RESEARCH/REVIEW ARTICLE

A preliminary synoptic assessment of soil frost on Marion Island and the possible consequences of climate change in a maritime sub-Antarctic environment

Werner Nel

Department of Geography and Environmental Science, University of Fort Hare, Alice 5700, South Africa

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Correspondence
Werner Nel, Department of Geography and Environmental Science, University of Fort Hare, Alice 5700, South Africa.
E-mail: wnel@ufh.ac.za

Abstract

Located in the sub-Antarctic, Marion Island (46° 54′ S, 37° 45′ E) has a distinct periglacial environment that is sensitive to climate change. Diurnal soil frost is the most important geomorphic process occurring on the island and this paper aims to understand the synoptic weather circulation pattern associated with summer soil frost occurrence in a sub-Antarctic environment. Preliminary results from automated microclimate measurements in the interior of Marion Island show that summer soil frost is dependent on Antarctic air mass circulation. This occurs exclusively during post-cyclonic airflow after the passage of a cold front connected to a mid-latitudinal cyclone and subsequent ridging in of the South Atlantic Anticyclone behind the cold front, or when a series of low pressure systems passes over the island. The duration and intensity of soil frost cycles are dependent on the duration of post-cyclonic Antarctic air mass circulation. Summer soil frost on Marion Island is driven by a complex interaction between the latitudinal position of the passing cyclone, the latitudinal position of the ridging anticyclone as well as the trajectory of the air mass circulation. The data suggest that predicted trends in synoptic climate change in the sub-Antarctic may lead to non-linear responses in soil frost dynamics.

Studies that investigate the modification of frozen ground characteristics are primarily focused on the Northern Hemisphere permafrost regions due to the interactions with the global carbon cycle (Zimov et al. 2006) and the potential positive feedbacks to current global warming and impacts on terrestrial ecosystems (Symon et al. 2005). In contrast, diurnal ground frost dominates the sub-polar region of the Antarctic, and the time scale at which climate drivers affect the ground frost conditions is on the order of hours to days (Nel, Boelhoewers et al. 2009), rather than seasonal or annual. At the diurnal time scale synoptic weather conditions control the temporal variability in ground temperature (Nel, Boelhouwers et al. 2009; Nel, Van der Merwe et al. 2009), which is superimposed on the seasonal shift in ground energy budget (Boelhouwers et al. 2008).

Presently, diurnal soil frost is a key geomorphic process occurring in these regions (Holness 2003), while frost creep is considered the dominant sediment transport mechanism (Holness 2001, 2003). Furthermore, *Azorella selago*, a keystone species on sub-Antarctic islands (Le Roux et al. 2005), interacts with the geomorphology of the dominant fellfield vegetation by affecting sediment distribution and ultimately terrace formation (Haussmann et al. 2009). Soil frost and resulting ice segregation and soil displacement have a well documented negative impact on *A. selago* through limiting seedling establishment and survival and stimulating early plant senescence (Le Roux 2004). Understanding soil frost in sub-Antarctic diurnal frost environments is therefore essential to understanding both geomorphological dynamics and its associated effect on the ecosystem. The climate of Marion Island has changed significantly over

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the last 30 years, with recorded increases in sunshine hours, pressure and temperature, together with a reduction in rainfall. These variations in local climate are more significant in summer than winter (Rouault et al. 2005) and are driven by changes in the synoptic weather systems (Smith & Steenkamp 1990; Rouault et al. 2005). The aim of this paper is to attempt a first understanding of the synoptic weather circulation pattern associated with soil frost occurrence on Marion Island and the possible implications of the current changes in the synoptic weather systems on the duration and intensity of summer soil frost in a maritime sub-Antarctic environment.

Study area

Marion Island (46° 54′ S, 37° 45′ E) lies in the sub-Antarctic and has a hyper-maritime setting and a sensitive periglacial environment which is important in understanding climate/surface interactions as well as the climate change effects on ground thermal processes (Nel, Boelhouwers et al. 2009; Nel, Van der Merwe et al. 2009). The island is situated in the southern Indian Ocean and the synoptic climate is characterized by sequences of mid-latitude depressions (cyclones), the passages of frontal systems and the influences of anticyclones (Vowinckel 1954; Le Roux 2008). Mid-latitude depressions (cyclones) are constantly being formed in the South Atlantic on the boundary between cold and warm air masses and on Marion Island an approaching cyclone is associated with a strengthening of the north-westerly winds, an influx of warm sub-tropical air and an increase in cloudiness (pre-cyclonic). Once the cold front connected to the mid-latitudinal cyclone has passed there is an advection of cold and dry Antarctic air with associated south-westerly winds and clearer skies (post-cyclonic). As a result, with the passing of each cyclone, Marion Island experience a repeated exchange from wet, warm pre-cyclonic conditions, to cold, clear and dry post-cyclonic conditions (Smith & Steenkamp 1990). In the sub-Antarctic, the low annual temperature ranges, high cloudiness and precipitation result in high frequencies of short duration freeze–thaw events with shallow soil penetration (Boelhouwers et al. 2003) such that sediment transport in the scoria areas on Marion Island is predominantly caused by needle ice induced frost creep (Holness 2004).

The study site is situated in the interior of Marion Island at Katedraalkrans (750 m a.s.l.) and is characterized by approximately 125 frost cycles per year (Boelhouwers et al. 2003). Vegetation is restricted to some moss and lichen growth on the leeward side of boulders and the study area consists of scoria and black lava deposits with needle-ice induced frost creep dominating at this altitude (Boelhouwers et al. 2001). Since vegetation is largely absent, the site allows a direct exchange between atmospheric conditions and ground temperatures.

Methodology

An intensive ground climate measurement campaign was implemented during the austral summer of 2008/09. A Mike Cotton Systems© (MCS; Cape Town, South Africa) 10-channel logger was installed at the study site and soil temperatures were recorded through thermocouple wire sensors inserted into the fine scoria at 1, 5 and 10 cm depth every five minutes at a resolution of 0.01°C. Also, attached to the logger was a temperature sensor housed in a radiation screen measuring air temperature at 40 cm above the surface.

The synoptic weather systems dominant during the recording period were assessed through data from the South African Weather Services (SAWS). The data were obtained from the meteorological station on the eastern side of Marion Island and include hourly atmospheric pressure, air temperature and wind direction measured. The SAWS data were further supplemented by field observations as well as the six-hourly synoptic shipping charts issued by SAWS.

Results

Cold temperatures and memory capacity problems limited the operation of the MCS© logger (Table 1). Even though the recording period was limited, 16 soil frost events were recorded, of which 14 lasted longer than 1 h (Table 2). The air circulation patterns that were present over the island when soil frost occurred were identified from SAWS data and shipping charts. A description of the characteristics of the major atmospheric circulation drivers associated with soil frost as well as the airflow characteristics experienced on Marion Island during soil frost are given in Table 3.

From this ensemble of data it seems that summer soil frost on Marion Island is a nocturnal occurrence

Table 1 The logger recording period at Katedraalkrans (750 m a.s.l.), Marion Island.

Month and year	Dates recorded	Total days recorded
November 2008	1 to 14	14
December 2008	2 to 19 and 29 to 31	21
January 2009	1 to 15 and 30 to 31	17
February 2009	1 to 16	16

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Table 2 Characteristics of summer soil frost cycles during the recording period.

No.	Date of soil frost	Duration of air frost (hours)	Start time of soil frost (GMT+3)	Duration of soil frost: (hours) 1 cm	5 cm	10 cm	Minimum air temperature (°C)	Minimum soil temperature (°C) 1 cm	5 cm	10 cm
1	03/11/08	40	21:25	39	37	32	−4.0	−0.9	−0.4	−0.4
2	08/11/08	16	18:25	8	no frost	no frost	−1.9	−0.2	0.2	0.6
3	12/11/08	8	00:30	10	no frost	no frost	−5.2	−0.5	0.1	0.8
4	03/12/08	9	04:10	6	no frost	no frost	−3.0	−0.2	0.8	2.0
5	05/12/08	15	20:40	11	no frost	no frost	−3.1	−1.0	0.1	1.1
6	09/12/08	16	00:30	9	no frost	no frost	−4.0	−1.0	0.3	1.4
7	12/12/08	7	03:05	5	no frost	no frost	−2.1	−0.8	0.9	2.4
8	13/12/08	20	19:35	23	5	0.1	−3.0	−0.9	−0.3	−0.2
9	14/12/08	20	21:20	22	32	0.1	−3.0	−0.9	−0.3	−0.2
10	18/12/08	8	00:50	6	no frost	no frost	−1.9	−0.8	1	2.8
11	03/01/09	49	19:00	37	24	no frost	−3.6	−1.2	−0.5	0.1
12	03/02/09	21	03:30	10	no frost	no frost	−4.3	−0.8	0.5	1.8
13	05/02/09	15	01:40	4	2	1	−1.6	−0.7	−0.3	−0.1
14	12/02/09	14	04:25	2	no frost	no frost	−1.9	−0.2	1.1	2.6

that is initiated by post-cyclonic airflow after the passage of a cold front connected to a mid-latitudinal cyclone and subsequent ridging in of the South Atlantic Anticyclone with its centre to the north-west of Marion Island, as shown, for example in Fig. 1a and 1c. All soil frost events except one are correlated with this synoptic air circulation pattern and this synoptic pattern always initiated soil frost during the summer recording period. The one soil frost cycle that does not correlate to this pattern is the soil frost cycle recorded on the 13 December 2008 (no. 8, Tables 2, 3, Fig. 1d). Soil frost on this occasion was associated with a series, or family, of cyclones with associated warm and cold fronts. The cold front from the first cyclone passed the island on the 13 December 2008 generating soil frost while the island remained in the occluded zone of the cyclone. The frost cycle was broken when the warm sector of the second cyclone moved over the island briefly. The cold front of the second cyclone moved over Marion Island on the 14th, again generating soil frost by post-cyclonic airflow and ridging in of the anticyclone (no. 9, Tables 2 and 3).

The Pearson Product Moment Correlation parametric test and linear regression were applied to discern any correlation with the related degree of significance between cyclone characteristics and the duration and intensity of air and soil frost. As expected the duration of shallow soil frost (1 cm) on Marion Island is strongly correlated with the duration of air frost ($r = 0.90$; $P < 0.001$), and both the duration of air frost ($r = 0.86$) and duration of shallow soil frost ($r = 0.84$) are significantly correlated at the 99% confidence level with the duration of post-cyclonic airflow. Minimum soil temperatures measured during post-cyclonic airflow at 1 cm depth are also significantly correlated with the duration of soil frost ($r = -0.62$; $P = 0.02$) and the duration of air frost ($r = -0.57$; $P = 0.04$). The minimum temperatures measured at greater depths (5 and 10 cm) are significantly correlated with the duration of soil frost ($r = -074$; $P = 0.002$ and $r = -0.69$; $P < 0.01$), the duration of air frost ($r = -0.67$; $P < 0.01$ and $r = -0.59$, $P = 0.03$) and the duration of post-cyclonic airflow ($r = -0.63$, $P = 0.02$ and $r = -0.57$, $P = 0.03$). The duration of post-cyclonic airflow is significantly positively correlated with the latitudinal position of the ridging anticyclone behind the cold-front ($r = 0.57$; $P = 0.04$).

Snowfall is a major driver of soil frost with both snowfall events that were recorded (3 November 2008 and 3 January 2009) being associated with long and deep soil freeze cycles (nos. 1 and 11, Tables 2, 3). The synoptic air circulation pattern associated with these two events are given in Fig. 1b and 1c. Both these snowfall and subsequent deep freeze penetration events are associated with the passage of a cold front linked to a strong meridional extending low pressure moving south of Marion Island and subsequent post-cyclonic airflow from the ridging anticyclone whose air mass had a long southerly trajectory that can be traced further south than 60°S (Fig. 1b) and even close to the Antarctic coast (Fig. 1c). When no snowfall is initiated by the cold front, the longest and deepest soil freeze cycle is associated with the Antarctic air mass circulation from the series of deep meridional extended low pressure systems passing over the island (Fig. 1d). However, when the mid-latitudinal cyclone is weaker and the trajectory

Table 3 Characteristics of the synoptic air circulation patterns and airflow during soil frost. The latitude and pressure of the cyclone centre are given when the cold front or the cyclone itself passes over Marion Island. The position (latitude, longitude) of the ridging anticyclone and pressure at its centre are given when post-cyclonic airflow is experienced. An evaluation of snowfall is given from direct observation.

No.	Date of soil frost	Air P at cyclone centre (hPa)	Latitude of cyclone centre (°S)	Latitude of ridging anticyclone behind cold front (°S)	Longitude of anticyclone (°E)	Air pressure at anticyclone centre (hPa)	Duration of post-cyclonic airflow (hours)	Snowfall from cold front (Yes/No)
1	03/11/08	980	53	38	18	1020	48	Yes
2	08/11/08	972	46	35	12	1028	21	No
3	12/11/08	996	47	40	3	1032	25	No
4	03/12/08	968	56	32	5	1024	14	No
5	05/12/08	964	58	35	7	1024	13	No
6	09/12/08	988	51	32	0	1024	15	No
7	12/12/08	976	55	35	5	1024	4	No
8	13/12/08	972	50	–		–	10	No
9	14/12/08	982	46	32	10	1020	17	No
10	18/12/08	988	55	40	18	1020	4	No
11	03/01/09	988	54	52	18	1028	60	Yes
12	03/02/09	976	52	39	0	1028	6	No
13	05/02/09	984	58	39	5	1028	8	No
14	12/02/09	960	63	40	18	1028	6	No

of the post-cyclonic Antarctic airflow more temperate like that which occurred on the 17 December 2008 (Fig. 1a) which generated soil frost in the early morning of the 18th (no. 10, Tables 2, 3) as well for the soil frost cycles on the 12 November 2008 and the 3 December 2008 (nos. 3 and 4, Tables 2, 3), the subsequent soil frost cycle is short and shallow. The duration of post-cyclonic airflow in these instances (no snowfall) are also significantly negatively correlated with the latitudinal position of the cyclone centre moving over or south of Marion Island ($r = -0.68$, $P = 0.02$)

Discussion

Recent preliminary results show that at the micro-scale diurnal soil surface temperatures on Marion Island are influenced by a complex interaction of radiation balance, air mass circulation, cloud cover and snow (Nel, Boelhouwers et al. 2009). Effective nocturnal cooling to below freezing point has historically been reported to depend on clear, windless nights (Outcalt 1971) and soil frost on Marion Island also appears dependent on clear skies (Nel, Boelhouwers et al. 2009), with frequencies ranging from 60 to over 200 days per year in a climate dominated by strong winds, cloud cover and high soil moisture values. Misty and overcast conditions are associated with maritime temperate air mass and westerly circulation. However, clear, cloudless conditions do frequently occur that are linked to southerly circulation and Antarctic air (Smith & Steenkamp 1990; Le Roux 2008). Findings presented here demonstrate that soil frost is initiated in summer when there is Antarctic air mass circulation. This happens at night when airflow occurs from a ridging anticyclone after the passage of a cold front connected to a mid-latitudinal cyclone. Soil frost occurs since radiative heat loss is more dominant under this southerly airflow, when cloud cover is less, while cooling of the soil surface results immediately after the passage of the cold front due to sensible heat exchange (Nel, Boelhouwers et al. 2009) between the air and soil surface. The correlation between the duration of air frost with the duration of soil frost and soil minimum temperatures confirm the findings of Nel, Boelhouwers et al. (2009) regarding the importance of non-radiative heat exchanges in the sub-Antarctic environment.

Approximately 100 cyclones pass Marion Island each year (Smith 2002) and the path followed by each cyclone, relative to Marion, determines the duration of pre- and post-cyclonic conditions (Le Roux 2008). When cyclones pass over the island, intense pre- and post-cyclonic activity is experienced, with an equal duration

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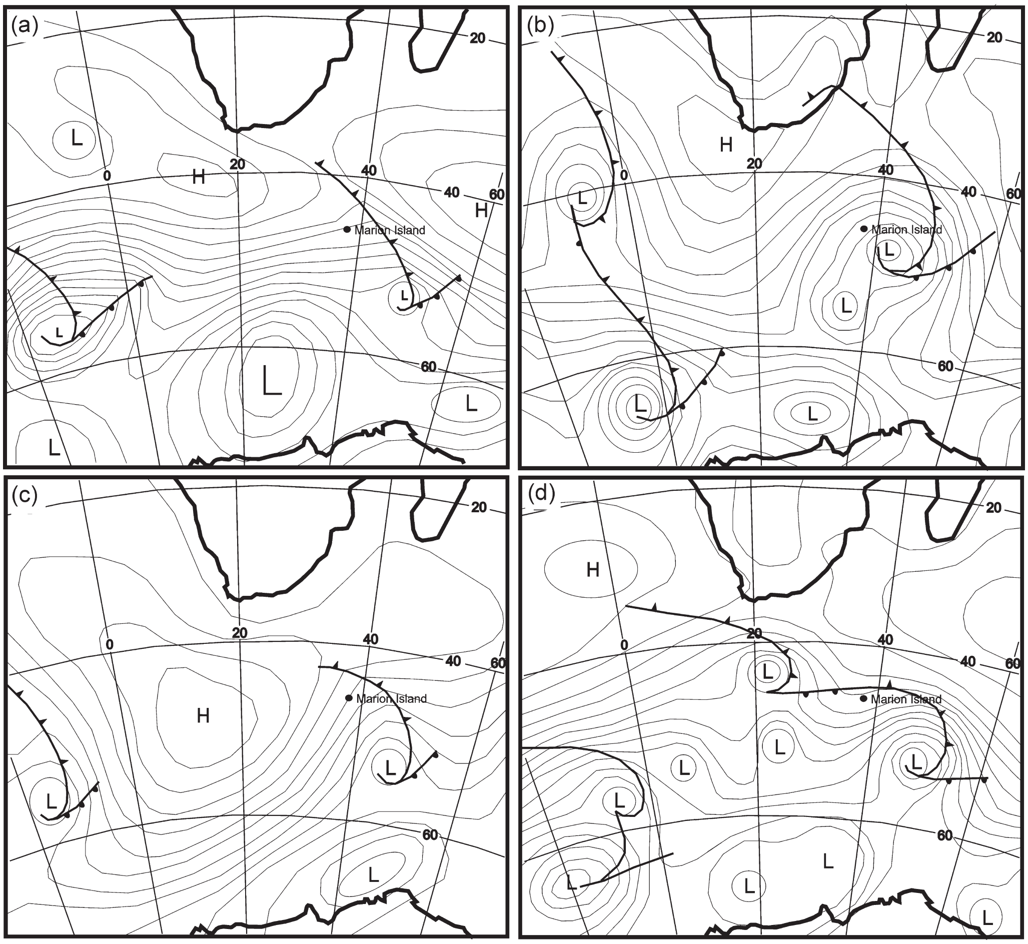

Fig. 1 Synoptic weather chart (surface pressure lines) of the Southern Ocean for (a) 17 December 2008 12:00 GMT, (b) 3 November 2008 18:00 GMT, (c) 3 January 2009 00:00 GMT and (d) 13 December 2008 18:00 GMT.

of each (Le Roux 2008). When a cyclone passes far south of the island, there is a longer but less intense pre-cyclonic period on the island, followed by a shorter post-cyclonic period (Smith & Steenkamp 1990). The seasonal displacement of the mean pressure field in summer and winter suggest that cyclonic activity as a whole is displaced southwards in summer (Schulze 1971). This implies that most mid-latitudinal cyclones pass south of Marion Island in summer. When this is the case the synoptic data show that the duration of post-cyclonic airflow is affected by the position of the anticyclone that moves in behind the cold front, and the position of the cyclone centre. This in turn influences the duration, intensity and depth of soil frost. By contrast, cyclones passing over or north of the island cause the duration of the post-cyclonic conditions to exceed that of the pre-cyclonic conditions (Le Roux 2008) and the island will experience mostly cold, clear weather (Smith & Steenkamp 1990). This is especially true in the occluded zone when the cold clear air has displaced the warm air to a greater vertical extent. This synoptic situation of a series of cyclones is a rarity in summer. Only one such situation occurred during the recording period, but it caused significant soil frost.

Snow is an extremely important control of ground microclimate in high altitude areas of the island (Holness 2003), where snow keeps the shallow soil temperatures at the freezing point of soil water and buffers the soil from temperature fluctuations (Nel, Boelhouwers et al. 2009). Therefore, the freezing cycles that are associated with snow cover had the longest duration and depth, as the presence of snow leads to deeper soil freezing coupled with ground heat flow to the contact surface with the snow (Nel, Boelhouwers et al. 2009). Even though the synoptic assessment of snowfall on Marion Island is beyond the scope of this study, it seems that snowfall is associated with the passage of a cold front linked to a strong system of low pressure just south of the island.

The ridging anticyclone behind this low pressure system also seems to be more persistent influencing the duration of post-cyclonic airflow and the southerly trajectory of the airflow. The case in point is the anticyclone on 3 January 2009, which remained in position for three days, acting as a blocking high and generating southerly, almost meridional post-cyclonic flow of 60 h (Table 2) with a trajectory that can be traced to the Antarctic coast (Fig. 1c). This southerly trajectory of air mass circulation also seems to increase the intensity of soil frost cycles.

Climate change implications

Under a changing climate, Marion Island will experience less cloud cover and more direct sunlight (Smith 2002). Rouault et al. (2005) also suggest that the pressure increase in summer measured on Marion corresponds to a decrease in rainfall, an increase in the number of days without precipitation and a northward shift in the wind direction. This suggests a change in cyclonic activity affecting the island with the reduction in the westerly wind component which, in turn, implies relatively more anticyclonic conditions over the island or a reduction in low pressure affecting the island in summer (Rouault et al. 2005). Smith & Steenkamp (1990) propose that the radiation and air temperature increases can be explained by the positions of cyclone tracks relative to the island. In warmer years the cyclonic centres pass, on average, further to the south of the island (Smith & Steenkamp 1990).

Climate change implications for soil frost dynamics on Marion Island therefore show various complex trends. The trend associated with a more southerly position of mid-latitudinal cyclones or a reduction in cyclone activity would reduce post-cyclonic airflow and the frequency, intensity and duration of soil frost through a reduction in cooling by sensible heat exchange. Also, recent climate amelioration has resulted in a reduction in snow cover at high altitudes (Sumner et al. 2004). The absence of snow cover facilitates a higher frequency of soil frost cycles in the interior (Holness 2001; Boelhouwers et al. 2003), but less snow will imply less deeply penetrating soil frost cycles with long duration. Another consideration is the impact of relatively more anticyclonic conditions over the island (Rouault et al. 2005). A persistent southerly positioned anticyclone has the potential to generated substantial Antarctic air mass circulation which will reduced cloud cover and increased radiational heat exchange at the soil surface. This could facilitate nocturnal cooling to an extent that may offset the influence of a warmer overall climate. The predicted changes in synoptic climate affecting the sub-Antarctic may, therefore, lead to a complex and non-linear response in terms of soil frost dynamics and its direct effects on soil sediment displacement and indirect effect on ecosystem dynamics.

Conclusion

All summer soil frost events recorded on Marion Island during this study were nocturnal and correlated to 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. The duration and intensity of the soil frost cycle is dependent on the duration of post-cyclonic airflow, which in turn seems to be connected to the latitudinal position of the ridging anticyclone and the passing cyclone. The length and depth of the soil frost cycles are also related to the southerly position of the trajectory of the post-cyclonic airflow. This paper suggests that the predicted trends in synoptic climate change for the sub-Antarctic may lead to a complex and non-linear response in terms of soil frost dynamics and its direct and indirect effects on the landscape.

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