Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

Ocean Science Discussions
Open Access EGU

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

Achim Randelhoff[1] and Arild Sundfjord[1]
[1]Norwegian Polar Institute, Fram Centre, N-9296 Tromsø, Norway
Correspondence to: Achim Randelhoff (achim@npolar.no)

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.

Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

Ocean Science
Discussions
Open Access

Shelf break upwelling has recently received increasing attention also in the Arctic Ocean (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: 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.

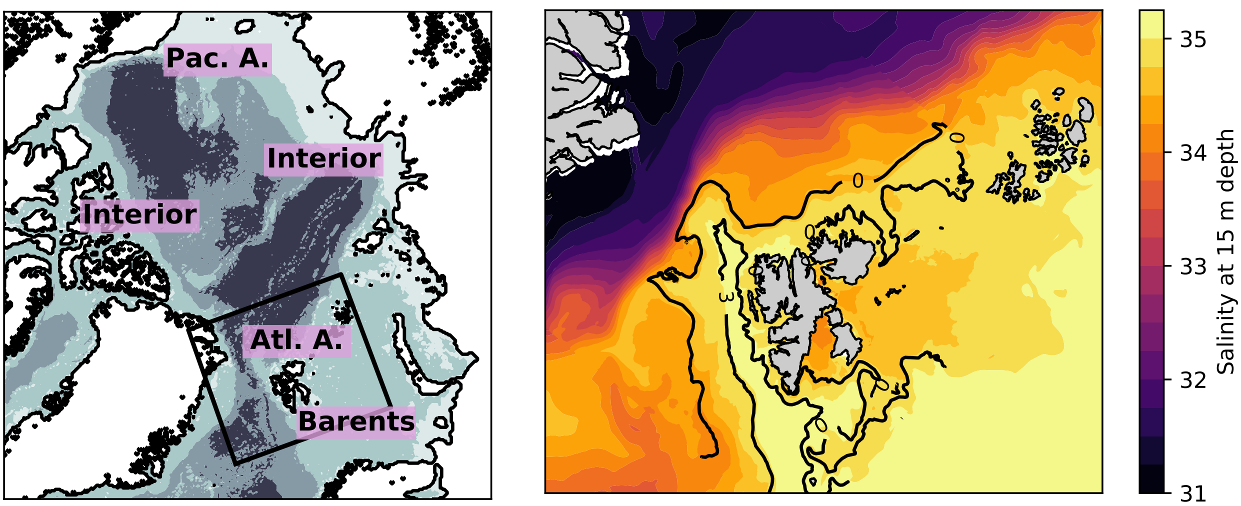

Figure 1. Left: Map of the Arctic Ocean, indicating the general hydrographic regimes: The Pacific Arctic, Atlantic Arctic, interior shelves (following Williams and Carmack, 2015); and the Barents Sea. The dashed line shows the sector in the panel to the right. Right: Inflowing warm and salty Atlantic Water increases 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))

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.

Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

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 of *the* "new" Arctic Ocean where global climate change is taking us. We will argue that some of the regional differences cannot be brushed over 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.

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 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. 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; Morison et al., 2012; Proshutinsky et al., 2015). When light water (at cold temperatures, this means fresher) sits on top of heavy water, mixing will not be as efficient, 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

Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

Ocean Science
Discussions
Open Access
EGU

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.

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). Seeing this situation in the contour plot of a hydrographic transect (see 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 Fig. 2 alone.

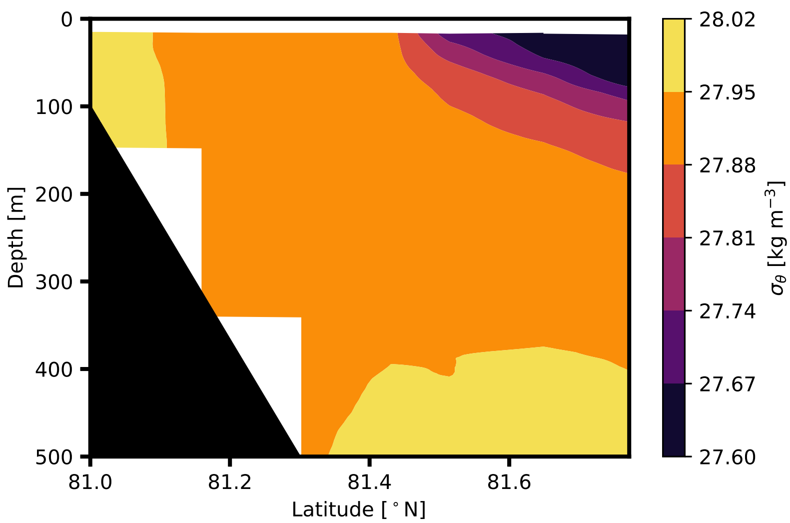

Figure 2. Seawater density in a typical wintertime transect across the shelf slope north of Svalbard, sampled in January 2014 (unpublished data from approximately 81.5°N, 17.5°E, RV Helmer Hanssen, Carbon Bridge project). Coming from the basin, the surface water is markedly heavier above the upper shelf slope.

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 Carmack, 2007). The salient point is this: As the Atlantic Water is cooled on its way north, it loses stability, 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

Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

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 shelf break upwelling, the 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 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.

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 at the Canadian shelf break. The atmospheric circulation in the Atlantic sector is more dynamic in summer, with less of a preference for a specific upwelling-favourable wind direction. 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).

Indeed, A. Renner and collaborators 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 occur-

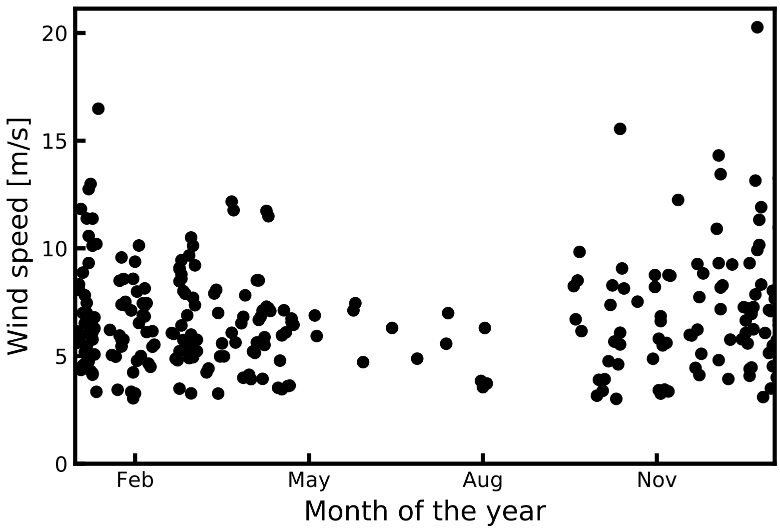

Figure 3. Days of "potentially upwelling-favourable" winds north of Svalbard 1987-2017, based on ERA-INTERIM data (Dee et al., 2011) for the region 79–81°N, 5–30°E. A daily windspeed was considered "potentially upwelling-favourable" if its (approximately easterly) along-shelf component exceeded 3 m s^{-1} 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.) From the beginning of May through August each year, ∼2% of all days were upwelling-favourable.

rence 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. 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 and the more dynamic first- and second year ice cover north of Svalbard. 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. 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.

Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

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).

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.

Acknowledgements. We thank Randi Ingvaldsen for very useful feedback and discussions on an earlier draft of the manuscript. AR was funded by the Norwegian Research Council project Carbon Bridge, a Polar Programme (project 226415) funded by the Norwegian Research Council. The model simulation fields shown in Fig. 1 are a product of the "ModOIE" project funded by the Fram Centre 'Arctic Ocean' flagship program.

Competing interests. The authors declare that no competing interests are present.

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., 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.

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.

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.

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. L., 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/http://dx.doi.org/10.1016/j.pocean.2016.10.004, http://www.sciencedirect.com/science/article/pii/S0079661116302051, 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.

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

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.

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.

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., 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.

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.

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.

Ocean Sci. Discuss., https://doi.org/10.5194/os-2017-68
Manuscript under review for journal Ocean Sci.
Discussion started: 30 August 2017

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.

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.