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Citation style: Dragańska-Deja Katarzyna, Błaszczyk Małgorzata, Deja Kajetan, Węsławski Jan Marcin, Rodak Jan. (2020). Tidewater glaciers as feeding spots for the Black-legged Kittiwake (Rissa tridactyla) : A citizen science approach. "Polish Polar Research" (vol. 41 no. 1 (2020), s. 69-93), doi 10.24425/ppr.2020.132570

POLISH POLAR RESEARCH
vol. 41 no. 1, pp. 69-93, 2020 DOI: 10.24425/ppr.2020.132570

Tidewater glaciers as feeding spots for the Black-legged Kittiwake (*Rissa tridactyla*): A citizen science approach

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Abstract: Thirty-one tidewater glacier bays in Spitsbergen Island were visited by yachts in August 2011, 2015, 2016 and 2017. Surface water samples were taken by volunteers, the members of the yacht crews, to measure concentrations of suspended matter, salinity, and temperature. Secchi disc measurements were used to measure water transparency. A series of photographs along the glacier fronts were taken and used to count seabirds that were present near the glacier cliff. Basic topographic features (depth, presence of a sill, exposure, glacier width) were obtained from sea charts and analysed. The number of preying Black-legged Kittiwakes (*Rissa tridactyla*; a target species) ranged from zero to over 2000 birds during 89 visits. High concentrations of individuals (above 100) were observed in 20% of the visits, while no birds were recorded in 42% of the visits. There was no statistical correlation between the topographic features of the glacier and bird concentrations. To our present knowledge, Black-legged Kittiwake feeding spots are random and temporary in time in which (or soon after) the juveniles are leaving the colony. They are a recurrent phenomenon related to krill abundance and simultaneous jet-like meltwater discharges.

Key words: Arctic, Spitsbergen, glacial bays, seabirds, gulls, foraging.

Introduction

Concentrations of marine top predators near the tidewater glaciers were first reported in the early 1930s (Hartley and Fisher 1936; Stott 1936). They were also recently analysed by Lydersen *et al.* (2014), who, on the basis of data from GPS transmitters attached to the animals, indicated that the tidewater glacier front was an attractive foraging site for seabirds, seals and white whales. Other works have focused on studying the mechanisms regulating food concentrations in such places. In glacial bays with a discharge of suspended matter (called the "brown zone"), large amounts of sea zooplankton, stunned or killed by osmotic shock, can be found (Węsławski *et al.* 2000; Urbański *et al.* 2017). Recent findings suggest that krill (Deja *et al*. 2019) and small fish (mainly polar cod) (Szczucka *et al*. 2017) tend to be abundant near the glacier front, and massive meltwater discharges create uplift that brings fish and krill to the sea surface, opening a window of opportunity for surface-feeding birds (mainly gulls, fulmars and terns). It is not a local upwelling, as was suggested in earlier studies (Hartley and Fisher 1936), nor estuarine circulation (Lydersen *et al.* 2014), but rather a jet-like outflow that may occur at various locations along the glacier front (Urbański *et al.* 2017). The accelerated warming of the climate in the Arctic is responsible for a massive change in habitats and niches, which directly affects tidewater glaciers, with a mean rate of retreat of over 45 m per year (Błaszczyk *et al.* 2013), with apparent consequences for seabirds (Stempniewicz *et al.* 2017).

However, the most important question that has yet to be answered is how predictable is the phenomenon of high bird concentrations in tidewater glacier bays. Specifically, it would be desirable to assess how much this is related to the glacier topography, its position in the fjord, the depth of the bay or the presence of a sill, which separates the proximal part of the glacier bay from the adjacent water body. We hypothesized that birds tend to aggregate in specific types of glacial bays, which likely support high food concentrations, with an obvious alternative (actually, a null hypothesis within statistical framework) being that bird aggregations in glacial bays are not connected with local physical and topographic conditions or glacier type. In our study, designed to investigate the above issue, we engaged volunteers, who were sailing the Svalbard archipelago and visiting glacier bays, to collect observations using an established data collection scheme.

Materials and methods

Material was collected from Spitsbergen, the largest island of the Svalbard archipelago, located in the NE Atlantic, between 76° and 80° N (Fig. 1). A recent description of the glacier position in the area was presented by Błaszczyk *et al.* (2009). The study area is situated between the main stream of the Atlantic water

Fig. 1. The research area. The numbers indicate the tested glaciers and correspond to those in the first column of Table 1.

inflow into the Arctic (West Spitsbergen Current) and the outflow of Arctic waters from the NE of the area (Barents Current, Sorkapp Current), which creates an important area for seabirds and sea mammals (Lydersen *et al.* 2014).

Thirty-one tidewater glacier bays were visited by the research vessel Oceania, where hydrographic (standard CTD – conductivity, temperature and depth profiling) and marine biological surveys were completed, as well as by pleasure boats, including yachts, with volunteers that collected ornithological observations and surface water samples. In our study, one of the glaciers has been divided into the northern and southern parts (Kongsbreen N and Kongsbreen S; Table 1), because these two parts are separated by a fragment of land and the glacier flows into two different glacial bays.

Table 1

Basic topographic information for glacial bays.

No.	Glacier	Depth (m)	Sill presence	Glacier front width (km)	Exposure	Bedrock
1	Aavatsmarkbreen	30	medium	4.25	very sheltered	diamictite
2	Blomstrandbreen	37	medium	2.7	medium sheltered	mica schist
3	Borebreen	16	high	5.45	medium sheltered	shale, siltstone, sandstone
4	Conwaybreen	27	high	1.8	very sheltered	sericite-chlorite schist
5	Dahlbreen	65	no	2.62	very sheltered	carbonate rocks
6	Esmarkbreen	21	high	3.1	medium sheltered	basic metavolcanics, greenstone
7	Fjortende Julibreen	69	medium	2.8	medium sheltered	mica schist
8	Gaffelbreen	16	low	1.1	very sheltered	phyllite, calcareous phyllite
9	Hansbreen	80	no	2.94	open coast	marble, garnet-mica schist
10	Harrietbreen	64	low	0.8	very sheltered	phyllite, calcareous phyllite
11	Hornbreen	60	low	4	very sheltered	shale, mudstone, siltstone
12	Kollerbreen	94	medium	2	medium sheltered	migmatite
13	Kongsbreen N	75	high	2.1	very sheltered	various metasediments

Table 1 continued

No.	Glacier	Depth (m)	Sill presence	Glacier front width (km)	Exposure	Bedrock
14	Kongsbreen S	36	high	3.8	very sheltered	diamictite
15	Konowbreen	41	low	2.14	very sheltered	carbonate rocks
16	Korberbreen	12	high	4.7	medium sheltered	sandstone, siltstone, shale (red or green)
17	Kronebreen	36	high	4.3	medium sheltered	granitoid rocks
18	Lilliehookbreen	189	no	13.2	medium sheltered	migmatite
19	Mayerbreen	76	no	0.44	medium sheltered	shale, siltstone, sandstone
20	Nansenbreen	30	high	4.1	medium sheltered	mica gneiss, garnet-mica schist
21	Nordenskioldbreen	20	no	6.1	open coast	sandstone, siltstone, shale (multicoloured)
22	Olsokbreen	26	high	5.27	open coast	diamictite
23	Osbornbreen	82	low	4.64	very sheltered	carbonate rocks
24	Paierlbreen	160	no	4.9	medium sheltered	chert, siliceous shale, sandstone, limestone
25	Sefstrombreen	40	high	3.81	very sheltered	granitoid rocks
26	Smeerenburgbreen	120	low	0.9	open coast	shale, siltstone, sandstone
27	Storbreen	60	low	5	very sheltered	chert, siliceous shale, sandstone, limestone
28	Sveabreen	40	high	3.7	medium sheltered	granitoid rocks
29	Tinayerbreen	83	no	1.3	medium sheltered	carbonate rocks
30	Tunabreen	42	no	3.67	medium sheltered	moraine
31	Wahlenbergbreen	22	high	2.15	medium sheltered	diamictite

Volunteers, who consisted of the yacht crews, conducted surveys along the glaciers between the 1st and 30th of August (in 2011, 2015, 2016 and 2017) – the time in which (or soon after) the birds are leaving the colony with juveniles. All photographs were taken from a 200 m distance from the glacier cliff, while the boat slowly navigated along the glacier face from one side to another. To cover the entire cliff length, usually three to nine images per site were collected. Then, they were analysed by biologists who were familiar with bird identification, participated in the field work and collected a proportion of the photos. The collected photos were analysed for the presence of Black-legged Kittiwakes, *Rissa tridactyla* (Linnaeus, 1758), by counted specimens (both in flight and on the water), avoiding a double count of the same specimen by preventing the same sector of the glacier cliff from being counted twice (based on distinctive morphological features of the cliff) (Table 2). The Black-legged Kittiwake was selected as a target species, as its representatives are often reported to stay near glaciers, and (contrary to ducks and guillemots) never dive – therefore, they are always visible.

Table 2

Black-legged Kittiwakes counts along glacier fronts in consecutive years.

Glacier	Number of black-legged Kittiwakes				
	2011	2015	2016	2016	2017
Aavatsmarkbreen	–	100	0	20	29
Blomstrandbreen	–	11	0	–	18
Borebreen	–	4	0	9	0
Conwaybreen	–	0	0	–	0
Dahlbreen	–	5	68	–	121
Esmarkbreen	–	5	20	0	0
Fjortende Julibreen	–	193	0	–	28
Gaffelbreen	–	3	32	–	0
Hansbreen	–	5	–	–	–
Harrietbreen	–	0	0	–	0
Hornbreen	2000	–	–	–	–
Kollerbreen	–	61	0	0	0
Kongsbreen N	–	13	0	–	11
Kongsbreen S	–	0	3	–	22

Table 2 continued

Glacier	Number of black-legged Kittiwakes				
	2011	2015	2016	2016	2017
Konowbreen	–	5	240	–	3
Korberbreen	–	0	–	–	–
Kronebreen	–	187	0	–	32
Lilliehookbreen	–	65	0	0	27
Mayerbreen	–	127	150	236	214
Nansenbreen	–	0	0	–	0
Nordenskioldbreen	–	155	46	0	0
Olsokbreen	–	–	0	–	–
Osbornbreen	–	20	311	–	73
Paierlbreen	–	25	–	–	–
Sefstrombreen	–	50	231	–	9
Smeerenburgbreen	–	–	772	104	–
Storbreen	1500	–	–	–	–
Sveabreen	–	20	1704	–	0
Tinayerbreen	–	488	0	0	0
Tunabreen	–	30	0	0	0
Wahlenbergbreen	–	4	1	–	0

As a result, the count of Black-legged Kittiwakes located near the whole width of the glacier cliff was obtained. The bird counts presented in Table 3 were carried out in 2016 and were conducted at a distance 200 m along the glacier front and along the fjord axis, which was the control transect. The counting was conducted from the vessel R/V Helmer Hansen following standard methodology used for counting birds at sea (Tasker *et al.* 1984). All birds within 200 m on one side of the boat were counted and identified to species near the glacier front. Along the control transect, birds were counted within a 90° arc (200 m on one site and 200 m forward) from one side of the ship. Time and position were recorded during all surveys. Because there were very few birds in general, there was no problem with overestimation. Surface water samples were collected in the immediate vicinity of the glacier forehead, where there was an outflow of suspended matter from the glacier visible in the form of plumes or the so-called brown zone. In the same

Table 3

Bird counts from R/V Helmer Hansen along the glacier foreheads and along the fjord axes (control transects). Abbreviations: BLKI, Black-legged Kittiwake.

Glacier	Date	Number of all birds	Number of BLKI	Density of all birds [ind/ km^2]	Density of BLKI [ind/km^2]
Kronebreen	24.08.2016	303	252	346.3	288
Control transect	24.08.2016	93	17	103.3	18
Kronebreen	23.08.2016	223	101	247.78	112.2
Control transect	22.08.2016	221	32	28.33	4.1
Lilliehookbreen	21.08.2016	325	220	309	209.5
Control transect	21.08.2016	204	99	34	16.5

location, water transparency measurements were also carried out using the Secchi disc (Table 4). Water samples of 1 dm^3 were transported to the lab in cold and dark storage containers and analysed using a salinometer for salinity. Then, the samples were filtered through specially prepared Wetman GF/F filters (25 mm diameter, 0.7 µm pore size). The filters were pre-combusted at 450°C for 4 hours and then washed with 500 ml of deionized, particle-free water to remove loose pieces of filter before filtration of the main sample. The filters were then dried at 60°C and pre-weighed. After filtration the water sample, filters were dried at 60°C for 24 hours and weighed again for the gravimetric analysis of the total suspended matter (see Woźniak *et al.* 2011).

Table 4

Water transparency and total suspended matter (TSM) near glacier fronts.

Glacier	Secchi	Secchi	Secchi	TSM	TSM
	depth [m]	depth [m]	depth [m]	mg/dm3	mg/dm3
	2015	2016	2017	2015	2016
Aavatsmarkbreen	0.9	1.1	0.35	120	27
Blomstrandbreen	1.65	1.1	1.6	29	36
Borebreen	2.55	1.7	0.6	–	25
Conwaybreen	0.5	0.5	0.35	75	77
Dahlbreen	0.45	0.3	0.35	47	40
Esmarkbreen	0.4	0.4	0.3	201	92

Table 4 continued

Glacier	Secchi depth [m] 2015	Secchi depth [m] 2016	Secchi depth [m] 2017	TSM mg/dm3 2015	TSM mg/dm3 2016
Fjortende julibreeen	1.1	1.1	1.6	122	29
Gaffelbreen	0.4	1.1	0.4	67	35
Hansbreen	0.6	–	–	220	–
Harrietbreen	2.15	2	2.7	144	95
Hornbreen	–	–	–	–	–
Kollerbren	1.3	0.9	0.55	20	38
Kongsbreen n	1.75	2.1	1.6	91	81
Kongsbreen s	0.95	0.6	0.9	23	209
Konowbreen	1.8	1.4	0.15	101	80
Korberbreen	0.8	–	–	157	–
Kronebreen	0.15	0.15	0.45	119	51
Lilliehookbreen	2	1.4	0.6	17	14
Mayerbreen	0.75	2.1	0.9	32	38
Nansenbreen	1	0.5	0.4	50	50
Nordenskioldbreen	0.2	0.3	0.3	150	30
Olsokbreen	–	1	–	–	–
Osbornbreen	2.5	0.3	0.35	112	66
Paierlbreen	1	–	–	439	–
Sefströmbreen	0.4	0.5	0.6	57	72
Smeerenburgfjorden	–	1.5	–	–	40
Storbreen	–	–	–	–	–
Sveabreen	0.7	0.5	0.65	–	87
Tinayerbreen	0.15	0.3	0.45	77	24
Tunabreen	0.35	1.6	1.5	471	5
Wahlenbergbreen	0.2	0.1	1	142	66

The studied tidewater glaciers varied in terms of their type, size, cliff lengths, front characteristics and retreat rates (Table 1; Fig. 2). Information regarding the depth, presence of a sill, the width of the glacier and type of bedrock were obtained from sea charts available at http://www.npolar.no/en/services/maps/ (a website of the Norsk Polarinstitutt). Thirteen out of thirty glaciers

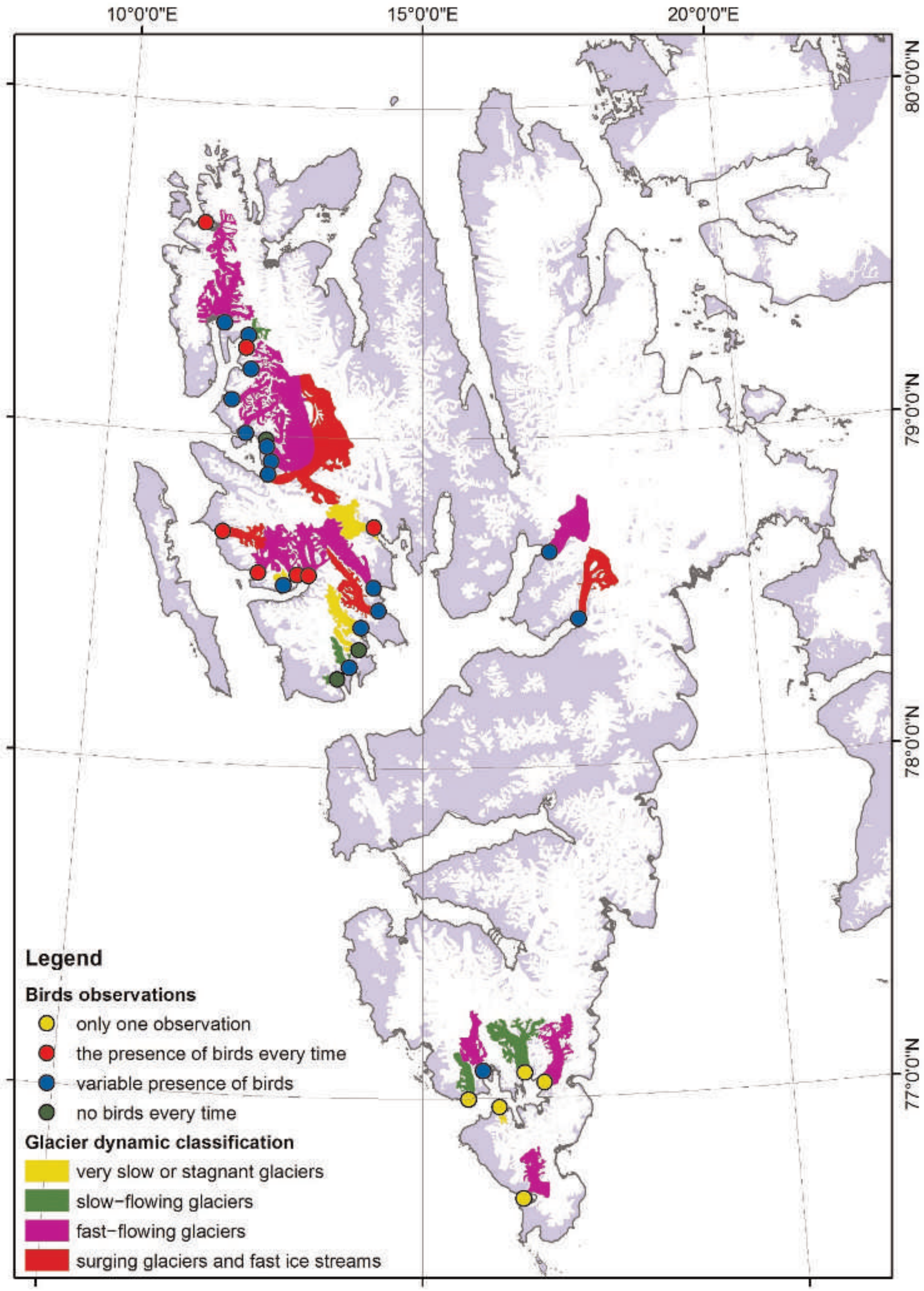

Fig. 2. Tidewater glacier types and Black-legged Kittiwake observations.

(Olsokbreen, Konowbreen, Dahlbreen, Aavatsmarkbreen, Osbornbreen, Kronebreen, Tunabreen, Nordenskioldbreen, Tinayrebreen, Mayerbreen, Kongsbreen S and Kongsbreen N, Hornbreen, Lilliehookbreen) were outlet glaciers with a draining ice field or ice cap. The lower parts of these glaciers were constrained by valleys, while their catchment areas could not always be clearly delineated (Hagen *et al.* 2003). The largest analysed glacier was Kronebreen (over 401 km^2), which has a flat accumulation area on Holtedahlfonna that it shares with other glaciers. Seventeen of the glaciers (Gaffelbreen, Hansbreen, Paierlbreen, Smeerenburgbreen, Sefstormbreen, Esmarkbreen, Nansenbreen, Borebreen, Wahlenbergbreen, Sveabreen, Conwaybreen, Blomstrandbreen, Fjortende Julibreen, Kollerbreen, Korberbreen, Storbreen, Harrietbrenn) were valley-type glaciers with well-defined catchment areas, sometimes flowing from cirques (Hagen *et al.* 2003). The smallest glacier analysed was the steep valley-type glacier Korberbreen in Hornsund with an area of 7.6 km^2. The active cliff lengths varied from 450 m (Mayerbreen) to approximately 12 km (Lilliehöökbreen). Eleven of the analysed glaciers (Tunabreen, Storbreen, Hornbreen, Lilliehookbreen, Aavatsmarkbreen, Paierlbreen, Osbornbreen, Blomstrandbreen, Nansenbreen, Korberbreen, Wahlenbergbreen) were surge-type glaciers in the quiescent phase, and three of them, Aavatsmarkbreen, Wahlenbergbreen and Tunabreen, were in active surge phases between 2013 and 2017.

The thermal regime of the studied glaciers was not identified in all cases; however, tidewater glaciers in Svalbard usually have a two-layered thermal structure typical of polythermal glaciers, as detected from their soundings with radar and direct ice temperature measurements (Dowdeswell *et al.* 1989; Macheret *et al.* 1993; Jania *et al.* 1996; Grabiec 2017). Firn and ice at the pressure melting point were noted throughout the body of the glacier in the accumulation zone, while in the ablation zone, cold ice overlaid temperate ice (Grabiec *et al.* 2012; Grabiec 2017). The amount of cold ice decreases with increasing glacier area. The thickness of the cold upper layer can reach up to 120 m, but the average thickness of the cold layer for glaciers in Hornsund amounts to approximately 30–50 m (Grabiec 2017).

The tidewater glacier termini were divided into four groups in accordance with dynamic classification guidelines set by Błaszczyk *et al.* (2009), based on differences in crevasse patterns and flow velocity, including (i) very slow or stagnant glaciers (five glaciers: Gaffelbreen, Sefstormnreen, Nansenbreen, Borebreen, Korberbreen), (ii) slow-flowing glaciers (five glaciers: Hansbreen, Esmarkbreen, Kollerbreen, Storbreen, Harrietbreen), (iii) fast-flowing glaciers (sixteen glaciers: Olsokbreen, Konowbreen, Dahlbreen, Paierlbreen, Osbornbreen, Smeerenburgbreen, Sveabreen, Nordenskioldbreen, Conwaybreen, Blomstrandbreen, Fjortende Julibreen, Tinayrebreen, Mayerbreen, Kongsbreen S and Kongsbreen N, Hornbreen, Lilliehookbreen), and (iv) surging glaciers (in the active surge phase) and fast ice streams (four glaciers: Aavatsmarkbreen, Kronebreen, Wahlenbergbreen, Tunabreen) (Fig. 2).

The analysed glaciers were also characterized by different retreat rates. Recession was estimated from Landsat 8 satellite data for the period 2014–2017. The glacier retreats were averaged over the terminus width (Howat *et al.* 2008; Błaszczyk *et al.* 2013). The estimated accuracy for the glacier front fluctuation data was ± 30 m. Four glaciers did not retreat in the analysed period, while two of them (Kronebreen and Storbeen) retreated at a rate of 320 $m \cdot a^{-1}$. The mean retreat rate for all glaciers was 96 $m \cdot a^{-1}$. One surging glacier, Wahlenbgergbreen, advanced at a rate of 500 $m \cdot a^{-1}$. Wave exposure was calculated as the direct distance from the open sea in QGIS software (QGIS Development Team 2018). Data on the distribution and size of Black-legged Kittiwake colonies were obtained from the Norwegian Polar Data Centre (https://data.npolar.no/mapview/44816ccf3f64e7666797e1ee2501841c). From each of the examined glaciers, a 50 km buffer was determined, and in this area – the number of colonies, their total size, size of the largest colony, distance to the nearest colony and size of the nearest colony were calculated using QGIS software (Table 5).

Statistical analyses were performed with Python programming language, using statistical functions from SciPy (Jones *et al.* 2001), Pandas (McKinney 2010), Seaborn (Waskom 2012) and NumPy (Oliphant 2006) libraries. To investigate statistical differences in three groups of glaciers, *i.e.*, those at which the occurrence of birds was noted at each observation, glaciers at which variable number of birds was recorded, and those where birds were never observed, the non-parametric Kruskal-Wallis test (also known as Kruskal-Wallis ANOVA) was used. This procedure does not assume data normality, the requirement not satisfied here.

In order to investigate the presence of more complex relationships between the occurrence of birds and the combination of various environmental parameters, Machine Learning techniques were used. Recent studies have suggested that machine-learning methodology may perform better than traditional regression-based algorithms (Elith *et al.* 2006). In our calculations, we used Random Forest Regression model (Breiman 2001). We utilized eleven environmental explanatory variables: depth, sill presence, glacier front width, exposure, bedrock, Secchi depth, total suspended matter (TSM), number of colonies within a 50 km radius, distance to the nearest colony within a 50 km radius, average colony size within a 50 km radius, size of the nearest colony (Tables 1, 4 and 5), that can correlate with birds distribution near glacier front (Table 2). Dummy coding was used to code a categorical variable into dichotomous form. At the first step, we used all the above-mentioned features as an input to the random forest model and the algorithm returned the list of important ones – those related to the dependent variable that contribute most to its variation. Then the model was retrained with reduced subset of features – only the most important ones were chosen.

Spearman's rank correlation coefficient (R_S) was calculated as a non-parametric measure of correlation between two variables. To measure association

Table 5

Examined glaciers and information about Black-legged Kittiwake colonies within a 50 km radius of each glaciers.

Glacier	Number of colonies in a 50 km radius	Distance to the nearest colony [km]	Total size of all colonies within a 50 km radius [no. of pairs]	Average colony size within a radius of 50 km [no. of pairs]	Max colony size within a radius of 50 km [no. of pairs]	Standard deviation of colony size within a radius of 50 km	Size of the nearest colony [no. of pairs]
Aavatsmarkbreen	16	20.3	11811	738	4286	1115	10
Blomstrandbreen	23	1.9	17147	746	4286	1066	906
Borebreen	9	16.0	29072	3230	13860	5192	54
Conwaybreen	23	7.6	17338	754	4286	1064	1932
Dahlbreen	13	4.0	5166	397	1932	540	511
Esmarkbreen	8	4.7	27521	3440	13860	5509	54
Fjortende Julibreen	26	2.2	21333	821	4286	1072	1753
Gaffelbreen	10	8.9	17381	1738	13860	4299	511
Hansbreen	5	6.5	15885	3177	7953	3247	7953
Harrietbreen	8	6.1	27521	3440	13860	5509	13866
Hornbreen	5	18.0	15885	3177	7953	3247	1350
Kollerbreen	28	9.8	18455	659	2795	791	147
Kongsbreen N	23	5.3	17338	754	4286	1064	1932
Kongsbreen S	23	3.5	17338	754	4286	1064	1932
Konowbreen	11	14.0	17831	1621	13860	4097	511
Korberbreen	5	1.5	15885	3177	7953	3247	1542

Table 5 continued

Glacier	Number of colonies in a 50 km radius	Distance to the nearest colony [km]	Total size of all colonies within a 50 km radius [no. of pairs]	Average colony size within a radius of 50 km [no. of pairs]	Max colony size within a radius of 50 km [no. of pairs]	Standard deviation of colony size within a radius of 50 km	Size of the nearest colony [no. of pairs]
Kronebreen	23	5.2	17338	754	4286	1064	1932
Lilliehookbreen	28	9.7	18915	676	2795	796	2795
Mayerbreen	28	5.5	18455	659	2795	791	147
Nansenbreen	9	8.6	29072	3230	13860	5192	54
Nordenskioldbreen	5	13.7	6571	1314	2476	751	522
Olsokbreen	4	29.5	15865	3966	7953	3148	5020
Osbornbreen	10	17.6	18521	1852	13860	4263	511
Paierlbreen	5	3.2	15885	3177	7953	3247	1350
Sefstrombreen	8	35.5	6604	826	1932	656	1150
Smeerenburgbreen	24	5.1	16110	671	2795	769	269
Storbreen	5	11.0	15885	3177	7953	3247	1350
Sveabreen	10	24.2	30186	3019	13860	4937	1150
Tinayerbreen	26	3.4	18102	696	2795	809	147
Tunabreen	5	17.1	6571	1314	2476	751	2476
Wahlenbergbreen	11	21.8	30466	2770	13860	4756	1156

between continuous feature and a categorical feature, Correlation Ratio, defined as the weighted variance of the mean of each category divided by the variance of all samples, was used. Hierarchical clustering of data corresponding to the glaciers was performed and its output was presented in the form of a dendrogram. Values on the tree depth axis correspond to Ward's distances between clusters (Ward's Minimum Variance method). The spatial analysis of data and visualization presented on the map were performed with QGIS software.

Results

Description of the bays. – The ice fronts in the glacier bays varied in width from 0.4 to 13.9 km, with a mean width of 3 km for 31 glacier fronts (Table 1). The bay depths in the vicinity of the cliff ranged from 12 to 189 m, with a mean value of 57 m. There were eight bays without a sill separating the basin from the adjacent water body, eleven with low and medium sills and twelve with a high, distinctive sill (Table 1). Exposure to waves and the open sea (fetch) varied, as four open-coast glaciers were fully exposed to ocean waves and eleven bays were very sheltered, located in the innermost branches of the fjords (Fig. 1). All locations contained the same type of sediment, fine glaciomarine mud; however, sediments were of various origins, from limestone to sandstone and quartzite, depending on the local bedrock type (Table 1). The hierarchical clustering of glaciers, based on five physical factors (Table 1), is presented in Figure 3. Total suspended matter measured directly from the water samples ranged between 5 and 471 $mg \cdot dm^{-3}$ (median = 50, standard deviation [SD] = 83.6). Secchi disc readings ranged from 0.1 to over 2 m, with a median value of 1.65 m at all visited sites (SD = 0.65). Surface salinity values varied mostly due to meltwater outflow and ranged from 27 to 33 PSU, with a mean value of 30.1 (SD = 2.2) (Table 4). Sea surface temperature values were not significantly variable and were close to the local air temperature with a mean of 5.6°C (SD = 1.2). Most of the examined glacier bays were within 8.6 km (median value) of the nearest Kittiwake colony and within a 50 km radius of ten other colonies (median value) (Table 5).

Seabird counts. – The majority of all birds observed and photographed near the glaciers were Black-legged Kittiwakes, with isolated observations of Northern Fulmars, *Fulmarus glacialis* (Linnaeus, 1761), Glaucous Gulls, *Larus hyperboreus* Gunnerus, 1767, Brünnich's Guillemots, *Uria lomvia* (Linnaeus, 1758), and Arctic Terns, *Sterna paradisaea*, Pontoppidan, 1763. Kittiwakes did not appear in 37 observations, and in the case of three glaciers (Conwaybreen, Nansenbreen and Harrietbreen), the birds were not observed during three consecutive summers (Table 2). At five other glaciers, the birds were observed

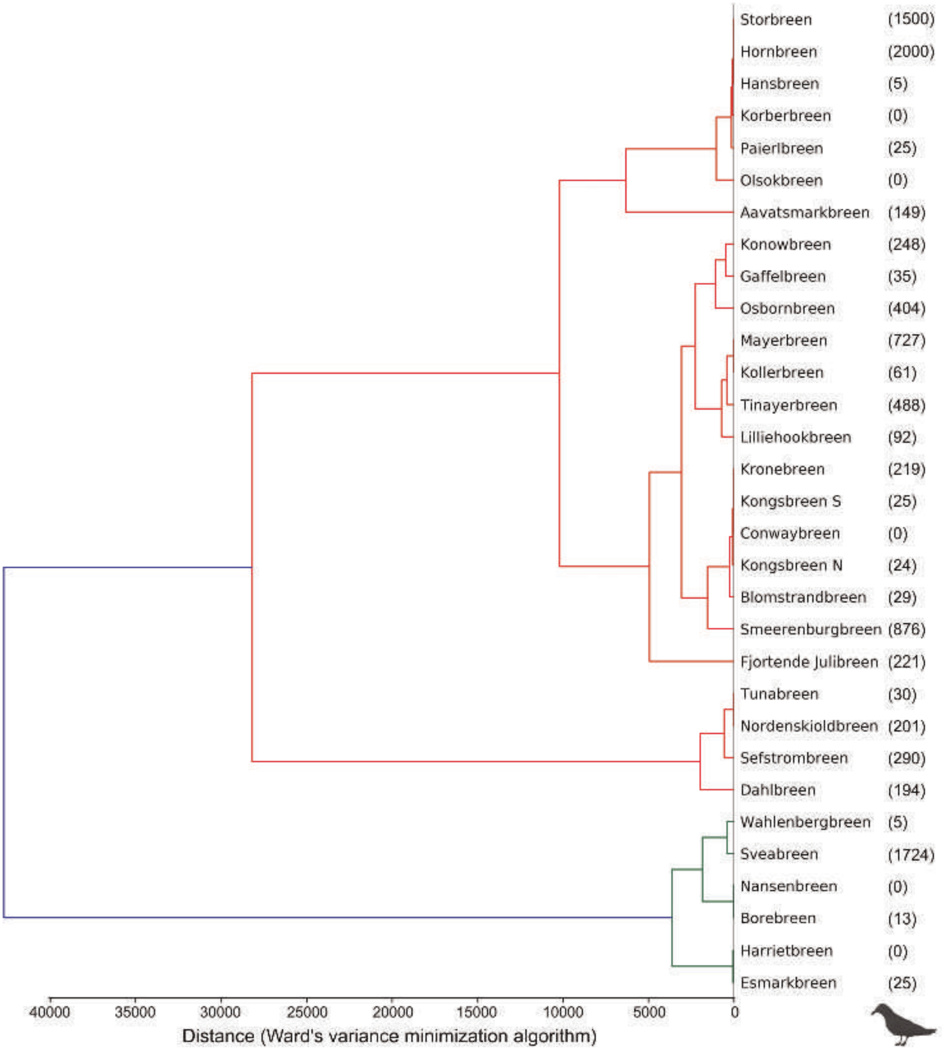

Fig. 3. Hierarchical clustering of examined glaciers (see Table 1 for compared features). Numbers in parentheses are totals for Black-legged Kittiwakes counts based on data from Table 2.

every summer, while at the remaining 22 glaciers, the results were inconsistent; however, seven of these glaciers were examined only in one season. The mean number of birds observed near the glacier cliffs each year was 58, 109 and 24, while no birds were recorded in five, 14 and 12 sites in 2015, 2016 and 2017, respectively. High bird concentrations (over 100 birds counted) were observed in six cases in 2015, in six cases in 2016 and in two cases in 2017 (Fig. 4). A record counts (over 1000 individuals) of Black-legged Kittiwakes were observed in

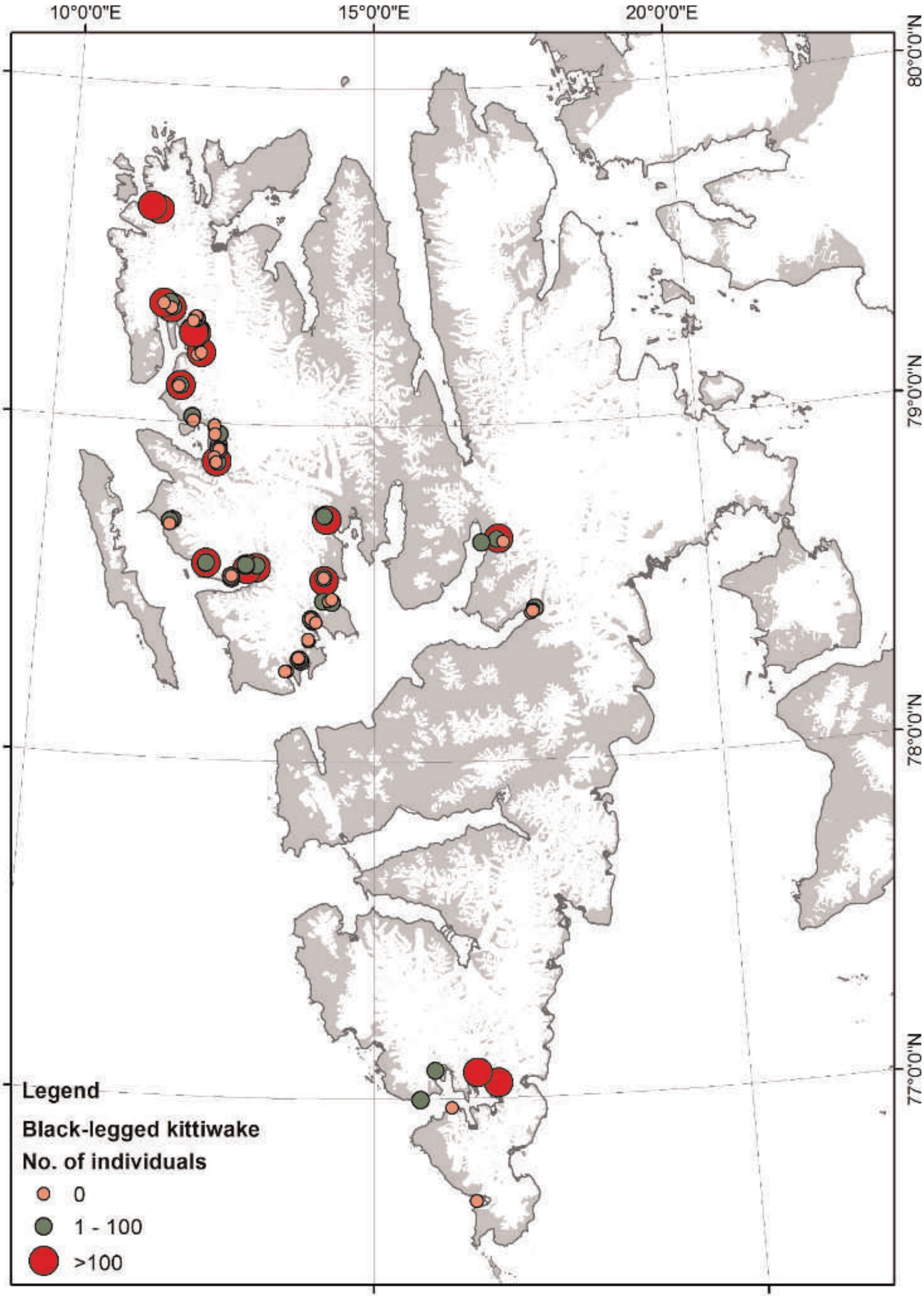

Fig. 4. Densities of Black-legged Kittiwakes observed near examined glacier fronts.

2016 (1704 individuals) near Sveabreen and twice in 2011 near Hornbreen and Storbreen.

The bird count carried out in 2016, conducted along the glacier front and then along the fjord axis as the control transect, proved that higher bird concentrations occurred at the glacier front (Table 3). Such results were consistent for all three of the studied glaciers, although the number of birds recorded in 2016 was much smaller than in the previous year. The densities of Black-legged Kittiwakes foraging in tidewater glaciers and in non-glaciated sectors (control transects) differed substantially.

Statistical analysis. – The three tidewater glaciers with no observed birds were dissimilar, as were the six bays with the most birds observed (Tables 1 and 4). Because Black-legged Kittiwake colonies are abundant on Svalbard, the mean distance to the nearest colony was only 11 km, whereas the furthest distance measured was 35.5 km. In eight cases, the distance was less than 5 km (Table 5). There was no correlation between the number of birds present near the glacier and the distance to the nearest colony ($R_s = 0.055$, $p = 0.610$) nor with the number of colonies ($R_s = 0.107$, $p = 0.318$). Glaciers at which the occurrence of birds was noted at each observation, those at which variable numbers of birds were recorded and those where birds were never observed, do not differ significantly in terms of the total size of these colonies (Kruskal-Wallis test, $H = 0.48$, $p = 0.786$) (Fig. 5A), in terms of distance to the nearest colony (Kruskal-Wallis test, $H = 0.94$, $p = 0.625$) (Fig. 5C) nor in terms of the number of colonies within a radius of 50 km (Kruskal-Wallis test, $H = 3.34$, $p = 0.188$) (Fig. 5D). On the other hand, there were significant differences in the depth between places where birds were always observed and those where they were not present at all. (Kruskal-Wallis test, $H = 6.21$, $p = 0.012$) (Fig. 5B). The dendrogram plot (Fig. 3), which accounts for five physical factors (Table 1), shows that bird concentrations did not match any of the single glacier groups. No correlation was found between the bird concentrations with the amount of suspended matter ($R_s = 0.202$, $p = 0.160$) nor was there a correlation with the presence of a sill or wave exposure – Correlation Ratio was 0.304 and 0.106, respectively.

Using Random Forest Regression model to investigate the occurrence of more complex relationships between the occurrence of birds and the combination of various environmental parameters (Table 1, Table 4 and Table 5) indicated that the most important features were: glacier front width, average colony size within a 50 km radius, depth and distance to the nearest colony. However, goodness of fit of our model measured as a coefficient of determination was low (0.16).

The analysis of geomorphometric parameters showed no correlation between the glacier type and average number of birds per year per glacier (Corelation Ratio = 0.08). However, a correlation was found with the dynamic classification of the glacier (Corelation Ratio was 0.86). Analyses showed that the largest

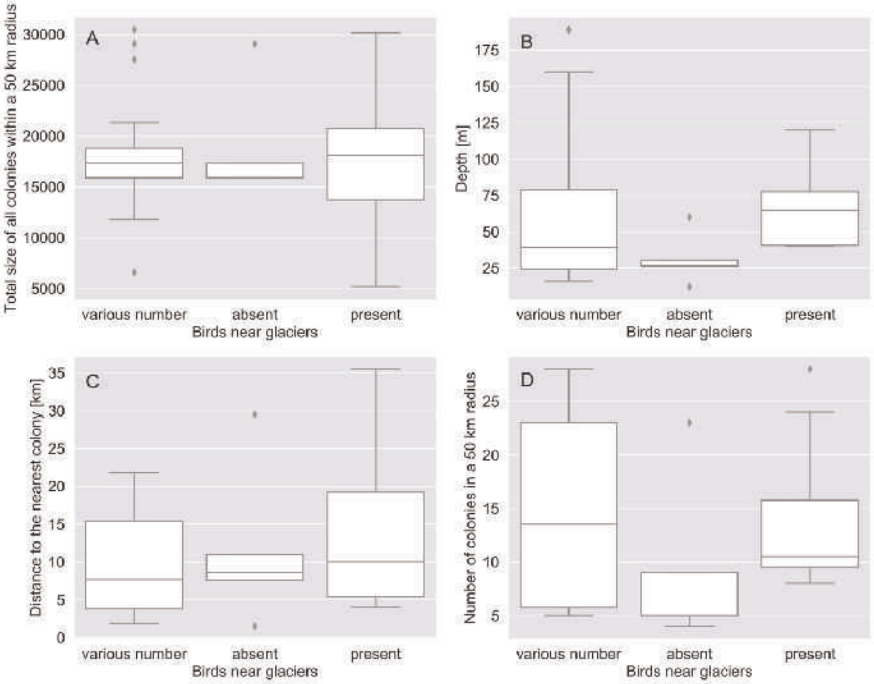

Fig. 5. Box-and-whisker plots showing distribution of: (A) total size of all colonies within a 50 km radius, (B) depth near glaciers front, (C) distance to the nearest colony [km] and (D) number of colonies within a 50 km radius in three groups of glaciers (first – where various number of birds were observed, second – where was no birds during all observations, and third – where birds were always present). Boxes represent 25th, 50th and 75th percentiles, whiskers – non-outlier range

numbers of birds (over 20 per year) were observed in the vicinity of 15 out of 20 fast-flowing or surging glaciers. Only one stagnant glacier (Sefströmbreen) and one slow-flowing glacier (Storbreen) were visited by such high numbers of birds.

Discussion

Topographical and oceanographic classification of glacier bays. – The examined glacier bays could be divided into two distinct groups. The first group included bays located in the innermost fjord basins with the presence of a sill inhibiting the exchange of near-bottom waters with the central part of the fjord and facilitating the retention of winter-cooled waters (Drewnik *et al.* 2016; Promińska *et al.* 2017). In several cases, high concentrations of Black-legged Kittiwakes were observed in such bays, for example, in the Hornsund fjords Burgerbukta and Brepollen (Stempniewicz *et al.* 2017; Urbański *et al.* 2017).

Our study showed that in some cases, such isolated bays hosted high numbers of birds, while in others cases – no birds were observed (Table 2). The second group of glacier bays included those exposed to unrestricted contact with shelf waters (no obstacles present to inhibit the water exchange). A typical example are bays in the southern part of Kongsfjorden and the exposed glaciers on the west coast, where Atlantic shelf waters can easily interact with glacier fronts (Promińska *et al.* 2017). These types of bays provided the same observations regarding bird presence as the first group, with high concentrations in some cases and no observations in others.

Seabird counts. – Black-legged Kittiwakes were recorded in very high concentrations near the glaciers on Svalbard, with up to over 8000 birds at one site, which represented half of the population of the nearest colony (Urbański *et al.* 2017). Very high densities of black-legged Kittiwakes near glaciers were recorded in the innermost part of the Hornsund fjord during the period 2013–2015; however, no consistent pattern was established for their occurrence (Stempniewicz *et al.* 2018). Counts of Black-legged Kittiwakes at sea never reached these numbers, with values usually between 10–20 birds per km^2 (Mehlum 1989; Isaksen 1995; Malinga and Stempniewicz 1995; Barrett and Tertitzki 2000). Telemetry revealed an alternating sequence of gull concentrations near the glaciers and at sea in the shelf frontal zone where most of the birds from the Hornsund colony were observed (Stempniewicz *et al.* 2018). Black-legged Kittiwakes at sea are usually not dispersed randomly, and most of the birds feed near the shelf break at the hydrological front zone or close to the pack ice edge (Mehlum 1989).

Black-legged Kittiwake food. – Black-legged Kittiwakes use two different foraging strategies during the egg incubation period and while feeding chicks, including short flights from the colony to the nearest glacier where macroplankton are their primary food source (Lydersen *et al.* 2014; Urbański *et al.* 2017) or long-distance flights of up to 500 km from the colony to the open sea to feed almost exclusively on fish (Mehlum and Gabrielsen 1993; Barrett 1996; Barrett and Krasnov 1996; Stempniewicz *et al.* 2018).

Black-legged Kittiwakes feed primarily on small fish, mainly polar cod, from the surface down to a depth of approximately 0.5 m in the Svalbard area; polar cod is associated with cold, coastal waters, ice, and capelin, which are common in the open shelf waters of the Atlantic (Anker–Nielsen *et al.* 2000; Vihtakari *et al.* 2018). The presence of small fish near the glacier front was confirmed by hydroacoustic surveys (Szczucka *et al.* 2017) and direct observations from trawls (personal observation from the UNIS cruise in 2013, led by Jorgen Borge). Both polar cod and capelin occur in schools and are able to escape adverse conditions (fresh and turbid waters). They are likely to form feeding aggregations where their food, zooplankton, occurs in abundance. Barrett (2007) and Vihtakari *et al.*

(2018) revealed a shift in the feeding behaviour of Black-legged Kittiwakes from Arctic-dominated (mainly polar cod) to Atlantic-dominated food (mainly capelin) in approximately 2010.

Krill, mostly *Thysanoessa inermis* (Krøyer, 1846) and a minor population of three other euphausiid species (Bucholtz *et al.* 2010; Węsławski *et al.* 2017), enters the fjords with the inflow of Atlantic waters. Krill concentrations near the glaciers have been previously recorded to be very high near the bottom (Deja *et al.* 2019) and near the surface (Urbański *et al.* 2017). The availability of macroplankton in surface waters in the vicinity of the glaciers may be related to the rapid mixing of seawater and meltwater, as osmotic shock may keep the dead plankton near the surface (Węsławski and Legeżynska 1998).

Foraging grounds and underlying mechanisms of food concentrations. – The concentration of food items is a leading factor in determining the open-sea-feeding habits of these birds. The collection of dispersed food costs energy (average concentration of krill in the water column is 1 indiv.$\cdot$m^{-3}) (Węsławski *et al.* 2000), while schools of krill may consist of over 500 indiv.$\cdot$m^{-3} (Deja *et al.* 2019). Krill concentrations may be caused by different behavioural reactions (Mauchline and Fisher 1969), yet schools near the glaciers are most likely the result of hydraulic forcing (Urbański *et al.* 2017). The increase in concentration might be caused by the krill becoming entrapped below the sill while trying to avoid the brackish water surface (Węsławski and Legeżynska 1998) or by the presence of feeding aggregations near the seabed (Deja *et al.* 2019).

Do glacier types matter? Warm and cold glaciers and shallow and deep bays. – Our results suggest that the abundance of birds was connected to the occurrence of organic matter trapped in the overdeepenings in the valleys, long before the glaciers occupied these valleys in their present form. In the case of the more active, fast-flowing glacier tongues, the old nutrients would be intensively eroded and eluviated. As a result, meltwater discharges in the form of plumes are rich in nutrients and attractive to birds. The existence of such glacial overdeepenings, far from the front, was confirmed for Hornbreen, Storbreen, which would explain the high number of birds observed at the fronts of those glaciers. In the case of slower flowing glaciers, the sediment traps were not so intensively eroded, and meltwater was less nutrient-rich, resulting in less frequent bird visits. Nonetheless, it is still not known why all of the fast-flowing glaciers were not visited by high numbers of birds. It could be connected to the lack of sediment traps mentioned previously and the surge history, given that during the active surge phase, the nutrients would have been washed out already.

Predictability of foraging hot spots. – The presence of a feeding hot spot near a glacier is controlled by the simultaneous occurrence of two independent variables. The first is the presence of food items, such as the concentration of krill or small fish large enough to be of importance for the bird flocks. The second is physical upwelling, which drives the food from deeper waters to the surface of the bay. Urbański *et al.* (2017) demonstrated that an estuarine circulation or wind-driven outflow of brackish surface waters was not strong enough to lift the macroplankton to the surface. A rapid outflow of meltwater is needed to produce a current strong enough to collect macroplankton from deeper waters and transport it to the surface (Urbański *et al.* 2017). This is associated with the meltwater supply, drainage characteristics and internal structure of the glacier. On the other hand, the initial concentration of food organisms (krill and other macroplankton) occurs either as a result of the presence of a trophic trap behind the sill (Węsławski *et al.* 2000) or feeding aggregations near the seabed (Deja *et al.* 2019). The depth of the glacier bay seems to be a predictor of food concentrations, as krill enter the fjord with the inflow of the Atlantic shelf waters, which requires a certain depth (Deja *et al*. 2019). Even if they are not predictable, foraging spots near glaciers are relatively common (approximately 25% of the observed cases), and once they occur, they provide an easily accessible and rich source of food that can attain a fresh weight in tonnes at a single glacier front (Deja *et al*. 2019). The steady retreat of glaciers and the eventual disappearance of the "boiling water" phenomenon will not be replaced by other similar hydrological forcing mechanisms and will most likely drive Black-legged Kittiwakes to the more distant, open-sea feeding areas.

Suitability of citizen science. – The volunteers participation was essential for our study, as their work was easy to organize in uniform schematic way – boat movement 200 m from the glacier and photo collection as well as the surface water samples and Secchi disk readings were easily performed and give little space for the methodological error.

The work of volunteers who touristically venture into this area allowed to explore a significant area of Spitsbergen which would be difficult to investigate from the research ship due to a different scientific program implemented there. In addition, the opportunity of active participation of the society in the study of the Arctic contributes to the interest of people in this subject thanks to which the research results are disseminated and the natural awareness increases.

Acknowledgements. – We would like to thank Atle Brekken and Peter Kolbjornsen from the Miraculix yacht, Eugeniusz Moczydłowski from the yacht Magnus Zaremba and Jan Dobrogowski from S/Y Toroa for their help and support in collecting samples and photographs, as well as Waldemar Walczowski from IOPAS and Piotr Wieczorek for providing us with their hydrographic data. This study is part of the GLAERE project by the Norwegian-Polish Research Fund (DZP/POL-NOR/1876/2013). The help offered by Paul Renaud and UNIS course members during the 2016 cruise onboard R/V Helmer Hansen is greatly appreciated. Thanks are extended to the two anonymous reviewers for constructive advice that improved the manuscript.

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Received 17 September 2019
Accepted 14 October 2019