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Short Note

The sub-Antarctic islands are increasingly warming in the 21st century

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This paper presents the rate of warming in the sub-Antarctic region in the 21st century and summarizes the landscape and ecosystem responses to the increased warming. The islands that constitute the 'core' of the sub-Antarctic region are South Georgia, Marion and Prince Edward islands, the archipelagos of Crozet and Kerguelen, Heard and McDonald islands and Macquarie Island (Convey 2020). These islands are located close to the Antarctic Polar Front, with air temperatures that are consistently cool and with annual and seasonal variability buffered by the surrounding cold ocean (Convey 2020). Climatic records from these sub-Antarctic islands have shown a warming air temperature trend throughout most of the mid- to late 20th century (Bergstrom & Chown 1999, Jacka *et al.* 2004, Pendlebury & Barnes-Keoghan 2007), and reports on the landscape and ecological impacts due to the warming climate during this period are numerous (see Bergstrom & Chown 1999). Generally, the main cause of ocean and atmospheric warming is the anthropogenic forcing of the trend towards the positive phase of the Southern Annular Mode (Pohl *et al.* 2021) and the associated intensification and poleward migration of the Southern Hemisphere westerly winds (Perren 2020). It is predicted that the sub-Antarctic region will continue to warm during the 21st century (Meehl *et al.* 2007). Given that we have entered the third decade of the 21st century, it is now possible to assess the recent warming trends over the core sub-Antarctic islands and to hypothesize as to what impacts the future air temperatures will have on landscape and ecosystem processes during the rest of the century.

Air temperature data for Marion Island (latitude: -46.883, longitude: 37.867), the Crozet Islands (Alfred Faure; latitude: -46.433, longitude: 51.850) the Kerguelen Islands (Port Aux Francais; latitude: -49.350, longitude: 70.250), Macquarie Island (latitude: -54.499, longitude: 158.937) and South Georgia (Grytviken; latitude: -54.283, longitude: -36.500) were downloaded from the GISTEMP v4 station data database (https://data.giss.nasa.gov/gistemp/). Mean annual air temperatures (MAATs) were analysed using the monthly means in the dataset, and if any monthly mean was missing in a specific year then that year was omitted from the analysis. For comparison, the MAATs for the New Zealand-associated 'sub-Antarctic' islands of Campbell (latitude: -52.550, longitude: 169.167) and Auckland (Enderby; latitude: -50.483; 166.300) were also analysed. Pearson's correlation coefficients showed that the MAATs of the core sub-Antarctic islands are positively correlated with their nearest neighbours (Table Ia). The temperature data from the two New Zealand islands are also strongly correlated. Of all the islands, the MAATs at Campbell Island appear most representative of the entire sub-Antarctic region based on the significant correlations with the other islands (> 95–99% confidence).

Macquarie, Kerguelen and Marion islands have warmed by between 0.8°C and 1.7°C since air temperature recordings started during the mid-20th century. These trends are significant at the 95–99% confidence level, except at the Crozet Islands (2006–2021) because of missing data (Table Ib). As expected, the warming trend established during the 20th century is continuing into the 21st century, but the recent (2000–2021) trend of warming (°C/100 years) is in all respects higher than the long-term trend (Table Ib, column 5). Since the turn of the century, the core sub-Antarctic islands (plus Campbell Island) show a warming trend of between 2.3 and 2.9°C/100 years, while the Auckland Islands (Enderby) shows a warming

Table I. a. Pearson's correlation coefficients (R^2) for mean annual temperature trends between stations and **b.** summary of linear regression statistics and rates of change of mean annual air temperature for sub-Antarctic stations.

a.	**Marion**						
Crozet	$R^2 = 0.49$** $n = 29$	**Crozet**					
Kerguelen	$R^2 = 0.58$** $n = 44$	$R^2 = 0.58$** $n = 20$	**Kerguelen**				
Macquarie	$R^2 = 0.53$** $n = 54$	$R^2 = 0.45$* $n = 25$	$R^2 = 0.49$** $n = 47$	**Macquarie**			
South Georgia	$R^2 = 0.22$ $n = 41$	$R^2 = 0.03$ $n = 20$	$R^2 = 0.31$ $n = 35$	$R^2 = 0.35$* $n = 40$		**South Georgia**	
Campbell	$R^2 = 0.55$** $n = 63$	$R^2 = 0.38$* $n = 30$	$R^2 = 0.52$** $n = 50$	$R^2 = 0.85$** $n = 60$		$R^2 = 0.32$* $n = 45$	**Campbell**
Auckland	$R^2 = 0.30$ $n = 17$	$R^2 = 0.21$ $n = 11$	$R^2 = 0.49$ $n = 15$	$R^2 = 0.78$** $n = 17$		$R^2 = 0.23$ $n = 8$	$R^2 = 0.92$** $n = 17$
b.	**Period**	**Mean (°C)**	**Trend (°C)**	**Trend (°C/100 years)**	R^2	P	n
Marion	1950–2021	5.4	+1.7	+2.4	0.76	< 0.01	64
	2000–2021	6.0	+0.6	+2.9	0.27	0.02	21
Crozet	1969–2021	5.3	+0.7	+1.2	0.26	< 0.01	31
	2006–2021	5.5	-	-	0.15	0.16	15
Kerguelen	1951–2020	4.8	+1.1	+1.5	0.49	< 0.01	51
	2000–2020	5.1	+0.6	+2.8	0.24	0.04	18
Macquarie	1951–2021	4.8	+0.8	+1.1	0.39	< 0.01	61
	2000–2021	5.1	+0.5	+2.3	0.28	0.01	21
South Georgia	1905–2019	2.6	+0.8	+0.7	0.22	< 0.01	89
Campbell	1944–2021	6.8	1.2	+1.5	0.49	< 0.01	75
	2000–2021	7.2	0.6	+2.5	0.32	< 0.01	21
Auckland	2000–2019	8.0	0.9	+4.7	0.60	< 0.01	18

*Significant at the 95% confidence level.
**Significant at the 99% confidence level.

trend of 4.7°C/100 years. From linear extrapolation of the long-term trends up to 2000, the predicted temperature in 2050 is 5.3°C at Macquarie Island, 5.9°C at the Kerguelen Islands and 6.7°C at Marion Island. However, from the rate measured since 2000, MAATs in the middle of the century (2050) are predicted to be 6.0°C at Macquarie Island, 6.3°C at the Kerguelen Islands and 7.2°C at Marion Island. Under current warming trends (2000–2021), the MAATs in 2050 at Campbell Island and the Auckland Islands could be as high as 8.2°C and 10.0°C, respectively. The current warming trend (since 2000) of between 2.3 and 2.9°C/100 years measured at the sub-Antarctic islands is already in line with the 2–3°C warming predicted for this region under the A2 emissions scenario by 2080–2099 (relative to 1980–1999; Meehl *et al.* 2007, fig. 10.8) and is within the projected change in surface air temperature (2–3°C) for the sub-Antarctic region at the end of the century (2081–2100) under the highest baseline emissions scenario of RCP8.5 (IPCC 2014, fig. SPM.7).

These measured (and extrapolated) warming trends in air temperature at the sub-Antarctic islands are impacting landscape and ecosystem processes. The further (accelerated) demise of glacial ice (from those islands that still have it), due to either the increase in air temperature (Sumner *et al.* 2004) and/or the decrease in snow accumulation (Favier *et al.* 2016), means that the cryosphere is fast approaching an irreversible tipping point in the sub-Antarctic, as predicted by Bakke *et al.* (2021). Warmer air temperatures will also modify ground thermal dynamics, which could impact the frequency and magnitude of needle ice growth, the freezing depths of both diurnal and seasonal frost and sediment movement and cycling. Needle ice formation is a very important diurnal soil frost process across most islands (Nel *et al.* 2021), impacting several keystone species and small-scale geomorphic processes in the fellfield habitat (Nel & Boelhouwers 2014). Transported propagules of invasive plant species have been shown to have increased rates of establishment and range expansion in the terrestrial habitats of the sub-Antarctic (Convey 2020). Invasive vertebrates pose a significant risk to the ecology of sub-Antarctic islands, as shown by the impacts of the mice currently existing on Marion Island on ecosystem structure and functioning (Greve *et al.* 2017) and on the predation on seabirds (Dilley *et al.* 2016; see also mousefreemarion.org). Under an increasingly warming climate, the risk posed by invasive species to the ecology of the sub-Antarctic islands is predicted to intensify. The effective implementation of biosecurity measures for the sub-Antarctic islands is becoming progressively more crucial (Convey 2020).

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Author contributions

All of the authors have made substantial contributions to this paper and approved the final version of the manuscript. The authors' contributions appear below as per CRediT guidelines: WN: Conceptualization, Methodology, Validation, Formal analysis, Writing - Original Draft. DWH: Validation, Writing - Review & Editing. EMR: Validation, Writing - Review & Editing.

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