Earth science research on Marion Island (1996-2020): A synthesis and new findings

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Abstract

Marion Island is a peak of a shield volcano located in the southern Indian Ocean. Annexed by South Africa in 1948, the island has been strategically important for the collection of climatological data and marine and terrestrial research in a vast, oceanic region of the globe. This paper reviews the series of earth science programmes on Marion Island over the last 25 years, provides a synthesis of the research outcomes and demonstrates how field and laboratory methods have developed over time. Marion Island has, globally, one of the most active soil frost environments in a distinctive periglacial setting and understanding this contemporary periglacial environment has been a key objective of the research programmes., Geomorphological processes have important implications for local ecosystem functioning and define the regional and global significance for diurnal soil frost environments and climate change. The review presented here shows that keeping abreast with the advancements of appropriate methodologies and technologies and the continued employment of a mix of new and established methods has driven the earth science research in this unique island environment. A series of short vignettes present the most recent advancements on old key questions and indicate that new techniques continuously challenges us to re-evaluate the most basic of assumptions that exist within our research.

Keywords: Marion Island, Geomorphology, Earth Science, Climate Change, Recent technologies

Introduction

Marion Island is a 293 km^2 summit of a shield volcano located in the southern Indian Ocean (46°54′S, 37°45′E). The island comprises of basaltic “grey” lavas dating from 50-450 kya BP overlain by Holocene “black” lavas and scoria cones (McDougall, Verwoerd, & Chevallier, 2001). Located in the so-called roaring forties just north of the Antarctic Polar Convergence, the island and its smaller companion, Prince Edward Island (46km^2) have a hyper-maritime, periglacial setting (Boelhouwers, Holness & Sumner, 2003). Observations from the 1950’s noted a permanent snowline at ~600m and ice at the summit, but the snowline has since receded and by the early 2000’s the ice had mostly melted (Sumner, Meiklejohn, Boelhouwers, & Hedding, 2004). Striations and grey lava moraines that extend down to the coastal areas are evidence for glacial events that predate the black lavas and scoria. Mires and a few streams characterise the lower slopes and sites of windblown scoria are testament to the strong winds that beset the island for much of the year.

Annexed by South Africa in 1948, Marion Island was used for the collection of climatological data from the late 1940’s (Chown & Hanel, 1998) and for marine and terrestrial research from the 1960’s. Prince Edward Island was inaccessible and remains so for earth science research. A consecutive series of earth science programmes based on Marion Island were first conceived in the mid-1990’s and continued, mostly uninterrupted, over 25 years to the present. Categorised broadly as Earth Science by the South African National Antarctic Programme (SANAP), the programmes encompassed aspects of geomorphology and environmental change, including periglacial- and palaeo-geomorphology, glacial reconstruction, rock weathering, contemporary and Holocene climate change, biogeomorphology, hydrochemical river dynamics as well as geology and volcanism. This review provides a synthesis of the research programmes and demonstrate how field and laboratory methods have developed over time. Then, in a series of short vignettes, new findings show how the island continues to provide new answers to old questions.

Synthesis of the programmes (1996-2020)

Prior to the 1990's, earth-science research on Marion Island focussed on geology (Verwoerd, 1971; Verwoerd, Russel, & Berruti, 1981), Quaternary-glaciology (Hall, 1978; 1980; 1982) and periglacial processes (Hall, 1979; see also Hall, 2002 for a review). Much of the work, undertaken under challenging field conditions, was descriptive in nature (Boelhouwers, Meiklejohn, Holness, & Hedding, 2008) but conformed to the norm for field studies and their palaeo-environmental interpretation of the times. No field based earth science projects were pursued from 1980 up until 1995 and the programmes that followed from 1996 can be broadly divided into the first decade (1996-2005) and the second period (2006-present) where there was a significant upscaling in personnel and budget.

Getting started: 1996-2005

A SANAP research programme entitled: *Cryogenic processes on Marion Island* commenced in 1996 and ran until 2000. Initially, the research was introduced to contrast with, and better understand, the paleoenvironmental periglacial record and current processes in southern African mountains. It was recognised early that Marion Island provided an active diurnal frost environment (Holness, 2001) where the maritime location and volcanic geology created a setting distinctive from the more continental southern African mountains. Environmental monitoring could for the first-time record ground temperatures along an altitudinal gradient and established high-frequency, low-intensity diurnal freeze-thaw cycles in a climate of low mean-annual temperature and low seasonal and diurnal temperature ranges (Holness & Boelhouwers, 1998; Holness 2001). As opposed to southern Africa, the high number of precipitation days does not constrain segregation ice formation in the soil and that the late Pleistocene glacial sediment, covering so-called grey lava surfaces, is uniformly highly susceptible to needle ice and surficial ice lenses (Holness, 2001) (Fig. 1a).

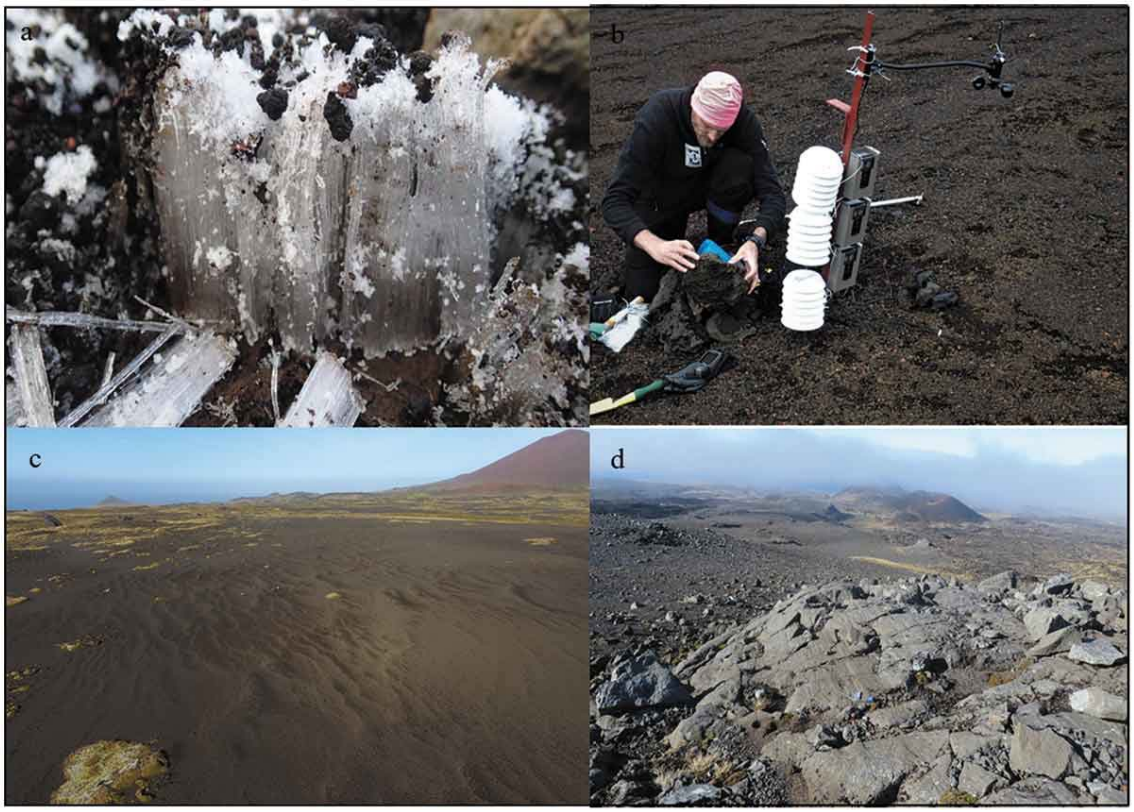

Figure 1. Selection of photos that show (a) needle ice on Marion Island supporting coarse material and growing out of a finer substrate. (b) Surface and subsurface ground temperature measuring station at Katedraalkrans, Marion Island. Note the Bushnell cameras for time-lapse photography. (c) Oblique aerial view of the Mesrug aeolian study site, Marion Island. (d) Striated glacially moulded grey lava bedrock at Tafelberg, Marion Island.

Marion Island and similar small landmasses in the mid-latitudinal Southern Hemisphere register were found to be some of the most active soil frost environments on the planet (Holness, 2004). In the field, measurement of air and soil temperatures were done through automated loggers, while measurement of sediment movement rates through simple painted stone markers and wooden dowels proved that surface sediment movement rates were some of the highest recorded globally (Holness, 2001; Holness, 2004). Through these simple methodologies and the use of high-tech (for the time) temperature loggers, the research on Marion Island, southern African mountains and elsewhere established the first characterisation of a global diurnal soil frost environment, conceptually parallel to seasonal frost and permafrost environments. In order to validate the results from Marion Island on climate-process-landform relationships in other environments, and the capacity to model diurnal frost process responses to climate change at the landscape scale, the environmental boundary conditions and mechanisms of soil frost and, specifically needle ice growth, needed to be known.

A second cycle of funding commenced in 2002, after a brief hiatus in 2001, under the auspices of the programme *Environmental responses to climatic change*. The main research thrust remained the investigation of the contemporary periglacial environment, including glacial landform descriptions (Boelhouwers, Holness, & Sumner, 2000; Holness 2003a; Nel, Holness, & Meiklejohn, 2003; Hedding, 2004; Holness 2004), relict landform interpretation in the context of Holocene (or earlier) settings (Nel et al., 2003; Holness, 2004; Sumner & Meiklejohn, 2004), and the effects of climate or environmental change on geomorphic processes and the landscape (Nel et al., 2003; Sumner, Meiklejohn, Boelhouwers, & Hedding, 2004a). The main output of this period was the description of Marion Island as a distinct periglacial environment (Boelhouwers et al., 2003) that built on findings from both funding periods. A secondary research focus during this period was on weathering studies, with emphasis on the use of weathering characteristics as a relative age indicator (Sumner, Nel, Holness, & Boelhouwers, 2002), placing the island's weathering environment within the context of other southern hemispheric sites (Sumner, Meiklejohn, Nel, & Hedding, 2004b) and determining weathering rates (Sumner, 2004). Landform descriptions were by observation and basic morphometrics (Boelhouwers et al., 2000; Holness 2003b; Nel et al., 2003; Holness 2004; Sumner & Meiklejohn, 2004; Hedding, 2006) supported on occasions by Schmidt Hammer assessments of rock hardness (Sumner & Nel, 2002; Sumner et al., 2002).

Upscaling the projects: 2006-present

From 2006, the projects increased both in terms of budget and the personnel involved. Two parallel projects ran from 2006-2011, 1) *Geomorphology and climate change* and 2) *Vegetation, microclimate and landform processes as drivers of sub-Antarctic terrestrial ecosystems: interactions and responses to climate change.* One of the most important outputs from the first project was the review of the existing understanding of the geology and geomorphology of the island (Boelhouwers et al., 2008) including observations on the significant zoogeomorphic impacts in the coastal zone. As with previous funding cycles, research on the description and observations of contemporary periglacial landforms on the island (Hedding, Sumner, Holness & Meiklejohn, 2007; Hedding, 2008) and the assessment of the paleo-ice distribution and the linkage from proxy data between deglaciation, faulting and volcanic activity (Hall, Meiklejohn, & Bumby, 2011) remained dominant themes. Without absolute exposure ages of the glacial landforms, the timing and extent of glaciation on the island remained speculative.

A new thrust in the first project considered the effects of synoptic air circulation patterns on surface and sub-surface temperature dynamics (and possible climate change implications) (Nel, Boelhouwers, & Zilindile, 2009a; Nel, van der Merwe, & Meiklejohn, 2009b; Nel, 2012). Automated temperature loggers that were superior in accuracy, resolution, battery life and memory to the earlier loggers, were used to measure the temperature fluxes in surface and subsurface material. Secondary weather data and synoptic charts from the South African Weather Services (SAWS) described the air circulation patterns. It became apparent that to understand the ongoing climate change impacts on soil temperatures, a future classification of synoptic-scale circulation patterns and associated long-term trends was necessary.

The second project presented the first phytogeomorphic findings on the interactions between the cushion plant *Azorella selago* and surface sediment transport (Haussmann, McGeoch & Boelhouwers, 2009a) as well as the fine scale variability in soil frost dynamics surrounding *Azorella selago* cushions (Haussmann, Boelhouwers, & McGeoch, 2009b). Digital images were, for the first time, used to relate cushion properties, such as elongation and growth angle, to directional differences in grain sizes (Haussmann et al., 2009b) and modern techniques like the use of ^{10}Be as an indicator of soil development were applied (Haussmann, Aldahan, Boelhouwers, & Possnert, 2010). Trusted methods such as the use of wooden dowels to measure frost heave, steel pins to measure soil erosion and the measurement of temperature and moisture through automated loggers were still employed (Haussmann et al., 2009b). Within the Fellfield complex of Marion Island (Gremmen & Smith, 2008) the frost-susceptible materials is shown to form a synergistic complex system of ground climate (soil frost cycle frequency, intensity and duration), slope sediment movement (differentiated by sediment size, microtopography and moisture availability) and *Azorella selago* response and feedbacks (microtopography, radiation balance, wind buffer, snow trapping effects). The outcome displays a remarkable self-organization of vegetation-landform patterning across scale, where geomorphic ground disturbance is balanced by *Azorella* stabilizing effects, similar to frost-boil ecosystems in tundra landscapes (Walker et al., 2004). Internal feedbacks drive the stability of the self-organized fellfield system and the island's vegetation zones at large. On the other hand, the external driver of global climate change in its island-specific landscape-scale expression is a clear primary driver of phytogeomorphic system change on the island at all altitudes. In response, the strength of internal feedbacks in the Azorella-terrace fellfield system is likely to determine the abruptness of spatial boundaries and temporal transitions, as shown for other landscape systems (Bathiany et al., 2016).

A new funding cycle started in 2012 under the project: *Landscape processes in Antarctic ecosystems*. The project included research on continental Antarctica and Marion Island and ran until 2014. The most significant contribution during this period was the involvement of Marion Island scientists in a community-based geological reconstruction of Antarctic ice sheet deglaciation since the Last Glacial Maximum (Bentley et al., 2014). This was part of a review into the terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation on the maritime-Antarctic and sub-Antarctic (Hodgson et al., 2014). Old questions on soil frost dynamics still remained and during this period the first direct observations of soil temperatures during needle ice formation in the sub-Antarctic were presented (Nel & Boelhouwers, 2014). However, the findings were inadequate and the boundary conditions under which needle ice formation occurred, remained unknown.

Since 2015, earth science research on Marion Island falls under the ongoing project *Landscape and climate interactions in a sub-Antarctic environment.* The focus remained geomorphological in nature (Hedding, & Sumner, 2013; Hedding, Nel & Anderson, 2015; Hedding 2016; Nguna, 2019) but with a strong climate change theme (Hedding & Greve, 2018) and the programme was extended to include the hydro-chemical nature of the rivers (Stowe, Harris, Hedding, Eckardt, & Nel, 2018a; Stowe, Hedding, Eckardt, & Nel, 2018b; Stowe, Hedding, Eckardt, & Nel, 2019). Research objectives, such as the dynamics of soil frost (Borg, 2017; Hansen, 2018), the effect synoptic weather has on the landscape (Nguna, 2019; Sinuka, 2019) and the glacial reconstruction of the paleo-landscape on Marion Island (Rudolph et al., 2020) remained.

New methods have become available, including time-lapse photography with detailed high-resolution, high-accuracy temperature measurements, the use of wind-aspirated sediment samplers and high-resolution environmental parameter measurements as well as cosmogenic nuclide exposure dating techniques such as ^{36}Cl analytics. The use of new software and modern data logging techniques, high-resolution topographic data, accurate Differential Global Positioning Systems (DGPSs) and Autonomous Aerial Vehicles (UAV's) have also made landform descriptions and morphometric measurements more accurate. Below we present case studies (in the form of short vignettes) that show how these new techniques and tools, together with the use of old trusted methods, have contributed to our knowledge of the contemporary geomorphology of the island and has given us a basis (or application) for further climate change research.

A synoptic classification system for assessing climate change impacts on terrestrial ecosystems by Jan Boelhouwers, Julian Cotrina and Werner Nel

Sediment movement and landform development on Marion Island, is to a large extent driven by high frequency diurnal soil frost cycles (Boelhouwers et al., 2003). These slope processes act as a disturbance for ecosystem functioning and the spatial patterning of vegetation across the island (Hausmann et al., 2009a). Diurnal soil frost activity responds to synoptic time-scale atmospheric conditions rather than mean annual trends (Borg, 2017) and to understand the influence of climate on soil frost conditions and terrestrial ecosystems, a classification of synoptic-scale circulation patterns and analysis of their long-term trends is required. Long-term meteorological observations (1960 to 2009) by the Marion Island weather station provided a basis for a single station principal component (PCA) and cluster analysis as described in Yarnal (1993). From this, eight distinct synoptic circulation types are identified and described for the island (Fig. 2).

Cluster 1 is characterized by a cool mP air flow from the WSW driven by a strong mid-latitudinal pressure gradient between the southerly-situated South Atlantic high and a polar low. The anticyclone ridges in behind the passage of a mid-latitudinal depression, located well north of Marion Island. The proximity of the anticyclone causes relatively low humidity and precipitation. Cluster 2 reflects a cut-off low pressure system over or just south of Marion Island, with low average temperature and humidity. The meridional component in the dominant airflow explains the low temperatures, but also suggests the potential to bring in a northerly maritime tropical air from lower latitudes east of the island, but the wind direction data do not indicate such a component in the data set. Cluster 3 is associated with an anticyclone northeast or northwest of Marion Island. A cold front has passed and is east of Marion Island with the centre of the mid-latitudinal depression and the polar front to the south. Mean temperature is relatively high as is the air pressure and sunshine hours, with low mean precipitation. The

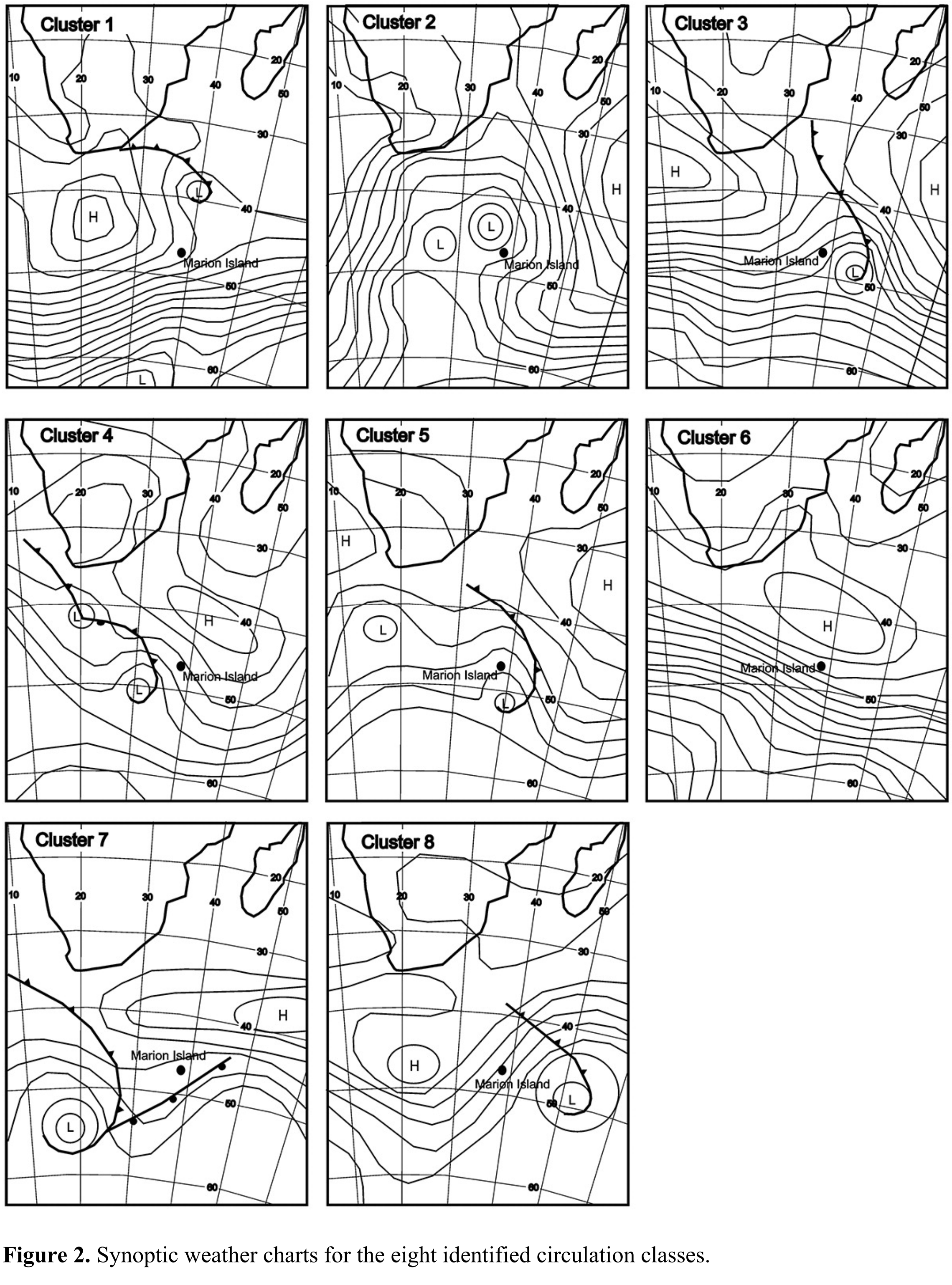

Figure 2. Synoptic weather charts for the eight identified circulation classes.

circulation pattern associated with cluster 4 is typified by an approaching frontal system to the west and an extension of the South Indian anticyclone north of 45 degrees. There is a westerly influx of moist air giving rise to high cloud cover and precipitation. Cluster 5 is associated with a low pressure just south of the island (or just south of 50°S) giving rise to a low mean air pressure. Air circulation over the island is post cold frontal with the cold front situated to the west and is characterised by moderate mean temperature, cloud cover and precipitation. Cluster 6 reflects an anticyclonic circulation north of Marion Island and south of 35°S. This results in a maritime tropical airflow with above-average mean temperature, high cloud cover and moderate rainfall. Marion Island is not influenced by any mid-latitudinal depressions and the polar front is positioned south of the island. Cluster 7 represents a circulation pattern where the island is situated within the warm sector of a mid-latitudinal depression. Air pressure is relatively low with high cloud cover and precipitation. The extension of the South Indian anticyclone to the north results in an influx of low-latitudinal air and an above-average mean air temperature. Cluster 8 is associated with an anticyclone with the centre of the high pressure W/WSW of Marion Island. The circulation is post cold frontal with a strong southerly component that results in a low mean temperature and moderate cloudiness and precipitation.

The daily air circulation classification in any of the eight clusters allows for analysis of changes in frequency of circulation patterns over Marion Island for the period (1960-2009) (Fig. 3). Annual frequency of cluster occurrence (number of days per year) is presented as a percentage of the total annual number of daily values. All circulation classes, except for cluster 1 show, statistically significant trends at the 99% confidence level and a trend of increased frequency of occurrence of clusters 2,3,6,7 and the reverse for clusters 4,5,8 can be hypothesized to depict an underlying shift in circulation patterns related to the pronounced warming and drying trend for Marion Island shown by Smith (2002) and Le Roux (2008) and Hedding and Greve (2018). MAAT increases are associated with increased frequencies of clusters 2,3,6,7 ($R^2 = 0.62$), while MAAT decreases are linked to increases in clusters 4,5,6 ($R^2 = 0.56$). The simultaneous transition in frequency of circulation group 2,3,6,7 (increasing trend) and circulation group 4,5,8 (decreasing trend) can be positively correlated to both the increasing mean annual temperatures and decreasing precipitation up to the year 2000. The data show the main separation of these two circulation groups from the early 1980's. Results from the cluster analysis proved to be internally consistent with the identified air circulation types and are also consistent with reported trends in regional climate change (Smith & Steenkamp, 1990; Rouault, Mélise, Reason & Lutjeharms, 2005).

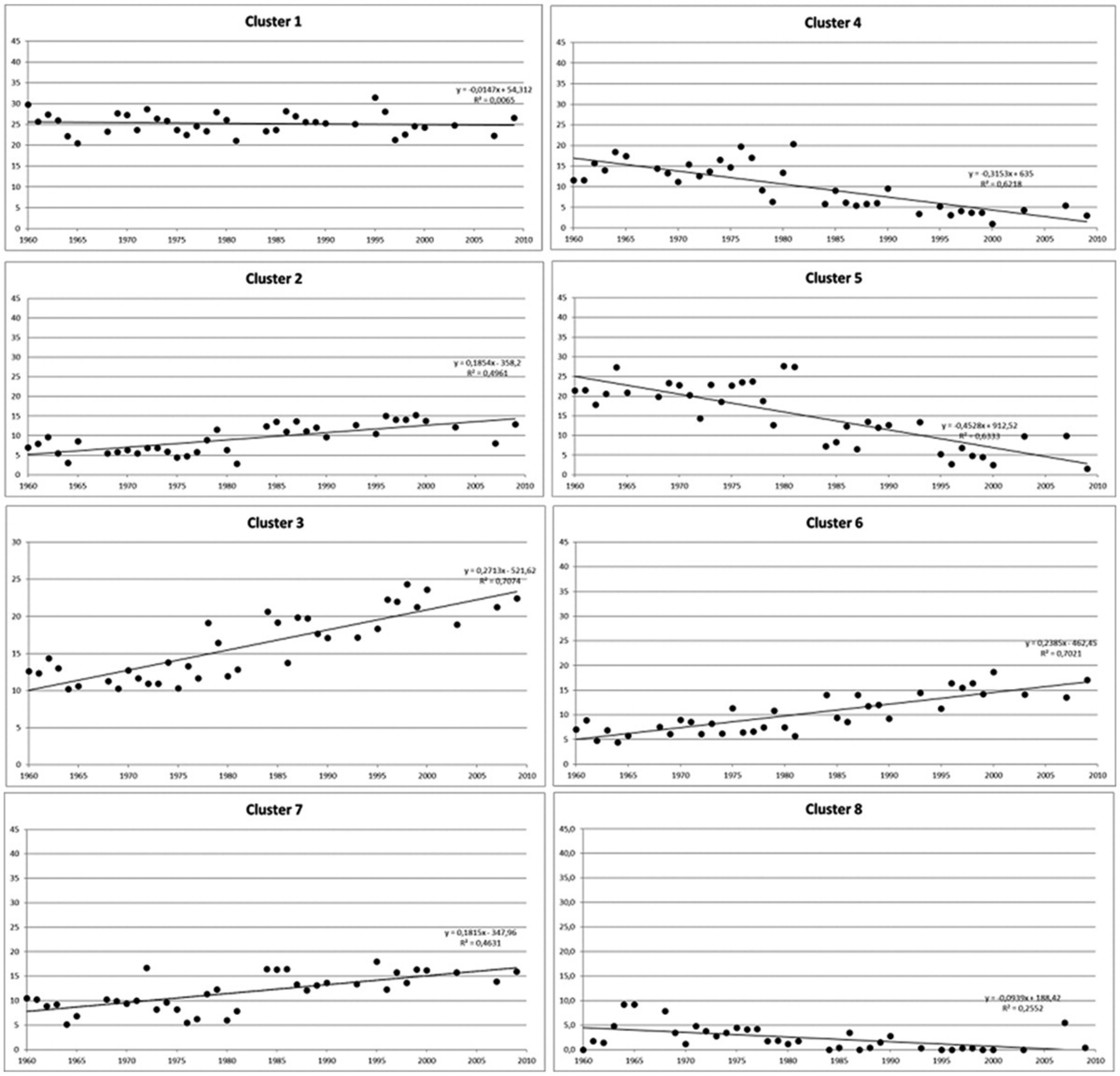

Figure 3. Trends in the annual frequency of circulation class occurrence in days, expressed as a percentage of annual total of classified days, at Marion Island over the period 1960–2009. All R^2 values of the linear regression are significant at $p < 0.01$ (except cluster 1).

The synoptic classification system and the changes in frequency of circulation pattern over Marion Island can be applied to correlate synoptic air circulation conditions with existing landscape observations. For example, Nel (2012) indicates that summer soil frost is strongly correlated with post cyclonic airflow from a ridging anticyclone after the passage of a cold front connected to a mid-latitudinal cyclone, or when a series of low-pressure systems passed over the island (similar to clusters 2 and 3). Days with soil frost measured on an altitudinal transect (Bierman, 2012) also show that these clusters (2 and 3) dominate the occurrence of soil frost. In mire ecosystems on Marion Island, the passage of synoptic-scale weather systems influence sub-surface temperatures and soil heat fluxes, especially in the upper 30 cm of the mire (Nel et al., 2009a). The dominant westerly airflow (cluster 1) depresses shallow ground temperatures, but mire temperature profiles show that an increase in the effects of the sub-tropical high pressure (cluster 3) and the warm fronts passing the island (cluster 7) could increase the average temperature of the mire and reduce the temperature variability with depth in the future. Furthermore, cyclonic circulation has the most pronounced effect on near-surface ground temperatures in mires and a decrease in the effects of travelling cyclones (cluster 4 and 5) will further increase mire temperatures as the sharp decrease in shallow temperatures during the passage of a cold front is nullified. This in turn could enhance soil respiration and decomposition potential in mires. Similar approaches can be applied to the role of erosion by surface runoff and mass wasting by linking threshold precipitation values with synoptic air circulation types and their trends. Such and other similar work can further explain landscape responses to long-term atmospheric circulation changes affecting the island.

Needle ice: growth criteria and sediment movement mechanisms by Carl-Johan Borg, Jan Boelhouwers, Ian Meiklejohn and Werner Nel

Needle ice grows and decays on diurnal time scales under variable synoptic weather conditions, but what are the boundary conditions under which ice formation can occur? Answering this question is essential for the conceptualization of what constitutes a diurnal soil frost environment and the capacity to model responses of such an environment to climate change. Real-time, high-frequency field monitoring of both ground climatic variables and the in-situ segregation ice development is thus required.

For the first time, high-resolution time-lapse photography using Bushnell Trophy Cam® IR cameras were used for visual recording of needle ice formation (Fig 1b). The camera creates an oblique image of the study site, which was corrected by overlay of a digital 3D reference grid to enable displacement measurements within the study site. The reference grid is based on measurement of the study plot dimensions, angle of the camera, angle of the plot surface, the in-picture scale bar and a 3D surface model of the study site. A 3D surface model was created using AgriSoft PhotoScan®. PhotoScan® and a number of overlapping images taken 360^{o} around an object that, using parallax distortions, creates a high-resolution 3D surface map from the images. Accuracy of the subsequent measurements in the study plot images is ~0.5 cm. Images were taken at 5-15 min intervals allowing automated recording over 4-5 months.

Climate parameters (temperature at -10, -5, -2.5, 0, 10 and 30 cm, soil moisture at -2.5 cm and -5 cm, wind speed and direction) were recorded at 5 min interval on a separate data logging system. Camera-clock and logger-clock synchronization was achieved as both systems are programmed through the computer clock during programming.

The combined environmental and camera monitoring registered 15 needle ice growth events between 27 April - 9 June 2014 (n = 4) and 20 February - 5 May 2015 (n = 11). Initiation of needle ice growth was established as the time of commencement of visual surface heave in the camera images. Surface temperatures at that point ranged between -2.0 °C and 4.3 °C, soil moisture between 0.4 % and 12.5 % and 1.4 % to 18.2 % at -2.5 cm and -5 cm, respectively. Wind measurements, although only available for 4 of the 15 events, ranged from calm to 7.5 m/s. Needle ice growth initiation requires a water phase change from liquid to ice that releases latent heat as sensible heat (Outcalt, 1971) and this can be observed by a sharp temperature increase during high-frequency temperature monitoring. Subsequent ice growth during a phase of nocturnal cooling reduces the rate of soil cooling. Where surface cooling and latent heat release compensate each other a so-called zero-curtain effect is established and is a well-known feature in seasonal and permafrost environments (Outcalt, Nelson, & Hinkel, 1990). These theoretical considerations are well demonstrated in the data record and could be compared with the visual heave recorded by the cameras. A zero-curtain effect is for the first time demonstrated empirically for diurnal freezing.

Early literature suggested the initiation temperature of needle ice at -2°C (Outcalt, 1971). However, Haussmann et al. (2009a) and Nel and Boelhouwers (2014) measured initiation temperatures at -0.2°C on Marion Island. The application of direct visual and high-frequency long-term measurement establishes needle ice initiation at a range of temperatures between -2.0°C and 4.3°C, *at the point of measurement.* The physical impossibility of water freezing at positive temperatures strongly suggests that the sensor was not located at the precise location of ice nucleation. Instead, during growth events with above 0 °C temperatures a two-dimensional bare soil surface acts as the primary or active surface of radiative heat exchange between atmosphere and soil (Oke, 2002). In such settings there is a sharp temperature gradient between air, active surface and soil. To further complicate matters, the level at which ice nucleation starts at or beneath the soil surface is shown to vary between individual events. It appears that availability of stored soil moisture and soil moisture transport is instrumental in determining where ice nucleates in the soil. In turn, this also determines the extent to which soil heaves (ice needle length) and causes soil creep upon thaw.

The range of sub-zero temperatures at which ice nucleation starts points at further complexity in the soil-water system. Supercooling of soil water is known to occur with higher freezing point depression (eutectic point) for smaller pore diameters (Kozlowski, 2009). Furthermore, local variation in micro-topography and ground characteristics, probably relating to moisture distribution and soil texture, is seen to affect growth intensity. The small-scale variability in needle ice growth efficacy and resultant sediment displacement observed in the study plots illustrates the complexity in soil and climate parameters involved in diurnal frost creep processes. Actual sediment displacement could be directly observed in film sequences created from the time-lapse images. Slope angle proves the major control in the study plots on both type and mechanisms of movement. Heave and resettling is the dominant mechanism especially in fine soil, while toppling of needles dominates when heave is more than ca. 1.5 cm. Rolling of small clasts occurred during ice needle decay when spherical to semi-spherical clasts are heaved over 1.5 cm. Displacement is limited when very cold (ca. -6 ºC) conditions exist during freezing of the surface into a stabilized solid crust and only heave and settling can occur. While theoretically discussed for almost 200 years, technology for the first time offers direct documentation of the actual mechanisms and movements taking place real time. The results question established frost creep models and cast doubt on the capacity for dynamic modelling at the landscape scale.

The frost environment: consideration of an altitudinal gradient by Christel Hansen, Ian Meiklejohn, Jan Boelhouwers, Werner Nel

On Marion Island, permafrost is absent and diurnal ground frost processes dominate the landscape (Holness, 2001; Holness 2004; Boelhouwers et al., 2003, Hedding, 2008), due to low-intensity and high-frequency frost cycles (Hansen, 2018). At altitudes below ± 300-400 m a.s.l. needle ice is predominant but at higher elevations deeper frost cycles and ice lensing may occur (Holness, 2001; Boelhouwers et al., 2003). Here we discuss data, on an altitudinal gradient, on ground frost using high accuracy, high-resolution automated ground thermal and moisture monitoring equipment supplemented by the use of buried painted markers, adapted from Pérez (1992) and Holness (2004), in 25 cm x 25 cm trenches at varying depths (see also Hansen, 2018). The thermal monitoring presents insights into the changes in the sub-surface temperatures while the painted markers show particle movement within the ground.

The altitude at which the frost environment was the most active was at 800m.a.s.l. where freeze-thaw cycles are shallow, suggesting dominant frost processes by needle ice. The average freeze-thaw cycle was 20 hours at this altitude, but the most common cycle spans one hour. While high altitude are characterised by potential freeze-thaw cycles throughout the year, it does not occur at lower altitudes (450 m.a.s.l). Snow cover has an insulating effect, thereby reducing observed freeze-thaw cycles at higher elevations. Seasonal frost occurs at depth at higher altitudes, while at 450m a.s.l no seasonal frost occurs. Data from this monitoring experiment illustrates the strong correlation of altitude to recorded temperature, as well as potential freeze-thaw events and freeze-thaw cycles.

Kolmogorov-Smirnov tests show that the soil texture from the sediment samples at different altitudes on Marion Island are statistically different ($p < 0.05$) with soil texture becoming increasingly coarse with increasing elevation. Lower sites with higher organic content, thus, promote a disparate frost environment compared to higher-altitudes sites that are associated with coarse soils and lower organic proportions. Moisture data further illustrates the increase in gravimetric water content with depth, suggesting loss of moisture to environmental parameters, such as deflation, with depths deeper within the ground insulated from moisture loss. Compared to surface samples, the sub-surface show deficiency in various textural fractions. Coarser particles migrate upwards in the direction of the freezing front when soil is frozen at the surface (Hallet, 1990), yielding coarser particles on the surface, and a relatively coarse-particle-poor sediment column at the depth of maximum freezing. This applies most to the high altitude site, which shows the greatest level of textural size deficiency when comparing sub-surface to surface samples. A deficiency of Phi (ϕ) values > 4 (silt and clay) near the surface shows the removal of these particles from the portion of the ground when freeze-thaw cycles take place.

Painted marker trenches indicate cycling of material within the ground. For all trenches except at the highest elevation, lateral extension downslope is evident. Dominant movement for all trenches occurs near the soil surface (-5 to 0 cm), with markers cycling up toward the ground surface. These cycles cause particles to move towards the freezing front, yielding a deficiency of a specific textural fraction up to the depth of where freeze-thaw occurs. While the dominant direction of movement is towards the ground surface, the cyclical nature of these processes is evident in particles moving deeper into the ground. Lateral movement of particles is also in evidence. As such, freeze-thaw processes yield lateral and vertical movement of particles and deficiency of certain textural fractions due to all three sorting mechanisms: 1) uplift of particles when freezing occurs from the top, 2) sorting as particles migrate away from the freezing plane approaching from the top or sides, and 3) mechanical sorting (see also Corte, 1966).

On Marion Island, bulk densities increase and moisture values decrease with increasing altitude (Conradie & Smith, 2012), mean annual ambient temperature is strongly correlation with elevation (Chown et al., 2012), climatic variation is evident across the Island's altitudinal ranges (Gabriel et al., 2001), and vegetation varies with altitude (Hugo-Coetzee & le Roux, 2018; Treasure, le Roux, Mashau, & Chown, 2019). As such, an altitudinal gradient exist for many physical and biological parameters. Results presented here illustrate that ground thermal and moisture dynamics exhibit a clear altitudinal gradient. This is reflected in increasing mean annual ground temperature with decreasing altitude, a decrease in temperature variability with decreasing altitude and a shallower vertical sorting depths of the ground, a decrease in average frozen duration with decreasing elevation, and longer continuous frost at greater depth. With a continuous increase in temperature experienced on Marion Island, the attitudinal gradient is expected to be affected and thresholds expected to shift attitudinally upward. This in turn has implications on ground frost processes active on the island, reducing freezing depths, shifting the freezing limit, and reducing cycling of soil due to frost cycles.

Aeolian processes and dynamics at Mesrug by Abuyiselwe Nguna, David Hedding, Sibusiso Sinuka, Werner Nel

Aeolian processes, involving the entrainment, transport, and deposition of sediment by wind, are important geomorphic processes operating in predominantly arid regions (Nickling & McKenna-Neumann, 2009). Aeolian activity can also have a significant influence on the geomorphology of landscapes in cold climates (Seppälä, 2012). The dominant climatic factors on sub-Antarctic Marion Island are low temperatures and high wind velocities. These factors are common across the sub-Antarctic islands (e.g. Löffler, 1983) and recent observations have recognised the increasing role of aeolian processes as a geomorphic agent on Marion Island (Callaghan, 2005; Hedding et al., 2015). At Mesrug (46° 56’ 41”S; 37° 49’ 59”E), a known aeolian feature on Marion Island (Hedding et al., 2015), high-resolution monitoring of climatic and environmental parameters (wind speed, wind direction, ambient air temperature and soil moisture) was undertaken using Pace Scientific XR5 data loggers (Fig. 1c). Aeolian sediment transport (flux) was measured using a vertical array comprising eight omni-directional wind-aspirated Big Spring Number Eight (BSNE) sediment samplers based on the design of Fryrear (1986). Systematic surveying of megga-ripples at the site over two years was undertaken using a GeoMax Zenith 10 DGPS supplemented by aerial photographs from a UAV.

The annual sediment flux at 0.05 m height was calculated as 2.29 kg cm^{-2} y^{-1} and monitoring showed the entire surface of the study area to have lowered through deflation, while the ripples shifted slightly eastward (down-wind). It is calculated that the site lost 3.4 m^3 of sediment between the two surveys and the relatively large particle size of surface sediments on Marion Island is a major contributor to the low annual aeolian sediment flux. Sediment movement occurs in gale force winds and horizontal precipitation and the data show (not conclusively) that prolonged periods of continuous gusts at an average of > 20 m/s causes sediment entrainment and transportation. Sediment supply is the limiting factor of aeolian sediment transport, but even though the perennial wetness experienced on the island is not a major limiting factor to sediment flux, it may influence rate of movement. Sediment movement occurs closest to the surface and weight of sediment moved as well as size of particles decreases vertically in the air column. The vast majority of moved particles are very fine gravel and very coarse sand, which is much coarser compared to other cold environments (Speirs, McGowan, & Neil, 2008; Arnalds, Gisladottir, & Orradottir, 2012; Seppälä, 2012). From linear regression analysis, it seems that the upper limit of aeolian sediment transport is 0.8 m above the ground and aeolian sediment transport is limited by the large particle size of surface sediment. Saltation of particles is the dominant aeolian transport mechanism on Marion while deflation is the formative process.

Aeolian features on Marion Island are limited to the areas covered with unconsolidated volcanic material (scoria). Sediment movement is seasonal (winter dominated) while armouring of the surface by larger particles prevents smaller particles from being transported by the wind. Needle ice occurs regularly at Mesrug and, through soil disturbance changing the texture of the surface, the ice increases the erosive capacity of the wind. Sediment transport is typically associated with cold fronts and concomitant high wind velocities and precipitation. Rain splash generated during these cold fronts may aid in dislodging larger particles disturbing the surface armouring through which smaller particles can be entrained by the wind. The wind-apirated sediment samplers also captured vast quantities of biotic material, including seeds, which indicate that relatively large pieces of biotic material can be transported by the wind on Marion Island further than previously thought (see Born, le Roux, Sphor, McGeoch, & Jansen van Vuuren, 2012). This suggests the efficiency of wind for the dispersal of plants in this sub-Antarctic environment may be underestimated both for the contemporary and for the palaeo dispersal of genetic material across the island.

Redefining Marion Island's LGM by Elizabeth M. Rudolph, David Hedding and Werner Nel

By the end of the previous decade, hypotheses for Marion Island's Quaternary glacial oscillations had been refined by McDougall et al. (2001), Boelhouwers et al. (2008), Hall et al. (2011) and Hodgson et al. (2014). These works were largely based on the foundation provided by Hall's (1978; 1980) early geomorphic assessments which could be summarized as follows: (i) the island's local Last Glacial Maximum (lLGM) coincided with the global Last Glacial Maximum (gLGM). This lLGM period was considered to span between ~11-35 ka ago, in Marine oxygen Isotope Stage 2 (MIS 2), and was redefined by McDougall et al. (2001) in order to revise the glacial reconstructions produced by Hall (1978, 1982). While Hall (1980) associates some coastal moraines with a specific "cold peak" advance at ~19.5 ka ago, other glacial features within the Pleistocene grey lavas were also assigned to this last glacial stage. (ii) Boelhouwers et al. (2008) surmised that retreat commenced at the end of the gLGM (~17-18 ka ago) and was near completion prior to Holocene volcanism and deglaciation, therefore, occurred rapidly. (iii) Cooling periods subsequent to this deglaciation brought on significant glacial re-advances during the Holocene (McDougall et al., 2001; Boelhouwers et al., 2008). (iv) The island maintained a few high-lying ice-free areas during the LGM, (Hall, 1980; Hall et al., 2011) which acted as genetic refugia (see Barendse, Mercer, Marshall, & Chown, 2002; Myburgh, Chown, Daniels, & Van Vuuren, 2007; Chau et al., 2019). In the absence of alternative proposals, these hypotheses were widely accepted and used by the broader scientific community to depict the last major glaciation of Marion Island (see Chown & Froneman, 2008).

Recent advancements in cosmogenic nuclide exposure dating techniques and Chlorine-36 analytics (Di Nicola, Schnabel, Wilcken, & Gméling, 2009; Marrero, Phillips, Caffee, & Gosse, 2016) now allow for the exposure dating of oceanic island basalts. These advancements have, and continue to, revolutionise glacial geomorphic studies world-wide (see Balco, 2011) and the recent application of ^{36}Cl exposure dating on Marion Island has altered the temporal constraints of previous glacial chronologies (Rudolph et al., 2020). Exposure ages of glacial features on the north-east coast (Fig. 1d) show that the last deglaciation began before 34 ka, and continued until ~17 ka ago, by which time the ice had retreated up to ~900 m a.s.l. (Rudolph et al., 2020). These findings challenge existing hypotheses and propose a revised glacial chronology stating that: (i) The island's local LGM did not coincide with the global LGM of MIS 2 (~19-23 ka ago) (Hughes & Gibbard, 2015), but instead correspond to a glacial stage in MIS 3 (~45 ka ago) or perhaps earlier (Schaefer et al., 2015); similar to glacial patterns shown by some other sub-Antarctic islands (e.g. Jomelli et al., 2018) and mountain glaciers in the Southern Hemisphere (e.g. Eaves, Mackintosh, & Anderson, 2019). The grey lava landscape is thus significantly older than previously considered and rates of periglacial processes, soil and peat formation, and ecological succession may be over-estimated. (ii) The island underwent slow retreat since the onset of deglaciation, as opposed to rapid, which challenges interpretations of the structural landscape history that was based on catastrophic events, such as isostatic rebound (Hall, 1982).

Progress remains to be made on determining the maximum extent and culmination of the island's last glaciation. Due to a lower sea-level, remnants of the lLGM would be off-shore but, these remain unverified and undated (Hodgson et al., 2014). Post-lLGM glacial re-advances also need further investigation, although events like these were probably restricted to the island's interior. Rudolph et al. (2020) also confirm the possibility of the existence of lLGM nunataks, such as at Katedraalkrans, but the temporal and spatial significance of these ice-free areas for genetic refugia remain unknown. The age of surface grey lavas in high-lying areas are estimated ~50 ka old (K-Ar dating; McDougall et al., 2001), landscape evolution should therefore be considered in light of these (and other) ages.

Since the glacial reconstructions of Hall (1978), McDougall et al. (2001), Boelhouwers et al. (2008), Hall et al. (2011) and Hodgson et al. (2014) there have been substantial headways in paleoclimate research, constraining the glacially oscillations of the Southern Hemisphere. It is increasingly apparent that the globe's ice sheets and mountain glaciers did not necessarily reach their last maximum extent simultaneously. It is hypothesised that local topography and the position of the southern hemispheric westerlies could have driven past glaciation on sub-Antarctic islands (Rudolph et al., 2020). What is becoming clear is that the last period of maximum ice extent in the Southern Hemisphere (Schaefer et al., 2015) and the sub-Antarctic (Jomelli et al., 2018; Eaves, et al., 2019; Rudolph et al., 2020) was not necessarily synchronous with the global LGM (see Hughes & Gibbard, 2015).

Conclusion

At the inception of earth science research on Marion Island in the mid-1990's, the island was seen as a laboratory that could explain similar processes elsewhere (notably the southern African mountains). However, it was quickly realized that the environment on Marion Island is unique and that it is extremely sensitive to climate change. A series of earth science programmes have operated for over 25 years encompassing research on numerous aspects of geomorphology and environmental change. Initial research was centered on understanding the contemporary periglacial environment, which remained a key objective. It was recognised early that Marion Island has globally one of the most active soil frost environments and a distinct periglacial setting. The earth sciences projects contributed to the understanding of the geology and geomorphology of the island and the interaction between the biotic and abiotic components especially in the dominant fellfield system of the sub-Antarctic. Instantaneous, high-frequency, field monitoring of both contemporary micro-scale ground climatic variables and in-situ segregation ice development has shown the mechanisms of needle ice growth and decay on diurnal time scales under current variable synoptic scale weather conditions. Contemporary summer soil frost on the island is strongly correlated with post cyclonic airflow and passing mid-latitudinal cyclones influences sub-surface mire temperature fluxes and surface sediment transport. Altitude and topography also influences local scale soil frost dynamics which in turn influences biotic activities at this scale. Geochronology studies show that the timing of maximum ice extent in the Southern Hemisphere and specifically in the sub-Antarctic are not necessarily synchronous to the global LGM and that local topography and the position of the southern hemispheric westerlies could have driven past glaciation on the sub-Antarctic islands. It is recognised (through the earth sciences research) that the processes occurring in the abiotic environment on Marion Island has island-scale implications for ecosystem functioning, acts as a regional indicator of the effect of climate change and has global significance for diurnal soil frost environments and the timing of the LGM.

Research techniques employed by the projects on Marion Island kept up with the times. As new appropriate technologies became available it was quickly adapted for use on the island. The use of these technologies was made possible due to the availability of funding through the SANAP. As time progresses key objectives remained, but new digital technologies, cutting edge chemistry analytics and new analog instruments made descriptions and measurements more accurate and easier to record. Not only has the use of these methods enhanced our understanding of the unique periglacial environment on the island but has, in most cases, given us more questions than answers and challenges us to continuously reassess the most basic of assumptions that exist within our research. It remains that the sub-Antarctic islands provide the only terrestrial record of Quaternary glaciations and climate within thousands of kilometres of ocean and given its long history, earth science research on Marion Island should remain a key objective of SANAP. Current work should continue to harness technological advances and should start to focus on obtaining the ages of the basaltic lava through Ar-Ar dating to place it within a geological chronology, which constrains landscape development and glaciation on Marion Island. Work should continue to use cosmogenic ^{36}Cl surface exposure dating to define Marion Island's glacial history within more accurate temporal and spatial scales to explain how deglaciation has facilitated landscape development and affected the colonisation and dispersal of biota. New avenues of research should also be pursued. This include the analysis of novel dust and sea salt aerosol proxies in peat deposits to quantify changes in the Southern Hemisphere Westerly Wind regime during the last major reorganisation of the climate system (Termination 1: 18,000–11,000 years ago). This is global significant work that will assist in determine how changes in the strength and position of the Southern Hemisphere Westerly Wind belt have controlled moisture delivery, and impacted on the ability of the Southern Ocean to modulate CO_2. Lastly, true to the roots of earth science research on Marion Island, research on the contemporary landscape should continue to determine landscape interaction with the current dominant westerly wind patterns to predict for future landform change.

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