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*Regular research paper*

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## NUTRIENTS AND CONDUCTIVITY IN PRECIPITATION IN THE COAST OF KING GEORGE ISLAND (ANTARCTICA) IN RELATION TO WIND SPEED AND PENGUIN COLONY DISTANCE

**ABSTRACT:** The present paper reports on the year-long study of atmospheric precipitation (rain and snow) composition, including nitrogen, phosphorus and mineral matter as conductivity, in ice-free area of western coast of Admiralty Bay (King George Island). The effects of the local Adelie penguin colony on nitrogen and phosphorus concentrations in atmospheric precipitation, as well as the role of wind on nitrogen and phosphorus enrichment of ice-free areas uncovered by a progressing deglaciation of the Ecology Glacier (ASPA 128) were examined. The effect of marine influence on the mineral matter level (as conductivity) in atmospheric precipitation was examined too. The determination of conductivity, nitrogen and phosphorus were assayed according to standard methods. Conductivity, nitrogen and phosphorus concentrations in atmospheric precipitation differed depending on sampling sites location, precipitation type (rain or snow), season (summer or winter), and also distance from a penguin rookery. The mean conductivity of rain and snow amounted to 189  $\mu\text{S cm}^{-1}$  and was higher in rain (up to 290  $\mu\text{S cm}^{-1}$ ) than in snow samples (87  $\mu\text{S cm}^{-1}$ ). Mean total nitrogen and total phosphorus concentrations in precipitation amounted to 0.208  $\text{mg N dm}^{-3}$  and 0.028  $\text{mg P dm}^{-3}$ , respectively. A higher conductivity was recorded in the precipitation transported by NNW winds (200  $\mu\text{S cm}^{-1}$ ), and lower in the precipitation transported by SSE winds (80  $\mu\text{S cm}^{-1}$ ). The seasonal variability of conductivity was characterized by a higher

values during summer (320  $\mu\text{S cm}^{-1}$ ) and lower – during winter (90  $\mu\text{S cm}^{-1}$ ). The most nutrient-rich samples were those collected in the centre of the penguin rookery, average values of TN and TP concentrations were 0.450  $\text{mg N dm}^{-3}$  and 0.090  $\text{mg P dm}^{-3}$ , respectively. At the other sites concentrations of TN and TP were lower. Seasonal variability of nitrogen and phosphorus concentrations were usually characterized by minimal concentrations during winter and maximal – during spring or summer. The concentrations of nitrogen and phosphorus were characterized by a statistically significant negative relation along the distance from the penguin rookery and along the altitude of sampling sites. The influence of the penguin rookery on the higher concentrations of biogenic compounds caused the high concentrations of ammonium nitrogen (averaging about 0.250  $\text{mg N dm}^{-3}$ ) during summer at all sampling sites, even at those, located farthest away (about 2200 m) from the penguin colony. The annual nitrogen and phosphorus loads deposited by atmospheric precipitation onto the ice-free area were estimated at about 0.752  $\text{kg N ha}^{-1}$  and 0.061  $\text{kg P ha}^{-1}$ , respectively.

**KEY WORDS:** Antarctica, atmospheric precipitation, conductivity, nitrogen, phosphorus

## 1. INTRODUCTION

A considerable attention is paid to the state of chemical composition of atmospheric precipitation in the Antarctic ecosystem (Shaw 1988; Bertler *et al.* 2005). In polar regions, aeolian transport is particularly important in redistribution of organic and mineral matter, including nitrogen and phosphorus (Fahnestock *et al.* 2000). In coastal

areas, the ocean is the major supplier of mineral salts ( $\text{Na}$ ,  $\text{Cl}$ ,  $\text{Mg}$ ,  $\text{SO}_4^{-2}$ ) and contributes to the salinity of freshwater bodies and soils (Björck *et al.* 1996; Legrand *et al.* 1998). Penguin colonies are the major source of nutrients (N, P) (Bertler *et al.* 2005; Fattori *et al.* 2005), and penguin faeces have played a part in the formation of ornithogenic soils (Pietr *et al.* 1983; Beyer *et al.* 1997; Tatur 2002). On the other hand, mineral and

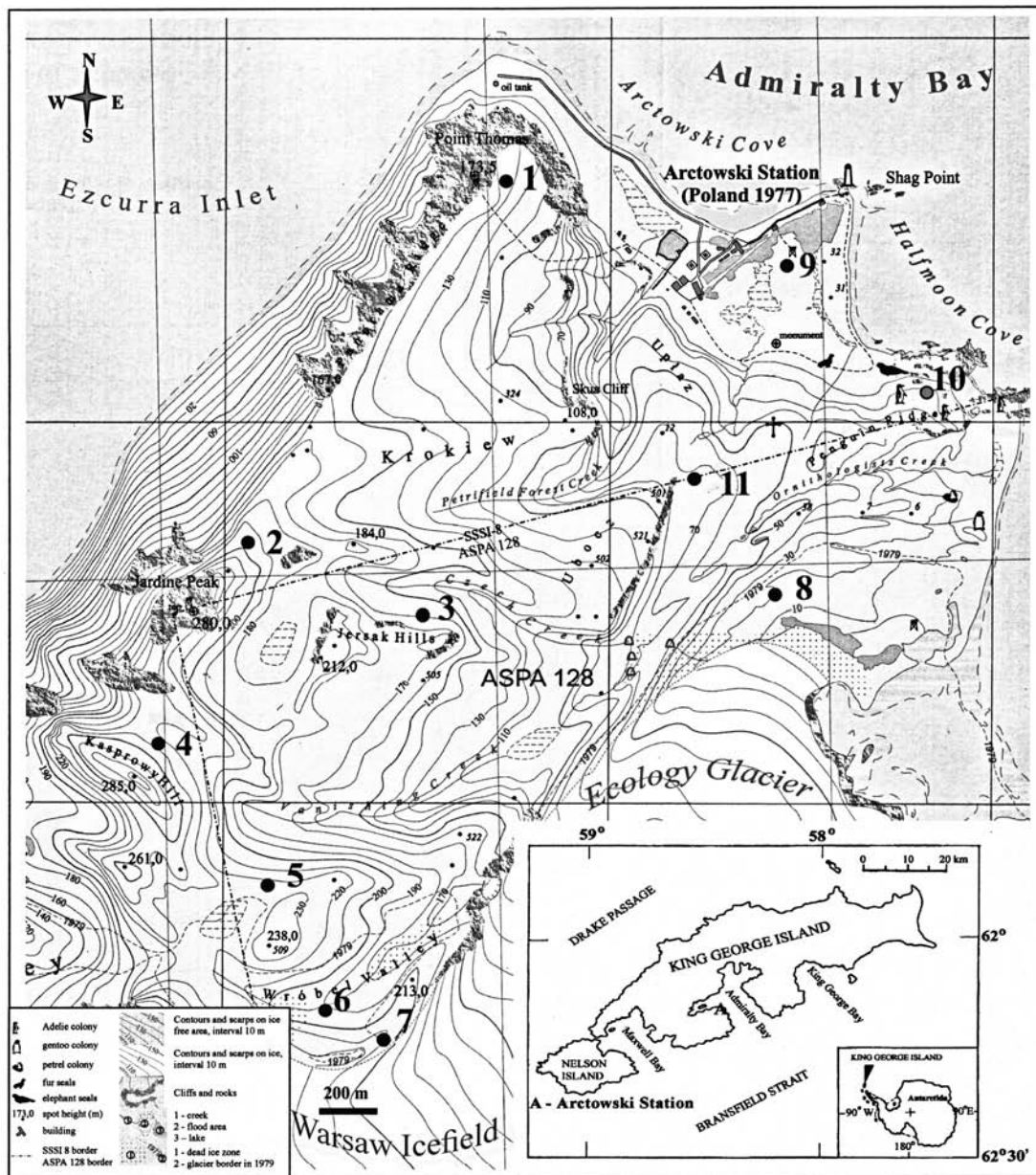


Fig. 1. Area of study and location of sampling sites (1–11) in the area of Antarctic Specially Protected Area No. 128 (ASP A 128), Site of Special Scientific Interest No. 8 (SSSI-8) and the Polish H. Arctowski Antarctic station (west coast of the Admiralty Bay, King George Island, South Shetlands).

nutrient concentrations are significantly diminished in offshore areas located away from the direct impact of penguin colonies (Speir and Cowling 1984; Björck *et al.* 1996; Juchnowicz-Bierbasz 1999; Juchnowicz-Bierbasz and Rakusa-Suszczewski 2002). Wind is the major source of minerals and nutrients for offshore areas (Aristarain and Delmas 2002; Suzuki *et al.* 2002; Abbott *et al.* 2004).

It is of particular importance in a new terrestrial areas formed at the front of retreating glacier. This process is observed in the Admiralty Bay (King George Island) (Fig. 1) where, during the last 30 years, the ice-free area increased from 21 to 38 km<sup>2</sup> (Braun *et al.* 2001). Deglaciation is particularly intensive on the western coast of the Admiralty Bay, in Antarctic Specially Protected Area 128 (ASP 128) (Battke *et al.* 2001). The soils there are primarily initial, impoverished in terms of nitrogen and phosphorus (Tatur and Myrcha 1988). Aeolian transport of nutrients, diaspores, and animal remains may contribute to the colonisation of those areas by plants and to an increase of plant production (Fisk *et al.* 1996).

This paper reports the results of a year-long study carried out in the maritime Antarctic (Admiralty Bay, King George Island, South Shetland Islands) (Fig. 1), which was aimed at: 1) assessment of the levels of salinity (conductivity) and fertility (nitrogen and phosphorus concentration) of atmospheric precipitation with reference to precipitation type (rain and snow) and wind speed along with direction; 2) demonstration of penguin colony effects on nitrogen and phosphorus concentrations in atmospheric precipitation; and 3) nitrogen and phosphorus enrichment of areas freed from ice, as a result of progressing deglaciation on the western shore of Admiralty Bay and Ecology Glacier (ASP 128).

## 2. METHODS

A year-long study of atmospheric precipitation was conducted in the vicinity of H. Arctowski Polish Antarctic Station at King George Island (60°09' S, 58°28' W) during the 29<sup>th</sup> Antarctic Expedition, from December 2004 to October 2005. Rain and

snow samples were collected from 11 sites (Fig. 1):

- site 1 was located near Point Thomas, 135 m above sea level (asl);
- site 2 – near Jardine Peak, 200 m asl;
- site 3 – near Jersak Hills, 160 m asl;
- site 4 – on Kasprowy Hill, 230 m asl;
- site 5 – on the plateau separating Kasprowy Hill and Dutkiewicz Cliff, 220 m asl;
- site 6 – in Wróbel Valley, 190 m asl;
- site 7 – on the hill between Wróbel Valley and Ecology Glacier, 220 m asl;
- site 8 – near the edge of Ecology Glacier, off the glacier's head, 10 m asl;
- site 9 – in a moss-vegetated area near the laboratory, 2 m asl;
- site 10 – in the penguin rookery centre, 20 m asl;
- site 11 – on the moraine between Puchalski's grave and Ubocz, on the ASP 128 border line, 75 m asl.

Wind direction and wind speed were recorded on each sampling date. Rain samples were collected during the austral summer and autumn. At that time, the N-NW winds were prevailing. Rain samples were collected in polyethylene containers 0.25 m<sup>2</sup> surface area and 10 dm<sup>3</sup> capacity, placed on steel greeds 1 m above the ground, which provided protection from contamination the samples by wind-borne coarse sand grains and organic remains.

Snow samples were collected during the austral winter and early spring when the prevalent winds blew both from N-NW as well as from S-SE. Snow samples were collected by scooping the surface layer (5 cm thick) of fresh snow from the surface of 1 m<sup>2</sup>.

The samples were collected immediately after the rain- or snowfall, delivered to the laboratory, heated to room temperature (18°C), and analysed.

Conductivity was measured with a WTW LF 197 conductometer. Inorganic forms of nitrogen (nitrite, nitrate, and ammonium), total nitrogen (TN), total reactive phosphorus (TRP), and total phosphorus (TP), were analysed at the water samples without filtration according to the standard colorimetric techniques recommended by Standard Methods (1995). Absorbances were measured at

Table 1. Average values of chemical parameters analysed in atmospheric precipitation throughout the period of study at different sampling sites 1–11 (Fig. 1) and averages for rain, snow, and total precipitation. Site 10 (bold) means penguin rockery.

Site	Type	n*	Conductivity		mg N dm <sup>-3</sup>							mg P dm <sup>-3</sup>		
			µS cm <sup>-1</sup>	n*	N-NO <sub>2</sub> <sup>-</sup>	N-NO <sub>3</sub> <sup>-</sup>	N-NH <sub>4</sub> <sup>+</sup>	TIN	TON	TN	TRP	TOP	TP	
1	Rain	7	108		0.002	0.024	0.059	0.085	0.089	0.174	0.005	0.009	0.014	
	Snow	8	62		0.001	0.018	0.040	0.059	0.120	0.179	0.004	0.003	0.007	
2	Rain	7	159		0.003	0.022	0.056	0.081	0.101	0.182	0.007	0.012	0.019	
	Snow	8	60		0.001	0.011	0.044	0.056	0.103	0.159	0.004	0.004	0.008	
3	Rain	7	89		0.002	0.023	0.071	0.095	0.091	0.186	0.008	0.006	0.014	
	Snow	8	39		0.001	0.012	0.046	0.058	0.110	0.168	0.004	0.003	0.007	
4	Rain	6	96		0.002	0.020	0.054	0.075	0.100	0.176	0.005	0.007	0.012	
	Snow	8	25		0.001	0.009	0.039	0.050	0.110	0.160	0.003	0.003	0.006	
5	Rain	7	118		0.003	0.023	0.062	0.088	0.090	0.178	0.006	0.014	0.020	
	Snow	8	110		0.001	0.017	0.045	0.063	0.091	0.154	0.004	0.003	0.007	
6	Rain	7	84		0.002	0.018	0.052	0.072	0.101	0.173	0.005	0.007	0.012	
	Snow	8	44		0.001	0.011	0.032	0.044	0.098	0.142	0.002	0.005	0.007	
7	Rain	7	139		0.002	0.023	0.051	0.076	0.061	0.137	0.003	0.013	0.016	
	Snow	8	44		0.001	0.008	0.033	0.044	0.096	0.140	0.004	0.003	0.008	
8	Rain	7	81		0.003	0.029	0.107	0.139	0.068	0.207	0.015	0.013	0.027	
	Snow	10	43		0.001	0.016	0.038	0.055	0.169	0.224	0.004	0.004	0.008	
9	Rain	7	1613		0.004	0.058	0.114	0.176	0.152	0.328	0.099	0.059	0.158	
	Snow	10	366		0.001	0.016	0.047	0.065	0.181	0.245	0.010	0.004	0.014	
10	<b>Rain</b>	<b>2</b>	<b>70</b>		<b>0.011</b>	<b>0.038</b>	<b>0.221</b>	<b>0.271</b>	<b>0.206</b>	<b>0.476</b>	<b>0.096</b>	<b>0.073</b>	<b>0.169</b>	
	<b>Snow</b>	<b>10</b>	<b>60</b>		<b>0.002</b>	<b>0.022</b>	<b>0.088</b>	<b>0.113</b>	<b>0.339</b>	<b>0.452</b>	<b>0.060</b>	<b>0.010</b>	<b>0.070</b>	
11	Rain	3	56		0.004	0.021	0.039	0.064	0.098	0.162	0.011	0.013	0.024	
	Snow	10	47		0.001	0.019	0.042	0.062	0.225	0.287	0.004	0.003	0.008	
Average values in rain		67	290		0.003	0.026	0.082	0.111	0.076	0.187	0.018	0.016	0.034	
Average values in snow		96	87		0.002	0.015	0.047	0.064	0.165	0.229	0.013	0.008	0.021	
<b>Average values in precipitation</b>		<b>163</b>	<b>189</b>		<b>0.003</b>	<b>0.021</b>	<b>0.065</b>	<b>0.088</b>	<b>0.126</b>	<b>0.208</b>	<b>0.016</b>	<b>0.012</b>	<b>0.028</b>	

\* number of samples

Table 2. The Pearson linear correlation coefficient “r” (statistically significant) between chemical constituents and wind speed, the altitude of sampling site and the distance of the penguin rookery ( $\alpha = 0.05$ ,  $n = 163$ ).

	Speed wind	Altitude	Distance from the penguin rookery
N-NO <sub>2</sub> <sup>-</sup>	–	–0.16	–0.20
N-NO <sub>3</sub> <sup>-</sup>	–	–0.23	–0.21
N-NH <sub>4</sub> <sup>+</sup>	–	–0.20	–0.22
TIN	–	–0.24	–0.26
TON	–	–0.39	–0.47
TN	–	–0.45	–0.52
TRP	–	–0.29	–0.30
TOP	–	–0.25	–0.23
TP	–	–0.32	–0.32
Conductivity	0.26	–0.26	–0.17

Table 3. Mean values of selected chemical parameters in rain and snow in relation to wind speed and direction.

Wind Speed	Wind Direction	Precipitation type	n	TIN	TN	TRP	TP	Conductivity
				mg N dm <sup>-3</sup>	mg P dm <sup>-3</sup>	mg P dm <sup>-3</sup>	μS cm <sup>-1</sup>	
0–10 m s <sup>-1</sup>	N-NW	Rain	29	0.141	0.200	0.012	0.029	114
	N-NW	Snow	11	0.051	0.258	0.003	0.004	6
	S-SE	Snow	43	0.070	0.207	0.011	0.022	55
10–30 m s <sup>-1</sup>	N-NW	Rain	38	0.087	0.173	0.023	0.038	438
	N-NW	Snow	26	0.055	0.261	0.020	0.025	135
	S-SE	Snow	16	0.068	0.196	0.014	0.019	151

the recommended wavelengths in a CARL ZEISS SPECOL-1100 spectrophotometer. Nitrite nitrogen was assayed with sulphanyl acid ( $\lambda = 543$  nm). Nitrate nitrogen was determined as nitrites after reduction on a Cu-Cd column. Ammonium nitrogen was assayed with indophenol blue ( $\lambda = 630$  nm). TN was determined, as nitrates, after mineralization with potassium hypersulphate. Total organic nitrogen (TON) content was calculated as the difference between TN and total inorganic nitrogen (TIN) (sum of nitrite, nitrate, and ammonium nitrogen contents). TRP was assayed using the molybdenate technique with ascorbic acid as a reducer ( $\lambda = 882$  nm). TP, after mineralization with potassium hypersulphate, was assayed as TRP. The difference between the two phosphorus fractions produced total organic phosphorus (TOP).

The data were subjected to statistical treatment involving one-way analysis of the Pearson's linear regression at  $\alpha = 0.05$ , using the Statistica 7.1 software (StatSoft Inc. 2005).

### 3. RESULTS AND DISCUSSION

#### 3.1. Conductivity of atmospheric precipitation

Mean conductivity of snow and rain amounted to 189  $\mu\text{S cm}^{-1}$  and was higher in the rain than in the snow samples (averages of 290 and 87  $\mu\text{S cm}^{-1}$ , respectively) (Table 1). The highest salinity of atmospheric precipitation was recorded at Site 9 on a marine terrace 50 m away from the Admiralty Bay, at the altitude of 2 m (Table 2). Coastal terraces are particularly intensely enriched with marine salts carried by the wind spray (Heywood 1968; Björck *et al.* 1996; Juchnowicz-Bierbasz 1999). At the other sites (1–8, 10 and 11) located further inland and at altitudes between 10 to 230 m above sea level (Fig. 1), conductivity was lower than at Site 9 (Table 1). In the present study, the level of mineral matter content of the atmospheric precipitation decreased as the altitude increased. The correlation between

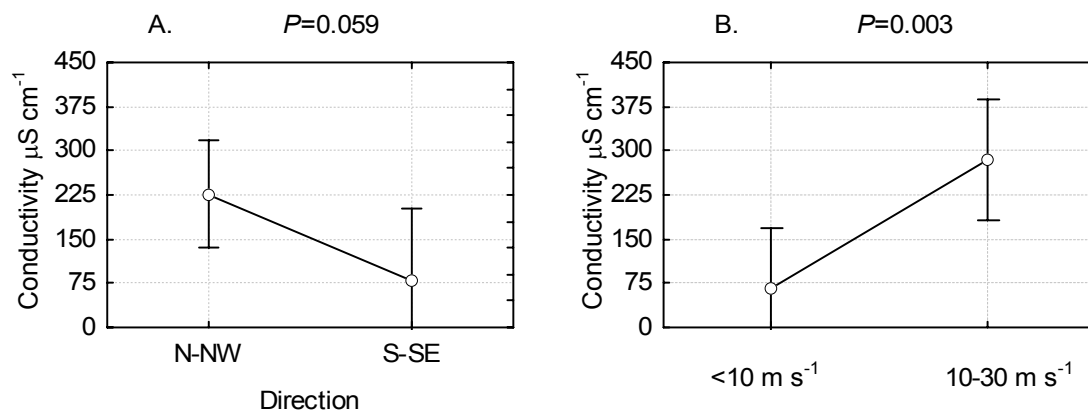


Fig. 2. Relationships between conductivity of atmospheric precipitation and wind direction (A) and speed (B).

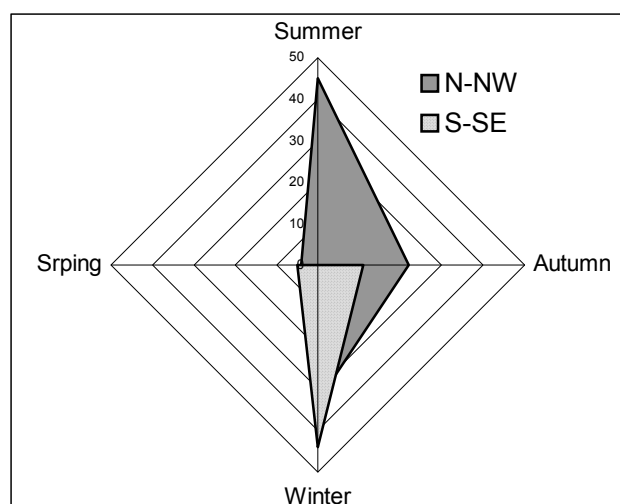


Fig. 3. Seasonal variability of winds at region of H. Arctowski Station (Fig. 1) during atmospheric precipitation samples collection.

conductivity and the altitude was statistically significant ( $r = -0.26$ ) (Table 2). Negative correlations between mineral concentrations in atmospheric precipitation and altitude in the Antarctic were also reported by Bertler *et al.* (2005).

The dependence of the mineral concentrations of atmospheric precipitation on the wind force involved an increase in the precipitation conductivity with increasing wind speed. Statistic analysis displayed significant positive correlation between conductivity and wind speed ( $r = 0.26$ ) (Table 2). The South Shetlands are notorious for their numerous storms with winds stronger than  $30 \text{ m s}^{-1}$ ; the mean wind speed in the area is  $8 \text{ m s}^{-1}$  (Gordon *et al.* 1978; Kowalski 1985;

Kejna and Láska 1999). The division of atmospheric precipitation samples on this collected during weak winds (lower than  $10 \text{ m s}^{-1}$ ) and this collected during storm winds ( $10-30 \text{ m s}^{-1}$ ) confirmed an increase mineral concentrations of atmospheric precipitation with increasing wind speed (Fig. 2B). The mean conductivity of atmospheric precipitation at winds blowing at speeds  $<10 \text{ m s}^{-1}$  was lower than that at speed  $10-30 \text{ m s}^{-1}$  (Table 3).

The conductivity of atmospheric precipitation was found to depend also on the direction of the wind and on the season. A higher conductivity was recorded in the precipitation transported by N-NW winds (about  $200 \mu\text{S cm}^{-1}$ ), which prevail during

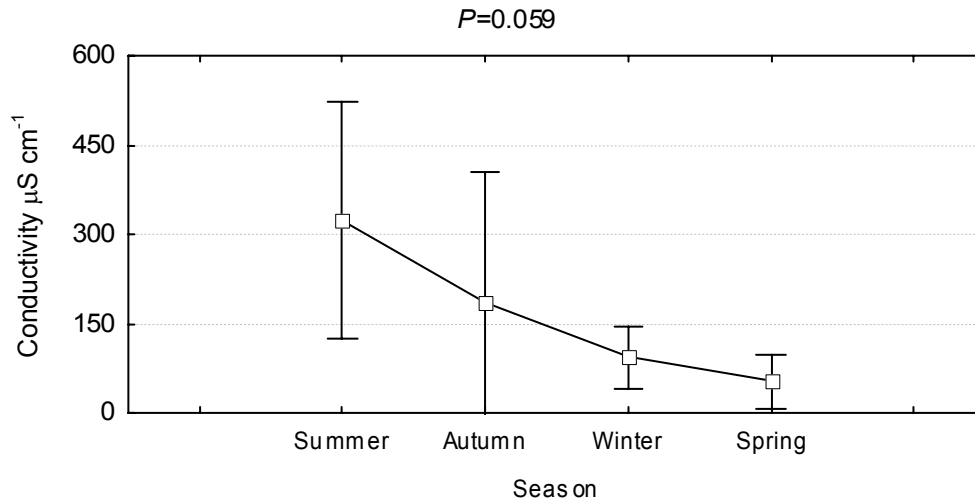


Fig. 4. Seasonal variability of conductivity in atmospheric precipitation.

summer and autumn (Fig. 3), and lower in the precipitation transported by S-SE winds (about 80  $\mu\text{S cm}^{-1}$ ) (Fig. 2A). The seasonal variability of conductivity was characterized by a higher values during summer and autumn (rain samples) and lower during winter and spring (snow samples) (Table 1, Fig. 4). This is most probably related to the effects of the sea surrounding the ASPA 128 area in the Admiralty Bay; sea areas off the South Shetlands most probably contribute to that effect as well. Jourdain and Legrand (2002), Mishra *et al.* (2004) and Bertler *et al.* (2005) reported higher content of major ions in summer and autumn, and lower in winter and spring, what were explained by the general air circulation patterns as well as the range and seasonality of ice cover around the Antarctic. Our results are comparable to those reported by Mishra *et al.* (2004) from the area near the Korean station King Sejong (King George Island) and by Jourdain and Legrand (2002) from the area off the French station Dumont d'Urville (Eastern Antarctic). Those authors found a similar relationship between the aerosol mineral content and the wind direction and season of sampling. Due to the long distance between the South Shetlands and major land masses (South America at North and Antarctica at South), the area receives mainly masses of maritime air containing considerable amounts of water vapour and oceanic aerosols, particularly during the N-NW circulation. The N and

NW winds prevail during the austral summer and are particularly forceful in autumn (Kowalski and Wielbińska 1989). Those winds blow inland over the Admiralty Bay, Ezcurra Inlet and Drake Passage (Fig. 1). On the other hand, during the austral winter, the ice-free area of the ocean off the South Shetlands diminishes, and the air advecting from N-NW, and particularly from S-SE, cannot absorb water vapour while moving above the sea ice (Marsz 2000). The low salinity level was typical for atmospheric precipitation transported by S-SE winds (winter and spring) seawards from the Warsaw Icefield and Bransfield Strait (Fig. 1). Our observations of icy processes on Admiralty Bay in 2001, reported, that during winter, for about 50 days, 60% of the Admiralty Bay was covered by a pack ice or fast ice. Lower extent of ice cover was observed in the Bransfield Strait. Ice pack was transported from the Strait into the Admiralty Bay by the currents.

### 3.2. Nitrogen and phosphorus in atmospheric precipitation

The mean TN and TP concentrations were 0.208  $\text{mg N dm}^{-3}$  and 0.028  $\text{mg P dm}^{-3}$ , respectively (Table 1). Of the analysed nitrogen forms, TON proved to be dominant over TIN and this pattern was consistent in snow samples but not in rain samples (Table 1). Among the TIN forms, ammonium

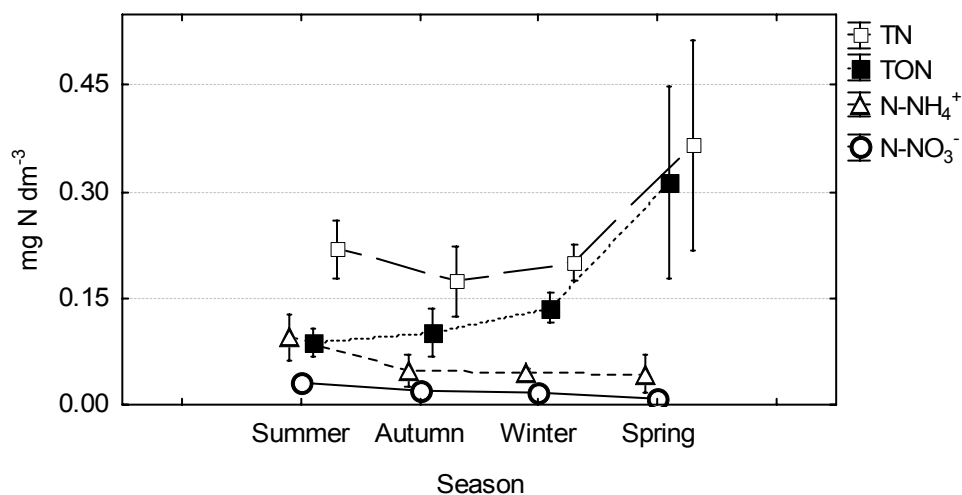


Fig. 5. Seasonal variability of total nitrogen (TN), total organic nitrogen (TON), ammonium nitrogen and nitrate nitrogen in atmospheric precipitation.

nitrogen dominated over nitrate and nitrite nitrogen. Total reactive phosphorus (TRP) was slightly dominating over organic phosphorus (TOP) (average of 0.016 vs 0.012 mg P dm<sup>-3</sup>); this pattern was consistent in both rain and snow samples (Table 1). Concentrations of nitrogen and phosphorus recorded in the present study were similar to this recorded around Antarctica (Bertler *et al.* 2005) and much lower than in other continents, especially at industrial regions. Reimann *et al.* (1997) found, in northern Europe, much higher concentrations of nitrogen, particularly nitrate nitrogen (about 0.500 mg NO<sub>3</sub><sup>-</sup> dm<sup>-3</sup>) resulting from atmospheric emissions of gases from industrial areas. Similar high concentrations of biogenic compounds in atmospheric precipitation were reported by Rodrigo *et al.* (2003) from Spain and Saxena *et al.* (1996) from Agra (India). The low phosphorus (TP) concentrations in the atmospheric precipitation samples in the present study were comparable to those reported by Reimann *et al.* (1997) from European Arctic. The most nutrient-rich samples were those collected at Site 10 in the centre of the penguin rookery, average values of total nitrogen and phosphorus concentrations were 0.450 mg N dm<sup>-3</sup> and 0.090 mg P dm<sup>-3</sup>, respectively. Concentrations of total nitrogen and total phosphorus at the other sites did not exceed 0.200 mg N dm<sup>-3</sup> and 0.020 mg P dm<sup>-3</sup>, respectively (Table 1). Legrand *et*

*al.* (1998) also reported the penguin colony effect on nitrogen and phosphorus contents in atmospheric precipitation throughout the year, the highest values are recorded during the austral summer.

Seasonal variability of nitrogen and phosphorus concentrations were usually characterized by high concentrations during summer, minimal during winter and maximal during spring (Figs 5, 6). Only for ammonium nitrogen and nitrate nitrogen the highest concentrations were reported during summer (Fig. 5). High concentrations of ammonium nitrogen (averaging about 0.250 mg N dm<sup>-3</sup>) were also recorded at all sampling sites from January to February 2005, even at those, located farthest away (about 2200 m) from the penguin colony. The concentrations of nitrogen and phosphorus were characterized by a statistically significant negative relation between the distance from the penguin rookery and the altitude of sampling sites (Table 2). The nitrogen and phosphorus concentrations at site 11 (about 600 m away from the penguin colony centre) were only slightly higher (the maximum difference of about 10% detected in ammonium nitrogen) than those recorded at sites further away from the penguin colony. As reported by Zdanowski *et al.* (2005), nitrogen and phosphorus losses from the fresh guano during the initial period of its decomposition under natural conditions amounts to about

15% and 10%, respectively, of the total guano nitrogen and phosphorus contents. Claesson and Steineck (1996) showed ammonium losses from natural fertilisers due to atmospheric emission of ammonia to be even in excess of 80% of the original ammonium content; this effect is perceived as an important source of nitrogen dispersal in the environment.

The increase of TON, TN, TOP and TP concentrations during spring after minimal values recorded during winter, could be accounted of particular organic matter increase (remains of grasses and lichens from ice-free regions, penguins guano and marine macroalgae) carried by the wind, than enriches atmospheric precipitations with biogenic compounds. The unpublished Nędzarek (2006) studies on the effect of marine macroalgal and lichen remains on snow nitrogen and phosphorus concentrations showed the snow samples containing macroalgal remains to have higher nutrient concentrations than the lichen remains-containing samples. The very high TON, TN, TRP and TP (in  $\text{mg N dm}^{-3}$  and  $\text{mg P dm}^{-3}$ ) concentrations Nędzarek (2006) recorded for snow samples with marine macroalgal remains (1.130, 1.220, 1.140 and 1.980 respectively) and much lower for snow samples with lichen remains (0.024, 0.054, 0.008 and 0.014). The relationships detected are similar to those described by Fahnestock *et al.* (2000): plant remains transported by the wind are redistributed and accumulated in the abiotic environment and modify it, thus increasing the tundra ecosystem fertility. The nitrogen and phosphorus loading in atmospheric precipitation was found to depend on the force and direction of the prevalent winds. Nutrient concentrations in atmospheric precipitation were found to increase with wind force, but the relationship was not as clear-cut as was in the case in conductivity (Table 3). The relationship was most distinct with respect to TN, and TP (concentrations increasing by  $0.094 \text{ mg N dm}^{-3}$  and  $0.010 \text{ mg P dm}^{-3}$ , respectively). Higher nitrogen and phosphorus concentrations were recorded in the samples collected during the prevalence of N-NW winds, what suggests, that the main nutrients source for atmospheric precipitation, like for conductivity, is ocean.

### 3.3. Estimation of nitrogen and phosphorus loads from atmospheric precipitation in areas denuded by deglaciation

Over the last 30 years, the ASPA 128 area featured a distinctly progressing deglaciation (the ice-free area increasing in the period from 21 to 38  $\text{km}^2$  – Braun *et al.* 2001), accompanied by colonisation and succession on the newly uncovered land areas. The nutrients transported by the wind inland originate from small surfaces of bird rookeries, pinniped breeding grounds, the remains of macroalgae found on the shore (Rakusa-Suszczewski and Zieliński 1993, Rakusa-Suszczewski and Nędzarek 2002; Nędzarek and Rakusa-Suszczewski 2004). This study, showed a substantial reduction in mineral concentrations and fertility of atmospheric precipitation in localities away from the penguin rookery. The site locates farthest away from it, and at the highest altitude (in areas uncovered by deglaciation of the last 30 years; sites 5–7), showed the total phosphorus loads to be a half of the mean values for the entire period of study, the total nitrogen content being lower by about 30%.

The mean annual precipitation in the H. Arctowski Station area is estimated at 505 mm (Hellmann rain meter) (Marsz and Styszyńska 2000). It may be assumed, based on the Hellmann rain meter measurements, that 1 square metre of the area uncovered during the last 30 years from beneath the Ecology Glacier (Fig. 1) (sites 5–7) receives, *via* atmospheric precipitation, about 75 mg of total nitrogen and 6 mg of total phosphorus a year (i.e.,  $0.752 \text{ kg N ha}^{-1}$  and  $0.061 \text{ kg P ha}^{-1}$ ) (Table 4). A comparison with data reported by Hiltbrunner *et al.* (2005) and Rodrigo *et al.* (2003) shows that the nutrient loads found in this study are lower than those reported in the literature about other Earth regions. For instance, the annual nitrogen load deposited with the atmospheric precipitation in Swiss Alps (the boreal tundra) was estimated at  $2.6\text{--}5.0 \text{ kg N ha}^{-1}$  (Hiltbrunner *et al.* 2005) and the total phosphorus load in northeast Spain (an industrial region) was estimated at  $0.15\text{--}0.24 \text{ kg P ha}^{-1}$  (Rodrigo *et al.* 2003). It was only in the precipitation sampled in the centre of the penguin rookery that the nitrogen and

Table 4. Nutrient load (based on Hellmann rainmeter data of 505 mm for magnitude of atmospheric precipitation) deposited throughout the year in areas uncovered during the last 30 years by deglaciation of Ecology Glacier (Fig. 1) (sites 5–7, n = 45) in relation to values recorded at the Adelie penguin colony (site 10, n = 12).

Site	N-NO <sub>3</sub> <sup>-</sup>	N-NH <sub>4</sub> <sup>+</sup>	TN	TRP	TP
	kg N ha <sup>-1</sup>			kg P ha <sup>-1</sup>	
5–7	0.091	0.232	0,752	0.020	0.061
10	0.126	0.626	2.267	0.268	0.394

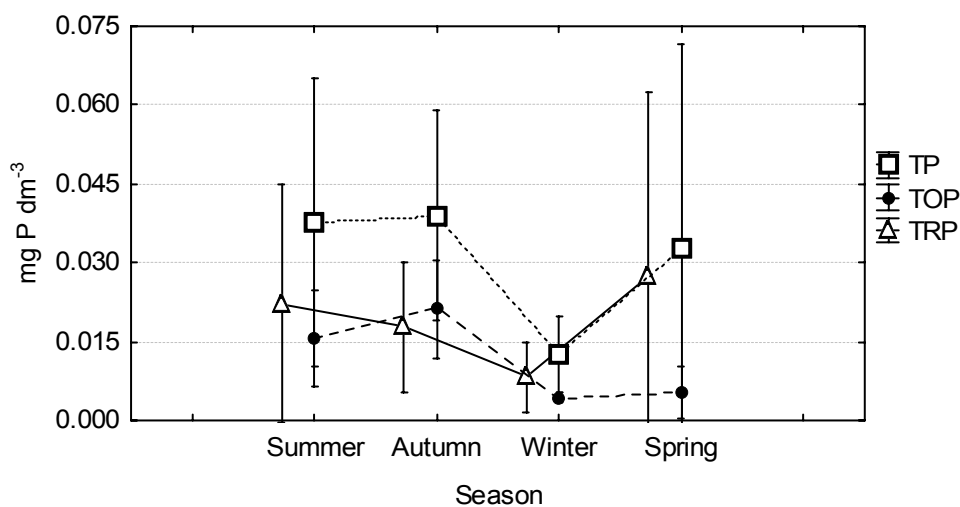


Fig. 6. Seasonal variability of total reactive phosphorus (TRP), total organic phosphorus (TOP) and total phosphorus (TP) in atmospheric precipitation.

phosphorus loads were comparable to the literature data (Table 4).

#### 4. CONCLUSIONS

Studies on atmospheric precipitation, carried out in the vicinity of the H. Arcowski Station, showed that the variability in conductivity, nitrogen and phosphorus concentrations depended on sampling site location, precipitation type (rain or snow), season (summer or winter), altitude, wind (speed and direction) and also a distance from a penguin rookery. The mean conductivity of rain and snow was higher in rain than in snow samples. A higher conductivity was recorded in the precipitation transported by N-NW winds and lower in the precipitation transported by S-SE winds. The seasonal variability of conductivity was characterized by a higher values during summer. The most nutrient-rich samples were those collected in the centre

of the penguin rookery. Seasonal variability of nitrogen and phosphorus concentrations were usually characterized by minimal concentrations during winter and maximal – during spring or summer. The increase of TON, TN, TOP and TP concentrations during spring after minimal values recorded during winter, could be accounted of particular organic matter increase (remains of: grasses and lichens from ice-free regions, penguins guano and marine macroalgae) carried by the wind that enriches atmospheric precipitations with biogenic compounds. The wind-borne distribution, particularly with respect to ammonium nitrogen, was extensive during the summer (penguin breeding season), and could reach to areas recently uncovered by deglaciation of the Ecology Glacier. The annual nitrogen and phosphorus loads deposited by atmospheric precipitation onto the ice free area were estimated at about 0.752 kg N ha<sup>-1</sup> and 0.061 kg P ha<sup>-1</sup>, respectively

and were lower than those reported from other areas of the Earth.

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