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# Role of shelfbreak upwelling in the formation of a massive under-ice bloom in the Chukchi Sea

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ABSTRACT

In the summer of 2011, an oceanographic survey carried out by the Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) program revealed the presence of a massive phytoplankton bloom under the ice near the shelfbreak in the central Chukchi Sea. For most of the month preceding the measurements there were relatively strong easterly winds, providing upwelling favorable conditions along the shelfbreak. Analysis of similar hydrographic data from summer 2002, in which there were no persistent easterly winds, found no evidence of upwelling near the shelfbreak. A two-dimensional ocean circulation model is used to show that sufficiently strong winds can result not only in upwelling of high nutrient water from offshore onto the shelf, but it can also transport the water out of the bottom boundary layer into the surface Ekman layer at the shelf edge. The extent of upwelling is determined by the degree of overlap between the surface Ekman layer and the bottom boundary layer on the outer shelf. Once in the Ekman layer, this high nutrient water is further transported to the surface through mechanical mixing driven by the surface stress. Two model tracers, a nutrient tracer and a chlorophyll tracer, reveal distributions very similar to that observed in the data. These results suggest that the biomass maximum near the shelfbreak during the massive bloom in summer 2011 resulted from an enhanced supply of nutrients upwelled from the halocline seaward of the shelf. The decade long trend in summertime surface winds suggests that easterly winds in this region are increasing in strength and that such bloom events will become more common.



## 1. Introduction

Shelfbreak upwelling is observed in all seasons in both the Alaskan and Canadian Beaufort Seas. It is most common in the fall and winter months when Aleutian low pressure systems, passing to the south, result in easterly winds along the north slope of Alaska and Canada. Under such conditions the normally eastward-flowing Pacific water shelfbreak jet reverses to the west, and water from the interior halocline is brought onto the shelf (e.g. Pickart et al., 2009; Schulze and Pickart, 2012; Williams et al., 2006). As part of this wind-driven exchange, heat and freshwater are fluxed offshore in the surface layer, while nutrients and $CO_2$ are transported upwards and onshore. The consequences of this shelf–basin transfer are significant. Pickart et al. (2013b) demonstrated that substantial ice melt can occur due to the offshore advection of warm Pacific water, which may also influence the freshwater reservoir of the Beaufort Gyre. Mathis et al. (2012) showed that significant outgassing of $CO_2$ to the atmosphere can take place due to the upwelling, and Pickart et al. (2013a) quantified the upward flux of nitrate into the surface layer in the vicinity of the shelfbreak. It was argued that such wind-driven transport of nutrients along the Beaufort shelf can spur primary productivity comparable to that which occurs during the summer months in the absence of storm events.

Using mooring data, Schulze and Pickart (2012) investigated the influence of pack ice on the oceanographic response to easterly winds in the Beaufort Sea. They divided the year up into three ice seasons—open water, partial ice, and full ice. Notably, upwelling occurred even when the ice concentration was 100% in the vicinity of the mooring array. The strongest response (for a given wind speed) was during the partial ice season, which is believed to be the consequence of enhanced surface stress resulting from the mobile ice keels (Pite et al., 1995; Williams et al., 2006; Pickart et al., 2013b). While the water column response was weakest for full ice cover, the strength of the reversed shelfbreak jet, as well as the value of the salinity anomaly near the upper-slope and shelf

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edge, was nearly comparable to that for open water, indicating that significant wind stress is transmitted through the ice to the ocean.

Upwelling is to be expected for easterly winds because onshore transport develops at depth in response to the offshore Ekman transport near the surface. Upwelling occurs in proportion to the bottom velocity times the bottom slope. It is large near the shelfbreak because the slopes are typically steep, however it is often carried in the bottom boundary layer, which is $O(10\ \text{m})$ thick. In order for nutrients to be available for primary production they must be transported into the euphotic zone, which is typically in the upper $O(20\ \text{m})$ of the water column. For a narrow shelf, as in the Beaufort Sea, this cross-shelf flow in the bottom boundary layer rapidly encounters shallow water near the coast where it upwells into the surface layer and large productivity is often found. The region of strongest upwelling is typically within a baroclinic deformation radius of the coast, $\leq O(20\ \text{km})$, Allen (1976).

Comparatively little is known about upwelling along the offshore edge of the Chukchi Sea, but there are reasons to expect that it may differ from that along the Beaufort shelf. The Chukchi shelf is $O(500\ \text{km})$ wide, effectively isolating the shelfbreak from the coast, while the Beaufort shelf is only $O(50\ \text{km})$ wide. Furthermore, the upper continental slope of the Chukchi Sea is significantly gentler, $O(.002–.004)$, compared to that of the Beaufort Sea, which is $O(.01)$. Depending on the bottom slope and mixing strength, it is expected that the cross-shelf exchange and upwelling may be very different for wide shelves compared to narrow shelves (e.g. Estrade et al., 2008). Hence, it is not obvious that the upwelling response should be the same in the two seas, nor is it clear that similar productivity would result even if there is upwelling.

There is, however, previous evidence of upwelling along the Chukchi shelfbreak. Llinás et al. (2009) presented a hydrographic and absolute geostrophic velocity section occupied across the shelfbreak at 160°W (approximately 200 km to the west of Barrow Canyon) during a period of easterly winds in August 2004. Both the observed currents and hydrographic fields were consistent with a partially recovered shelfbreak jet near the end of an upwelling event. In particular, the isopycnals of the Atlantic water in the lower halocline were elevated in the vicinity of the upper slope, and there was a surface-intensified jet flowing to the west seaward of the shelfbreak. Furthermore, in the immediate vicinity of the shelfbreak, there was a double-peaked eastward flow structure reminiscent of the case study presented by Pickart et al. (2011); the deeper flow was akin to the “rebound jet” that consistently appears during the spin-down phase of upwelling (see also Nikolopoulos et al., 2009). Although not conclusive, these results strongly suggest that upwelling does occur along the Chukchi shelfbreak.

In summer of 2011 an extensive survey of the central/eastern Chukchi Sea revealed the presence of a massive phytoplankton bloom under the ice (Arrigo et al., 2012; Arrigo et al., this issue). It is believed that the thin pack ice (order 1 m thick), in conjunction with a preponderance of melt ponds, allowed enough sunlight to penetrate the surface water column for phytoplankton to tap nutrients and spur the production. The under-ice bloom was observed on two different transects, and in both instances the highest values of chlorophyll occurred in the vicinity of the shelfbreak. In fact, the vertically integrated chlorophyll in the second transect was one of the largest values ever observed in the global ocean (Arrigo et al., this issue). This suggests that there was a prolonged supply of nutrients to the surface layer, yet the shelfbreak here is located far from the coast where the strongest upwelling into the surface layer is expected to occur.

In this paper we propose a physical mechanism responsible for the shelfbreak “mega-bloom”. The in-situ hydrographic and velocity data suggest that upwelling had occurred prior to and during the biological sampling, which is consistent with the atmospheric forcing as well. The central issue is how nutrients from the deep, offshore ocean can be introduced to the surface layer near the shelfbreak. We invoke a simple numerical model to identify the underlying cause of the bloom, using parameters appropriate to the Chukchi shelf and slope. The model suggests that, under the conditions in which the bloom was observed, upwelling and mixing in the vicinity of the shelfbreak transported nutrients from the halocline to the surface layer, consistent with the hydrographic and biological observations. We begin the paper with a short background on upwelling in the Beaufort Sea in order to provide context. This is followed by a presentation of the atmospheric circulation in the region, and the wind forcing during the specific period of the field program. Next the observational evidence for upwelling is presented along with a description of the bloom. Finally, the numerical results are used to propose a simple physical process responsible for the mega-bloom.

## 2. Data and methods

### 2.1. *in situ ocean measurements*

In summer 2011, the Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment (ICESCAPE) program carried out a survey of the central and eastern Chukchi Sea aboard the USCGC *Healy*. The cruise took place from 28 June–24 July. Extensive biological, ice, and physical oceanographic sampling was carried out during the cruise. For a complete description of the different measurements the reader is referred to Arrigo et al. (this issue). Here we present data from one of the ICESCAPE transects occupied from 4–8 July (Fig. 1). This is the section where the largest under-ice values of chlorophyll were observed in the vicinity of the shelfbreak. The hydrographic sampling was done using a SeaBird 911+ conductivity-temperature-depth (CTD) instrument attached to a 12-position rosette with 30-liter Niskin bottles. The CTD included a WETLabs fluorometer. Water samples were analyzed for nutrient concentrations and chlorophyll. Details concerning the observational methods and instrument accuracies are presented in Arrigo et al. (this issue) and Brown et al. (submitted for publication).

Velocity measurements were made throughout the cruise using *Healy's* hull-mounted 150 KHz acoustic Doppler current profiler (ADCP). The University of Hawaii UHDAS acquisition system was used, and additional processing was done using the CODAS3 software package (see http://currents.soest.hawaii.edu). The processed velocities were subsequently de-tided using the Oregon State University model (http://volkov.oce.orst.edu/tides; Padman and Erofeeva, 2004). The accuracy of the de-tided product is estimated to be $\pm 2$ cm/s.

Shipboard data from an earlier cruise in the region are analyzed as well. This was a hydrographic survey done on the USCGC *Polar Star* during July–August, 2002 when the atmospheric conditions were significantly different than during the ICESCAPE program. A similarly configured CTD system was used, whose set-up and instrument accuracies are described in Pickart et al. (2005a). Since the *Polar Star* did not have a shipboard ADCP, a dual-300 KHz RD Instruments ADCP system was attached to the rosette frame, which provided vertical profiles of velocity at the station sites. The profiles were similarly de-tided (although tidal amplitudes are small in this region), and the resulting accuracies are estimated to be 2–3 cm/s. We focus on the 2002 hydrographic transect that was located in the vicinity of the mega-bloom observed during ICESCAPE (Fig. 1).

Mooring data from the Beaufort Sea are used in Section 3 to provide context for the upwelling observed on the Chukchi slope. The mooring array was part of the Shelf–Basin Interactions (SBI)

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