

RESEARCH/REVIEW ARTICLE

Aeolian processes and landforms in the sub-Antarctic: preliminary observations from Marion Island

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Marion Island; climate change; wind; erosion; dispersal.

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E-mail: heddidw@unisa.ac.za**Abstract**

Sub-Antarctic Marion Island has a hyperoceanic climate, with cold and wet conditions and consistently strong wind velocities throughout the year. Recent observations recognized the increasing role of aeolian processes as a geomorphic agent, and this paper presents the first data for transport by aeolian processes on a sub-Antarctic island. Data were collected through an intensive and high-resolution measurement campaign at three study sites using Big Spring Number Eight sediment traps and surface sediment samplers in conjunction with an array of climatic and soil logger sensors. Observed aeolian landforms are megaripples, and the data suggest that aeolian processes are also modifying solifluction landforms. The sediment traps and sediment samplers collected wind-blown scoria at all three study sites, and the annual (horizontal) aeolian sediment flux extrapolated from this preliminary data is estimated at $0.36\text{--}3.85\text{ kg cm}^{-2}\text{ y}^{-1}$. Importantly, plant material of various species was trapped during the study that suggests the efficiency of wind for the dispersal of plants in this sub-Antarctic environment may be underestimated. This paper advocates long-term monitoring of aeolian processes and that the link between aeolian processes and synoptic climate must be established. Furthermore, wind as a means to disperse genetic material on Marion Island should be investigated.

Although winds in cold (periglacial) environments tend to be much stronger and more persistent than those in hot desert regions (Bateman 2013), very little research has been done on wind as a geomorphic agent in cold environments (see McKenna Neuman 1993; Seppälä 2004; Bullard 2013). André (2003) suggests that wind accounts for between <2% and <13% of erosion in periglacial environments but again data are limited. Furthermore, research on aeolian processes and landforms in the sub-Antarctic has typically been limited to descriptive observations of the landforms (e.g., Löffler 1984; Adamson et al. 1988; Holness 2001a; Callaghan 2005; Hedding 2008), while the only process study used erosion pins to measure rates of wind and water erosion of an exposed area of peat and sand on Macquarie Island (Selkirk & Saffigna 1999).

Aeolian landforms on Marion Island ($46^{\circ}54'S$, $37^{\circ}45'E$) appear to be limited to areas that comprise well-drained volcanic (scoria) sediments in relatively flat areas, which are particularly exposed to the wind through the local topography (Verwoerd & Lagengger 1968).

Consistently high wind velocities throughout the year coupled with declining precipitation (Le Roux 2008), increasing mean annual temperatures (Smith 2002) and a receding snowline (Smith 2002; Sumner et al. 2004) on Marion Island over the past 40 years may, in the future, influence aeolian processes on exposed surfaces devoid of vegetation (Boelhouwers et al. 2008; Hedding 2008). Aeolian processes may also increasingly modify periglacial landforms (Hall 1979; Holness 2001a, b; Hedding 2008) as periglacial processes wane under climatic amelioration

(Sumner et al. 2004). However, aeolian sediment flux is yet to be assessed, and no quantitative studies on aeolian sediment transport have been conducted thus far in the sub-Antarctic. Given this paucity of data, this paper will present preliminary findings on aeolian sediment transport and the geomorphological characteristics of aeolian landforms on sub-Antarctic Marion Island. Moreover, the implications for the dispersal of plants and invertebrates through wind and the consequences of possible future climate change will be specifically addressed.

Environmental setting

Situated in the “Roaring Forties,” Marion Island represents the tip of an oceanic interplate volcano (McDougall et al. 2001), which is still volcanically active (Hedding 2008). The island is characterized by a hyperoceanic climate with cold and wet conditions (Boelhouwers et al. 2003) and experiences consistently strong wind velocities throughout the year (Le Roux 2008). It has a distinct periglacial environment (Boelhouwers et al. 2003), and the landscape is dominated by relict glacial and periglacial landforms (Boelhouwers et al. 2008). The first volcanic period, during the Pleistocene, produced grey-coloured lavas that have been glaciated whilst the second period, during the Holocene, is represented by black-coloured lava and scoria cones that show no sign of glaciation. The approximately 130 scoria cones scattered around the island result from the most recent phase of volcanic activity (Verwoerd 1971). The island surface is therefore characterized by extensive areas of black lava and scoria cones, grey lava moraines and tills from earlier glaciations (Sumner 2004).

Pedogenesis on Marion Island is limited (Gribnitz et al. 1986; Lubbe 2010), but cohesionless volcanic (scoria) materials, with their high permeability (Boelhouwers et al. 2008), may be extremely susceptible to transport by wind. Meteorological observations at the scientific station on the eastern coast of the island indicate that winds mostly originate from a westerly to north-westerly direction, which is related to the predominant synoptic conditions (Le Roux 2008; Nel et al. 2009; Nel 2012). Winds measured 5 m above the ground at the research station are generally very strong, with an average daily velocity of 8.4 m s^{-1} , while gusts of up to 55 m s^{-1} have been recorded (Hall 1979). Gales exceeding 18.3 m s^{-1} often last 10 hours. Wind plays an important role in the desiccation of the ground on Marion Island (Holness 2001a), which may affect pedogenesis, vegetation growth and soil frost formation and can increase the likelihood of transport of particles. The total annual precipitation has decreased approximately 45% from its peak in the 1960s at an average of 2726.9 mm to

an average of 1876 mm in the 2000s; 2011 is the driest year on record (1671.4 mm). A 50% increase in the maximum duration between rainfall events (from an average of four to six days) identified by Le Roux & McGeoch (2008) is also significant for aeolian processes.

Study sites and methods

Three sites with evidence of aeolian processes were selected to investigate aeolian sediment flux on Marion Island: two sites, nearer to the coast, at altitudes of 205 m a.s.l. (Mesrug) and 244 m a.s.l. (Third Sister) and a third site (Katedraalkrans) at a higher altitude of 750 m a.s.l. (Fig. 1). The aeolian landforms on Marion Island typically take the form of ripples in lag gravels and deflation hollows (Hedding 2008). Although aeolian processes are slowed in the central highland of Marion Island because of persisting snow cover and seasonal freezing of the ground, aeolian landforms are nevertheless present (Hedding 2008). Needle-ice development produces surfaces that are aerodynamically rough and highly susceptible to deflation following a thaw (McGowan 1997).

An intensive ground climate and sediment flux measurement campaign was implemented during part of April/May 2013. Local meteorological conditions were monitored at 0.5 m above the surface. Wind speed, wind direction and rainfall were monitored at one-minute intervals using Pace Scientific (Mooresville, NC, USA) sensors and recorded on Pace Scientific XR5 data loggers. A Sensit (Redlands, CA, USA) H14-LIN Wind Eroding Mass Flux (piezoelectric) sensor was installed at the Mesrug and Third Sister sites to investigate the threshold wind velocity for the entrainment of sediment, but interference from consistent but intermittent rainfall made it impossible to separate impacts from saltating sediment particles and rainfall droplets. Aeolian sediment flux was monitored at each site using a minimum of two wedge-shaped Big Spring Number Eight (BSNE) omnidirectional samplers (Custom Products, Big Spring, TX, USA) based on the design of Fryrear (1986). Shao et al. (1993) report that BSNE sediment traps have an overall sampling efficiency of $90\% \pm 5\%$ for aeolian and sand-sized particles. The wind-aspirated BSNE sediment traps were installed 0.05 m above the surface in the windward sections of ripples. BSNE sediment traps were mounted to pivoting wind vanes just above the ground surface because observations by Hedding (2008) suggest that sediment is not entrained higher up in the airstream. Wind-aspirated surface sediment creep/saltation traps (Custom Products, Big Spring, TX, USA) were also installed at the Mesrug and Third Sister sites to assess surface creep. Horizontal mass flux or the amount of soil passing by a unit area of a vertical

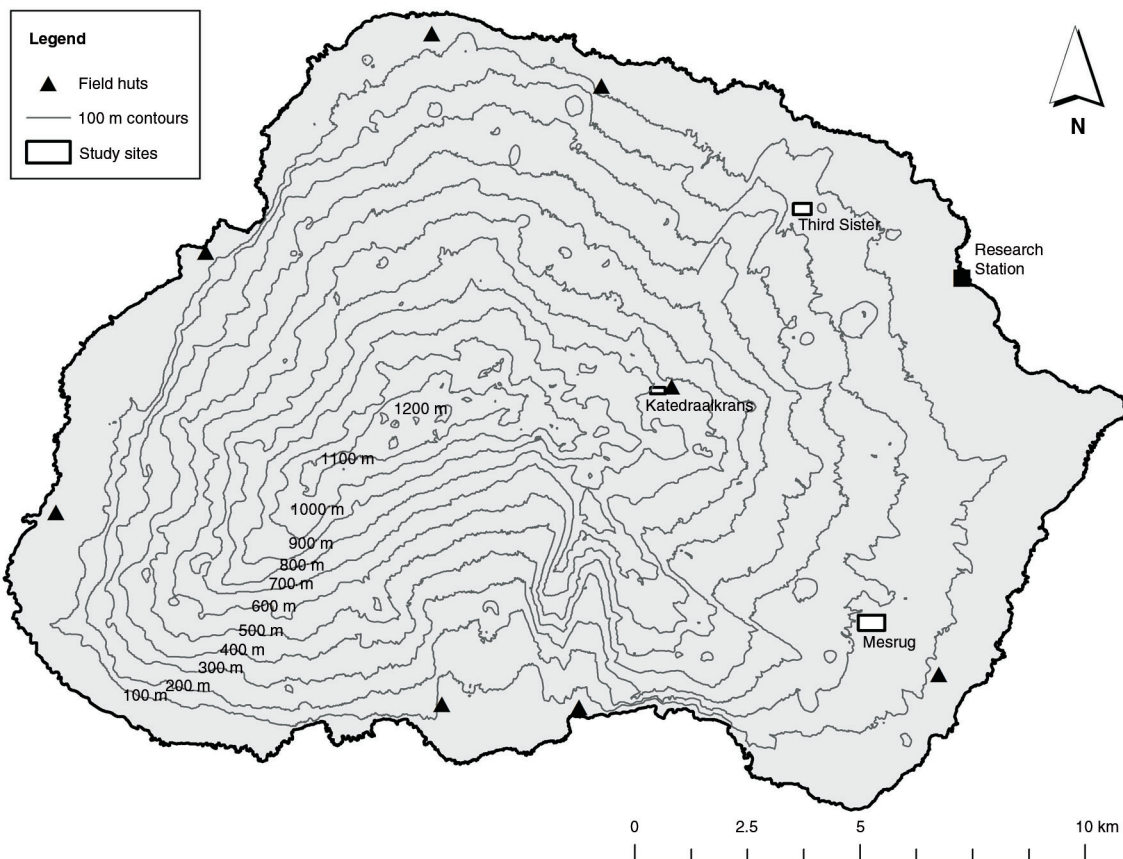


Fig. 1 Location of study sites on Marion Island.

plane in each individual sampler (g cm^{-2}) was calculated following the method of Mendez et al. (2011) so that:

$$b = x/c, \tag{1}$$

where b is the horizontal mass flux, x is the amount of material and the area of the sampler opening is c . Aeolian sediment flux, q ($\text{kg cm}^{-2} \text{h}^{-1}$), was determined at each site by adapting the methodology of Speirs et al. (2008), where:

$$q = d/a/t \tag{2}$$

This method standardizes the mass of material collected in each trap (d) to the area of the sampler opening (a) and the duration (hours) of the measurement period (t).

Sampling for texture analysis was systematic, and samples were taken from different parts of ripples and evenly spread out along sediment patches. The orientation of the ripples was recorded at all of the study sites. The amplitude and wavelength of the ripples were measured on three transects at each of the study sites in order to investigate their association with the prevailing wind direction. Textural analyses were done on all samples using the

sieve method as described by Goudie (1981). Texture histograms and cumulative texture graphs were compiled, and then used to calculate parameters such as the phi mean, phi median, sorting, skewness and kurtosis (Briggs 1977). Differences in texture at various segments on the landforms and between sites were compared.

Results and observations

Most of the landform segments sampled display poor sorting and are positively skewed (Table 1). Briggs (1977) indicates that a positively skewed distribution is one in which greater amounts of fine material occur. The skewness data presented in Table 1 indicates that, in relative terms, a greater percentage of fines can be found in the lee of the Mesrug and Third Sister landforms. Cumulative percentages of particle size indicate that the risers of the forms at Third Sister and Katedraalkrans comprise the coarsest material whereas the crests of the landforms at Mesrug comprise the coarsest material (Fig. 2). These findings can be associated with the predominant wind direction observed at each site.

Table 1 Summary of the particle size analysis of the sediment of the landforms surveyed at each study site.

Feature segment (wind direction)	Third Sister			Katedraalkrans			Mesrug		
	Crest	Riser (windward)	Tread (leeward)	Crest	Riser (leeward)	Tread (windward)	Crest	Stoss (windward)	Lee (leeward)
Phi median	-2.20	-2.90	-1.09	-2.75	-3.25	-1.03	-3.11	-1.90	-1.71
Phi mean	-2.18	-2.88	-0.96	-2.66	-3.18	-0.60	-2.88	-2.08	-1.59
Skewness	0.05	0.19	0.44	0.27	0.28	0.28	0.20	-0.06	0.43
Description	Near symmetrical	Positively skewed	Very positively skewed	Positively skewed	Positively skewed	Positively skewed	Positively skewed	Near symmetrical	Very positively skewed
Sorting	1.58	1.48	1.88	1.34	0.84	2.75	1.67	1.51	1.76
Description	Poorly sorted	Poorly sorted	Poorly sorted	Poorly sorted	Moderately sorted	Very poorly sorted	Poorly sorted	Poorly sorted	Poorly sorted
Kurtosis	0.97	1.15	1.51	1.00	0.98	0.84	0.78	0.99	1.41
Description	Mesokurtic	Leptokurtic	Very leptokurtic	Mesokurtic	Mesokurtic	Platykurtic	Platykurtic	Mesokurtic	Leptokurtic

The largest and best-defined aeolian landforms on Marion Island are found in fine-grained volcanic scoria at the Mesrug study site that is near-horizontal and largely devoid of vegetation. These landforms exhibit an average height of 0.22 m, have a mean ripple spacing of 3.82 m and are sinuous in plan-form. The landforms at Mesrug exhibit longer shallow stoss (upwind) and short steeper lee (downwind) segments with average gradients of 7.9 and 15.5 degrees, respectively. The stoss and lee segments of the Mesrug landforms are rectilinear and slightly concave, respectively (Fig. 3). The surfaces of the crests are armoured with courser material, and the data suggest that these landforms are aeolian in origin. These aeolian bed forms are defined as megaripples (see Zimelman et al. 2012) and are formed when the wind is strong enough to remove the smaller sand-sized particles through saltation. It is suggested that rain may play an ancillary role to translocate particles downward coarsening the particle size distribution of the surface material.

Cumulatively, the data suggest that the landforms at Katedraalkrans and Third Sister represent wind-modified forms of solifluction terraces in scoria. The windward (stoss) side of the forms at Third Sister represents the risers (downslope) side of the solifluction terraces and material is blown upslope, whereas the windward side of the forms at Katedraalkrans represents the treads (upslope) of the terraces and material is blown downslope (Fig. 3). The risers and treads of the wind-modified solifluction landforms at Katedraalkrans and Third Sister are slightly convex and rectilinear in cross profile (Fig. 3). Interestingly, some Pleistocene grey lava boulders located where the wind is funnelled by the local topography near the Katedraalkrans study site represent rudimentary ventifacts, with some evidence of abrasion and etching.

BSNE sediment traps collected a total of 0.5, 3.2 and 4.1 g of sediment at the Third Sister, Katedraalkrans and Mesrug study sites, respectively. Particles in the traps range in size from fine gravel to fine sand. Seeds from several species of flora, including *Acaena magellanica*, *Azorella selago*, *Poa cookie*, *Poa annua*, *Agrostis magellanica* and *Agrostis stolonifera*, were also collected in the traps. Table 2 summarizes the wind characteristics, average horizontal mass flux (g cm^{-2}) and aeolian sediment flux ($\text{kg cm}^{-2} \text{h}^{-1}$) recorded at each study site. The maximum average wind speed and wind gust measured at 0.5 m above ground level were 7.6 and 21.6 m s^{-1} , respectively, and were both recorded at the Mesrug study site. No major storms moved over Marion Island during the study period, so the average wind speed was marginally lower than the yearly average. Surface sediment creep/saltation samplers installed at the Mesrug and Third Sister study sites collected a total of 0.3 and 0.2 g of sediment, respectively (Table 3).

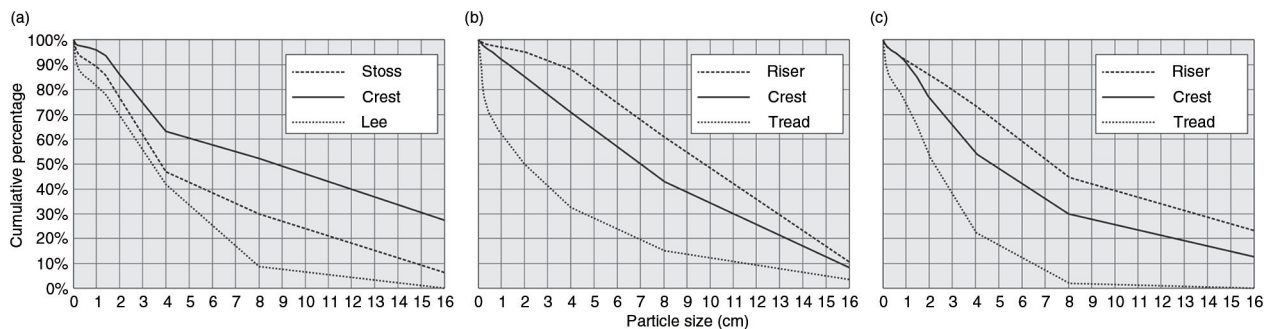


Fig. 2 A comparison of the particle size distribution of (a) the aeolian megaripples at Mesrug and the modified solifluction terraces at (b) Katedraalkrans and (c) Third Sister. Note the higher percentage of coarse material in the crest of the Mesrug megaripples with the risers of the solifluction terraces at Katedraalkrans and Third Sister.

These values may be unrepresentative because the width (5 mm) of the opening of the surface sediment creep/saltation samplers may prevent the collection of the relatively coarse particles on Marion Island. The particle size distributions of the surface lag gravels at Mesrug and Third Sister (Table 2) suggest that most particles less than 1 mm have been removed by the wind or rain moving finer particles downward. When assessed in conjunction with the average wind speed at the two sites (7.4 m s^{-1}), this supports the suggestion of Bateman (2013), that the transportation of fine to medium sand ($125\text{--}500 \text{ }\mu\text{m}$ diameter) typically require wind speeds of $5\text{--}8 \text{ m s}^{-1}$. The calculation of the aeolian sediment flux shows that the highest rate of sediment transport occurs at Mesrug ($3.85 \text{ kg cm}^{-2} \text{ y}^{-1}$), and the site at Mesrug exhibits the largest aeolian landforms (megaripples) on Marion Island (Fig. 4).

Discussion

Previously, Gribnitz et al. (1986) doubted the existence of aeolian processes on Marion Island. Aeolian processes may have been limited on the island in the past on account of the perennially wet conditions that resulted in damp

substrate conditions, protection of sediment from snow cover and seasonal frost cementing fine particles. The climate of Marion Island has, however, changed significantly over the last 30 years, with recorded increases in sunshine hours, pressure and temperature, together with a reduction in rainfall (Le Roux 2008). This recent climatic amelioration has resulted in declining snow cover in spatial extent and temporal persistence (Sumner et al. 2004). The increased persistence of clear skies could increase the potential for soil frost and its direct effects on soil sediment displacement (Nel 2012), particularly through aeolian processes. Therefore, although the observed aeolian landforms reflect current climatic conditions, receding snow cover, reducing rainfall and increasing temperature, which cumulatively increase sediment availability for transport, may lead to the intensification of aeolian activity on Marion Island in the future.

Bateman highlights that “elevated windiness (both in terms of speed and duration), combined with more efficacy of sediment transport in colder temperatures, means a higher potential for aeolian processes to play a substantial role in shaping landscapes” (2013: 427). The winds on Marion Island winnow out the fine fraction of the poorly to moderately sorted sediment, so that a lag develops on

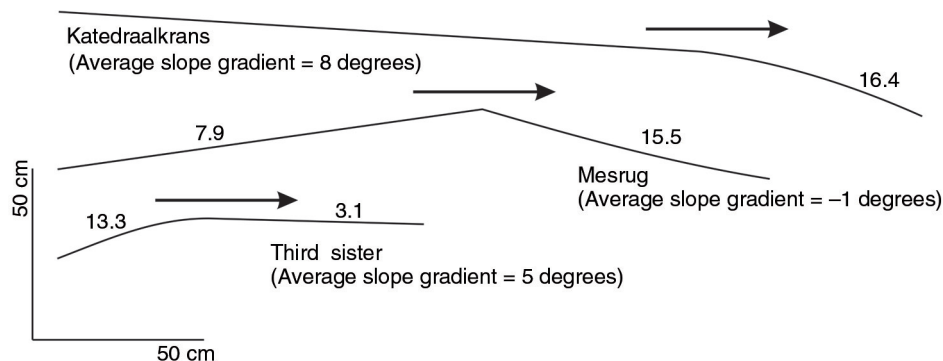


Fig. 3 Cross profile of average landform morphology. Arrows indicate the predominant wind direction over the crest of the landforms.

Table 2 Wind characteristics and aeolian sediment flux for the study sites during the study period in 2013. Traps mounted at 0.05 m above the surface.

Site (m a.s.l.)	Measurement period (hours)	Mean ripple orientation	Mean wind direction, 0.5 m	Mean wind speed, 0.5 m (m s ⁻¹)	Maximum wind gust (m s ⁻¹)	Average sand trap mass (g)	Average horizontal mass flux (g cm ⁻²)	Aeolian sediment flux (kg cm ⁻² h ⁻¹)	Annual aeolian sediment flux (kg cm ⁻² y ⁻¹)
Mesrug (205)	17 April–6 May (467)	N–S	233.3	7.6	21.6	2.05	0.205	0.000439	3.85
Katedraalkrans (750)	19 April–4 May (369)	N–S	230.4	4.7	15.2	1.07	0.107	0.000290	2.54
Third Sister (244)	20 April–7 May (417)	WNW–ESE	273.4	7.3	18.4	0.17	0.017	0.000041	0.36

the surface; comparable to the observation of McKenna Neuman (1990). Strong winds, acting in combination with near-surface cryoturbation (frost heave and needle-ice growth), scour exposed areas and produce a distinctive form of megaripples (Ballantyne & Whittington 1987). Similar to Ballantyne (1984), these landforms are particularly evident in lag deposits where sediment is cohesionless. It is believed that fine sediment availability on Marion Island is further enhanced by surface processes like frost heave and needle-ice.

A tentative comparison of the annual aeolian sediment flux extrapolated from this preliminary data for sub-Antarctic Marion Island of 0.36–3.85 kg cm⁻² y⁻¹ with Victoria Valley, Antarctica at 8–5000 kg m⁻¹ y⁻¹ (e.g., Speirs et al. 2008) and Iceland at 100–1000 kg m⁻¹ y⁻¹ (e.g., Arnalds et al. 2012) reveals that the annual aeolian sediment flux at Marion Island seems to be relatively low. Presented rates of sediment transport on Marion Island may be marginally lower than could be expected since the average wind speed was lower than the yearly average and no severe storms with intense wind speeds occurred during the study period. Severe storms with gale-force winds are typically significant for aeolian transport because of the power relationship between aeolian sediment flux and wind speed (e.g., Bagnold 1941). However, in the sub-Antarctic, severe storms are accompanied with rain and/or snow that could limit aeolian processes. Therefore, the influences of severe storms on aeolian processes in the sub-Antarctic should be studied in more detail.

Born et al. (2012) indicate that despite the high frequency of gale-force winds on Marion Island (occurring on >100 days per annum), gene dispersal distance

estimates are surprisingly low (<10 m). This is attributed to frequent precipitation and high humidity that may considerably reduce pollen clouds and accelerate floral dehiscence, respectively (Born et al. 2012). Also high wind velocities are typically associated with cold fronts that bring precipitation, limiting their effectiveness to transport pollen. Nevertheless, plant material (including seeds) was collected in the BSNE sediment traps at all of the study sites. It must be noted that the Mesrug study site is approximately 80–100 m downwind from the nearest vegetation, while the Katedraalkrans site is above 750 m a.s.l. in an area that is largely devoid of vegetation (Huntley 1970; Le Roux 2008). This demonstrates the efficacy of the wind to disperse plant material through saltation and suspension over long distances and even during periods of precipitation, which suggests that previous gene dispersal distance estimates (Born et al. 2012) may have been underestimated.

Conclusion and further research

Preliminary results of aeolian sediment transport rates are reported for sub-Antarctic Marion Island. Aeolian landforms described in this paper represent megaripples, reptation and creep processes, with a second type being wind-modified solifluction terraces. As expected, preliminary data on aeolian sediment transport on Marion Island suggest that it is less than in other polar and sub-polar regions where sediment transported by wind has been reported. Observations indicate that this could be due to consistently wet surfaces and the lack of appropriate sediment for transport. Nevertheless, the data

Table 3 Surface sediment creep/saltation collected at the study sites during the study period. The samplers were installed level with the surface.

Site (m a.s.l.)	Measurement period (hours)	Total mass of surface creep/saltation (g)	Mass (g) of sediment (sampling height 0–3 mm)	Mass (g) of sediment (sampling height 3–10 mm)	Mass (g) of sediment (sampling height 10–20 mm)
Mesrug (205)	17 April–6 May (467)	0.3	0.1	0.1	0.1
Third Sister (244)	20 April–7 May (417)	0.2	0.03	0.1	0.07



Fig. 4 Megaripple landforms at the study site near Mesrug, Marion Island. The staff is 1.2 m long (photograph taken on 20 April 2013).

indicate that aeolian processes are effective mechanisms to transport sediment and plant material in this wet, periglacial environment.

The climate of Marion Island has changed significantly over the last 30 years, and indications are for further change that is driven by changes in the synoptic weather systems (Smith & Steenkamp 1990; Rouault et al. 2005). However, no data exist at this location on the relationships between synoptic climate, threshold wind speeds that initiate material movement, and aeolian sediment fluxes. Furthermore, long-term monitoring of aeolian processes is needed to thoroughly compare the aeolian processes and sediment fluxes described here with those found in other polar and sub-polar areas (e.g., Löffler 1984; Speirs et al. 2008; Arnalds et al. 2012; Gillies et al. 2012; Bullard 2013; Gillies et al. 2013). Finally, wind as a means to disperse genetic material on Marion Island must be investigated and, as suggested by McKenna Neuman (1990), some consideration should be given to modifying conventional instrumentation and techniques to operate under the prevailing conditions in this sub-Antarctic environment.

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