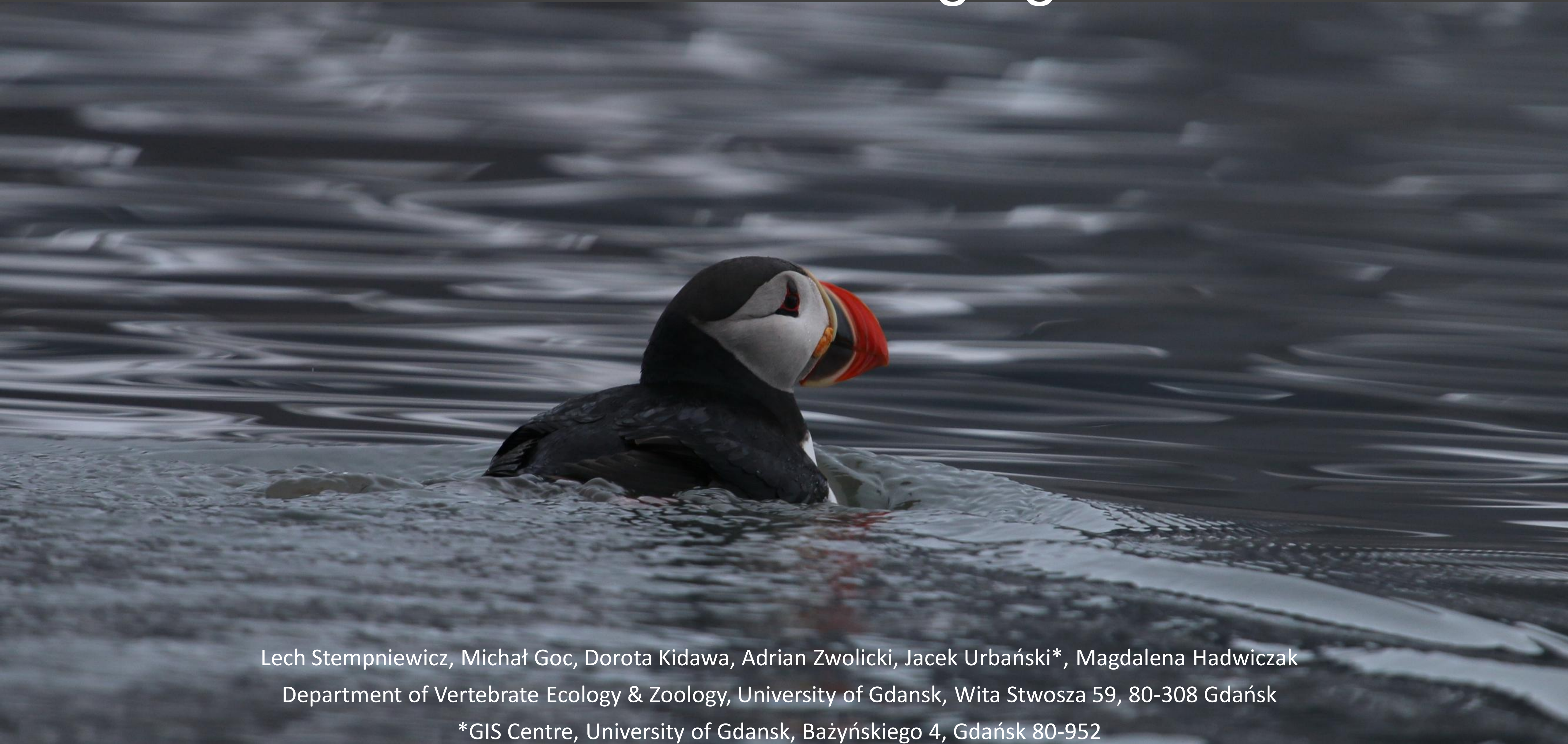
Ecological consequences of rapid fjord deglaciation for birds and mammals foraging in Hornsund



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Introduction

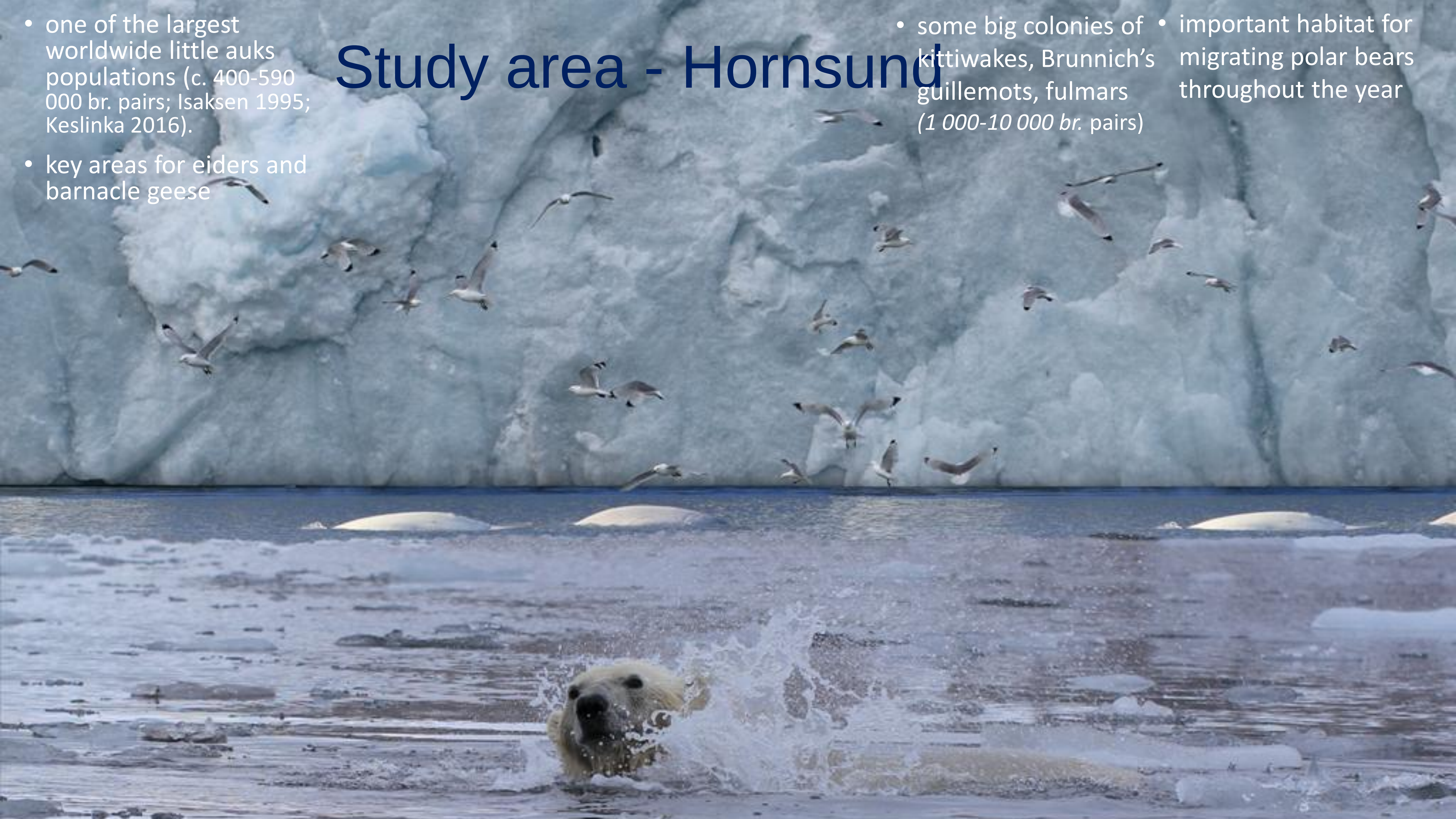
- sea ice shrinking including glacier retreating
  - prominent effect of climate warming
- involves reduction of the MIZ - an important part of the Arctic marine ecosystem
  - detrimental consequences for ice-associated organisms (Barber et al. 2015)
- strong relationship between glacial recession and decline of Kittlitz's murrelets population found in Alaska (Kuletz et al. 2003).
- glacier retreating-new habitats/feeding grounds (Lydersen et al 2014; Grémillet et al. 2015)
- knowledge on population size of marine birds and mammals is deficient (Hop et al. 2002).
- baseline information - essential to monitoring population changes, estimating role in ecosystem functioning and proper conservation and management strategies (Laidre et al. 2008; Diemer et al. 2011).
- studies of breeding colonies prioritized over distribution and numbers on feeding grounds
- more attention to open sea yet assessing impacts of rapidly changing environment concerns fjords and glacier bays (Freitas et al. 2012; Lydersen et al. 2014; Gall et al. 2016).

Objectives

1) recognizing species composition and abundance of marine birds and mammals foraging in the study area (Burgerbukta)
2) assessing their distribution and foraging habitat preferences in the fjord
3) basing on this knowledge - evaluating consequences of climate-induced deglaciation for seabirds and mammals foraging in the Arctic fjord.

Study area - Hornsund

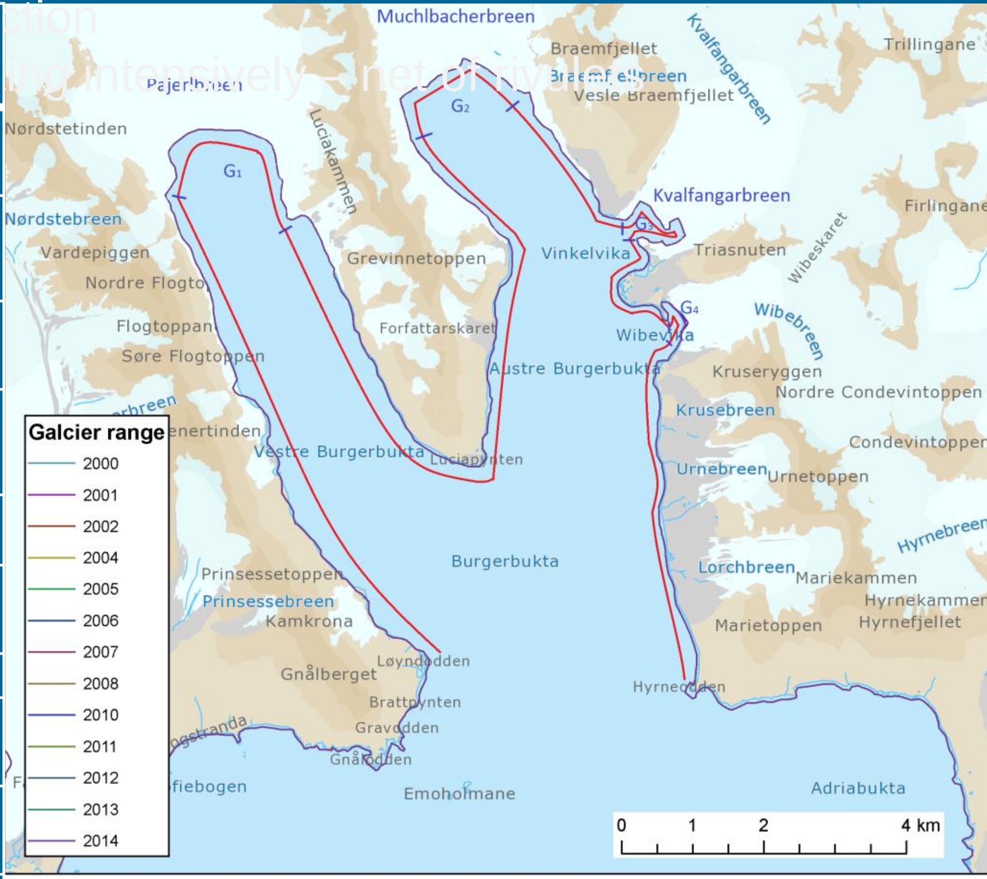
- one of the largest worldwide little auks populations (c. 400-590 000 br. pairs; Isaksen 1995; Keslinka 2016).
- key areas for eiders and barnacle geese
- some big colonies of kittiwakes, Brunnich's guillemots, fulmars *(1 000-10 000 br.* pairs)
- important habitat for migrating polar bears throughout the year



Study area - **Burgerbukta (34.4 km^2)** sectors length **0.52-9.0 km**, total length - **29.52 km**.

- survey included whole coastline, 9 linear sectors of different coast and littoral character, representative for bird distribution
- glacier melting in Hornsund rapid (Błaszczyk et al. 2009) - changes topography and foraging habitats of marine birds & mammals
- glaciers studied: different retraeting stage - weather depending calving activity – different amount of floating ice
- **Pajerlbreen** & **Muhlbacherbreen** (**G1-G2**): sea-terminating tidewater glaciers (**STTG**), calving intensively, rapidly receding, large drifting ice production, deep glacier bays, long frontal zone - c. **1.5 km**
- **Kvalfangarbreen** & **Wibebreen** (**G3-G4**): coastline-terminating glaciers (**CLTG**), short frontal zone (**< 0.5 km**),

Sector	Habitat	Length (km)	Area km^2	Exposi tion	Littoral zone	Coast type
A	NGCS	8,50	2,55	NE	narrow, steep, deep	low skjerra, steep rocky backshore, rocky cliffs
G1	STTG	1,40	0,42	S	no littoral, deep glacier bay	tidal glacier cliff, dead ice aside, large glacier river surfacing in the lagoon
B	NGCS	9,00	2,70	WE	narrow, steep, shallow at Lucia	cliff with abrasive shelf, dead ice cliff, moraine beach, low gravel beach
G2	STTG	1,60	0,48	SE	no littoral, deep glacier bay	tidal glacier cliff, dead ice, large glacier river debouching superficially aside from the glacier
C	NGCS	2,30	0,69	WS	narrow, steep	cliff-abrasive shelf, dead ice, low gravel beach
G3	CLTG	0,52	0,16	WS	shallow glacier bay	coastal terminating glacier, dead ice cliff, superficial glacier river in the lagoon
D	NGCS	2,00	0,60	W	broad, shallow	moraine low gravel beach
G4	CLTG	0,30	0,09	W	shallow glacier bay	coastal terminating glacier, dead ice cliff, superficial glacier river in the lagoon
E	NGCS	3,90	1,17	W	broad, shallow	moraine low gravel beach, several rivulets from melting glaciers receded far inland



Changes in the ice-free area of Burgerbukta due to glacier retreating 2000-2015

Dates [yyyy.mm]	Vestre Burger area [km²]	change [km²]	Austre Burger area [km²]	change [km²]	Burgerbukta total [km²]	change [km²]
2000.06	9.407		7.979		17,386	
2001.06	10.454	+1.047	8.475	+0.496	18,929	1,543
2002.07	10.702	+0.248	8,651	+0.176	19,353	0,424
2010.08	11.934	+1.232	9.840	+1.189	21,774	2,421
2010.09	12.400	+0.106	9.988	+0.148	22,388	0,614
2014.08	13.201	+1.161	11.279	+1.291	24,480	2,092
2015.07	13.143	-0.058	11.343	0.063	24,486	0,006
Change 2000-2015		**3,736**		**3,364**		**7,100**

Changes in the length of retreating glacier fronts in Burgerbukta 2000-2015

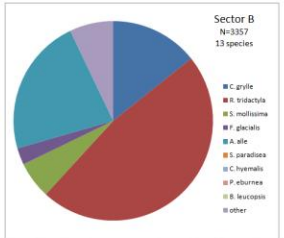
Dates	Pajerlbreen [m]	Muchlbacher [m]	Kvalfangar [m]	Wibebren [m]	All glaciers in total [m]
2000.06	2650	1551	541	550	5292
2001.06	1657	1472	466	554	4149
2002.07	1511	1534	-	-	3045
2010.08	1910	1804	614	516	4844
2014.08	2840	2200	1447	529	7016
2015.07	3396	2115	1455	522	7488
Change 2000-2015	**+ 746**	**+ 564**	**+ 914**	**- 28**	**+ 2196**

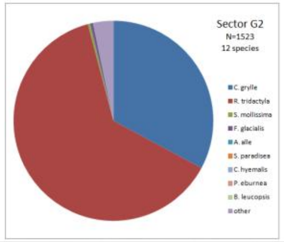
Number (N) of marine birds and mammals in the study area in 2014/2015 (GS: glaciated sectors, NGCS: non-glaciated coastline sectors; spatial foraging guilds: surface feeding [SF], pursuit diving [PD] and benthic feeding [BF], coastal feeders [CF] and pelagic feeders [PF]).

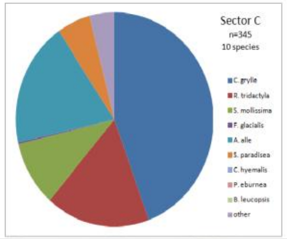
taxon	Guild	Spatial foraging type	Total N observed 2014/2015	Mean N/1 counting 2014/2015	% in GS (mean/1 count) [2014/15]	% in STTG	% in CLTG	% in NGCS (mean/1 count) [2014/15]	Total N in Burgerbukta (mean/1 count) [2014/15]
Rissa tridactyla	SF	C	3694/14417	371.4/2069.5	77.0/75.3	73.9/75.1	3.1/0.2	23.0/24.7	371.4/2069.5
Cepphus grylle	BF	C	1356/1451	138,7/210,6	25.0/52.4	23.1/49.2	1.9/2.4	75.0/48.4	138.7/210.6
Alle alle	PD	P	91/1908	9.6/273.9	1.0/0.1	1.0/0.1	0/0	99.0/99.9	37.2/1064.0
S. mollissima	BF	C	384/452	39.2/65.2	5.3/2.4	0.5/0.9	4.8/1.5	94.7/97.6	39.2/65.2
Fulmarus glacialis	SF	P	168/53	17.7/7.9	4.0/43.5	4.0/43.5	0/0	96.0/56.5	68.6/30,6
Uria lomvia	PD	P	133/53	13.9/7.7	5.0/1,9	4.3/0	0.7/1.9	95.0/98.1	53.8/29.9
Larus hyperboreus	SF	C/P	107/48	11.0/6.9	10.9/29.1	10.9/20.8	0/8.3	89.1/70.9	11.0/6.9
Branta leucopsis	SF	C	50/71	5.0/10.1	0/0	0/0	0/0	100/100	5.0/10.1
Sterna paradisea	SF	P	38/77	3.8/11.0	42.0/39.0	2.6/14.3	39,4/24.7	58.0/61.0	14.8/42.7
A.brachyrhynchus	SF	C	20/92	2.1/13.1	0/0	0/0	0/0	100/100	2.1/13.1
Fratercula arctica	PD	P	47/9	4.9/1.3	0/0	0/0	0/0	100/100	18.9/5.0
Clangula hyemalis	BF	C	8/38	0.8/5.4	100.0/21.1	0/0	100.0/21.1	0/78.9	0.8/5.4
Pagophila eburnea	SF	C/P	20/18	2.0/2.6	75.0/77.8	45.0/61.1	30.0/16.7	25/22.2	2.0/2.6
S. parasiticus	SF	C/P	2/16	0.2/2.3	0/0	0/0	0/0	100/100	0.2/2.3
S.spectabilis	BF	C	0/2	0/0.3	-/0	-/0	-/0	-/100	0/0,3
D.s leucas	PD	C	23/0	2.3/0	43.5/-	43,5/-	0/-	56.5/-	2.3/0
Pusa hispida	PD	C	5/11	0.5/1.7	60/100	20.0/74.3	40.0/25.7	40/0	0.5/1.6
Erignathus barbatus	BF	C	5/0	0.5/0	60/-	20.0/-	40.0/-	40/-	0.5/0
Ursus maritimus	SF	C	1/1	0.1/0.1	n.a.[3]	n.a.[3]	n.a.[3]	n.a.[3]	0.1/0.1
Σ SF			4099/14792	413.2/2113.3	70.4/73.9	67.1/73.5	3.3/0.4	29,6/26.1	475.1/2177.9
Σ BF			1753/1943	179.0/277.6	21.2/39.1	18.1/37.0	3.1/2.5	78.8/60.5	179.0/281.5
Σ PD			299/1981	31.1/283	6.8/0.7	5.8/0.5	1.0/0.2	93.2/99.3	193.3/1100.6
Σ CF			5674/16617	573.6/2373.9	57.1/70,6	54.0/69.6	3.1/0.5	42.9/29,9	573.6/2387.7
Σ PF			477/2100	49.8/300	6.2/2.7	3.0/1.8	3.2/0.9	93.8/97.3	763.8/1172.3.
birds in total			6118/18705	620.2/2672.1	53.1/62.6	50.0/62.0	3.1/0.6	46.9/37.4	1190.6/3558.3
mammals in total			34/12	3.4/1.7	48.5/100	36.4/74.3	12.1/25.7	51.5/0	3.2/ 1.8

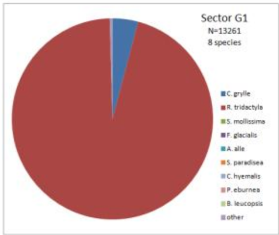
Species composition and numbers

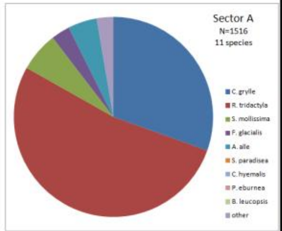
- we recorded a total of 10 568 individual birds of 15 species (10 surveys - 2014) and 18 705 (7 surveys - 2015 - mean 1056.8 and 2672.1 per survey, respectively
- most abundant bird species observed: black-legged kittiwake, black guillemot, little auk, eider
- least numerous: king eider and ivory gull, both species of special conservation concern
- four species of marine mammals (17 surveys), sixteen ringed seals, five bearded seals, twenty-three belugas and two polar bears
- surface feeders constituted 65.0% of the estimated total number of seabirds foraging daily in Burgerbukta, followed by pursuit divers (25.4%) and benthic feeders (9.6%)
- spatial foraging preferences - proportion of coastal feeders was 71.4%, far outnumbering pelagic feeders (28.6%).

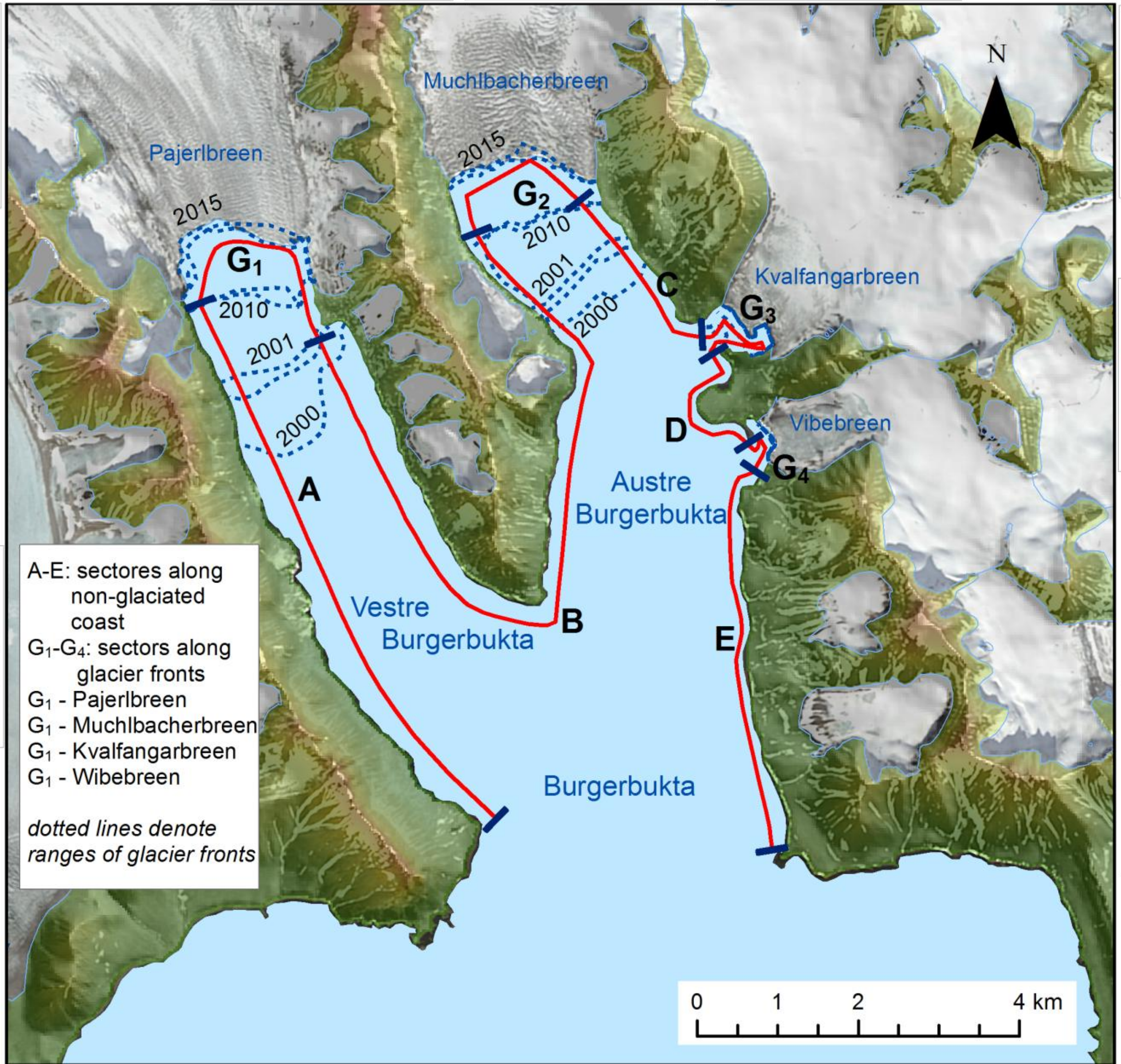


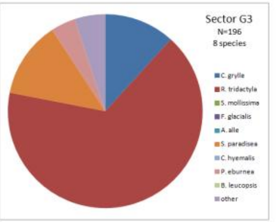


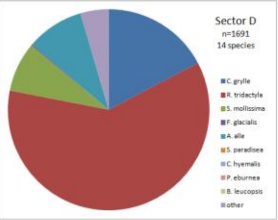


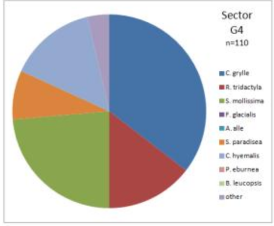


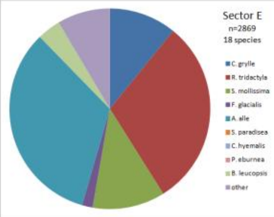




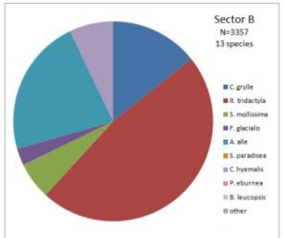


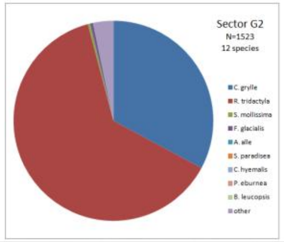


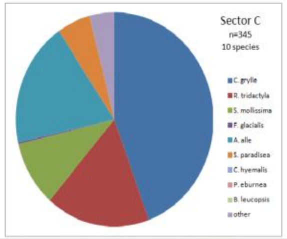




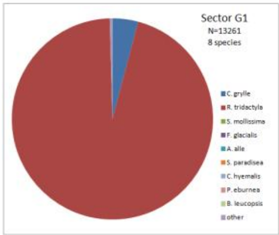
Distribution and habitat preferences

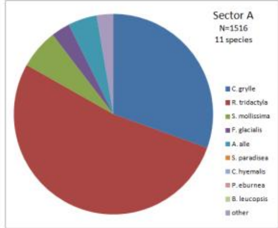


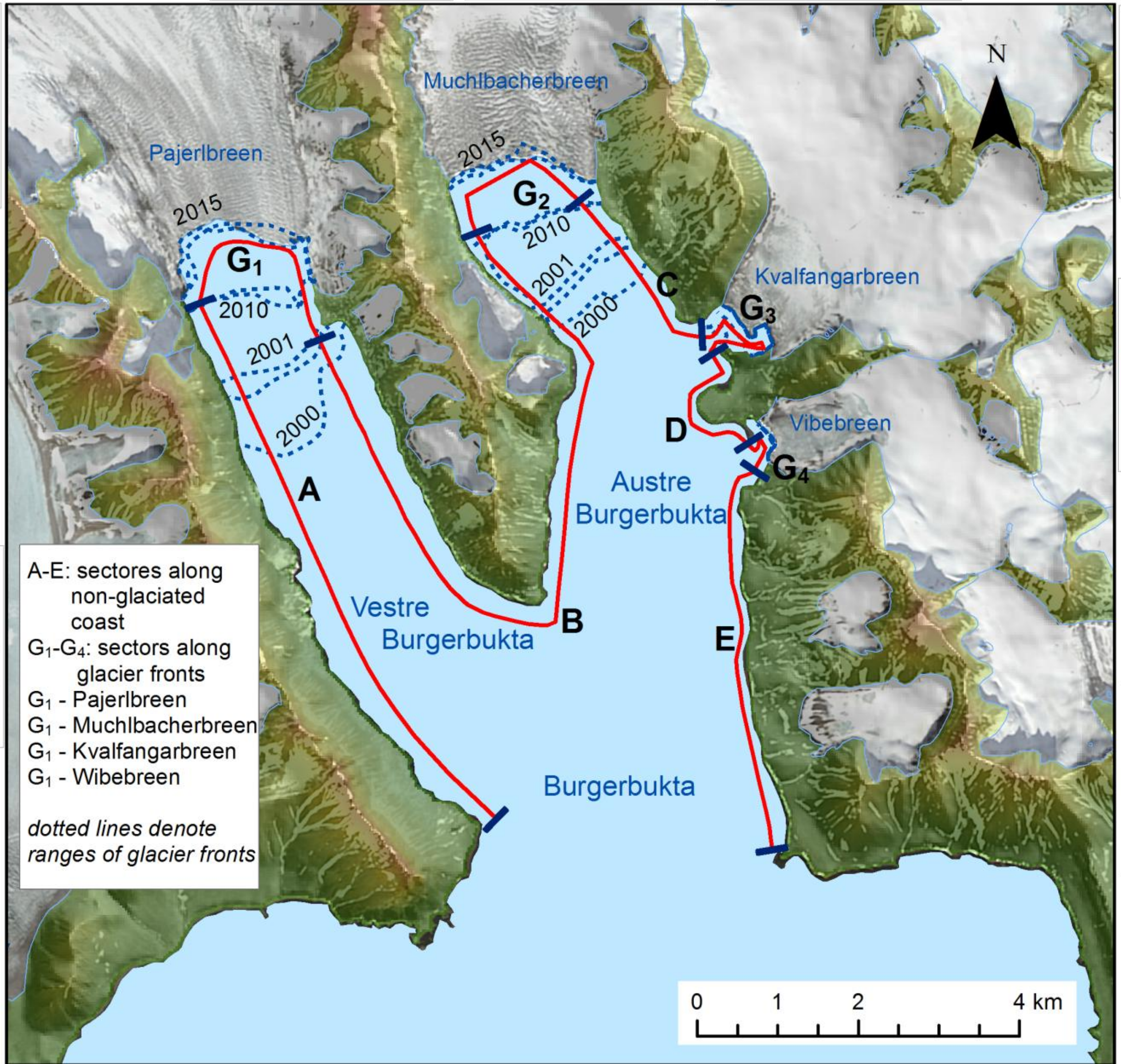


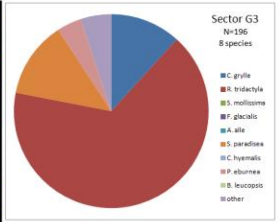


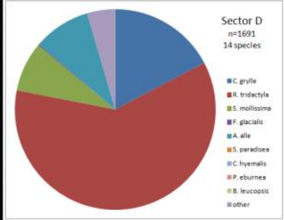
- great majority of kittiwakes, ivory gulls, ringed and bearded seals observed in glacier bays
- >90% of the little auks, Brunnich's guillemots and eiders, majority of glaucous gulls, fulmars and Arctic terns, observed in non-glaciated sectors
- kittiwakes observed in frontal zones of tidewater glaciers in much higher densities compared to coastline terminating glaciers and non-glaciated sectors ($p<0.0001$).
- black guillemots preferred tidewater glaciers, then coastline terminating glaciers and non-glaciated sectors ($p<0.0001$).
- eiders preferred non-glaciated sectors (D-E most preferred) avoided glaciers ($p<0.0001$).
- little auks foraging in higher densities in non-glaciated sectors ($p<0.005$).

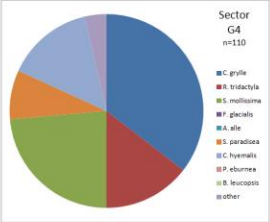


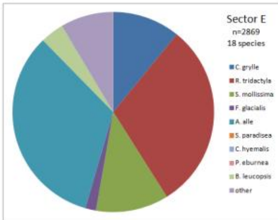


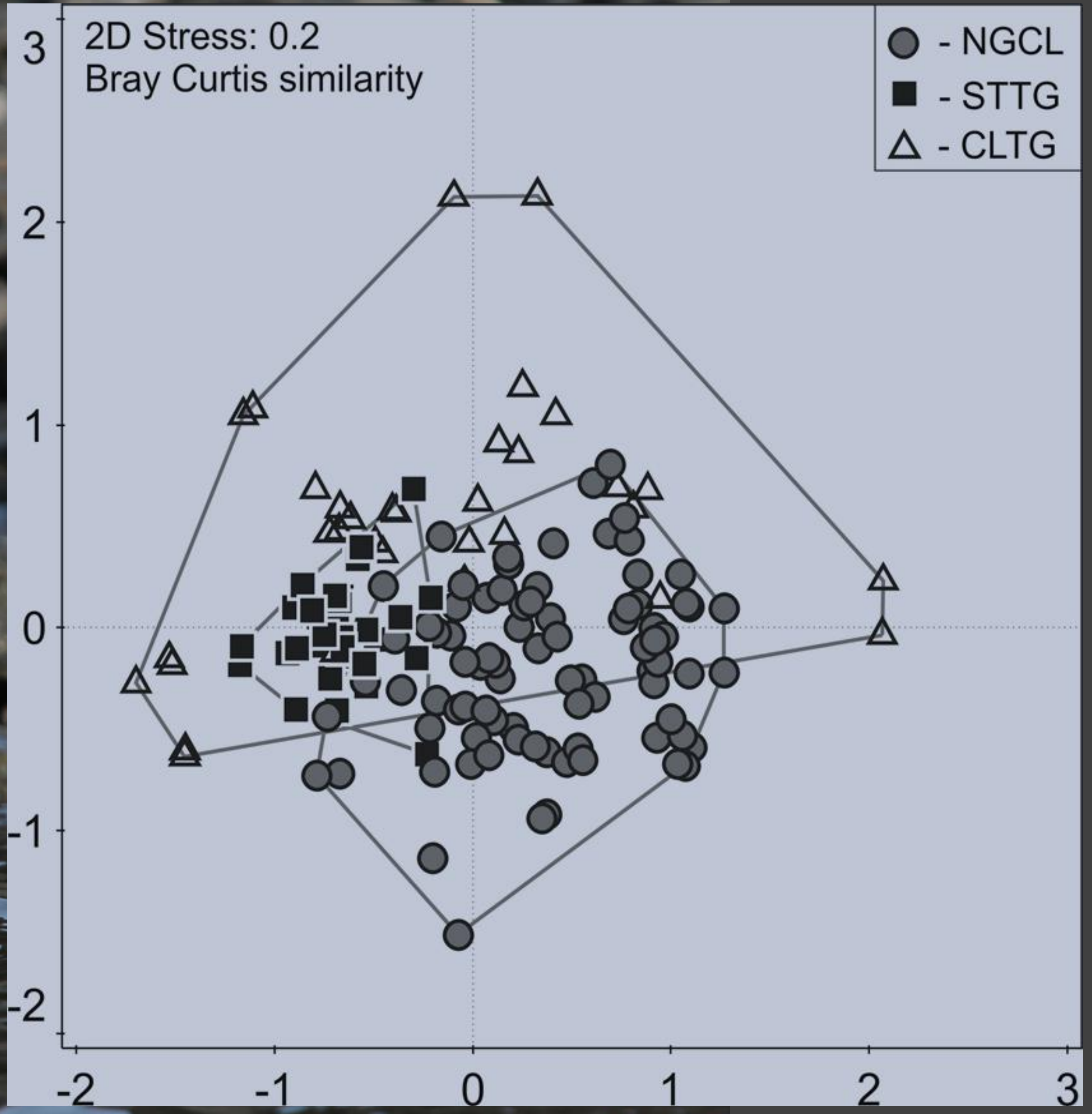












Non-metric multidimensional scaling (NMDS) based on species composition similarity shows clear separation of the habitat types. STTG show the smallest differentiation (MVDI=0.36), CLTG (MVDI=1.33) and NGCL (MVDI=1.06). ANOSIM one-way analysis, global test, R=0.37, p=0.001, all pairwise comparisons p=0.001)

Similarity Percentage Analysis (SIMPER; pairwise) of species composition in the 3 habitats (NGCL, STTG, CLTG).
AA - average abundance, HP - habitat preferences based on T-value biplot: significant positive T > 2 [+] and negative −2 > T [−];
AD - average dissimilarity. Selection based on 4 most contributing species in dissimilarity at cumulative contribution level ≥ 60 %.

- clear differentiation of habitats high average dissimilarity (> 60)
- the highest caused by kittiwake then by black guillemot (STTG)
- eider, with highest density in NGCL, also made an important contribution to the dissimilarity.
- NGCL characterized by highest abundance of little auk
- CLTG by highest abundance of Arctic tern.
- kittiwake - positive preferences to both glaciated habitats, with highest abundance in STTG.
- significant preference for NGCL only for little auk and eider.

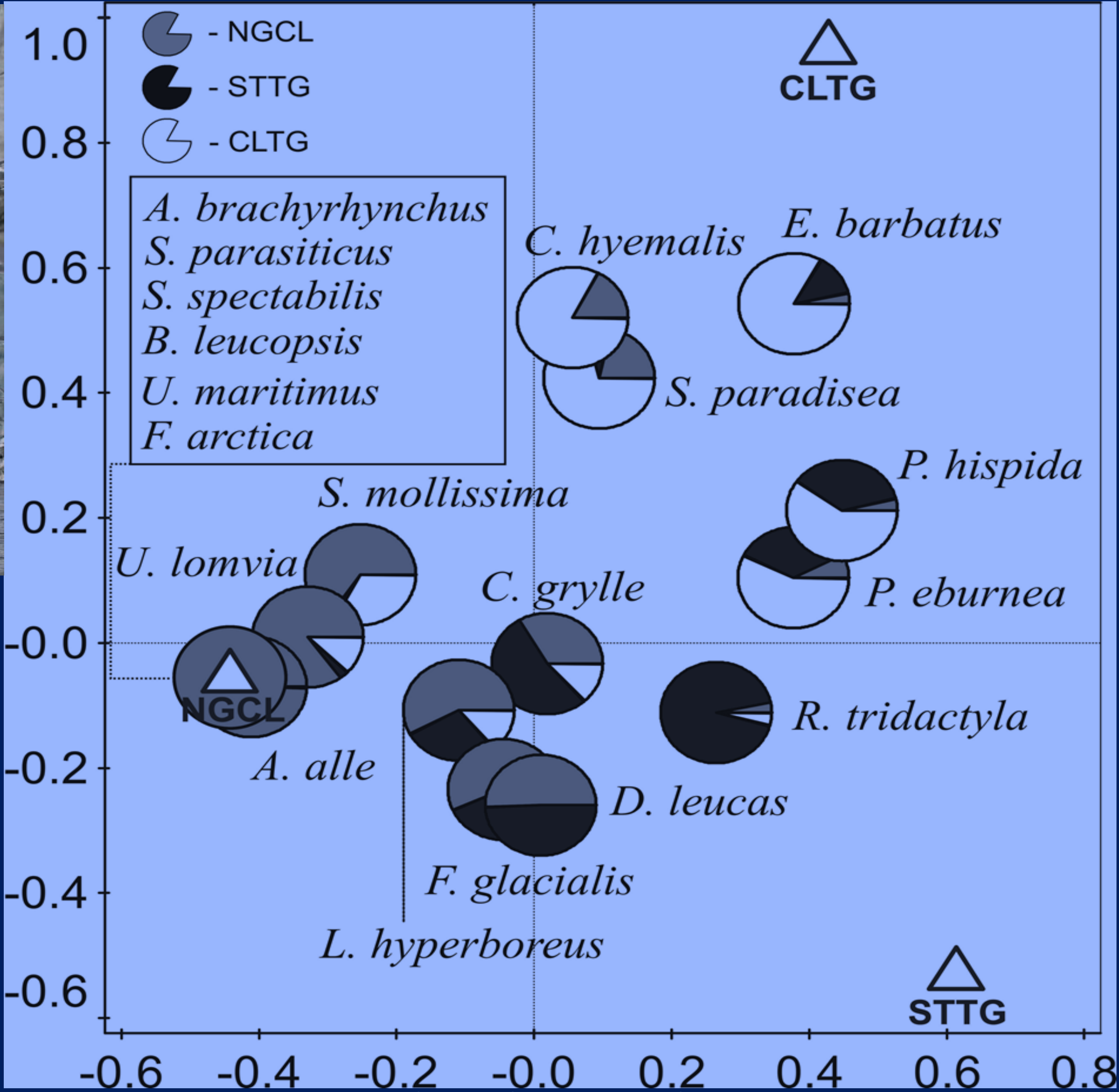
	NGCL		STTG		NGCL vs. STTG; total AD = 60.00		
Species	AA [N/km^2]	HP	AA [N/km^2]	HP	AD	Contrib. [%]	Cum. [%]
Rissa tridactyla	190.57	[−]	51.99	[+]	20.62	34.37	34.37
Cepphus grylle	23.63	[−]	30.47	[+]	6.91	11.52	45.89
S. mollissima	6.46	[+]	1.55	[−]	6.65	11.08	56.97
Alle alle	15.03	[+]	0.57	[−]	4.61	7.69	64.66

	NGCL		CLTG		NGCL vs. CLTG; total AD = 67.96		
Species	AA [N/km^2]	HP	AA [N/km^2]	HP	AD	Contrib. [%]	Cum. [%]
Rissa tridactyla	190.57	[−]	21.31	[+]	11.65	17.14	17.14
Cepphus grylle	23.63	*ns*	21.88	*ns*	10.17	14.96	32.11
S. mollissima	6.99	*ns*	8.24	*ns*	9.68	14.24	46.34
Sterna paradisea	2.10	[−]	1.76	[+]	8.10	11.92	58.27

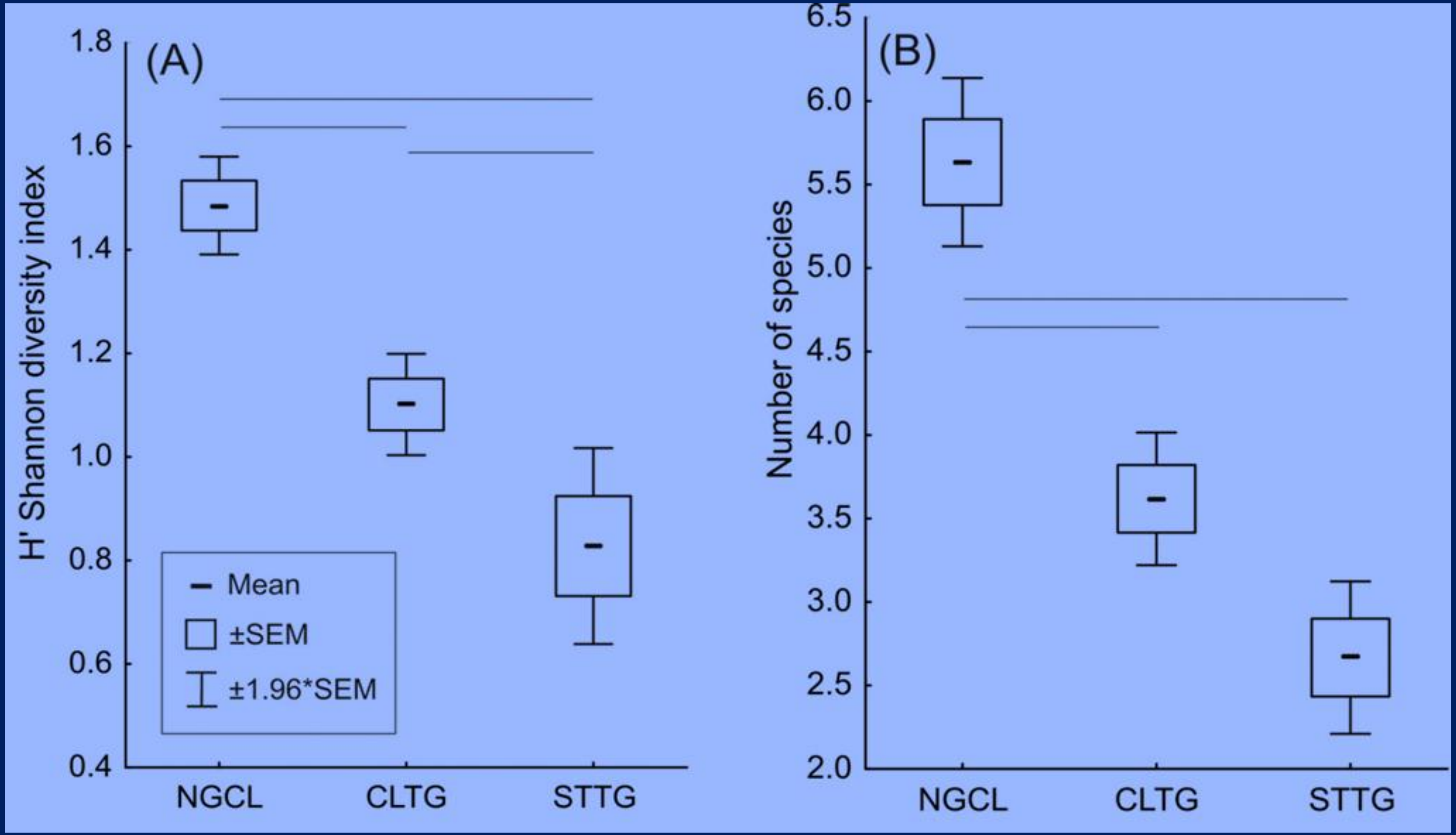
	STTG		CLTG		STTG vs. CLTG; total AD = 60.41		
Species	AA [N/km^2]	HP	AA [N/km^2]	HP	AD	Contrib. [%]	Cum. [%]
Rissa tridactyla	51.99	[+]	21.31	[−]	19.33	32.00	32.00
Cepphus grylle	30.47	*ns*	21.88	*ns*	11.41	18.88	50.88
Sterna paradisea	4.09	[−]	1.76	[+]	7.00	11.59	62.47

Kittiwakes foraging aggregation at front of Storbreen (c. 10 000 birds, July 2015)

- CCA confirmed species: habitat relationship
- >50 % of kittiwakes and black guillemots foraged in STTG
- long-tailed ducks, Arctic terns, ivory gulls, seals, in CLTG
- little auks, Brunnich's guillemots and eiders in NGCL
- fulmar and beluga shared NGCL and STTG in similar ways
- habitat factor significantly explained 13.4 % of the total variation in the species composition (CCA, Monte Carlo permutation test, pseudo-F=12.5 df=2; p=0.002).



CCA ordination diagram with pie charts describing species participation in density within the three distinguished types of habitat NGCL, STTG, CLTG. Triangles present ordination of environmental factor.



Shannon diversity index (A) and number of marine bird and mammal species (B) in the three habitats), plotted with envelopes. Significant differences ($p<0.01$) indicated by horizontal lines.

- highest values for (NGCL) sectors (ANOVA Welch test, $F=37.33$, and $F=25.69$, $df=2$, $p>0.001$ respectively, with significant differences in all pairs ($p<0.01$) except the number of species in the CLTG vs. STTG.
- STTG bays - large numbers of foraging birds and mammals, principally kittiwake, and low species richness.

Seasonal variations

- considerable interseasonal differences in seabird densities observed foraging in the study area - higher numbers in 2015 than in 2014.
- kittiwakes - the most striking difference (M-W test, $W=3475$, $p=0.0059$) little auks (M-W test, $W=1837$, $p<0.0001$).
- seasonality had no effect on either distribution or habitat preferences of marine birds and mammals (shared partitioning variation between habitat and seasonality = -0.0038; -0.4 % of total variability).
- density of kittiwakes and black guillemots during particular surveys (2 study seasons) was significantly correlated (Spearman $r_s=0.79$, $p=0.0016$).

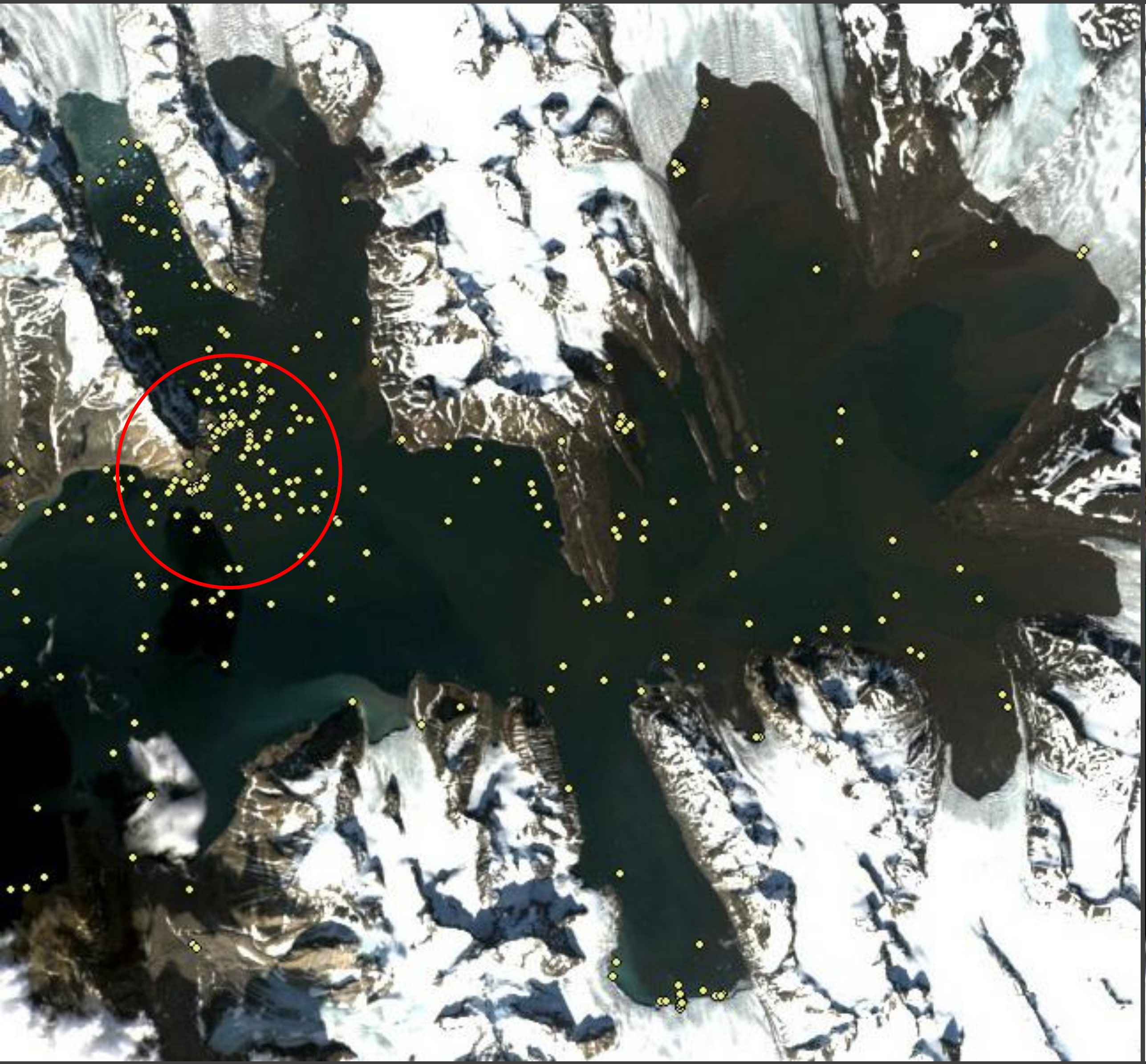
Wind characteristics* and proportion of kittiwakes foraging in Hornsund in July 2014 and 2015

wind speed [m/s]	July 2014	July 2015	1978-2013
monthly mean ± SD	3,67 ± 1,97	5,11 ± 4,02	4,0
max mean at observation	12,5	18,0	19
mean wind gust ± SD	13,89 ± 3,48	18,67 ± 6,09	-
max wind gust	20,0	33,0	
days with strong wind [≥10m/s]	9	13	7
total no. of foraging episodes**	3052	2952	
no. of foraging episodes in fjord	429	1446	
% of foraging episodes in fjord	14,06	48,98	

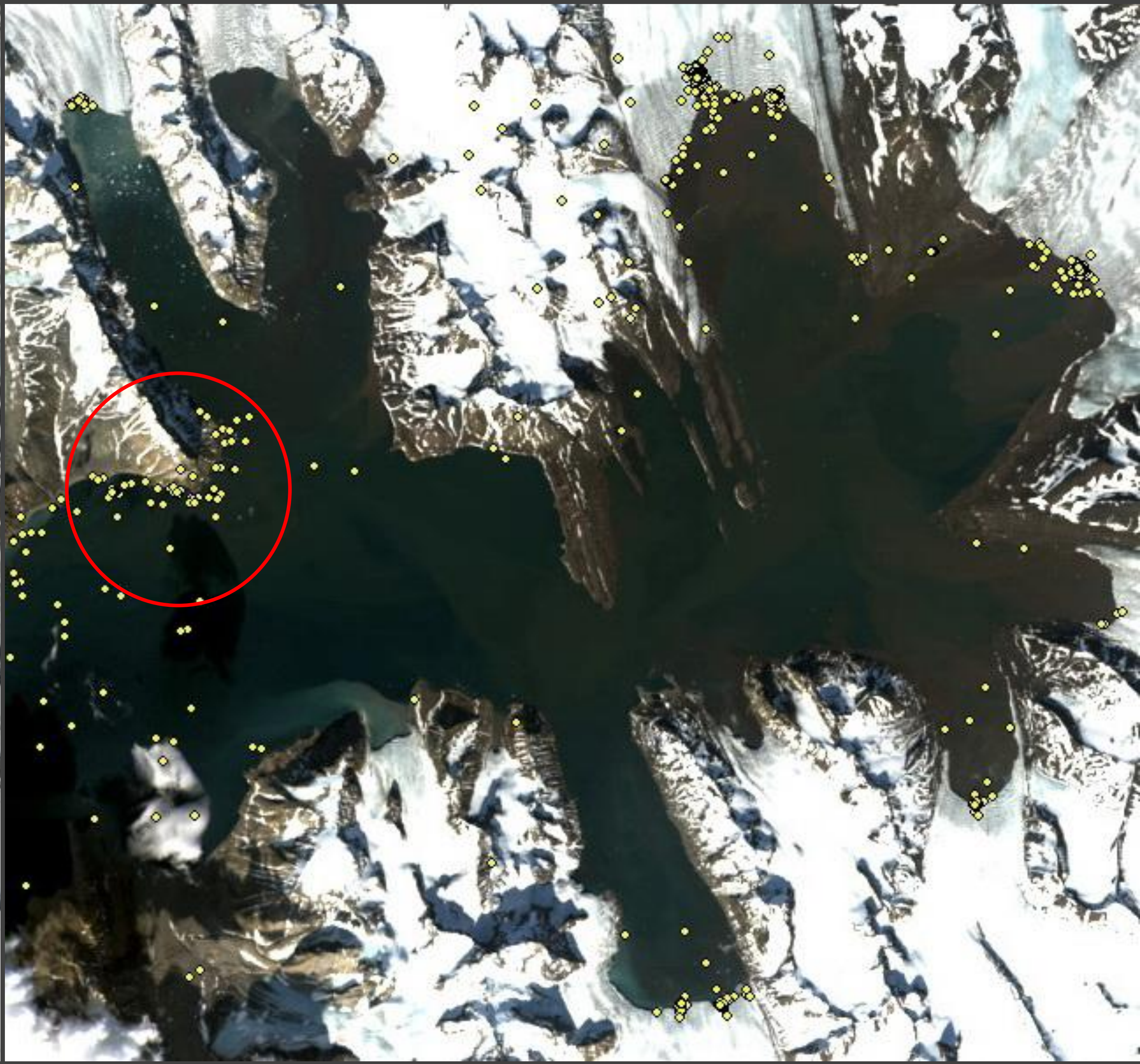
* data from Meteorological Bulletin, Polish Polar Station, Institute of Geophysics, Polish Academy of Sciences; note: wind gust was significantly stronger in July 2015 ($t = -2.14107$; $df=22$; $p < 0,05$).

** foraging episodes measured as no. of bird's contact with water registered by GPS loggers (own unpubl. data).

GPS-tagged kittiwakes in July 2014 and 2015;
yellow points denote water contacts = foraging & bathing; red circles = bathing sites



2014 – more spread



2015 clumped in glacier bays

Summary

- the first reliable estimates of abundance and habitat preferences of marine birds and mammals in Hornsund, which can be used in modeling food web and functioning of fjord ecosystem
- coastal surface feeders (Rissa) prevailed over benthic feeders (Cepphus) and pelagic pursuit divers (Alle, Uria)
- deep tidewater glacier bays: most numerous/least heterogeneous foraging community in contrast to shallow lagoons of coast-terminating glaciers and deglaciated shorelines
- during 15 years of glacier receding in Hornsund the sea-ice contact zone used by marine birds and mammals has not declined
- contrarily, increasing freshwater supply by glacier rivers debouching deep underwater and rising zooplankton onto the surface, thus making it available to seabirds, enhances attractiveness of deep tidewater glacier bays
- depending on retreating stage glacier bays have different importance for coastal vertebrate communities
  - reaching the coastline by glacier terminus and shallowing of the glacier bay worsen foraging conditions
- glacier retreating unveils/enlarges area of littoral habitats accessible for bethophages
- colony-close glacier bays are used as alternative/emergency feeding grounds by seabirds that usually forage out of the fjord
  - especially important during chick-rearing period (high energy demands) and during bad weather conditions in the open sea
- so far abundance and species diversity of seabirds foraging in Hornsund are high (comparing to other recognized Arctic fiords), suggesting they benefit from current intensive glacier melting
- such nonlinear responses complicate predicting future polar ecosystem dynamics.