POAC'17
Busan, KOREA

Proceedings of the 24th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 11-16, 2017, Busan, Korea

Investigation of Large Ice Rubble Field in the Barents Sea

N.A.Marchenko[1], A.V.Marchenko[1]
[1] The University Centre in Svalbard, Longyearbyen, Norway

ABSTRACT

Characteristics of ice ridges and rubble fields in the Barents Sea are of great interest for the formulation of design criteria for offshore structures. But there are quite a few field observations and measurements. On 2 of May 2016 UNIS researchers and students, due to unusual little ice coverage, reached on RV Lance Northern-East end of the Edge Island (East of Spitsbergen) and observed large ice rubble field with frozen in icebergs stretching on several km along the coast. Laser scanning from the Lance board was performed to estimate spatial variations of vertical elevation of above water part of the rubble. 2 CTD profiles performed near the rubble identified that entire water column of 40 m depth was around the freezing point with couple of fresher water intrusions on different depths.
Further investigation of high-resolution satellite images since 2009 gave information about structure, size, formation and evolution of the rubble every year and revealing possible cause as grounded on the shallow icebergs. Analysis of ice drift data from IFREMER and own ice trackers allowed to describe possible origins of the ice rubble and its future development.

KEY WORDS: Ice; Rubble; Barents Sea

INTRODUCTION

A characteristic of ice-covered waters is the presence of ice ridges and rubbles. Pressure ridges are composed of ice fragments that are piled up along a line, with the steep-sloped ridge rising up as much as 5 to 10 feet or more above the adjacent stretches of level ice. Rubble ice, by comparison, is a jumble of ice fragments or small pieces of ice (such as pancake ice) that covers a larger expanse of area without any particular order to it. The height of surface features in rubble ice is often lower than in ridges. Rubble ice can cover large expanses, such as in Antarctica where the ocean swells breaks up newly forming ice and herds it together into rubble ice field (NOAA, 2017).

The investigations devoted to ice ridges (Timco and Burden, 1997) and ice rubble (Barker and Timco, 2017) describes their shapes and sizes. Studies of ice rubble was performed by laboratorial experiments (Liferov and Bonnemaire, 2005), field observation and modeling (Marchenko et al., 2016). Observations in the Caspian and Beaufort Seas show maximum rubble heights of about 15m above the ice line can be achieved, even with relatively thin ice

(McKenna et al., 2011)(Croasdale, 2012). Mathematical models of ice ridge formation were formulated by R.R.Parmeter and M.D.Coon (Parmeter and Coon, 1972) and A.V. Marchenko (Marchenko and Makshtas, 2005). Discrete elements model of ice ridge build was elaborated by M.Hopkins (Hopkins, 1998) Formulas for the estimates of upper bounds of vertical sizes of ice ridges and rubble sails and keels were considered in (Hopkins, 1998) and (Marchenko, 2016a).

T.Vinje and Å.Kvambekk describing drifting ice in the Barents Sea wrote: "Ridging events may take place with onshore winds. Rubble fields, possibly due to this effect, are often observed in the NW part of the Barents Sea and ice piles 10-15m high have been observed on the shore of the islands. The height of the ridging is also illustrated by the fact that fairly large accumulations of ice blocks may be observed on top of 7-15 m high grounded icebergs (Løset et al., 1988, Vinje et al., 1989). Ice ridging also occurs in convergences caused by wind, currents and land constraints. The most frequent ridge height observed from the meteorological station on Hopen is 2 m. The most frequent ridge density in the ice fields of the Barents Sea as observed from a long term project using aircraft is about 10 km-l. The frequency distribution is fairly broad, with a maximum of 26 km-' (Vinje, 1985)" (Vinje and Kvambekk, 1991). But these characteristics are related to cold 1980-s. Multiple Norwegian and Russian expeditions performed since 2003 reported about maximal draft of ice ridge registered by drilling studies about 15 m (Marchenko et al., 2009, Hoyland, 2007, Zubakin, 2006). Origins of big ice ridges are usually related to ice drift from Arctic Ocean into the Barents Sea.

On the background of "global warming" and Arctic Ice shrinking in last years, it was very interesting to discover the huge ice rubble in the western part of the Barents Sea and make investigation, using modern equipment. Knowledge about ice rubble is very important for many engineering problems, and relevant for future hydrocarbon exploration in the Barents Sea. That's why our research of the rubble can be interesting both from a purely scientific and practical point of view.

DISCOVERING AND LOCATION

The rubble field had been discovered during cruise on RV Lance in the frame of UNIS course AT-211 and research work. The weather conditions this spring was unusually warm and Barest Sea was almost ice free, with ice not going south longer than 76ºN. On the 2 of May 2016 UNIS researchers and students finished the investigation on the first station south in Ryke Yse Island and moved in the NW direction looking for large enough and stable ice floe. Ice in the area was presented by drifting ice floes average size 300 m with ice thickness 40-50 cm, smaller floes and ice free water. Near the north-east end of Edge Island, the large ice rubble field with frozen in icebergs stretching on several km along the coast was observed. (Figure 1,2) The edge of rubble was high (3-3,5 m) surprisingly vertical and sharp/even, as it was cut by huge knife.   Offshore of rubble field was ice free water (Figure 1).

Figure 1. Ice rubble field discovering. Photo: N.Marchenko

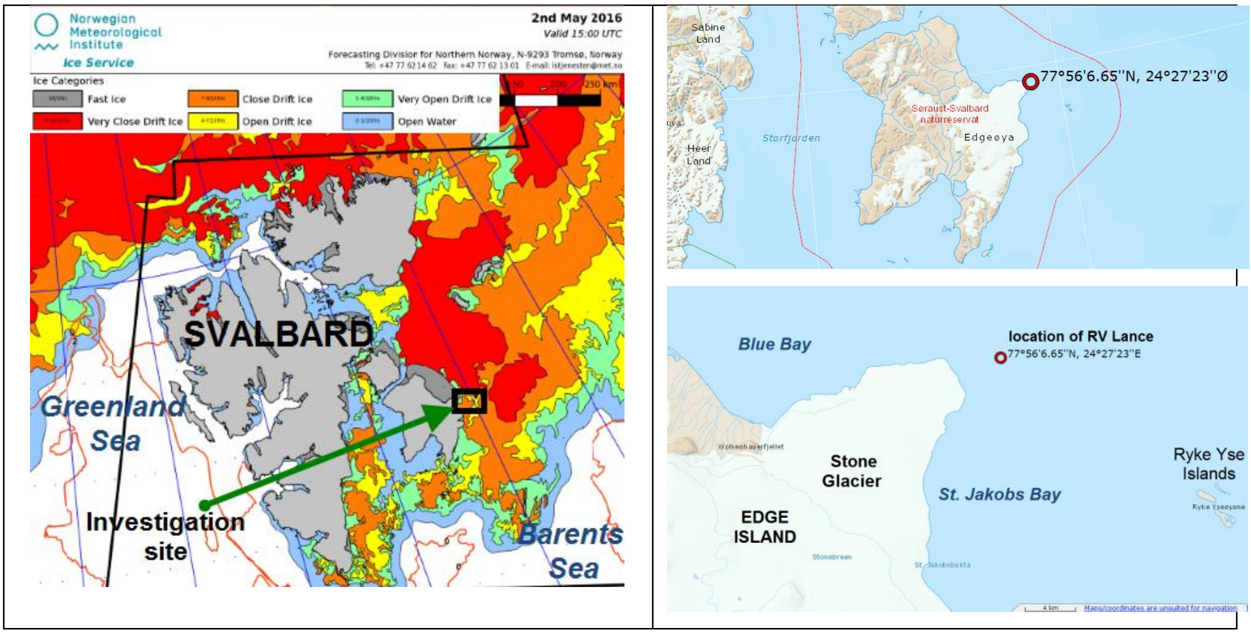


Figure 2. Geographical location of the discovered ice rubble on the base map (Norwegian Polar Institute, 2017) and sea ice map for the day of observation (Norwegian Meteorological Institute, 2017)

LASER SCANNING AND RUBBLE SPATIAL CHARACTIRISTICS

Laser scanning from the Lance board was performed to estimate spatial variations of vertical elevation of above water part of the rubble with scanner REIGL VZ-1000 from the board of Lance. Scanning from several positions (program: 950m (150kHz) and resolution 0,03 deg) had been done, but due to short distance between them it was not possible to create full 3D image. So there is a shadow from high ice objects on scan. Foggy weather created significant noise on the point cloud around the scanner and the quality of the picture decreases considerably farther than the distance 300-400 m. Nevertheless the obtained point cloud clearly shows the structure of the rubble and dimension. Scans were processed in RiScan program: The high of ice wall near the ship was more than 3 m, high of nearest iceberg – more than 9,5 m.

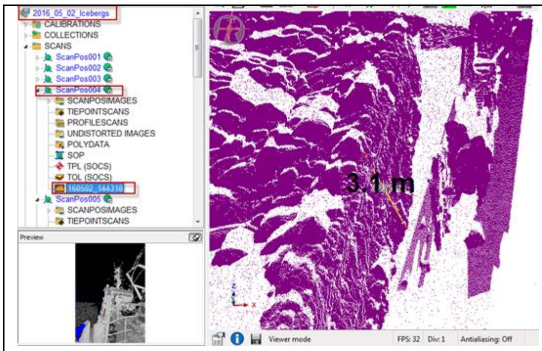
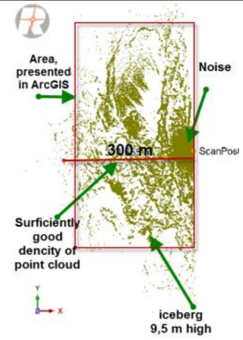
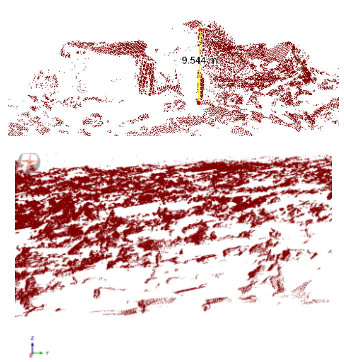
		
Rubble scan in RiScan program	Scan orientation	Iceberg (above) and rubble (below)

Figure 3. Point cloud images of ice rubble in RiScan software.

Point cloud was exported to ArcGIS software, where elevation distribution was mapped and estimated (Figure 3-4). Among 160 thousand measured points min is 0 (water level, near the RV Lance), max – 11,96 m (iceberg). Mean value is 1,61m. Taking into consideration that considerable part of points was in the shadow of large ice pieces, mean vertical size of the rubble is estimated as above two m. Histogram in Figure 4a shows smooth distribution of measured values of the rubble high in the points of laser scanning. Pink histogram in Figure 4b is constructed by the multiplication of the rubble sail high on 4.4 according to the sail-keel proportion discovered by Timco and Burden (1997). Blue histogram in Figure 4b is constructed by the multiplication of the rubble sail high on 9 according to the sail-keel proportion of tabular icebergs. Gray area in Figure 4a is bounded by ice thicknesses 5.5 m and 15 m calculated with the formulas specifying the upper and lower boundaries of the rubble draft (Marchenko, 2016a)

$$h_k = 4.6 + 2.88 \cdot h(\mathrm{m}),\;\; h = 0.3\,\mathrm{m};\;\; h_k \approx 15\sqrt{h}(\mathrm{m}),\;\; h = 1\,\mathrm{m}.$$

These dependencies were formulated with the assumption that level ice is broken by bending when it forms the floating rubble. The observed rubble is not completely floating, and can be partially grounded. It may explain high estimated values of the draft up to 30 m (Figure 4b).

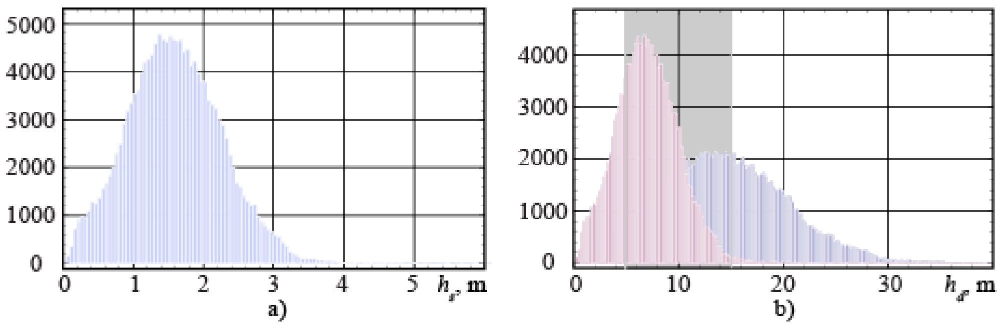


Figure 4. Frequency Distribution of point elevation above sea level (a) and below sea level calculated with

On Figure 5 the space distribution of point elevation in ice rubble and profiles across rubble are presented on the map in ArcGIS software.

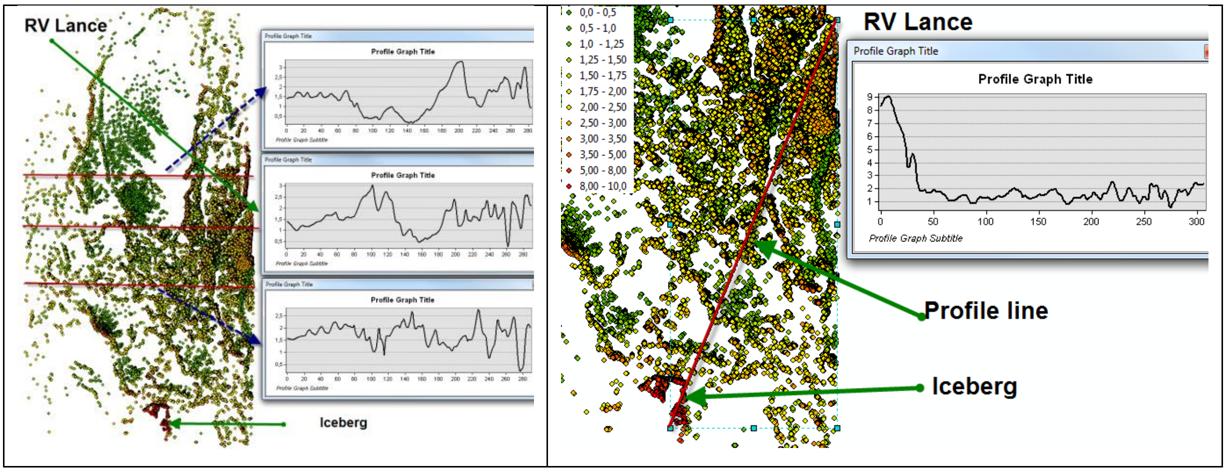
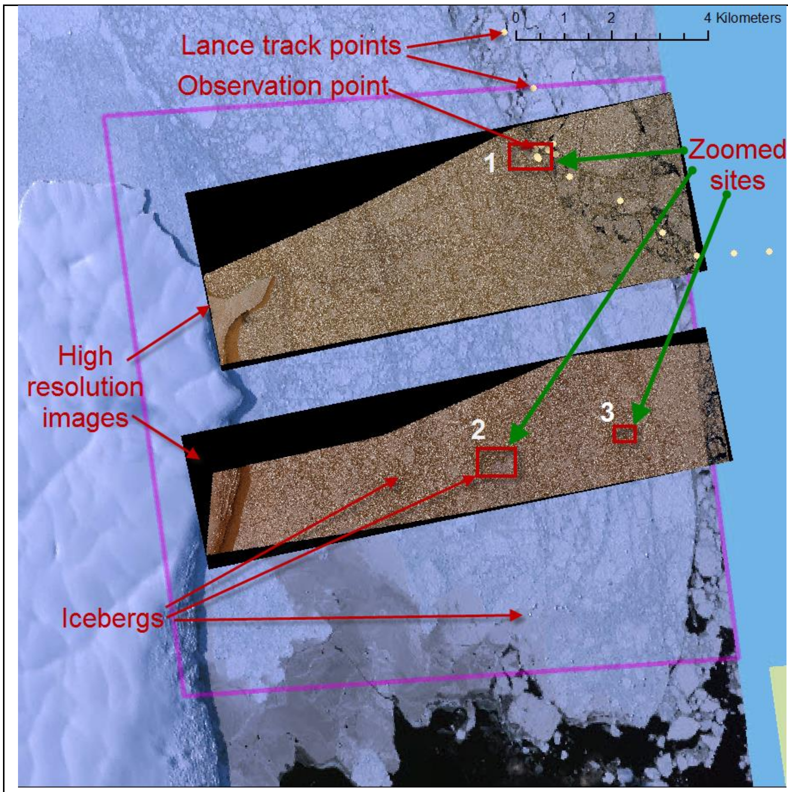


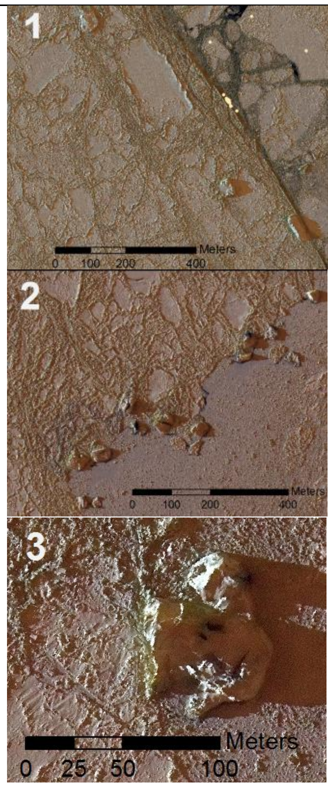
Figure 5. Elevation above sea level of scanned points in the rubble on the map and on profiles in ArcGIS software

HIGH RESOLUTION IMAGES. RUBBLE STRACTURE AND ORIGIN

Fortunately, our location was captured by satellite high resolution (50 cm) image in suitable time and two images from 25 April (Sensor WV3, Off-nadir 25 º , sun elevation 10 , sun azimuth – 297,4) was bought from Apollo mapping service (Figure 6).



Location of high resolution images on the back ground of low resolution images



Zoom to 1)the RV Lance place, 2)icebergs, 3)one of the biggest iceberd.

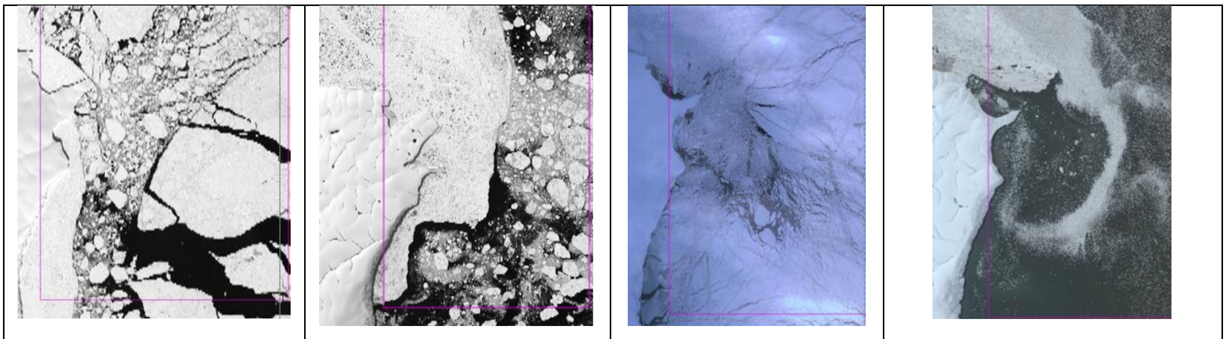
Figure 6. High resolution images (location and zoom to particular featres)

On the satellite images the width of rubble field can be estimated as 9 km. It consists of different size flat ice floe (small 50-150 m and large – 400-500 m) connected by compressed ridges, stretching along the floes. Some of ridges reach up to 1 km length.

We can assume also the origin and forming process of the rubble field as stopping of drifting from the North ice by aground icebergs and further accumulation and compression of ice on the shallow. Such icebergs are visible on the south image (number 2, 3 on Figure 6). Icebergs gather in the groups of 2-5 ones along the line and hold the ice flow (Figure 6. 2). The size of small icebergs is 10-50 m, the large icebergs reach up to 50 m (Figure 6.3). Over time, the ice fills the entire space to the bottom.

LOW RESOLUTION SATELITE IMAGES. YEARLY AND INTERYEAR DYNAMICS AND LARGE SPATIAL CHARACTIRISTICS

The set of satellite images was taken from Apollo Mapping web-site (Apollo Mapping). They present on site as preview of high resolution images and give nearly 50 m resolution). 28 images such captured from 2009 in light time show that the rubble field starts to form in this place every year at the end of March, reaches max at the end of April and exists in some years till the end of June (Figure 7). In 2015 rubble was still on the place on the 2 of July (Figure 8). The remnants of the destroying rubble drift to the south, following the general scheme of drift



1 April 2013	28 June 2009	1 March 2016	21 June 2016

Figure 7. Satellite images of rubble for different years and dates.

Modis image of 2 July 2015 shows huge rubble (80 km long) fasted to the Edge Island - The width changes from 10 to 20 km. The rubble is separated from the main body of floating ice massive with width 100-120 km by clear polynya.

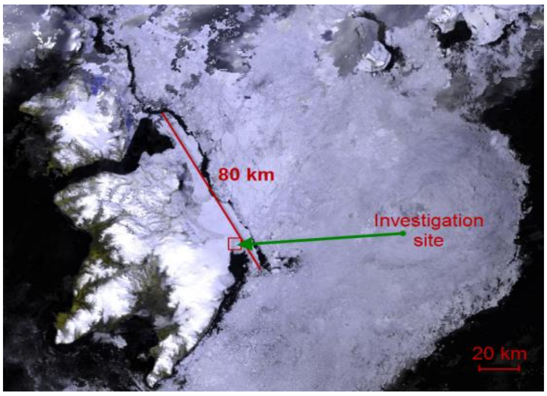


Figure 8.MODIS image 2 July 2015

(NASA, 2017)

SEA ICE PRODUCTS AND DRIFTING BUOYS. ICE MOVEMENT TO AND FROM RUBBLE PLACE

Information about actual ice drift can be obtained using drifting buoys and by interpretation consequent satellite images. Several institutions and agencies provide so called “Sea ice products”, showing mean ice motion vector, derived from passive microwave sensors, visible and infrared sensors, and other sources. Among them as in was found in (Marchenko, 2016c) , IFREMER (Ifremer, 2017) is the most relevant for our region and purpose. We took IFREMER data for 2003 and 2010 with 6 days interval and constructed drifting lines, which show south-west direction of drift (Figure 9). The distance of 250 km was passed in 55 days, so near Bear Island (the new hydrocarbon exploration area), locating in 400 km on South-West, such ice creature would be in two and half month in case of average drift. But in case of polar cyclones and strong wind gust, the drift can be much faster. As it was shown in (Marchenko et al., 2016) ice fields in our region can drift with speed 1,7 m/s and reach Bear Island in a month. The significant consolidation of ice rubble occurs due to the melting from below if the rubble drifts from the region of Kong Karls Land to the Bear Island. On the satellite images Terra the ice tongues reaching Bear Island was visible both in March 2015 and March 2016 (Marchenko et al., 2016).

Our ice trackers, installed on ice floe show more detail picture of the drift, as they transmit coordinated each 10 minutes. Tidal loops and short time changing of the direction are visible on the plot (Figure 9). In case of strong wind with combination with current, which goes along the south east coasts of Spitsbergen and Edge Island, ice floe can make several tenths km per day.

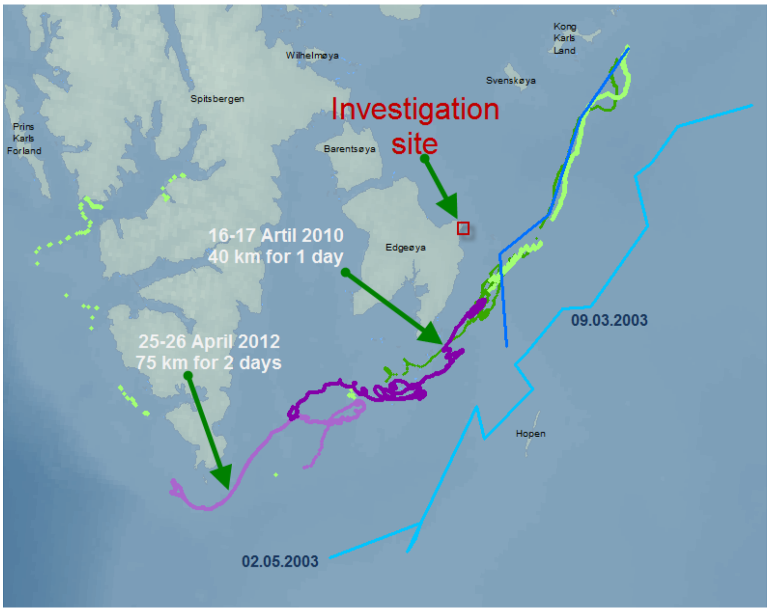


Figure 9. Drifting line of ice trackers (installed in 2010 – green, and 2012 – violet) and constructed from (Ifremer, 2017) data (dark blue – 2010, light blue – 2003)

CTD PROFILING

CTD profiling was performed with SBE 19 from the Lance board near the rubble wall in two locations. The horizontal distance between the locations was 20-30 m. Sea depth about 40 m was registered in both places. The ship hull may influence the profiling within the ship draft of 5.5 m. Dependencies of the temperature, salinity and density of the water from the depth are shown in Figure 10 and Figure 11. In both of the locations the entire water column is above the freezing point. The difference between the actual temperature and the freezing point increases with the approaching to the sea surface. Temperature and salinity profiles are not monotonic and include 4 local maxima in the location 1 and 2 local maxima in the location 2 at depth below 10 m. Density profiles shown in Figure 11b are very stable, but also include similar local maxima. The origin of the observed vertical water structure can relate to the convection and double diffusion of salt water caused by the rubble melting. Similar structures were observed in the experiment (Josberger and Martin, 1981) and obtained in numerical simulations (Gayen et al, 2015).

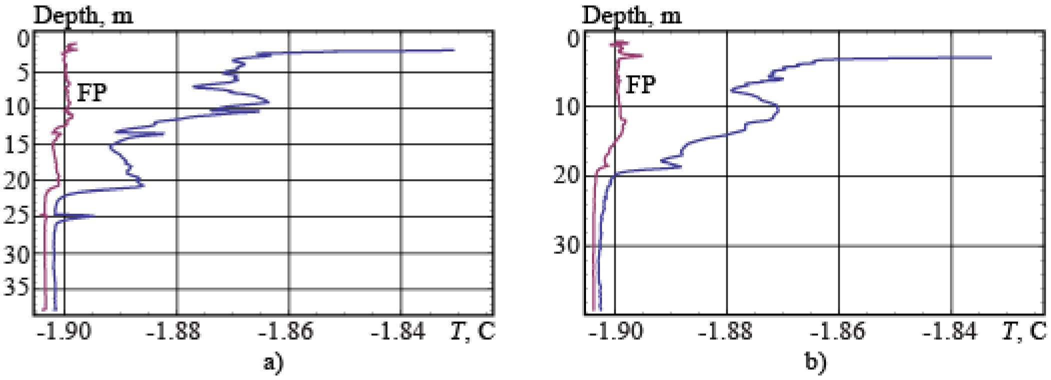


Figure 10. Vertical profiles of the temperature and freezing point measured near the rubble in two locations 1 (a) and 2 (b).

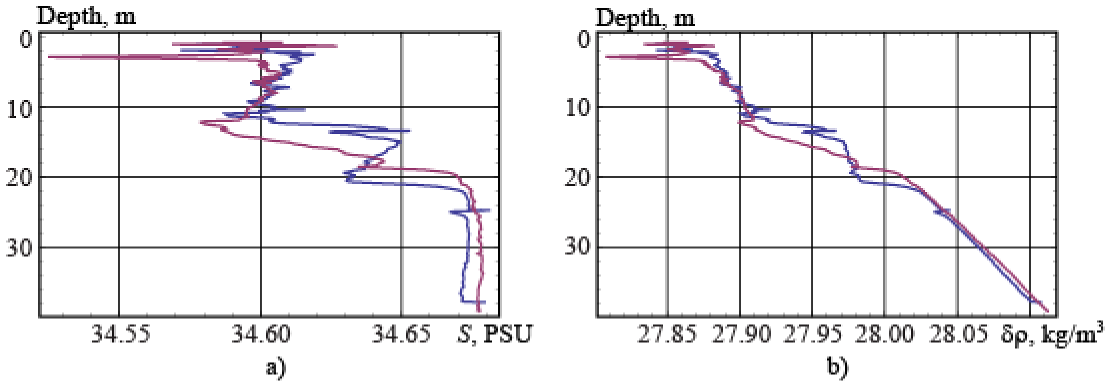


Figure 11. Vertical profiles of the salinity (a) and density fluctuations (b) measured near the rubble in two locations 1 (blue lines) and 2 (pink lines).

CONCLUSIONS

Large ice rubble, unusual for such warm period and location was discovered on 2 of May near North East point of Edge Island (NW Barents Sea). Investigations using laser scanning, and high resolution satellite images shown that it is a part of the rubble forming regularly in spring by stopping of ice drifted from the North by grounded icebergs. The average sizes of icebergs in 2016 were 20x40 m and concentration 20 icebergs per 1 km^2. In May 2016 the rubble had vertical size of edge wall – 3 m, average elevation above water level 2 m (that gives us draft 18 m), width from the coastal line 8 km and stretching in N-S direction along s coast was more than 20 km. Rubble formed at the beginning of April and existed till the beginning of July.

In July 2015 the rubble of 80 km long and 10-20 km width was fasted to the NE of Edge Island. Estimation on the base of IFREMER and ice trackers data show that such ice formation can potentially reach Bear Island region (the new hydrocarbon exploration site) in two and half month in case of average drift and in a month in case of polar cyclones and strong wind gust.

ACKNOWLEDGEMENTS

The authors would like to thank the FIMA and SAMCoT project (funded by the Research Council of Norway), the SITRA project (funded by the Norwegian Centre for International Cooperation in Education) and the colleagues for supporting this study.

REFERENCES

APOLLO MAPPING. *Image hunters* [Online]. Boulder, Colorado, USA. Available: https://apollomapping.com/, https://imagehunter.apollomapping.com/.

BARKER, A. & TIMCO, G. W. 2017. Maximum pile-up heights for grounded ice rubble. *Cold Regions Science and Technology,* 135**,** 62-75.

CROASDALE, K. R. 2012. Ice rubbling and ice interaction with offshore facilities. *Cold Regions Science and Technology,* 76-77**,** 37-43.

HOPKINS, M. A. 1998. Four stages of pressure ridging. *Journal of Geophysical Research-Oceans,* 103**,** 21883-21891.

HOYLAND, K. V. 2007. Morphology and small-scale strength of ridges in the North-western Barents Sea. *Cold Regions Science and Technology,* 48**,** 169-187.

IFREMER 2017. psi-drift/quicklooks/arctic/. *In:* IFREMER (ed.) *Index of /ifremer/cersat/products/gridded.*

LIFEROV, P. & BONNEMAIRE, B. 2005. Ice rubble behaviour and strength: Part I. Review of testing and interpretation of results. *Cold Regions Science and Technology,* 41**,** 135-151.

LØSET, S., VINJE, T., LØVÅS, S. M., JOHNSEN, A. S., JENSEN, H., ERLINGSSON, B. & VEFSOMO, S. 1988. IDAP 88 Vessel deployment. Volume 2. Field observations and analysis. Trondheim: Norwegian Hydrotechnical Laboratory.

MARCHENKO, A. 2016a. Physical mechanisms limiting sizes of pressure ice ridges and model of ice rubble formation. *23nd IAHR International Symposium on Ice.* Ann Arbor, Michigan USA,.

MARCHENKO, A., DIANSKY, N., FOMIN, V., MARCHENKO, N. & KSENOFONTOVA, D. 2016. Consolidation of Drifting Ice Rubble in the North-West Barents Sea. *23nd IAHR International Symposium on Ice.* Ann Arbor, Michigan USA,.

MARCHENKO, A. V., DIANSKY, N. A., ONISHCHENKO, D. A., CHUMAKOV, M. M., NIKITIN, M. A., FOMIN, V.V.. & MARCHENKO, N. A. 2016. Studies of ice drift and ridge consolidated layer evolution in the North-West Barents Sea. *Proceedings of Hydrometcentre of Russia*. - 2016. - Vol. 361. - P. 231–260.

MARCHENKO, A. B. & MAKSHTAS, A. 2005. A dynamic model of ice ridge buildup. *Cold Regions Science and Technology,* 41**,** 175-188.

MARCHENKO, N. A. 2016c. Comparison of Sea Ice Products and data of drifting buyos. *23rd IARH International Symposium on Ice (IAHR-ICE 2016).* AnnArbor, Michigan-US.

MARCHENKO, A.V., OGORODOV, S.A., TSVETCINSKY, S.A., SHESTOV,A.S.,2009. D angerous ice phenomena on the shelf of the Barents and Kara Seas. *Proc. RAO/CIS Offshore 2009,* St.-Petersburg, HIMIZDAT, V.1, pp. 91-96.

NASA. 2017. *MODIS. Moderate resolution imaging spectroradiometer* [Online]. Available: https://modis.gsfc.nasa.gov/.

NOAA. 2017. *What is the difference between rubble ice and pressure ridges?* [Online]. Available: http://www.pmel.noaa.gov/arctic-zone/ice-rubble-pressure.html.

NORWEGIAN METEOROLOGICAL INSTITUTE. 2017. *Icechart and Ice information* [Online]. Available: http://polarview.met.no/index_HI.html.

NORWEGIAN POLAR INSTITUTE. 2017. *TopoSvalbard* [Online]. Available: http://toposvalbard.npolar.no/ [Accessed 2017.

PARMETER, R. & COON, M. 1972. Model of pressure ridge formation in sea ice. *J. Geophys. Res.,* 77**,** 6565– 6575.

TIMCO, G. W. & BURDEN, R. P. 1997. An analysis of the shapes of sea ice ridges. *Cold Regions Science and Technology,* 25**,** 65-77.

VINJE, T. 1985. Drift, composition, morphology and distribution of the sea ice fields in the Barents Sea. *Norsk Polarinstititutt Skrifrer.* Oslo.

VINJE, T., JENSEN, H., JOHNSEN, A. S., LØSET, S., HAMRAN, S., LØVÅS, S. M. & ERLINGSSON, B. 1989. IDAP-89 R/V LANCE deployment. Volume 2: Field observations and analysis. Oslo: Norsk Polarinstitutt.

VINJE, T. & KVAMBEKK, A. S. 1991. Barents Sea Drift Ice Characteristics. *Polar Research,* 10**,** 59-68.

ZUBAKIN, G. K. 2006. Ice formation of the seas of Western Arctic. Saint Petersburg, AARI.