RESEARCH ARTICLE

Variability of biothermal conditions in the vicinity of the Polish Antarctic station in the South Shetlands, West Antarctica

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Abstract

There are nine year-round and 11 seasonal scientific stations in the South Shetland Islands, an area often visited by cruise ships and sailing yachts. Although this is the warmest part of Antarctica, the weather conditions may be demanding for humans. We analysed the variability of biothermal conditions near Henryk Arctowski Station Polish Antarctic Station, on King George Island, during the period 2013–2021, using the wind chill index (WCI), which combines air temperature and wind speed, to determine thermal sensation. WCI values were interpreted using two cold sensation categorisations. Hourly WCI values were assigned to thermal sensation classes that ranged from "comfortable" to "frosty." The most favourable biothermal conditions occurred from December to February. The "cold" sensation was dominant in all months, its average occurrence frequency ranging from 56.4% (in January) to 84.4% (in July). From November to March, there was no risk of frostbite to uncovered body parts. Such conditions occurred only from April to October, with a frequency of 0.2–6.8%; biothermal conditions were also the most variable in this period. Maximal WCI hourly values show that dangerous weather conditions may occur throughout the day in June and for most of the day from July to September. An abrupt change in biothermal conditions was more often caused by wind speed change than by air temperature change. The most marked WCI changes occurred from April to September, on average five times per year. Our results indicate that biothermal conditions in the vicinity of Arctowski Station are predominantly favourable for outdoor work only if a person wears proper winter clothing.

Keywords

Bioclimate; work environment; work hazards; polar occupational medicine; wind chill index; frostbite

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Abbreviation:

WCI: wind chill index

Introduction

The South Shetland Islands are the most densely populated part of Antarctica. There are nine year-round and 11 seasonal scientific stations (Secretariat of the Antarctic Treaty 2019). Stations workers, especially during the summer season, from December to March, spend a lot of time outdoors carrying out scientific and technical tasks. The South Shetland Islands and Antarctic Peninsula are also the part of Antarctica that receives the most visits by cruise ships and sailing yachts (Secretariat of the Antarctic Treaty 2020). This is the warmest part of Antarctica, but the weather conditions may be demanding, so information about biometeorological conditions and their variability during the year can be useful for those planning to work there.

Investigations concerning biometeorological conditions and their impact on humans in the polar regions have been conducted for a long time, especially in the Arctic, which is populated by indigenous and non-indigenous people, including personnel at scientific stations and other seasonal workers (e.g., Eagan 1966; Mäkinen et al. 2006; Mäkinen 2007; Araźny 2008; Araźny et al. 2010; Brozovsky et al. 2021). Several methods and indexes have been developed for describing and assessing the biometeorological conditions in the polar regions (e.g., Siple & Passel 1945; Kozłowska-Szczęsna et al. 1997; Maarouf & Bitzos 2001; UK Hydrographic Office 2004). In the case of Antarctica, where humans have been present for only 200 years, biometeorological research has concerned the influence of the Antarctic environment conditions and long-term isolation on various aspects of human health, such as physical performance (e.g., Simpson & Maynard 2012), cold acclimatisation (e.g., Budd 1962; Bodey 1978; Naidu & Sachdeva

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1993), sleep quality (e.g., Bhattacharyya et al. 2008), hormonal balance (e.g., Sawhney et al. 1998; Chengli et al. 2003; Chen et al. 2016), mental health (e.g., Chen et al. 2016; Kuwabara et al. 2021) and other health-related issues (e.g., Belkin & Karasik 2001; Otani et al. 2004; Bhatia et al. 2013; Ikeda et al. 2019). This research has focused on the effects of environmental conditions rather than on the conditions themselves, as discussed by Wilson (1967) and Lu et al. (2015).

Biometeorological research hitherto conducted in the vicinity of the Henryk Arctowski Polish Antarctic Station (hereafter Arctowski Station) presented results for the summer season (December–March) in the period 1977–1990 (Gregorczuk 1977; Styszyńska 1989, 1994) and for the whole year in the period 2015–19 (Węglowska 2021). Wind chill during the whole year was discussed by Styszyńska (2000), on the basis of data from the period 1978–1998. Consistent with the general observations of expedition members, these works concluded that biometeorological conditions were predominantly safe for a suitably dressed person. However, rapid wind speed changes could suddenly bring on conditions that may lead to frostbite or hypothermia for people not properly dressed or far from a shelter (Styszyńska 2000). An abrupt change in weather conditions creates an additional threat for those working at the sea. This underlined the need for better knowledge of the frequency and intensity of changes in biometeorological conditions.

The research reported herein investigated the variability of biothermal conditions in the vicinity of Arctowski Station, on King George Island, in the South Shetland Islands, using the WCI. Particular attention was paid to the frequency of rapid WCI value changes, its multi-annual variability and the frequency of safe and dangerous conditions.

Methods and research area

The South Shetland Islands, the warmest part of Antarctica, lie approximately 120 km north of the Antarctic Peninsula, in the Subantarctic maritime climate zone (Marsz & Styszyńska 2000). The climate in this region is mostly determined by the sea-surface temperature and the extent, concentration and distribution of sea ice (Marsz & Styszyńska 2000; Kejna et al. 2013; Turner et al. 2013). The air-pressure lows that often pass through the region also play an important role (Simmonds et al. 2003). Together, these factors create meteorological conditions that vary greatly from year to year (Marsz & Styszyńska 2000; Turner et al. 2013). The region is also experiencing some of the most significant climate warming in the world (Bromwich et al. 2013; Gonzalez & Fortuny 2018; Gonzalez-Herrero et al. 2022). The analysis of biothermal conditions may also be interesting in this context.

The research was based on data collected by an automatic weather station located close to Arctowski Station, on the western shore of Admiralty Bay, King George Island. More than 90% of the island is covered by glacier caps that have an elevation of up to 700 m a.s.l. (Rückamp & Blindow 2012). The weather station is located on a low sea terrace 2 m a.s.l., 150 m from the main station's building and 100 m from the coast (Fig. 1). Air temperature and wind speed from the period 2013–2021, measured every hour, were used in the research. Air temperature is measured by a Vaisala HMP155 sensor installed at 2 m above ground. The accuracy of the measurements is ±0.2°C. Wind speed is measured at 2.5 m. From January 2013 to January 2017, it was measured by a Gill Wind sonic sensor (accuracy ±0.2% at 12 m/s) and from January 2013 to February 2017 to December 2021 by a Vector Instrument A100R mechanic sensor (accuracy ±0.1 m/s at 0–10 m/s; 1% at 10–55 m/s; 2% above 55 m/s). Mean multi-annual (2013–2021) air temperature at Arctowski Station was -1.3°C. The coldest month was August (mean multi-annual monthly air temperature -5.6°C) and February the warmest (2.0°C; Fig. 2). The highest hourly temperature values were about 5°C in June–September and about 10°C in the remaining months. The lowest values ranged from -3.1°C in January to -22.1°C in July. The mean annual wind speed was 5.6 m/s, but the maximum records reached up to 32 m/s (115 km/hr; Fig. 2). All times given are local time, which is zone UTC-3.

WCI was used to determine thermal sensation. Invented by P.A. Siple and C. Passel during investigations in Antarctica in the first half of the 20th century, the index represents the rate of heat loss from the unprotected surface of the skin. As modified by Court (1948), the formula for determining WCI (in W/m^2) is as follows:

$$WCI = (10.9*\sqrt{v}+9.0-v)*(33.0-t)*1.163,$$

where v is wind speed (m/s) and t is air temperature (°C).

WCI was chosen for our study because it is used for weather conditions with low air temperature and has been used many times in bioclimatological analyses of polar regions (Kozłowska-Szczęsna et al. 1997). Determining the real rate of heat loss by a human exposed to low temperature and wind is complex and demands taking account of such individual factors as body heat production, fat tissue and clothing. Siple and Passel's WCI formula (modified by Court) was chosen for this study because it involves only environmental measurements, with no need to consider

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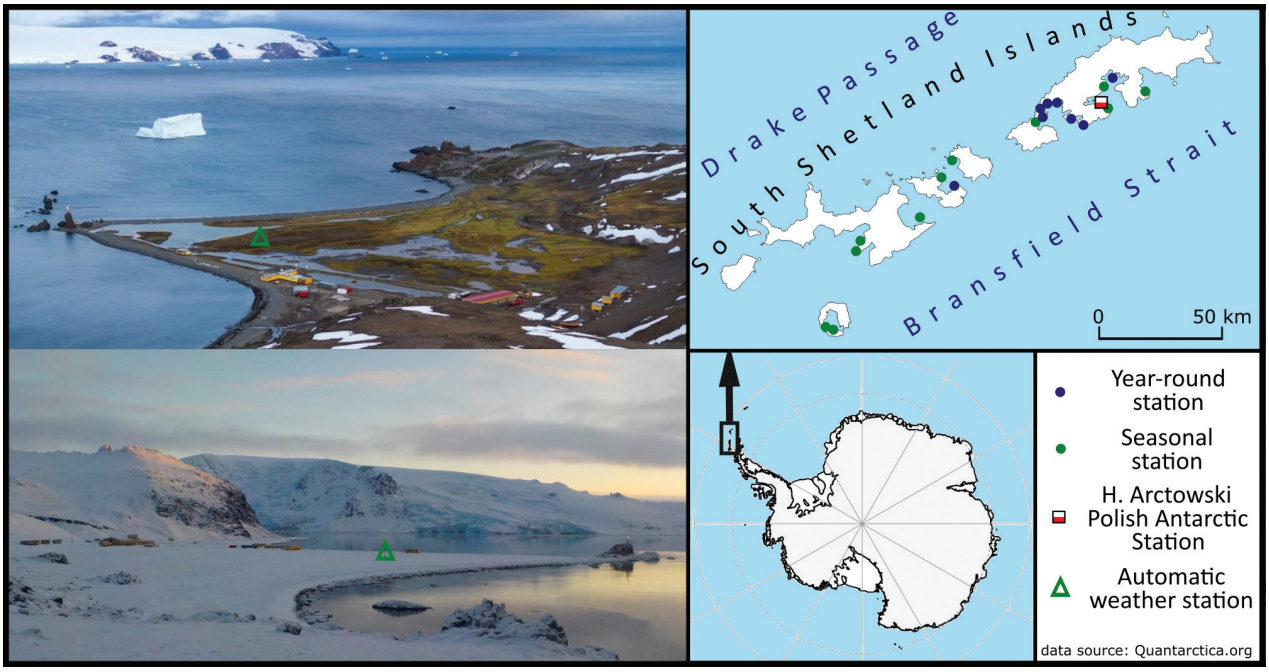

Fig. 1 Location of the study area and landscape in the vicinity of Arctowski Station during summer and winter. (Photos: P. Andryszczak & J. Plenzler.)

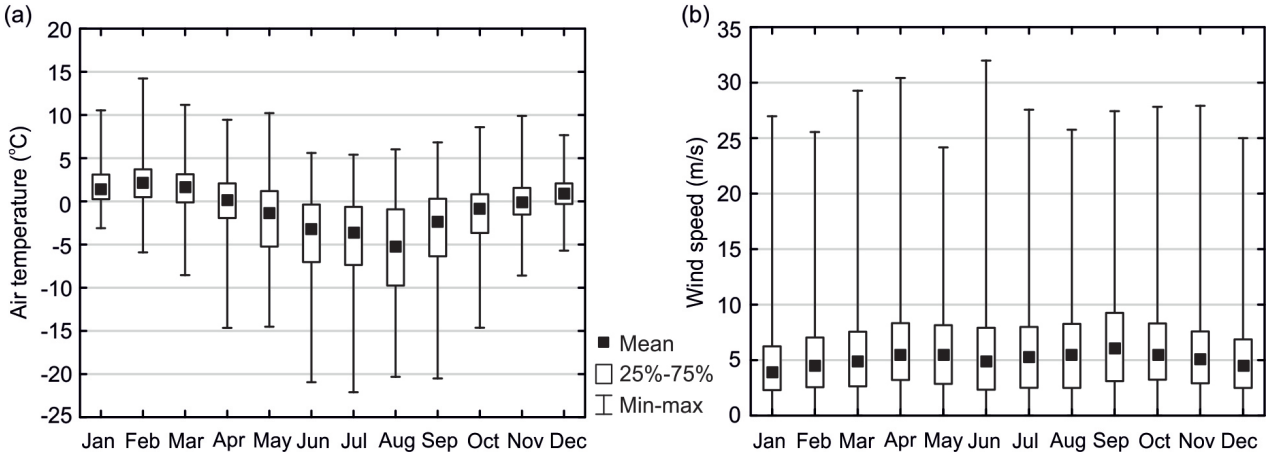

Fig. 2 Variability of (a) hourly air temperature and (b) wind speed for each month at Arctowski Station (2013–2021).

physiological aspects of heat loss and individual characteristics (Shitzer 2006; Lankford & Fox 2021).

The mean WCI values in individual months and years that we present were calculated on the basis of hourly values. Hourly values were classified according to the thermal sensations experienced by a person wearing winter clothing with a level of thermo-insulation at 4.0 clo (Kent 2006): heavy other clothing, including thermo-insulative underwear, woollen sweater, heavy coat, cap, gloves and boots (Holmér 1988; Kozłowska-Szczęsna et al. 1997; Maarouf & Bitzos 2001; Table 1). According to this classification, referred to as the "thermal sensation" system herein, when WCI is higher than 1628.2 W/m^2, corresponding to the sensations "frosty" and "extremely frosty," there is a risk of frostbite to uncovered parts of the body, even when they are only briefly exposed to the cold. When WCI is higher than 2326 W/m^2 frostbite of uncovered parts of the body occurs after just 30 seconds and staying inside is recommended (Maarouf & Bitzos 2001).

Another classification system, which is applied to operations in the polar regions, assigns WCI values to seven categories of cooling—numbered from I (mildest)

to VII (coldest)—and includes recommendations for how to behave in particular conditions (Marsz & Styszyńska 2000; UK Hydrographic Office 2004; Table 2). According to this classification system, referred to herein as the "cooling category" system, the most favourable conditions are when WCI is below 930 W/m^2.

Table 1 Thermal sensations of a human dressed in heavy outer clothing corresponding to the range of WCI values (Kozłowska-Szczęsna et al. 1997; Maarouf & Bitzos 2001). Asterisks mark categories that were found to have occurred during the study reported here.

WCI (W/m^2)	Thermal sensation
<58.3	Extremely hot
58.3–116.3	Hot
116.4–232.6	Warm
232.7–581.5	Comfortable*
581.6–930.4	Cool*
930.5–1628.2	Cold*
1628.3–2325.9	Frosty*
≥2326.0	Extremely frosty

Results

During 2013–2021, the mean hourly WCI values for each month were from 853.9 W/m^2 (January 2020) to 1327.0 W/m^2 (August 2020). These values correspond predominantly to the "cold" thermal sensation (see Table 1); only in January 2018 and 2020 did the "cool" sensation prevail (Fig. 3).

The highest mean annual value (1116.1 W/m^2) occurred in 2015, which was the coldest year of the analysed period (Fig. 3). The lowest (1057.4 W/m^2) was in 2020, a relatively warm and windy year (Fig. 3). The most favourable biothermal conditions were in January,

Table 2 Characteristics of each cooling category according to WCI values (UK Hydrographic Office 2004: 177). Asterisks mark categories that were found to have occurred during the study reported here.

Category	WCI (W/m^2)	Characteristics of the category
I*	< 930	Comfortable with normal precautions.
II*	930–1394	Work becomes uncomfortable on overcast days unless properly clothed.
III*	1395–1626	Work becomes more hazardous even on clear days unless properly clothed. Heavy outer clothing is necessary.
IV*	1627–1859	Unprotected skin will freeze with direct exposure over a prolonged period, depending on degree of activity, amount of solar radiation and state of skin and circulation. Heavy outer clothing becomes mandatory.
V*	1860–1975	Unprotected skin can freeze in 1 min with direct exposure. Multiple layers of clothing are mandatory. Adequate face protection becomes important. Work alone is not advisable.
VI*	1976–2091	Adequate face protection becomes mandatory. Work alone must be prohibited and supervisors must control exposure time by careful scheduling.
VII	>2091	Survival efforts are required. Personnel become easily fatigued, and mutual observations of companions is mandatory.

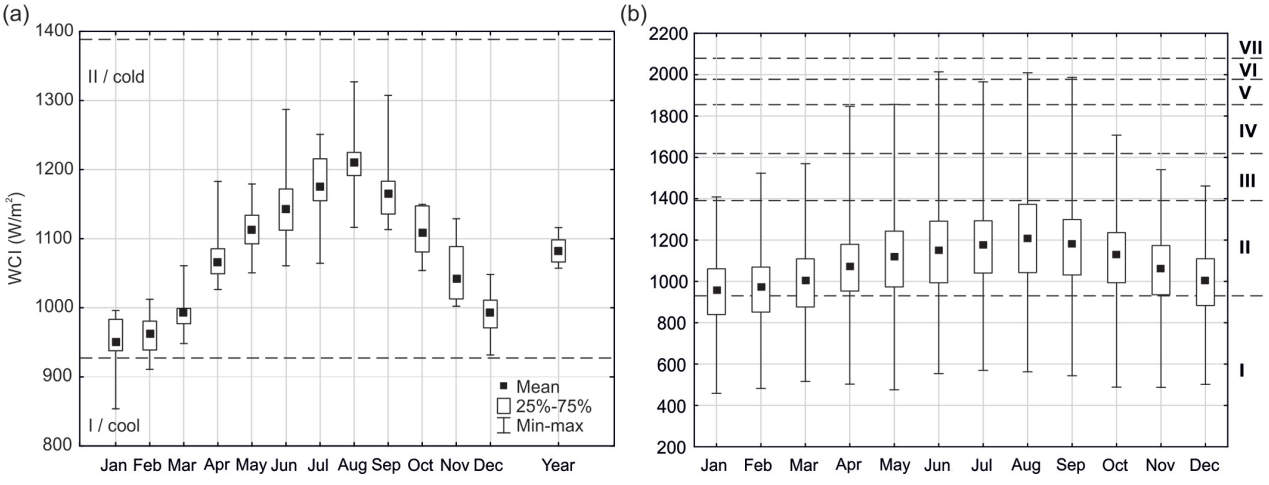

Fig. 3 Variability of (a) mean monthly and (b) actual hourly WCI values (W/m^2) at Arctowski Station (2013–2021). The dashed lines show the limits of the cooling category (see Table 2 for explanations).

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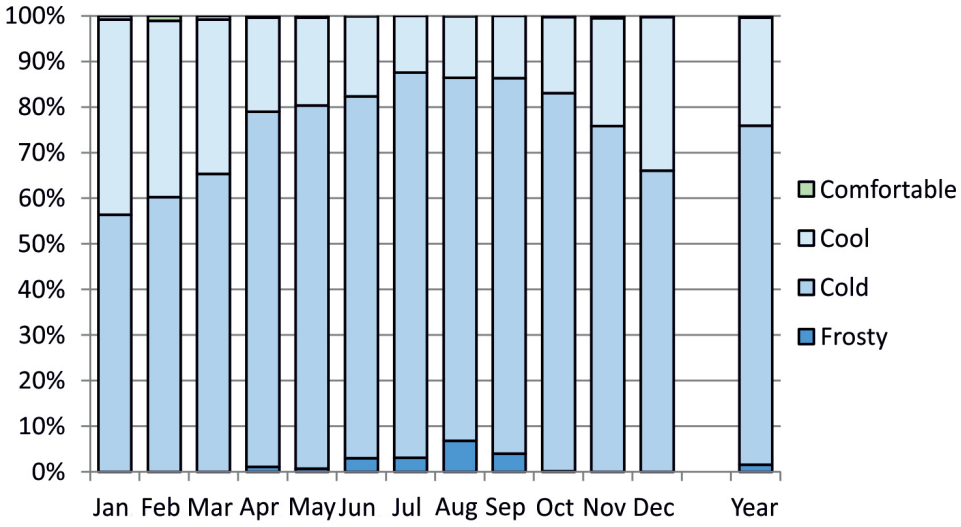

Fig. 4 Thermal sensation frequency (%) according to WCI hourly values at Arctowski Station (2013–2021).

Table 3 The frequencies of cooling categories (%) according to WCI hourly values at Arctowski Station (2013–2021).

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
I	43.5	39.7	34.5	21.0	19.6	17.6	12.4	13.5	13.6	16.9	24.1	33.9	24.0
II	56.5	59.8	64.0	74.2	70.4	67.8	74.4	63.5	71.7	77.5	74.5	66.0	68.4
III	0.0	0.5	1.4	3.7	9.1	11.5	10.1	16.1	10.6	5.4	1.4	0.1	5.9
IV	-	-	-	1.1	0.8	2.5	2.9	6.2	3.7	0.2	-	-	1.5
V	-	-	-	-	-	0.4	0.3	0.5	0.4	-	-	-	0.1
VI	-	-	-	-	-	0.1	-	0.1	0.0	-	-	-	0.0

February and December. In those months, mean hourly WCI values were usually lower than 1000 W/m^2, but in individual hours, they exceeded 1400 W/m^2, that is, cooling category III (see Table 2). In the winter season (May–October), mean WCI values were predominantly higher than 1100 W/m^2, with a maximum in June and August (2000–14 W/m^2; Fig. 3).

Hourly WCI values during the investigated period fell into thermal sensation classes ranging from "comfortable" to "frosty" (Fig. 4). In all months, the thermal sensation "cold" was dominant; its average occurrence frequency was from 56.4% in January to 84.4% in July. During the summer months, especially in January, "cool" conditions occurred often (up to 42.8%). From November to March, there were no "frosty" conditions, which means that there was no risk of frostbite to uncovered body parts. Conditions carrying a risk of frostbite occurred from April to October with a frequency of 0.2–6.8% (Fig. 4). It is important to note that even during the winter season there were single hours that a properly clothed person (clo 4.0) would sense as "comfortable." Those were the hours with positive air temperature and wind speed lower than 0.4 m/s; their frequency was <0.1% in July and September and 1.1% in February (Fig. 4).

Some other conclusions can be assumed from analyses of the cooling categories (Table 2). During the analysed nine years, only cooling category VII (requiring survival efforts) did not occur. Category VI occurred in only a single hour in June, August and September, and it constituted only 0.2% of all WCI hourly cases in the year. In this category, face protection becomes mandatory, and it is forbidden to work alone outside. The most frequent was category II (work becomes uncomfortable on overcast days unless the person is properly clothed), which constituted more than 55% of all WCI hourly cases in the year (Table 3). During each month, 12.4 to 43.5% of the WCI hourly values were in cooling category I: work outside was comfortable for a properly clothed person.

Minimal WCI hourly values in particular months (Fig. 5) show that in the middle of winter (July) "comfortable" thermal sensation conditions occurred only at 06:00, 20:00 and 23:00 and in September only at 15:00 and 18:00. From December to February, "comfortable" thermal sensation conditions occurred almost every hour.

(a)

Mon \ Hrs	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Day
Jan.	525	459	556	537	537	529	528	578	550	491	531	542	531	563	613	481	461	593	528	625	544	550	554	503	459
Feb.	543	579	560	592	517	569	514	544	517	483	571	555	521	518	509	565	528	559	536	525	540	530	579	608	483
Mar.	528	558	557	535	529	516	584	545	641	558	524	554	525	535	583	538	535	539	578	539	548	615	524	541	516
Apr.	534	571	533	627	532	546	534	578	643	574	590	620	503	588	573	646	553	640	613	572	543	519	611	582	503
May	595	476	610	553	616	580	499	645	568	646	544	524	597	599	575	559	507	573	576	593	574	537	566	603	476
Jun.	606	621	624	621	580	571	586	587	592	598	638	611	623	566	574	583	630	597	592	644	602	601	554	601	554
Jul.	619	640	701	664	620	688	574	638	658	604	690	619	690	644	626	683	594	636	621	625	580	636	592	570	570
Aug.	601	641	715	634	575	573	585	607	621	672	579	657	644	586	590	581	563	596	643	623	649	691	569	583	563
Sep.	627	607	658	645	591	645	640	652	587	624	676	635	659	617	612	569	587	619	544	602	583	680	603	598	544
Oct.	560	618	631	575	605	606	591	587	582	605	587	489	618	563	562	581	609	529	547	548	629	562	593	565	489
Nov.	543	502	553	550	594	591	556	570	571	540	560	598	535	512	488	602	546	565	641	638	565	558	564	532	488
Dec.	587	552	578	586	550	567	578	543	541	547	562	620	521	580	605	547	590	502	525	658	624	597	634	603	502
Year	525	459	533	535	517	516	499	543	517	483	524	489	503	512	488	481	461	502	525	525	540	519	524	503	459

(b)

Mon \ Hrs	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Day
Jan.	1374	1385	1397	1345	1361	1374	1322	1303	1322	1345	1388	1363	1371	1382	1369	1321	1339	1384	1370	1367	1346	1409	1382	1386	1409
Feb.	1464	1427	1342	1461	1424	1382	1524	1432	1466	1481	1438	1445	1428	1425	1419	1398	1443	1428	1515	1493	1494	1490	1500	1501	1524
Mar.	1525	1465	1569	1511	1511	1487	1446	1522	1507	1506	1521	1508	1519	1465	1490	1467	1493	1522	1465	1501	1527	1510	1510	1530	1569
Apr.	1738	1703	1751	1728	1774	1735	1720	1718	1746	1790	1731	1805	1798	1808	1840	1845	1840	1724	1847	1796	1771	1787	1712	1722	1847
May	1653	1687	1723	1726	1710	1690	1730	1694	1856	1740	1739	1725	1688	1621	1681	1674	1736	1649	1602	1658	1700	1709	1664	1672	1856
Jun.	1874	1951	1954	1991	2008	1994	2014	1950	1948	1920	1916	1957	1964	1972	1998	2008	2001	1926	1948	1911	1978	1917	1998	1922	2014
Jul.	1939	1916	1882	1792	1836	1823	1903	1861	1838	1836	1815	1831	1891	1853	1933	1950	1965	1886	1916	1821	1888	1935	1859	1865	1965
Aug.	1864	2007	1955	1971	1928	2009	1970	1901	1992	1979	2008	1940	1912	1962	1896	1849	1843	1893	1950	1864	1896	1901	1845	1855	2009
Sep.	1924	1905	1870	1981	1871	1899	1911	1903	1889	1861	1987	1919	1815	1884	1831	1908	1951	1879	1767	1809	1893	1706	1877	1951	1987
Oct.	1560	1538	1599	1614	1573	1570	1647	1611	1620	1632	1612	1671	1683	1607	1676	1708	1698	1624	1629	1651	1624	1606	1641	1532	1708
Nov.	1488	1419	1454	1430	1473	1541	1539	1468	1530	1527	1522	1503	1533	1510	1492	1461	1530	1451	1429	1495	1448	1422	1394	1427	1541
Dec.	1395	1461	1431	1397	1434	1385	1326	1362	1366	1328	1343	1369	1369	1351	1350	1357	1370	1375	1378	1375	1418	1355	1395	1394	1461
Year	1939	2007	1955	1991	2008	2009	2014	1950	1992	1979	2008	1957	1964	1972	1998	2008	2001	1926	1950	1911	1978	1935	1998	1951	2014

Cooling category	I	I	II	III	IV	V	VI
Thermal sensation	comfortable	cool	cold	cold	frosty	frosty	frosty

Fig. 5 (a) Minimal and (b) maximal WCI values (W/m²) for particular hours during each month at Arctowski Station (2013–2021). The corresponding cooling categories and thermal sensations are indicated.

All minimum values were in cooling category I. Mean WCI values calculated for each hour, separately for each month during the analysed multi-year period (for example, the mean WCI at 06:00 throughout the month of January across all years in the investigated period), all fell within cooling category III, which corresponds to the "cold" thermal sensation. Work under such conditions becomes more hazardous even on clear days unless one is properly clothed. Maximal WCI hourly values show that dangerous weather conditions (cooling categories V and VI) may occur throughout the day in June and for most of the day from July to September (Fig. 5). Unprotected skin can freeze in 1 minute with direct exposure. Work alone then is not advisable and should even be prohibited (Table 2). In December and January, and during several hours in November and February, temperature and wind speed were favourable to milder conditions (cooling category II), when even the maximum WCI values did not exceed 1394 W/m².

In order to describe and better understand biothermal conditions in the vicinity of Arctowski Station, particular attention was paid to the daily course of WCI values (Fig. 6) and changes of its hourly values from one hour to the next one (hereafter hour-to-hour changes; Table 4). The most dangerous cooling category—VI—occurred in the analysed period in 2013, 2017 and 2021 and was caused by air temperatures below -16.0°C and wind speeds above 10.0 m/s. Such conditions were recorded at various parts of the day, for example at 03:00, 06:00, 09:00 and 15:00 (Fig. 6). Conditions that create a threat of freezing of unprotected skin within 1 minute (cooling category V) must be considered in the period from June to September, throughout the day. Opportunities for safely working outdoors may be limited by the risk of freezing of unprotected skin if it is exposed over a prolonged period (cooling category IV) from April to October, especially from 12:00 to 15:00, when the frequency of such conditions was up to 7.2% (Fig. 6). From November

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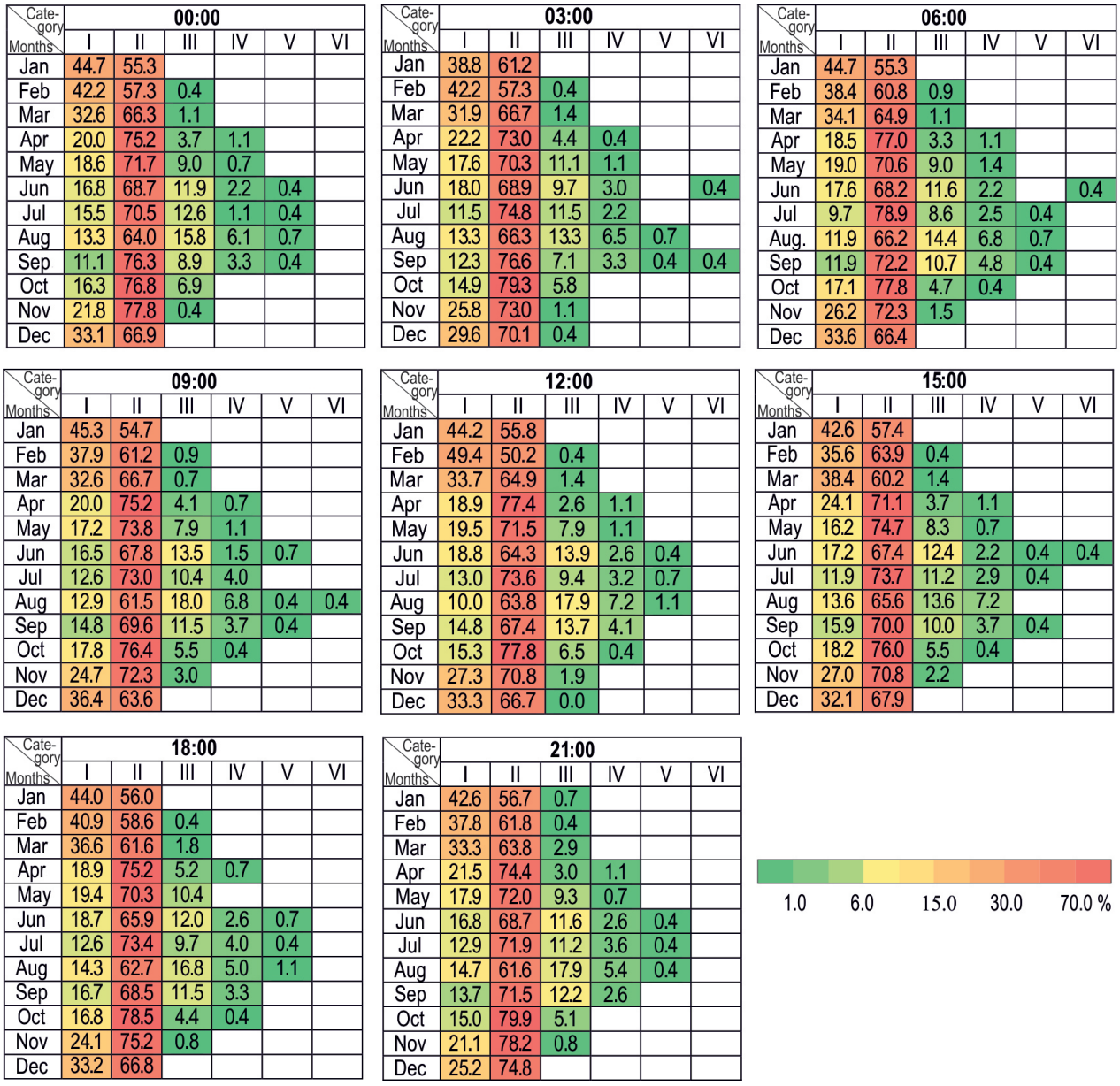

Category / Months	00:00 I	II	III	IV	V	VI
Jan	44.7	55.3				
Feb	42.2	57.3	0.4			
Mar	32.6	66.3	1.1			
Apr	20.0	75.2	3.7	1.1		
May	18.6	71.7	9.0	0.7		
Jun	16.8	68.7	11.9	2.2	0.4	
Jul	15.5	70.5	12.6	1.1	0.4	
Aug	13.3	64.0	15.8	6.1	0.7	
Sep	11.1	76.3	8.9	3.3	0.4	
Oct	16.3	76.8	6.9			
Nov	21.8	77.8	0.4			
Dec	33.1	66.9				

Category / Months	03:00 I	II	III	IV	V	VI
Jan	38.8	61.2				
Feb	42.2	57.3	0.4			
Mar	31.9	66.7	1.4			
Apr	22.2	73.0	4.4	0.4		
May	17.6	70.3	11.1	1.1		
Jun	18.0	68.9	9.7	3.0		0.4
Jul	11.5	74.8	11.5	2.2		
Aug	13.3	66.3	13.3	6.5	0.7	
Sep	12.3	76.6	7.1	3.3	0.4	0.4
Oct	14.9	79.3	5.8			
Nov	25.8	73.0	1.1			
Dec	29.6	70.1	0.4			

Category / Months	06:00 I	II	III	IV	V	VI
Jan	44.7	55.3				
Feb	38.4	60.8	0.9			
Mar	34.1	64.9	1.1			
Apr	18.5	77.0	3.3	1.1		
May	19.0	70.6	9.0	1.4		
Jun	17.6	68.2	11.6	2.2		0.4
Jul	9.7	78.9	8.6	2.5	0.4	
Aug.	11.9	66.2	14.4	6.8	0.7	
Sep	11.9	72.2	10.7	4.8	0.4	
Oct	17.1	77.8	4.7	0.4		
Nov	26.2	72.3	1.5			
Dec	33.6	66.4				

Category / Months	09:00 I	II	III	IV	V	VI
Jan	45.3	54.7				
Feb	37.9	61.2	0.9			
Mar	32.6	66.7	0.7			
Apr	20.0	75.2	4.1	0.7		
May	17.2	73.8	7.9	1.1		
Jun	16.5	67.8	13.5	1.5	0.7	
Jul	12.6	73.0	10.4	4.0		
Aug	12.9	61.5	18.0	6.8	0.4	0.4
Sep	14.8	69.6	11.5	3.7	0.4	
Oct	17.8	76.4	5.5	0.4		
Nov	24.7	72.3	3.0			
Dec	36.4	63.6				

Category / Months	12:00 I	II	III	IV	V	VI
Jan	44.2	55.8				
Feb	49.4	50.2	0.4			
Mar	33.7	64.9	1.4			
Apr	18.9	77.4	2.6	1.1		
May	19.5	71.5	7.9	1.1		
Jun	18.8	64.3	13.9	2.6	0.4	
Jul	13.0	73.6	9.4	3.2	0.7	
Aug	10.0	63.8	17.9	7.2	1.1	
Sep	14.8	67.4	13.7	4.1		
Oct	15.3	77.8	6.5	0.4		
Nov	27.3	70.8	1.9			
Dec	33.3	66.7	0.0			

Category / Months	15:00 I	II	III	IV	V	VI
Jan	42.6	57.4				
Feb	35.6	63.9	0.4			
Mar	38.4	60.2	1.4			
Apr	24.1	71.1	3.7	1.1		
May	16.2	74.7	8.3	0.7		
Jun	17.2	67.4	12.4	2.2	0.4	0.4
Jul	11.9	73.7	11.2	2.9	0.4	
Aug	13.6	65.6	13.6	7.2		
Sep	15.9	70.0	10.0	3.7	0.4	
Oct	18.2	76.0	5.5	0.4		
Nov	27.0	70.8	2.2			
Dec	32.1	67.9				

Category / Months	18:00 I	II	III	IV	V	VI
Jan	44.0	56.0				
Feb	40.9	58.6	0.4			
Mar	36.6	61.6	1.8			
Apr	18.9	75.2	5.2	0.7		
May	19.4	70.3	10.4			
Jun	18.7	65.9	12.0	2.6	0.7	
Jul	12.6	73.4	9.7	4.0	0.4	
Aug	14.3	62.7	16.8	5.0	1.1	
Sep	16.7	68.5	11.5	3.3		
Oct	16.8	78.5	4.4	0.4		
Nov	24.1	75.2	0.8			
Dec	33.2	66.8				

Category / Months	21:00 I	II	III	IV	V	VI
Jan	42.6	56.7	0.7			
Feb	37.8	61.8	0.4			
Mar	33.3	63.8	2.9			
Apr	21.5	74.4	3.0	1.1		
May	17.9	72.0	9.3	0.7		
Jun	16.8	68.7	11.6	2.6	0.4	
Jul	12.9	71.9	11.2	3.6	0.4	
Aug	14.7	61.6	17.9	5.4	0.4	
Sep	13.7	71.5	12.2	2.6		
Oct	15.0	79.9	5.1			
Nov	21.1	78.2	0.8			
Dec	25.2	74.8				

Fig. 6 Cooling categories frequency (%) according to WCI hourly values at Arctowski Station (2013–2021).

to March, the frequency of weather conditions during which work becomes dangerous if the appropriate clothing is not worn (cooling category III) was low during almost all hours of the day. As mentioned above, cooling categories I and II were the most frequent during each month and each part of the day. The share of these categories was a little bit higher between 9:00 and 18:00 than between 21:00 and 06:00 (Fig. 6).

Situations when weather conditions—and biothermal sensations—become abruptly more severe may be dangerous. The analysis of hour-to-hour changes was conducted for the whole year and for summer (October–March) and winter (April–September) half-years (Table 4). Cases when there was no change—78.3% of cases—were not included.

The most frequent were the changes between cooling categories I and II (Table 4). Such cases constituted 80.4% of all change cases during the year and 95.4% during the summer half-year. During the summer half-year, two-category jumps occurred intermittently and were comprised of rapid changes between cooling categories I and III; these were less than 0.1% of all hour-to-hour changes from October to March. The most biting changes from

Table 4 Frequency of hour-to-hour cooling category changes at Arctowski Station (2013–2021). Cases without change (78.3%) were not included.

Category change from hour to hour	Jan-Dec	Apr-Sep	Oct-Mar
I–II	40.2	33.2	47.7
I–III	0.1	0.2	0.0
II–I	40.2	33.3	47.7
II–III	7.3	11.9	2.2
II–IV	0.2	0.3	–
III–I	0.1	0.2	0.0
III–II	7.3	12.0	2.2
III–IV	1.9	3.6	0.1
III–V	0.0	0.0	–
IV–I	0.0	0.0	–
IV–II	0.1	0.2	–
IV–III	2.0	3.7	0.1
IV–V	0.3	0.5	–
IV–VI	0.0	0.0	–
V–III	0.0	0.0	–
V–IV	0.3	0.6	–
V–VI	0.0	0.1	–
VI–IV	0.0	0.0	–
VI–V	0.0	0.1	–

cooling category I to category III occurred in October 2015 and 2020 (at 07:00–08:00 and 23:00–24:00), while changes from cooling category III to I occurred in October 2015 and 2017 (at 08:00–09:00 and 04:00–05:00). They were chiefly caused by an abrupt increase or decrease in wind speed (from 1 to 10 m/s or conversely) at a stable air temperature of circa -4.0°C.

During the winter half-year (April–September) changes in biothermal conditions occurred very abruptly. Hour-to-hour changes by two cooling categories constituted 1% of cases (Table 4). They occurred most frequently in August and September, almost half of them (47.0%) between 09:00 and 18:00, the hours of the highest fieldwork activity. During the investigated nine-year period, the most intense WCI changes occurred from April to September: shifts from cooling category I to III occurred on average twice per year; and changes from II to IV occurred two to three times per year. Changes from cooling category III to V (in September) and IV to VI (August–September) occurred sporadically: once in three years, in August or September (Fig. 7). An abrupt decrement from cooling category III to I (May–October) and from IV to I (July–September) occurred on average once or twice a year. Changes from IV to I and from V to III were recorded only two or three times during the investigated period and a change from VI to IV only once, in September 2013.

Abrupt shifts in biothermal conditions were more often caused by changes in wind speed rather than air temperature change. The largest recorded hour-to-hour

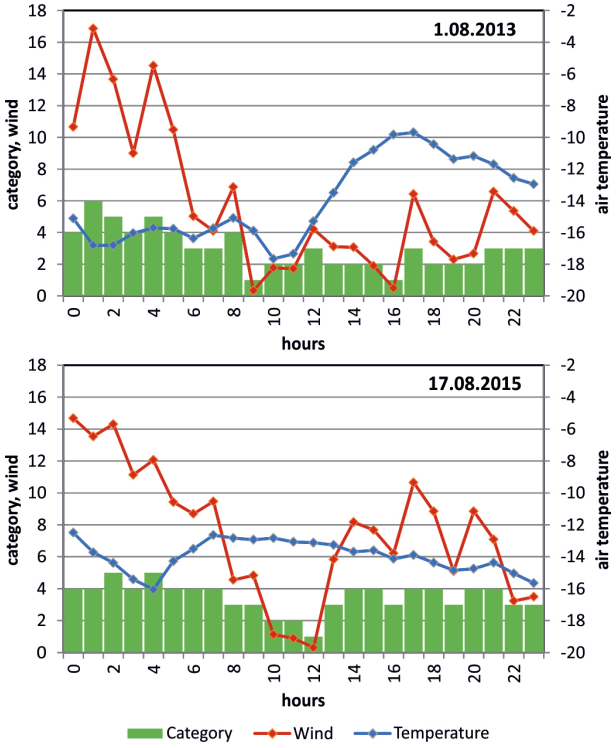

Fig. 7 Examples of the daily course of air temperature (°C), wind speed (m/s) and cooling categories, with WCI values, at Arctowski Station.

changes were drops by three cooling categories, from IV to I, which occurred at 06:00–07:00 in July 2017 and at 08:00–09:00 August 2013 (Fig. 7).

Discussion

Although people have dwelled in northern circumpolar areas for millennia, the human body has only a slight physiological ability to adapt to a cold environment. The most important health issues related to stays in the polar regions are hypothermia, frostbite, non-freezing cold injury (e.g., trench foot/immersion foot, chilblains/pernio, frostnip), sunburns and snow-blindness. Falling into cold water may bring on a cold shock response, cardiac arrest through bradycardia or arrhythmia; injuries may result from exposure to icy surfaces (Long et al. 2005; Rathjen et al. 2019; Nyssen et al. 2020; Zafren 2021). Discomfort caused by prolonged exposure to the cold may also affect aspects of mental performance, such as concentration, and may therefore heighten the risk of work accidents (Palinkas 2001). Additionally, there are very high energetic costs incurred when the body produces more heat to offset a cold environment and in bearing the weight of clothing that is a necessary protection. It is assumed that each additional kilogramme of clothing increases the energy costs of the

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body by 3% (Mäkinen & Hassi 2009). Exposure to cold can also exacerbate chronic disease (Rathjen et al. 2019).

This paper focused on air temperature and wind speed. Low temperature is the main cause of hypothermia and frostbite, but wind speed enhances the cooling of a body and is responsible for thermal sensation. The higher the wind speed, the greater the heat loss, leading to the perception of a lower temperature than indicated on a weather thermometer.

There are 10 scientific stations on King George Island, three of which are in the neighbourhood of Arctowski Station: the year-round Comandante Ferazz Antarctic Station (Brazil) and the summer stations Copacabana (US) and Machu Picchu Scientific Base (Peru) (Fig. 1). Arctowski Station is a year-round station where 8–11 people are employed on whole-year contracts and up to 30 more people work during the summer. Fieldwork is conducted on land and glaciers and at sea. Technical work, such as maintaining the station's building, also entails working outside. Motorboats are very often used as transport. During the summer season field excursions are undertaken almost every day. Over a dozen people are working outdoors for one to circa 16 hours, from the early morning (04:00) to late evening (22:00). During winter, the time spent outdoors is shorter (circa 6–8 hours), proportionate to the hours of daylight. Even though outside work is avoided during very challenging weather conditions (especially strong wind), it may sometimes be necessary even in such conditions to make outdoor repairs or to transfer between station buildings. Therefore, 24-hour WCI values were analysed in this paper.

The tourist season in West Antarctica lasts from the beginning of December to the end of February, the period with the most favourable biothermal conditions. Between the years 2008 and 2018, Arctowski Station was visited by 500 to 7000 tourists per season (Wilkońska et al. 2020). A relatively large proportion of cruise ship passengers are elderly people: 42% percent of respondents in a study by Wilkońska et al. (2020) were 60 or more years old. Such persons often suffer from chronic illnesses and may experience relatively high discomfort because of cold and wind or abrupt changes in weather conditions; however, these are very individual characteristics.

The mean monthly and annual WCI values (2013–2021) that we have presented here are lower than those obtained by Styszyńska (2000) on the basis of a 1977–1998 data series. This difference is not because of Styszyńska having used an older version of the WCI formula than we used: the formula applied in our research usually results in higher values than those calculated using the older one. During the period 1977–1998, the range of mean monthly WCI values was from 915.1 W/m^2 (January 1990) to 1532.3 W/m^2 (July 1982), and mean monthly WCI values in July were classified as belonging to cooling category III six times, while there were no such cases during 2013–2021 (Fig 3). This indicates that biothermal conditions were slightly milder during 2013–2021 than 1977–1998. This may be a result of climate warming observed in the region, which, among other things, had lower absolute minimal temperatures in 1977–1998 than in 2013–17 (Plenzler et al. 2019).

Mean monthly and annual WCI values (2013–2021) at Arctowski Station are similar to WCI values presented by Araźny (2008) for Svalbard (1971–2000), particularly for meteorological stations at Ny-Ålesund, Svalbard Airport, Hornsund, Hopen and Bjørnøya. However, at those stations, multi-annual monthly WCI values of summer months were classified, according to the thermal sensation categories, as "cool," whereas at Arctowski Station they were "cold." That indicates slightly cooler summer conditions at Arctowski Station comparing to Svalbard. In the case of mean daily WCI values in southwest Spitsbergen, the thermal sensations "cool" and "cold" were dominant, similar to Arctowski Station (Araźny 2008; Sikora et al. 2010; Sikora et al. 2011).

An important limitation of our study is that it was based on measurements from a weather station located at sea level, so the results apply only to the low-lying parts of the island. At its highest point, the ice cap is about 700 m a.s.l., and the air temperature is lower there: the temperature gradient is 0.6°C /100 m (Kejna 2008). Consequently, biometeorological conditions are expected to be more severe at high altitudes on the island and to investigate them it would be advisable to use a more complex index that considers also barometric pressure. WCI is calculated on the basis of only air temperature and wind speed. The application of a more complex biothermal index would require surface radiation measurements that were not available for the whole period of 2013–2021. Our broad preliminary approach should help determine the most important issues for future investigation. For example, our results from the area around Arctowski Station, where the temperature is often above 0°C, point towards further research to determine how often conditions occur that could cause non-freezing cold injuries.

As the South Shetland archipelago is not very large, and the main factors that shape the climate on the individual islands are similar, our results may be generally representative for the whole area. According to Bañón et al. (2013), there is a strong correlation between the mean daily air temperature on Byers Peninsula (western Livingston Island) and Bellingshausen Station (Russia) on King George Island (Fig. 1) and between the mean daily air temperature on Byers Peninsula and Deception

Island (Pearson correlation coefficients were 0.97 and 0.93, respectively, confidence 95%). The mean annual air temperature at Arctowski during 2013–17 was about 0.5°C higher than at Bellingshausen and Base Presidente Eduardo Frei Montalva (Chile) stations and similar to Carlini Base (Argentina; (Plenzler et al. 2019). Because of its location in the lee of the ice cap, Arctowski Station usually experiences weaker winds than the other stations on King George Island, which are not protected from the prevailing wind, which in this area come from the north-west. Biothermal conditions might be slightly milder there, but additional investigation would be needed to confirm this.

Conclusions

The results of this study show that biothermal conditions in the vicinity of Arctowski Station are mainly favourable for outdoor work if people are wearing heavy winter clothing. This confirms previous scientific research and the observations of people working in this area. During the investigated period, daily biothermal conditions varied within particular years but in every year "cool" and "cold" thermal sensations predominated. Biothermal conditions may deteriorate abruptly during any season, but it is during the winter months that such changes pose the greatest threat. People planning a wintertime stay in the area should bear in mind that even though large, abrupt shifts in biothermal conditions occurred very seldom, they did occur in each of the years we investigated.

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