REVIEW #1

[Below, please find: Your comments preceded by RC, “Reviewer Comment”, and our replies preceded by AR, “Author Reply”]

RC:
The authors made good points on explaining the shelf-break upwelling is regional phenomena and there are other factors need to be considered, such as the wind stress, stratification, vertical mixing and advection. The authors proactively cautioned crowning the shelf-break upwelling as a universal paradigm over new ice depleting Arctic Ocean.

1. Are the authors arguing a false impression? The self break upwelling itself is a regional phenomena. Did any of the papers that the authors refereed, Carmack and Chapman, 2003; Falk-Petersen et al., 2014; Wassmann et al., 2015; Våge et al., 2016; Haug et al., 2017), claimed that the shelf break upwelling is a “universal” phenomena?

AR:
> Thank you very much for reviewing our paper. Below, find our replies to your general comments.

> To our knowledge none of these papers claimed that it is a “universal” phenomenon, and neither did we claim that they had done so. However, based on the available literature, there are multiple claims that (and investigations whether) shelf break upwelling all across the Arctic enhances productivity. Calling this a “paradigm”, a way of thinking, intends to say: Whenever someone talks about “Arctic shelf break” and “productivity”, many people appear to associate that with “upwelling” and next “increasing upwelling leading to increased productivity due to receding sea ice”.

RC:
2. The example that the authors gave, the Barents Sea, does not have favourable wind for the wind driven upwelling. Why the authors suggest that people will mistakenly think that the salinity front observed is a shelf break upwelling?

AR:
> There are two issues here. To take your second point first, we are as puzzled as you are that this salinity front as such is sometimes considered to be due to shelf break upwelling. But it has happened and continues to do so; please see references given in the text (section “Upwelling in the Arctic”).

> We are happy that you agree with us on the general point that not every front at an Arctic shelf break is indicative of upwelling. This is a pretty basic point, and taken at face value, we assume few would defend it in all its generality. However, as complex as the underlying physics are, we have felt the need to clarify its most salient aspects as a basis for discussions of (the even more involved issue of) biological productivity. We believe our paper is helpful for two audiences: People interested mostly in the biology, perhaps with less familiarity with the underlying physics, and people who do know the physics but are looking into how this links to the biology.

> To your first point and eventually linking back to the point we were just making: The Barents Sea actually does (during wintertime, see our Figure 3) have winds that could, just based on alignment of the wind with the shelfbreak and coastline, drive upwelling if a number of additional factors are satisfied. What is dubious, however, is the link to biology, because, as

we show based on available literature, nutrients are abundant in that region without any need for this wintertime upwelling. It is exactly the link to biology which is the focus of our paper, as we are not aware of any equally accessible, concise paper that lays out these kinds of processes.

REVIEW #2

[Below, please find: Your comments preceded by RC, “Reviewer Comment”, and our replies preceded by AR, “Author Reply” and MC, “Manuscript Change”]

RC:
Review of “Short Commentary on Marine Productivity at Arctic Shelf Breaks: Upwelling, Advection and Vertical Mixing” by Achim Randelhoff and Arild Sundfjord

The authors discuss shelf break upwelling in the Arctic Ocean and argue that it should have different characteristics in different parts of the Arctic Ocean and not necessarily will be pronounced phenomena in the Atlantic sector of the Arctic Ocean in general and on the Barents shelf break in particular as a result of the climate change.

Major comments
It seems that authors try to argue with the opinion expressed in some of the recently published papers, that in the future conditions for the shelf break upwelling in the Atlantic sector of the Arctic will become more favourable. However, from the introduction
(or rather “Upwelling in the Arctic” section) it is not clear what are the arguments authors fighting against. They mention personal communications and reference several papers, but did not provide any details.

The counter argumentation is very week. It is basically a collection of statements that are not supported by any evidence. It is just author’s speculations on the topic with ideas that may or may not be true.

I have a hard time to define the type of this article and the purpose it is written for. The topic of the shelf break upwelling in Atlantic sector is very interesting and it would make a great contribution to our understanding of the Arctic Ocean when investigated properly though numerical modelling or data analysis. Unfortunately, this manuscript lacks any scientific novelty supported by evidence. I also believe it is too shallow to be a review. I do not recommend this manuscript for publishing in “Ocean Science”.

AR:
> Thank you for taking the time to review our manuscript. Below, find our replies that we hope might help convince you regarding the purpose and quality of our “short commentary”.

> First, about the type of article and intended readership. You correctly state that this paper lacks the novelty to be an original research article. It is also not a comprehensive review of every study that has been done on this issue (the choice “review article” in OSD is for practical reasons mostly, and suggested by the Editor). Rather, as the title states, it is a “Short Commentary” - implying we take a stance in a debate. (If you do not believe there is such a debate, please go to a relevant conference, mention Arctic shelf break upwelling, sit back and enjoy the discussion.)

> You mention readers “familiar with Arctic Ocean hydrography” would not hold some of the misconceptions we argue against. We can agree here, maybe pending some clarifications about what constitutes “familiar”. But not everyone interested in the biological productivity in Arctic shelf regions is equally well-versed in the underlying physics. This readership in particular may profit from having all the contributing factors laid out in a single, accessible, quick-to-read piece of text, instead of wading through a lot of more detailed literature to acquire the familiarity with the material. (Something similar goes for physicists wishing to link

their research to biology.) With the present manuscript, we tried to provide such an easily accessible text, which has not been published before as far as we know. Following our initial inquiry, we have been encouraged by the handling editor to submit such a text.

> Second, you repeatedly claim that the entirety of the manuscript is based on speculations and statements for which there is no evidence. You must certainly mean “support in the literature” or some such. To this effect, we have in the revised version added a good number of references that will hopefully clarify what we base our reasoning on, even if we initially (and mistakenly) thought these issues were too basic to have to reference them.

> Overall, you criticise us for not writing a different kind of article, which is fair enough, but misses the point of whether this article is useful to large enough an audience.

RC:
Minor comments

AR:
> [Below, please find: Your comments preceded by RC, our replies preceded by AR, and our edits to the text preceded by MC.]

RC:
P 2, L 2 It would be nice to provide references, showing that it “received increased attention”. Now after the sentence you make a reference to the figure, which seem strange and out of place.

AR:
> The reference (after the words “Arctic Ocean”) should have been to the left panel of Fig. 1 only, which shows a map of the Arctic Ocean. We apologize and appreciate that you brought this to our attention so it could be clarified as it should.
MC:
> The reference now reads “see below for a list of references; for an overview of the geography, see the left panel of Fig. 1”, and a later reference to Fig. 1 now reads “an illustration is also given in the right panel of Fig. 1”.

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.

RC:
P3, L5-7 You should really provide more evidence that this is now a “universal paradigm” and that the paper you mention above are actually directly and uncondi-

tionally transfer results obtained for the Pacific sector to the Atlantic Sector.

AR:
> No, it is not (yet). That is why we state "it might appear as if [it is] being cemented", rather than that it "has been" cemented. We also never used the words "directly and unconditionally" (the former only in a different context).

> As for providing evidence that the referenced papers do transfer results from the Pacific side to the Atlantic one, the reader is free to check for themselves; in such a short exposition it would only destroy the flow of the text to quote and paraphrase from all those articles.
But see e.g. Våge et al.; "A comparison to hydrographic data from the Pacific Water boundary current in the Canada Basin under similar atmospheric forcing suggests that upwelling was taking place during the survey." [which took place north of Svalbard, our comment]

> On another note, calling this "a paradigm" does not require that it is occurring everywhere, all the time. Instead, a paradigm is a way of thinking about things. That means that the habit of phrasing shelf break productivity primarily in terms of shelf break upwelling (e.g., Falk-Petersen et al. 2014, Williams&Carmack 2015) we believe qualifies as a paradigm; see also our reply to reviewer 1 on this point.
MC:
> We amended the sentence to "... currently being cemented as a universal paradigm to conceptualize ..." to make this distinction clearer.

RC:
P3, L21 Gradients of what?

AR:
> In this context, what matters are the gradients of physical properties, even though there are plenty more.
MC:
> We added "[large gradients] in physical properties".

RC:
Fig. 2 Why you use this transect? Is it typical? Why not climatology or reanalysis?

AR:
> Yes, it is typical as it says in the figure caption. Otherwise, it is an illustration, and the same comments apply as for Fig. 1 earlier.

> Just as an example, quoting Falk-Petersen et al. (2014), who were measuring in this area and at the same time of the year, "all transects had very similar hydrographic characteristics, with an upwelling zone of warm Atlantic Water (temperature 3–4 °C, salinity ~35 psu) stretching from west to east along the northern Svalbard Shelf".

> As another illustration, see the attached plot below (showing a transect at a similar location across the shelf break) produced (for wind conditions that people might refer to as neutral in terms of "upwelling-favourability") from the same ROMS 800x800 m model that was used for the right panel of Figure 1. It was made for another (quantitative) manuscript on circumpolar upwelling that is going to be submitted in the not too distant future. We do however choose not to include it in the present manuscript we are currently discussing in order to not clutter the paper; also based on the available literature (Våge et al. 2016, Cokelet et al. 2008, and others) there should be no doubt that the situation we present in Fig. 2 is representative.

RC:
P4, L4-9 It is not clear to me why any reader familiar with Arctic Ocean hydrography must think that Fig. 2 show typical upwelling situation?

AR:
> Well, that is exactly one of our points, and we are just as puzzled as you are. Then again, not everyone interested in the biological implications might be sufficiently "familiar" with Arctic Ocean hydrography. Given experiences in other regions of the world ocean, it is at any rate not an abstruse idea to think of upwelling when one sees isolines outcropping at the surface close to a shelf break or coastline.

RC:
P4, L13 Ivanov et al., 2016 show that under certain conditions heat from the Atlantic Water can mix up to the surface, but this process is not constant and over the northern Barents Sea shelf the thermal stratification in the upper 100 meters is actually still quite strong most of the time.

AR:
> You are right.
MC:
> We added "potentially [leading to....]" before wintertime convection.

RC:
P5 L3-15 Statements in this section need supporting evidence. Now it is pure speculations.

AR:
> Assuming by "supporting evidence" you mean references:
MC:
> We have now inserted a number of references in that section.

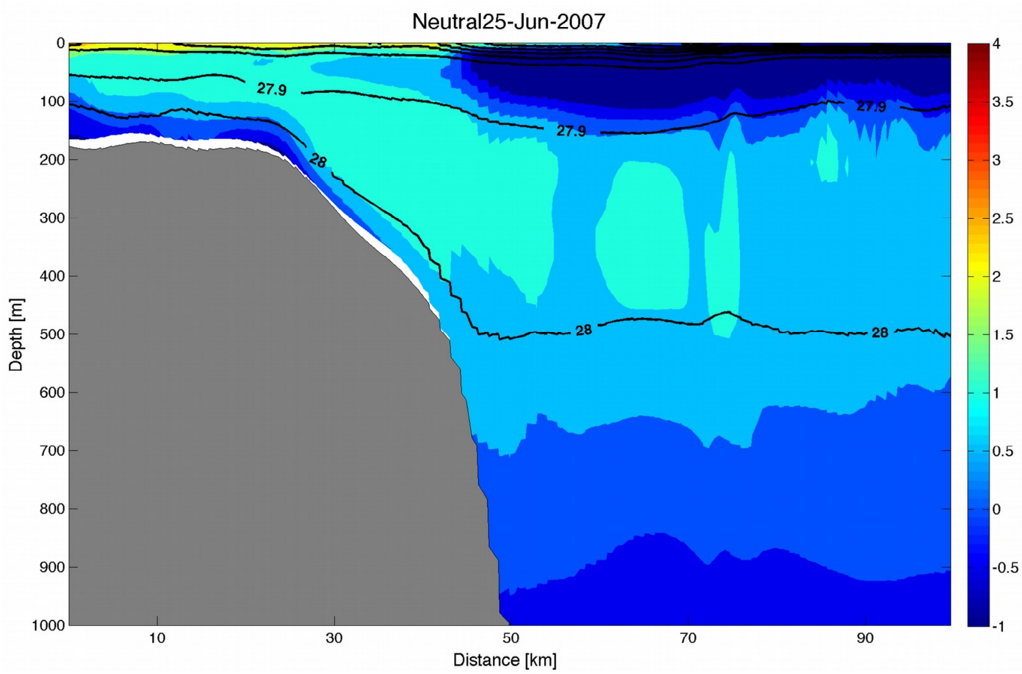
RC:
P5, L 17 No, we haven't. You just claim it to be true earlier, but you did not show anything to support this claim.

AR:
> Specifically, on p.4 l.12-14 (original version) we give two references for how vertical mixing is strong in winter (namely, weak thermal stratification), which directly implies that the mixed layer replenishment of nutrients can happen "without recurrence to wintertime upwelling". That doesn't mean wintertime upwelling is not happening or cannot ever happen, it just means that "upwelling" is not strictly necessary to replenish nutrients.
MC:
> We amended the text to "can be replenished" to better express this uncertainty.

RC:
I am sorry but most of the rest of the analysis is again just pure speculations and to my opinion have no value as a review.

AR:

> See our comments at the outset about intended article type and audience. More details as to what exactly you think is speculation would have been helpful, as certainly not “most” of our statements are.
> At any rate, we added many references that you will hopefully find helpful. Also, we did add a sentence to the paragraph explaining why a shelf has to be sufficiently shallow and/or narrow to allow for wind-driven upwelling in order to stress our reasoning there as one of the more central parts of the whole line of arguments.



REVIEW #3

[Below, please find: Your comments preceded by RC, “Reviewer Comment”, and our replies preceded by AR, “Author Reply” and MC, “Manuscript Change”]

RC:
This short commentary manuscript brings up a hot and important topic on how wind-driven upwelling, in conjunction with dramatic sea ice loss, may affect ocean productivity on the vast Arctic continental shelves. The authors argued that “shelf break up-welling is likely not a universal but rather a regional, albeit recurring feature of the new Arctic.” I do agree with the authors that regional geographic, atmospheric, oceano-graphic, and sea ice conditions must be taken into account when assessing pan-arctic upwelling phenomena and their impacts on upper ocean nutrient supply and primary production processes. Nonetheless, the authors can better justify their arguments and greatly improve the paper by providing more concrete data analysis and evidence, particularly in the northern Barents Sea shelf where the authors claim upwelling may function differently from other Arctic shelf systems.

AR:
> We appreciate the reviewer’s support for our key statement that a number of basic conditions, including geographical, together determine if and how upwelling and associated effects on the ecosystem are important in different parts of the Arctic. As you will see from our replies to the two first reviewers’ comments we acknowledge that the purpose of the paper, and therefore also the reason for relying on general examples rather than comprehensive data analysis, should have been more clearly explained in the submitted manuscript. Namely, the goal of this paper is (partly) to show that just by general physical considerations, many conclusions can be reached already. These conclusions can help guide hypotheses and field measurements. In the revised version we have attempted to make the key points clearer; that these basic conditions can and should be assessed for different regions, and that snapshot data don’t necessarily allow for underlying mechanisms to be deduced. We hope that our responses and suggested manuscript amendments detailed below are sufficient to clarify these key aspects.

> [Below, please find: Your comments preceded by RC, our replies preceded by AR, and our edits to the text preceded by MC.]

RC:
Other comments:
Figure 1: The illustrations are too vague and lack important geographic and hydro-graphic features. In the left panel, I would suggest the following changes: (1) add lati-tudinal 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.

RC:
In section “Many interconnected phenomena”: The authors tried to explain different physical mechanisms that drive upwelling and other physical processes that interact with upwelling. I am uncomfortable that the authors did not attempt to put their discussion in the context of rich literature in upwelling. There is not a single citation in the section, which is unusual.

AR:
> You are right, and this was also mentioned by reviewer #2. We have added a fair amount of citations throughout the text to be sure to make it clear to the reader that what we base our argument on is well-established in the literature and not our own speculation.

RC:
In section “Drivers of marine productivity vary across the Arctic Ocean”: The authors should provide observational evidence when claiming Beaufort Gyre region is “one of most nutrient-depleted regions of the world ocean”.

AR:
> Agreed; see also our reply immediately above.
MC:
> We have now inserted Codispoti et al., 2013, as a reference.

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.

RC:
Figure 3: This is not an effective way to illustrate wind patterns. Did black dots represent speeds of east wind component? So only those with 3 m/s or more were showed in the figure? How often were the wind measured? The author stated “only 2% of all

summer days through the last 30 years can be considered upwelling-favorable", but what's the sample size in total? It didn't look to me that 30-year wind measurements were included in the analysis given this few data points. To demonstrate seasonal differences in wind patterns and highlight the summer season, a plot of four wind roses that aggregate seasonal wind measurements might be more informative and illustrative.

AR:
> Exactly, so the take-home message is that even taking 30 years of wind data only results in so few data points where wind could potentially be upwelling-favourable (*IF* the shelf break was shallow enough, see the preceding arguments in our manuscript). A wind rose would not discriminate between short episodes of easterly wind (not sufficiently long to affect Ekman transport) and would hence tend to "overestimate" the occurrence of upwelling-favorable winds.

MC:
> *We added "[rather low a wind speed and makes for a generous criterion in this regard]; there is no universally accepted measure" to make it clearer to the readers that this methodology is more of a tentative thought experiment, assuming that the wind could drive upwelling in the first place even though the shelf is rather deep in the area in question. The figure caption now also says "assuming the local bathymetry facilitates such upwelling".*

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 [...]"*

RC:
In section "Climate Change and the Future of Arctic Marine Productivity", I think another relevant point is the changing phytoplankton abundance and species composition in response to changing hydrography and nutrients. I would suggest the authors to briefly touch on this point. Two examples are: 1) Li, W. K. W., F. A. McLaughlin, C. Lovejoy, and E. C. Carmack (2009), Smallest algae thrive as the Arctic Ocean freshens, Science, 326, 539; 2) Li, W. K. W., E. C. Carmack, F. A. McLaughlin, R. J. Nelson, and W. J. Williams (2013), Space-for-time substitution in predicting the state of picoplankton and nanoplankton in a changing Arctic Ocean, J. Geophys. Res. Ocean., 118(10), 5750–5759.

AR:
> We did not originally include this story about plankton size spectra because our focus has been on the shelf breaks specifically, but we agree that this is important for the large-scale picture.
MC:

> We have now included them as you suggest; please see last paragraph in the “Climate Change and the Future…” section..

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

Achim Randelhoff[1] and Arild Sundfjord[1]

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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.

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.).

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). As the ice cover 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): 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 ~~around~~ 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.

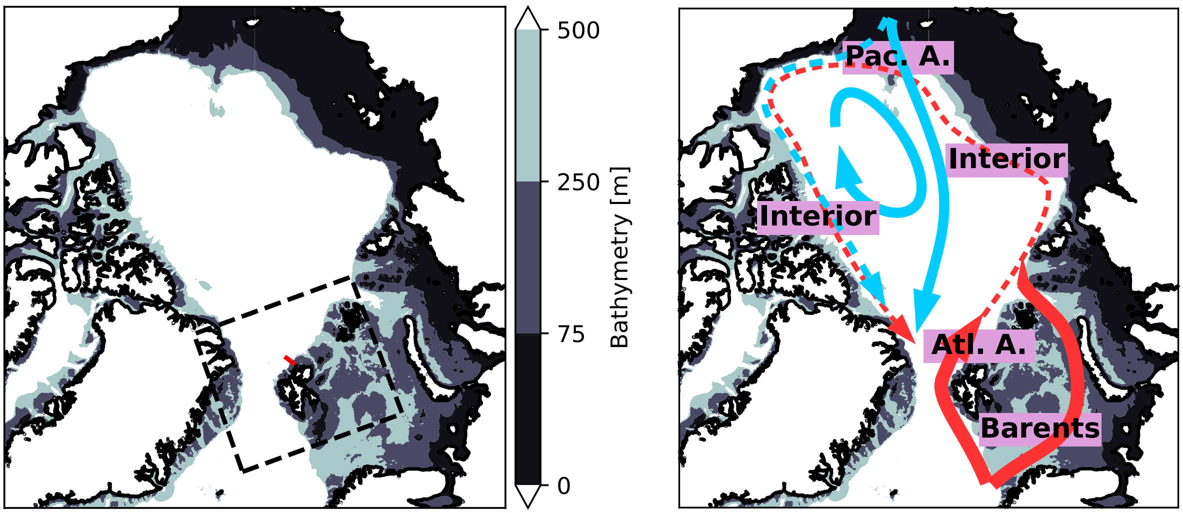

Figure 1. ~~Left:~~ Map of the Arctic Ocean (based on Jakobsson et al., 2012), indicating the general ~~hydrographic~~ geographic regimes. Left: Bathymetry of the shelf and shelf break area. The black box shows the area in Fig. 2, left panel. The red line shows the location of the transect shown in Fig. 2, right panel. Right: The Pacific Arctic, Atlantic Arctic, interior shelves (following Williams and Carmack, 2015); and the Barents Sea. ~~The dashed line shows~~ Arrows show selected patterns of the ~~sector in the panel to the right~~general circulation (after Polyakov et al., 2012). ~~Right~~Blue arrows: ~~Inflowing warm~~ Pacific-derived and ~~salty Atlantic Water increases surface salinity on and around~~ other freshwater flowing along the shelf break, ~~enabling convection when~~ through the ~~surface waters are cooled~~ Transpolar Drift and in ~~winter~~the Beaufort Gyre. ~~Color scale shows salinity~~Red arrows: Atlantic-derived water entering the Arctic Ocean through Fram Strait and the Barents Sea, ~~black contour lines show~~ flowing along the ~~0~~ shelf break, submerging north of the Barents Sea and ~~3°C isotherms~~recirculating along the shelf break through the Arctic Ocean. ~~(January 2010 mean at 15 m depth from an 800 x 800 m horizontal resolution ROMS ocean and sea ice simulation, see Hattermann et al. (2016))~~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. 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 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; Wassmann et al., 2015; Våge et al., 2016; Haug et al., 2017)~~(see e.g. Falk-Petersen et al., 2014; Tetzla Thus it might appear as if shelf break upwelling is currently being cemented as a universal paradigm ~~of~~ to conceptualize *the* "new" Arctic Ocean where global climate change is taking us. We will argue that some of the regional differences cannot be ~~brushed over~~ 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. Aagaard and Carmack, 1989)~~(e.g. Morison et al., 2012; Proshutinsky et al., 2015). When light water (at ~~cold~~ low temperatures, this means fresher) sits on top of heavy water, mixing will not be as efficient (e.g. Osborn, 1980), which means that ~~given a certain amount of energy to stir the ocean, the~~ 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 the Beaufort Gyre~~is~~ , 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).

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 Rudels, 2016, for example; also Fig. 1)~~(see e.g. Rudels, 2016, ; an illustration Seeing this situation in the contour plot of a hydrographic transect (see right panel of Fig. ~~??~~2) 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. ~~??~~ 2 alone.

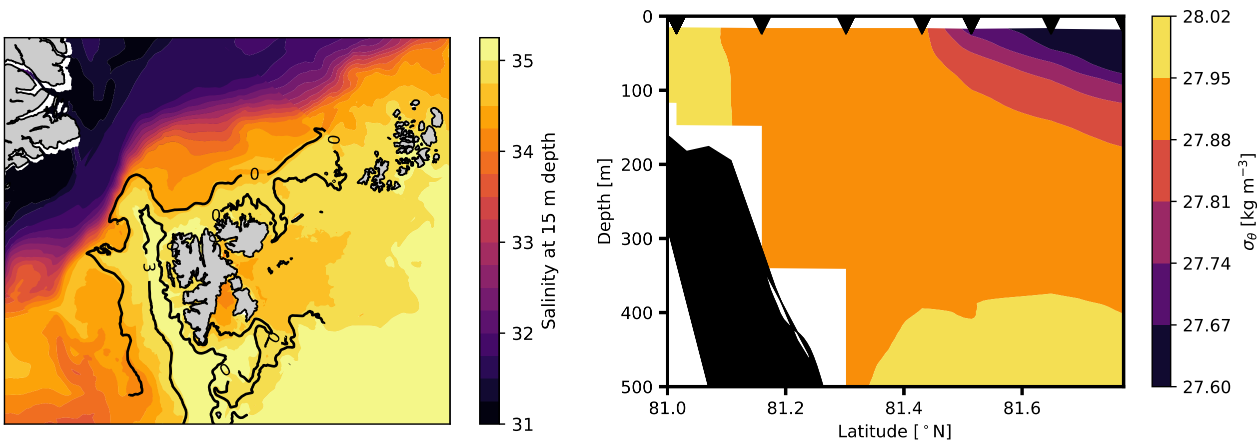

Figure 2. Representative illustration of the hydrographic regime in the Atlantic inflow area along the northern Barents Sea shelf break. Left: Inflowing warm and salty Atlantic Water maintains high surface salinity on and around the shelf, enabling convection when the surface waters are cooled in winter. Color scale shows salinity, black contour lines show the 0 and 3°C isotherms. (January 2010 mean at 15 m depth from an 800 x 800 m horizontal resolution ROMS ocean and sea ice simulation, see Hattermann et al. (2016).) Right: Seawater density in a typical wintertime transect across the shelf slope north of Svalbard, sampled in January 2014 (unpublished data from ~~around~~ approximately 81.5°N, 17.5°E, RV Helmer Hanssen, Carbon Bridge project~~)~~; see Fig.~~Coming from the basin~~ 1, ~~the~~ left panel, for location). The surface water is markedly heavier above the upper shelf slope than over the deep basin. Black triangles mark hydrographic stations.

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 by Ca~~ The salient point is this: As the Atlantic Water is cooled ~~off~~ 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 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 concentration. 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.

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.

~~For~~ In addition, shelf break upwelling ~~, the~~ requires a sufficiently shallow shelf. This is because the previously mentioned divergence in off-shelf surface transport can only be potent enough when the shelf itself is shallow enough to actually constrict the surface flow over the shelf. Whereas most continental shelves of the Arctic Ocean are extremely shallow (in parts less than 50 m), the Northern Barents Sea shelf break is relatively deep at around 150-200 m. 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 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 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 at the northern Barents Sea shelf break ~~are~~ can be replenished 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 ~~westerlies~~ 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. 3). This comes on top of a general pattern where wind speeds north of Svalbard are lower in summer than in winter. Fig. 3 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).

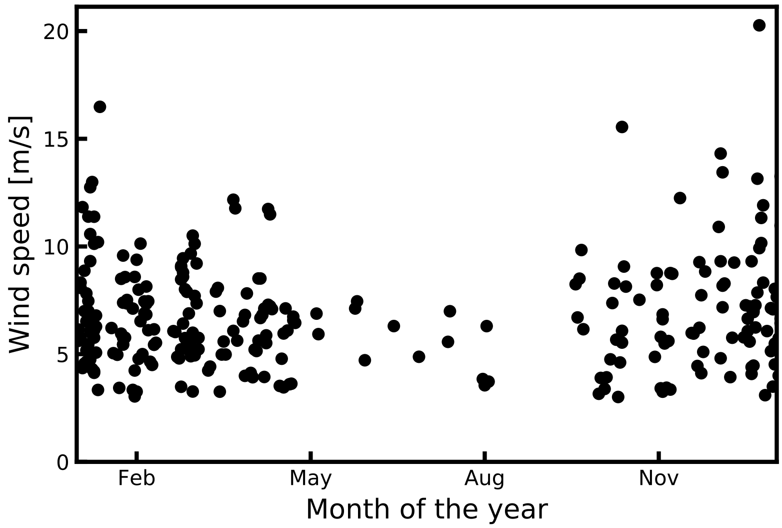

Figure 3. Days of "potentially upwelling-favourable" winds north of Svalbard 1987-2017 assuming the local bathymetry facilitates such upwelling, based on ERA-INTERIM data (Dee et al., 2011) for the region 79–81°N, 5–30°E. A daily windspeed was considered "potentially upwelling-favourable" if its (approximately 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 and makes for a generous criterion in this regard; there is no universally accepted measure.) From the beginning of May through August each year, ~2% of all days were "potentially upwelling-favourable".

~~Indeed,~~ 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 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.).

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 wind driven upwelling (or for Ekman pumping for that sake). 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, 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 is sufficiently cooled and subsequently can subduct 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.

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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