Topic Editor Decision: Reconsider after major revisions (18 Feb 2018) by Mario Hoppema Comments to the Author: Dear Drs. Randelhoff and Sundfjord,

Thanks for your resubmission. I am sorry to convey that I am not satisfied with some of your modifications. I think you did not apply the useful suggestions from the referees to the best extent possible. Please see my comments to that and some further minor comment below. I still think the manuscript is worth publishing and it could convey an important message.

Once again, thank you very much for your efforts in evaluating this manuscript. We are glad you see the value in our manuscript, despite our initial divergence in opinion about the best way to convey some of the elements in it. Below find a detailed response.

Among the major changes, we modified a number of figures according to your suggestions.

In particular, we now added a figure that shows the depth of the Arctic shelf break. This clearly illustrates one of the points we had made in the text: That in most areas of the Arctic Ocean, the shelf break is quite deep and thus a dynamic coupling to wind-driven Ekman transport (hence upwelling) is unlikely. (Again, note how the Chukchi and Laptev seas stand out with rather shallow shelf breaks as opposed to the others.)

Also, we now show a schematic of the wind-driven shelf break upwelling mechanism in another figure (now Figure 3), giving an intuitive picture of what we previously described only in the text.

Furthermore, we now use Mercator data for the surface salinity map in the Svalbard area (formerly Figure 2), as has been initially suggested by one of the reviewers - unfortunately, climatology data was too scarce for our intended use.

Please see more details on these two key points in the point by point responses below, along with the other amendments we have made.

From referee #2 and your response (and also referee #3 touches upon this issue, see below)

RC: Fig. 1. Why you illustrate Atlantic Water inflow by snapshot from the model, that can be pretty far from reality (Hattermann et al., 2016 do not use data assimilation)? Why not from climatology or some reanalysis product (e.g MERCATOR OCEAN)?

AR: >As you say yourself, it is an illustration, and it does in fact capture the real-world features and patterns that are relevant for this paper (inflow of near-surface warm and salty water). We could have hand-drawn something (this, too, “pretty far from reality”, but which would still capture the same essence), but for ease of producing the figure and because it looks nicer than what we could have assembled in a graphics editor, we used this data and plotting software that we had at hand. >Note that this picture is confirmed by e.g. Cokelet et al. , 2008, and several other papers going back a few decades, but we believe you will agree that the situation we depict in Fig. 1 is at least qualitatively fully supported by available literature.

EDITOR: I am not satisfied with your response. First, you only show this at one location in the Barents Sea. Your response is that this is only an illustration. I think an illustration is not sufficient. If you want to show that this situation holds for a larger region (and I think you would like to make this point), you have to show that with data. And secondly, you do not show it based on real data. The referee suggests climatology or a reanalysis product; you did not do anything with this suggestion. I think this is indeed the right data to use here. Actually, my comments especially hold for Figure 2. For showing this it doesn’t suffice to use modelled data, only real data take away any doubt.

As you and the reviewer suggest, we now use Mercator ocean reanalysis data for this plot. The main features of the figure as well as the conclusions remain the same, but we agree that using a reanalysis, especially one that assimilates sea ice data, could lend better support to our claims than the ROMS we previously used. (We still think that the ROMS is generally in good agreement with data in this region, but you are right that many readers will be more convinced by a reanalysis.) Text describing the Mercator simulations has now been included in the figure caption.

(We also tried using the climatology MIMOC, but as expected data is too scarce for this area in winter.)

From referee #3

RC: Other comments: Figure 1: The illustrations are too vague and lack important geographic and hydrographic features. In the left panel, I would suggest the following changes: (1) add latitudinal circles and longitudinal lines, (2) use a better color map to illustrate bathymetry (or at least supplement a color bar for the grayscale), (3) draw general surface and bottom circulation patterns.

MC: >We have now added the broad patterns of surface and Atlantic layer circulation patterns as far as they are relevant to our manuscript; the bottom circulation, however, is not relevant to the manuscript and we did not illustrate it. >The following was added to the figure caption: "Arrows show selected patterns of the general circulation citep[after][]{polyakov2012warming}. Blue arrows: Pacific-derived and other freshwater flowing along the shelf break, through the Transpolar Drift and in the Beaufort Gyre. Red arrows: Atlantic-derived water entering the Arctic Ocean through Fram Strait and the Barents Sea, flowing along the shelf break, submerging north of the Barents Sea and recirculating along the shelf break through the Arctic Ocean. Other major currents are not indicated here as they are of minor importance to this paper." >We have also added a colorbar and the location of the transect shown later in the manuscript. AR: >We think longitude/latitude coordinates do not contribute significantly in this context, they would rather clutter the figure, which is why we refrain from adding them. If the reviewer has particular reasons for why they should be included we will be happy to reconsider.

EDITOR: This is again about Figure 1. As referee #1, this referee is not satisfied with Fig 1, and I agree with that. The quality of this Figure is just not high enough. Actually, it is very much distracting from the message. The commentary discusses features along the shelf break, then those shelf breaks should be clearly visible with all of their details. The Figure just does not make a good impression. Please why don't you just provide a high-quality figure with latitude-longitude (of course, every map needs lat-long, no discussion at all). You do not provide a deep data analysis, which is ok as this commentary is not meant to do that, but then at least you can give care to the production of insightful figures, which also enhance the message.

We have now developed a quite detailed map of the Arctic shelf break all along the boundary current, excluding only the Saint Anna Trough and the Chukchi Borderlands. A detailed description and the Python code are included with the supplementary material.

This map (the new Figure 2) shows clearly that in most areas of the Arctic Ocean, the shelf break itself is actually quite deep most places, except off Alaska and in the Laptev Sea.

Latitudes and longitudes are now included in Fig 1 and the new Figure 2.

Comment by referee #3 and your response:

RC: Figure 2: Please mark corresponding transect in Fig 1 left panel. Why not plotting temperature, salinity and density fields in this transect all together so that readers can better interpret Atlantic and Arctic water masses, vertical mixing, thermal or haline stratification? How many CTD profiles were casted along this transect? Please mark the CTD cast locations. What were the wind conditions during this transect sampling? I think wind diagnosis would be critical in answering whether or not vertical mixing was caused by upwelling.

AR: >Fig. 2 (Fig 2, right panel in revised version) is an illustration of what the density field looks like, generically, without consideration of special wind situations. Discussing the specifics of this transect would only distract from the general points we are trying to make: That a) these kinds of cross-slope hydrographical snapshot transects do not tell us anything about whether upwelling was happening or not (and so whether we plotted temperature and salinity should not change the reader's judgement anyway), and b) that there is no physical reason to expect a dominant signal. Fig. 2, left panel (previously Fig 1 right panel), illustrates the geographical salinity and temperature patterns, thus indicates water masses present at the surface. MC: >We added a sentence to the figure caption to make clear that this is "just" a representative illustration. >The revised figure also includes station markers now and for completeness' sake bottom bathymetry from IBCAO3 plotted into the transect.

EDITOR: I agree with the comments by the referee and think the authors wipe away the valid arguments of the referee too easily. For the reader it is certainly quite useful to see temperature, salinity and density. The authors argue that it should not change the reader's judgement anyway, but please leave that to the reader. For the authors it suffices to show everything that might be important and relevant, explain it and leave the judgment to the reader indeed. Do not care about distraction from the general points you are trying to make: It is especially distracting if obvious factors are left out. So, what about the wind patterns and their analysis? Seems to be a factor when talking about upwelling. At a later stage in the manuscript, the authors do indeed mention the wind patterns as a factor for upwelling, so why not here?

We have now re-made the transect plot with salinity and temperature following your advice. We also added the wind conditions in the figure text.

The location of the transect is now included in the left-hand panel of that figure, instead of in Fig 1.

From referee #3 and response:

RC: In section "Summertime upwelling north of Svalbard?", the argument is unconvincing without showing results from mooring or ship-based hydrographic measurements. Personal communication is not sufficient.

AR: >The argument rests entirely on general physical arguments. The personal communication is just an illustration. MC: >To get our point better across in the manuscript, we inserted "As we have seen, consideration of general physical and geographical patterns alone such as boundary layer physics and wind patterns already leads us to conclude that upwelling should not be expected to feature very prominently on the Barents side of the Arctic. This is not to say that upwelling events cannot ever happen (and indeed, in a system as complex as the Earth, it would be surprising if they would never happen), but no known physical mechanism would suggest a magnitude, frequency or importance similar to what has been found in the Pacific sector. To illustrate our point, let us just mention some upcoming work by A. Renner and collaborators [...]"

EDITOR: It would be more convincing if the mentioned general physical and geographical patterns were explained so that the reader would understand. Actually, this is exactly what such a review-like paper should convey.

The sentence in question was restructured to "As has been shown above, wind statistics as well as general physical considerations and geographical features - the northern Barents Sea shelf being too deep for surface and bottom Ekman layers to overlap and produce shelf break upwelling - imply that upwelling should not be expected to feature very prominently on the Barents side of the Arctic." in order to make the sentence clearer. Also, we now show a schematic of the wind-driven shelf break upwelling mechanism in yet another figure (now Figure 3), giving an intuitive picture of what we previously described only in the text.

The abstract does not reflect the contents of the manuscript. It is all about the physical environment and upwelling, but there is hardly any word about what this means to primary productivity. Laying the connection between those two is after all the main goal of the paper. Please restructure the abstract.

We added the following to close the loop back to the beginning of the abstract and make the connection to the biology, as you suggest: " Still, other factors can contribute to marked future increases in biological productivity along the Arctic shelf break. A warming inflow of nutrient-rich Atlantic Water feeds plankton at the same time as it melts the sea ice, permitting increased photosynthesis. Concurrent changes in sea ice cover and zooplankton communities advected with the boundary currents make for a complex mosaic of regulating factors that do not allow for Arctic-wide generalizations."

P1, L18 Many regions, but only one reference. Please give some more.

The reference is to the entire recent book by Kämpf and Chapman on upwelling systems, which has chapters on almost every region of the global ocean. A literature search on our side did not yield review articles with a similar scope, and any regional study would pale in comparison.

P1, L22 What is ibid here? It is definitely clearer to give the correct citation here.

The reference is now made explicit as the textbook by Kämpf and Chapman.

P2, L1 I think this is the right place to give at least several references, and possibly add: "and more below")

We followed your suggestion.

P2, L2 "As the ice cover recedes from the shelves into the basin" It is not clear what time scale is valid here, seasonal, annual, decadal? Maybe rephrase to make this clear.

The text now specifies that we mean interannual time scales.

P2, L3 "primary production is projected to keep increasing (Arrigo and van Dijken, 2015):" Some reasons for higher production are mentioned. There are also factors that may cause less production, e.g. enhanced stratification. Since it is not clear at all whether the production would increase, I think the entire story should be told here. Moreover, only one study with a positive response is cited here. Since the increase of primary production is a central point in your argument, you need to refer to more studies that may predict higher production. If at all known, also studies that project no increase in production should be cited.

We rephrased this as "has been observed" to take away the focus from the projection into the future which is, as you indicate, a much more controversial issue than the satellite-based overall increases in new primary production.

We have also clarified in the text "net" primary production to make this distinction clear, and inserted two more references. (The "net" PP distinction is important because new production is something else and might possibly go the other way as stratification increases, as you remark.)

P2, L9 "and argued that decreased ice concentrations will enhance upwelling in the area" For what reason did they argue that? That should be important info for the reader here.

The text now clarifies their reasoning.

Figure 1 caption L2: delete: black (word is not necessary, and giving the wrong associations)

We did as you suggested, and replaced by "the box in dashed lines"

P4, L2 delete: Not surprisingly (not appropriate here)

We followed your suggestion.

P4, L3 in the Arctic Ocean (instead of in the world ocean)?

I think it is safe to say world ocean here; we added two more references to show that.

Figure 2 In such a figure, latitude and longitude is of much help to the reader and it is standard indeed. For example, it would be visible where the section is situated. The cruise data presented in the second panel need a reference.

[tbd] The updated figure now includes the coordinates. We have added reference to the data set, which has been published and has a doi.

I agree with referees # 2 and # 3 that it would be more correct to take real data instead of modelled data. Is there any evidence that the larger-scale situation is exactly in agreement with this model? In a situation like this, real data, if available, is always preferred above modelled data.

As discussed above, we now use the Mercator Ocean reanalysis for this plot.

P5, L4-5 "In contrast, the Beaufort sea is strongly stratified throughout the year; there, winter upwelling can be an important factor contributing to the pre-bloom nutrient pool" Earlier it was stated (and the data from Codispoti et al show it as well) that the nutrient concentration, even in winter are very low, i.e. not much productivity there, and so upwelling does not enhance productivity in reality.

We now see that our original sentence was ambiguous - the revised version is explicit that we mean that potentially increasing winter upwelling (because of the receding ice edge etc.) would enhance the pre-bloom nutrient reservoir.

P5, L22 "This is because water that already is at the surface will not profit from further upwelling" This is not unequivocal. The characteristics of this water at the surface should at least be added.

Our original sentence was awkward and prone to be misunderstood; we deleted it in the revised version because it did not contribute much to the paragraph.

P5, L28 delete: as we will see later

We did as you suggested.

Figure 3: There is also a comments by referee #3 about this. What surprises me is the piece of text: "based on ERA-INTERIM data". Does this mean that those data, and all of those data, were used? But then, the reference is from 2011, while the data should be for 1987-2017?

ERA-Interim is operational and updated contiuously; the reference we give is the one describing their assimilation system, officially endorsed on their web site (`https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-inte`

In the caption of Figure 3 "A daily windspeed was considered "potentially upwelling-favourable" if its (approximately easterly) along-shelf component exceeded 3 m s-1 for at least 3 consecutive days. (3 m s-1 is rather low a wind speed and makes for a generous criterion in this regard; there is no universally accepted measure.)" First, I wonder where the criterion comes from. There must be some literature about such issues, I think. And then second, if the criterion is not generally accepted, as you write, this strongly reduces the validity of your argument. As to the few appropriate data, could it be that the model data and reanalysis data are biased with regard to along-shelf winds?

There is of course literature about this, nicely summarized in Chapter 2.1 of the book by Kämpf and Chapman (albeit for the case of coastal upwelling). The upshot is that wind speeds of 5 m/s and durations of 5 days would be appropriate numbers in a typical coastal upwelling area at lower latitudes, but we devided to err on the "upwelling-favourable" side to make our point clearer (that the appropriate winds are rare) and not leave the readers wondering whether relaxing the criterion would have made a huge difference.

The figure text of Figure number 4 (formerly 3) is now changed accordingly.

As for the potential bias you mention, we are not aware of any in this regard, and the ERA-Interim web site (`https://software.ecmwf.int/wiki/display/CKB/ERA-Interim+known+issues`) does not state any such issues either. However, if you can point us to indications of such a bias, we are happy to take a closer look and discuss it in the manuscript as needed.

> P7, L1-2 "But it should be kept in mind that ice cover by itself is not a show stopper for wind driven upwelling (or for Ekman pumping for that sake)" The connection to the previous sentence could be guessed at most. I think the steps you are making are too big. Please rephrase clearly what you intend to convey here.

We reworded this sentence: "But it should be kept in mind that the mere earlier presence of an ice cover would not have prohibited wind driven upwelling (or Ekman pumping for that sake), and could even have enhanced it in some circumstances."

In addition to the changes described above, we have made some minor adjustments to wording in a few places. None of these change the substance, but should ease reading or add precision. All changes are visible in the tracked changes version.

Short Commentary on Marine Productivity at Arctic Shelf Breaks: Upwelling, Advection and Vertical Mixing

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Abstract.

The future of Arctic marine ecosystems has received increasing attention in recent years as the extent of the sea ice cover is dwindling. Although the Pacific and Atlantic inflows both import huge quantities of nutrients and plankton, they feed into the Arctic Ocean in quite diverse regions. The strongly stratified Pacific sector has a historically heavy ice cover, a shallow shelf and dominant upwelling-favourable winds, while the Atlantic sector is weakly stratified, with a dynamic ice edge and a complex bathymetry. We argue that shelf break upwelling is likely not a universal but rather a regional, albeit recurring feature of “the new Arctic”. Instead, it is the regional oceanography that decides its importance through a range of diverse factors such as stratification, bathymetry and wind forcing. Teasing apart their individual contributions in different regions can only be achieved by spatially resolved timeseries and dedicated modelling efforts. The Northern Barents Sea shelf is an example of a region where shelf break upwelling likely does not play a dominant role, in contrast to the shallower shelves north of Alaska, where ample evidence for its importance has already accumulated. Still, other factors can contribute to marked future increases in biological productivity along the Arctic shelf break. A warming inflow of nutrient-rich Atlantic Water feeds plankton at the same time as it melts the sea ice, permitting increased photosynthesis. Concurrent changes in sea ice cover and zooplankton communities advected with the boundary currents make for a complex mosaic of regulating factors that do not allow for Arctic-wide generalizations.

Introduction

Surface waters throughout most of the world ocean are generally low in nutrients. In order to sustain primary production, new nutrients are required. These can come by means of mineral-rich rivers draining into coastal areas, turbulent small-scale mixing where underlying waters are rich in nutrients, upwelling of deeper nutrient rich waters, or even nitrogen fixation by some bacteria. In fact, upwelling in certain coastal areas and at shelf breaks in many regions of the world ocean supports intense marine production and can sustain rich regional fisheries (see e.g. Kämpf and Chapman, 2016). Where upwelling occurs, it is often intimately linked to specific weather and climate patterns, such as storms (cyclones), or wind blowing from a preferential direction. The basic concept is that the winds set up spatially varying surface transport or forces surface water away from the coast, creating a divergence that draws up deeper waters which would otherwise be too heavy to be brought up by vertical mixing alone (ibid.). (Kämpf and Chapman, 2016).

Shelf break upwelling has recently received increasing attention also in the Arctic Ocean (see below for a list of references; for an overview of the geography, see Fig. 1). (Carmack and Chapman, 2003; Arrigo and van Dijken, 2015; Williams and Carmack, 2015, As the ice cover edge recedes from the shelves into the basin (e.g. Stroeve et al., 2012), primary production is projected to keep increasing (Arrigo and van Dijken, 2015)further and further each year (e.g. Stroeve et al., 2012), net primary production has been oberved to have increase Arctic-wide (Arrigo and van Dijken, 2011; Bélanger et al., 2013; Arrigo and van Dijken, 2015): Not only would less ice allow more solar radiation into the ocean, providing more of a scarce requirement for photosynthesis. It is also assumed that winds can move the surface waters more effectively and lead to more pronounced shelf break upwelling (Carmack and Chapman, 2003), another flavour of the Arctic as that region of the world where the impacts of climate change are most pronounced.

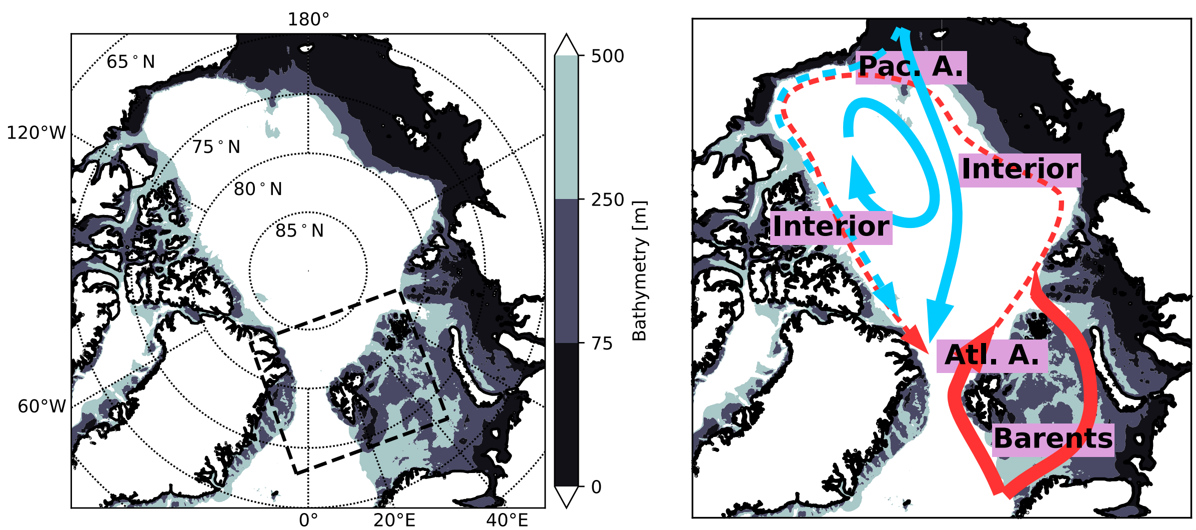

Figure 1. Map of the Arctic Ocean (based on Jakobsson et al., 2012), indicating the general geographic regimes. Left: Bathymetry of the shelf and shelf break area. The black box in dashed lines shows the area in Fig. 4, left panel. The red line shows the location of the transect shown in Fig. 4, right panel. Right: The Pacific Arctic, Atlantic Arctic, interior shelves (following Williams and Carmack, 2015); and the Barents Sea. Arrows show selected patterns of the general circulation (after Polyakov et al., 2012). Blue arrows: Pacific-derived and other freshwater flowing along the shelf break, through the Transpolar Drift and in the Beaufort Gyre. Red arrows: Atlantic-derived water entering the Arctic Ocean through Fram Strait and the Barents Sea, flowing along the shelf break, submerging north of the Barents Sea and recirculating along the shelf break through the Arctic Ocean. Other major currents are not indicated here as they are of minor importance to this paper.

Upwelling in the Arctic

In their seminal 2003 paper mentioned above, Carmack and Chapman applied a numerical model to study shelf-basin exchange on the Beaufort Sea shelf and argued that decreased ice concentrations will enhance upwelling in the area. The argument goes like this: When a thick ice cover lies like a lid on the ocean, it absorbs most of the wind stress instead of transferring it to the underlying ocean. When the ice edge recedes far enough north that the shelf break is exposed, however, the winds can move around the surface waters more easily. Sustained easterlies, for example, will lead to a northward Ekman transport, and where the shelf is shallow enough that it affects surface currents (see Fig. 2 and 3), deeper waters are drawn up to balance the off-shelf transport.

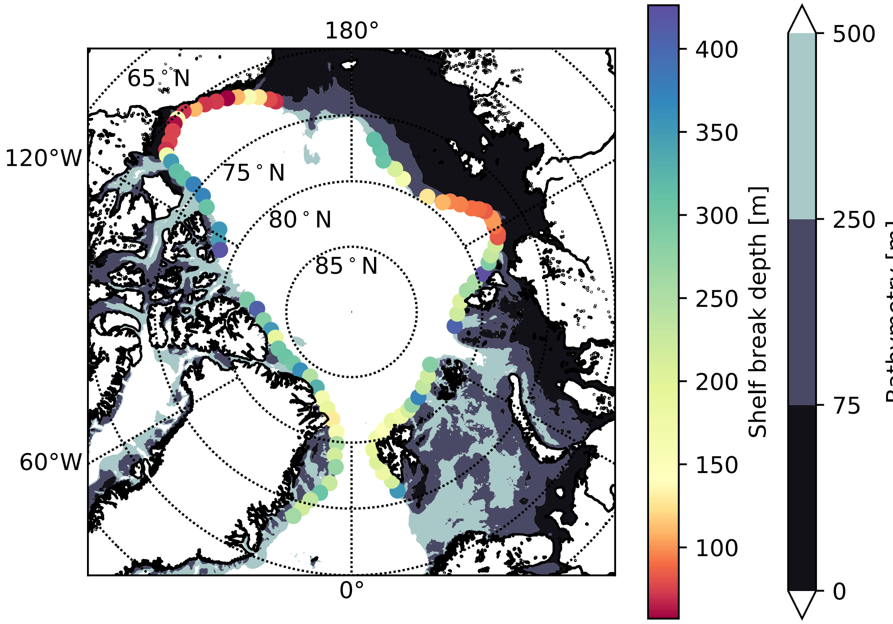

Figure 2. Depth of the Arctic shelfbreak extracted from the IBCAO V3 bathymetry of the Arctic Ocean (Jakobsson et al., 2012), excluding only the Saint Anna Trough and the Chukchi Borderland. Most visible are the continental shelf off Alaska and the westernmost part of the Canadian shelf, where Carmack and Chapman (2003) conducted their study and upwelling has been frequently documented, and north of the Laptev Sea. In most other areas of the Arctic Ocean, the shelfbreak is several hundred meters deep and therefore out of reach to interact significantly with Ekman-driven surface ocean dynamics. For a detailed explanation of the algorithm and the computer code used to extract shelfbreak depths, see the supplementary material.

This argument was reinforced by a number of studies conducted in the Pacific Arctic (Williams et al., 2006; Schulze and Pickart, 2012; Spall et al., 2014; Arrigo et al., 2014; Lin et al., 2016), which directly extended earlier direct observations of shelf break upwelling dating back to at least the 1980s (e.g. Aagaard et al., 1981). A detailed study (Spall et al., 2014) on the

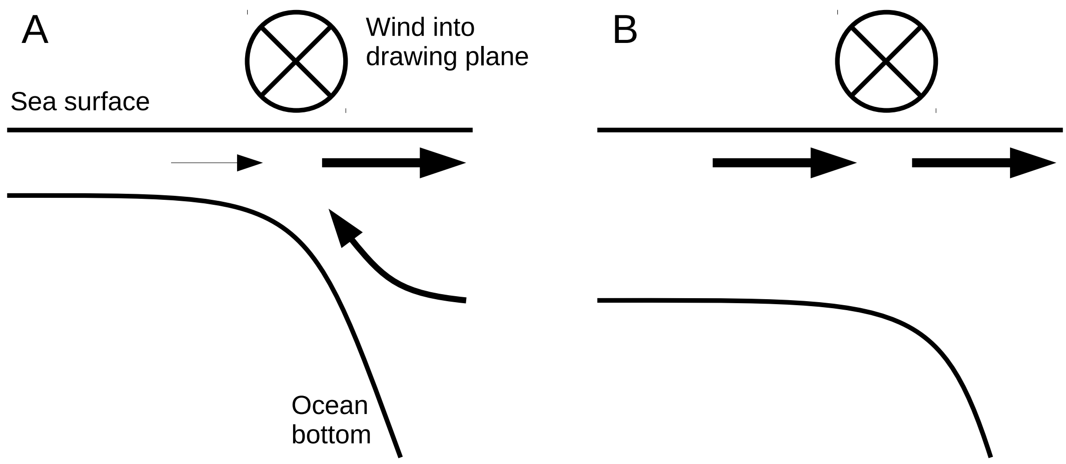

Figure 3. Schematic of the mechanism behind wind-driven shelf break upwelling. When wind blows along the shelf break, it generates an Ekman current (horizontal arrows) off-shelf. A: When the shelf is shallow enough, the current over the shelf is slowed down, leading to a horizontal divergence and thus pressure gradient that is filled by drawing up deeper waters. B: When the shelf is deeper, there is no horizontal divergence. Other mechanisms, such as dynamic uplift, are independent from wind and not discussed here, but see e.g. the book by Kämpf and Chapman (2016).

dynamic response during one particularly impressive example of shelf break upwelling in the Chukchi Sea (Arrigo et al., 2014) demonstrated potentially large contributions to primary productivity in that area.

The idea has since caught on to explain or project marine productivity also in other regions of the Arctic Ocean, for example at the Barents Sea shelf break. There it has appeared both in numerous personal communications among the community working with the physical and ecological environment of the Barents Sea, as well as a number of published articles (see e.g. Falk-Petersen et al., 2014; Tetzlaff et al., 2014; Wassmann et al., 2015; Hunt et al., 2016; Våge et al., 2016; Haug et al., 2017). Thus it might appear as if shelf break upwelling is currently being cemented as a universal paradigm to conceptualize *the* "new" Arctic Ocean where global climate change is taking us. We will argue that some of the regional differences cannot be ignored when discussing what governs productivity in the various shelf regions.

Many interconnected phenomena

Upwelling comes in many different forms: The well-known upwelling that feeds so many productive coastal areas of the world is created by winds blowing along-shore, driving an offshore surface current that "pulls up" nutrient rich waters. (This will in practice most often be the Ekman transport; however, shelf break upwelling would function in much the same way at the equator where there is no Coriolis force, even though upwelling-favourable winds would then blow directly off-shelf instead of along-shelf.) The divergence sets up a horizontal gradient in sea surface height that balances the Coriolis force, meaning that deeper waters are drawn towards the surface and/or onto the shelf (again, see e.g. Kämpf and Chapman, 2016).

Alternatively, storms can lift deeper waters up to the shelf break, making them spill over and mix with shelf waters. Canyons and troughs that cut into a continental shelf may aid by steering the flow there through its topography. All of these phenomena can act together to bring new nutrients into shelf waters.

But besides upwelling, other factors are at play. Two important ones are vertical mixing and advection with large scale ocean currents, and both of them can become entangled with upwelling in that they can lead to similar effects in the regional oceanography and be hard to tell apart by the most basic means of hydrography which are vertical profiles of temperature and salinity. Because different areas within the Arctic Ocean are subject to very different forcing, large gradients in physical properties exist between e.g. Bering Strait, Fram Strait and the Siberian Shelf. Naturally, this means that also the drivers of marine productivity will vary strongly between these areas.

Drivers of marine productivity vary across the Arctic Ocean

There is an ample storage of freshwater in the Arctic Ocean because of the large rivers draining Siberia and North America, but also because the inflow of Pacific Water through Bering Strait is much fresher than its Atlantic counterpart (Aagaard and Carmack, 1989). But the freshwater is not evenly distributed: Most of it is found in the Beaufort Gyre located around the Canadian Basin (e.g. Morison et al., 2012; Proshutinsky et al., 2015). When light water (at low temperatures, this means fresher) sits on top of heavy water, mixing will not be as efficient (e.g. Osborn, 1980), which means that the most important factor for vertical mixing is vertical stability (since overall, there is a given amount of energy available to stir the ocean, e.g. from tides, wind and so on.) ~~Not surprisingly, in~~ In the Beaufort Gyre, all the freshwater and the resulting strong stratification severely restrict the upward supply of fresh nutrients, making it one of the most nutrient-depleted regions of the world ocean ~~(Codispoti et al., 2013)~~(Gruber and Sarmiento, 1997; Codispoti et al., 2013; Tremblay et al., 2015).

In contrast, the Atlantic inflow along the shelf break north of Svalbard is much denser than the surface waters of the central Arctic Ocean, but nevertheless extends up to the surface (see e.g. Rudels, 2016, ; an illustration is also given in Fig. 4). Seeing this situation in the contour plot of a hydrographic transect (see right panel of Fig. 4) may at first look like a classical upwelling scenario: Surely there must have been upwelling to get the heavy waters up there in the first place? The answer is that not necessarily - what we are seeing is Arctic and Atlantic water masses meeting, and the narrow but strong gradient is maintained by a continuous inflow of more Atlantic Water. In the absence of detailed (hydrographic) timeseries, it is impossible to say anything conclusive about the state of upwelling from the right panel of Fig. 4 alone.

We thus need to distinguish between basin-scale and regional hydrography, that is between strong haline stratification in the Arctic Ocean in general and weak thermal stratification in the Atlantic inflow (see the distinction between “alpha” and “beta” oceans as in Carmack, 2007). The salient point is this: As the Atlantic Water is cooled on its way north, it loses stability, potentially leading to wintertime convection (Ivanov et al., 2016) and efficient vertical mixing. The result is that the surface layer nutrient reservoirs are replenished long before the end of winter (Randelhoff et al., 2015); increased wintertime upwelling

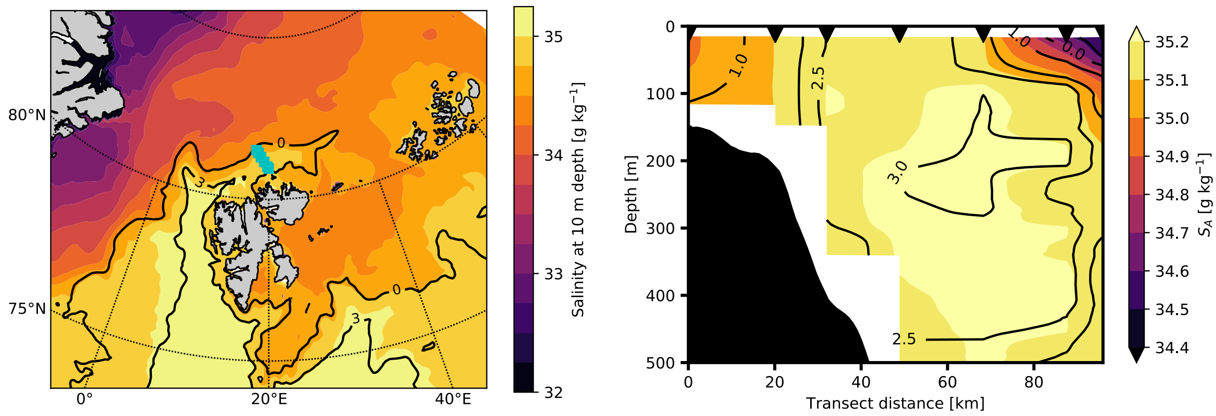

Figure 4. Representative illustration of the hydrographic regime in the Atlantic inflow area along the northern Barents Sea shelf break. Left: Inflowing warm and salty Atlantic Water maintains high surface salinity on and around the shelf, enabling convection when the surface waters are cooled in winter. Color scale shows salinity, black contour lines show the 0 and 3°C isotherms. (Average of 2015-2018 monthly January 2010 mean at 15 10 m depth from an 800 x 800 m horizontal resolution ROMS the operational ocean and sea ice simulationreanalysis Mercator, see Hattermann et al. (2016)downloaded from http://marine.copernicus.eu. The version of Mercator used for this plot is a global ocean forecasting model on a 1/12°×1/12° grid and showed good agreement with winter data for this area in a study by Koenig et al. (2017).) The cyan line indicates location of transect displayed in right panel. Right: Seawater density absolute salinity S_A and conservative temperature in a typical wintertime transect across the shelf slope north of Svalbard, sampled in January 2014 (unpublished data from approximately 81.5°N, 17.5°E, RV Helmer Hanssen, Carbon Bridge project (Randelhoff and Sundfjord, 2017, published dataset; see also Randelhoff et al., article submitted to Frontiers in Marine Science); see Fig. 1, left panel , for location). Salinity is plotted on the color scale, temperature is marked (in °C) on the black isolines inside the plot. The surface water is markedly heavier above the upper shelf slope than over the deep basin. Black triangles mark hydrographic stations. The black patch marks the along-transect bathymetry extracted from the IBCAO V3 bathymetry (Jakobsson et al., 2012). During the sampling of this transect, winds were moderate southerlies to south-south-easterliers, so mean Ekman transport in the surface was mainly directed along-shelf to the east.

will not bring more nutrients to the surface. Essentially, the upwelling water mass would have the same salinity and nutrient characteristics as the one that is already present in the surface; upwelling does not add nutrients when there is no vertical gradient in nutrient concentrationconcentrations. In contrast, the Beaufort sea is strongly stratified throughout the year; there, winter upwelling if winter upwelling is to increase there because of reduced sea ice, this can be an important factor contributing to the pre-bloom nutrient pool.

In contrast to storms, which can lift deeper waters independently from any sort of topographic constraint (i.e. Ekman pumping), coastal and shelf break upwelling driven by specific wind directions need the presence of a coastline or a sufficiently shallow shelf. This is because it requires a horizontal divergence in the off-shelf transport of surface waters.

In addition, shelf break upwelling requires a sufficiently shallow shelf. This is because the previously mentioned divergence in off-shelf surface transport This divergence can only be potent enough when the shelf itself is shallow enough to actually constrict the surface flow over the shelf . (Fig. 3). Whereas most large swaths of the continental shelves of the Arctic Ocean are extremely very shallow (in parts less than 50 m), the Northern Barents Sea shelf break is relatively deep at around 150-200 m . 150-250 m (see Fig. 2). Because surface and bottom boundary layers will not overlap in this case (common values for Ekman layer depth in the literature are few tens of meters, see Price and Sundermeyer, 1999), shelf break upwelling as an effect of along-shore winds is presumably negligible. (Also note that Ekman layer depth decreases with increasing Coriolis parameter latitude and decreasing wind strength (Wang and Huang, 2004), and that during the stratified summer period, the Ekman layer will at any rate be restricted to at most the surface mixed layer, see e.g. Price et al. (1987)).

In general, the regions that (only based on the depth of the shelf break) stand out as most prone to wind-driven shelf break upwelling are the aforementioned continental shelves of Alaska and the westernmost part of northern Canada, and possibly the Laptev Sea, although the shelf is rather wide here, potentially diminishing the effect of easterlies somewhat. In regions where the shelf is narrow, the presence of the coastline can aid in upwelling of deeper waters. Seeing that the Chukchi and Siberian shelves are rather wide, potential upwelling will likely be relatively weak across large swaths of the Arctic shelf regions.

Summertime upwelling north of Svalbard?

We have seen how surface nutrient inventories the pre-bloom surface nutrient inventory at the northern Barents Sea shelf break can be replenished just by the inflowing Atlantic water, without recurrence to wintertime upwelling. This is because water that already is at the surface will not profit from further upwelling. In summer, however, nutrients are depleted in surface waters, such that even sporadic upwelling could inject nutrients that could be utilized immediately and funneled into the food web (see e.g. Ch. 3.2, Kämpf and Chapman, 2016).

Here, another difference between the Atlantic and Pacific inflow areas comes into play, namely dominant wind patterns: The Beaufort Sea shelf is dominated by the Beaufort High–Aleutian Low system, meaning predominantly easterlies at the Canadian shelf break (e.g. Serreze and Barrett, 2011). The atmospheric circulation in the Atlantic sector is more dynamic in summer, with less of a preference for a specific upwelling-favourable wind direction as we will see later (see e.g. Fig. 5). This comes on top of a general pattern where wind speeds north of Svalbard are lower in summer than in winter. Fig. 5 illustrates how only roughly 2% of all summer days through the last 30 years can be considered upwelling-favourable, using a very generous criterion for what constitutes “upwelling-favourable”, and even this is assuming that the local topography would allow for this kind of upwelling. (Again, note the difference to the Beaufort shelf, where winds are very much upwelling-favourable also in June, see Lin et al. (2016).) There might still be storms that make deeper waters spill onto the shelf by Ekman pumping alone, but also these have a tendency to occur more frequently in the winter season (see also Lind and Ingvaldsen, 2012).

As we have seen, consideration of general physical and geographical patterns alone such as boundary layer physics and wind patterns already leads us to conclude has been shown above, wind statistics as well as general physical considerations and geographical features - the northern Barents Sea shelf being too deep for surface and bottom Ekman layers to overlap and

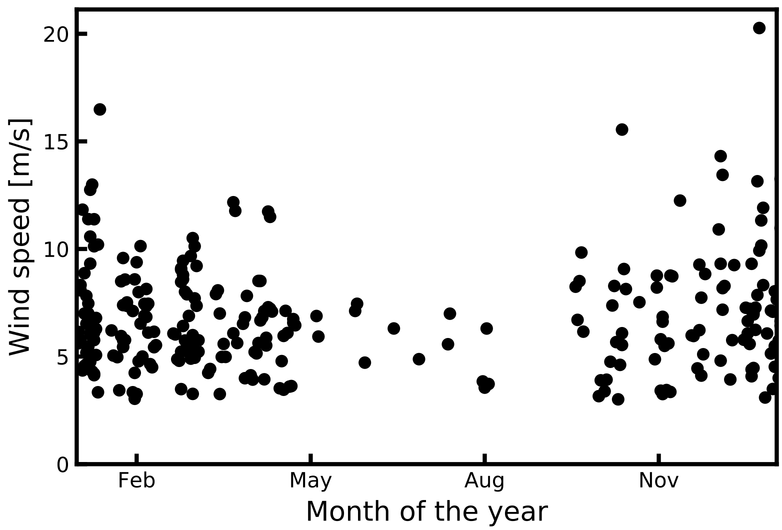

Figure 5. Days of "potentially upwelling-favourable" winds north of Svalbard 1987-2017 assuming the local bathymetry facilitates such upwelling, based on ERA-INTERIM data (Dee et al., 2011) for the region 79–81°N, 5–30°E. A daily windspeed was considered "potentially upwelling-favourable" if its (approximately easterly) along-shelf component exceeded 3 m s^{-1} for at least 3 consecutive days. (3 m s^{-1} is rather low a wind speed, well below the "optimal environmental window" of 5–6 m s^{-1} for upwelling suggested by (Cury and Roy, 1989). and makes for a generous criterion in this regard~~; there is no universally accepted measure~~. Likewise, Kämpf and Chapman (2016, Ch. 2.1) give a timescale of around 5 days from the onset until the complete development of coastal upwelling. Effectively, both criteria should err on the upwelling-favourable side.) From the beginning of May through August each year, ∼2% of all days were "potentially upwelling-favourable".

produce shelf break upwelling - imply that upwelling should not be expected to feature very prominently on the Barents side of the Arctic. This is not to say that upwelling events cannot ever happen (and indeed, in a system as complex as the Earth, it would be surprising if it would never happen), but no known physical mechanism would suggest a magnitude, frequency or importance similar to what has been found in the Pacific sector. To illustrate our point, we refer to recent analysis by A. Renner and collaborators. They have analysed the first year-long time series from a moored CTD array over the shelf slope north of the Barents Sea (A-TWAIN project, at 30°E). Applying methods that have successfully detected frequent occurrence of upwelling over the Beaufort Sea slope (Lin et al., 2016), they could not identify signatures of upwelling in the density field in response to possibly favourable along-slope winds (A. H. H. Renner, pers. comm. and article in review for Journal of Geophysical Research).

Climate Change and the Future of Arctic Marine Productivity

Shelf break upwelling is often thought to become more prominent in the Arctic as the ice recedes poleward with ongoing climate change, exposing the shelf break more and more (see references given in the previous section "Upwelling in the Arctic"). But it should be kept in mind that ~~ice cover by itself is not a show stopper for~~ the mere earlier presence of an ice cover would not have prohibited wind driven upwelling (or ~~for~~ Ekman pumping for that sake), and could even have enhanced it in some circumstances. For instance, Martin et al. (2014) showed how a loose ice cover (80–90% ice concentration) can yield an optimum transfer of wind energy into the upper ocean when internal ice stresses are negligible, seeing that sea ice has a rougher surface than open water and can therefore be moved around more easily by the winds. This is consistent with the observation of Schulze and Pickart (2012) that the upwelling response at the Beaufort Sea shelf off Alaska was strongest when there was partial ice cover. Once again, there are differences between the historically thick, multiyear ice cover of the Pacific Arctic (Maslanik et al., 2007) and the more dynamic first- and second year ice cover north of Svalbard (Renner et al., 2013). In the latter area, it is not a new feature that the ice cover is quite dynamic and rough, which possibly leads to an efficient transfer of wind energy as was demonstrated in the previously mentioned paper by Martin et al. (2014). It is therefore not a given that reduced ice cover north of Svalbard automatically will make surface currents more responsive than they were in the past, especially ~~in summer~~ under the responsive summer pack ice, when upwelling would have the chance to substantially alter the marine ecosystem through sporadic nutrient input.

In fact, there are pathways entirely unrelated to upwelling through which climate change probably is impacting and enhancing marine productivity. Indeed, the regional loss of sea ice has been attributed to inflow of warmer Atlantic Water (Onarheim et al., 2014). As ~~it takes more and more time before~~ the Atlantic Water travels further and further east along the shelf break before it is sufficiently cooled and ~~subsequently can subduct~~ its core is subsequently subducted under the Arctic water masses, it pushes back the ice edge and erodes stratification (Polyakov et al., 2017) – meaning it provides access to nutrients and light at the same time! This will enhance regionally averaged primary production by itself, without the need to invoke shelf break upwelling.

In addition to heat, salt and nutrients, the Atlantic (like the Pacific) water also carries large amounts of zooplankton. This makes the inflow areas perfect feeding grounds for larger fish and mammals, adding onto local primary production. For instance, there is an excess of organic carbon production NW of Spitsbergen in May and June (Maria Vernet, pers. comm.), in agreement with modelling results (e.g. Wassmann et al., 2015). As sea ice recedes north- and eastward, it might extend this region of net heterotrophy (carbon consumption). However, results from a coupled ocean and ecosystem model indicate that by the end of the 21st century, zooplankton advection along the shelf break will dwindle, and marine life in the area might rely much more on local production (Wassmann et al., 2015). Such processes would contrast a projected pan-Arctic strengthening of upper ocean stratification that might lead to a smaller plankton size-spectrum, fuelling a food web that recycles more than providing food for higher trophic levels (e.g. Li et al., 2009, 2013).

Summary and Conclusions

Detailed measurements and analyses with spatial and temporal resolution are necessary in order to detect upwelling in general; shelf break upwelling in the Arctic is no exception. In general, moored CTD arrays in conjunction with wind data are a solid foundation to detect upwelling in the field; hydrographic snapshots are rarely enough to establish its dynamics and drivers. The 2-dimensional modelling approach of Spall et al. (2014) has proven particularly valuable for mapping out upwelling-driven nutrient transport across the Beaufort Sea shelf break, and a similar model could yield essential insight in other areas of the Arctic Ocean as well. Furthermore, the role of "dynamic uplift" (Kämpf and Chapman, 2016, Ch. 2.1) - where e.g. eddy shedding of a boundary current can lead to changes in its position onto the shelf - for shelf-basin exchange is not yet well understood in this area.

More generally, it would appear that changes in cross-shelf exchange are most important for the interior shelves (sensu Williams and Carmack, 2015) where nutrients are rather scarce to begin with. There is the projection that continued warming will release organic nutrients bound in the permafrost landscapes of northern Siberia and Alaska and flush them out into the Arctic Ocean (Frey and McClelland, 2009). Beyond these, rivers do not carry significant amounts of nitrate, one of the scarcest and most important mineral nutrients in the Arctic Ocean. Profound changes in the on-shelf transport of nutrient-rich water from the Atlantic Water boundary current might thus have big impacts on integrated productivity. Changes in the position of the ice edge can also effect changing storm tracks and hence Ekman pumping. This too is a complex issue and there are no clear answers regarding its effect on nutrient transport onto the shelf.

Whatever the final result, Arctic marine life will find itself in a vastly different habitat within a tangible number of decades, showcasing the Arctic as a region where drastic changes are happening fast and, equally important, non-linearly. This also means that even dynamically isolated phenomena have to be evaluated against their specific regional backgrounds.

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References

Aagaard, K. and Carmack, E. C.: The role of sea ice and other fresh water in the Arctic circulation, Journal of Geophysical Research: Oceans, 94, 14 485–14 498, https://doi.org/10.1029/JC094iC10p14485, 1989.

Aagaard, K., Coachman, L., and Carmack, E.: On the halocline of the Arctic Ocean, Deep Sea Research Part A. Oceanographic Research Papers, 28, 529–545, 1981.

Arrigo, K. R. and van Dijken, G. L.: Secular trends in Arctic Ocean net primary production, Journal of Geophysical Research, 116, https://doi.org/10.1029/2011jc007151, http://dx.doi.org/10.1029/2011JC007151, 2011.

Arrigo, K. R. and van Dijken, G. L.: Continued increases in Arctic Ocean primary production, Progress in Oceanography, 136, 60–70, https://doi.org/10.1016/j.pocean.2015.05.002, http://www.sciencedirect.com/science/article/pii/S0079661115000993, Synthesis of Arctic Research (SOAR), 2015.

Arrigo, K. R., Perovich, D. K., Pickart, R. S., Brown, Z. W., van Dijken, G. L., Lowry, K. E., Mills, M. M., Palmer, M. A., Balch, W. M., Bates, N. R., Benitez-Nelson, C. R., Brownlee, E., Frey, K. E., Laney, S. R., Mathis, J., Matsuoka, A., Mitchell, B. G., Moore, G., Reynolds, R. A., Sosik, H. M., and Swift, J. H.: Phytoplankton blooms beneath the sea ice in the Chukchi Sea, Deep Sea Research Part II: Topical Studies in Oceanography, 105, 1 – 16, https://doi.org/http://dx.doi.org/10.1016/j.dsr2.2014.03.018, //www.sciencedirect.com/science/article/pii/S0967064514000836, the Phytoplankton Megabloom beneath Arctic Sea Ice: Results from the {ICESCAPE} Program, 2014.

Bélanger, S., Babin, M., and Tremblay, J.-E.: Increasing cloudiness in Arctic damps the increase in phytoplankton primary production due to sea ice receding, Biogeosciences, 10, 4087–4101, https://doi.org/10.5194/bg-10-4087-2013, https://www.biogeosciences.net/10/4087/2013/, 2013.

Carmack, E. and Chapman, D. C.: Wind-driven shelf/basin exchange on an Arctic shelf: The joint roles of ice cover extent and shelf-break bathymetry, Geophys. Res. Lett., 30, https://doi.org/10.1029/2003gl017526, http://dx.doi.org/10.1029/2003GL017526, 2003.

Carmack, E. C.: The alpha/beta ocean distinction: A perspective on freshwater fluxes, convection, nutrients and productivity in high-latitude seas, Deep Sea Research Part II: Topical Studies in Oceanography, 54, 2578–2598, https://doi.org/10.1016/j.dsr2.2007.08.018, 2007.

Codispoti, L., Kelly, V., Thessen, A., Matrai, P., Suttles, S., Hill, V., Steele, M., and Light, B.: Synthesis of primary production in the Arctic Ocean: III. Nitrate and phosphate based estimates of net community production, Progress in Oceanography, 110, 126–150, https://doi.org/10.1016/j.pocean.2012.11.006, http://dx.doi.org/10.1016/j.pocean.2012.11.006, 2013.

Cury, P. and Roy, C.: Optimal Environmental Window and Pelagic Fish Recruitment Success in Upwelling Areas, Canadian Journal of Fisheries and Aquatic Sciences, 46, 670–680, https://doi.org/10.1139/f89-086, https://doi.org/10.1139/f89-086, 1989.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, http://dx.doi.org/10.1002/qj.828, 2011.

Falk-Petersen, S., Pavlov, V., Berge, J., Cottier, F., Kovacs, K. M., and Lydersen, C.: At the rainbow's end: high productivity fueled by winter upwelling along an Arctic shelf, Polar Biology, https://doi.org/10.1007/s00300-014-1482-1, http://dx.doi.org/10.1007/s00300-014-1482-1, 2014.

Frey, K. E. and McClelland, J. W.: Impacts of permafrost degradation on arctic river biogeochemistry, Hydrological Processes, 23, 169–182, https://doi.org/10.1002/hyp.7196, http://dx.doi.org/10.1002/hyp.7196, 2009.

Gruber, N. and Sarmiento, J. L.: Global patterns of marine nitrogen fixation and denitrification, Global Biogeochemical Cycles, 11, 235–266, https://doi.org/10.1029/97GB00077, http://dx.doi.org/10.1029/97GB00077, 1997.

Hattermann, T., Isachsen, P. E., von Appen, W.-J., Albretsen, J., and Sundfjord, A.: Eddy-driven recirculation of Atlantic Water in Fram Strait, Geophysical Research Letters, 43, 3406–3414, https://doi.org/10.1002/2016gl068323, http://dx.doi.org/10.1002/2016GL068323, 2016.

Haug, T., Bogstad, B., Chierici, M., Gjøsæter, H., Hallfredsson, E. H., Høines, A. S., Hoel, A. H., Ingvaldsen, R. B., Jørgensen, L. L., Knutsen, T., Loeng, H., Naustvoll, L.-J., Røttingen, I., and Sunnanå, K.: Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: A review of possibilities and constraints, Fisheries Research, 188, 38 – 57, https://doi.org/http://dx.doi.org/10.1016/j.fishres.2016.12.002, www.sciencedirect.com/science/article/pii/S0165783616304131, 2017.

Hunt, G. L., Drinkwater, K. F., Arrigo, K., Berge, J., Daly, K., Danielson, S., Daase, M., Hop, H., Isla, E., Karnovsky, N., Laidre, K., Mueter, F. J., Murphy, E. J., Renaud, P. E., Smith, W. O., Trathan, P., Turner, J., and Wolf-Gladrow, D.: Advection in polar and sub-polar environments: Impacts on high latitude marine ecosystems, Progress in Oceanography, 149, 40–81, https://doi.org/10.1016/j.pocean.2016.10.004, 2016.

Ivanov, V., Alexeev, V., Koldunov, N. V., Repina, I., Sandø, A. B., Smedsrud, L. H., and Smirnov, A.: Arctic Ocean heat impact on regional ice decay - a suggested positive feedback, Journal of Physical Oceanography, p. 151103140145004, https://doi.org/10.1175/jpo-d-15-0144.1, http://dx.doi.org/10.1175/JPO-D-15-0144.1, 2016.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H. W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R. M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J. V., Hall, J. K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M. T., Travaglini, P. G., and Weatherall, P.: The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL052219, 2012.

Kämpf, J. and Chapman, P.: Upwelling Systems of the World, Springer, 2016.

Koenig, Z., Provost, C., Villacieros-Robineau, N., Sennéchael, N., Meyer, A., Lellouche, J.-M., and Garric, G.: Atlantic waters inflow north of Svalbard: Insights from IAOOS observations and Mercator Ocean global operational system during N-ICE2015, Journal of Geophysical Research: Oceans, 122, 1254–1273, https://doi.org/10.1002/2016JC012424, http://dx.doi.org/10.1002/2016JC012424, 2017.

Li, W. K. W., McLaughlin, F. A., Lovejoy, C., and Carmack, E. C.: Smallest Algae Thrive As the Arctic Ocean Freshens, Science, 326, 539–539, https://doi.org/10.1126/science.1179798, http://dx.doi.org/10.1126/science.1179798, 2009.

Li, W. K. W., Carmack, E. C., McLaughlin, F. A., Nelson, R. J., and Williams, W. J.: Space-for-time substitution in predicting the state of picoplankton and nanoplankton in a changing Arctic Ocean, Journal of Geophysical Research: Oceans, 118, 5750–5759, https://doi.org/10.1002/jgrc.20417, http://dx.doi.org/10.1002/jgrc.20417, 2013.

Lin, P., Pickart, R. S., Stafford, K. M., Moore, G. W. K., Torres, D. J., Bahr, F., and Hu, J.: Seasonal variation of the Beaufort shelfbreak jet and its relationship to Arctic cetacean occurrence, Journal of Geophysical Research: Oceans, 121, 8434–8454, https://doi.org/10.1002/2016JC011890, http://dx.doi.org/10.1002/2016JC011890, 2016.

Lind, S. and Ingvaldsen, R. B.: Variability and impacts of Atlantic Water entering the Barents Sea from the north, Deep Sea Research Part I: Oceanographic Research Papers, 62, 70–88, https://doi.org/10.1016/j.dsr.2011.12.007, http://dx.doi.org/10.1016/j.dsr.2011.12.007, 2012.

Martin, T., Steele, M., and Zhang, J.: Seasonality and long-term trend of Arctic Ocean surface stress in a model, J. Geophys. Res. Oceans, 119, 1723–1738, https://doi.org/10.1002/2013jc009425, http://dx.doi.org/10.1002/2013JC009425, 2014.

Maslanik, J. A., Fowler, C., Stroeve, J., Drobot, S., Zwally, J., Yi, D., and Emery, W.: A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss, Geophysical Research Letters, 34, https://doi.org/10.1029/2007GL032043, 2007.

Morison, J., Kwok, R., Peralta-Ferriz, C., Alkire, M., Rigor, I., Andersen, R., and Steele, M.: Changing Arctic Ocean freshwater pathways, Nature, 481, 66–70, https://doi.org/10.1038/nature10705, http://dx.doi.org/10.1038/nature10705, 2012.

Onarheim, I. H., Smedsrud, L. H., Ingvaldsen, R. B., and Nilsen, F.: Loss of sea ice during winter north of Svalbard, Tellus A, 66, https://doi.org/10.3402/tellusa.v66.23933, http://dx.doi.org/10.3402/tellusa.v66.23933, 2014.

Osborn, T. R.: Estimates of the Local Rate of Vertical Diffusion from Dissipation Measurements, J. Phys. Oceanogr., 10, 83–89, https://doi.org/10.1175/1520-0485(1980)010<0083:EOTLRO>2.0.CO;2, 1980.

Polyakov, I. V., Pnyushkov, A. V., and Timokhov, L. A.: Warming of the Intermediate Atlantic Water of the Arctic Ocean in the 2000s, J. Climate, 25, 8362–8370, https://doi.org/10.1175/jcli-d-12-00266.1, http://dx.doi.org/10.1175/JCLI-D-12-00266.1, 2012.

Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., Goszczko, I., Guthrie, J., Ivanov, V. V., Kanzow, T., Krishfield, R., Kwok, R., Sundfjord, A., Morison, J., Rember, R., and Yulin, A.: Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean, Science, 356, 285–291, https://doi.org/10.1126/science.aai8204, http://science.sciencemag.org/content/356/6335/285, 2017.

Price, J. F. and Sundermeyer, M. A.: Stratified Ekman layers, Journal of Geophysical Research: Oceans, 104, 20 467–20 494, https://doi.org/10.1029/1999JC900164, 1999.

Price, J. F., Weller, R. A., and Schudlich, R. R.: Wind-driven ocean currents and Ekman transport, Science, 238, 1534–1538, 1987.

Proshutinsky, A., Dukhovskoy, D., Timmermans, M.-L., Krishfield, R., and Bamber, J. L.: Arctic circulation regimes, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 373, https://doi.org/10.1098/rsta.2014.0160, http://rsta.royalsocietypublishing.org/content/373/2052/20140160, 2015.

Randelhoff, A. and Sundfjord, A.: Carbon Bridge CTD hydrography 2014, https://doi.org/10.21334/npolar.2017.f40317d5, https://doi.org/10.21334/npolar.2017.f40317d5, 2017.

Randelhoff, A., Sundfjord, A., and Reigstad, M.: Seasonal variability and fluxes of nitrate in the surface waters over the Arctic shelf slope, Geophysical Research Letters, 42, 3442–3449, https://doi.org/10.1002/2015gl063655, http://dx.doi.org/10.1002/2015GL063655, 2015.

Renner, A. H., Hendricks, S., Gerland, S., Beckers, J., Haas, C., and Krumpen, T.: Large-scale ice thickness distribution of first-year sea ice in spring and summer north of Svalbard, Annals of Glaciology, 54, 13–18, https://doi.org/10.3189/2013AoG62A146, 2013.

Rudels, B.: Arctic Ocean stability: The effects of local cooling, oceanic heat transport, freshwater input, and sea ice melt with special emphasis on the Nansen Basin, Journal of Geophysical Research: Oceans, 121, 4450–4473, https://doi.org/10.1002/2015jc011045, http://dx.doi.org/10.1002/2015JC011045, 2016.

Schulze, L. M. and Pickart, R. S.: Seasonal variation of upwelling in the Alaskan Beaufort Sea: Impact of sea ice cover, Journal of Geophysical Research: Oceans, 117, n/a–n/a, https://doi.org/10.1029/2012JC007985, http://dx.doi.org/10.1029/2012JC007985, 2012.

Serreze, M. C. and Barrett, A. P.: Characteristics of the Beaufort Sea High, Journal of Climate, 24, 159–182, https://doi.org/10.1175/2010JCLI3636.1, https://doi.org/10.1175/2010JCLI3636.1, 2011.

Spall, M. A., Pickart, R. S., Brugler, E. T., Moore, G., Thomas, L., and Arrigo, K. R.: Role of shelfbreak upwelling in the formation of a massive under-ice bloom in the Chukchi Sea, Deep Sea Research Part II: Topical Studies in Oceanography, 105, 17 – 29, https://doi.org/http://dx.doi.org/10.1016/j.dsr2.2014.03.017, //www.sciencedirect.com/science/article/pii/S0967064514000824, the Phytoplankton Megabloom beneath Arctic Sea Ice: Results from the {ICESCAPE} Program, 2014.

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., and Barrett, A. P.: The Arctic's rapidly shrinking sea ice cover: a research synthesis, Climatic Change, 110, 1005–1027, https://doi.org/10.1007/s10584-011-0101-1, http://dx.doi.org/10.1007/s10584-011-0101-1, 2012.

Tetzlaff, A., Lüpkes, C., Birnbaum, G., Hartmann, J., Nygård, T., and Vihma, T.: Brief Communication: Trends in sea ice extent north of Svalbard and its impact on cold air outbreaks as observed in spring 2013, The Cryosphere, 8, 1757–1762, https://doi.org/10.5194/tc-8-1757-2014, https://www.the-cryosphere.net/8/1757/2014/, 2014.

Tremblay, J.-E., Anderson, L. G., Matrai, P., Coupel, P., Bélanger, S., Michel, C., and Reigstad, M.: Global and regional drivers of nutrient supply, primary production and CO2 drawdown in the changing Arctic Ocean, Progress in Oceanography, 139, 171–196, https://doi.org/10.1016/j.pocean.2015.08.009, http://dx.doi.org/10.1016/j.pocean.2015.08.009, 2015.

Våge, K., Pickart, R. S., Pavlov, V., Lin, P., Torres, D. J., Ingvaldsen, R., Sundfjord, A., and Proshutinsky, A.: The Atlantic Water boundary current in the Nansen Basin: Transport and mechanisms of lateral exchange, Journal of Geophysical Research: Oceans, 121, 6946–6960, https://doi.org/10.1002/2016jc011715, http://dx.doi.org/10.1002/2016JC011715, 2016.

Wang, W. and Huang, R. X.: Wind Energy Input to the Ekman Layer, Journal of Physical Oceanography, 34, 1267–1275, https://doi.org/10.1175/1520-0485(2004)034<1267:WEITTE>2.0.CO;2, https://doi.org/10.1175/1520-0485(2004)034<1267:WEITTE>2.0.CO;2, 2004.

Wassmann, P., Kosobokova, K., Slagstad, D., Drinkwater, K., Hopcroft, R., Moore, S., Ellingsen, I., Nelson, R., Carmack, E., Popova, E., and Berge, J.: The contiguous domains of Arctic Ocean advection: Trails of life and death, Progress in Oceanography, 139, 42 – 65, https://doi.org/http://dx.doi.org/10.1016/j.pocean.2015.06.011, //www.sciencedirect.com/science/article/pii/S0079661115001548, overarching perspectives of contemporary and future ecosystems in the Arctic Ocean, 2015.

Williams, W. J. and Carmack, E. C.: The "interior" shelves of the Arctic Ocean: Physical oceanographic setting, climatology and effects of sea-ice retreat on cross-shelf exchange, Progress in Oceanography, 139, 24–41, https://doi.org/10.1016/j.pocean.2015.07.008, http://dx.doi.org/10.1016/j.pocean.2015.07.008, 2015.

Williams, W. J., Carmack, E. C., Shimada, K., Melling, H., Aagaard, K., Macdonald, R. W., and Ingram, R. G.: Joint effects of wind and ice motion in forcing upwelling in Mackenzie Trough, Beaufort Sea, Continental Shelf Research, 26, 2352 – 2366, https://doi.org/http://dx.doi.org/10.1016/j.csr.2006.06.012, //www.sciencedirect.com/science/article/pii/S0278434306002068, 2006.