## 1.0 Methods

### 1.1 Arctic fisheries data

We accessed the most recently published annual dataset of fish and shellfish landings in the Arctic Ocean: the year 2014 data from the 'Sea Around Us' database (Pauly and Zeller 2020). Data was downloaded in the format of large marine ecosystems zones, we then categorized each into five biogeochemical regions, based on previous work by Carmack and Wassmann (2006) and following Findlay et al. (2015): the inflow shelves of the Atlantic influenced seas (AiS) and Pacific influenced seas (PiS); the river influenced seas (RiS); the central Arctic Ocean (CAO); and the outflow shelves (OFS) of the Canadian Arctic and East Greenland (Figure 1) (Supplementary Table 4). We chose to only include in our review landings of organism that had been identified down to species level, that had recorded landings over 2000 tonnage as a landing value cut off, this was used as cut off to capture the most economically important species whilst still relatively low to capture some of the lower-level fish species, such as the Norway lobster (*Nephrops norvegicus)* which had a tonnage of 2,008. This resulted in forty-seven species (see list below). We then carried out a literature search on those forty-seven species.

### 1.2 Literature search

Google scholar was used to search key terms such as common species and scientific names including: Atlantic cod *Gadus morhua,* Atlantic herring *Clupea harengus,* Blue whiting *Micromesistius poutassou,* Atlantic mackerel *Scomber scombrus*, Capelin *Mallotus villosus*, Haddock *Melanogrammus aeglefinus,* Saithe *Pollachius virens*, Alaska pollock *Theragra chalcogramma*, Northern prawn *Pandalus borealis*, Greenland halibut *Reinhardtius hippoglossoides*, Golden redfish *Sebastes norvegicus,* Beaked redfish *Sebastes mentella*, Ling *Molva molva,* Tusk *Brosme brosme*, European plaice *Pleuronectes platessa,* Lumpfish *Cyclopterus lumpus*, Pink salmon *Oncorhynchus gorbuscha*, Atlantic wolffish *Anarhichas lupus,* Northern wolffish *Anarhichas denticulatus,* Red king crab *Paralithodes camtschaticus,* Pacific herring *Clupea pallasii,* Spotted wolffish *Anarhichas minor,* Snow crab *Chionoecetes opilio,* Sockeye salmon *Oncorhynchus nerka*, Chum salmon *Oncorhynchus keta*, Coho salmon *Oncorhynchus kisutch,* Golden King crab *Lithodes aequispinus,* Arrowtooth flounder *Atheresthes stomias,* American plaice *Hippoglossoides platessoides,* Pacific cod *Gadus macrocephalus*, Pacific ocean perch *Sebastes alutus*, Pacific sandlance *Ammodytes personatus*, Pacific saury *Cololabis saira,* Norway lobster *Nephrops norvegicus,* American lobster *Homarus americanus*, Pacific halibut *Hippoglossus stenolepis*, Yellowfin sole *Limanda aspera,* Rock sole *Lepidopsetta bilineata*, Flathead sole *Hippoglossoides elassodon*, Rex sole *Glyptocephalus zachirus,* Same-spine stone crab *Lithodes aequispinus*, Atka mackerel *Pleurogrammus monopterygius*, Flathead grey mullet

*Mugil cephalus,* Sablefish *Anoplopoma fimbria,* Yellowtail flounder *Limanda ferruginea,* American sea scallop *Placopecten magellanicus,* Queen scallop *Aequipecten opercularis* and Saffron cod *Eleginus gracilis.*

Then words 'ocean acidification', 'Arctic Ocean', 'multi stressor'. Relevant papers were then filtered by abstract, under the criteria that the paper included OA impact study of one of the forty-seven top landed species. Then the 'snowballing technique' was applied to find further work from references of relevant papers (Malinauskaite et al., 2019). Information from the papers was summarised into Table S2. For the literature search regarding stressors Google scholar was used to search key terms 'stressor', 'Arctic Ocean', 'changing Arctic', 'warming', 'carbonate chemistry', 'total alkalinity', 'dissolved inorganic carbon', 'pH', '$CO_2$', 'ice loss', 'freshwater input', 'light availability', 'invasive species'. We included any publications that had been published up until June 2020.

## 2.0 Supplementary tables

**Supplementary table 1. Studies of ocean acidification impact on the top 60 landed species by weight in the Arctic Ocean catch data found at 'Sea around Us' database (Pauly & Zeller 2020). Stressors: OA = ocean acidification, T = temperature, F = food. Stressor effects: NSR = no significant response, SAR =significant altered response, PR= positive response, NR= negative response. Life stages: S= sperm, E = embryo, L = larval, P = post larval, J = juvenile, Sa = subadult, A = adult. $pCO_2$ = partial pressure of $CO_2$, pH and scale stated if published, $pH_T$ = total scale, $pH_{NSB=}$ NBS scale, $pH_F$= free scale, $pH_s$= seawater scale. AiS= Atlantic influenced seas; PiS= Pacific influenced sea; RiS= River influenced seas; CA= central Arctic; OFS = Outflow shelf**

| **Figure 1b reference map reference** | Ecological process | **Species** | **Region** | **Stressor** OA | **T** | **F** | **OA + T** | **OA + F** | **Mechanism Tested** | **Life Stage** | **Method** | **References** | **Notes** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Sperm motility | *Gadus morchua* Atlantic cod | AiS OFS | NSR | | | | | Sperm speed, rate of change of direction & percent motility | S | $pCO_{2:}$ 380, 1400 µatm; $pH_T$ 8.08, 7.55; T: 8–9.5°C | Frommel *et al.* 2010 | Baltic cod stock |
| **2** | Growth and development | *Gadus morchua* Atlantic cod | AiS OFS | NR | | | | | Larval growth, development of internal organs | L | $pCO_{2:}$ 380, 1800, 4200 µatm; $pH_T$ 8.08, 7.45, 7.08; duration: 46 days post hatch | Frommel *et al.*, 2012 | Tissue damage found in larvae with decreasing pH, though large difference between medium and high $pCO_2$ treatment levels, hard to identify the larval threshold. |
| **3** | Gene expression | *Gadus morchua* Atlantic cod | AiS OFS | NR | | | | | Transcriptome profiling mRNA sequencing, gene ontology | L | $pCO_{2:}$ 503, 1179 µatm; T: 6-10°C; duration: 36 days post hatch | Mittermayer et al. 2019 | Different response between larval stages, high mortality and histological tissue change as a result of treatment. |
| **4** | Calcification of the otoliths | *Gadus morchua* Atlantic cod | AiS OFS | SAR | | | | | Otolith surface area and growth rates | L | $pCO_2$ 370, 1800, 4200 µatm; $pH_T$ 8.08, 7.45, 7.08; T: 5- 10°C; duration: 46 days | Maneja *et al.*, 2013 | Signif. difference in size of otoliths between treatments but not in shape of otoliths.<br>Bergen/ North Sea stock |
| **5** | Metabolic rates and swimming speeds | *Gadus morchua* Atlantic cod | AiS OFS | NSR | | | | | Standard and active metabolic rates, critical | A | Exp.1: $pCO_{2:}$ 5792, 537.2 ppm; $pH_T$: 7.01, 8.01; duration: 1 year | Melzner et al. 2009 | Each experiment used fish from different location; North Eastern Arctic Cod and North Sea Cod. |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | swimming speeds | | Exp.2: $pCO_{2}$: 3080, 528.3 ppm; $pH_T$: 7.30, 8.02; duration: 4 months<br>Both T: 5-5.5°C. | | |
| **6** | Metabolic performance | *Gadus morchua*<br>Atlantic cod | AiS OFS | SAR | SA R | S A R | Maximal oxidative phosphorylation capacity of permeabilised heart muscle fibres | A | $pCO_{2}$: 400, 1170 µatm; T: 3, 8, 12, 16°C; Duration: 4 months | Leo et al. 2017 | Northeast Arctic cod |
| **7** | Gene and protein expression and ion and acid–base regulation in gills | *Gadus morchua*<br>Atlantic cod | AiS OFS | SAR | SA R | S A R | Transepithelial ion transporters and ATPases | A | $pCO_{2}$: 550, 1200, 2200 µatm; T: 10, 18°C; Duration: 4 weeks | Michael et al., 2016 | Results suggest physiology plasticity to warming and OA |
| **8** | Hatching, survival, development and otolith size | *Gadus morchua*<br>Atlantic cod | AiS OFS | Exp1 NSR<br>Exp2 NSR<br>Exp3 NSR<br>Exp4 NSR | Exp 5 SA R | E x p 5 N S R | Exp. 1: egg survival and hatching success<br>Exp. 2: development<br>Exp. 3: biochemical indicators<br>Exp. 4: development<br>Exp. 5: OA and increased temperature effect on biochemical indicators and otolith analysis | E, L | Exp. 1: $pCO_{2}$: 380, 560, 860, 1120, 1400, 4000 µatm; $pH_{NBS}$ 7.97, 7.83, 7.75, 7.68, 7.62, 7.21; T: 7°C; duration: until hatched.<br>Exp. 2: $pCO_{2}$: 380, 840, 1400, 4000 µatm; $pH_{NBS}$ 7.87, 7.68, 7.55, 7.16; T: 6.6°C; duration: 11 days post-hatch.<br>Exp. 3: $pCO_{2}$: 380, 1400, 4000 atm; $pH_{NBS}$ 8.00, 7.64, 7.38; T: 7.4°C; duration: 7days post-hatch.<br>Exp. 4: $pCO_{2}$: 380, 1400 µatm; $pH_{NBS}$ 7.87, 7.60; T: 7.4°C; duration: 7- 10 days post-hatch | Frommel *et al.*, 2013 | Individuals used in this experiment from Baltic population where in situ $pCO_2$ has already been recorded to be 1100 µatm. The lack of response to OA conditions could be down to localised adaptation |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Exp. 5: $pCO_2$: 380, 1400, 4000 µatm; $pH_{NBS}$: 7.97, 7.60, 7.18; T: 5, 7, 9°C; duration: 91 days | | |
| **9** | Intestinal Ion Transport | *Gadus morchua* Atlantic cod | AiS OFS | SAR | SA R | N S R | Intestinal acid–base regulatory machinery | J | $pCO_2$: 550, 1200, 2200 µatm; T: 10, 18°C; duration: 4 weeks | Hu et al. 2016 | From Gullmarsfjord, Sweden |
| **10** | Growth, feed consumption and standard metabolic rate | *Gadus morchua* Atlantic cod | AiS OFS | NSR | SA R | N S R | Metabolism and performance | A | $pCO_2$: 390 and 1170 µatm; $pH_T$: 7.61, 8.01; T: 3, 8, 12, 16°C; duration: 4 months | Kunz et al. 2016 | No effect of increased $pCO_2$ conditions alone and combined warming and OA nonsignif. trends. Atlantic cod had higher fitness to conditions than polar. |
| **11** | Energy budget and gill ion regulatory mechanisms | *Gadus morchua* Atlantic cod | AiS OFS | SAR | NS R | S A R | Energy budget and gill ion regulatory mechanisms | A | $pCO_2$: 550, 1200, 2200 µatm; $pH_T$: 7.97, 7.65, 7.37; T: 10, 18°C; duration: 3–4 weeks | Kreiss et al. 2015 | From Gullmarsfjord, Sweden |
| **12** | Development | *Gadus morchua* Atlantic cod | AiS OFS | NR | N R | N R | Hatching success, oxygen consumption, mitochondrial functioning, | E | $pCO_2$: 400, 1100 µatm T: 0, 3, 6, 9, 12°C | Dahlke et al. 2017 | From Øresund Strait, Baltic Sea. OA will narrow the thermal tolerance range of embryos |
| **13** | Recruitment and survival | *Gadus morchua* Atlantic cod | AiS OFS | NR | N S R | NS R | Survival | L | $pCO_2$: 400–500, 1100 µatm; T: 6-10°C; duration: 32 days | Stiasny *et al.*, 2016 | In the first 25 days post hatching there was twice the mortality rate in the high $CO_2$ treatment. Consistent results for two different cod population Barents Sea & Western Baltic. |
| **14** | Recruitment and survival | *Gadus morchua* Atlantic cod | AiS OFS | NR | N R | N R | Survival, transgeneration al alleviation | L | $pCO_2$: 400–500, 1110 µatm; T: 6-10°C; duration: parents 6 weeks before spawning; larvae 16 days post hatch | Stiasny *et al.*, 2018 | Transgenerational alleviation dependant on food resources |
| **15** | Growth & survival | *Gadus morchua* Atlantic cod | AiS OFS | SAR | N R | N R | Growth, survival, organ development, skeletogenesis | E,L | $pCO_2$: 503, 1179 µatm; duration: 35–36 days | Stiasny *et al.*, 2019 | Larvae in treatment with no food experienced developmental problems with internal organs, trade-off |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | between growth and organ development |
| **16** | Behaviour | *Gadus morchua* Atlantic cod | AiS OFS | NSR | | | Swimming activity, emergence from shelter, absolute and relative lateralization | J | *p*$CO_2$: 500, 1000 µatm; T: 14 - 15°C | Jutfelt and Hedgärde 2015 | |
| **17** | Behaviour | *Gadus morchua* Atlantic cod | AiS OFS | NSR | SA R | N S R | behavioural laterality spontaneous activity | J | *p*$CO_2$: control 374−515 µatm, high 852−1416 µatm; T: 3, 8, 12, 16°C; duration: 6 weeks | Schmidt et al. 2017 | Stock from western Svalbard |
| **18** | Swimming kinematics | *Gadus morchua* Atlantic cod | AiS OFS | SAR | | | Swim duration, distance and speed, stop duration, and horizontal and vertical turn angles | L | *p*$CO_2$: 370, 1800, 4200 µatm; $pH_T$: 8.08, 7.45, 7.08; T: 5-10°C; duration: 15 days | Maneja et al. 2013 | Stop duration signif. reduced but no signif. difference in other variables. Norwegian cod stock |
| **19** | Development | *Clupea harengus* Atlantic herring | AiS OFS | SAR | | | Embryogenesis, hatch rate, length, dry weight, yolk sac area, otolith and RNA/DNA ratios | E, L | *p*CO2: 480, 1260, 1859, 2626, 2903, 4635 µatm; $pH_F$: 8.08, 7.67, 7.49, 7.33, 7.28, 7.05; T: 14°C; duration: until hatched | Franke and Clemmesen 2011 | Signif. negative effect found in RNA/ DNA ratio but everything else no effect seen.<br>Hatching RNA low which could mean decrease in protein biosynthesis<br>From Western Baltic Sea. |
| **20** | Development | *Clupea harengus* Atlantic herring | AiS OFS | NR | | | Growth, development of organs | L | *p*$CO_2$: 0.0385, 0.183, 0.426 kPa; $pH_T$: 8.08, 7.45, 7.07; T: 5-10°C; duration: 39 days post hatch | Frommel *et al.*, 2014 | Decreased growth and development rate and severe tissue damage |
| **21** | Development | *Clupea harengus* Atlantic herring | Airs OFS | NSR | | | Length, proteome structure | E, L | *p*$CO_2$: 370, 1800 µatm; $pH_T$: 7.45, 7.08; T: 5-10°C; duration: one month | Maneja *et al.*, 2014 | Proteome not signif. affected by reduced pH, but a small difference seen |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **22** | Behaviour | *Clupea harengus* Atlantic herring | AiS OFS | NSR | | | Swimming Kinematics and foraging behaviour | L | *p*$CO_2$: 370, 1800, 4200 µatm; $pH_T$: 8.08, 7.44, 7.08; temperature: 5-10°C; duration: 34 days post hatch | Maneja et al. 2015 | |
| **23** | Survival | *Clupea harengus* Atlantic herring | AiS OFS | PR | | PR | Survival | L | *p*$CO_2$: 380, 760 µatm; T: 8.5-15.5°C; duration: 113 days | Sswat, Stiasny, Taucher, et al. 2018 | Ecosystem based perspective- Survival of larvae increased by 19 % due to enhanced primary production from phytoplankton at higher *p*$CO_2$ level, positive bottom up effect. Stock from Swedish west coast |
| **24** | Growth performance and survival | *Clupea harengus* Atlantic herring | AiS OFS | NSR | N R | N R | Survival, growth, swimming activity | L | *p*$CO_2$: 400, 900 µatm; pH 7.8, 8.1; T: 10, 12°C; duration: 32 days | Sswat, Stiasny, Jutfelt, et al. 2018 | Strong temperature effect, $CO_2$ effects were minimal in comparison<br><br>Stock from Oslo-Fjord |
| **25** | Development | *Theragra chalcogramma* Alaska pollock | PiS | NSR | | | Growth, changes in otolith accretion and elemental composition | J | Exp 1: *p*$CO_2$: 414,478, 815, 1805 µatm; T: 8-9°C; duration: 6 weeks<br>Exp 2: (a) *p*$CO_2$: 596, 828, 1285, 2894 µatm; T: 8ºC; (b) *p*$CO_2$: 225, 386, 643, 1543 µatm; T: 2.4ºC; (both) duration: 12 weeks; | Hurst et al. 2012 | |
| **26** | Development | *Theragra chalcogramma* Alaska pollock | PiS | NSR | | | Hatch time, condition index, eye diameter, yolk area, growth rate, final condition | E, L | Eggs: *p*$CO_2$: 310, 475, 828, 1933 µatm<br>Larvae 1: *p*$CO_2$: 287; 457; 805;1773 µatm<br>Larvae 2: *p*$CO_2$: 293, 411, 910, 1812 µatm<br>Larvae 3: *p*$CO_2$: 297, 426, 941, 1858 µatm<br>All: T: 8ºC; duration: 30 days | Hurst, Fernandez, and Mathis 2013 | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **27** | Development | *Pandalus borealis* Northern prawn | AiS OF PiS | NR | | | Survival and developmental time | L | $pCO_2$: 368–381, 1291–1332 µatm; T: 5℃; duration: 35 days | Bechmann et al. 2011 | No signif. effect on survival but signif. on development time, individuals in increased $pCO_2$ took longer to develop. |
| **28** | Development | *Pandalus borealis* Northern prawn | AiS OF PiS | NR | N R | N R | Hatching timing and success, and development, survival, feeding, respiration and growth | E, L | $pCO_2$: 337–474, 1,038–1,437 µatm; T: 6.7, 9.5°C | Arnberg et al. 2013 | Increased $pCO_2$ caused delay in development, elevated temperature reduced survival but increased metabolic feeding and development rates |
| **29** | Survival and consumer sensory appeal | *Pandalus borealis* Northern prawn | AiS OF PiS | NR | | | Survival and consumer sensory appeal | A | $pCO_2$: 459, 1368 µatm; T: 11°C; duration: 3 weeks | Dupont et al. 2014 | Increased $pCO_2$ increased mortality. Appearance and taste quality also reduced. |
| **30** | Development | *Oncorhynchus gorbuscha* Pink salmon | PiS | NR | | | Growth, metabolic rate and behaviour | E, L | $pCO_2$: constant 450, 1600 µatm, diurnal fluctuating 450-2000 µatm; $pH_T$: 8.1, 7.5, 7.6 (peak); T: 6.8°C; duration: 10 weeks | Ou et al. 2015 | Negative effect on olfactory, growth, metabolism and anti- predator behaviour |
| **31** | Development | *Paralithodes camtschaticus* Red king crab | PiS AiS | NR | | | Growth, condition, calcification, and survival | J | $pCO_2$: 438, 792, 1638 µatm; $pH_F$: 8.04, 7.80, 7.50; T: 4.4–11.9°C; duration: 200 days | Long *et al.*, 2013a | At $pCO_2$ 1638 µatm all crabs died after 95 days. |
| **32** | Development | *Paralithodes camtschaticus* Red king crab | PiS AiS | NR | | | Morphometrics, hatch duration, survival and condition | E, L | $pCO_2$: 963, 397 µatm; $pH_F$: 7.71, 8.04 T: 3–5°C | Long *et al.*, 2013b | Increase larval size and calcium %, mean hatch duration 33% longer, decreased survival |
| **33** | Development | *Paralithodes camtschaticus* Red king crab | PiS AiS | NR | | | Oxygen consumption, growth and feeding ration. | J | $pCO_2$ 332, 768, 1555 µatm; $pH_F$: 8.14, 7.80, 7.50; T: 6°C; duration: 3 weeks | Long, *et al.*, 2019 | Increased oxygen consumption, reduced growth and increased mortality with increased $pCO_2$. Feeding did not change |
| **34** | Development | *Paralithodes camtschaticus* Red king crab | PiS AiS | SAR | SA R | N R | Structure and composition of the cuticle | J | Duration: 184 days; (Ambient) $pCO_2$: 491, 538, 587, $pH_F$: 8.0, 7.97; 7.94 T: 8.5, 10.3, 12.3°C | Coffey et al. 2017 | Altered properties of the cuticle, with unknown fitness consequences |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | (treatment) $pCO_2$: 826, 896, 955 µatm; $pH_F$:7.79, 7.76, 7.75. T: 8.6, 10.5, 12.3°C | | |
| **35** | Development | *Paralithodes camtschaticus* Red king crab | PiS AiS | NR | N R | N R | Survival, growth, and morphology | | Duration: 184 days; $pCO_2$: 491-587, 826-955; pHF: ~7.99, pH 7.8; T: Ambient, Ambient +2, Ambient +4 °C | Swiney, Long, and Foy 2017 | Mortality increased with temperature and decrease in pH |
| **36** | Development | Norway lobster Nephrons norvegicus | AiS | SAR | PR | N S R | yolk consumption, mean heart rate, rate of oxygen consumption, and oxidative stress | E | pCO2 330- 632 µatm; $pH_T$: 7.87- 8.11; 7.47-7.71; T: 5, 10, 12, 14, 16, 18°C; duration: 4 months | Styf, Nilsson Sköld, and Eriksson 2013 | Signif. effect on oxidative stress in control group. Concluded insensitive to OA. |
| **37** | Development | Norway lobster Nephrops norvegicus | AiS | NSR | | N R | Metabolic rate, Growth | E, J | $pCO_2$: 596, 1599, 615, 1415 µatm; $pH_{NBS}$: 7.9, 7.5, 7.89, 7.55; T: 15°C; salinity 33.6, 21, 17.1; duration: 12 days | Wood et al. 2015 | Starvation with OA showed a greater mortality, OA conditions require greater energy requirements. |
| **38** | Immune response | Norway lobster Nephrops norvegicus | AiS | * NR | | | Total haemocyte counts<br><br>*Combined hypoxia or Mn with OA negative effect | A | $pCO_2$: 500, 1550 µatm; $pH_T$ 8.1, 7.6; duration: 8 weeks Last 2 weeks + stress of either hypoxia (~23% oxygen saturation) or Mn (~9 mg $L^{-1}$) | Hernroth, Krång, and Baden 2015 | Reduction in haemocyte counts when OA stressor combined with hypoxia or Mn. *Vibrio parahaemolyticus* unaffected by stressors. |
| **39** | Development | Spotted wolffish *Anarhichas minor* | AiS | NR | | | Growth, food conversion efficiency and nephrocalcinosis | J | $pH_T$ 8.10, 6.98, 6.71, 6.45; T: 6°C; duration: 10 weeks | Foss, Røsnes, and Øiestad 2003 | Growth and feeding rates signif. reduced at highest $pCO_2$ |
| **40** | Exp.1 behaviour Exp. 2 growth | Pacific cod *Gadus macrocephalus* | PiS | SAR | | | Behaviour, growth and condition experiment | L | Exp. 1 $pCO_2$: 600, 1500, 2250 µatm. $pH_s$ 7.86, 7.51, 7.32; T: 7.7- 7.8°C | Hurst et al. 2019 | Increased phototaxis at high $pCO_2$, |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Exp.2: $pCO_2$: 500, 1700 µatm; $pH_s$ 7.98, 7.43; T: 7.4°C; duration: 5 weeks two different feeding regimes | | |
| **41** | Development | American lobsters *Homarus americanus* | OTF | NR | | | Growth and development | L | $pCO_2$ 400, 1200 ppm; pH 7.7, 8.1; T: 20°C; duration: 12 days | Keppel, Scrosati, and Courtenay 2012 | Shorter body length conditions and greater time to molt under OA, could make them more susceptible to predators as larger time in water column. |
| **42** | Physiology | American lobsters *Homarus americanus* | OTF | NSR | | N R | Cardiac performance, haemocyte abundance, and hemolymph chemistry | Sa | $pCO_2$: 850, 490 ppm; $pH_{NBS}$ 8.0, 7.6; T: 12-28°C; duration: 60 days | Harrington and Hamlin 2019 | Results suggested an immunosuppression in response to OA and reduction in carrying capacity. Warming and OA lead to reduction in cardiac performance. |
| **43** | Physiology | American lobsters *Homarus americanus* | OTF | SAR | N R | N R | Survival, development, oxygen consumption and feeding rate | L, P | $pCO_2$: 380, 750 ppm; pH 8.0, 7.8; T: 16, 19°C | Waller et al. 2016 | Increased food consumptions at high temperature and high $pCO_2$. Larger impact from temperature than $pCO_2$. |
| **44** | Physiology | American lobsters *Homarus americanus* | OTF | NR | | | Survival, development time, metabolic and feeding rates, carapace composition, and energy metabolism enzyme function | P, J | $pCO_2$: 400, 600, 1000, 1200, 2000, 3000 µatm; $pH_T$ 8.0, 7.9, 7.8, 7.7, 7.7, 7.4, 7.2; T: 18°C; duration: 40 days | Menu-Courey et al. 2019 | An increase in mortality and longer development time could result in lower recruitment |

Supplementary table 2. The seas each region encompasses

| Region name | The Seas each region encompasses |
|---|---|
| Atlantic influenced seas (AiS) | Faroe Plateau, Iceland shelf and Sea, Norwegian Sea, Barents Sea |
| Pacific influenced seas (PiS) | East Bering Sea; Aleutian Island; West Bering Sea; and Northern Bering- Chukchi Sea |
| River influenced seas (RiS) | Kara Sea; Laptev Sea; East Siberian Sea and Beaufort Sea |
| Central Arctic Ocean (CAO) | Central Arctic |
| Outflow shelves (OFS) | Greenland Sea- East Greenland; Canadian high Arctic- north Greenland; Canadian Eastern Arctic- West Greenland, Hudson Bay, and Labrador- Newfoundland |

Supplementary table 3. Summary table of the characteristics of each Arctic region (AiS= Atlantic influenced seas; PiS= Pacific influenced sea; RiS_B=Beaufort Sea; RiS_S= Siberian sea; Laptev sea, Kara sea; CA= central Arctic; OFS = Outflow shelf). Data provided are mean, standard deviation (SD), range and number of data points (N) for each region. Sea surface salinity (SSS), sea surface temperature (SST), sea surface chlorophyll a (Chl a), sea surface oxygen ($O_2$), sea surface total alkalinity (TA), sea surface dissolved inorganic carbon (DIC), and sea surface pH are taken from GLODAP version 2019 (Olsen et al. 2019). Sea surface fugacity of $CO_2$ ($fCO_2$) is taken from SOCAT version 2019 (Bakker et al. 2016). River discharge from the major rivers of each region is taken from Dittmar and Kattner, (2003) for AiS and RiS, Déry et al., (2016) for PiS and OFS. The surface area of each region is taken from Skjoldal and Mundy, (2013).

| | **AiS** | | **PiS** | | **RiS_B** | | **RiS_S** | | **CA** | | **OFS** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean ±SD** | **Range (N)** | **Mean ±SD** | **Range (N)** | **Mean ±SD** | **Range (N)** | **Mean ±SD** | **Range (N)** | **Mean ±SD** | **Range (N)** | **Mean ±SD** | **Range (N)** |
| **Area** | 3.74 | | 3.72 | | 1.11 | | 2.56 | | 3.33 | | 4.92 | |
| **(million km $^{3}$)** | | | | | | | | | | | | |
| **SSS** | 34.5 ±0.9 | 13.6 - 35.4 | 29.4 ±2.7 | 0 - 33.6 | 25.9 ±5.1 | 0 - 32.6 | 24.5 ±9.4 | 0 - 34.3 | 32.4 ±2.2 | 13.4 - 35.1 | 33.1 ±1.8 | 14.8 - 35.4 |
| **(PSS-78)** | | N 1811 | | N 1076 | | N 1007 | | N 270 | | N 1316 | | N 1809 |
| **SST (°C)** | 5.6 ±3.7 | -1.9 - 13.7 | 1.9 ±3.5 | -1.8 - 13.9 | 1.4 ±2.8 | -1.7 - 15.7 | 0.4 ±2.6 | -1.8 - 10.6 | 0.3 ±2.2 | -2.2 - 8.1 | 1.3 ±3.0 | -2.3 - 1.4 |
| | | N 1833 | | N 1069 | | N 980 | | N 225 | | N 1325 | | N 1836 |
| **$fCO_2$ (µatm)** | 323.4 ±46.5 | 102.0 - 2415.0 | 310.3 ±88.2 | 78.4 - 767.7 | 349.9 ±58.1 | 104.2 - 626.7 | 320.6 ±57.2 | 183.6 - 388.2 | 256.6 ±54.4 | 101.0 - 414.0 | 279.3 ±52.5 | 110.4 - 597.9 |
| | | N 1406662 | | N 317793 | | N 154677 | | N 9427 | | N 393701 | | N 699539 |
| **Chl a** | 1.3 ±1.3 | 0.0 - 10.9 | 0.8 ±1.4 | 0.0 – 16.0 | 0.5 ±1 | 0.0 - 7.3 | no data | | 1.1 ±1.4 | 0.0 - 11.1 | 1.2 ±1.5 | 0.0 - 11.1 |
| **(µg kg $^{1}$)** | | N 249 | | N 415 | | N 216 | | | | N 233 | | N 243 |
| **$O_2$** **(µmol kg $^{1}$)** | 323.4 ±31.4 | 250.5 - 459.1 | 365.3 ±40.4 | 197.8 - 572.3 | 368.8 ±28 | 209.9 - 529.5 | 364.9 ±27.5 | 193.1 – 470 | 364.9 ±32.1 | 293.8 - 484.9 | 357.0 ±35.3 | 276.5 - 484.9 |
| | | N 1192 | | N 869 | | N 807 | | N 209 | | N 908 | | N 1264 |
| **TA** **(µmol kg $^{1}$)** | 2273.6 ±45.7 | 2112.4 - 2352.9 | 2056.7 ±161.8 | 565.4 - 2313.9 | 1951.9 ±198.9 | 595.3 - 2330.9 | 1621.9 ±532.8 | 65.0 - 2276.6 | 2202.5 ±104.2 | 1314.5 - 2325.5 | 2232.2 ±66.4 | 1953.6 - 2320.4 |
| | | N 639 | | N 487 | | N 506 | | N 182 | | N 522 | | N 633 |
| **DIC (µmol kg $^{1}$)** | 2078.0 ±43.7 | 1877.8- 2161.4 | 1897.0 ±154.1 | 606.2- 2236.7 | 1878.8 ±212.4 | 526.0 - 2514.8 | 1681.9 ±433.0 | 141.7 - 2147.1 | 2027.6 ±98.0 | 1257.8 - 2174.8 | 2048.2 ±89.7 | 1385.0 - 2215.1 |
| | | N 856 | | N 360 | | N 445 | | N 126 | | N 599 | | N 748 |
| **pH (Total scale)** | 8.2 ±0.1 | 8.1 - 8.3 | 8.2 ±0.1 | 7.9 - 8.5 | 8.1 ±0.1 | 7.9 - 8.3 | 8.0 ±0.2 | 7.6 - 8.3 | 8.1 ±0.1 | 7.8 - 8.3 | 8.2 ±0.1 | 8.0 - 8.4 |
| | | N 52 | | N 170 | | N 123 | | N 90 | | N 79 | | N 202 |
| **Discharge ($km^3$ $yr^{-1}$)** | <300 | | >100 | | >300 | | <2000 | | | | >1000 | |

Supplementary table 4. Literature examples of potential stressors in different Arctic regions. AiS= Atlantic influenced seas; PiS= Pacific influenced sea; RiS= River influenced seas; CAO= central Arctic ocean; OFS = Outflow shelf; DIC= dissolved inorganic carbon; TA= total alkalinity

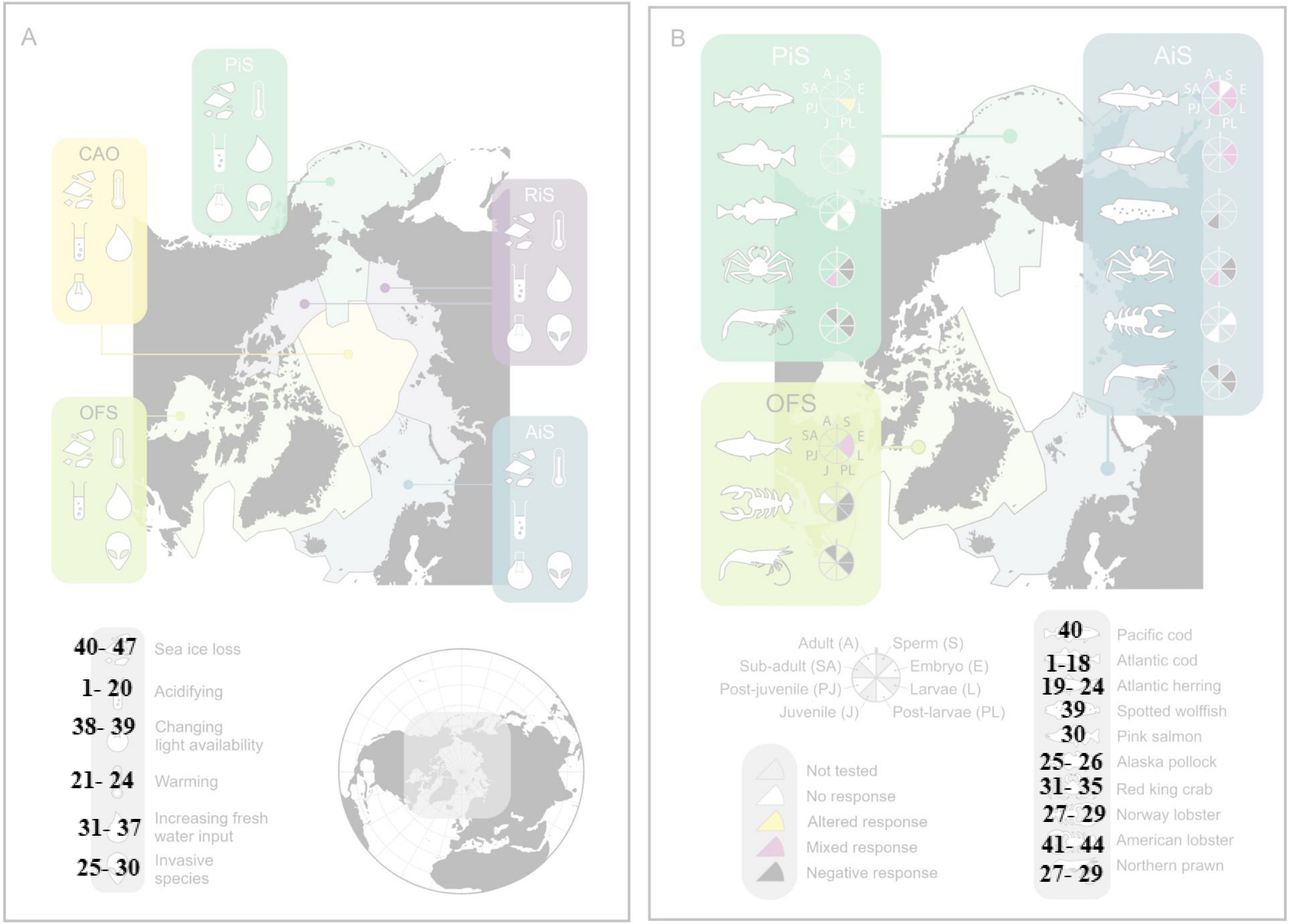
| **Figure1a reference map reference** | **Stressor** | **Region** | **Impact** | **Examples** |
|---|---|---|---|---|
| 1 | **Acidifying conditions** | CAO | From 1991-2011 DIC increased in the upper Polar Deep-Water layer and Arctic Atlantic Water layer by 0.4-0.6 µmol $kg^{-1}yr^{-1}$ and 0.6-0.9 µmol $kg^{-1}yr^{-1}$, respectively. | Ericson *et al.*, 2014 |
| 2 | | CAO | Undersaturation of aragonite in the Beaufort Gyre region of Canada Basin | Yamamoto-Kawai *et al.*, 2009 |
| 3 | | CAO | Rapid decrease between 2003- 2007 of aragonite saturation, declined by -0.09 $year^{-1}$ which is 10 times fast than other oceans. This was due to melting of sea ice which caused a large area to be exposed for gas exchange and decrease in buffering capacity of surface water due to a large influx of freshwater from the melting of sea ice. After 2007 it did not decline further. | Zhang, Yamamoto-Kawai, and Williams 2020 |
| 4 | | CAO | Both Makarov and Canada basins have shown a pH decrease of 0.05. | Woosley and Millero 2020 |
| 5 | | CAO | Summer $pCO_2$ increased at double the atmospheric rate in Canadian basin from 1994- 2017 | Ouyang et al. 2020 |
| 6 | | CAO | Undersaturation of aragonite | Jutterström and Anderson 2010 |
| 7 | | CAO, RiS | pH decreased by 0.02 - 0.055 units and aragonite saturation state declined by 0.05 – 0.18 units depending on area | Ulfsbo et al. 2018 |
| 8 | | OTF | Sub polar north Atlantic gyre was a $CO_2$ source in 2003 because of late summer bloom and high warming. Low TA found and $pCO_2$ increasing from 1993- 2003 | Corbière et al. 2007 |
| 9 | | RiS | Waters around the Mackenzie shelf in Beaufort Sea at depth around 100-150m pH 7.8 in August & September 2014 | Mol et al. 2018 |
| 10 | | RiS | Undersaturation of aragonite of Eastern Siberian shelf | Semiletov et al. 2016 |
| 11 | | RiS | Eastern shelf of Laptev Sea source of $CO_2$, high $pCO_2$ level of 650 µatm | Pipko, Pugach, and Semiletov 2016 |

| | | | | |
|---|---|---|---|---|
| 12 | | RiS | Low pH observed in the Mackenzie shelf region | Chierici and Fransson 2009 |
| 13 | | RiS | East Siberian Sea undersaturation of aragonite in bottom waters | Anderson et al. 2011; Semiletov et al. 2016 |
| 14 | | RiS | The Eastern Laptev Sea is already supersaturated with $CO_2$, and has been found to release $CO_2$ back into the atmosphere during the ice-free season | Pipko *et al.*, 2016 |
| 15 | | AiS | Iceland and Nordic Seas decreased pH and aragonite saturation from 1985 to 2008 | Olafsson et al. 2009 |
| 16 | | PiS | Bering Sea low aragonite saturation in bottom waters | Mathis, Cross, and Bates 2011 |
| 17 | | PiS | Chukchi Sea low aragonite saturation in bottom waters | Bates, Mathis, and Cooper 2009 |
| 18 | | PiS | Stratified conditions mean that bottom waters have been found to have acidified conditions with high $pCO_2$ and low aragonite saturation | Cross et al. 2018 |
| 19 | | PiS | Upwelling increased net $CO_2$ outgassing in Southern Bering Sea 1995-2001 | Fransson, Chierici, and Nojiri 2006 |
| 20 | | PiS | Low pH in bottom shelf water of waters of Chukchi sea, pH range from 7.66- 8.13 | Qi et al. 2020 |
| 21 | **Warming** | AiS | Water column warmed by 1.5 °C between 2000-2016 | Lind, Ingvaldsen, and Furevik 2018 |
| 22 | | AiS | 19-year study from 1982-2016 of the diet of Black-legged Kittiwake showed a shift from Arctic prey dominance to a more even spread of Arctic and Atlantic species | Vihtakari et al. 2018 |
| 23 | | AiS | Boreal fish moving in Barents Sea | Kortsch et al. 2015 |
| 24 | | Arctic wide | Winter temperature across the Arctic have risen between 1989 and 2016 | Screen 2017 |
| 25 | **Invasive species** | OFS | Increased shipping in the Canadian Arctic could introduce new invasive species to the area, model show that 8 modelled species have the potential to be successful in the area. | Goldsmit et al. 2018 |
| 26 | | OFS AiS PiS | Model out predict Hudson Bay, Labrador, Chukchi, Eastern Bering, Barents seas to be area with high numbers of invasive species under future scenarios of climate change | Goldsmit et al. 2020 |

| | | | | |
|---|---|---|---|---|
| 27 | | AiS PiS RiS | From 1960- 2015 54 non-native species were recorded across the regions, the highest number around the Iceland shelf | Chan et al. 2019 |
| 28 | | AiS | Pacific Arctic diatom *Neodenticula seminae* established in the Nordic Seas | Miettinen, Koç, and Husum 2013 |
| 29 | | AiS | Borealization of communities in Barents Sea | Fossheim et al. 2015 |
| 30 | | AiS | Invasive *Chionoecetes Opilio* Snow Crab in the Barents Sea | Kaiser, Kourantidou, and Fernandez 2018 |
| 31 | **Increased freshwater input** | RiS | Freshwater budget in Arctic are changing, increased runoff and less storage in multiyear ice. A dilution of TA reduces the buffering capacity of the ocean and affects the resultant carbonate chemistry. | Carmack, *et al.*, 2016 |
| 32 | | RiS | From 1936-1999 river discharge from 6 largest rivers (Kolyma, Lena, Yenisey, Ob', Pechora, Severenaya Dvina) increased by 7 % at average annual rate of 2.0 $km^3yr^{-1}$. | Peterson et al. 2002 |
| 33 | | CAO | Increased freshening in Canada and Makarov basins from 1994-2015 | Woosley and Millero 2020 |
| 34 | | PiS | Freshening of the PiS from the Yukon River | Andreev, Chen, and Sereda 2010 |
| 35 | | RiS | Increasing trend in discharge of the rivers Ob and Yenisey from 1930- 2016 | Polukhin 2019 |
| 36 | | RiS | Freshwater discharge increasing in East Siberian Arctic | Semiletov et al. 2016 |
| 37 | | OFS | Labrador Sea freshening | Zhang et al. 2021 |
| 38 | **Increased light availability** | CAO, RiS | Light penetrates through first year ice nearly 3 times as much as multi-year ice | Nicolaus et al. 2012 |
| 39 | | AiS, PiS | Increased visual search ability by 2.7- 4.2 % per decade due to sea ice retreat | Langbehn and Varpe 2017 |
| 40 | **Ice loss** | OTF | The Canadian Arctic Archipelagos have seen a decline in multi-year ice | Howell, Duguay, and Markus 2009 |
| 41 | | PiS, OTF, CAO, RiS | Between the years 1954-2010 30% of winters had temperatures higher than -5°C | Graham et al. 2017 |

| | | | |
|---|---|---|---|
| 42 | CAO | The largest sea ice loss is found in the Makarov and Canada basins | Woosley and Millero 2020 |
| 43 | RiS | Winter sea percentage cover reduced by the stratification of Eastern Eurasian Basin releasing heat reducing ice formation | Polyakov *et al.*, 2017 |
| 44 | Arctic wide | Area of open water increased from 1980-2010 in all months of the year | Barber et al. 2015 |
| 45 | Arctic wide | Sea ice cover declined from 1979-2016 | Dai et al. 2019 |
| 46 | AiS | Decline in Barents Sea ice cover from 1970-2016 | Lind, Ingvaldsen, and Furevik 2018 |
| 47 | AiS | From 1998-2008 ice cover declined by nearly 50 %, retreating in the Eastern Barents Sea by 240km | Årthun et al. 2012 |

**References for figure 1, numbers correspond to Supplementary table 4 and for A Supplementary table 1 for B**



A
PiS
CAO
RiS
OFS
AiS
40- 47
Sea ice loss
1- 20
Acidifying
38- 39
Changing light availability
21- 24
Warming
31- 37
Increasing fresh water input
25- 30
Invasive species
B
PiS
AiS
OFS
A S SA E PJ L J PL
Adult (A)
Sperm (S)
Sub-adult (SA)
Embryo (E)
Post-juvenile (PJ)
Larvae (L)
Juvenile (J)
Post-larvae (PL)
Not tested
No response
Altered response
Mixed response
Negative response
40
Pacific cod
1-18
Atlantic cod
19- 24
Atlantic herring
39
Spotted wolffish
30
Pink salmon
25- 26
Alaska pollock
31- 35
Red king crab
27- 29
Norway lobster
41- 44
American lobster
27- 29
Northern prawn

## 3.0 References


Anderson, L. G., Björk, G., Jutterström, S., Pipko, I., Shakhova, N., Semiletov, I., et al. (2011). East Siberian Sea, an Arctic region of very high biogeochemical activity. *Biogeosciences* 8, 1745–1754. doi:10.5194/bg-8-1745-2011.

Andreev, A. G., Chen, C. T. A., and Sereda, N. A. (2010). The distribution of the carbonate parameters in the waters of Anadyr Bay of the Bering Sea and in the western part of the Chukchi Sea. *Oceanology* 50, 39–50. doi:10.1134/S0001437010010054.

Arnberg, M., Calosi, P., Spicer, J. I., Tandberg, A. H. S., Nilsen, M., Westerlund, S., et al. (2013). Elevated temperature elicits greater effects than decreased pH on the development, feeding and metabolism of northern shrimp (*Pandalus borealis*) larvae. *Mar. Biol.* 160, 2037–2048. doi:10.1007/s00227-012-2072-9.

Årthun, M., Eldevik, T., Smedsrud, L. H., Skagseth, and Ingvaldsen, R. B. (2012). Quantifying the influence of atlantic heat on Barents sea ice variability and retreat. *J. Clim.* 25, 4736–4743. doi:10.1175/JCLI-D-11-00466.1.

Barber, D. G., Hop, H., Mundy, C. J., Else, B., Dmitrenko, I. A., Tremblay, J. E., et al. (2015). Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. *Prog. Oceanogr.* 139, 122–150. doi:10.1016/j.pocean.2015.09.003.

Bates, N. R., Mathis, J. T., and Cooper, L. W. (2009). Ocean acidification and biologically induced seasonality of carbonate mineral saturation states in the western Arctic Ocean. *J. Geophys. Res.* 114, 1–21. doi:10.1029/2008JC004862.

Bechmann, R. K., Taban, I. C., Westerlund, S., Godal, B. F., Arnberg, M., Vingen, S., et al. (2011). Effects of ocean acidification on early life stages of shrimp (*Pandalus borealis*) and mussel (*Mytilus edulis*). *J. Toxicol. Environ. Heal. - Part A Curr. Issues* 74, 424–438. doi:10.1080/15287394.2011.550460.

Carmack, E. C., Yamamoto-Kawai, M., Haine, T. W. N., Bacon, S., Bluhm, B. A., Lique, C., et al. (2016). Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. *J. Geophys. Res. G Biogeosciences* 121, 675–717. doi:10.1002/2015JG003140.

Carmack, E., and Wassmann, P. (2006). Food webs and physical-biological coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives. *Prog. Oceanogr.* 71, 446–477. doi:10.1016/j.pocean.2006.10.004.

Chan, F. T., Stanislawczyk, K., Sneekes, A. C., Dvoretsky, A., Gollasch, S., Minchin, D., et al. (2019). Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. *Glob. Chang. Biol.* 25, 25–38. doi:10.1111/gcb.14469.

Chierici, M., and Fransson, A. (2009). Calcium carbonate saturation in the surface water of the Arctic Ocean: undersaturation in freshwater influenced shelves. *Biogeosciences Discuss.* 6, 4963–4991. doi:10.5194/bgd-6-4963-2009.

Coffey, W. D., Nardone, J. A., Yarram, A., Long, W. C., Swiney, K. M., Foy, R. J., et al. (2017). Ocean acidification leads to altered micromechanical properties of the mineralized cuticle in juvenile red and blue king crabs. *J. Exp. Mar. Bio. Ecol.* 495, 1–12. doi:10.1016/j.jembe.2017.05.011.

Corbière, A., Metzl, N., Reverdin, G., Brunet, C., and Takahashi, T. (2007). Interannual and decadal variability of the oceanic carbon sink in the North Atlantic subpolar gyre. *Tellus, Ser. B Chem. Phys. Meteorol.* 59, 168–178. doi:10.1111/j.1600-0889.2006.00232.x.

Cross, J. N., Mathis, J. T., Pickart, R. S., and Bates, N. R. (2018). Formation and transport of corrosive water in the Pacific Arctic region. *Deep. Res. Part II* 152, 67–81. doi:10.1016/j.dsr2.2018.05.020.

Dahlke, F. T., Leo, E., Mark, F. C., Pörtner, H. O., Bickmeyer, U., Frickenhaus, S., et al. (2017). Effects of ocean acidification increase embryonic sensitivity to thermal extremes in Atlantic cod, *Gadus morhua*. *Glob. Chang. Biol.* 23, 1499–1510. doi:10.1111/gcb.13527.

Dai, A., Luo, D., Song, M., and Liu, J. (2019). Arctic amplification is caused by sea-ice loss under increasing $CO_2$. *Nat. Commun.* 10, 1–13. doi:10.1038/s41467-018-07954-9.

Dupont, S., Hall, E., Calosi, P., and Lundve, B. (2014). First Evidence of Altered Sensory Quality in a Shellfish Exposed to Decreased pH Relevant to Ocean Acidification. *J. Shellfish Res.* 33, 857–861. doi:10.2983/035.033.0320.

Ericson, Y., Ulfsbo, A., Heuven, S. van, Kattner, G., and Anderson, L. G. (2014). Increasing carbon inventory of the intermediate layers of the Arctic Ocean. *J. Geophys. Res. Ocean. Res.* 119, 2312–2326. doi:10.1002/2013JC009514.Received.

Findlay, H. S., Gibson, G., Kędra, M., Morata, N., Pavlov, A. K., Reigstad, M., et al. (2015). Responses in Arctic marine carbon cycle processes : conceptual scenarios and implications for ecosystem function. *Polar Res.* 34. doi:10.3402/polar.v34.24252.

Foss, A., Røsnes, B. A., and Øiestad, V. (2003). Graded environmental hypercapnia in juvenile spotted wolffish (*Anarhichas minor* Olafsen): Effects on growth, food conversion efficiency and nephrocalcinosis. *Aquaculture* 220, 607–617. doi:10.1016/S0044-8486(02)00613-0.

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., and Dolgov, A. V. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nat. Clim. Chang.* 5, 673–677. doi:10.1038/nclimate2647.

Franke, A., and Clemmesen, C. (2011). Effect of ocean acidification on early life stages of Atlantic herring (Clupea harengus L.).

*Biogeosciences* 8, 3697–3707. doi:10.5194/bg-8-3697-2011.

Fransson, A., Chierici, M., and Nojiri, Y. (2006). Increased net $CO_2$ outgassing in the upwelling region of the southern Bering Sea in a period of varible marine climate between 1995 and 2001. *J. Geophys. Res. Ocean.* 111, 1–21. doi:10.1029/2004JC002759.

Frommel, A., Maneja, R., Lowe, D., Pascoe, C., Geffen, A. J., Folkvord, A., et al. (2014). Organ damage in Atlantic herring larvae as a result of ocean acidification. *Ecol. Appl.* 24, 1131–1143.

Frommel, A. Y., Maneja, R., Lowe, D., Malzahn, A. M., Geffen, A. J., Folkvord, A., et al. (2012). Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. *Nat. Clim. Chang.* 2, 42–46. doi:10.1038/nclimate1324.

Frommel, A. Y., Schubert, A., Piatkowski, U., and Clemmesen, C. (2013). Egg and early larval stages of Baltic cod, *Gadus morhua*, are robust to high levels of ocean acidification. *Mar. Biol.* 160, 1825–1834. doi:10.1007/s00227-011-1876-3.

Frommel, A. Y., Stiebens, V., Clemmesen, C., and Havenhand, J. (2010). Effect of ocean acidification on marine fish sperm (Baltic cod: *Gadus morhua*). *Biogeosciences* 7, 3915–3919. doi:10.5194/bg-7-3915-2010.

Goldsmit, J., Archambault, P., Chust, G., Villarino, E., Liu, G., Lukovich, J. V., et al. (2018). Projecting present and future habitat suitability of ship-mediated aquatic invasive species in the Canadian Arctic. *Biol. Invasions* 20, 501–517. doi:10.1007/s10530-017-1553-7.

Goldsmit, J., McKindsey, C. W., Schlegel, R. W., Archambault, P., and Howland, K. L. (2020). What and where? Predicting invasion hotspots in the Arctic marine realm. *Glob. Chang. Biol.* doi:10.1111/gcb.15159.

Graham, R. M., Cohen, L., Petty, A. A., Boisvert, L. N., Rinke, A., Hudson, S. R., et al. (2017). Increasing frequency and duration of Arctic winter warming events. *Geophys. Res. Lett.* 44, 6974–6983. doi:10.1002/2017GL073395.

Harrington, A. M., and Hamlin, H. J. (2019). Ocean acidification alters thermal cardiac performance, hemocyte abundance, and hemolymph chemistry in subadult American lobsters *Homarus americanus* H. Milne Edwards, 1837 (Decapoda: Malcostraca: Nephropidae). *J. Crustac. Biol.* 39, 468–476. doi:10.1093/jcbiol/ruz015.

Hernroth, B., Krång, A. S., and Baden, S. (2015). Bacteriostatic suppression in Norway lobster (*Nephrops norvegicus*) exposed to manganese or hypoxia under pressure of ocean acidification. *Aquat. Toxicol.* 159, 217–224. doi:10.1016/j.aquatox.2014.11.025.

Howell, S. E. L., Duguay, C. R., and Markus, T. (2009). Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979-2008. *Geophys. Res. Lett.* 36, 2–7. doi:10.1029/2009GL037681.

Hu, M. Y., Michael, K., Kreiss, C. M., Stumpp, M., Dupont, S., Tseng, Y. C., et al. (2016). Temperature modulates the effects of ocean acidification on intestinal ion transport in Atlantic cod, *Gadus morhua*. *Front. Physiol.* 7, 1–18. doi:10.3389/fphys.2016.00198.

Hurst, T. P., Copeman, L. A., Haines, S. A., Meredith, S. D., Daniels, K., and Hubbard, K. M. (2019). Elevated $CO_2$ alters behavior, growth, and lipid composition of Pacific cod larvae. *Mar. Environ. Res.* 145, 52–65. doi:10.1016/j.marenvres.2019.02.004.

Hurst, T. P., Fernandez, E. R., and Mathis, J. T. (2013). Effects of ocean acidification on hatch size and larval growth of walleye pollock (*Theragra chalcogramma*). *ICES J. Mar. Sci.* 70, 812–822.

Hurst, T. P., Fernandez, E. R., Mathis, J. T., Miller, J. A., Stinson, C. M., and Ahgeak, E. F. (2012). Resiliency of juvenile walleye pollock to projected levels of ocean acidification. *Aquat. Biol.* 17, 247–259. doi:10.3354/ab00483.

Jutfelt, F., and Hedgärde, M. (2015). Juvenile Atlantic cod behavior appears robust to near-future $CO_2$ levels. *Front. Zool.* 12, 1–7. doi:10.1186/s12983-015-0104-2.

Jutterström, S., and Anderson, L. G. (2010). Uptake of $CO_2$ by the Arctic Ocean in a changing climate. *Mar. Chem.* 122, 96–104. doi:10.1016/j.marchem.2010.07.002.

Kaiser, B. A., Kourantidou, M., and Fernandez, L. (2018). A case for the commons: The Snow Crab in the Barents. *J. Environ. Manage.* 210, 338–348. doi:10.1016/j.jenvman.2018.01.007.

Keppel, E. A., Scrosati, R. A., and Courtenay, S. C. (2012). Ocean acidification decreases growth and development in American lobster (Homarus americanus) larvae. *J. Northwest Atl. Fish. Sci.* 44, 61–66. doi:10.2960/J.v44.m683.

Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A. V., and Aschan, M. (2015). Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proceeding R. Soc. Biol.* 282. doi:10.5061/dryad.73r6j.

Kreiss, C. M., Michael, K., Lucassen, M., Jutfelt, F., Motyka, R., Dupont, S., et al. (2015). Ocean warming and acidification modulate energy budget and gill ion regulatory mechanisms in Atlantic cod (Gadus morhua). *J. Comp. Physiol. B Biochem. Syst. Environ. Physiol.* 185, 767–781. doi:10.1007/s00360-015-0923-7.

Kunz, K. L., Frickenhaus, S., Hardenberg, S., Johansen, T., Leo, E., Pörtner, H. O., et al. (2016). New encounters in Arctic waters: a comparison of metabolism and performance of polar cod (*Boreogadus saida*) and Atlantic cod (*Gadus morhua*) under ocean acidification and warming. *Polar Biol.* 39, 1137–1153. doi:10.1007/s00300-016-1932-z.

Langbehn, T. J., and Varpe, Ø. (2017). Sea-ice loss boosts visual search: fish foraging and changing pelagic interactions in polar oceans. *Glob. Chang. Biol.* 23, 5318–5330. doi:10.1111/gcb.13797.

Leo, E., Kunz, K. L., Schmidt, M., Storch, D., Pörtner, H. O., and Mark, F. C. (2017). Mitochondrial acclimation potential to ocean acidification and warming of Polar cod (*Boreogadus saida*) and Atlantic cod (*Gadus morhua*). *Front. Zool.* 14, 1–12. doi:10.1186/s12983-017-0205-1.

Lind, S., Ingvaldsen, R. B., and Furevik, T. (2018). Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. *Nat. Clim. Chang.* 8, 634–639. doi:10.1038/s41558-018-0205-y.

Long, W. C., Pruisner, P., Swiney, K. M., and Foy, R. J. (2019). Effects of ocean acidification on the respiration and feeding of juvenile red and blue king crabs (*Paralithodes camtschaticus* and *P. platypus*). *ICES J. Mar. Sci.* 76, fsz090. doi:10.1093/icesjms/fsz090.

Long, W. C., Swiney, K. M., and Foy, R. J. (2013a). Effects of ocean acidification on the embryos and larvae of red king crab, *Paralithodes camtschaticus*. *Mar. Pollut. Bull.* 69, 38–47. doi:10.1016/j.marpolbul.2013.01.011.

Long, W. C., Swiney, K. M., Harris, C., Page, H. N., and Foy, R. J. (2013b). Effects of Ocean Acidification on Juvenile Red King Crab *(Paralithodes camtschaticus*) and Tanner Crab (*Chionoecetes bairdi*) Growth, Condition, Calcification, and Survival. *PLoS One* 8. doi:10.1371/journal.pone.0060959.

Malinauskaite, L., Cook, D., Davíðsdóttir, B., Ögmundardóttir, H., and Roman, J. (2019). Ecosystem services in the Arctic: a thematic review. *Ecosyst. Serv.* 36. doi:10.1016/j.ecoser.2019.100898.

Maneja, R. H., Dineshram, R., Thiyagarajan, V., Skiftesvik, A. B., Frommel, A. Y., Clemmesen, C., et al. (2014). The proteome of Atlantic herring (*Clupea harengus* L.) larvae is resistant to elevated p$CO_2$. *Mar. Pollut. Bull.* 86, 154–160. doi:10.1016/j.marpolbul.2014.07.030.

Maneja, R. H., Frommel, A. Y., Browman, H. I., Clemmesen, C., Geffen, A. J., Folkvord, A., et al. (2013a). The swimming kinematics of larval Atlantic cod, *Gadus morhua* L., are resilient to elevated seawater p$CO_2$. *Mar. Biol.* 160, 1963–1972. doi:10.1007/s00227-012-2054-y.

Maneja, R. H., Frommel, A. Y., Browman, H. I., Geffen, A. J., Folkvord, A., Piatkowski, U., et al. (2015). The swimming kinematics and foraging behavior of larval Atlantic herring (*Clupea harengus L*.) are unaffected by elevated p$CO_2$. *J. Exp. Mar. Bio. Ecol.* 466, 42–48. doi:10.1016/j.jembe.2015.02.008.

Maneja, R. H., Frommel, A. Y., Geffen, A. J., Folkvord, A., Piatkowski, U., Chang, M. Y., et al. (2013b). Effects of ocean acidification on the calcification of otoliths of larval Atlantic cod *Gadus morhua*. *Mar. Ecol. Prog. Ser.* 477, 251–258. doi:10.3354/meps10146.

Mathis, J. T., Cross, J. N., and Bates, N. R. (2011). Coupling primary production and terrestrial runoff to ocean acidification and carbonate mineral suppression in the eastern Bering Sea. *J. Geophys. Res. Ocean.* 116, 1–24. doi:10.1029/2010JC006453.

Melzner, F., Göbel, S., Langenbuch, M., Gutowska, M. A., Pörtner, H. O., and Lucassen, M. (2009). Swimming performance in Atlantic Cod (*Gadus morhua*) following long-term (4-12 months) acclimation to elevated seawater $PCO_2$. *Aquat. Toxicol.* 92, 30–37. doi:10.1016/j.aquatox.2008.12.011.

Menu-Courey, K., Noisette, F., Piedalue, S., Daoud, D., Blair, T., Blier, P. U., et al. (2019). Energy metabolism and survival of the juvenile recruits of the American lobster (*Homarus americanus*) exposed to a gradient of elevated seawater $pCO_2$. *Mar. Environ. Res.* 143, 111–123. doi:10.1016/j.marenvres.2018.10.002.

Miettinen, A., Koç, N., and Husum, K. (2013). Appearance of the Pacific diatom Neodenticula seminae in the northern Nordic Seas - An indication of changes in Arctic sea ice and ocean circulation. *Mar. Micropaleontol.* 99, 2–7. doi:10.1016/j.marmicro.2012.06.002.

Mittermayer, F. H., Stiasny, M. H., Clemmesen, C., Bayer, T., Puvanendran, V., Chierici, M., et al. (2019). Transcriptome profiling reveals exposure to predicted end-of-century ocean acidification as a stealth stressor for Atlantic cod larvae. *Sci. Rep.* 9. doi:10.1038/s41598-019-52628-1.

Mol, J., Thomas, H., Myers, P. G., Hu, X., and Mucci, A. (2018). Inorganic carbon fluxes on the Mackenzie Shelf of the Beaufort Sea. *Biogeosciences* 15, 1011–1027. doi:10.5194/bg-15-1011-2018.

Nicolaus, M., Katlein, C., Maslanik, J., and Hendricks, S. (2012). Changes in Arctic sea ice result in increasing light transmittance and absorption. *Geophys. Res. Lett.* 39, 1–6. doi:10.1029/2012GL053738.

Olafsson, J., Olafsdottir, S. R., Benoit-Cattin, A., Danielsen, M., Arnarson, T. S., and Takahashi, T. (2009). Rate of Iceland Sea acidification from time series measurements. *Biogeosciences* 6, 2661–2668. doi:10.5194/bg-6-2661-2009.

Ou, M., Hamilton, T. J., Eom, J., Lyall, E. M., Gallup, J., Jiang, A., et al. (2015). Responses of pink salmon to $CO_2$-induced aquatic acidification. *Nat. Clim. Chang.* 5, 950–957. doi:10.1038/nclimate2694.

Ouyang, Z., Qi, D., Chen, L., Takahashi, T., Zhong, W., Michael, D., et al. (2020). Sea-ice loss amplifies summertime decadal $CO_2$ increase in the western Arctic Ocean. *Nat. Clim. Chang.* 7, 195–199. doi:10.1038/nclimate3228.

Pauly D., Zeller D., M.L.D., P., and (Editors) (2020). Sea Around Us Concepts, Design and Data. Available at: seaaroundus.org.

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., et al. (2002). Increasing river discharge to the Arctic Ocean. *Science (80-. ).* 298, 2171–2173. doi:10.1126/science.1077445.

Pipko, I. I., Pugach, S. P., and Semiletov, I. P. (2016). Assessment of the $CO_2$ fluxes between the ocean and the atmosphere in the eastern part of the Laptev Sea in the ice-free period. *Dokl. Earth Sci.* 467, 398–401. doi:10.1134/S1028334X16040127.

Polukhin, A. (2019). The role of river runoff in the Kara Sea surface layer acidification and carbonate system changes. *Environ. Res. Lett.* doi:10.1088/1748-9326/ab421e.

Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., et al. (2017). Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science (80-. ).* 356, 285–291. doi:10.1126/science.aai8204.

Qi, D., Chen, B., Chen, L., Lin, H., Gao, Z., Sun, H., et al. (2020). Coastal acidification induced by biogeochemical processes driven by sea-ice melt in the western Arctic ocean. *Polar Sci.* 23. doi:10.1016/j.polar.2020.100504.

Schmidt, M., Windisch, H. S., Ludwichowski, K. U., Seegert, S. L. L., Pörtner, H. O., Storch, D., et al. (2017). Differences in neurochemical profiles of two gadid species under ocean warming and acidification. *Front. Zool.* 14, 1–13. doi:10.1186/s12983-017-0238-5.

Screen, J. A. (2017). Climate science: Far-flung effects of Arctic warming. *Nat. Geosci.* 10, 253–254. doi:10.1038/ngeo2924.

Semiletov, I., Pipko, I., Gustafsson, Ö., Anderson, L. G., Sergienko, V., Pugach, S., et al. (2016). Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. *Nat. Geosci.* 9, 361–365. doi:10.1038/ngeo2695.

Sswat, M., Stiasny, M. H., Jutfelt, F., Riebesell, U., and Clemmesen, C. (2018a). Growth performance and survival of larval Atlantic herring, under the combined effects of elevated temperatures and $CO_2$. *PLoS One* 13, 1–19. doi:10.1371/journal.pone.0191947.

Sswat, M., Stiasny, M. H., Taucher, J., Algueró-Muñiz, M., Bach, L. T., Jutfelt, F., et al. (2018b). Food web changes under ocean acidification promote herring larvae survival. *Nat. Ecol. Evol.* 2, 836–840. doi:10.1038/s41559-018-0514-6.

Stiasny, M. H., Mittermayer, F. H., Göttler, G., Bridges, C. R., Falk-Petersen, I. B., Puvanendran, V., et al. (2018). Effects of parental acclimation and energy limitation in response to high $CO_2$ exposure in Atlantic cod. *Sci. Rep.* 8, 1–8. doi:10.1038/s41598-018-26711-y.

Stiasny, M. H., Mittermayer, F. H., Sswat, M., Voss, R., Jutfelt, F., Chierici, M., et al. (2016). Ocean acidification effects on Atlantic cod larval survival and recruitment to the fished population. *PLoS One* 11, 1–11. doi:10.1371/journal.pone.0155448.

Stiasny, M. H., Sswat, M., Mittermayer, F. H., Falk-Petersen, I. B., Schnell, N. K., Puvanendran, V., et al. (2019). Divergent responses of

Atlantic cod to ocean acidification and food limitation. *Glob. Chang. Biol.* 25, 839–849. doi:10.1111/gcb.14554.

Styf, H. K., Nilsson Sköld, H., and Eriksson, S. P. (2013). Embryonic response to long-term exposure of the marine crustacean *Nephrops norvegicus* to ocean acidification and elevated temperature. *Ecol. Evol.* 3, 5055–5065. doi:10.1002/ece3.860.

Swiney, K. M., Long, W. C., and Foy, R. J. (2017). Decreased pH and increased temperatures affect young-of-theyear red king crab (*Paralithodes camtschaticus*). *ICES J. Mar. Sci.* 74, 1191–1200. doi:10.1093/icesjms/fsw251.

Ulfsbo, A., Rabe, B., Jones, E. M., Karcher, M., Casacuberta, N., Korhonen, M., et al. (2018). Rapid Changes in Anthropogenic Carbon Storage and Ocean Acidification in the Intermediate Layers of the Eurasian Arctic Ocean: 1996-2015. *Global Biogeochem. Cycles* 32, 1254–1275. doi:10.1029/2017gb005738.

Vihtakari, M., Welcker, J., Moe, B., Chastel, O., Tartu, S., Hop, H., et al. (2018). Black-legged kittiwakes as messengers of Atlantification in the Arctic. *Sci. Rep.* 8, 1–11. doi:10.1038/s41598-017-19118-8.

Waller, J. D., Wahle, R. A., McVeigh, H., and Fields, D. M. (2016). Linking rising $pCO_2$ and temperature to the larval development and physiology of the American lobster (*Homarus americanus*). *ICES J. Mar. Sci.* 74, 1210–1219. doi:10.1093/icesjms/fsw154.

Wood, H. L., Eriksson, S. P., Nordborg, M., and Styf, H. K. (2015). The effect of environmental stressors on the early development of the Norway lobster *Nephrops norvegicus* (L.). *J. Exp. Mar. Bio. Ecol.* 473, 35–42. doi:10.1016/j.jembe.2015.08.009.

Woosley, R. J., and Millero, F. J. (2020). Freshening of the western Arctic negates anthropogenic carbon uptake potential. *Limnol. Oceanogr.*, 1–13. doi:10.1002/lno.11421.

Yamamoto-Kawai, M., McLaughlin, F. A., Carmack, E. C., Nishino, S., and Shimada, K. (2009). Aragonite Undersaturation in the Arctic. *Science (80-. ).* 326, 1098–1100. Available at: http://www.ncbi.nlm.nih.gov/pubmed/19965425.

Zhang, J., Weijer, W., Steele, M., Cheng, W., Verma, T., and Veneziani, M. (2021). Labrador Sea freshening linked to Beaufort Gyre freshwater release. *Nat. Commun.* 12, 6–13. doi:10.1038/s41467-021-21470-3.

Zhang, Y., Yamamoto-Kawai, M., and Williams, W. J. (2020). Two Decades of Ocean Acidification in the Surface Waters of the Beaufort Gyre, Arctic Ocean: Effects of Sea Ice Melt and Retreat From 1997–2016. *Geophys. Res. Lett.* 47, 1–11. doi:10.1029/2019GL086421.