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Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere

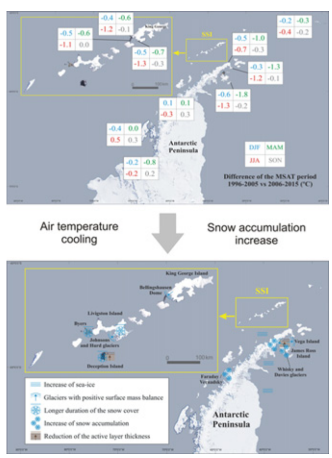
M. Oliva [a,*], F. Navarro [b], F. Hrbáček [c], A. Hernández [d], D. Nývlt [c], P. Pereira [e], J. Ruiz-Fernández [f], &, R. Trigo [d]

[a] Centre for Geographical Studies - IGOT, Universidade de Lisboa, Lisbon, Portugal
[b] Departmento de Matemática Aplicada, Universidad Politécnica de Madrid, Madrid, Spain
[c] Department of Geography, Masaryk University, Brno, Czech Republic
[d] Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal
[e] Environmental Management Center, Mykolas Romeris University, Vilnius, Lithuania
[f] Department of Geography, University of Oviedo, Oviedo, Spain

HIGHLIGHTS

- We examine climate variability since the 1950s in the Antarctic Peninsula region.
- This region is often cited among those with the fastest warming rates on Earth.
- A re-assessment of climate data shows a cooling trend initiated around 1998/1999.
- This recent cooling has already impacted the cryosphere in the northern AP.
- Observed changes on glacial mass balances, snow cover and permafrost state

GRAPHICAL ABSTRACT



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ABSTRACT

The Antarctic Peninsula (AP) is often described as a region with one of the largest warming trends on Earth since the 1950s, based on the temperature trend of 0.54 °C/decade during 1951–2011 recorded at Faraday/Vernadsky station. Accordingly, most works describing the evolution of the natural systems in the AP region cite this extreme trend as the underlying cause of their observed changes. However, a recent analysis (Turner et al., 2016) has shown that the regionally stacked temperature record for the last three decades has shifted from a warming trend of 0.32 °C/decade during 1979–1997 to a cooling trend of −0.47 °C/decade during 1999–2014. While that study focuses on the period 1979–2014, averaging the data over the entire AP region, we here update and re-assess the spatially-distributed temperature trends and inter-decadal variability from 1950 to 2015, using data from ten stations distributed across the AP region. We show that Faraday/Vernadsky warming trend is an

Abbreviations: AP, Antarctic Peninsula; DJF, December-January-February; ENSO, El Niño–Southern Oscillation; JJA, June-July-August; MAAT, Mean Annual Air Temperature; MAM, March-April-May; MSAT, Mean Seasonal Air Temperature; PDO, Pacific Decadal Oscillation; SAM, Southern Annular Mode; SMB, Surface Mass Balance; SON, September-October-November; SSI, South Shetland Islands.

* Corresponding author.
E-mail address: oliva_marc@yahoo.com (M. Oliva).

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extreme case, circa twice those of the long-term records from other parts of the northern AP. Our results also indicate that the cooling initiated in 1998/1999 has been most significant in the N and NE of the AP and the South Shetland Islands (>0.5 °C between the two last decades), modest in the Orkney Islands, and absent in the SW of the AP. This recent cooling has already impacted the cryosphere in the northern AP, including slow-down of glacier recession, a shift to surface mass gains of the peripheral glacier and a thinning of the active layer of permafrost in northern AP islands.

1. Introduction

During recent years several studies have analysed the evolution of Antarctic climate during the second half of the 20th century and the beginning of the 21st century. While there is no agreement on the magnitude and rate of warming for the whole continent (Vaughan et al., 2001; Steig et al., 2009; Schneider et al., 2012; Bromwich et al., 2013, 2014), all studies consistently show evidence of the pronounced warming that occurred on and around the Antarctic Peninsula (AP) prior to the 2000s (King, 1994; Marshall et al., 2002; Vaughan et al., 2003; Turner et al., 2005a; Stastna, 2010; Kejna et al., 2013). In fact, the AP has recorded one of the strongest warming rates on Earth, with an increase of ~0.5 °C/decade since 1950 (Turner et al., 2014). Accordingly, the vast majority of recent studies published examining marine and terrestrial ecosystem dynamics, and the evolution of the cryosphere in the AP region have referred to the review papers (e.g. Turner et al., 2014) and international reports (e.g. Vaughan et al., 2013) that underline this regional thermal increase. Higher temperatures have been accompanied by increased precipitation, as suggested both by observations (Turner et al., 2005b; Miles et al., 2008) and modelling (van den Broeke et al., 2006), which has led to higher snow accumulation, particularly in the western AP (Thomas et al., 2008). Marshall et al. (2006) attributed these trends to increased westerlies across the northern AP region associated to variations in the Southern Annular Mode (SAM) and El Niño–Southern Oscillation (ENSO) atmospheric teleconnections (Ding et al., 2011; Clem and Fogt, 2013) as well as to ozone depletion (Thompson & Solomon, 2002).

Observed processes occurring in the natural systems of the AP region have been related to this "recent" regional atmospheric warming trend, and concurrent oceanic changes, including (1) reductions of the seasonal sea-ice extent (Stammerjohn et al., 2008; Goosse & Zunz, 2014; Li et al., 2014), (2) increased ocean temperatures both in the Weddell (Robertson et al., 2002) and Bellingshausen seas (Meredith & King, 2005), (3) retreating ice fronts of both marine- and land-terminating glaciers in the region (Rau et al., 2004; Cook et al., 2005, 2014, 2016), (4) ice-shelf disintegration or retreat and subsequent acceleration of the inland glaciers feeding the ice-shelves (Rignot et al., 2004; Scambos et al., 2004; van den Broeke, 2005; Cook & Vaughan, 2010), (5) enhanced glacier dynamic thinning, acceleration and retreat driven by basal melting of ice shelves (Pritchard et al., 2012; Rignot et al., 2013; Wouters et al., 2015; Fürst et al., 2016), (6) changes on terrestrial biology (Convey, 2003; Convey & Smith, 2006; Convey et al., 2009), and (7) variations of geomorphic processes, permafrost degradation and active layer thickness in ice-free environments (Bockheim et al., 2013; Oliva & Ruiz-Fernández, 2015).

However, most of these studies, typically using periods spanning between the late 1950s and the early 2000s, often do not include climatic data referred to the last decade. Moreover, the trends are usually inferred for the whole period of the instrumental series, but generally do not analyse the interdecadal or short-term variability. Certain reports recently presented preliminary indications that the warming over the AP region has slowed down markedly since the beginning of the century (Blunden & Arndt, 2012; Turner et al., 2015). Carrasco (2013) detected a decrease in the warming rate in stations from the western side of the AP between 2001 and 2010 with even a slight cooling trend in King George Island (South Shetland Islands, SSI). More recently, Turner et al. (2016) have presented a thorough analysis of the regional stacked temperature record of the AP for the period 1979–2014, with the choice of 1979 as start of the time series because it marks the start of the availability of reliable atmospheric reanalyses datasets that incorporate satellite data, as well as fields of sea-ice concentration. Their analysis has shown a diverging trend from warming (by 0.32 ± 0.20 °C/decade) during 1979–1997 to cooling (by −0.47 ± 0.25 °C/decade) during 1999–2014, with the cooling trend being largest in summer.

However, the analysis by Turner et al. (2016) has considered a stacked temperature record describing the regional average temperature evolution, and does not use the complete temperature time series available. We here complete and extend their study by presenting an updated assessment of the spatially-distributed temperature trends and interdecadal variability of mean annual air temperature (MAAT) and mean seasonal air temperature (MSAT) from 1950 to 2015, using data from ten stations distributed across the AP region. Some recent studies have presented indications of certain environmental impacts on the cryosphere of this recent cooling, though a regional analysis is still lacking. To fill this gap, in this paper we pay special attention to the evaluation of the spatial distribution of the regional cooling between the two most recent decades, and analyse its cryospheric impacts, including slow-down of glacier recession, a shift to surface mass gains of the glaciers peripheral to the AP, and thinning of the active layer of permafrost in the northern AP islands. As the paper by Turner et al. (2016) provides a detailed study of the main atmospheric drivers of the recent cooling trend, here we specifically focus on the role of sea ice – a component of the cryosphere – as a controlling factor of the observed changes in the cryosphere.

2. Study area

The AP is a mountainous landmass stretching northwards >1000 km between 63° and 73°S. This ridge-shaped peninsula encompasses an emerged terrestrial surface exceeding 520,000 km^2 (Summerhayes et al., 2009), which corresponds to the northernmost part of the Antarctic continent (Fig. 1). The average altitude of the AP summit plateaux is ~1500 m a.s.l. (Summerhayes et al., 2009), with an average width of ~70 km between 63° S and 69° S and of ~200 km between 69° and 73°S. Along this N-S mountain chain, several islands and archipelagos surround the AP.

About 98% of the AP is ice-covered (Bockheim, 2015), with a large ice sheet extending over the terrestrial surface and some ice shelves along the western and eastern margins of the peninsula. Moreover, most of the peripheral islands are heavily glaciated and covered by ice caps and valley glaciers (Bliss et al., 2013). The AP Ice Sheet has experienced significant mass losses in recent decades, especially in its northern part, mostly resulting from the acceleration and thinning of outlet glaciers following ice-shelf break-up (Vaughan et al., 2013). These losses currently (2005–2010) contribute 0.10 ± 0.03 mm a^{-1} to global sea level rise (Shepherd et al., 2012). The contribution to sea level rise from the peripheral glaciers is currently believed to be negligible, at 0.017 ± 0.028 mm a^{-1} for the period 2003–2009 (Gardner et al., 2013), contrary to some previous estimates suggesting a rather large contribution of 0.22 ± 0.16 mm a^{-1} for the period 1961–2004 (Hock et al., 2009).

The low-pressure systems moving eastward-southeastwards across the AP bring prevailing westerly winds along the AP during the whole year, more intense in the northern tip of the peninsula. The AP ridge constitutes an orographic barrier to the wet westerly winds, which causes a föhn effect in the eastern side (Grosvenor et al., 2014; Elvidge et al., 2015) inducing a warming effect over this region, associated with the

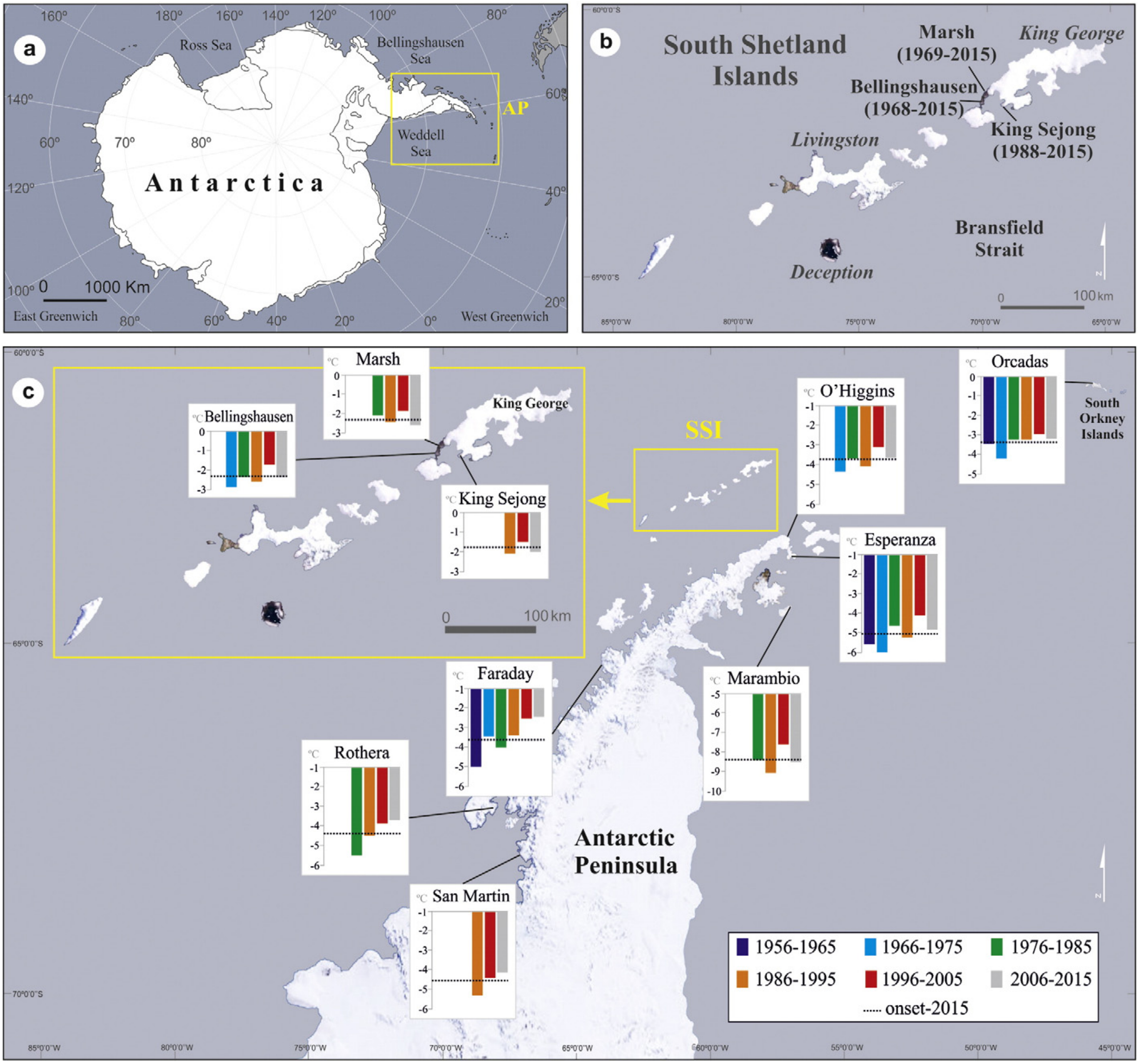

Fig. 1. Location of the AP within the Antarctic continent. b. Detail of the South Shetland Islands and its stations. c. Distribution of the stations on the Peninsula and neighbouring islands, with inter-decadal MAAT variations since 1956 across the AP region.

adiabatic heating from the air subsidence. It also implicates distinct moisture content values in the two sides of the AP, with the eastern side becoming comparatively drier than the western side. However, the eastern side of the AP is also strongly affected by the cold air masses associated with the northwards ocean circulation in the Weddell Sea. A similar pattern was found for air circulation, for which cold southerly barrier winds (or low-level jets; Stensrud, 1996) flowing along the eastern coast of the AP are typical. Overall, the strength of this second mechanism is stronger than the föhn effect thus introducing important thermal asymmetries between the western (warmer and wetter) and eastern (colder and drier) parts of the AP. At latitudes 62–64°S, the contemporary mean annual temperatures on the western side of the AP are ca. −2 °C at sea level (e.g. SSI), while on the eastern side are ca. −7 °C (e.g. James Ross Island).

Ice-free terrestrial environments are distributed along the coastal fringes of the AP and surrounding islands, as well as in small areas protruding the ice in the AP plateaux. The largest ice-free areas are located in islands distributed along the NE side of the AP, such as the Ulu Peninsula on James Ross Island (ca. 300 km^2), Vega Island (ca. 80 km^2) and Seymour Island (ca. 70 km^2). By contrast, ice-free areas on the western side of the AP are significantly smaller, with the largest Byers Peninsula on Livingston Island (ca. 60 km^2) and Fildes Peninsula on King George Island (ca. 30 km^2).

3. Data and methods

We studied climatic data, namely mean monthly temperature series from 10 meteorological stations across the AP region (Table 1), distributed into three main areas (Fig. 1):

- SSI: Bellingshausen, Marsh and King Sejong stations.
- SW: Faraday/Vernadsky, Rothera and San Martin stations.
- N-NE: Orcadas, Esperanza, O'Higgins and Marambio stations.

The data were obtained from the READER (2016) (REference Antarctic Data for Environmental Research) database (https://legacy.bas.ac.

Table 1
Meteorological stations and corresponding temperature climate series examined in this research.

Region	Station	Available data	Latitude	Longitude	Elevation (m)
SSI	Bellingshausen	1968–2015	62.2 S	58.9 W	16
	Marsh	1969–2015	62.2 S	58.9 W	10
	King Sejong	1988–2015	62.2 S	58.7 W	11
SW	Faraday/Vernadsky	1950–2015	65.4 S	64.4 W	11
	Rothera	1976–2015	67.5 S	68.1 W	32
	San Martin	1980–2015	68.1 S	67.1 W	4
N-NE	Orcadas	1903–2015	60.7 S	44.7 W	6
	Esperanza	1945–2015	63.4 S	57.0 W	13
	O'Higgins	1963–2015	63.3 S	57.9 W	10
	Marambio	1971–2015	64.2 S	56.7 W	198

uk/met/READER/surface/stationpt.html). We took into account mean monthly values that include at least 85% of the original daily observations. The months without temperature data, or not reaching the minimum 85% threshold of daily observations, were completed using multiple regressions based on data from the best correlated stations in the region (Table 2). The percentage of missing monthly data is <5% for all stations except for San Martin, where missing monthly data is ca. 30%. However, due to the fact that San Martin corresponds to the southernmost station and also considering the high correlations existing with other nearby stations (i.e. Rothera, Faraday) we have maintained this station in the analysis.

Three stations have measured climatic data at least since 1950 (Orcadas, Esperanza, Faraday/Vernadsky), other three were set up in the late 1960s (O'Higgins, Bellinghausen, Marsh), two more were established during the 1970s (Marambio, Rothera) and the last two stations used in this study were installed during the 1980s (San Martin, King Sejong). A few other stations existing in the region were discarded because of the significant amounts of data gaps.

Monthly data have been analysed for the entire period included for every station — depending on climate data availability for each site — as well as subdivided into decadal series starting from the most recent available data backwards. We have quantified climate parameters: MAAT, MSAT and their associated linear trends for the: 1) entire periods 2) period until 2005 which corresponds approximately to earlier assessments (e.g. Vaughan et al., 2003; Turner et al., 2005a), and 3) the most recent decade 2006–2015. The significance of all series trends was calculated using the Mann-Kendall test. Statistically significant differences were considered at $p < 0.05$.

4. Spatio-temporal variations of air temperature trends in the AP region

4.1. Mean annual temperatures

Despite the differences as a function of the station and time period considered, all the MAATs were negative in all the study sites across the AP region during the entire study period (Table 3). However, the sign and magnitude of the temperature trends were different depending on the location and period considered (Fig. 2 and Table 4). For the 30-year period 1986–2015, for which there are data available for the considered meteorological stations, the highest temperatures were recorded on the SSI, to the NW of the AP, with annual mean values ranging from −1.8 to −2.3 °C (Table 3). Moving southwards, in the western AP region, annual temperatures showed slightly cooler values, with −2.8 °C at Faraday/Vernadsky (65°S), −4.1 °C at Rothera (67°S) and −4.6 °C at San Martin (68°S). The stations situated in the N and NE tip of the AP, despite being located at similar latitudes as those on the SSI, recorded colder temperatures such as −3.6 °C at O'Higgins and −4.7 °C at Esperanza. The proximity of Marambio station to the colder Weddell Sea and its higher elevation (196 m a.s.l.) is reflected in the significantly lower MAAT (−8.3 °C). This influence is also recorded in the South Orkney Islands, where, despite being located at 54°S latitude, the MAAT at Orcadas station was 1 °C colder than that of the SSI (62°S), with an average of −3.2 °C.

4.2. Variability of decadal temperatures

The longest available climate records show that 1956–1965 was the coldest decade in the southern AP region, with a MAAT −2.5 °C below the 2006–2015 average at Faraday/Vernadsky station (Table 5 and dark blue column in Fig. 1c), whereas in the northern AP region and surrounding archipelagos the following decade 1966–1975 was the coldest in the instrumental period, with MAATs between 0.5 (Bellingshausen) and 1.2 °C (Esperanza) colder than the 2006–2015 average (Table 5 and light blue column in Fig. 1c). The decade 1976–1985 showed MAATs similar to the 2006–2015 average in the northern AP region, but significantly lower (1.6 °C) at the southernmost stations of Faraday/Vernadsky and Rothera (Table 5 and green column in Fig. 1c).

Focusing on the last 30-year period 1986–2015, for which temperature data are available at all stations, the coldest decade was 1986–1995 (orange column in Fig. 1c), which was also colder than the previous decade (1976–1985) in all stations except at Faraday/Vernadsky and Rothera, where MAATs increased by 0.7 and 0.9 °C, respectively (Table 5). The warmest decade across the region was 1996–2005 (red column in Fig. 1c), except for the SW corner of the AP, where the 2006–2015 decade was 0.1–0.2 °C warmer than the previous decade (Table 5). For the remaining stations, the last decade 2006–2015 was cooler than the preceding one, though the magnitude of the change was significantly different depending on the location (Table 5 and grey column in Fig. 1c).

4.3. Seasonal temperature trends observed during the 2006–2015 decade

Decadal changes of annual temperature are important to analyse (Fig. 1c and Table 5) but are bound to amalgamate different behaviours at the seasonal scale. In order to better understand the evolution of seasonal temperatures at the decadal scale we provide the seasonal

Table 2
Correlation matrix between mean annual temperatures (above) and the number of years supporting these correlations (below). Significance differences at a $p < 0.05$ (in italic) and $p < 0.01$.

	Bellingshausen	Marsh	King Sejong	Faraday	Rothera	San Martin	Orcadas	Esperanza	O'Higgins	Marambio
Bellingshausen		0.97	0.85	0.65	0.68	0.63	0.75	0.87	0.94	0.85
Marsh	30		0.82	0.63	0.65	0.54	0.77	0.87	0.91	0.84
King Sejong	28	28		0.62	0.63	0.53	0.74	0.67	0.77	0.65
Faraday	48	30	28		0.95	0.85	0.53	0.53	0.58	*0.35*
Rothera	39	30	28	39		0.92	0.63	0.52	0.66	0.48
San Martin	31	30	28	31	31		0.56	0.57	0.67	0.50
Orcadas	48	30	28	66	39	31		0.77	0.72	0.71
Esperanza	48	30	28	64	39	31	64		0.92	0.97
O'Higgins	48	30	28	53	39	31	53	53		0.91
Marambio	44	30	28	44	39	31	44	44	44	

Table 3
Annual, summer, autumn, winter and spring mean air temperature at all the studied meteorological stations in different periods. The periods included are: 1) the longest recording period for each station, 2) the longest period with data recorded at all stations (1986–2015), 3) the period from the start of recoding at each station till the end of the previous decade (2005), and 4) the last decade (2006–2015).

Region	Station	Period	Annual MAAT (°C)	Summer (DJF) MSAT (°C)	Autumn (MAM) MSAT (°C)	Winter (JJA) MSAT (°C)	Spring (SON) MSAT (°C)
SSI	Bellingshausen	1968–2015	−2.3	1.1	−1.6	−6.1	−2.7
		1986–2015	−2.2	1.2	−1.5	−5.9	−2.8
		1968–2005	−2.3	1.2	−1.7	−6.1	−2.7
		2006–2015	−2.3	0.9	−1.4	−6.0	−2.8
	Marsh	1969–2015	−2.3	1.0	−1.6	−6.0	−2.7
		1986–2015	−2.3	0.9	−1.6	−5.7	−2.8
		1969–2005	−2.3	1.2	−1.6	−5.9	−2.6
		2006–2015	−2.5	0.6	−1.6	−6.0	−3.0
	King Sejong	1986–2015	−1.8	1.5	−1.2	−5.3	−2.2
		1986–2005	−1.8	1.7	−1.1	−5.1	−2.0
		2006–2015	−2.1	1.2	−1.2	−5.8	−2.5
SW	Faraday	1950–2015	−3.7	0.4	−2.5	−8.0	−4.6
		1986–2015	−2.8	0.7	−1.6	−6.3	−4.1
		1950–2005	−3.9	0.3	−2.7	−8.4	−4.8
		2006–2015	−2.5	0.8	−1.4	−5.8	−3.7
	Rothera	1977–2015	−4.3	0.7	−3.0	−9.7	−5.5
		1986–2015	−4.1	0.8	−2.7	−9.3	−5.2
		1977–2005	−4.6	0.8	−3.2	−10.1	−5.7
		2006–2015	−3.8	0.6	−2.5	−8.5	−4.9
	San Martin	1985–2015	−4.6	1.2	−3.0	−11.0	−5.7
		1986–2015	−4.6	1.2	−3.0	−11.0	−5.7
		1985–2005	−4.8	1.2	−3.2	−11.3	−5.8
		2006–2015	−4.2	1.2	−2.6	−10.1	−5.2
N-NE	Orcadas	1950–2015	−3.4	0.7	−2.4	−8.8	−3.2
		1986–2015	−3.2	1.0	−2.1	−8.4	−3.1
		1950–2005	−3.5	0.7	−2.5	−8.9	−3.2
		2006–2015	−3.2	1.0	−1.8	−8.2	−3.0
	Esperanza	1952–2015	−5.1	0.4	−6.1	−10.6	−4.3
		1986–2015	−5.1	0.4	−6.1	−10.6	−4.3
		1952–2005	−5.2	0.3	−6.2	−10.6	−4.3
		2006–2015	−4.8	0.9	−5.4	−10.8	−4.3
	O'Higgins	1963–2015	−3.8	0.2	−3.6	−7.9	−3.7
		1986–2015	−3.6	0.3	−3.4	−7.6	−3.8
		1963–2005	−3.8	0.3	−3.7	−8.0	−3.7
		2006–2015	−3.7	0.1	−3.2	−7.6	−3.8
	Marambio	1971–2015	−8.5	−1.7	−10.0	−14.8	−7.4
		1986–2015	−8.3	−1.4	−9.7	−14.7	−7.4
		1971–2005	−8.4	−1.7	−10.0	−14.7	−7.3
		2006–2015	−8.4	−1.6	−9.8	−15.1	−7.7

changes detected during the 2006–2015 decade with respect to the 1996–2005 decade average, which showed different spatial patterns across the AP region (Fig. 3).

In the SSI, the most pronounced differences were recorded during the winter season (JJA), whose MSATs were between 0.8 and 1.7 °C colder, and the lowest differences were those of the spring season (SON), with stable or slightly negative temperature trends (0.0–0.3 °C). Summer (DJF) temperatures showed a moderate diminution (0.2–0.5 °C), more accentuated in autumn (MAM) (0.6–0.7 °C).

In the SW corner of the AP region, seasonal temperature variations showed divergent patterns. Winter temperatures decreased at Faraday/Vernadsky and San Martin (0.2 and 0.3 °C, respectively), but increased at Rothera station by 0.5 °C. Spring recorded higher temperatures during the 2006–2015 decade in all stations (with an increase of 0.2–0.3 °C). Summer was colder at stations below 67–68° S latitude by 0.2–0.4 °C, but was slightly warmer at Faraday/Vernadsky (0.1 °C). In contrast, autumn saw rather stable temperatures in the AP region except for the southernmost San Martin station, which showed a significant decrease of 0.8 °C.

The stations located in the N and NE tip of the AP showed a similar behaviour to that observed on the SSI, though the magnitude of the changes was more pronounced. Autumn (1–1.8 °C) and winter (0.7–1.3 °C) showed the strongest cooling in the decade 2006–2015, more intense southwards. The summer months were also colder than during the previous decade 1996–2005 (0.3–0.6 °C), as well as the spring season, which was also slightly colder (0.1–0.3 °C). The South Orkney Islands showed a similar seasonal pattern with colder MSATs during all the seasons. The interdecadal temperature decrease was moderate in winter (0.4 °C) and autumn (0.3 °C), and slightly weaker in spring and summer (0.2 °C).

5. Discussion

The low number of meteorological stations with climate records in Antarctica prior to the 1970s–1980s hinders inferring clear trends for the entire continent (e.g. Steig et al., 2009; Bromwich et al., 2013). This situation is less marked in the AP region, where a significant number of stations have recorded climatic data during the second half of the 20th century, providing a higher density network in comparison with the rest of the Antarctic continent. Using climatic data from these stations, we examine to what extent the recent widespread cooling of the AP region since the mid-2000s fits within the long-term spatio-temporal variations detected in the AP since the mid-20th century as well as how the seasonal changes observed during the last decade may have impacted the cryosphere in the region. This is of interest, because until now many recent cryospheric and life sciences studies focusing on the AP region have related their dynamics to the warming trend recorded over the last decades (e.g. Convey, 2003; Convey & Smith, 2006; Convey et al., 2009; Bockheim et al., 2013; Li et al., 2014; Turner et al., 2014). Within this paradigm, in these studies there is a

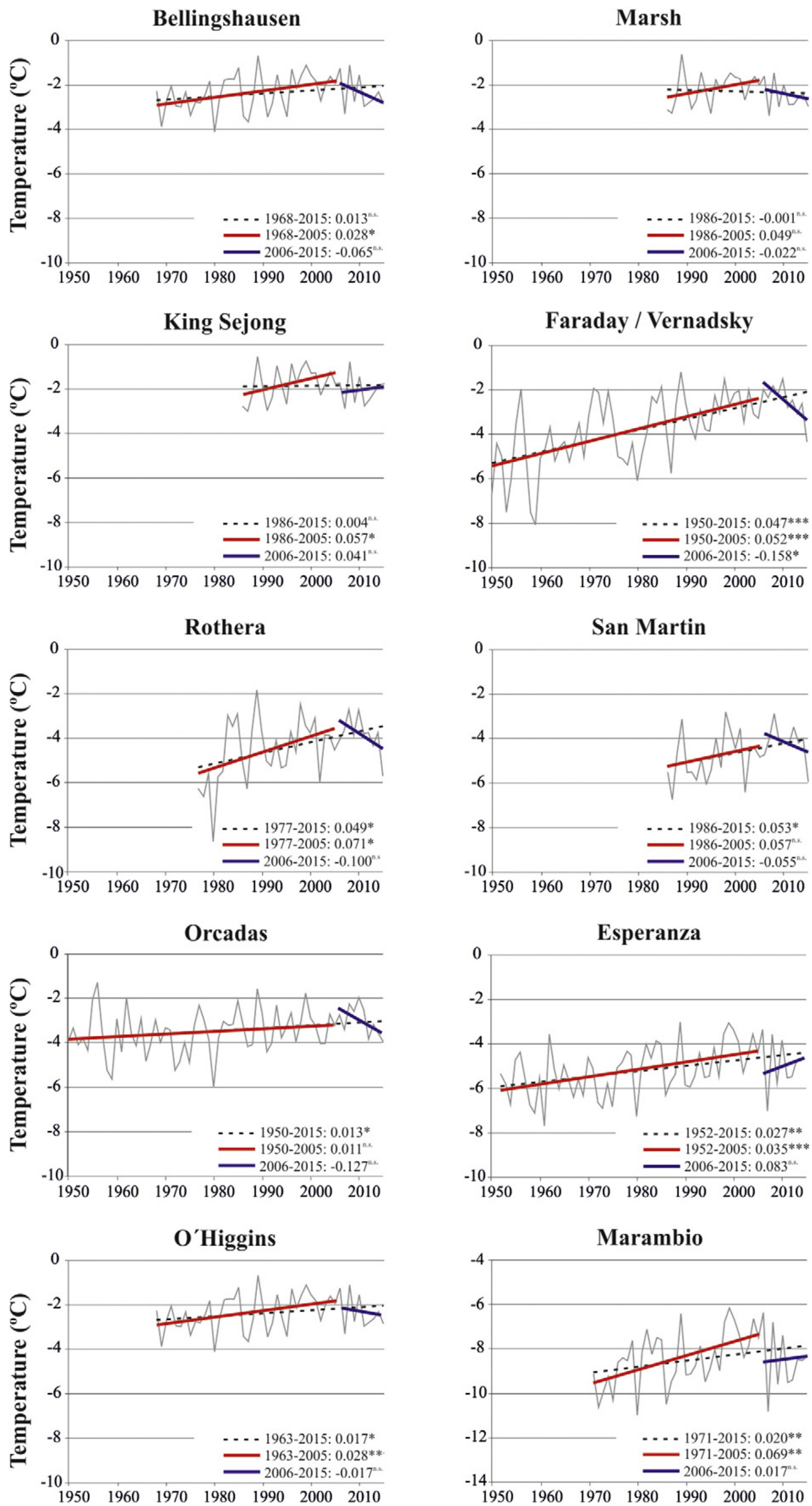

Fig. 2. Temporal evolution of the MAATs for selected stations, including significant trends at $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$ and n.s. (not significant at $p > 0.05$).

Table 4
Annual, summer, autumn, winter and spring trends of air temperature at all the studied meteorological stations, for: 1) the entire recording period for each station, 2) the period between the start of recording at each station and 2005, and 3) the last decade. Trends are presented in °C per year.

Region	Station	Period	Annual Trend	Summer (DJF) Trend	Autumn (MAM) Trend	Winter (JJA) Trend	Spring (SON) Trend
SSI	Bellingshausen	1968–2015	0.013$^{n.s.}$	0.005$^{n.s.}$	0.024*	0.030$^{n.s.}$	−0.004$^{n.s.}$
		1968–2005	0.028*	0.020*	0.037*	0.059*	0.000$^{n.s.}$
		2006–2015	−0.065$^{n.s.}$	−0.172**	−0.033$^{n.s.}$	−0.017$^{n.s.}$	−0.143$^{n.s.}$
	Marsh	1986–2015	−0.001$^{n.s.}$	−0.027**	0.012$^{n.s.}$	0.019$^{n.s.}$	−0.018$^{n.s.}$
		1986–2005	0.049$^{n.s.}$	−0.008$^{n.s.}$	0.068$^{n.s.}$	0.129$^{n.s.}$	0.014$^{n.s.}$
		2006–2015	−0.022$^{n.s.}$	−0.133*	0.048$^{n.s.}$	0.092$^{n.s.}$	−0.120$^{n.s.}$
	King Sejong	1986–2015	0.004$^{n.s.}$	−0.040**	0.004$^{n.s.}$	−0.027$^{n.s.}$	−0.038$^{n.s.}$
		1986–2005	0.057*	−0.022$^{n.s.}$	0.056$^{n.s.}$	0.061$^{n.s.}$	0.028$^{n.s.}$
		2006–2015	0.041$^{n.s.}$	−0.127*	0.057$^{n.s.}$	0.006$^{n.s.}$	−0.065$^{n.s.}$
SW	Faraday	1950–2015	0.047***	0.019***	0.037***	0.093***	0.028**
		1950–2005	0.052***	0.022***	0.043***	0.105***	0.028**
		2006–2015	−0.158*	−0.100$^{n.s.}$	0.042$^{n.s.}$	−0.087$^{n.s.}$	−0.317*
	Rothera	1977–2015	0.049*	0.004$^{n.s.}$	0.041**	0.087*	0.040$^{n.s.}$
		1977–2005	0.071*	0.029$^{n.s.}$	0.067*	0.103$^{n.s.}$	0.078$^{n.s.}$
		2006–2015	−0.100$^{n.s.}$	−0.104	0.000$^{n.s.}$	−0.033$^{n.s.}$	−0.211$^{n.s.}$
	San Martin	1986–2015	0.053*	0.000$^{n.s.}$	0.029$^{n.s.}$	0.082$^{n.s.}$	0.026$^{n.s.}$
		1986–2005	0.057$^{n.s.}$	0.000$^{n.s.}$	0.078$^{n.s.}$	0.061$^{n.s.}$	0.069$^{n.s.}$
		2006–2015	−0.055$^{n.s.}$	−0.020$^{n.s.}$	−0.028$^{n.s.}$	−0.017$^{n.s.}$	−0.267*
N-NE	Orcadas	1950–2015	0.013*	0.015***	0.014$^{n.s.}$	0.015$^{n.s.}$	0.002$^{n.s.}$
		1950–2005	0.011$^{n.s.}$	0.016*	0.014$^{n.s.}$	0.009$^{n.s.}$	0.003$^{n.s.}$
		2006–2015	−0.127$^{n.s.}$	−0.180$^{n.s.}$	−0.233$^{n.s.}$	0.217$^{n.s.}$	−0.220$^{n.s.}$
	Esperanza	1952–2015	0.027**	0.029***	0.044**	0.016$^{n.s.}$	0.007$^{n.s.}$
		1952–2015	0.035***	0.036***	0.053*	0.037$^{n.s.}$	0.018$^{n.s.}$
		2006–2015	0.083$^{n.s.}$	−0.106$^{n.s.}$	0.300$^{n.s.}$	0.133$^{n.s.}$	−0.100$^{n.s.}$
	O'Higgins	1963–2015	0.017*	0.008$^{n.s.}$	0.039**	0.033$^{n.s.}$	−0.001$^{n.s.}$
		1963–2005	0.028**	0.023***	0.055**	0.050*	0.007$^{n.s.}$
		2006–2015	−0.017$^{n.s.}$	−0.117*	0.067$^{n.s.}$	0.154$^{n.s.}$	0.011$^{n.s.}$
	Marambio	1971–2015	0.020**	0.028*	0.048$^{n.s.}$	0.020$^{n.s.}$	0.003$^{n.s.}$
		1971–2005	0.069**	0.061**	0.100*	0.061$^{n.s.}$	0.037$^{n.s.}$
		2006–2015	0.017$^{n.s.}$	−0.252*	0.300$^{n.s.}$	0.175$^{n.s.}$	−0.167$^{n.s.}$

*** Significant difference at $p < 0.001$.
** Significant difference at $p < 0.01$.
* Significant difference at $p < 0.05$.
$^{n.s}$ Non-significant at $p > 0.05$.

widespread use, as representative example of this warming trend, of the warming rate recorded at Faraday/Vernadsky station for the period 1951–2011, 0.54 °C/decade and almost twice as much in winter, which is one of the fastest warming rates on Earth (Turner et al., 2014). Similar warming rates have been inferred from meteorological data (Steig et al., 2009; Bromwich et al., 2013, 2014) and ice-core records (Thomas et al., 2013) from several sites in coastal and continental West Antarctica.

Up to now, most of the studies referred to the AP region did not include instrumental data collected after 2005 and thus did not capture the diverging trend towards cooling initiated around 1998–2000 shown in the instrumental records (Fig. 4) and confirmed by the most recently published works (e.g. Carrasco, 2013; Turner et al., 2016). This implies that there is a time offset between some of the recent changes observed in terrestrial and marine environments in the AP region since the mid-2000s and the period of climate records considered in the corresponding studies. Even if the warming across the AP region has not been uniform, neither in space nor in time, many researchers have repeatedly related the observed changes to this long-term warming trend.

5.1. Interdecadal variability of MAATs in the AP region

The accurate analysis of the available climatic series in the AP region until 2015 shows evidence of the significant variability of the climate at decadal scale in the region. The MAATs recorded during the decades 1956–1965 and 1966–1975 were the lowest measured since the 1950s in all stations across the AP region (Table 5 and Fig. 4). However, the warming recorded since then to present in the SW corner of the AP region is not representative of the entire area. In fact, the long-term warming recorded at Faraday/Vernadsky since the decade 1956–1965 to present (2.5 °C) is more than twice the change observed in other long-term AP records, such as the temperature increase measured since the decade 1966–1976 to present at Esperanza (1.2 °C), Faraday and Orcadas (0.9 °C), O'Higgins (0.6 °C) and Bellingshausen (0.5 °C). The highest warming rates since the decade 1976–1985 correspond to

Table 5
Differences between decadal mean temperatures with respect to the period 2006–2015.

Decade	SSI			SW			N-NE			
	Bellingshausen	Marsh	King Sejong	Faraday	Rothera	San Martin	Orcadas	Esperanza	O'Higgins	Marambio
1956–1965	–	–	–	−2.5	–	–	−0.3	−0.9	–	–
1966–1975	−0.5	–	–	−0.9	–	–	−0.9	−1.2	−0.6	–
1976–1985	0.0	0.4	–	−1.6	−1.6	–	−0.1	0.1	0.0	0.1
1986–1995	−0.3	0.1	−0.1	−0.9	−0.7	−1.1	−0.1	−0.5	−0.4	−0.5
1996–2005	0.5	0.6	0.6	−0.1	−0.1	−0.2	0.2	0.7	0.6	0.9

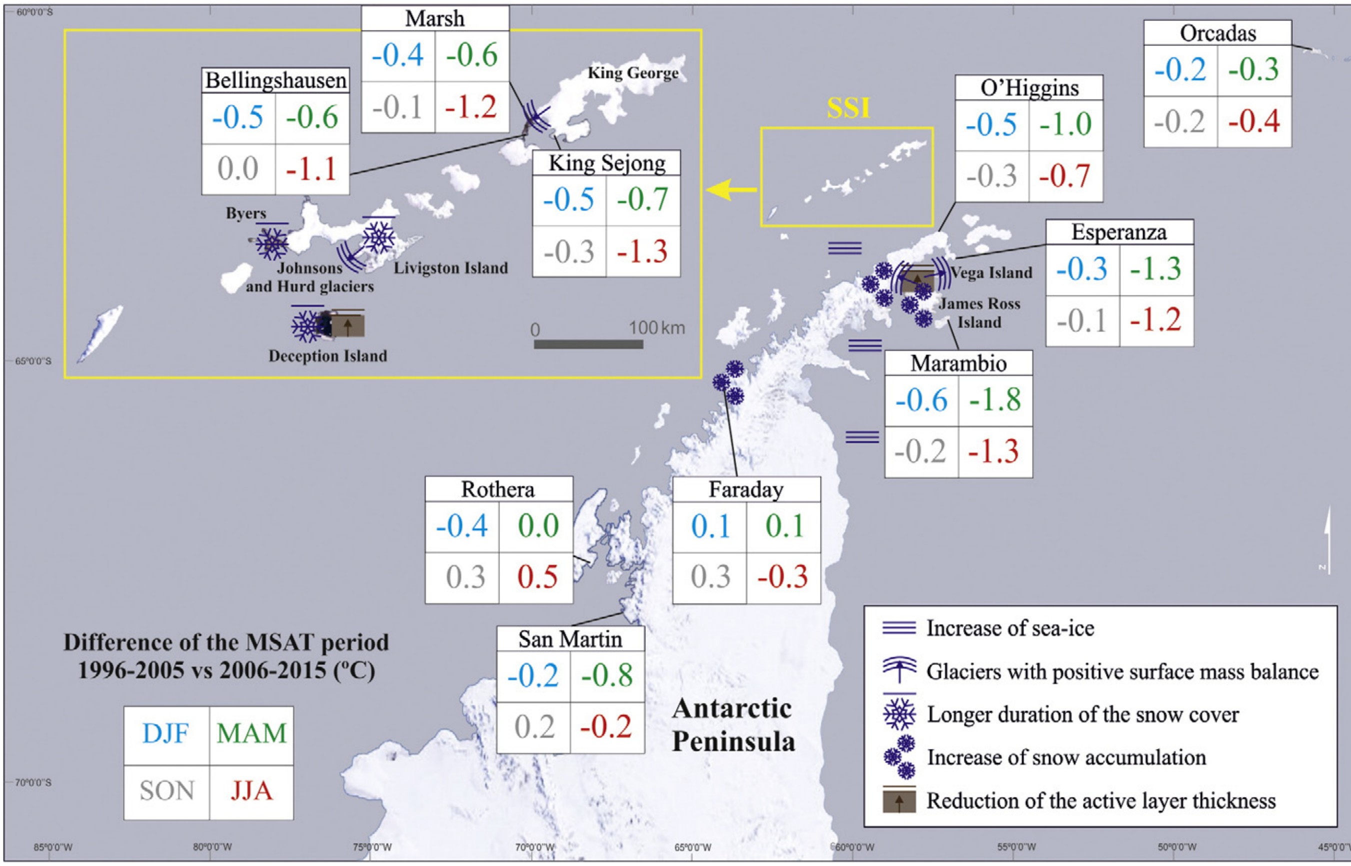

Fig. 3. Seasonal temperature change between 1996 and 2005 and 2006–2015, with the observed impacts on the cryosphere in the AP region.

Faraday/Vernadsky and Rothera stations, and the highest warming rate since 1986–1995 corresponds to San Martin station, all of them distributed in the SW sector of the AP, along the Bellingshausen Sea coast. In all of these stations, however, the warming rates have decreased markedly since the decade 1996–2005 and even show a short-term cooling trend during the last decade (Table 5 and Figs. 2 and 4).

The long-term temperature increase observed in the SW sector of the AP since the mid-20th century constitutes the most pronounced warming in the AP region. Interestingly, the largest decadal variation in MAAT recorded in the AP region was detected at Faraday/Vernadsky station between 1956 and 1965 and 1966–1975 when MAATs increased by 1.6 °C. From 1998 onward, a turning point has been observed in the evolution of MAATs across the AP region (Turner et al. 2016), changing from a warming to a cooling trend (Fig. 4). This year coincides with one of the strongest El Niño events of the last decades (Trenberth et al., 2002). The same pattern was also observed after the El Niño event of

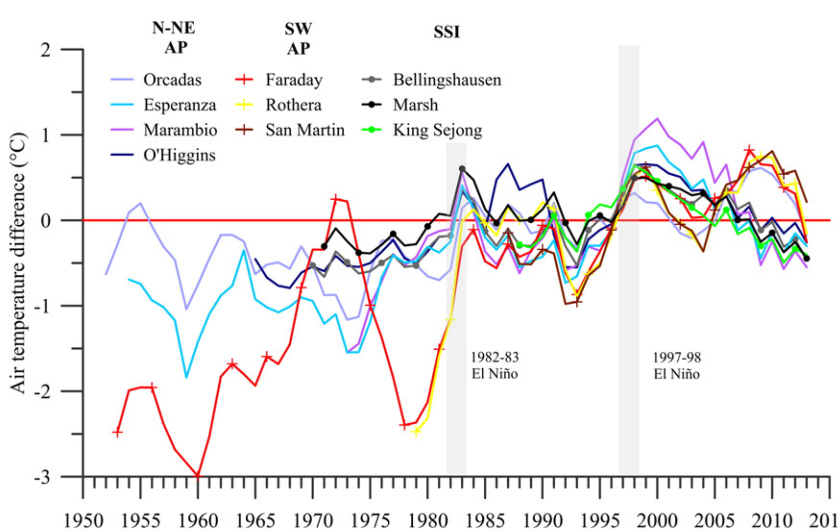

Fig. 4. Temporal evolution of the difference between the MAATs and the 1966–2015 average temperature for each station (3-year moving averages).

1982–83, although the magnitude of the temperature decrease was smaller. We thus see that, after strong El Niño events, with temperatures higher than usual, the temperature records across the AP region experienced multiannual decreasing trends within the longer-term general warming trend (Figs. 2 and 4).

The warmer temperatures recorded during the El Niño event of 1997–1998 conditioned that the 1996–2005 decade was the warmest decade in the instrumental record in all regions (red column in Fig. 1c), with the exception of the SW sector. The most significant changes in decadal average temperatures (between 1986 and 1996 and 1996–2005) were detected in the northern tip of the AP, with temperature increases of 1.0–1.4 °C. This area appears to be a very sensitive spot as regards to climate variability, with changes significantly more pronounced than those in the SSI and South Orkney Islands. This sensitivity is again manifested during the 2006–2015 decade, when was recorded the most significant MAAT decrease in the AP with respect to the previous decade (0.6 to 0.9 °C), while this cooling was of only 0.2 °C in Orcadas station. Colder temperatures (by 0.5 to 0.6 °C) were also recorded during the decade 2006–2015 on the SSI, but decadal temperatures remained above average in the SW corner of the AP region with a slight increase of 0.1–0.2 °C. With the exception of Faraday and Rothera, the values observed during the last decade (2006–2015) were relatively similar to the MAATs measured during the 1976–1985 decade (Fig. 1).

5.2. Sea ice as an amplifying factor of the recent cooling

Seasonal and annual air temperature decadal averages in the AP region are only representative of the atmosphere component of the climate system. Nevertheless, the ocean and the cryosphere are two components that, due to their much larger heat capacity, store considerably more heat energy when there is an unbalanced radiative budget (Peixoto & Oort, 1992) and thus show much slower response times to environmental changes. However, besides air temperature, other processes or variables related with the oceanic or the cryosphere components, such as oceanic currents and sea ice cover, present important decadal variability and trends in the AP region (Turner et al., 2016). The asymmetric temperature rise across the AP is likely related to the non-linear coupling of atmospheric and oceanic factors driving the distinct extent and time duration of the sea ice cover along the two sides of the AP, i.e. the Bellingshausen Sea and the Weddell Sea, and their effect in controlling temperatures inland (Turner et al., 2005a, 2014).

Sea ice plays a crucial role on land surface temperatures along the AP region (Jacobs & Comiso 1997; Turner et al., 2013). Changes in the MSATs and the associated cooling trend are strongly influenced by the variability on the extent and duration of sea ice, which is known to be controlled, to a large extent, by the prevailing phases of the two major atmospheric oscillation modes that control conditions in the AP region, namely SAM and ENSO (Stammerjohn et al., 2008). These authors showed that regional sea ice trends in the western AP and southern Bellingshausen Sea region largely resulted from wind-driven sea ice changes. Negative sea level pressure anomalies towards the AP in the 1990s, resulting from positive phases of SAM coexistent with strong La Niña conditions, strengthened northerly and westerly winds in this region during autumn-spring, leading to an earlier retreat and later sea ice advance. The 2000s have also been dominated by positive SAM and La Niña-like conditions (Marshall et al. 2013; Kosaka & Xie, 2013) and, therefore, a similar pattern was observed during these years in the stations situated in the SW of the AP. However, the role played by the coupling of SAM and ENSO patterns is distinct on the two adjacent AP seas. In fact, Stammerjohn et al. (2008) also showed that, unlike the Bellingshausen Sea, sea ice changes in the western Weddell Sea were not particularly dependent on the phases of the SAM and ENSO oscillations.

Even if sea-ice extent in Antarctica has significantly increased since 1979 (Meehl et al., 2016), some of the seas surrounding the AP have recorded the strongest decay rates in Antarctic sea ice cover since the late 1970s, as measured by satellite data, such as the Amundsen-Bellingshausen Sea (Simpkins et al., 2012; Simmonds, 2015). This trend has been also confirmed by ice core records (Abram et al., 2010), which might contribute to explain the increase in MAATs observed at the SW stations (Fig. 4). This long-term pattern towards less sea ice may mask shorter past periods with more abundant sea ice, which may have induced a decrease in MAATs.

However, since 1999 there has been an increase of sea ice in most of the peninsula, particularly in its northern half that has influenced the deceleration of the regional warming trend recorded during the 2006–2015 decade. Between 1999 and 2014 the increase of sea ice in the northern AP region has exceeded 10% per decade in comparison with the decadal decay below 6% per decade recorded between 1979 and 1997 (Turner et al., 2016). These authors relate this recent sea ice increase with the enhanced cyclonic conditions in the Drake Passage and NW Weddell Sea due to a stronger mid-latitude jet advecting cold air towards the AP and pushing sea ice towards the east coast of the AP, which would have amplified the cooling inland (Turner et al., 2016).

In the NW Weddell Sea, the larger extent and longer presence of sea ice in recent summers (Parkinson & Cavalieri, 2012; Nývlt et al., 2016) has most likely driven the significant recent decrease of MAATs recorded in the northern AP region, which is particularly remarkable in autumn (MAM) and winter (JJA) (Fig. 3). This recent cooling has being particularly pronounced in the N-NE tip of the AP, with temperature differences between 1996 and 2005 and 2006–2015 of 1–1.8 °C during the autumn and 0.7–1.3 °C during the winter. The decreases have been also noteworthy in the SSI (0.6–0.7 and 1.1–1.3 °C, for the respective seasons). The increase in sea-ice cover in the Weddell Sea has been particularly pronounced during the summer (DJF) and autumn (MAM) seasons, ca. 29 and 9%, respectively, during the period 1979–2010 (Parkinson & Cavalieri, 2012). Delayed melting of fast sea ice during the summer implies faster freezing of the sea due to the freshening of its surface during the subsequent autumn, affecting significantly the atmospheric temperature in the late summer and in autumn. The freshwater influx from basal melting of the ice shelves along the eastern AP coast, coupled with the melting of drifting icebergs, generates a freshwater lid on the NW Weddell Sea continental shelf surface waters (Hellmer et al., 2011), which tends to freeze faster in autumn and favours sea ice formation (Bintanja et al., 2013). The surface ocean circulation in the Weddell Sea is controlled by the Weddell Gyre (Diekmann & Kuhn, 1999), which transports icebergs and pack ice northwards along the AP continental shelf to the northern islands in the NE fringe of the AP. The presence of more sea ice around these islands favours temperature decrease inland, a geographical pattern which has been largely observed in the Arctic (Screen & Simmonds, 2010) and affects ecological dynamics in terrestrial and freshwater ecosystems (Nedbalová et al., 2013; Nývlt et al., 2016). A similar behaviour has also been observed in the South Orkney Islands (Fig. 3).

Moreover, this freshening of surface sea waters may also drive the seasonal changes recently observed in the SSI, although with a time delay. In this area, the largest decadal temperature decrease corresponds to the winter season (1.1 to 1.3 °C, between 1996 and 2005 and 2006–2015). The occurrence of coreless winters in the SSI during the decade 1996–2005 has been related to the presence of massive and rapid advection of warm air by northerly and westerly winds associated with a migration of sea ice southwards (Styszyńska, 2004). This pattern has changed during the decade 2006–2015, with significantly lower winter temperatures that have brought sea ice northwards again (Turner et al., 2016). This cooling pattern persists over all seasons. Although moderate in summer (DJF) (0.5 °C), it has significant implications on land system dynamics, as will be discussed later.

No clear common seasonal trends have been observed in the SW region of the AP since 2006 (Fig. 3), where a slight sea ice decrease of 2–6% per decade has been recorded between 1999 and 2014 (Turner et al., 2016). Despite a widespread decelerated warming rate across the region or even a slight cooling trend (Table 4), the sense and magnitude of change differs substantially from one station to another. A weak to moderate diminution has been detected in summer temperatures at latitudes 67–68°S, where more sea ice has been observed since 2007–2008 (NSIDC, 2016).

5.3. Major cryospheric impacts of climate changes in the AP region

The climate cooling of the last decade has not yet impacted the main large landed or floating ice masses in the region, such as the AP ice sheet and its outlet glaciers and ice shelves, because their large size implies generally slow and delayed responses to climate changes. However, smaller ice masses in the northern AP and surrounding islands are already showing signs of this impact.

5.3.1. Marine and land-terminating glaciers on the northern AP

Davies et al. (2012) did a study, based on 194 glaciers on Trinity Peninsula (the northernmost part of the AP), Vega Island and James Ross Island, analysing separately the periods 1988–2001 and 2001–2009. This study shows various evidences of decelerated recession between both periods (indicated in Fig. 3): 1) during 1988–2001, 90% of glaciers receded, as compared with 79% during 2001–2009, and the glaciers in the western side of the Trinity Peninsula showed the lowest recession; 2) the losses of total glacierized area in the northern AP declined from 11.1% during 1988–2001 to 3.3% during 2001–2009; 3) the tidewater glaciers on the drier, cooler eastern Trinity Peninsula receded fastest during 1988–2001, with little frontal retreat afterwards; 4) the land-terminating glaciers on James Ross Island also had their fastest retreat in the period 1988–2001. Regarding the suggested mechanisms for this behaviour, Davies et al. (2012) point out that reduced shrinkage on the western AP may result from higher snowfall, and that the slow-down of the rates of area loss on the eastern side of the Trinity Peninsula can be attributed to the floating ice tongues receding into the fjords and reaching a new dynamic equilibrium. While the rapid shrinkage of tidewater glaciers on James Ross Island is expected to continue because of their low elevations and flat surface profiles, the higher and steeper inland tidewater glaciers on the eastern AP will likely attain equilibrium and stable frontal positions more quickly following the removal of low-lying ablation areas.

5.3.2. Peripheral glaciers

As noted by the IPCC 2013 Report, the small glaciers and ice caps around the globe, in spite of holding only about 1% of the ice volume stored by the Antarctic and Greenland ice sheets, have currently a larger contribution to sea-level rise (27% of estimated contributions for glaciers vs 21% for the ice sheets; Church et al., 2013). The main reason is that, due to its smaller size, they have a much faster response, both thermal and dynamic, to changes in climate.

Among the glaciers in the globe, those surrounding the Antarctic mainland cover 18% of the global glacier area (Pfeffer et al., 2014). According to the inventory by Bliss et al. (2013), 1133 ice caps and 1619 mountain glaciers, with a total area of $132{,}867 \pm 6643$ km^2 and an estimated total volume of 0.121 ± 0.010 m SLE are located in the Antarctic periphery (these numbers include the ice rises and rumples within the ice shelves). Of this total glacier area, 99% drains either into ice shelves (63%) or into the ocean (36%). A large fraction of these ice masses are located in the AP region, which includes 1235 glaciers and ice caps, totalling 80,874 km^2 in area and 32,363 km^3 of ice volume in the region bounded by 50–75°S and 50–80°W (figures estimated using the Randolph Glacier Inventory 4.0 by Pfeffer et al. (2014)).

There is some controversy on the estimates of the mass budget of the Antarctic peripheral glaciers. While Hock et al. (2009) gave an estimate of -22 ± 16 Gt year^{-1} for the period 1961–2004, which represents 28% of the total glacier mass budget around the globe, the more recent consensus estimate by Gardner et al. (2013) gives an estimate of -6 ± 10 Gt year^{-1} during 2003–2009, which makes up only 2% of the global glacier wastage. These estimates correspond to the entire Antarctic periphery, but most of the losses are concentrated in the AP region. This discrepancy could thus be partly an expression of the regional cooling observed during the last decade in the AP region, but the differences are far too large, suggesting that methodological aspects of the calculation procedure are also involved. A more comprehensive and detailed comparison of all studies in the region could shed some light, and a key question to analyse is whether the behaviour of these peripheral glaciers has experienced any noticeable changes during the last decade as compared with previous ones.

During the second half of the 20th century and the earlier years of the 21st century, nearly all of the glaciers peripheral to the AP have experienced significant retreats and mass losses, in line with the regional responses to climate observed for the AP ice sheet, ice shelves and inland glaciers (e.g. Calvet et al., 1999; Molina et al., 2007; Rückamp et al., 2011; Engel et al., 2012). However, during the most recent years all the glaciers in the islands peripheral to the northern AP with surface mass balance (SMB) records (>13 years) in the World Glacier Monitoring System database (http://wgms.ch) have shown a shift from consistently negative SMBs (i.e. surface mass losses) to predominantly positive (i.e. surface mass gains). In particular, this shift occurred in 2007/08 for Hurd and Johnsons glaciers, on Livingston Island (Navarro et al., 2013), and in 2009/10 for Bahía del Diablo Glacier, on Vega Island (Marinsek & Ermolin, 2015). The Bellingshausen Ice Dome on King George Island, though with a shorter SMB record, also shows a shift to positive SMBs in 2009/10 (Mavlyudov, 2014). Mostly positive SMBs have also been reported for Davies Dome and Whisky Glacier on James Ross Island for 2009–2014 (Láska et al., 2015). Though all of these glaciers are located on the northern AP region, they sample both its western and eastern sides.

The mass balance records for Hurd and Johnsons glaciers distinguish between summer and winter balances, and thus provide some clues about the likely reason of the observed shift in SMB. As pointed out by Navarro et al. (2013), both increased winter accumulation and decreased summer melt play a role on the observed positive mass balances, with predominance of one or the other process depending on the year. They attribute the increase in accumulation to the larger precipitation associated with the recent deepening of the circumpolar pressure trough, and the melt decrease to the lower summer surface temperatures recorded in the AP region during the last decade. As shown in the present paper, the mean summer temperatures have decreased by 0.3–0.6 °C between 1996 and 2005 and 2006–2015 around the locations of the mentioned glaciers (Fig. 3). Though this may seem a small decrease, modelling of melting on Hurd Peninsula glaciers by Jonsell et al. (2012) shows an extremely high sensitivity to air temperature changes, implying that a 0.5 °C temperature increase (decrease) entails a 56% (44%) increase (decrease) in melt rate. These authors attribute this high sensitivity of melt to the fact that the glaciers on the SSI have average summer temperatures very close to zero, so small changes in summer temperature imply a shift from non-melting to melting conditions, or vice versa. This is in agreement with the findings by Abram et al. (2013), who concluded that ice on the AP is now particularly susceptible to rapid increases in melting and loss in response to relatively small increases in mean temperature.

All of the SMBs discussed in this section were calculated at the glacier-basin level. Osmanoğlu et al. (2014) have extrapolated the SMB gradients measured on Johnsons (tidewater) and Hurd (land-terminating) glaciers by Navarro et al. (2013) to the whole set of glacier basins of Livingston Island, depending on whether they terminate at sea or on land, to estimate the SMB of the entire Livingston Island ice cap. The resulting SMB is slightly positive for the period that they analyse (2007–2011), indicating that frontal ablation (combination of iceberg calving and submarine melting at the glacier fronts) is currently the dominant process of mass loss in the SSI (Osmanoğlu et al., 2013, 2014).

The fact that the SMB of the SSI, Vega Island and James Ross Island glaciers are currently slightly positive is in agreement with recent findings by Mernild et al. (2015) indicating that the glaciers on the sub-Antarctic islands are only slightly out of balance (4%). This study has an added interest, as it analyses the teleconnections of the observed SMBs. By evaluating the patterns of temporal and spatial glacier annual SMB variations using an Empirical Orthogonal Function analysis, Mernild et al. (2015) show that, overall, the spatiotemporal cycles identified correlate to the multivariate ENSO Index promptly (zero-year lag-time) and to the Pacific Decadal Oscillation (PDO) with an approximately eight-year lag-time. The timings of these responses are consistent, since ENSO cycles typically remain in the same phase for 6–18 months, whereas PDO can remain in the same phase for one–two decades. Their overall dataset includes both Andean and sub-Antarctic and maritime Antarctic Island glaciers (Hurd, Johnsons, Bahía del Diablo). While they find the mentioned correlation, the signal observed is opposite, being positive for the Andean glaciers and negative for the sub-Antarctic and maritime Antarctic Island glaciers. This dichotomy indicates that the glaciers in both regions respond in opposite directions to changes in ENSO and PDO, which is in agreement with the opposing observed trends in SMB between both regions for 1993–2002 as compared with 2003–2012. Furthermore, Mernild et al. (2015) indicate that the differences in SMB variations shown for the sub-Antarctic and maritime Antarctic islands could be due to the existence of different climate forcings compared with the rest of the dataset. In particular, they note that, according to Li et al. (2014), the AP is influenced by other climate forcings besides the radiative forcing and remote Pacific climate variability, such as forcings from the north and tropical Atlantic Ocean and from the Atlantic Multidecadal Oscillation (see Li et al. (2014) and references therein). Another reason for the distinct SMB variability between the sub-Antarctic and maritime Antarctic islands and the Andes regions could be their different topographical and local climate conditions.

5.3.3. Permafrost, active layer and snow cover

The comparison between the first measurements of the active layer thickness in the 1950–60s and recent monitoring data has revealed an increase of the active layer depth since the mid-20th century in some areas of the SSI and Palmer area (Vieira et al., 2010; Bockheim et al., 2013). On Signy Island, Cannone et al. (2006) inferred a strong dependence of active layer thickness on MAAT, which resulted in a deepening of the active layer of ca. 30 cm between 1963 and 1990, but it thinned by the same amount between 1990 and 2000 due to colder conditions.

Since 1850 snow accumulation has doubled in the western AP (Turner et al., 2005b; Frey et al., 2006; Thomas et al., 2008, 2015). Snow cover plays a key role in geomorphological processes in the ice-free regions of the western AP and controls permafrost conditions and active layer dynamics (e.g. Oliva et al., 2017, Ramos et al., 2017), however its effect on eastern AP is probably not significant in general (e.g. Hrbáček et al., 2016a, 2017). In recent years, lower summer temperatures have promoted a longer duration of snow cover in some areas such as the SSI (de Pablo et al., 2017). Therefore, the cooling trend recorded since ca. 2005, associated with long-lasting snow cover has been translated into the soil thermal regime. Between 2006 and 2014 in some regions of the SSI, such as in Deception Island, there has been a reduction of the active layer thickness at a rate of about 1.5–2 cm a^{-1} (Goyanes et al., 2014; Ramos et al., 2017), with an obvious cooling trend inferred from annual freezing indexes (Ramos et al., 2012). A similar pattern was also observed in James Ross Island (eastern AP), where decreasing summer air temperatures led to a decrease of active layer thickness of about 3.0 cm a^{-1} between 2006 and 2014 (Hrbáček et al., 2016b).

6. Conclusions

Over the last decade the AP region has largely been described as one of the fastest warming regions on Earth, with comparable amplitude to the Arctic region. The IPCC (2007) suggested an increase of MAAT between 2 and 3 °C for 2080–2099 with respect to the average 1980–1999, although this range was later reduced by the latest IPCC assessment (IPCC, 2013) to circa 1.8 °C for the entire continent. It should be stressed that these recent temperature increments are significantly lower than the corresponding temperature increase projected in the Arctic by the end of the 21st century estimated at 4.9 °C (IPCC, 2007, 2013). Most of the research dealing with terrestrial and marine regional earth systems and ecosystems has used this warming paradigm as the climatic framework. This widely accepted framework can be found in many papers published since the early 2000s that take into account the long-term trend recorded during the second half of the 20th century. However, this trend masks the internal short-term climate variability of a highly sensitive climatic region where feed-back processes (e.g. sea ice and snow cover extent and duration) strongly influence the regional climatic trends and their impacts on the cryosphere and on ecosystems.

The largely referred warming at Faraday/Vernadsky station since the late 1950s constitutes the largest increase recorded within the AP region, and to a certain extent, is not representative of the whole AP. The SW corner of the AP is the area which has warmed most over the last decades, with an increase of 1.6 °C since the 1976–1985 decade and of 0.7–1.1 °C since the 1986–1995 decade. For the rest of stations, the MAATs during the 1960–70s were considerably lower, within the range of 0.5–1.2 °C colder than during the 2006–2015 decade and the warmest temperatures were recorded during the 1996–2005 decade. The shift to a cooling trend initiated around 1998/1999 has implied a decrease in temperatures between the decades 1996–2005 and 2006–2015 by 0.5–0.9 °C in most of the AP region (at Orcadas station, the cooling was of only 0.2 °C), with the exception in the SW sector of the AP. Here, despite the rate of increase has significantly decreased during the most recent decade 2006–2015, the MAATs have still been 0.1–0.2 °C higher than those of the previous decade.

The recent cooling has been seasonally dependent, being particularly pronounced in the N-NE tip of the AP and the SSI during the autumn and winter seasons. By contrast, no clear changes in the MSAT variability have been recorded in the SW of the AP. These changes (and relative stability) of the MSATs are strongly influenced by the variations on the extent and duration of sea ice, which is known to be partially controlled by the prevailing SAM-ENSO conditions in the AP region. However, besides the regional influence of the large-scale modes of climate variability, local factors, such as topography, would also play a key role. The lower MAATs detected in the region during the last decade may explain some of the observed environmental changes, including increase in the extent of sea ice, positive mass-balance of peripheral glaciers and thinning of the active layer of permafrost.

We acknowledge that, similarly to other regions of the world, it is rather difficult to disentangle climate change trends from decadal and inter-annual variability, particularly when both natural (e.g. ENSO and SAM) as well as anthropogenic (greenhouse gas emissions and ozone depletion) factors play significant roles in the evolution of the climate of Antarctica in general and the AP in particular. In this regard, it will be particularly important to evaluate the regional impact of the recent major El-Niño episode unfolding between 2015 and 2016, in particular to see if this event will induce widespread warming in the entire AP region, as happened following the 1982–83 and 1997–98 El Niño events (Fig. 4).

The recent cooling has not still impacted the large AP ice masses, such as ice sheets and outlet glaciers and ice shelves, but smaller ice masses in the northern AP and surrounding islands are already showing signs of this warming trend. Nevertheless, some initial impacts on cryosphere have been observed already. Marine and land-terminating glaciers on the northern AP experienced a decelerated recession for the 2000s. Peripheral glaciers in the northern AP islands have shown a shift from surface mass losses to surface mass gains, highlighting that ice on the AP is now particularly susceptible to rapid increases in melting and loss in response to small mean temperature oscillations. Finally, in recent years, the cooling trend recorded since the mid-2000s and the related long-lasting snow cover have clearly affected the soil thermal regime. The reduction of the active layer thickness has appeared in some regions of the SSI and N-NE Antarctic Peninsula.

Future research will unveil if the recent cooling trend observed in significant parts of the AP is part of the natural climatic variability in the region, or shows a turning point in the long-term warming trend observed during the second half of the 20th century.

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