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Wintertime water dynamics and moonlight disruption of the acoustic backscatter diurnal signal in an ice-covered Northeast Greenland fjord

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Key points:

- ***DVM in Young Sound persisted throughout the entire winter including the period of polar night;***
- ***Polynya-enhanced circulation disrupted DVM favouring zooplankton to occupy the surface layer;***
- ***Weaker intensity of DVM beneath ice during polar night was observed when the moon was in full phase.***

Diel vertical migration (DVM) of zooplankton is a process of synchronized movement of the organisms from the mesopelagic zone up to the epipelagic zone at night and returning back during the day. DVM is considered to be the largest synchronized diel movement of biomass on the planet. It also acts as a biological pump in transferring organic carbon from the surface of the ocean to depth.

Recent studies based on acoustic backscatter data showed presence of synchronized DVM behavior of zooplankton that continued throughout the Arctic winter, in both open as in ice-covered waters] While significant progress has been made in understanding DVM and its driving mechanisms, the oceanographic forcing interaction with of DVM in high latitude waters remains poorly understood. Vertical density stratification and water dynamics along with sea-ice cover are among the most important factors that seem to be capable to modify the regular patterns of DVM . Arctic fjords with relatively isolated water columns exposed to the interaction with the shelf only through the fjord entrances, allow clear attribution of the oceanographic forcing and therefore represent an excellent research laboratory for investigating the impact of the oceanographic forcing on DVM.

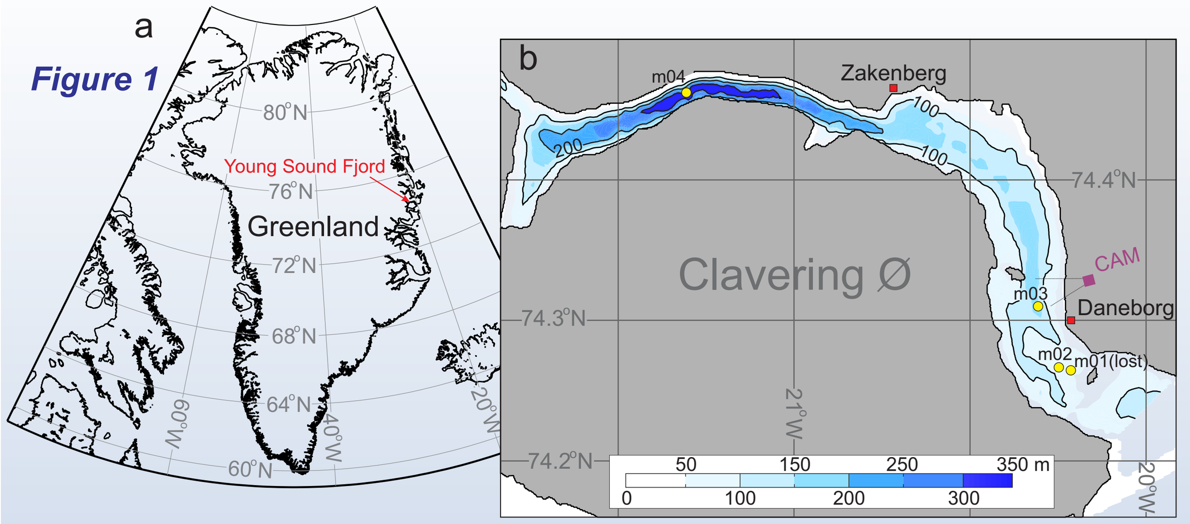


Figure 1

1. Introduction

Young Sound (YS) fjord in Northeast Greenland at ~74°N. YS represents a relatively deep (340 m) and long (~90 km) high latitude fjord with a water depth of 40 m at the sill at its mouth. Land-fast ice covers the fjord from late October to beginning of July. During winter, the land-fast ice extends off the YS mouth by 10-30 km and completely eliminates wind stress to the water column. Based on oceanographic observations we show that the DVM signal was disrupted below the land-fast ice when a polynya opened over the YS outlet to the Greenland Sea and caused enhanced surface layer (0-40 m) transport toward the mouth of the fjord and inflow to the fjord in a layer below (~40-140 m). We also show that DVM below the 60-90 cm thick land-fast sea ice and up to 50 cm of snow cover was affected by the moon cycle during polar night showing a disrupted signal in the subsurface layer and a generally weaker intensity of vertical migrations at the full moon phase.

2. Data

Mooring setup

Between October 2013 and May 2014, four land-fast ice-tethered moorings were deployed from the stationary land-fast ice in YS **(Figure 1)**. All moorings included 300 kHz downward-looking Workhorse Sentinel ADCPs by Teledyne RD Instruments, mounted in 2 m long land-fast ice-tethered PVC pipes.

To correct for beam geometry we derived volume backscatter strength (VBS) S_v in dB from echo intensity following the procedure described by *Deines*, [1999] . The ADCP-derived vertical velocity can also be used to study rates of zooplankton DVM.

The mooring-based observations were complemented by conductivity-temperature-depth (CTD) profiling during the deployment and recovery of moorings **(Figure 2b)** with an SBE-19plus (Sea-Bird Electronics).

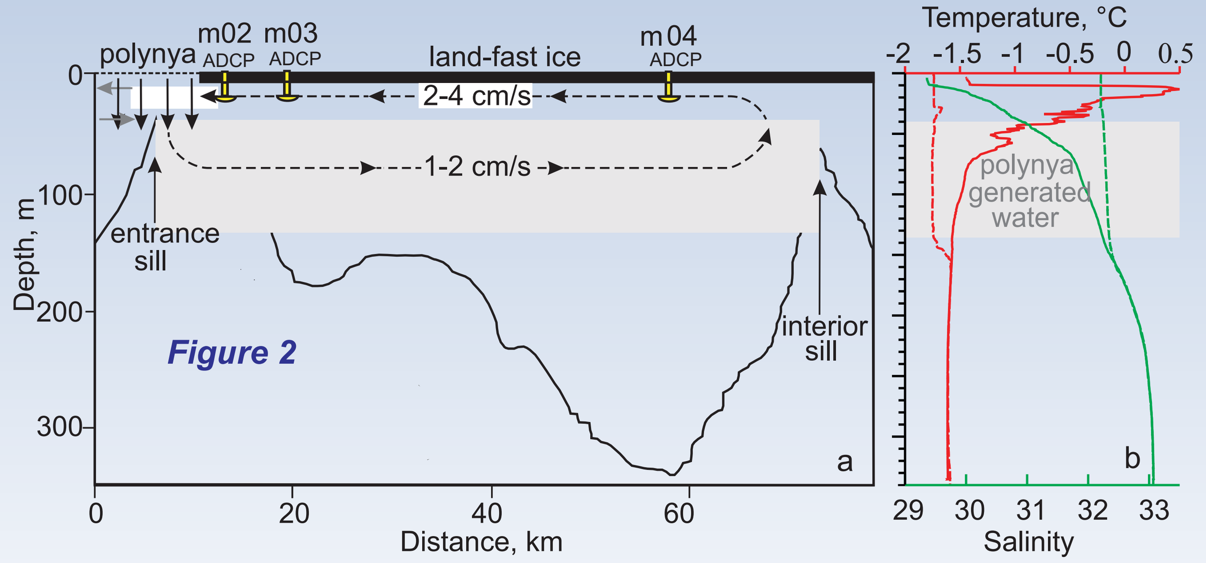


Figure 2

Snow and ice thickness, illumination during polar night

An ice-mass balance buoy (IMB) [Kirillov et al., 2015] deployed at the *m04* position in October 2013 provided data on ice thickness and snow depth **(Figure 4a)**.

The lengths of daylight and twilight were calculated using trigonometry equations. A modelled total sky illumination for day and night was calculated using the astronomy package for Matlab [Ofek, 2014]. Under ice illumination was calculated using exponential decay radiative transfer model [Perovich, 1996].

For monitoring ice, snow and illumination conditions and visual verification, a time lapse camera was installed in the mouth of fjord overlooking mooring *m03* **(Figure 3)**. The total cloud cover (%) for the YS region was obtained from the National Centers for Environmental Prediction (NCEP).

The polar night period (near complete darkness) for YS at 74.4°N lasted from 28 November to 10 January, while civil twilight lasted from 3 November to 3 February **(Figures 3 and 4a)**. Even though YS is located south of 78° zone of nautical polar night latitudes , the illumination in the fjord interior (mooring *m04*) remained close to that of the nautical polar night due to the significant shadowing effect of the ~1000 m high mountains bordering the fjord.

For the analysis of acoustic backscatter data we used wavelet transformation to derive the time-dependent behaviour of the acoustic backscatter at the diurnal frequency band that dominates the backscatter spectrum

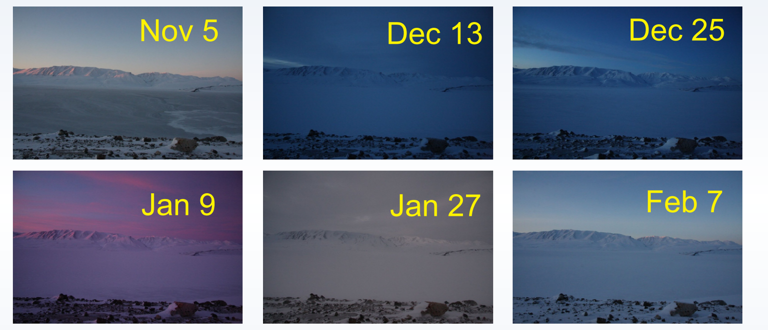
3. Results

Acoustic backscatter intensity time series

The time series of the VBS from the moorings *m02* and *m03,* located near the mouth of fjord, show maxima in backscattering at depths beneath 40 m until 20 December **(Figure 4)**. After that a period of enhanced circulation commenced and lasted until 23 January. During this period, both moorings showed the maximum backscatter in the sub-surface layer (6-40 m) decreasing with depth **(Figures 4f, and 4i)**. For mooring *m04*, located in the fjord interior, the VBS pattern was almost reverse. For the period preceding the winter solstice, maximum backscatter at *m04* was located in the subsurface layer while after, and especially during the cell circulation the high backscatter was detected throughout the water column with some decrease in the subsurface layer by the end of cell circulation period. A general tendency of acoustic backscatter to decrease from the YS interior (*m04*) to the YS mouth (*m02*) was also noted.

Precise identification of zooplankton species is not possible just from acoustic data. However, based on previous studies the possible species involved in DVM could be surmised with some confidence. ADCP velocity observations detect the presence of relatively fast moving animals with vertical velocities of ~1.5 cm/s that migrate to ~80 m or deeper **(Figure 7)**. Krill (*Euphausiacea*) and *Themisto* are known to move down to 100-300 m depth in DVM at 70°N.

Figure 3



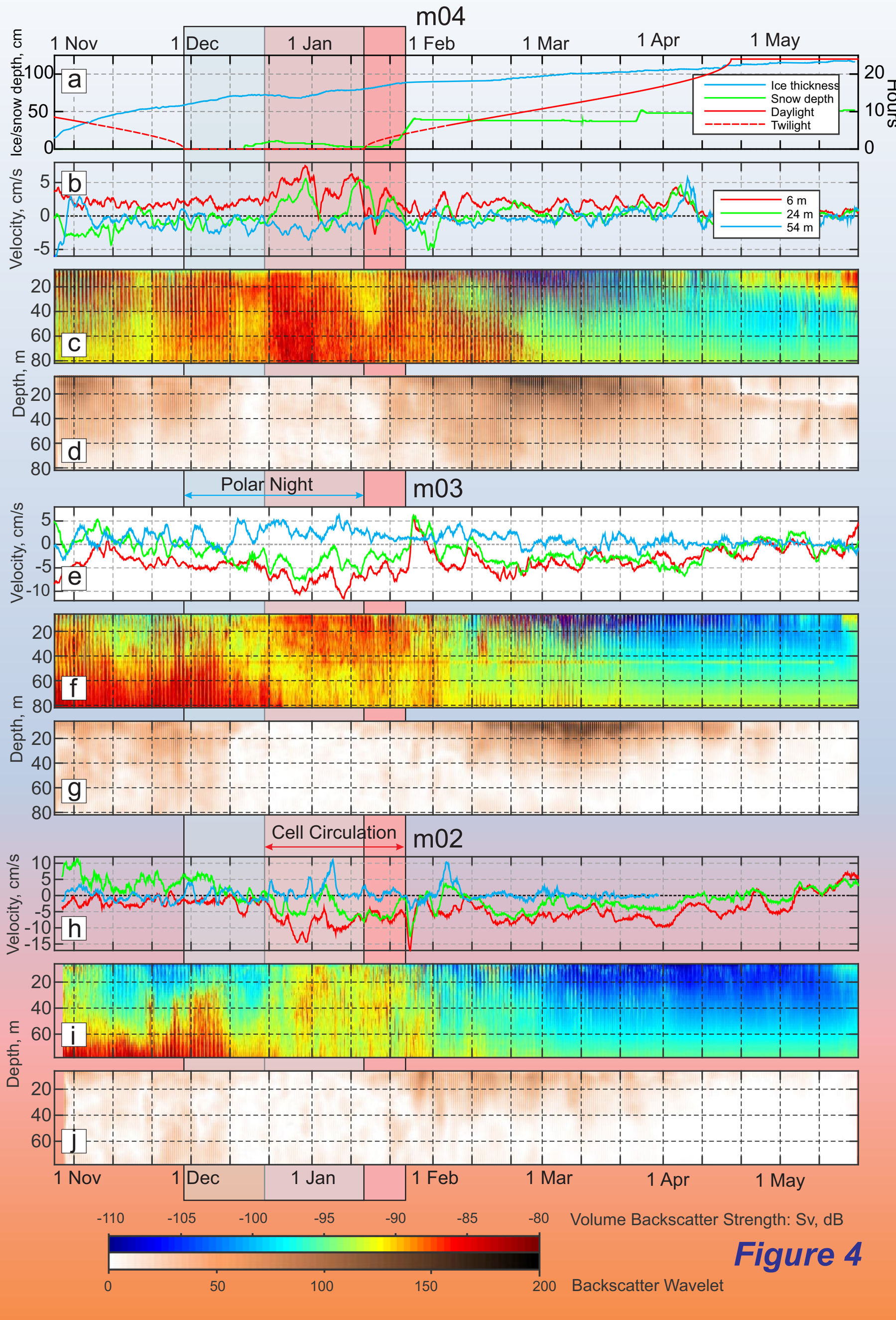


Figure 4

VBS actograms were computed for the depth of 6, 24 and 54 m for all three moorings **(Figure 5)**. In general, these actograms display evidence for expanding the period of high VBS from the midnight in polar day to the entire 24-h period at winter solstice. They are nearly symmetric around the astronomic midnight (horizontal dashed line). However, during the period of enhanced cell circulation (20 December 2013 – 23 January 2015) induced by the polynya opening at the YS mouth, the diurnal periodicity of the signal was notably disrupted.

In contrast to the symmetry relative to the astronomic midnight, the actograms reveal asymmetry with respect to winter solstice (vertical white dashed line) that are consistent with wavelet results. At the *m2* and *m3* moorings, located closer to the mouth of the fjord, the diurnal cycle was indiscernible in the whole water column from about 10 days prior to about 30 days after winter solstice. This period showed a high VBS around -85dB during the entire 24-hour period. A weakening of the circulation cell was associated with the return of the diurnal signal from about 20 January 2014. Towards the polar day, the period of high VBS was gradually narrowing around the astronomic midnight until full disappearance on 18 April, which was simultaneously observed at *m04* and *m03* **(Figures 5a-f)**. At *m02*, the diurnal signal pattern was noticeably irregular and completely absent at 54 m depth **(Figures 5g-i).**

Effect of the moon

Another set of actograms was generated for modelled under ice illuminance **(Figure 6a)** and the ADCP-measured vertical velocity averaged for 16-30 m (above the interface) and 40-54 m (below the interface), respectively **(Figures 6c-h)**. The averaging over 14 m layers and over 7 ensembles (1 hour) reduces velocity error estimates down to 2.2 mm/s, respectively. The bias correction for vertical velocity was performed according to *Plueddemann and Pinkel* and for each of three mooring was estimated around 0.2 mm/s.

Moonlight was the main source of continuous illumination during civil twilight and civil polar night in YS **(Figure 6a)**. Even below the 35-85 cm sea ice with an up to 30 cm thick snow cover **(Figure 4a)**, it was found the regular pattern of vertical velocity was disrupted during full moon, such that a weak but on average upward (positive) net flow was observed throughout the day (mooring *m04*, **Figure 6c**). Moreover, this disruption occurred only when the moon was above the horizon and illuminated the YS ice surface directly (compare **Figure 6a** and **Figure 6c**). This allows direct attribution of the diurnal cycle disruption to the moon illumination. The impact of the moon phase on the vertical velocity irregularities described above was obvious at *m04* **(Figures 6c and 6d)**, recognisable at *m03* **(Figures 6e and 6f)** and fairly masked at *m02* **(Figures 6g and 6h)**. At *m04*, the net upward flow in 16-30 m at the full moon **(Figure 6c)** was consistent with insignificant, but recognisable loss of VBS at 24 m **(Figure 5b)**. However, it was not associated with gain in VBS at 6 m **(Figure 5a)**. Thus, this allows for speculation that the backscattering zooplankton were redistributed to the surface layer that was not resolved by ADCP observations.

Additional evidence of the impact of the moon's illumination on disrupting the diurnal velocity signal arises from the cloud data. NCEP-derived cloud cover data has been found to be unreliable for high latitude regions , however, this data source is the only available information on clouds for the YS region. During the full moon on 14-20 December 2013, moon illumination was likely attenuated due to the ~70% cloud cover **(Figures 6a-c)**. This resulted in a weaker disruption of the diurnal vertical velocity signal compared to the preceding quarter moon phase when the mean cloud cover was about 40%.

Our data revealed a noticeable difference in vertical velocity between the new and full moon phases during the fall transition to civil twilight. The time series of the 2-m binned vertical velocity profiles were computed for *m04* by averaging the individual velocity profiles recorded during the new moon phase, that occurred between 31 October and 6 November **(Figure 7a)**, and full moon phase between 14 and 20 November 2013 **(Figure 7b)** with corresponding error margin of ~0.5mm/s. Intensive downward and upward flow was observed during ~3 h from 6 to 9 h and from 15 to 18 h, respectively. For the new moon, the vertical velocities were about ±0.4-0.5 cm/s and the diurnal velocity signal was present already below 10 m depth. For the full moon, velocities were about half as much and the diurnal velocity signal was distinguishable only at depth below 25 m which is consistent with **Figures 6a and 6b**.

The vertical velocities seen in Figure 6 are consistent with active backscatters moving up- and down through the water column with diurnal periodicity. From the velocity distribution in **Figure 7a**, an approximation has been made for the vertical upward and downward movement following the maximal velocities (white solid lines in **Figure 7a**). This approximation allowed estimations of the vertical displacement velocities of ~1.5 cm/s.

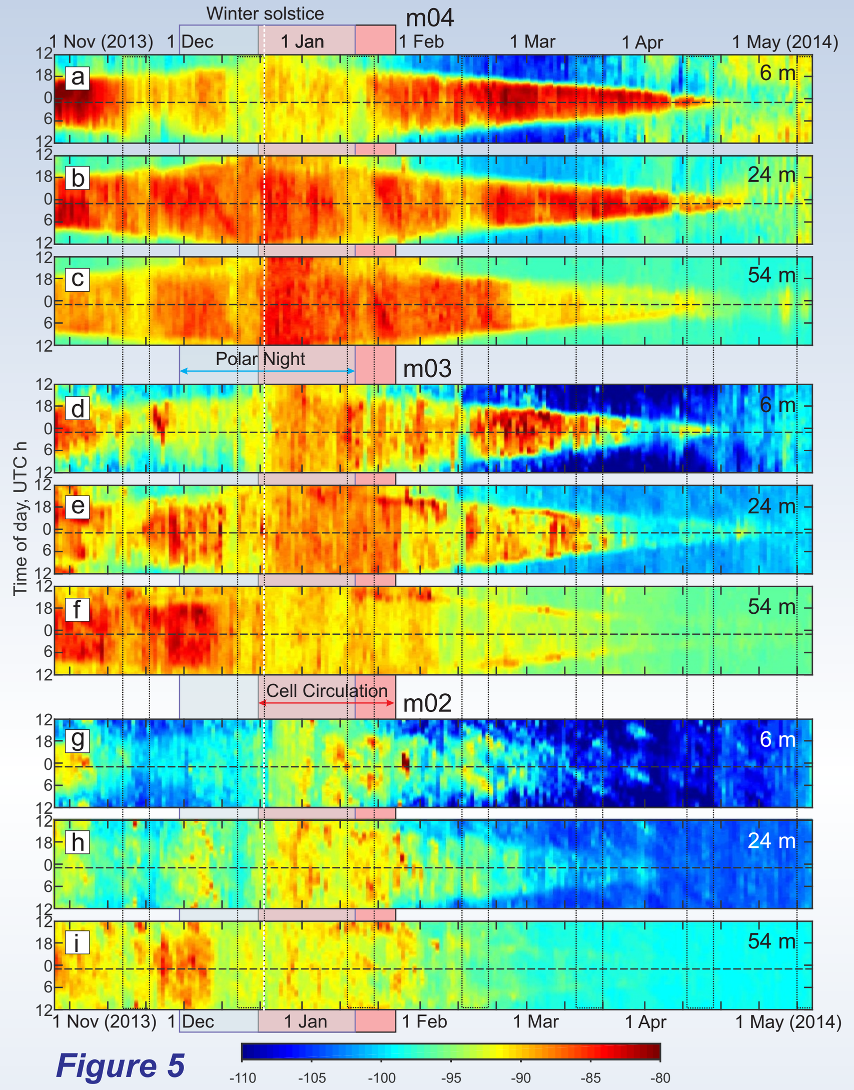


Figure 5

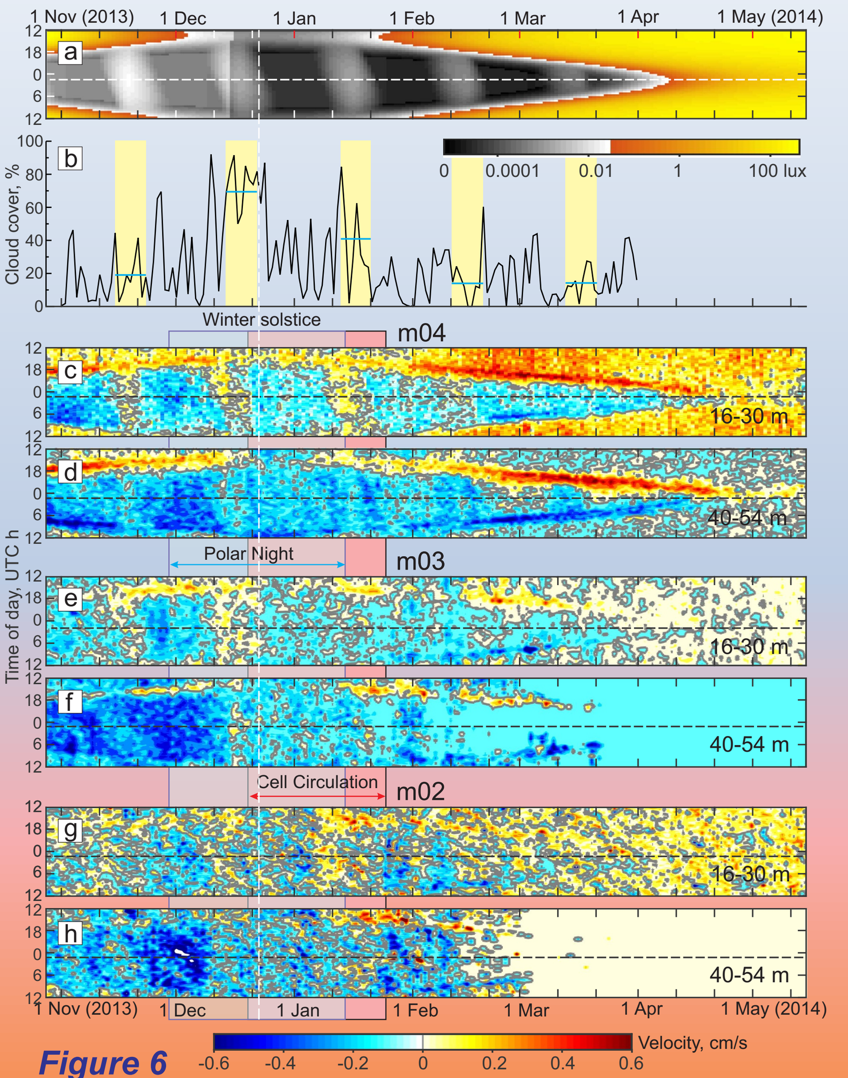


Figure 6

4. Discussion

Possible species associated with DVM

The observed patterns of the ADCP-derived VBS and vertical velocity below the land-fast ice during winter 2013-2014 were consistent with diel vertical migration (DVM) of zooplankton, during which zooplankton moved toward the surface during the evening, and descends the next morning. Without zooplankton sampling, it was not possible for us to specify the exact species involved in DVM , and hence we follow those studies that use only acoustical methods to determine and interpret the patterns of the DVM signal

The estimated vertical migration speed fits nicely into the range of 1-6 cm/s characteristic for copepods and euphausiids]. Previous zooplankton sampling in YS revealed an abundant community of copepods. These studies found that among the copepods, *Microstella norvegica* constituted 32-49% or 5,000-10,000 ind/m^3, while *Calanus* spp. constituted 9-24%. Among the non-copepods, krill comprised about 70 ind/m^3 and *Themisto* just 0.1 ind/m^3. Krill is expected to be very abundant in east Greenland fjords, and *Thysanoessa inermis* and *Meganytiphanes norvegica* was also recorded in high number by *Einarsson* during the warm 1930s. Small copepods as *Oithona, Microcalanus, Microstella* are too small (less than 1.5 mm) to be recorded by ADCP and does not perform large seasonal migration or measurable DVM [*G. Darnis*, 2014, pers. com.] in Arctic waters. *Calanus* species perform seasonal vertical migration and the larger part of the population stays at depth, below those investigated in this study, from early autumn to late spring . *Berge et al.* [2014] also concluded, based on comparison between acoustic and net data, that the acoustic backscatter signal from *Calanus* copepods is typically overwhelmed by the signal from larger zooplankton species such as krill and pelagic amphipods. We therefore suggest that krill and possibly *Themisto* were the main scatters in the backscatter signal.

Disruption of under-ice DVM by polynya formation

The period of DVM disruption matches the cell-circulation period. In the following, we propose two possible explanations for the irregular behaviour of zooplankton associated with enhanced water dynamics.

(i) During the polynya event over the YS mouth, the along fjord inflow/outflow maximum velocities temporally exceeded 7/12 cm/s **(Figures 4b, e and h)** thereby creating an enhanced velocity gradient across the interface at ~40 m (depth of sill) between the inflow in the intermediate layer at ~40-140 m and outflow in the subsurface layer at ~6-40 m **(Figure 2a)**. Based on the observed patterns, it therefore appears that the zooplankton avoided spending additional energy crossing this interface for regular DVM and preferred to remain in the subsurface layer. Besides predator and starvation avoidance, this strategy of minimizing energy use due to advection in the case of enhanced water dynamics was previously reported by

(ii) The polynya-enhanced cell circulation was accompanied by a relative increase in temperature of the subsurface layer that resulted in the upward heat flux to the ice-water interface by up to 22-24 W/m^2 at the outer fjord (moorings *m02* and *m03*) and up to 14.5 W/m^2 in the inner fjord (mooring *m04*) [*Kirillov et al*., 2015]. The relatively strong thermal gradient, observed by *Dmitrenko et al.* between the warmer upper layer above the 40 m depth and deeper waters may have caused zooplankton to favour the upper water layer.

Disruption of under-ice DVM by the moon cycle

In addition to water dynamics, another disrupting factor for DVM was the moon cycle.In contrast to lower latitudes, very little is known about the exact mechanism of how the moon cycle exert control over DVM during polar night . A recent study conducted by *Last et al.* over the open water nearby Svalbard showed DVM disruption by lunar cycle during polar night. They reported that variation in the zooplankton layer depth within the surface layer (~50 m) correlated with lunar altitude periodicity (24.8 hrs) and that zooplankton practice surface avoidance.

Our under-ice VBS data revealed that the DVM signal pattern also was disrupted during full moon phases (**Figure 6)**. The zooplankton, that were the likely cause of the VBS signal, appeared to be more distributed within the upper layer below the sea-ice during full moon. This signal was relatively weak, but remained detectable at *m03* and *m04* during the snow free period **(Figures 4a-e)**. During the full moon, the vertical velocity observations indicated near-zero (~0.01 cm/s) diel-independent net velocities **(Figures 6c-e)**, which supports the lack of coordinated movement by zooplankton. Specifically, no DVM was observed to occur in the subsurface layer down to 20-30 m depth during the full moon stage **(Figure 7b)**. However, below 30 m depth the vertical velocity profiles gave evidence for a weaker, but still well recognizable DVM, which may have been related to a transition in light levels below a threshold of predator's perception at that depth.

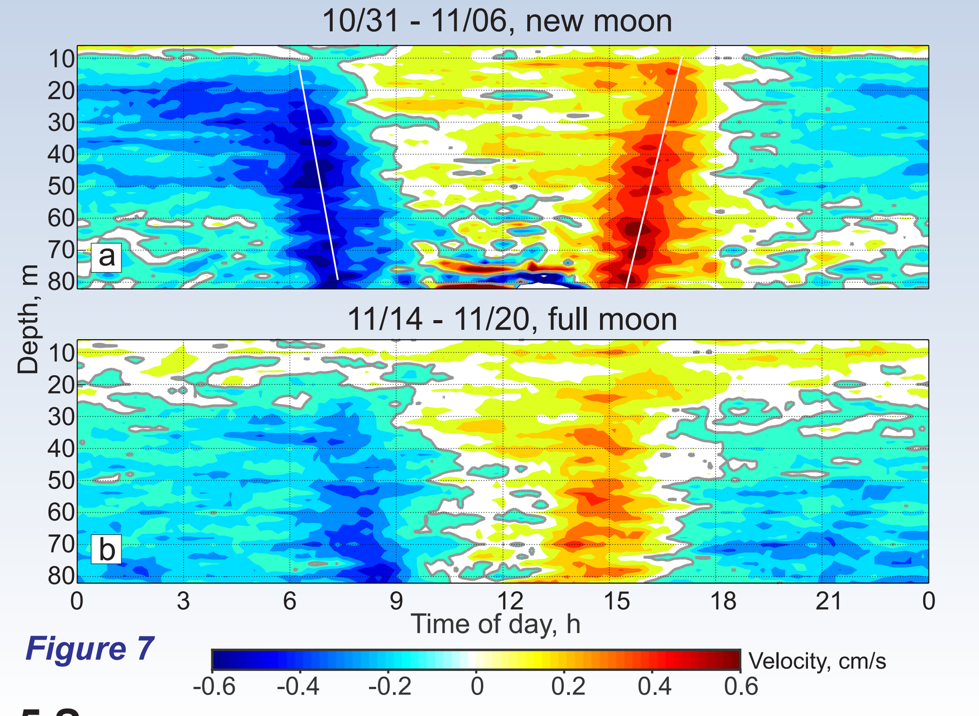


Figure 7

5.Summary

In contrast to many previous studies of the high Arctic regions, the DVM signal in Young Sound persisted throughout the entire winter and even during the period of polar night. However, the DVM signal was significantly disrupted (i) by estuarine-like water dynamics enhanced by a polynya forming over the Young Sound outlet to the Greenland Sea and (ii) during the full moon phase of the moon cycle.

(i) *Disruption by water dynamics*: Our data suggests that the zooplankton species likely responsible for DVM tended to avoid spending additional energy crossing the interface at around 40 m depth between inflow to the fjord in the intermediate layer and outflow in the subsurface layer where a relatively strong velocity gradient was observed. Instead the zooplankton tended to favour remaining in the upper 40 m where also the relatively warmer water temperatures.

(ii) *Disruption by moon light*: During civil twilight and civil polar night, moonlight is the major significant source of illumination besides stars and aurora borealis. During full moon phases, the VBS and vertical velocity observations revealed that the signal was disrupted and zooplankton were homogeneously redistributed within the upper layer below the 60-90 cm thick land-fast sea ice with ~10 cm snow cover. This signal tends to disappear at high cloud and snow cover. Our modelled analysis suggests that the zooplankton in question have an outstanding sensitivity to illuminance levels of 0.002 lux and less. We speculate that this extraordinary sensitivity favours zooplankton to harvest and avoid predation below the land-fast ice during polar night during full moon phases thereby reducing their light-dependent mortality risk.

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