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Introduction

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The changing Arctic Ocean: consequences for biological communities, biogeochemical processes and ecosystem functioning

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1. Introduction

The Arctic region is undergoing some of the most rapid rates of climate change in the world [1], with dramatic transformations underway in terrestrial, coastal and offshore environments that have immediate and long-term consequences for socio-ecological systems (e.g. [2–5]). Significant changes in the type, extent and thickness of ice cover [6], meltwater input [7] and water mass dynamics [8], coupled with warming and ocean acidification [9], have already begun to impact ecosystem processes and the flora and fauna that inhabit a range of Arctic habitats [10]. The pace of change is such that our understanding of the way in which Arctic systems are structured and function is outdated, and insufficient to inform management, mitigation and adaptation efforts across the region [11,12]. Projections indicate that, even if global stabilization of temperature below 1.5°C is realized, changes will continue to manifest over an extended period, perhaps even millennial timescales [13] and may include unprecedented shifts in structure [14]. Changes to key components of Arctic ecosystems are already occurring, yet the collated evidence of how changes to baseline conditions are proceeding across the Arctic Ocean is still poorly constrained [15], focused on a limited number of exemplar areas [16], and seldom adopts a holistic view that begins to provide a nuanced understanding of the *modus operandi* of the Arctic [17]. This is concerning because informed decision- and policy-making benefits from a broad understanding of system dynamics, including feedbacks and the likelihood of ecological surprises [18], yet the focus of study is already shifting from the natural sciences to social sciences and humanities to meet legislative and policy demands [19]. Now more than ever, foundational concepts and evidence are needed to support sustainable management and policy, preferably with a focus on continually acquiring, interpreting and applying new interdisciplinary knowledge to enhance understanding [20].

2. New evidence and emerging themes

With the recognition of the complexity of system dynamics comes a need to synthesize evidence on how climatic forcing is changing the fundamentals of the system. It was within this spirit that this thematic section was commissioned, with interdisciplinary contributions from a range of active national and international research programmes. In doing so, we did not seek to represent all active areas of Arctic science, nor was it the intention to produce a comprehensive overview of specific topics of interest, rather our motivation was to highlight some of the emerging themes and evidence, stimulate discussion and expedite insight. The contributions received consider the mechanistic basis and consequences of change over a variety of spatio-temporal scales and for a number of different Arctic regions and form three research clusters: the water column, seasonality and benthic–pelagic coupling. Here, we briefly introduce the contributed papers within the context of the wider literature before offering some observations on the salient research deficiencies, challenges and opportunities that show promise in establishing a practical research agenda.

(a) The water column

The waters of the Arctic Ocean respond quickly and in multiple ways to changing forcing parameters, including changes in freshwater input from land, modulations of ocean currents and water mass distribution, and shorter and more dispersed sea ice cover [8]. Of particular interest are processes in the shallowest part of the Arctic Ocean, the photic zone, where changes in primary productivity and ecosystem dynamics are expected to have significant effects on carbon sequestration from the atmosphere. The photic zone is affected most directly by changing sea ice conditions, increasing light availability, as well as stratification and nutrient limitation. A better understanding of plankton ecology and biogeochemical processes in the photic zone is therefore of critical importance to understand the role of a future Arctic Ocean as a potential atmospheric carbon sink. In this respect, the extent to which under-ice algal blooms contribute to primary production in the Arctic Ocean has become a highly topical issue (e.g. [21,22]). Bouman *et al*. [23] use a spectrally resolved model of primary production to identify the set of conditions under which subsurface chlorophyll maxima contribute to water column productivity, a key feature that escapes detection by satellites. They conclude that the uneven distribution and sparsity of chlorophyll measurements in the Arctic Ocean mean that the common practice of spatial and temporal averaging of profile data underestimates the importance of subsurface chlorophyll maxima. Next, Kostakis *et al*. [24] study a multitude of biogeochemical parameters in the Barents Sea water column under different ice conditions using a glider system, a technology capable of covering wide areas of the ocean autonomously and complementary to satellite-derived data. Using these data, they develop and test a bio-optical model that links commonly measured parameters from glider-mounted sensors with satellite-derived measurements of bulk optical properties. Combining satellite data with discrete shipboard measurements, Orkney *et al*. [25] adopt a similar philosophy to highlight the northward migration of certain phytoplanktonic groups (especially *Phaeocystis* algae) in the Barents Sea. They confirm previous suggestions of a north-eastward expansion in coccolithophore blooms and suggest that observations of increased levels of chlorophyll *a* in the region may, at least in part, be explained by increasing frequencies of *Phaeocystis* blooms. Finally, Noethig *et al*. [26] use sediment traps to quantify the export of different biogenic particles from the photic zone into the deeper waters of the Arctic Ocean, a crucial aspect of pelagic-benthic coupling needed to move fixed carbon from shallow to deep waters and, ultimately, to the seafloor—and a process that is currently impossible to resolve using remote sensing technology, and poorly constrained by most models. They observe negligible export fluxes of particulate matter and biomarkers during the Polar Night, but an increase in export fluxes under reduced sea ice cover during the summer reflecting enhanced primary production. However, they also find that export fluxes of particulate matter in the Nansen and Amundsen basins decrease with depth, indicating a strong degradation of organic matter in Arctic surface waters.

(b) Seasonality

Perhaps the most characteristic feature of the Arctic region is the intense seasonality in physical, chemical and biological features, both on land and in the sea. This seasonality results in pulses of primary productivity that largely sustain ecosystems for the entire year. Warmer air and water temperatures, however, affect timing of ecological processes via changing phenologies of plants and animals, migration/advection patterns of predators and prey, and community composition as Arctic species are replaced by advancing southern taxa [27–30]. These changes can have substantial implications for ecosystem functioning by altering carbon drawdown and storage, trophic interactions, nutrient cycling and the integrity of Arctic assemblages. Here, Henley *et al*. [31] document seasonal availability of nitrate in the surface ocean on the northern Barents Sea shelf. They show that, while availability varies little between ice-covered and ice-free locations, the productivity season in ice-free waters is extended by advection of nutrients in Atlantic waters. Increased Atlantification in the region could contribute to prolonged uptake of atmospheric carbon in a warming Arctic. Von Jackowski *et al*. [32] investigate bacterioplankton dynamics that are affected by changes in the organic matter pool. They show that seasonal patterns in pelagic primary production affect availability of dissolved organic matter (DOM), and the availability of substrate has a greater impact on bacterial activity than increasing temperature. Further, as Tisserand *et al*. [33] show, algal community composition determines the lability of DOM available for bacterial growth, and the bacterial strains that are most effective at its cycling. Thus, complex relationships within the microbial community and at the base of the food web may be profoundly altered by changes in seasonality of nutrient supply and algal community structure. The fate of fixed carbon is tightly linked to climate feedback mechanisms via sedimentary processes, such as bioturbation. Solan *et al*. [34] examine how invertebrate faunal activity and associated ecosystem functioning is influenced by seasonal ice cover that affects food supply to the seafloor, and by mesoscale oceanographic features that influence benthic community structure. Their experiments, conducted over two consecutive summers along a transect intersecting the Barents Sea Polar Front, reveal that while faunal composition reflects proximity to Arctic versus boreal conditions, faunal activity is moderated by seasonal variations in sea ice extent that influence food supply to the benthos. In a recently ice-free Arctic fjord, however, Morata *et al*. [35] document a reduction in seasonality in bioturbation and benthic carbon cycling, although nutrient fluxes retain a strong seasonal signal. These authors suggest that increased detrital carbon dampens the seasonal carbon signal from pelagic phytoplankton. In the only time-series study in this themed section capable of detecting climate-related changes, Al-Habahbeh *et al*. [36] report slow recovery times from disturbance and abrupt shifts in community structure for two shallow hard-bottom communities and conclude, based on trait analyses, that Arctic systems may be particularly vulnerable to climate-related perturbations. Food–web interactions in the Arctic are highly influenced by seasonal migrations of both predators and prey. Hutchison *et al*. [37] incorporate migration into a food–web model and find better approximation of predator-prey cycles than when a static model is used. Seasonal and interannual variability, therefore, modifies processes at the base of the food chain, with consequent effects through microbial and faunal processing, up to trophic interactions reaching top predators. Recent studies have indicated that the seasonal paradigms of the Arctic are not so straightforward as once thought (e.g. [38]), and climate change is likely to further alter perspectives as communities and their functioning respond to multiple changing drivers.

(c) Benthic–pelagic coupling

Benthic–pelagic coupling plays a major role in determining the production, biological structure and food web stability of both systems [39]. This coupling is often stronger in shallower areas compared to deeper areas, due to the shorter distance between the productive, euphotic zone and the benthic realm [40]. However, in northern Baffin Bay, Olivier *et al*. [41], using a bivalve, provide evidence of a strong benthic–pelagic coupling to 600 m depths. They identify a clear shift in bivalve growth variation since the late 1970s related to food supply. Over the last half-century, a more regular export of diatoms from the euphotic zone may have increased food supply to the benthos. Two hypotheses are possible to explain a more regular export of food supply: the potential temporal or spatial mismatch between the phytoplankton bloom and its pelagic consumers, and/or local changes in sea ice dynamics that moderate phytoplankton production. Climate change leading to ice loss could result in major gains in stored (probably sequestered) carbon at the shelf seafloor adjacent to parts of Antarctica [42]. Here, Souster *et al*. [43] compare the stocks of zoobenthic blue carbon between the Barents Sea and shelf seas of the Western Antarctic Peninsula. They find that the blue carbon stock of the Barents Sea is twice that of the Antarctic soft sediment shelf and could have great potential for increased carbon drawdown. Their results highlight the need to investigate zoobenthic blue carbon in the Arctic to better inform global estimates of carbon budgets and climate feedbacks. Along these lines, Faust *et al*. [44] explore how ongoing changes in the Barents Sea will change the organic and inorganic sediment composition in the future. Their results, based on comparisons between the seasonally ice-covered north and permanently ice-free south Barents Sea, imply that continuing sea ice reduction and the associated modification of vertical carbon fluxes might create shifts in surface sedimentary organic carbon content which, in turn, may result in overall reduced carbon sequestration. As the sea ice reduction will continue northward and modify the ocean primary production, patterns of the benthic–pelagic phosphorus cycle are also likely to change. By comparing sediments and porewaters from the Barents Sea slope and the Yermak Plateau, Tessin *et al.* [45] conclude that increased delivery of labile organic matter in response to elevated surface productivity will increase the oxidant demand and Fe remobilization within sediments and cause the Yermak Plateau to shift towards the conditions observed in the Barents Sea slope. Increased organic carbon fluxes on the Barents Sea slope may result in large fluxes of P from sediments to bottom waters, as a large stock of P has been accumulated in surface sediments. Stevenson *et al*. [46] demonstrate mechanistic links between microbial processing and changes in organic and inorganic parameters that are coupled to biological mixing and the reactivity of organic material. They find direct links between aerobic processes, reactive organic carbon and highest abundances of bacteria and archaea in the uppermost sediment layer followed by dominance of microbes involved in nitrate/nitrite and iron/manganese reduction across the oxic-anoxic redox boundary and sulphate reducers at depth. Using an original approach, Freitas *et al*. [47] combine field observations from the Barents Sea with a Reaction-Transport model to quantify organic matter processing and its drivers. Their results indicate that, at sites influenced by Atlantic Water, there is a clear burial of highly reactive marine derived organic matter. This allows them to establish a baseline systematic understanding of seafloor geochemistry, helping to anticipate likely modifications linked to future climatic scenarios in the Arctic. From all these studies, it is clear that ice reduction, alongside other components of climate change, affects the underlying seafloor without significant delay and plays a central role in moderating and redefining benthic–pelagic coupling processes.

3. Research priorities

By focusing on distinguishing natural variation and/or localized responses from long-term regional climatic forcing, the contributions in this thematic issue provide a sensible focus for new innovative science in the immediate future. While we acknowledge that the conclusions drawn here are not based on a comprehensive review and gap analysis of the wider literature, it is clear that contrasting regional responses to climate change across multiple seasons and locations are informative and, when taken together, can hasten understanding. Based on this overview, and in no particular order of importance, we offer the following observations in the hope they will stimulate debate and novel lines of inquiry:

1. *Value basic discovery and observational science, museum collections and historical archives and use this repository of information and perspectives to inform hypothesis driven investigation.*
   A cursory look at the literature cited by the contributors to this theme reveals that phenomenological observations are common and well-articulated, reflecting major investments in the recent past that stimulated much effort in establishing the basic science of the Arctic region. Emphasis is now needed to move beyond confirmatory observation and towards interrogation of system complexities, including unambiguous experimental demonstration of key mechanisms in the absence of confounding or collinear factors.
2. *Undertake diversification in the gathering of knowledge and evidence while adopting a holistic pan-Arctic view.*
   The major geographical and seasonal bias in knowledge needs to be addressed by diverting effort away from regionally and/or temporally constrained study and focusing on testing the generality of observations, theory and/or conceptual advances. Historical compartmentalization of disciplines [48] has compounded this problem as there are large gaps in understanding about the extent to which different landscapes are interconnected [49].
3. *Remove over-reliance on infrequent occupancy by embracing new technology, including cultural knowledge, satellite-derived information and autonomous systems, while extending ground-truthing and calibration efforts.*
   Synoptic efforts are required to routinely gather information at large scales and across all seasons, with a view to understanding system generalities and localized exceptions. Effort will be needed to expand capability beyond the current subset of variables and to employ novel complex-system approaches to identify inter-linkages and distinguish natural variability from directional change. Such efforts will need thorough interrogation, even relatively well-established parameters like chlorophyll concentrations in relatively accessible marginal parts of the Arctic Ocean require a more detailed deconvolution.
4. *Establish detailed unambiguous understanding of the vulnerability and/or resilience of Arctic species and ecosystems to the type, timing, sequence and combination of multiple drivers of change.*
   Most projections of the fate of Arctic species, ecosystems and associated levels of ecosystem functioning are based on assumed or extrapolated responses to change. There is little empirical backing for assumptions made, and little attention has been devoted to establishing the relative importance of the different components, or properties, of directional forcing (e.g. [40,50,51]).
5. *Divert effort from using bulk or integrative indicators of ecosystem response towards establishing specific mechanistic understanding of how and when specific drivers of change operate.*
   While various measures of ecosystem response are accepted and routinely used, the relative roles of specific pathways or components that underpin the bulk signal are less known, but have been summarized [52]. For carbon, for example, which degradation pathways are important, what type of carbon matters, and what are the relative roles of deposition versus burial? [53] Further, the adequacy and utility of methods for measuring and assessing the stocks and flows of various aspects of ecosystem responses have received little attention [54–56].

6. *Transition from documenting negative impacts of change to formulating a socio-ecological, solution-based narrative that will be effective in providing evidence to support decision and policy making across the Arctic.*
   Very little attention has been devoted to formulating an integrated sustainable management plan for the Arctic, or to determining which evidence is needed to support decision and policy making. Indeed, a solution-based narrative is not well-developed for the marine benthos [57], and there are virtually no socio-economic studies for the Arctic [58,59]. Approaches involving multiple disciplines that mobilize and build on indigenous and local knowledge are urgently required [16,60], but need to be supplemented by socio-ecological contributions to aid understanding of system dynamics.

4. Conclusion

Understanding the consequences of climate change and anthropogenic activity in the Arctic requires a multi-faceted approach and, as the contributions in this themed issue indicate, there has been significant progression in a number of areas. However, it is clear that Arctic science is undergoing a transition from observational and phenomenological documentation to interrogative empirical research aimed at developing theory and mechanistic understanding. Recent availability of national and international funding has fuelled this evolution, and the extensive use of observing technology, coupled with the extended occupancy time of field researchers within the Arctic, is allowing new insights about seasonal dynamics and processes that occur over larger spatial scales. Nevertheless, investigations remain regionally constrained and compartmentalized within disciplines or domains, although an integrative comprehension is beginning to materialize. Our brief analysis here, albeit limited in scope, suggests a developing directional change in research foci towards an interdisciplinary research agenda focused on understanding how whole system changes lead to alternative outcomes. Achieving this research agenda will require the merger of perspectives, scaling up of data acquisition and analysis, and pooled initiatives that pursue the mechanistic basis of consequential change for biological communities, biogeochemical processes and ecosystems. For the moment, as this themed section illustrates, compiling new and existing data, and taking advantage of state-of-the-art models and adopting upscaling approaches, allows generalities to be established about how Arctic systems respond to perturbation. As new data become available, model-data comparisons will highlight areas of divergence, allowing refinement of hypotheses and data needs, while field data and experiments will provide mechanistic information to enable the re-parameterization of models to reflect new understanding of system complexity. It will be important to implement this knowledge to identify thresholds and feedbacks, minimize uncertainty and provide evidence/advice for prioritizing mitigation and/or adaptation needs as the expression of climate change intensifies.

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References

1. Burrows MT *et al.* 2011 The pace of shifting climate in marine and terrestrial ecosystems. *Science* **334**, 652–655. (doi:10.1126/science.1210288)

2. Carmack E, 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)
3. Lafrenière MJ, Lamoureux SF. 2019 Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. *Earth Sci. Rev.* **191**, 212–223. (doi:10.1016/j.earscirev.2019.02.018)
4. Meier WN *et al.* 2014 Arctic sea ice in transformation: a review of recent observed changes and impacts on biology and human activity. *Rev. Geophys.* **52**, 185–217. (doi:10.1002/2013rg000431)
5. Ruscio BA, Brubaker M, Glasser J, Hueston W, Hennessy TW. 2015 One Health – a strategy for resilience in a changing arctic. *Int. J. Circumpolar Health* **74**, 27913. (doi:10.3402/ijch.v74.27913)
6. Stroeve J, Notz D. 2018 Changing state of Arctic sea ice across all seasons. *Environ. Res. Lett.* **13**, 103001. (doi:10.1088/1748-9326/aade56)
7. Haine TWN *et al.* 2015 Arctic freshwater export: Status, mechanisms, and prospects. *Glob. Planet. Change* **125**, 13–35. (doi:10.1016/j.gloplacha.2014.11.013)
8. Timmermans M, Marshall J. 2020 Understanding Arctic ocean circulation: a review of ocean dynamics in a changing climate. *J. Geophys. Res. Oceans* **125**, e2018JC014378. (doi:10.1029/2018jc014378)
9. Terhaar J, Kwiatkowski L, Bopp L. 2020 Emergent constraint on Arctic Ocean acidification in the twenty-first century. *Nature* **582**, 379–383. (doi:10.1038/s41586-020-2360-3)
10. Jørgensen LL, Primicerio R, Ingvaldsen RB, Fossheim M, Strelkova N, Thangstad TH, Manushin I, Zakharov D. 2019 Impact of multiple stressors on sea bed fauna in a warming Arctic. *Mar. Ecol. Prog. Ser.* **608**, 1–12. (doi:10.3354/meps12803)
11. Fidler C, Noble BF. 2013 Advancing regional strategic environmental assessment in Canada's Western Arctic: implementation opportunities and challenges. *J. Environ. Assess. Policy Manage.* **15**, 1350007. (doi:10.1142/s1464333213500075)
12. Vogel B, Bullock RCL. 2020 Institutions, indigenous peoples, and climate change adaptation in the Canadian Arctic. *GeoJournal* (doi:10.1007/s10708-020-10212-5)
13. Nicholls RJ *et al.* 2018 Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Phil. Trans. R. Soc. A* **376**, 20160448. (doi:10.1098/rsta.2016.0448)
14. Beaugrand G *et al.* 2019 Prediction of unprecedented biological shifts in the global ocean. *Nat. Clim. Change* **9**, 237–343. (doi: 10.1038/s41558-019-0420-1)
15. Bjorkman AD *et al.* 2019 Status and trends in Arctic vegetation: Evidence from experimental warming and long-term monitoring. *Ambio* **49**, 678–692. (doi:10.1007/s13280-019-01161-6)
16. Falardeau M, Bennett EM. 2020 Towards integrated knowledge of climate change in Arctic marine systems: a systematic literature review of multidisciplinary research. *Arctic Sci.* **6**, 1–23. (doi:10.1139/as-2019-0006)
17. Taylor JJ *et al.* 2020 Arctic terrestrial biodiversity status and trends: a synopsis of science supporting the CBMP State of Arctic Terrestrial Biodiversity Report. *Ambio* **49**, 833–847. (doi:10.1007/s13280-019-01303-w)
18. Wookey PA *et al.* 2009 Ecosystem feedbacks and cascade processes: understanding their role in the responses of Arctic and alpine ecosystems to environmental change. *Glob. Change Biol.* **15**, 1153–1172. (doi:10.1111/j.1365-2486.2008.01801.x)
19. Biresselioglu ME, Demir MH, Solak B, Kayacan A, Altinci S. 2020 Investigating the trends in arctic research: the increasing role of social sciences and humanities. *Sci. Total Environ.* **729**, 139027. (doi:10.1016/j.scitotenv.2020.139027)
20. Malinauskaite L, Cook D, Davíðsdóttir B, Ögmundardóttir H, Roman J. 2019 Ecosystem services in the Arctic: a thematic review. *Ecosyst. Services* **36**, 100898. (doi:10.1016/j.ecoser.2019.100898)
21. Horvat C, Rees Jones D, Iams S, Schroeder D, Flocco D, Feltham D. 2017 The frequency and extent of sub-ice phytoplankton blooms in the Arctic Ocean. *Sci. Adv.* **3**, e1601191 (doi:10.1126/sciadv.1601191)
22. Johnsen G *et al.* 2018 The advective origin of an under-ice spring bloom in the Arctic Ocean using multiple observations platforms. *Polar Biol.* **41**, 1197–1216 (doi:10.1007/s00300-018-2278-5)
23. Bouman HA, Jackson T, Sathyendranath S, Platt T. 2020 Vertical structure in chlorophyll profiles: influence on primary production in the Arctic Ocean. *Phil. Trans. R. Soc. A* **378**, 20190351. (doi:10.1098/rsta.2019.0351)

24. Kostakis I, Röttgers R, Orkney A, Bouman HA, Porter M, Cottier F, Berge J, McKee D. 2020 Development of a bio-optical model for the Barents Sea to quantitatively link glider and satellite observations. *Phil. Trans. R. Soc. A* **378**, 20190367. (doi:10.1098/rsta.2019.0367)
25. Orkney A, Platt T, Narayanaswamy BE, Kostakis I, Bouman HA. 2020 Bio-optical evidence for increasing *Phaeocystis* dominance in the Barents Sea. *Phil. Trans. R. Soc. A* **378**, 20190357. (doi:10.1098/rsta.2019.0357)
26. Nöthig E-M, Lalande C, Fahl K, Metfies K, Salter I, Bauerfeind E. 2020 Annual cycle of downward particle fluxes on each side of the Gakkel Ridge in the central Arctic Ocean. *Phil. Trans. R. Soc. A* **378**, 20190368. (doi:10.1098/rsta.2019.0368)
27. Clairbaux M, Fort J, Mathewson P, Porter W, Strøm H, Grémillet D. 2019 Climate change could overturn bird migration: Transarctic flights and high-latitude residency in a sea ice free Arctic. *Sci. Rep.* **9**, 17767. (doi:10.1038/s41598-019-54228-5)
28. Frainer A, Primicerio R, Kortsch S, Aune M, Dolgov AV, Fossheim M, Aschan MM. 2017 Climate-driven changes in functional biogeography of Arctic marine fish communities. *Proc. Natl Acad. Sci. USA* **114**, 12 202–12 207. (doi:10.1073/pnas.1706080114)
29. Post E. 2017 Implications of earlier sea ice melt for phenological cascades in arctic marine food webs. *Food Webs* **13**, 60–66. (doi:10.1016/j.fooweb.2016.11.002)
30. Wassmann P, Slagstad D, Ellingsen I. 2019 Advection of Mesozooplankton Into the Northern Svalbard Shelf Region. *Front. Mar. Sci.* **6**, 458. (doi:10.3389/fmars.2019.00458)
31. Henley SF, Porter M, Hobbs L, Braun J, Guillaume-Castel R, Venables EJ, Dumont E, Cottier F. 2020 Nitrate supply and uptake in the Atlantic Arctic sea ice zone: seasonal cycle, mechanisms and drivers. *Phil. Trans. R. Soc. A* **378**, 20190361. (doi:10.1098/rsta.2019.0361)
32. von Jackowski A, Grosse J, Nöthig E-M, Engel A. 2020 Dynamics of organic matter and bacterial activity in the Fram Strait during summer and autumn. *Phil. Trans. R. Soc. A* **378**, 20190366. (doi:10.1098/rsta.2019.0366)
33. Tisserand L, Dadaglio L, Intertaglia L, Catala P, Panagiotopoulos C, Obernosterer I, Joux F. 2020 Use of organic exudates from two polar diatoms by bacterial isolates from the Arctic Ocean. *Phil. Trans. R. Soc. A* **378**, 20190356. (doi:10.1098/rsta.2019.0356)
34. Solan M, Ward ER, Wood CL, Reed AJ, Grange LJ, Godbold JA. 2020 Climate-driven benthic invertebrate activity and biogeochemical functioning across the Barents Sea polar front. *Phil. Trans. R. Soc. A* **378**, 20190365. (doi:10.1098/rsta.2019.0365)
35. Morata N, Michaud E, Poullaouec M-A, Devesa J, Le Goff M, Corvaisier R, Renaud PE. 2020 Climate change and diminishing seasonality in Arctic benthic processes. *Phil. Trans. R. Soc. A* **378**, 20190369. (doi:10.1098/rsta.2019.0369)
36. Al-Habahbeh AK, Kortsch S, Bluhm BA, Beuchel F, Gulliksen B, Ballantine C, Cristini D, Primicerio R. 2020 Arctic coastal benthos long-term responses to perturbations under climate warming. *Phil. Trans. R. Soc. A* **378**, 20190355. (doi:10.1098/rsta.2019.0355)
37. Hutchison C, Guichard F, Legagneux P, Gauthier G, Bêty J, Berteaux D, Fauteux D, Gravel D. 2020 Seasonal food webs with migrations: multi-season models reveal indirect species interactions in the Canadian Arctic tundra. *Phil. Trans. R. Soc. A* **378**, 20190354. (doi:10.1098/rsta.2019.0354)
38. Berge J, Johnsen G, Cohen JH (eds). 2020 Polar Night. Marine ecology. Life and light in the dead of night. Advances in Polar Ecology 4. Berlin, Germany: Springer International Publishing. (https://www.springer.com/gp/book/9783030332075)
39. Griffiths JR *et al.* 2017 The importance of benthic-pelagic coupling for marine ecosystem functioning in a changing world. *Glob. Change Biol.* **23**, 2179–2196. (doi:10.1111/gcb.13642)
40. Roy V, Iken K, Archambault P. 2014 Environmental drivers of the Canadian Arctic Megabenthic Communities. *PLoS ONE* **9**, e100900. (doi:10.1371/journal.pone.0100900)
41. Olivier F *et al.* 2020 Shells of the bivalve *Astarte moerchi* give new evidence of a strong pelagic-benthic coupling shift occurring since the late 1970s in the North Water polynya. *Phil. Trans. R. Soc. A* **378**, 20190353. (doi:10.1098/rsta.2019.0353)
42. Barnes DKA. 2017 Polar zoobenthos blue carbon storage increases with sea ice losses, because across-shelf growth gains from longer algal blooms outweigh ice scour mortality in the shallows. *Glob. Change Biol.* **23**, 5083–5091. (doi:10.1111/gcb.13772)
43. Souster TA, Barnes DKA, Hopkins J. 2020 Variation in zoobenthic blue carbon in the Arctic's Barents Sea shelf sediments. *Phil. Trans. R. Soc. A* **378**, 20190362. (doi:10.1098/rsta.2019.0362)

44. Faust JC, Stevenson MA, Abbott GD, Knies J, Tessin A, Mannion I, Ford A, Hilton R, Peakall J, März C. 2020 Does Arctic warming reduce preservation of organic matter in Barents Sea sediments? *Phil. Trans. R. Soc. A* **378**, 20190364. (doi:10.1098/rsta.2019.0364)
45. Tessin A, März C, Kędra M, Matthiessen J, Morata N, Nairn M, O'Regan M, Peeken I. 2020 Benthic phosphorus cycling within the Eurasian marginal sea ice zone. *Phil. Trans. R. Soc. A* **378**, 20190358. (doi:10.1098/rsta.2019.0358)
46. Stevenson MA *et al.* 2020 Transformation of organic matter in a Barents Sea sediment profile: coupled geochemical and microbiological processes. *Phil. Trans. R. Soc. A* **378**, 20200223. (doi:10.1098/rsta.2020.0223)
47. Freitas FS, Hendry KR, Henley SF, Faust JC, Tessin AC, Stevenson MA, Abbott GD, März C, Arndt S. 2020 Benthic-pelagic coupling in the Barents Sea: an integrated data-model framework. *Phil. Trans. R. Soc. A* **378**, 20190359. (doi:10.1098/rsta.2019.0359)
48. Raffaelli D, Solan M, Webb TJ. 2005 Do marine and terrestrial ecologists do it differently? *Mar. Ecol. Prog. Ser.* **304**, 283–289
49. Ward ND, Bianchi TS, Medeiros PM, Seidel M, Richey JE, Keil RG, Sawakuchi HO. 2017 Where carbon goes when water flows: carbon cycling across the aquatic continuum. *Front. Mar. Sci.* **4**, 7. (doi:10.3389/fmars.2017.00007)
50. Seifollahi-Aghmiuni S, Kalantari Z, Land M, Destouni G. 2019 Change Drivers and Impacts in Arctic Wetland Landscapes—Literature Review and Gap Analysis. *Water* **11**, 722. (doi:10.3390/w11040722)
51. Renaud PE, Wallhead P, Kotta J, Włodarska-Kowalczuk M, Bellerby RGJ, Rätsep M, Slagstad D, Kukliński P. 2019 Arctic Sensitivity? Suitable Habitat for Benthic Taxa Is Surprisingly Robust to Climate Change. *Front. Mar. Sci.* **6**, 538. (doi:10.3389/fmars.2019.00538)
52. Parmentier F-JW *et al.* 2017 A synthesis of the arctic terrestrial and marine carbon cycles under pressure from a dwindling cryosphere. *Ambio* **46**, 53–69. (doi:10.1007/s13280-016-0872-8)
53. Wiedmann I, Ershova E, Bluhm BA, Nöthig E-M, Gradinger RR, Kosobokova K, Boetius A. 2020 What feeds the benthos in the Arctic Basins? Assembling a carbon budget for the deep Arctic Ocean. *Front. Mar. Sci.* **7**, 224. (doi:10.3389/fmars.2020.00224)
54. Petrokofsky G *et al.* 2012 Comparison of methods for measuring and assessing carbon stocks and carbon stock changes in terrestrial carbon pools. How do the accuracy and precision of current methods compare? A systematic review protocol. *Environ. Evidence* **1**, 6. (doi:10.1186/2047-2382-1-6)
55. Virkkala A-M, Virtanen T, Lehtonen A, Rinne J, Luoto M. 2018 The current state of CO_2 flux chamber studies in the Arctic tundra. *Prog. Phys. Geogr. Earth Environ.* **42**, 162–184. (doi:10.1177/0309133317745784)
56. Heino J, Culp JM, Erkinaro J, Goedkoop W, Lento J, Rühland KM, Smol JP. 2020 Abruptly and irreversibly changing Arctic freshwaters urgently require standardized monitoring. *J. App. Ecol.* **57**, 1192–1198. (doi:10.1111/1365-2664.13645)
57. Solan M, Bennett EM, Mumby PJ, Leyland J, Godbold JA. 2020 Benthic-based contributions to climate change mitigation and adaptation. *Phil. Trans. R. Soc. B* **375**, 20190107. (doi:10.1098/rstb.2019.0107)
58. Crépin A-S, Karcher M, Gascard J-C. 2017 Arctic Climate Change, Economy and Society (ACCESS): integrated perspectives. *Ambio* **46**, 341–354. (doi:10.1007/s13280-017-0953-3)
59. Scharffenberg KC, Whalen D, MacPhee SA, Marcoux M, Iacozza J, Davoren G, Loseto LL. 2020 Oceanographic, ecological, and socio-economic impacts of an unusual summer storm in the Mackenzie Estuary. *Arctic Sci.* **6**, 62–76. (doi:10.1139/as-2018-0029)
60. Falardeau M, Raudsepp-Hearne C, Bennett EM. 2018 A novel approach for co-producing positive scenarios that explore agency: case study from the Canadian Arctic. *Sustainability Sci.* **14**, 205–220. (doi:10.1007/s11625-018-0620-z)