AEOLIAN BLOWOUT DYNAMICS IN SUBARCTIC LAPLAND BASED ON DECADAL LEVELLING INVESTIGATIONS

BY
JUKKA KÄYHKÖ

Department of Geography, University of Turku, Turku, Finland

Käyhkö, J., 2007: Aeolian blowout dynamics in subarctic Lapland based on decadal levelling investigations. *Geogr. Ann.*, 89 A (1): 65–81.

ABSTRACT. Aeolian processes in the subarctic ecocline were investigated by measuring present-day erosion and deposition rates over a decade in blowouts scoured into stabilized Early to Mid-Holocene dunes. Four localities from different vegetation zones in Finnish Lapland were surveyed using precision levelling (infrared tachymeter) along eight transects at 1-m intervals. During an 11-year observation period, a total of 1439 observation points were monitored in three measurement campaigns, in 1993, 1994 and 2004. Together with dating results reported elsewhere, the results demonstrate the relative quiescence of these subarctic blowouts compared to many coastal dunes. On average, the deflation rate of the studied basins was 8.8 mm a^{-1}, which corresponds well with the age and depth of the blowouts. Net deposition had taken place at 30% of the observation points, and one of the eight studied transects showed net deposition as the transect average. Symmetrical, smooth basins showed more consistent changes than basins with a complex form, indicating that internal factors are important in blowout formation under the Lapland climatic range. The deepest part of a blowout was generally found in the upwind end. The erosion/deposition patterns of the transects over a one-year monitoring period were interpreted with Fourier analysis revealing along-transect cyclicity, possibly reflecting the movement of small migrating bedforms in the blowouts. Generally, deflation rates at the latitudinal pine forest line were smaller than at those well outside the pine forest suggesting that the coniferous forest at the subarctic ecocline affects the intensity of present-day aeolian activity in Fennoscandia.

Key words: aeolian, dune, blowout, levelling, subarctic, wind erosion

Introduction

Blowouts are deflation features eroded into loose sediments, typically in vegetated dunes, and are common on coasts and stabilized dunes on desert margins (Livingstone and Warren 1996). Blowouts occur and survive in a wide range of environments with differing processes and highly variable rates of activity. Present-day aeolian activity in continental Fennoscandia typically occurs in the form of scattered blowouts, or deflation basins, within suitable substrate, i.e. largely stabilized Early Holocene parabolic dunes, or sands of glaciofluvial or glaciolacustrine origin (Seppälä 1972, 1995; Tikkanen and Heikkinen 1993; Käyhkö *et al.* 1999a). The sedimentary deposits surrounding the active blowout areas in Lapland often show stacked palaeosols indicating recurrent cyclicity during the Holocene. Hence, blowouts can potentially be used as an indication of changes in environmental parameters, such as changes in climatic conditions, or human or animal disturbance. Once initiated, blowout growth may continue as a self-organized process even though the conditions for initiation are no longer present. Grazing pressure by domestic reindeer has been shown to produce dramatic changes in vegetation cover in Fennoscandia (e.g. Tømmervik and Lauknes 1987; Käyhkö and Pellikka 1994). Reindeer grazing has also been suggested as one of the potential factors responsible for wind erosion (e.g. Kotilainen 1991, 2004; Tikkanen and Heikkinen 1995). Systematic studies of current wind erosion processes are therefore needed to determine how and why deflation processes take place in Lapland.

Studies on the spatial distribution and the history of aeolian activity in northern Fennoscandia have been reported by Käyhkö *et al.* (1999a,b) and the current dynamics of aeolian activity have previously been quantified at one location only (Seppälä 1974, 1984; Käyhkö 1994a). Therefore, information is largely lacking on whether the present estimates of average deflation rates are spatially representative, and what environmental parameters govern the processes operating currently.

This work examines present-day blowout evolution processes by monitoring the erosion and deposition rates within selected deflation basins. The aim is to better understand the relationship between the present-day rates of aeolian activity and environmental parameters by attempting to answer the following questions:

– What is the average rate of aeolian processes in the study area?
– How does aeolian intensity vary locally and regionally?
– What local or regional parameters can be identified as potential factors governing aeolian processes in the study area?
– What is the temporal character of aeolian activity, i.e. are the size and age of the blowouts in agreement with the present-day change rates?

Earlier studies

Published research reports of blowout evolution include studies from the early 20th century onward (e.g. Högbom 1923; Landsberg 1956). More recently, Jungerius *et al.* (1981) and Jungerius and van der Meulen (1989) have studied blowout evolution on the Dutch coastal dunes. Lancaster (1986) investigated the dynamics of deflation hollows in the Cape Province in South Africa, whereas Livingstone (1993) monitored linear dune surface change over a decade in Namib. Pluis and de Winder (1989) and Pluis and van Boxel (1993) studied the effect of algal crusts on sand transport, again on Dutch dunes. In Australia, Hesp and Hyde (1996) studied the flow dynamics and geomorphological development of a trough blowout in NSW. Dech *et al.* (2005) studied blowout evolution on the coastal dunes of Lake Huron in Canada using colour air photos over a 25-year period. In cold regions, systematic sand budget studies have been undertaken by Seppälä (1974, 1984), who studied blowout processes at Hietatievat in Finnish Lapland.

Earlier studies demonstrated the large range of physical environments where blowouts occur, and the great variations in blowout dynamics. On the coastal dunes of the Netherlands (Jungerius *et al.* 1981; Jungerius and van der Meulen 1989) blowouts occur at various locations in the dune field; they grow rapidly but are small in size and stabilize quickly. The whole system is in a rapid, continuous phase of relief modification. In contrast, the blowouts in South Africa (Lancaster 1986) are formed on undulating cover sands deposited several millennia ago. They have subsequently been stabilized and have only been reactivated during the last two centuries. At the present day, however, they show significant change rates of up to 200 mm of total (cumulative) erosion and 1000 mm or more of deposition annually.

Studies on cold climate blowout dynamics have been undertaken in Finnish Lapland using both sand-trapping methods (Seppälä 1974) and net change monitoring over a three-year period using erosion pins (Seppälä 1984). The annual average values for net deflation in the three successive years were 2.5 cm, 1.6 cm and 2.1 cm. Seppälä (1984) suggested that the erosion pin method allowed a more realistic approach to determining long-term aeolian transport rate than the instantaneous trapping of moving sand. Käyhkö (1994a), also, reported both instantaneous sand-trap experiments as well as long-term net change monitoring in a deflation basin at Hietatievat. The average net change for the two-year period was –3.0 cm. Based on these limited observations, sand transport rates measured in Lapland seem small compared to those in, for example, South Africa or the Netherlands.

Both Seppälä's and Käyhkö's results of the net change suggest a net vertical erosion of *c.* 1–2 cm a^{-1} in the studied blowouts. However, a weakness of this work is that just one location was investigated and the observation periods were short. Hence there is a need for a more comprehensive approach considering a greater number of sites, and higher monitoring accuracy.

Study methods

Wind data

The wind data used in this study consisted of two sets: a general wind pattern based on long-term (1961–1990) averages, and a more detailed analysis for a one-year period (1993–1994) (Fig. 1). The data were collected at weather stations run by the **Finnish Meteorological Institute (FMI)**. After careful evaluation, data from four weather stations covering the study sites were considered suitable in terms of location and the quality of data (Table 1).

For the detailed one-year (1993–1994) wind analysis, it was assumed that aeolian processes are negligible during the period with snow cover on the ground. Winter sublimation processes (cf. Law and van Dijk 1994) like those described in North America, by McKenna Neuman (1989, 1990), Lewkowicz and Young (1991) and van Dijk and Law (1995, 2003) are not known in the region

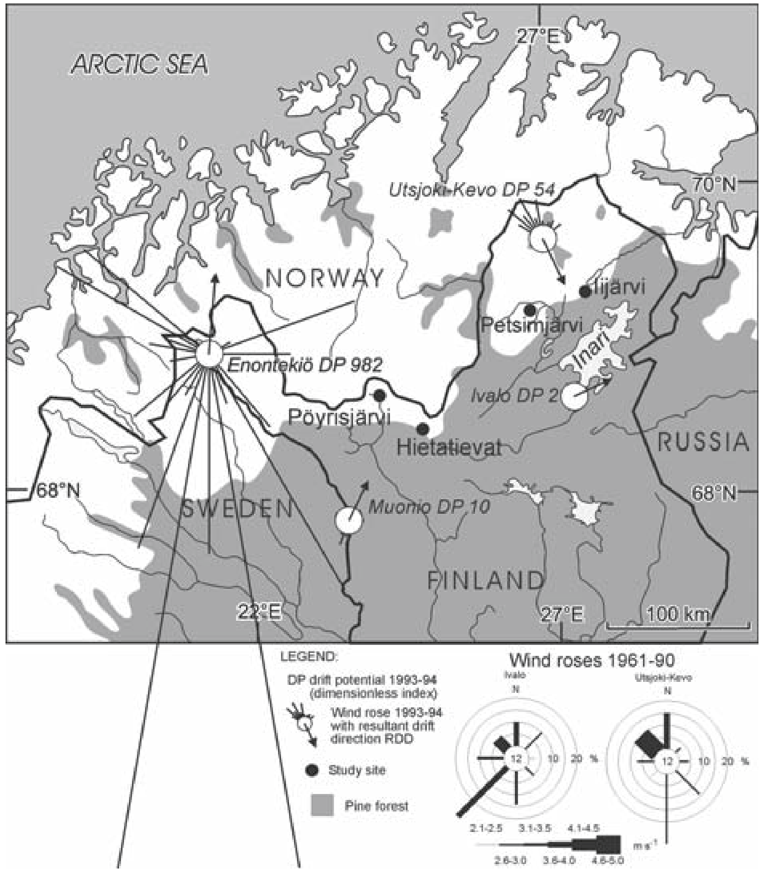

Fig. 1. The four study sites and the four weather stations with respective drift potential values calculated from observations at 3-hour intervals on snow-free days, from 15 August 1993 to 31 August 1994. The 1961–1990 wind data from two stations are also shown, together with the extent of the pine forest (data: FMI 1991)

due to blanketing snow cover. Therefore, only the snow-free period was taken into account when calculating the wind parameters. The dimensionless indices of **drift potential (DP)**, **resultant drift potential (RDP)** plus the **resultant drift direction** (**RDD**) presented by Fryberger and Dean (1979), were employed in the description of wind characteristics for the period 1993–1994 in the study area. The wind data from various stations with varying instrument height were first standardized at the 10 m level using the von Kármán-Prandtl logarithmic velocity profile law. The observations from the four stations show clear differences due to local topography. For example, the Kilpisjärvi automatic weather station at Enontekiö, which is located at the top plateau of the

Table 1. The four weather stations used in this study (see Fig. 1). For the period 1993–94, indices for aeolian transport capacity, the so-called drift potential, were calculated based on Fryberger and Dean (1979). Southerly winds dominate on all stations apart from Utsjoki-Kevo. By far the highest drift potential can be found at Kilpisjärvi fell plateau

Station	Location (WGS84)	Elevation (m)	Instrument height m	No. of obs.	Period 1993–94 DP	RDD	RDP	RDP/DP
Muonio	67°58’, 23°41’	253	12	1188	10.1	27°N	5.3	0.53
Enontekiö	69°02’, 20°51’	1015	53	1117	982	4°N	507	0.52
Ivalo	68°37’, 27°25’	145	12	1161	1.6	64°N	0.5	0.30
Utsjoki	69°45’, 27°02’	107	16	1179	53.6	154°N	35.9	0.69

Fig. 2. The levelling equipment (tachymeter and datalogger) at the benchmark at Petsimjärvi dune field. View towards the north. Notice the elongated form of the blowout and the steep slopes at the secondary rim deposits at the edges. Vascular plants Empetrum nigrum and Arctostaphylos uva-ursi support small sand hummocks

Saana fell (1029 m), showed much higher DP values than the rest of the sites (Table 1, Fig. 1).

Despite the potential bias due to local relief, the available wind data show distinctive patterns across the study area. In the northern and northeastern part of the study region, northwesterly winds dominate, in contrast to the rest of the area where the effective wind direction is from the southwest. The general wind climate is liable to differ from the winds acting at individual blowouts. Local relief will divert the airflow, and field observations show that the effective wind direction in blowouts is often diverted parallel with the depression long axis. Any airflow blowing perpendicular to the axis of an elongate blowout will be substantially hampered due to the high, vegetated secondary rim deposits at the blowout margins.

Tachymetric levelling

The present-day changes in the blowouts were investigated with the aid of repeated tachymeter levelling along transects across blowouts in the summer seasons of 1993, 1994 and 2004. The levelling equipment consisted of a Nikon DTM-A Lg-10 infrared total station, Geonic datalogger and a hand-held prism (Fig. 2). Local benchmarks were established by driving 1-m-long wooden poles into the ground. The observed differences in the sand surface elevation between successive measurements were taken to represent the net erosion/deposition at the particular point. In order to prevent the prism pole from sinking into sand during observations, a plastic plate of 60 mm diameter was attached at the bottom end and care was taken to always reposition the pole gently on the sand surface.

The observations in this study were made along linear transects at 1-m intervals. Any vegetation growing on the transects was mapped and taken into account in the evaluation of the observed changes in sand surface elevation. The changes in sand surface elevation were analysed statistically by calculating the arithmetic mean and standard deviation for each transect. The observed changes were investigated using standard moving average data smoothing and Fourier analysis for potential spatial change trends within the blowouts.

Estimating the accuracy of the levelling method

In the tachymeter levelling approach the theoretical equipment accuracy is ±0.78 mm at a distance of 100 m. In addition to the theoretical accuracy of the equipment, one has to take into account human errors due to slight variations between the sightings. The potential sources of errors in the tachymeter levelling method employed in this study include: inadequate instrument resolution in measuring the vertical angle; changes in the benchmark elevation between successive levelling campaigns (frost lift etc.); inaccuracy in the positioning of the prism on the observation point (e.g. incorrect positioning in the X–Y direction, tilting of the prism pole from true vertical, inconsistency in the degree of sinking of the prism pole into the sand surface); and inaccuracy in the sighting (the angle adjustment should be done in such a manner that the cross-hair always closes in upon the prism centre from the same direction (e.g. from the left and below), otherwise the small free movement within the lens bearings may cause an error).

In order to estimate the total error included in the measurements, a set of 50 repeated measurements were made to a stable prism at 100 m and 200 m distance, rotating the lens, focusing, and aiming at the prism between each measurement. The maximum difference between the elevations recorded at the 200 m distance was 15.7 mm (standard deviation 4.7 mm). The observations were distributed symmetrically around the mean, and no cyclicity was found in the series (determined by Fourier analysis) (see Table 4). The longest levelling distance measured in this study was 287 m, and consequently, with a 68% probability, the measured elevation at this distance should lie within ±6 mm of the true elevation. With respect to individual observations, this limitation is of importance and should not be ignored, but in terms of hundreds of observations, any trends in elevation changes should be reasonably unaffected because the errors are randomly distributed.

Land cover / vegetation analysis

Vegetation adjacent to the blowouts was quantified with a GIS-based overlay and buffer method. A simplified version of the National Land Cover and Forest Classification (LUFC) (Vuorela 1995) was overlaid with Landsat TM-based mapping of aeolian features in Lapland (Käyhkö *et al*. 1999b) using a 100-m (i.e. four pixels, 25 m × 25 m) buffer around the detected deflation basins. This method provides information of the land cover type adjacent to the deflation features. The selected buffer width was considered a good compromise, since a wider buffer would not have revealed the immediate environment around the aeolian activity. A narrower buffer, on the other hand, would have excluded forest stands, which could still affect the local wind climate. For the interpretation, the 25 or so land cover classes present in the study area of the forest classification were combined to form four GIS classes: 1, pine forest; 2, birch forest; 3, mire/water; and 4, barren ground. This procedure simplified the interpretation of the GIS results, but was still considered as being distinctive enough to summarize the aeolian environment.

Study area and the four study sites

The study area lies between latitudes 68° and 70°N in the inland area of northern Lapland. The Pleistocene Fennoscandian ice sheets covered the whole Baltic Shield, sweeping clean the old peneplain and polishing the surfaces of the hard rocks. Basal till blankets the whole study region apart from scattered outcrops of bedrock in the higher areas. In places, the basal till is covered with hummocky ablation moraine, or glaciofluvial and glaciolacus-

Table 2. Basic information about the four study sites (see Fig. 1)

Locality	Location N, E (WGS84)	Elevation m a.s.l.	Total area deflation ha*	Type and size† of study blowout	Sediment type	Vegetation	Levelling transects: length, direction
Petsimjärvi	26°51'59.7" 69°16'25.5"	200	3.5	Pearl necklace, 600 m × 50 m × 4 m	aeolian	birch/pine	200 m, 351°N
Iijärvi	69°22'29.5" 27°37'43.6"	200	11	Pearl necklace, 460 m × 50 m × 6 m	aeolian	birch/pine	175 m, 319°N; 288 m 167°N
Hietatievat	68°28'4.4" 24°42'26.7"	350	41	Tray, 200 m × 200 m × 5 m	aeolian/glac. -lacustrine	birch/pine	1: 133 m, 34°N, 2: 67 m 278°N
Pöyrisjärvi	68°41'38.1" 23°50'39.0"	420	166	Tray/pearl necklace, 1 km × 150 m × 6 m	aeolian/glac. -lacustrine	dwarf/shrub heath	3: 58 m, 177°N 1: 73 m, 85.5°N 2: 207 m, 10.5°N 3: 239 m, 173.5°N

* based on Käyhkö *et al*. 1999a
† size: length × width × depth

trine sediments, which were deposited by meltwaters during deglaciation. The eskers of the region run mainly in N–S or NE–SW direction, indicating the former meltwater routes. It was mainly these water-sorted sediments, that acted as a sediment source for aeolian transport after the deglaciation. Parabolic dunes were formed, and subsequently stabilized and reactivated in a rather complex manner (Clarke and Käyhkö 1997; Käyhkö *et al.* 1999a,b).

The climate in the study region is reasonably mild due to the warming effect of the Gulf Stream. Annual mean air temperature varies from +1°C in the south to –2°C in the northwest (Helminen 1987). The northern part of the area is affected by sporadic permafrost in the form of palsa mounds in mires. The average maximum depth of seasonal frost is *c.* 1.3 m. Cyclonic activity causes variable wind directions, with slight prevalence by southwesterlies in the south, and northwesterlies in the north (cf. Fig. 1, Table 1). Long-term annual average (1961–1990) wind roses were compiled for two meteorological stations (Utsjoki-Kevo and Ivalo) and are presented in Fig. 1. In the snow-free period *(c.* May–October), the strongest winds blow from the north-northwest in the north at Utsjoki-Kevo, whereas further south at Ivalo southwesterly winds dominate.

Precipitation in the area shows a gradient from humid coastal areas to drier inland areas. Typically, the annual precipitation is 500–550 mm, approximately half of which falls as snow. The annual number of days without precipitation is 180–200, and the potential evaporation varies between 100 and 225 mm. Snow lies for 200–220 days per year, and the average maximum snow depth on open ground is 50–70 cm, slightly more in the forests (Solantie 1987).

The study area is within the northern boreal zone, or taiga. The tree line in northern Fennoscandia consists of mountain birch (*Betula pubescens* ssp. *cherepanovii*). In this study, the vegetation zone systems of Ahti *et al.* (1968) and Oksanen *et al.* (1995) for Fennoscandia are followed. The boreal zone consists of treeless heaths in oceanic sectors, and steppes in arid provinces (Hämet-Ahti 1981). The area above the tree limit is referred to as orohemiarctic, or subalpine, tundra. The duration of the growing season in the study region varies between 95 and 130 days. Polar tree lines for both Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) cross the area. It is in this diffuse ecocline where most of the aeolian activity is concentrated in Finnish Lapland (Käyhkö *et al.* 1999a). Further north, and at higher elevations in the hills, trees are limited to mountain birch, which forms a sparse scrub with a flourishing lichen ground layer in open ground and dwarf shrubs under tree coppice (Hämet-Ahti 1963). Lichen-rich forests commonly occur on fixed and forest-clad ancient sand dunes. Ahti and Oksanen (1990) point out that lichen-rich stands are also common in the earlier stages of dune stabilization. However, due to intensive reindeer herding, many naturally lichen-rich areas are currently almost devoid of lichens such as *Cladina stellaris* and *C. mitis*, which form important winter forage for these animals. *Cladina* species have been replaced by dwarf shrubs and other lichen species, like *Stereocaulon* sp. (Käyhkö and Pellikka 1994).

Four localities from different parts of Finnish Lapland were subjected to the monitoring study (Fig. 1, Table 2). In addition to differences in vegetation, the localities show various sediment types and consequently different blowout forms. The se-

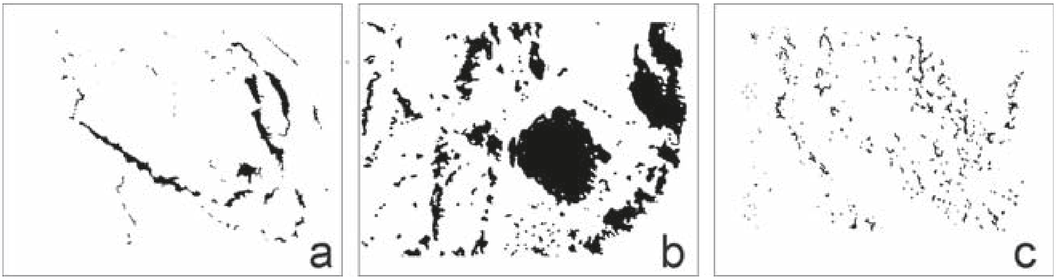

Fig. 3. Bitmaps traced from aerial photographs showing the three characteristic blowout types in Lapland. (a) Pearl necklace blowouts at Petsimjärvi dunefield showing nested deflation basins following the parabolic dune crest areas (wind from the NW). (b) A large tray blowout and adjacent pearl necklace blowouts at Hietatievat on flufiolacustrine and aeolian sediments. (c) Small scar blowouts at Ravdopuolddšak esker enlargement on coarse glaciofluvial sediments. Each box is 1 km wide

lection of study sites across Lapland and the employment of varying observation periods allow judging the relative impacts of different parameters on aeolian activity to be judged.

A nomenclature to describe three distinctive types of deflation basins, namely pearl necklace blowouts, tray blowouts and scar blowouts, is introduced here, based on a comprehensive mapping of aeolian activity in Lapland (Käyhkö *et al.* 1999a). Parabolic dune crests sustain numerous small and rather steep-sided elliptical blowouts, which are connected by narrow conduits. These chains of deflation hollows follow the original parabolic dune crest and may form '*pearl necklace blowouts'* up to several hundred metres long. Type areas of these can be found, for example, at Petsimjärvi dunes (Fig. 3a). These blowouts are normally narrow (30–50 m) and reasonably deep (in excess of 5 m). The surrounding rim deposits are narrow and high.

Glaciolacustrine sediment plateaux sustain large semi-circular or amoeba-shaped '*tray blowouts*', which are relatively shallow and flat-bottomed due to the near vicinity of ground water level and/or resistant underlying fine sediment. These can reach 200 m in diameter. The adjacent rim deposits are low and wide, reflecting the long transport distance of fine sediments. A typical primary blowout sitting between the parabolic dune arms is an example of a tray blowout. In Lapland, however, the primary parabolic dune blowouts are very rarely active at present. A type example of a tray blowout can be found at Hietatievat (Fig. 3b).

Environments such as eskers, with somewhat coarser glaciofluvial sediment, sustain shallow (typically in the order of 0.5 m), lag-covered '*scar blowouts'* (Fig. 3c), which show almost non-existing surrounding secondary deposits. The coarse lag on the blowout surface inhibits wind action and individual scar blowouts reach diameters of only a few metres. Typically they are numerous and are often located along reindeer paths, or ridge crests, suggesting a link to deep frost penetration due to thin snow cover in the winter. This type was not included in the present monitoring study.

Site 1: Petsimjärvi

The Petsimjärvi study site is located adjacent to a glaciofluvial–glaciolacustrine formation, which was deposited in a glacial lake during the deglaciation of the Scandinavian ice sheet (Seppälä 1980). The main dune complex, lying at an elevation of 200–205 m a.s.l., was formed adjacent to this esker, mainly by winds blowing from the WNW–NW (Seppälä 1971). Active surfaces are located on the original dune crests reflecting the initial course of the dunes (pearl necklace type). The dune arms at Petsimjärvi indicate a reasonably long migration distance for this region, as the longest arm can be traced for at least 700 m. The studied blowout follows the former crest of the dune in a horse-shoe form, opening towards the west. The levelling transect runs in an almost N–S direction (351°N) along the blowout at the dune-nose portion (see Fig. 2), consisting of 200 observation points at 1-m intervals.

Site 2: Iijärvi

The Iijärvi dune field is located at the southern end of lake Iijärvi, and has been derived from glaciofluvial sediments, which form one of the longest eskers *(c.* 150 km) in Finnish Lapland. The main part of the studied dune is similar to a long-walled transgressive ridge, (e.g. Pye and Tsoar 1993, Fig.

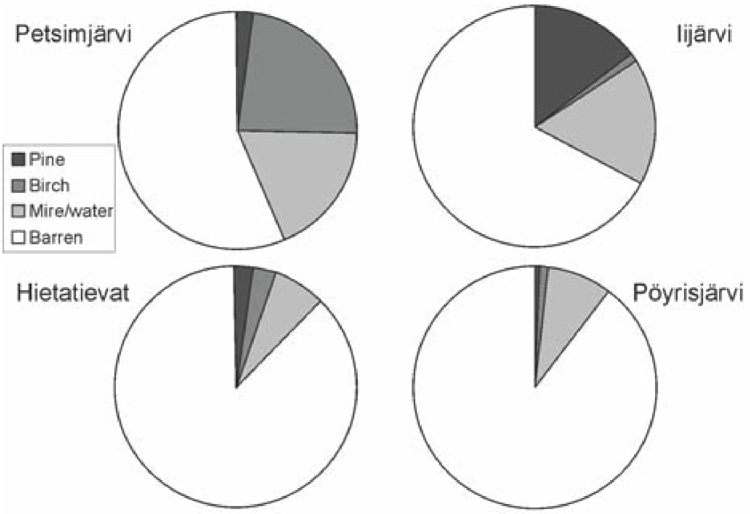

Fig. 4. Relative proportions of the four land cover classes (simplified from the National Land Use and Forest Classification) on 100-m buffer zones surrounding the aeolian sites. Notice the small proportion of pine forest and the large differences in birch scrub area

6.49f), with an almost straight middle part and the tails slightly pointed towards the wind. Further south, the dune ridge forms a more typical parabolic nose towards the SE, with some secondary ridges on the upwind side. The study blowout is the largest one in the vicinity, and corresponds to the former dune crest. The bench mark was established one-third of the way along the transect to allow shorter sighting distances to both directions (see Table 2).

Site 3: Hietatievat

Hietatievat esker enlargement *(sensu* Lindström 1993) was deposited in conjunction with the glacial lake Käkkälö a few kilometres to the south (proximal side) of the Arctic Ocean–Baltic Sea water divide (Tanner 1915; Käyhkö 1994a). The eastern side of the feature is blanketed with a fine sand apron which consists partly of glaciolacustrine beds, partly of aeolian sands, sustaining a few large semi-circular tray blowouts. On the dune ridges, typical strings of narrow, elongated pearl necklace blowouts prevail. The monitored amoeba-shaped tray blowout differs markedly from the elongated basins at Iijärvi and Petsimjärvi. Three levelling transects were established from the benchmark towards different directions (see Table 2). The benchmark sits at 48 m along transect Hietatievat 1.

Site 4:Pöyrisjärvi

The surroundings of lake Pöyrisjärvi sustain the largest occurrence of aeolian activity in Lapland (Käyhkö *et al.* 1999a). The area is located on the proximal side of the water divide between the Baltic Sea and the Arctic Ocean, and supported a large extramarginal lake during the late Pleistocene deglaciation. The extensive deposits of glaciolacustrine material were subsequently subjected to aeolian processes. The largest presently active blowout in the area – and in the whole of northern Fennoscandia – with a total area of 14 ha, was selected for the monitoring studies. This basin has grown to a tray blowout, although it still reflects the original form of the dune parabola. The deepest part of the basin is located towards the northern end, which suggests an effective wind direction from the north at present. The basal area is affected by the vicinity of the ground water table, giving rise to mosses, lichens, grasses and some dwarf shrubs. Three transects, Pöyrisjärvi 1, 2 and 3, with a total of 521 observation points, were levelled across the basin towards different directions. The benchmark is located on top of a 4-m-high vegetated promontory of sand pointing towards the basin at its western margin.

Results

Vegetation around the deflation basins

The GIS overlay and buffer analysis demonstrate that the highest pine density within the 100-m buffer zones surrounding the barren deflation features was found at Iijärvi, (14.7%), followed by Hietatievat (2.6%), Petsimjärvi (2.1%) and Pöyrisjärvi (0.6%) (Fig. 4). In reality, however, it is the Petsimjärvi region which has the highest pine occurrence, but due to edaphic factors, the paludified surroundings of the dune blowouts support mountain

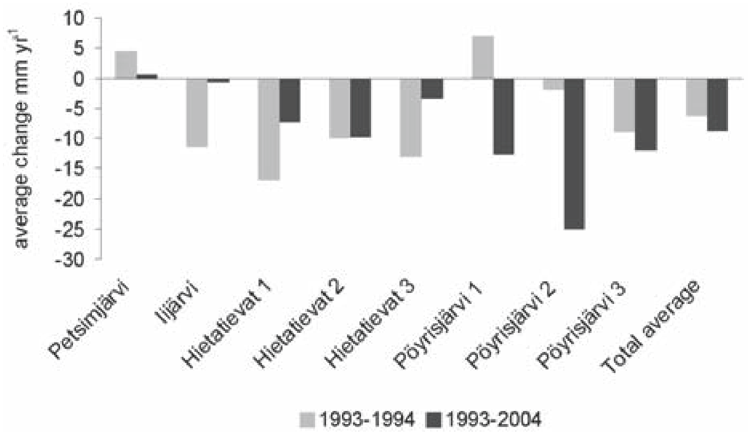

Fig. 5. Summary diagram of observed surface changes at all eight transects for the two periods 1993–1994 and 1993–2004

birch scrub with only few pine trees. Pöyrisjärvi, on the other hand, is outside the pine forest zone by a margin of several kilometres, and the small pine occurrence is a classification error in the LUFC. Field checks suggest that wide, tabular junipers (*Juniperus communis*) are erroneously classified as pine. Outside the pine forest zone junipers typically grow in a low but extensive form, which is mistaken for pine crown in satellite data. In general, the sites can be arranged in order of increasing aeolian exposure due to decreasing forest density as follows: Petsimjärvi, Iijärvi, Hietatievat and Pöyrisjärvi.

Erosion and deposition patterns

In the following, some examples of the results are discussed and illustrated in diagrams. A summary of all levelling results is presented in Table 3 and Fig. 5. During both the one-year observation period (1993–1994), and the 11-year observation period, some 65% of the 1439 data points revealed net erosion. The average net change of all points was –6.4 mm in 1993–1994, and –8.8 mm a^{-1} during the 11-year period. Hence, broadly speaking the results for the two periods are rather similar, but detailed com-

Table 3. Summary of the levelling results for the two observation periods 1993–1994 and 1993–2004

Locality, transect number	No. of observation	σ elevation (m a.s.l.)	Monitoring period	Average change (mm/a^{-1})	σ of changes (mm)	Max. deposition (mm)	Max. erosion (mm)	No. deposition points (% of all points)
Petsimjärvi	200	0.96	1993–1994	+4.5	11.5	32.0	–46.5	142 (71%)
			1993–2004	+0.6	4.8	22.2	–14.9	113 (57%)
Iijärvi	464	2.06	1993–1994	–11.7	40.8	267.8	–236.6	113 (24%)
			1993–2004	–0.7	4.8	29.8	–20.5	159 (34%)
Hietatievat 1	133	1.08	1993–1994	–17.0	43.1	66.0	–184.1	40 (30%)
			1993–2004	–7.2	22.3	53.0	–74.0	38 (29%)
Hietatievat 2	67	0.86	1993–1994	–10.0	36.1	92.0	–99.2	19 (28%)
			1993–2004	–9.9	15.4	27.9	–47.7	15 (22%)
Hietatievat 3	58	0.69	1993–1994	–13.0	37.1	84.4	–99.9	22 (38%)
			1993–2004	–3.4	0.6	21.6	–26.3	26 (45%)
Pöyrisjärvi 1	73	0.55	1993–1994	+7.0	29.5	70.7	–165.7	41(56%)
			1993–2004	–12.7	15.5	30.7	–99.7	11 (15%)
Pöyrisjärvi 2	207	1.03	1993–1994	–2.0	15.5	86.8	–42.2	60 (29%)
			1993–2004	–25.1	13.2	18.2	–50.5	15 (7%)
Pöyrisjärvi 3	239	0.65	1993–1994	–9.0	21.8	145.3	–105.7	44 (18%)
			1993–2004	–12.0	24.1	38.0	–68.8	66 (28%)
All sites total	1439		1993–1994	–6.4	24.0	122.5	105.6	481 (37%)
			1993–2004	–8.8	12.6	30.2	–50.3	443 (30%)

Note: σ elevation = standard deviation of the levelling point elevations (a measure of 'roughness'); average change = arithmetic mean of the observed elevation changes in mm; σ of changes = standard deviation of the observed elevation changes

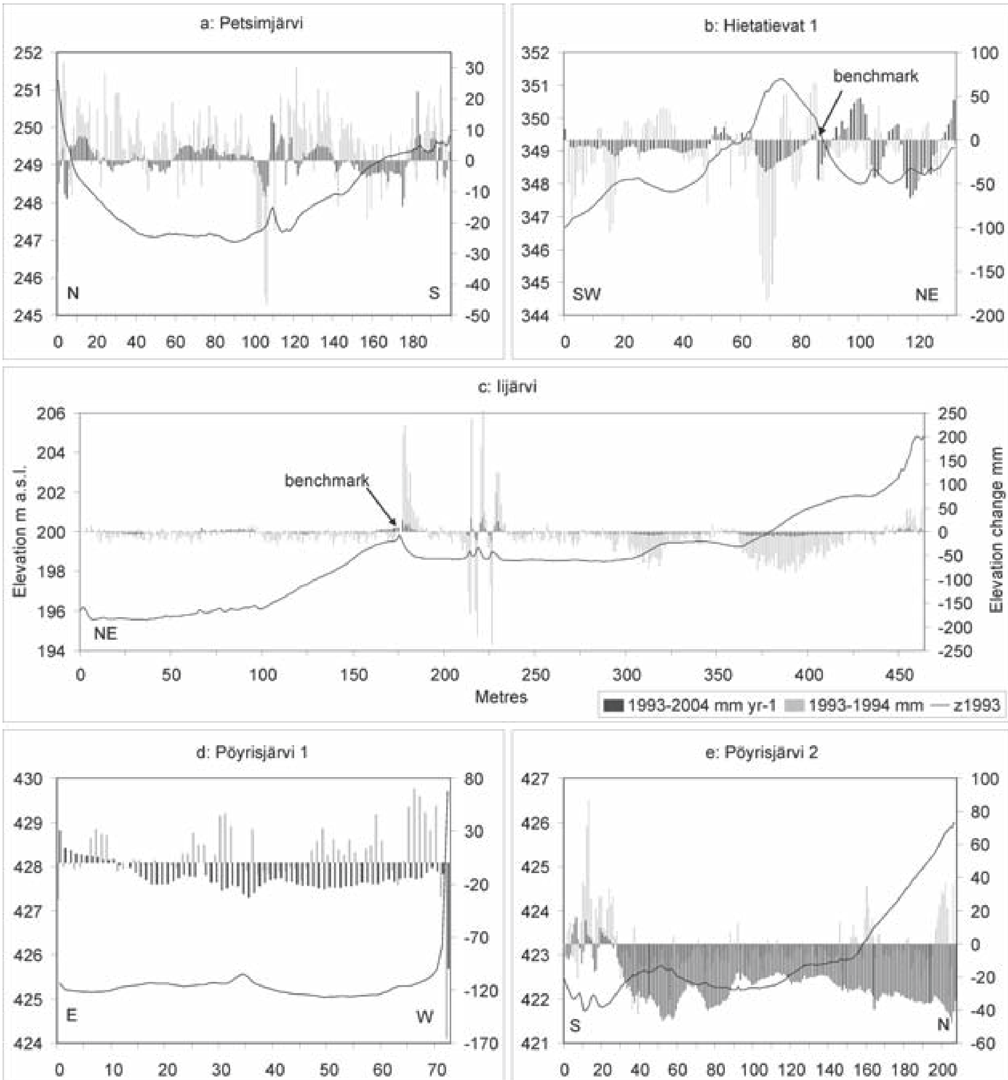

Fig. 6. Examples of changes in sand surface elevation at the four locations. Legend is in the central panel. For details, see text

parison exposes spatio-temporal differences in the erosion/deposition behaviour.

Site 1: Petsimjärvi

Petsimjärvi was the only levelling transect that showed consistent net deposition as the transect average during both observation periods (Table 3, Fig. 6a). The average net change of the surface elevation for the observation period 1993–1994 (365 days) was +4.5 mm with a standard deviation of 11.5 mm. For the whole 11-year observation period (1993–2004), the elevation change was +0.6 mm a^{-1}, with standard deviation of 4.8 mm (Fig. 6a). The largest changes have taken place at vegetated parts of the transect, for example around the 0.5-m-high embryo dune between *c*. 106 and 113 m along the transect supported by *Empetrum* and *Arctostaphylos*. The northern side of the hummock has experienced erosion, whereas the southern side has experienced net deposition, indicating gradual southward migration of the feature.

Site 2: Iijärvi

The total net change of the sediment surface along the Iijärvi during the one-year observation period was on average –11.7 mm. Of the 464 monitoring points, 351 points had encountered net erosion, and 113 points (24%) net deposition. For the 11-year period, the respective values were clearly smaller: average annual change –0.7 mm with 159 (34%) depositional points (Fig. 6c).

The deepest part of the blowout towards the NE from the benchmark at 175 m has experienced smaller changes than the more elevated portion towards the SW. Basically, unvegetated parts of the transect were deflated, whereas vegetated patches had experienced complex alterations from erosion to deposition between successive points. For example, a vegetated portion of the blowout between approximately 65 and 100 m from the northern end shows abundant small-scale variation both in the relief and the monitored changes. The vegetation consisted of lichens (e.g. *Cladina* spp., *Stereocaulon* spp. and *Solorina crocea*), mosses (*Polytrichum piliferum* and *Racomitrium canescens*), plus vascular species (*Festuca rubra*, *Juncus* spp., *Empetrum nigrum* subsp. *hermaphroditum* and *Arctostaphylos uva-ursi*) covering 70–80% of the sand surface. No wind ripples were detected on the sand surface during the measurements; instead the blowout was covered by reindeer hoof marks, suggesting quite stable conditions at present.

Anomalous changes in surface elevation have occurred at four sand hummocks with colonies of *Arctostaphylos uva-ursi* and *Empetrum nigrum* subsp. *hermaphroditum* between 175 and 230 m, especially during the one-year observation period (Fig. 6c). Erosion dominates at the elevated flat part of the blowout bottom, being highest along the steepest portions around 320 m and 375–400 m.

Site 3: Hietatievat

For the one-year period, the mean net deflation for the transect Hietatievat 1 was –17 mm with a standard deviation of 43 mm (Fig. 6b). Altogether 40 points (30%) of the total of 133 had encountered net deposition. The 11-year period showed an average annual change of –7.2 mm with standard deviation of 22 mm and 38 (29%) depositional points. The transect crosses an erosion remnant between 50 and 90 m. These remnants have escaped erosion due to the influence of individual mountain birches, whose roots support the sediment resulting in a miniature ‘butte’, or table hummock. The birch growing on top of the hummock is gradually buried and killed by the deposition of sediment from the surroundings. Eventually the birch dies, the root support disappears and the sediment hummock collapses. This process is currently taking place at a location 70 m along Hietatievat 1.

All three transects at Hietatievat showed clearly how the steep slopes of the sand mound are being eroded the fastest. The deflation takes place in the form of slope retreat with an approximate horizontal speed of up to 450 mm a^{-1}. Simultaneously with the slope retreat, the mound is being deflated at the unvegetated apex area.

Site 4:Pöyrisjärvi

Pöyrisjärvi 1 runs across the basin from west to east (85.5°N) consisting of 73 points at 1-m intervals. During the one-year period (1993–1994), most of the transect (56% of the observation points) had experienced net deposition resulting in a strongly positive average change of +7 mm, with a standard deviation of 29.5 mm. The 11-year period shows a rather different overall trend with only 11 (15%) depositional points, an average change of –12.7 mm a^{-1} and standard deviation of 15.5 mm (Fig. 6d).

Transect Pöyrisjärvi 2 runs almost perpendicular to the previous transect, towards the north (10.5°N) starting from the benchmark (Fig. 6e). The transect is devoid of vascular plants throughout its 207-m length. During the period 1993–1994, 60 observation points (29%) experienced net deposition. The average surface change for the whole transect was –2 mm with a standard deviation of 15.5 mm. Again, the 11-year period shows much more pronounced erosion with only 15 (7%) depositional points, and an average annual change of –25.1 mm, with standard deviation of 13.2 mm.

The results of the three transects at Pöyrisjärvi can be combined to provide an overall view of the sediment dynamics of the basin. Pöyrisjärvi 2 is located in the deep area of the basin, where the elevation is mostly 422–423 m a.s.l. This is the region of strongest erosion although currently the basal sand surface at the southern end is blanketed with mosses and lichens. Pöyrisjärvi 1 runs across the basin close to the southern end of transect 2. This middle area of the basin lies at around 425 m elevation and can periodically act as a sediment sink, as demonstrated by the sediment gain during the observation period 1993–1994. Pöyrisjärvi 3

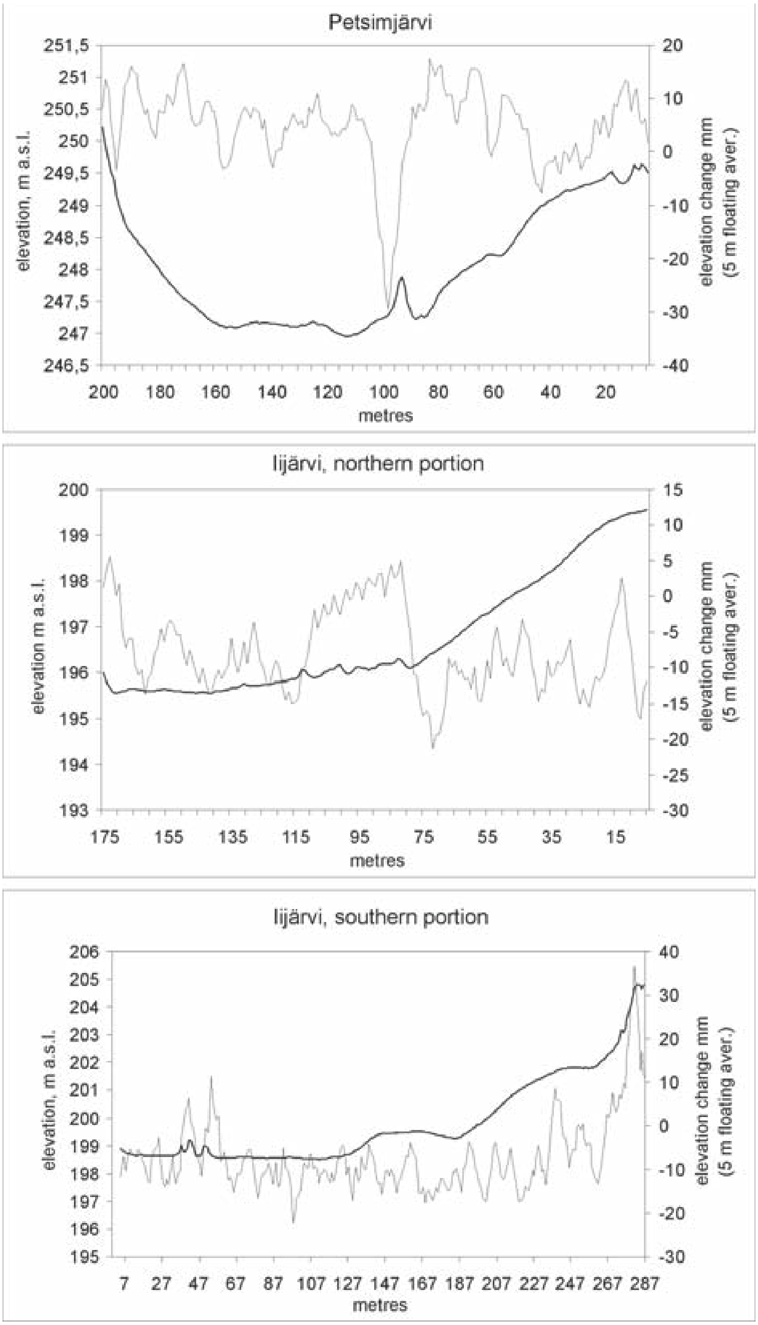

Fig. 7. Changes at Petsimjärvi and Iijärvi in 1993–1994, smoothed with 5-m moving average. Vertical scale is highly exaggerated (upper plot *c*. 21×, middle and lower *c*.13×). For Iijärvi south, the cyclicity is statistically significant at *c*. 4-m period as analysed by the Fourier method, whereas for Petsimjärvi, only long period (>20 m) cyclicity proved to be significant. For details, see text and Table 4

runs almost parallel to Pöyrisjärvi 2 towards the south from the benchmark and extends all the way to the southern margin of the basin. Most of the transect lies between 425 and 426 m altitude, i.e. 3 m higher than transect 2. The basin sustains net deflation at present. Taking into consideration the large size of the basin, the redeposited rim on the western margin of the blowout is unexpectedly small. As the larger rim would be expected to be found on the eastern side towards lake Kenttälom-

Table 4. Summary of the Fourier analysis results for the data period 1993–1994. If the Kolmogorov–Smirnov (K-S *d*) value is smaller than the equivalent K-S test value, the series is white noise. Conversely, the series may show genuine cyclicity. See text for further details

Data set	Interpreted section (m) from benchmark	*n*	Three strongest periods (m)	Periodogram values	K-S *d*	K-S *d* test value at p = 0.05	White noise or cyclicity
Test sighting		48	3, 4, 5	55, 49, 42	0.1344	0.19221	white noise
Petsimjärvi	1–199	198	66, 49, 19	2176, 1957, 1202	0.3005	<0.13403	cyclicity
	103–158	56	19, 2, 4	294, 266, 212	0.0947	0.17823	white noise
Iijärvi, north	18–78	60	4, 8, 12	427, 335, 317	0.0978	0.17231	white noise
	109–169	60	5, 4, 5	632, 173, 135	0.1476	0.17231	white noise
Iijärvi, south	56–264	208	4, 15, 2	990, 621, 602	0.1415	<0.13403	cyclicity
	61–135	74	4, 4, 5	767, 712, 532	0.1757	0.1554	cyclicity
Hietatievat 1	6–126	120	60, 30, 24	27660, 27194, 25913	0.6750	<0.13403	cyclicity
Hietatievat 2	24–56	32	32, 30, 24	1285, 469, 416	0.5086	0.23424	cyclicity
Hietatievat 3	27–47	20	4, 7, 5	5837, 2401, 1674	0.3987	0.29408	cyclicity
Pöyrisjärvi 1	9–68	60	30, 20, 9	2798, 2657, 1913	0.4679	0.17231	cyclicity
Pöyrisjärvi 2	55–149	94	10, 7, 6	555, 363, 211	0.2348	0.13818	cyclicity
Pöyrsijärvi 3	102–177	76	25, 38, 19	2573, 989, 871	0.4790	0.15342	cyclicity
	13–232	220	110, 44, 8	9486, 3641, 2705	0.3543	<0.13403	cyclicity

polot, this water body must act as a sediment sink for much of the material leaving the basin.

Interpretation of the levelling results

Local trends in the observed changes

Generally, changes over a one-year period showed substantially more variation than for the longer period. Some annual changes were quite dramatic, such as at Iijärvi, where almost 25 cm deflation had occurred at 227 m, with a similar amount of deposition just 5 m apart. For the 11-year period, the average annual change rates for these points were an order of magnitude smaller, a mere 2 cm. These observations demonstrate clearly that long observation periods will give a realistic view of the blowout net development, whereas shorter monitoring periods may give better insight to the actual processes operating in the sediment system (cf. Käyhkö, 1994b). Hence, these two types of data serve slightly different objectives.

In order to gain understanding of the sediment transport processes, the one-year data were investigated. The noise in the data was smoothed by the moving (floating) average method. From the different smoothing options available, the so-called Hamming window (Blackman and Tukey 1958) was used here with a window width of 5 units. The smoothing revealed an interesting, rather symmetrical sinusoidal change pattern especially on flat portions of the pearl necklace blowouts at Petsimjärvi and Iijärvi (Fig. 7). For Petsimjärvi, visual investigation of the smoothed net change curve revealed apparent peaks at approximately 20-m intervals in the northern portion of the basin, and for the unvegetated part of the southern portion. The transect can be divided into portions according to the net erosion/deposition pattern. Deposition has taken place mainly due to the dune nose portion of the long blowout chain acting as a sediment sink during westerly winds, receiving material from the long basin scoured from the left arm of the primary dune.

At the northern portion of the Iijärvi transect, a similar cyclicity in the erosion/deposition pattern is obvious, with peaks and troughs at approximately 11-m intervals. The pattern is less pronounced and more noisy in the upslope section of the transect, and the peaks and troughs occur at a higher interval, *c.* 5–7 m apart. For the southern part of Iijärvi, the moving average showed some cyclicity in the 5-m averages. For the reasonably flat portion of the blowout, the peaks (least erosion) in the smoothed net change curve seemed to occur at *c.* 15-m intervals. At the transition zone between the slope and crest on both sides of the gentle swelling between 120 and 170 m from the bench mark, the peaks seem to be suppressed or missing, but the cyclicity remains until the steeper portion of the slope, where it disappears.

Fourier analysis

Visual interpretation of the smoothed one-year data suggested that in some cases the erosion/deposition patterns show a degree of along-transect cyclicity. The spectrum analysis algorithm **fast Fourier transform** (**FFT**) was used to statistically verify the visual impression. The analysed data sets consisted of elevation changes at successive observation points between the years 1993 and 1994. As variable relief is liable to obscure airflow and bedform development, cyclicity similar to that on flat terrain cannot be expected to occur within such parts. Hence, instead of the whole transect length, only the relatively flat portions were incorporated in the analysis. Table 4 shows a summary of the analyses.

Petsimjärvi may seem to bear cyclicity under visual inspection (cf. Fig. 7), but Fourier analysis demonstrates that for the central portion (103–158 m), for example, the series is white noise (Table 4). In many cases, such as at Iijärvi, the cyclicity proved to be statistically significant, but the physical justification of the cyclicity is difficult to ascertain. One possible explanation is migration of large ripple-type bedforms (megaripples) along the transect. Such migration would, in theory, appear as cyclicity in high-resolution topographic data. This assumes that the observation interval is not coincident with the bedform migration speed of any multiple of the wavelength (i.e. the successive migrating ripple has not precisely replaced the previous one during the observation interval). A prerequisite to their detection, however, is that the movement of bedforms takes place parallel to the transect. As the transect orientation in each case was selected on the basis of basin form rather than, for example, effective wind direction, identifying the migrating bedform signal may fail even if such forms existed on the blowout. In the case of long pearl necklace blowouts (e.g. Iijärvi), the local wind direction is diverted parallel to the blowout and the transect by the surrounding relief.

Discussion

This levelling study of the changes in sand surface elevation demonstrates that the deflation basins in Lapland are generally being slowly eroded at present. At the local scale, the blowout basins consisted of erosional and depositional areas, and at Petsimjärvi, the average net change for the whole transect was positive. This can be explained by the position of the transect in an area of the blowout where sediment is being transferred and deposited. Much of the sand moved around by the wind cannot escape the basin due to the steeply concave form of the blowout. Consequently, some parts of the basins become temporary sediment sinks. This phenomenon reflects the mild wind climate and the steep secondary relief formed by the secondary rim deposits around the deflation basin. In general, it was the northern parts of the basins that proved to be the deepest, the only anomaly being Hietatievat. Hietatievat shows the most complex form of the deflation basins. It is rather obvious that blowout dynamics cannot be fully resolved with a two-dimensional transect approach, as this is a somewhat arbitrary sample of the complexity. A grid, covering perhaps the whole basin, would give a more comprehensive sample, and it would allow calculation on the transported sand volumes and the sediment budget of the whole basin. This approach, however, requires a much larger number of observation points and is probably best addressed using modern RTK-GPS techniques, for example.

The largest observed changes in the blowout surface were often related to local relief, such as small sand hummocks supported by vascular plants (*Empetrum* and *Arctostaphylos*). Also, steep slopes of the blowout edges experienced rapid changes, presumably due to aeolian and colluvial processes acting together. Flat portions of the basins experienced rhythmic erosion–deposition variation, which became obvious when the one-year data were smoothed with a 5-m floating average. The FFT analysis on the cyclicity showed that the majority of transects showed a cyclicity in the net elevation changes ($p = 0.05$) over the one-year period (Table 4). In many cases, the observed cyclicity frequencies were small, and the corresponding periodogram values large, covering from one-third to the whole transect length within one cycle. Such periodogram results were considered significant based on the Kolmogorov–Smirnov statistics, and they are believed to depict the typical pattern of change in the basins, i.e. one end suffering from deflation and the other end gaining sediment. Only the short periodicities of 4–5 m are believed to reflect the immediate processes, possibly small aeolian bedforms migrating along the transects. These periods were found at Iijärvi and Hietatievat 3. The size, as well as the migration rate, of such migrating bedforms is difficult to interpret based on the FFT analysis. As the form of typical aeolian bedforms does not follow either cosine or sine distribution, the value of the period should not be taken as representing the dimensions of the bedform (i.e. wavelength, amplitude).

A simple correlation analysis between the elevation difference of two successive points along the transect and the net change at the neighbouring points suggests a partial control of the process by microrelief. The highest correlation (0.42, significant with 95% confidence level) arose when comparing the elevation difference between two successive points (e.g. 1 and 2), and the change in elevation at a point 1 m to the south (e.g. point 3). This finding may suggest that the elevation change responds to the microrelief 1–2 m on the upwind side.

Typical areas of deposition within the studied basins included the toe areas of stoss slopes. The deposition here could possibly imply decrease in the shear stress in the case of upslope (often northerly) winds. However, the hypothesis of decreasing shear stress and accompanying sand deposition at the toe section of a dune has been disputed: for example Wiggs (1993), did not find evidence of such a process in his field studies either in Oman or subsequent laboratory wind tunnel experiments. In the present study, however, the wind climate is more variable, and the sand slope more gentle than in the case of a desert barchan. Consequently, the two examples cannot be compared directly.

This levelling study also revealed some regional differences in the blowout dynamics. The blowouts at Petsimjärvi and Iijärvi were less active than the ones at Hietatievat and Pöyrisjärvi (see Table 3 and Fig. 5). This finding must arise from a complex function of various interdependent parameters such as sediment type, blowout form, vegetation and wind climate. The pearl necklace blowouts experienced smaller changes than the tray blowouts. This is believed to be related to the degree of concavity of the basin. The gentle slopes of the secondary rims surrounding tray blowouts allow sediment to escape from the basin, whereas the steep and high rim deposits of pearl necklace blowouts efficiently trap the sediment inside the basin. Hence, despite the seemingly limited activity in terms of net changes, the basin may experience abundant sand movement inside the basin. Furthemore, the deep concave form also diminishes the shear stress at the sediment surface. A growing deflation basin becomes a semi-closed system with limited lateral or vertical growth.

Some proportion of the revealed differences in activity may be explained by vegetation. Sites inside the pine forest zone (Petsimjärvi and Iijärvi) suffer from less intensive deflation than the more exposed sites (Hietatievat and Pöyrisjärvi) outside the pine forest. This is an expected result, as forest very effectively hinders aeolian processes by slowing down the airflow at ground level. Pöyrisjärvi, with some 90% dwarf-shrub heath, also showed the highest activity. The levelling results support the idea of aeolian activity as a 'pinephobic' phenomenon in inland Lapland, clearly demonstrated in the satellite-based mapping of aeolian features (Käyhkö *et al.* 1999a).

Aeolian processes are known to show a high degree of temporal variation. This quality makes it difficult to extrapolate results in space or time. In the present study the two observation periods give somewhat contradictory change patterns (Table 4). In some localities (e.g. Hietatievat 2, Pöyrisjärvi 3) the changes are in concordance, whereas in others (e.g. Pöyrisjärvi 1 and 2) the two periods show substantially different development. A longer period gives more consistent and smooth changes with smaller standard deviations. Dating results from the studied blowouts (Clarke and Käyhkö 1997, Käyhkö *et al.* 1999b) demonstrate that the basins have existed for centuries or even millennia. At Iijärvi, for example, at least three buried soil horizons can be found in the secondary rim deposits demonstrating cyclic periods of activity and inactivity. **Infra-red stimulated luminescence** (**IRSL**) dates from buried sediment horizons across Lapland suggest that the latest, current phase of aeolian activity commenced 930–350 years ago (around AD 1100–1650) across Lapland, possibly due to climatic deterioration (the Little Ice Age). For the blowouts investigated here, the IRSL ages from the base of the youngest redeposited beds at secondary rims are as follows (Käyhkö *et al.* 1999b): Petsimjärvi 580 ± 55 years, Iijärvi 580 ± 55 years, Hietatievat 560 ± 55 years and Pöyrisjärvi 390 ± 40 years. These ages fit well with the commonly found maximum blowout depth of 4–6 m and the present-day average net deflation rate of <1 cm a^{-1}. There is naturally no reason to assume that the deflation rates would have been constant through time. Future climate change is expected to encourage forest growth and advance the pine forest line in Lapland (Mikkola and Virtanen 2006). Based on the historical data on aeolian activity in Lapland, the present-day distribution of aeolian processes and the results from this study on the blowout dynamics, the projected climatic warming will probably suppress aeolian activity in this region.

Conclusions

Based on the 11-year observation period of aeolian processes using tachymeter levelling along transects on selected deflation basins, the following conclusions related to blowout dynamics in Lapland can be made.

1. On a decadal average, the deflation rate of the studied basins was 9 mm a–[1]
2. Positive changes (net deposition) had taken place at 30% of the total number of 1439 observation points. Due to the steep concave relief of the blowouts, approximately one-third of the basin area acts as a temporary sediment sink, whereas roughly two-thirds is being eroded more or less continually.
3. Pearl necklace blowouts, with their deep concave form, efficiently hinder sediment from escaping the basin. They show less activity than the shallow tray blowouts, demonstrating the semi-closed sedimentary system of mature blowouts.
4. Symmetrical, smooth basins (Petsimjärvi, Iijärvi) showed more consistent changes than basins with complex form (Hietatievat), indicating that internal factors substantially affect the blowout evolution in the Lapland climatic range.
5. The deepest part of a blowout is generally located in the upwind end (in the study area often the northern end) with respect to the effective wind direction. These areas may show stability at present due to the closeness of the water table and/or exposed resistant fine sediments.
6. Strongest deflation often takes place at steep slope angles, for example around the 'butte' type erosion remnants, which will eventually be eroded away.
7. Deposition often occurs in relation to change in slope angle, possibly indicating a local decrease in shear stress (kink upslope) or flow separation (kink downslope)
8. Data smoothing by the floating average method with Fourier analysis suggests that at flat surfaces, the observed erosion/deposition shows along-transect cyclicity. In cases where the wavelength was a few metres (typically in the order of 4 m), the cyclicity may reflect the slow movement of small migrating bedforms (megaripples) parallel to the transect. A long period was interpreted as reflecting the general blowout dynamics, one end of the basin suffering from deflation, the other end experiencing net deposition (see point 5 above).
9. The observed long-term mean changes on different blowouts and their relation to land cover type suggest that deflation processes become more intensive with decreasing pine density (i.e. in the mountain birch scrub and tundra).
10. The approximate age (*c.* 500 years) and depth (*c.* 5 m) of the studied blowouts correspond well with the average deflation rate of *c.* 1 cm a^{-1}

Acknowledgements

This work was initiated in the early 1990s as part of PhD research by the author at the University of Reading. It has been funded by the British Council, Emil Aaltonen Foundation, The Academy of Finland (projects 1012238 and 2247), Maj and Tor Nessling Foundation, Alfred Kordelin Foundation, University of Helsinki and University of Turku Foundation. Invaluable help in the field was given by Dr Steve Gurney and Mr Sakari Palo. This work was initiated in the early 1990s as part of PhD research by the author at the University of Reading, supervised by Dr Ken Pye and Prof. Peter Worsley.

J. Käyhkö, Department of Geography, University of Turku, FI-20014 Turku, Finland

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Manuscript received Oct. 2006, revised and accepted Nov. 2006.