol a dyddodol. Nodwyd gwahaniaethau yng nghrynodiad cemegol peirannau a llwyfandiroedd, yn deillio o drawsgludiad gwynt uwch a lluwch yn y safleoedd mwyaf agored. Mae goblygiadau'r gwaith hyn yn bwysig i strategaethau samplu ac yn awgrymu y dylid astudio cemeg eira ar raddfa dalgylch. Yn ychwanegol, mae'r canfyddiadau hyn yn awgrymu y gall nodweddion cemegol eira gael eu defnyddio i fedru gwahaniaethu ardaloedd lle mae chwythiad eira yn gydgyfeiriol neu yn ddargyfeiriol.

## 1 Introduction

The Celtic uplands experience regular snowfall, and particularly in the Highlands of Scotland a seasonal snow cover forms, which can contain an ecologically important chemical load of strong acid ions (Davies *et al.*, 1984; Morris and Thomas, 1985). These ions reside in and on snow grains in particulates, as components of the ice matrix, and in aqueous form in liquid and liquid-like layers. When snow melts, the ionic load elutes preferentially from the snowpack in a highly concentrated solution, with implications for soil and stream chemistry (Tranter *et al.*, 1988; Davies *et al.*, 1993). A general characteristic of Celtic snow chemistry is its high sea-salt component, as no Celtic land is far from the sea and the contributions of sea spray components via dry deposition to snow or via wet deposition of sea-derived snowfall (Landsberger *et al.*, 1989). However, this mixture of snow and salt does not fall evenly to the ground to await melt and elution, and it is not satisfactory to assume that the snow cover is the sum of snowfall less melt or that snow chemical load is the sum of wet plus dry deposition (Pomeroy *et al.*, 1995).

Jones (1985) and Davies *et al.* (1987) pointed out that that completely conservative ion behaviour in snow cover, in which ion mass is neither lost from nor gained to the system and proportions are preserved, is not often observed during snow transformations. In particular both dry and wet deposition can be spatially variable and reversed by transport processes that induce post-depositional redistribution. Upland Celtic snow is commonly redistributed by wind. In the Scottish and Welsh uplands some of the highest wind speeds on Earth have been recorded (Green, 1981). These winds redistributed snow from exposed to sheltered sites, resulting in a high degree of spatial variability to snow mass, depth, density and chemical load.

Tranter *et al.* (1987) examined the spatial variability of fresh snowfalls (without blowing snow) in the Scottish highlands and found coefficients of variation (CV) for sea salt components (Na, Cl, Mg) in a single snowfall to be low, from 3–4% within a region or site. It may not be possible to simply transfer this result to snow on the ground because of redistribution processes that both mix and transform surface snow chemistry. Redistribution of snow by wind results in enhanced concentrations of most major ions in blowing and deposited snow and is related to the degree of wind transport and sublimation (Pomeroy *et al.*, 1991a,b; Pomeroy and Jones, 1996). The enhancement of ion concentration with wind transport is particularly high for the sea salts. Essery *et al.* (1999) used a coupled complex terrain windflow and blowing snow transport and sublimation model to demonstrate that hilly terrain can be divided into zones of flow convergence and divergence which can be used to distinguish between widely differing regimes of snow mass accumulation and erosion. Their wind speed maps as a function of wind direction showed that these convergence and divergence zones were dependent upon both wind direction and topography. An empirical approximation of blowing snow transport applied using a complex terrain wind flow indicator showed similarly variable snow accumulation and erosion regimes in the Cairngorm Mountains of Scotland (Purves, *et al.*, 1999). Using the insight gained by coupled windflow and blowing snow models, the objective of this study is to examine a 1989 Cairngorm blowing snow chemistry experimental dataset in order to detect the effect of blowing snow on the spatial variability of snow chemical concentration and determine whether the chemical signature of snow covers has potential as a tool to distinguish between zones of blowing snow convergence or divergence.

## 2 Observations

### 2.1 Field measurements

The experiment was conducted in the high Cairngorms, Scotland, Lat. 57° 07' N, Long. 3° 38' W (Figure 1). Two sites were used, a sheltered corrie catchment, Ciste Mhearad (area 0.4 km<sup>2</sup>, elevation 1010–1160 m.a.s.l.) and a well-exposed plateau (elevation of 1135 m.a.s.l.) near Cairn Gorm. Snow is regularly relocated between the two sites by wind transport. Wind speeds at the summit of Cairn Gorm (1245 m.a.s.l.) have reached 88 m/s; snowfalls occur in all seasons. Blowing snow was sampled from the plateau, along with snow from a surface cover that was generally shallow and frequently eroded by wind. Surface snow was sampled during and after blizzards from Ciste Mhearad. Snow accumulation in Ciste Mhearad was much deeper, reaching 20m depth.

Two meteorological masts were used. The larger held anemometers, blowing snow particle detectors, thermistors and hygrometers, whilst the smaller held filter-fabric blowing snow chemistry samplers. The latter consisted of a machined PVC tube "nozzle" (40 mm inside diameter) with a sewn nylon filter-fabric sack of 0.03 m<sup>3</sup> volume hanging downwind. The filter-fabric sack was of 80 µm diameter mesh and trapped blowing snow whilst allowing air to pass through.

A measurement "run" consisted of attaching the blowing snow chemistry samplers to mast arms at heights of approximately 0.1, 0.2, 0.5 and 0.9 m, and uncovering the caps until the bags near the surface had filled with snow. The length of time the samplers were exposed was between 10 and 67 min. With the caps replaced, the samplers were removed to a tent where the contents were emptied into acid-washed plastic bottles. The bottles were then sealed in clean plastic bags. Deionised water was used to clean the samplers before each day's use. Tests with snow in the laboratory showed no measurable increase in ion concentration when snow was placed in samplers that had been cleaned by deionised water in this manner.

During each blowing snow chemistry "run", surface snow was sampled at sites within 100 m upwind of and parallel to the mast. Sites of active snow erosion and deposition were selected based upon visual identification. For example, erosion was evident on well-exposed snow surfaces where thin layers of snow were revealed at the edges of and within a snowpatch and deposition appeared as a lighter, fresher snow accumulating in a protected site. During a particularly heavy blizzard sites of erosion and deposition were sampled in Ciste Mhearad on a spatial grid through the corrie. Acid-washed (3% HNO<sub>3</sub> solution) PTFE-coated hand scoops were used to skim the top 20-mm layer of these snows. An acid-washed 500-ml bottle of eroding snow and one of accumulating snow were filled for each run and then sealed in clean bags.

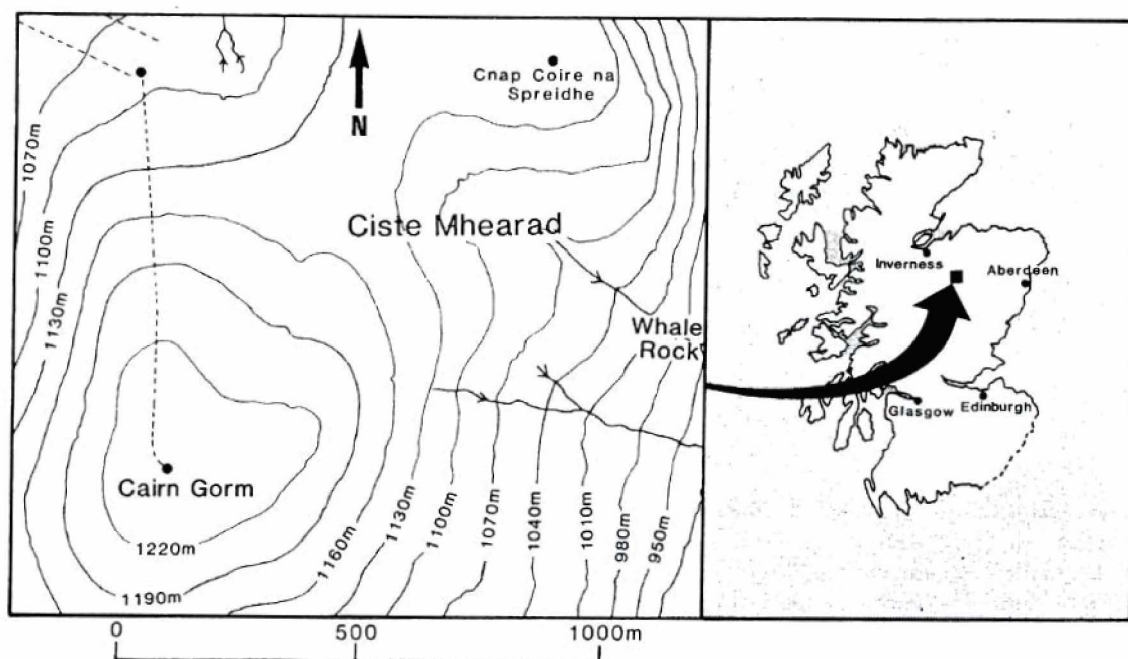


Figure 1 Location of Ciste Mhearad and Cairn Gorm, Cairngorm Mountains, Scotland (Abrahams *et al.*, 1988)

## 2.2 Laboratory analysis

All snow samples were kept frozen until analysis. Samples were rapidly melted, filtered through 0.45  $\mu\text{m}$  nucleopore filters (blank-tested), then stored in acid-washed bottles at 4°C. The concentrations of Cl, NO<sub>3</sub> and SO<sub>4</sub> were determined using a Dionex Model 2000i ion chromatograph with precision of 2% and detection limits of 0.2  $\mu\text{eq l}^{-1}$ . Ammonium concentrations were measured using the blue indophenol method (Parsons *et al.*, 1984) with a precision of 1  $\mu\text{g l}^{-1}$ . The cations, Na, K and Mg were analysed on a Pye Unicam SP9 atomic absorption spectrophotometer. Precision was between 1 and 2  $\mu\text{eq l}^{-1}$ , a magnitude greater than the limits of detection.

Sample size collected by the blowing snow samplers diminished with height above the surface, hence for some runs the volume of samples was too small for analysis of the complete set of ions.

## 3. Results and discussion

### 3.1 Ciste Mhearad corrie snowdrifts

An intense blowing snow event resulted in redistribution of deposited snow within the Ciste Mhearad corrie on 28 March 1989. The mean pH of samples was 4.5. The chemical concentration of surface snow was sampled by collecting snow on a plan grid within the corrie. Individual ion concentrations were ranked against each other and correlated with sample location (x or y map coordinate). The rank correlations were quite small, the largest being 0.29,  $n = 16$  with most correlations falling to less than 0.1. This suggests that any larger scale spatial trends (altitude, distance from sea, snowfall orogenesis, local source) had an insignificant effect on ion concentrations at the corrie scale (<0.4 km<sup>2</sup>).

When sampling sites were discriminated into eroding and accumulating snow based on visual inspection, significant differences in concentration became apparent as calculated using the F statistic. The effect is most striking for the sea salts (Cl, Na, Mg) for which an almost doubling of concentration was found in accumulating windblown snow (Table 1). The CV of ion concentrations are in all cases much higher than that found by Tranter

*et al.* (1987) for fresh snowfall without redistribution; the highest CVs are found for the sea salt ions. The CVs in all cases are smaller, sometimes by half, for accumulating snow than for eroding snow.

Table 1 shows differences between accumulating and eroding snow at various levels of significance. For most ions, significant differences due to accumulating snow concentrations being found in excess of eroding snow concentrations. This trend is reversed for NO<sub>3</sub> in which the eroding concentration is higher. Pomeroy and Jones (1996) suggested that volatilisation of NO<sub>3</sub> may occur during wind transport, however this is the first dataset showing a loss of NO<sub>3</sub> greater than proportional to the loss of H<sub>2</sub>O during sublimation. The increases in concentration in accumulating snow at the highest levels of confidence (>90%) are for the sea salt ions (Cl, Na, Mg). Ratios of accumulation to erosion for the major sea salt ions are similar (1.7 to 1.97) suggesting that little fractionation of sea salt occurred during blowing snow within the corrie. Pomeroy *et al.* (1991b) suggested that electrophoresis of sea salt aerosols to blowing snow particles accounted for the increase in observed sea salt concentrations in wind blown snow. The increase in SO<sub>4</sub> and NH<sub>4</sub> concentrations are small (1.14 and 1.07). Pomeroy and Jones (1996) suggested that these ions are conservative and that any increase in concentration would be proportional to H<sub>2</sub>O removal from a blowing snow particle by sublimation. Since fetch distances are small in the corrie, sublimation is small and hence the results for SO<sub>4</sub> and NH<sub>4</sub> are consistent with the mechanism suggested by Pomeroy and Jones.

**Table 1.** Ciste Mhearad Surface Snow Chemistry (n=30, sufficient fit to normal distribution). ANOVA F-tests were used to determine the significance of differences between concentrations and attribute these differences to erosional status.

Ion	Cl	NO <sub>3</sub>	SO <sub>4</sub>	NH <sub>4</sub> <sup>x</sup>	Na	K	Mg
Mean Eroding (ppm)	1.6	1.04	0.93	3.4	0.66	0.074	0.08
Mean Accumulating (ppm)	2.7	0.87	1.06	3.7	1.3	0.097	0.16
CV Eroding (%)	56	21	37	13	73	49	71
CV Accumulating (%)	18	17	20	10	19	27	19
Ratio Accum/Erosion	1.7	0.84	1.14	1.07	1.95	1.31	1.97
Sig. 60% Conf. Level	*	*	*	*	*	*	*
Sig. 70% Conf. Level	*	*		*	*	*	*
Sig. 80% Conf. Level		*			*	*	
Sig. 99% Conf. Level	*				*		*

<sup>x</sup> concentration in  $\mu\text{eq l}^{-1}$

### 3.2 Cairngorm Plateau wind-blown snow

Samples collected on the Cairngorm Plateau on 29 March 1989 are of snowfall previously deposited on the plateau and actively eroded from the surface by a strong blowing snow event (air temperature -3°C, wind speed 30 m s<sup>-1</sup> at 10 m height). The mean pH for these samples was 4.5, similar to that in Ciste Mhearad. Table 2 shows mean concentrations of eroding snow ions generally higher than eroding snow concentrations in the sheltered corrie nearby (Table 1) and eroding snow concentrations from the plateau close to concentrations from snow accumulating in the corrie. This suggests that the originally deposited snow underwent greater wind transport upon deposition on the plateau than did that in the corrie and was accordingly chemically transformed. This is reflected most strongly in the concentrations of sea salts and least in that of NO<sub>3</sub>, consistent with the previous discussion.

The CV of ion concentrations are not generally higher in eroding snow on the plateau than eroding snow on the corrie, however the CV of snow on the plateau is not reduced by wind transport in that it does not decline for accumulating snow. This suggests that overall, high wind exposure in a consistently windy environment can increase the variability of snow chemical concentration.

Concentrations of sea salt ions increase substantially (doubling for Na) as snow is transformed from eroding to accumulating snow on the plateau. Significant differences at various confidence levels are indicated in Table 2. At high levels of confidence (>90%) only the sea salts (Cl, Na, Mg) showed significantly enhanced concentrations in accumulating windblown snow. The degree of increase is similar to that measured in the nearby corrie (1.7-2.2). As in the corrie the effect is subdued for SO<sub>4</sub> and NH<sub>4</sub> and non-existent for NO<sub>3</sub>. As snow was blown from the south-southeast this increase in ion concentration was accompanied by a relocation of snow from windward to leeward sections of the plateau. For this plateau Pomeroy *et al.* (1991) modelled an increase in ion concentrations due to removal of ice from blowing snow grains via sublimation of 15% to 33% which would explain the increases in concentrations of SO<sub>4</sub> and NH<sub>4</sub> but not the large increases in sea salt concentrations. Pomeroy and Jones (1996) suggest the increase in sea salt ion concentrations in wind blown snow is due to electrophoretic scavenging of sea salt aerosols by charged blowing snow particles. They also suggest that the relatively constant concentration of NO<sub>3</sub> is due to volatilisation in proportion to sublimation. In

the corrie however NO<sub>3</sub> was lost in excess to blowing snow sublimation suggested an enhanced NO<sub>3</sub> volatilisation in certain cases.

**Table 2** Cairngorm plateau surface snow chemistry (n=8, normal). ANOVA F-tests were used to determine the significance of differences between concentrations and attribute these differences to erosional status.

Ion	Cl	NO <sub>3</sub>	SO <sub>4</sub>	NH <sub>4</sub> <sup>x</sup>	Na	K	Mg
Mean Eroding (ppm)	2.4	1.1	1.1	4.7	0.9	0.07	0.13
Mean Accumulating (ppm)	4.2	1.1	1.4	6.1	2.0	0.1	.023
CV Eroding	44	27	24	28	74	42	47
CV Accumulating	49	31	25	38	62	55	54
Ratio Accum/Erosion	1.75	0.97	1.2	1.3	2.16	1.67	1.73
Sig. 75% Conf. Level	*		*	*	*	*	*
Sig. 80% Conf. Level	*		*		*		*
Sig. 90% Conf. Level	*				*		*

<sup>x</sup> concentration in µeq l<sup>-1</sup>

When taking the data as a whole and ranking the differences between eroding and accumulating snows by their F statistic the following sequences for degree of concentration enhancement are evident for the corrie and plateau samples respectively:

Corrie	Mg > Na > Cl > K > NH <sub>4</sub> > SO <sub>4</sub>
Plateau	Na > Cl > Mg > K > SO <sub>4</sub> > NH <sub>4</sub>

The important aspect of this sequence is that sea salt ions have the greatest concentration enhancement due to blowing snow redistribution and that this also leads to high CV both within a relatively sheltered corrie and on an exposed plateau, apparently linked to both erosion and depositional processes. The higher CV on the plateau may be explained by more active redistribution and sublimation processes in that more exposed environment.

#### 4. Conclusions

Blowing snow erosion and redistribution strongly increased the small-scale spatial variability of sea salt concentration in snow, by almost doubling many constituents when relocating snow from erosion to deposition areas within a landscape type. This result has important implications for scaling up point representations of snow chemistry to a basin or landscape, to interpreting field samples of snow chemistry in wind-blown areas and in designing sampling strategies that would calculate an areal mean within a specific error band (Pomeroy and Gray, 1995). An effective sampling strategy would be to stratify the landscape into zones of accumulation and erosion and sample within each, then produce a landscape areal average based upon weighted means of samples from both surface types.

The spatial variability observed at small scales <300 m was also evident when comparing mean concentrations at larger scales as between corrie and plateau. Difference between plateau and corrie concentrations is likely due to greater wind transport and drifting on the plateau compared to the corrie. Pomeroy *et al.* (1995) noticed such macro-scale variations in snow chemistry near the treeline in the Canadian Arctic, with higher ion concentrations on tundra than in sheltered forest. It is suggested that examination of sea salt ion concentrations in snow and changes in the ratio of sea salts ions to NO<sub>3</sub> can be applied to distinguish between convergent and divergent blowing snow zones. This technique might be useful where detailed meteorological data are not available and to confirm the predictions of models of blowing snow over complex terrain, particularly in Celtic mountains where interest in application of such techniques is increasing and the implications for water balance and weathering await investigation.

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