UDC 551.467
DOI: 10.24412/2658-4255-2021-1-33-49

Citing:
Alekseeva T.A., Frolov S.V., Serovetnikov S.S. Review of methods and main results of sea ice thickness measurements in the Arctic. 2021; 12: pp. 33-49 (In Russ.). 10.24412/2658-4255-2021-1-33-49

Received: 15.03.2021
Approved: 29.03.2021
Published: 05.04.2021

REVIEW OF METHODS AND MAIN RESULTS OF SEA ICE THICKNESS MEASUREMENTS IN THE ARCTIC

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Abstract: Review of main methods of sea ice thickness measurements and results of published researches about climate and interannual variability of this parameter in the Arctic Basin and in the Arctic Seas are presented. Following methods of thickness measurements are developed and widely used: ice drilling, acoustic (echo sounder), electromagnetic method, visual and TV ship observations. Maximum area of the Arctic sea ice can be covered by acoustic measurements from submarines, visual and TV ship observations from ice class vessels and icebreakers. Results of thickness measurements in the Arctic reviewed in present research were obtained in various regions of the Arctic, in various seasons, by various methods and various periods, and, consequently, do not allow to estimate unambiguously a climate and interannual variability of sea ice thickness in the Arctic. However, authors concluded that changes of average sea ice thickness in the Arctic Basin are influenced in first turn by dynamic processes caused by changes in the atmosphere circulation. TV-complex developed in the AARI is a perspective method to automate process of sea ice thickness measurements from the shipboards.

Keywords: drill-hole measurements, climate changes, visual ice observations, fast ice thickness, ice thickness, EM sea ice thickness measurements

Introduction

Ice thickness is a key feature of ice cover in the freezing areas of the Global Ocean. As sea ice exists at the interface of the ocean and atmosphere, its thickness and geographic distribution serve as integrated indicators of climate change and dynamic atmospheric and hydrological processes, and thus characterize both ocean and atmosphere.

Interannual and climatic variability of ice thickness along the navigable routes are an essential characteristic for assessment and planning of new prospective marine transportation systems, design and building of new ships and icebreakers, safety navigation and hydrocarbon extraction on the shelves of the freezing seas.

At the same time sea ice thickness is hard to measure in a global scale. The main emphasis is on the development of remote non-contact methods of ice thickness measuring based on information from satellites and aircrafts, as well as from submarines and mooring subglacial buoys. At the same time ship-based video monitoring systems are developed and used actively on vessels and icebreakers for ice thickness and snow depth measurements. This review presents the existing methods and obtained results of only *in situ* sea ice measurements.

Main methods of sea ice thickness measurements

Sea ice is a result of salt sea water freezing, being thereby a multicomponent system composed of pure ice crystals together with brine and solid salts, as well as small amount of air bubbles and organic and terrigenous impurities [1]. Flat sea ice has non-uniform thickness and varying salt and density vertical stratification even in a single ice floe due to different conditions of ice formation. Deformed ice (i.e. ice breccia, hummock, rafting) has even more complicated structure. Large-scale measuring of sea ice thickness is thus one of the most topical and complex issues. Several methods have been currently developed and are widely used in the field.

1. *Drilling* is the most accurate and at the same time the most time-taking method for measuring ice thickness. It is carried out by drilling an ice floe with an auger or a motor-driven power drill and further measuring of ice thickness in the hole with ice thickness tape (Figure 1). This method is successful for local control measurements but is not good for wide-range in situ observations because of its duration, hardness and high cost of management. Drill-hole technique is applied either for local short-term ice thickness measurements prior to the organization of ice stations during marine expeditions or for routine measurements in the area of shore stations or drifting ice stations. Accuracy of drill-hole measurements is up to 1 cm and thus they are the

Figure 1 – Drilling of sea ice for further ice thickness measurements (research station 'Ice base Cape Baranov', Severnaya Zemlya Archipelago, May 2014). Photo: V.Borodkin.

most accurate of all techniques for measuring ice thickness [2].

2. *Sounding (echo sounding)* is applied on submarines and unmanned vehicles as well as on the moored sonobuoys. The most representative publicly available data were derived from upward looking sonars mounted on submarines during the period from 1958 to 2000. This technique measures ice draft. The sonar antenna emits a sound pulse which reflects off the ice underside and is recorded by receiver. Ice draft calculation is based on total travel time of the pulse and gauge depth [3]. Depth of sonar antenna is determined from absolute hydrostatic pressure and is used as a reference level [4, 5]. Ice thickness is calculated according to the mean ratio of draft to thickness which is 93% [6]. Estimation errors may vary from 0.15 to 0.38 m according to different sources [5-7]. This rate of errors is not essential for a thick ice, though it is significant for a thin ice. Data from sonobuoys are obtained in a delayed mode, which is not suitable for operation tasks. High cost of power supply unites and depth limitations also reduce the use of this technique.

3. *Electromagnetic (EM) sounding* is the most widely used method for small- and medium depth measuring on land. In 1980-s the American and Canadian researchers began to use it for sea ice thickness measurements [8, 9]. In 2001 the electromagnetic-induction system EM-bird was designed in Alfred Wegener Institute (Bremerhafen, Germany). Currently there are three modifications of EM-systems dedicated for sea ice thickness measurements, these are EM-bird for the airborne measurements from helicopter or aircraft with accuracy of ice thickness measurements of ±0.1 m [10], EM-31 for shipborne measurements and EM-31 Ice for ground-based ice thickness measurements (Figure 2). The EM-system consists of external PC, GPS-module, a laser and two electromagnetic antennas (transmitter and receiver coils). EM sounding is based on measuring ice conductivity considering that low conductivity corresponds with high ice thickness. The transmitting coil of EM-system generates EM field which penetrates the sea ice. Eddy currents are generated in the sea water below the sea ice underside and induce a secondary EM field. The boundary between sea water and sea ice is thus well detected due to large difference between their conductivities. Further recalculation of conductivity values to ice thicknesses estimations requires a calibration of the EM instrument. For this purpose several holes are drilled in sea ice (5-10 holes) to measure sea ice thickness with both ice thickness tape and EM instrument simultaneously. Snow thickness should be measured additionally at the same holes because EM

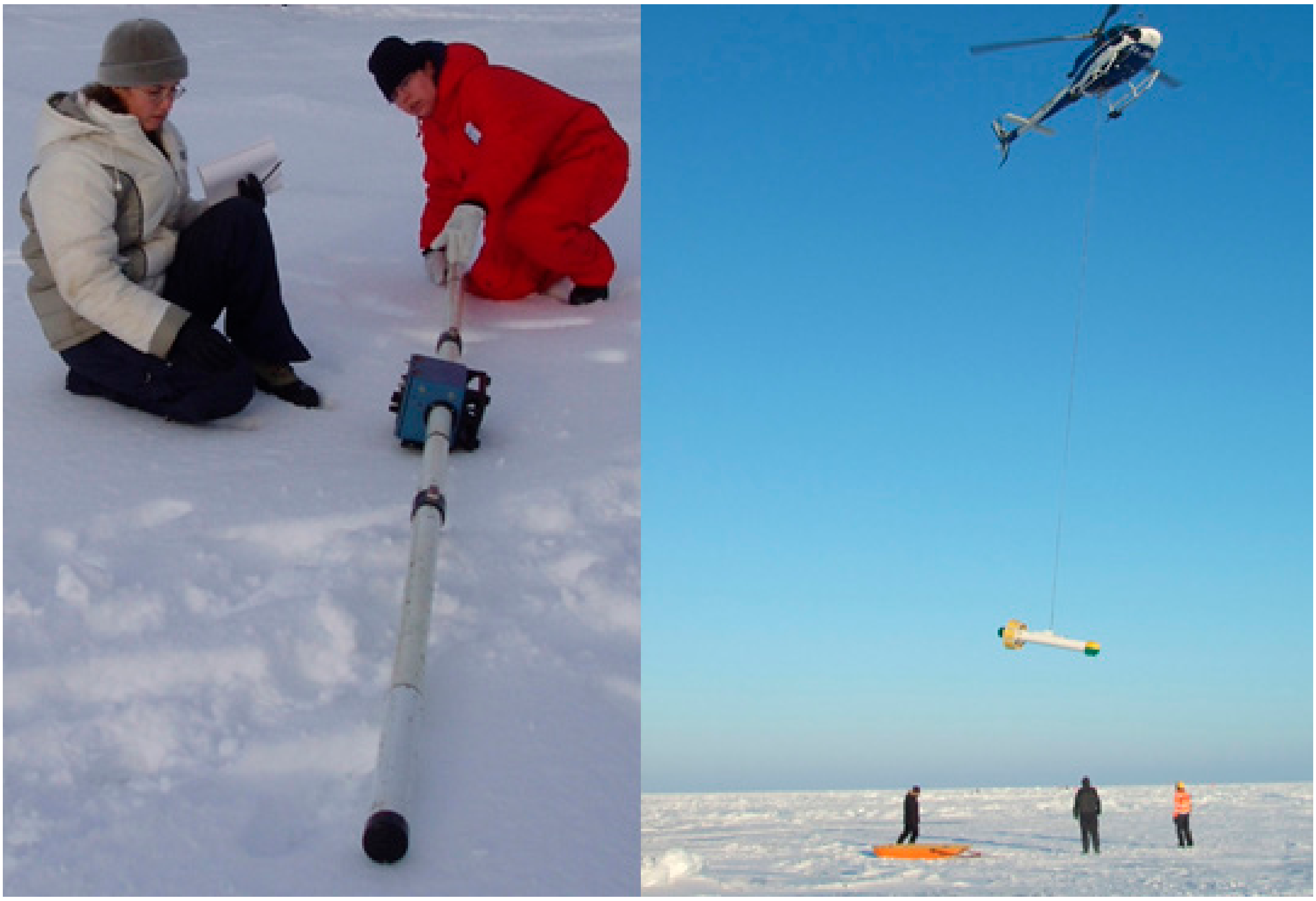

Figure 2 – Sea ice thickness measurements by EM-31 made from ice surface (left image – August 2004, research expedition onboard the icebreaker Kapitan Dranitsyn) and by EM-bird (right image – March 2011, expedition onboard the research vessel Aranda). Photo: T.Alekseeva.

instrument determines total (i.e. ice plus snow) thickness [11-14].

4. *Visual ship-based observations* are conducted by ice observer from the bridge of the ship. The observer estimates thickness of the overturned ice floe near the ship board by eye, with range-finding field glasses or with a scaled yard stick (Figure 3). Specialists of the Arctic and Antarctic Research Institute (AARI) has developed a standard ice-observing methodology for ship-based observations [15, 16]. International ice observations are specified by ice observation protocols of either ASPeCt http://www.aspect.aq or IceWatch/

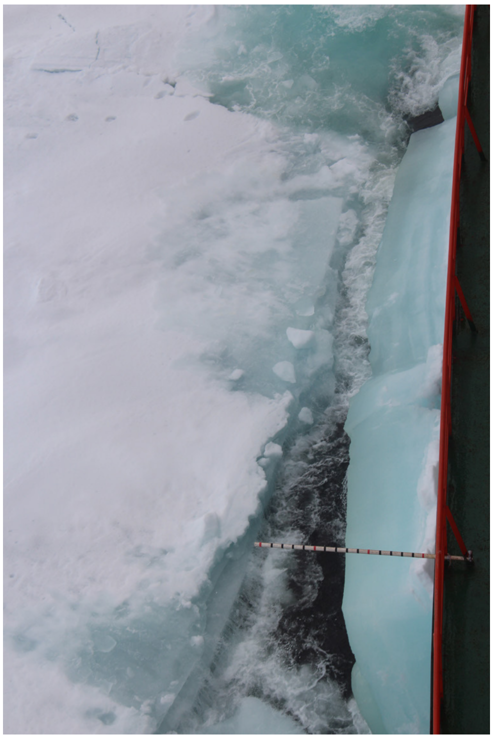

Figure 3 – Visual ship-based observations of ice thickness with a scaled yard stick (10-cm scale) fixed to the lower deck from board of nuclear icebreaker 50 let Pobedi. Photo: S. Serovetnikov, June 2019

ASSIS00T Arctic Ship-Based Sea Ice Standardization, http://icewatch.gina.alaska.edu). The accuracy of visual ice observations is ±10 cm.

5. *Video observations (TV ship observations)*. The principle of the method is similar to visual observations. During the independent movement of ship in ice area the ice floes near the ship board are overturned to side-up position and thus provide an opportunity to estimate thickness of the ice side. Thickness is estimated with reference to the previously measured control values with geometric calculations based on optical characteristics of the data-recording camera. Accuracy of sea ice thickness measurements is ±2 cm [17-19]. A number of Japanese researchers [20, 21] describe a video monitoring technique for observing the overturned ice floes during ship movement which was developed in 1990s. This method was applied during expeditions in the Sea of Okhotsk and to Antarctic. However, manual processing of received images took a long time, as automatic method of treating ice thickness from images was not developed. In 2004 a digital ship-based TV-system for ice thickness measurements was developed and introduced into the AARI sea ice monitoring operations [17]. The implementation of digital TV-system in dedicated ship observations aims to get high-quality and statistically significant data set of sea ice thickness along the ship track. The main task of the system is to automatize and standardize time-consuming observations as well as to exclude the influence of subjective factors on quality and quantity of sea ice observations. Digital ship-based TV system is a standard video monitoring system which is customized by the AARI specialists for specific conditions of sea ice observations. Initially processed video files are further processed by a special software developed by the AARI specialists. The software for computerized processing of sea ice images is made in the Microsoft Visual Basic 6.0 Integrated Development Environment. The software allows user to specify the beginning and the end of line which crosses the overturned side of ice by clicking and thus to estimate sea ice thickness (Figure 4). Comparing of real values of sea ice thicknesses and those measured by ship-based TV-system showed difference up to 3.8%. It provides data on sea ice thickness and snow depth along the ship track. The system operates autonomously and is able to work for a long time without special technical support. Thus there is an opportunity to maintain the TV-system on any vessels and icebreakers with minimal service and monitoring charges. In a whole the TV-system demonstrates working efficiency and resistance to technogenic impacts (i.e. power failure, vibration, shocks) and climatic impacts (i.e. solid precipitation and rainfall,

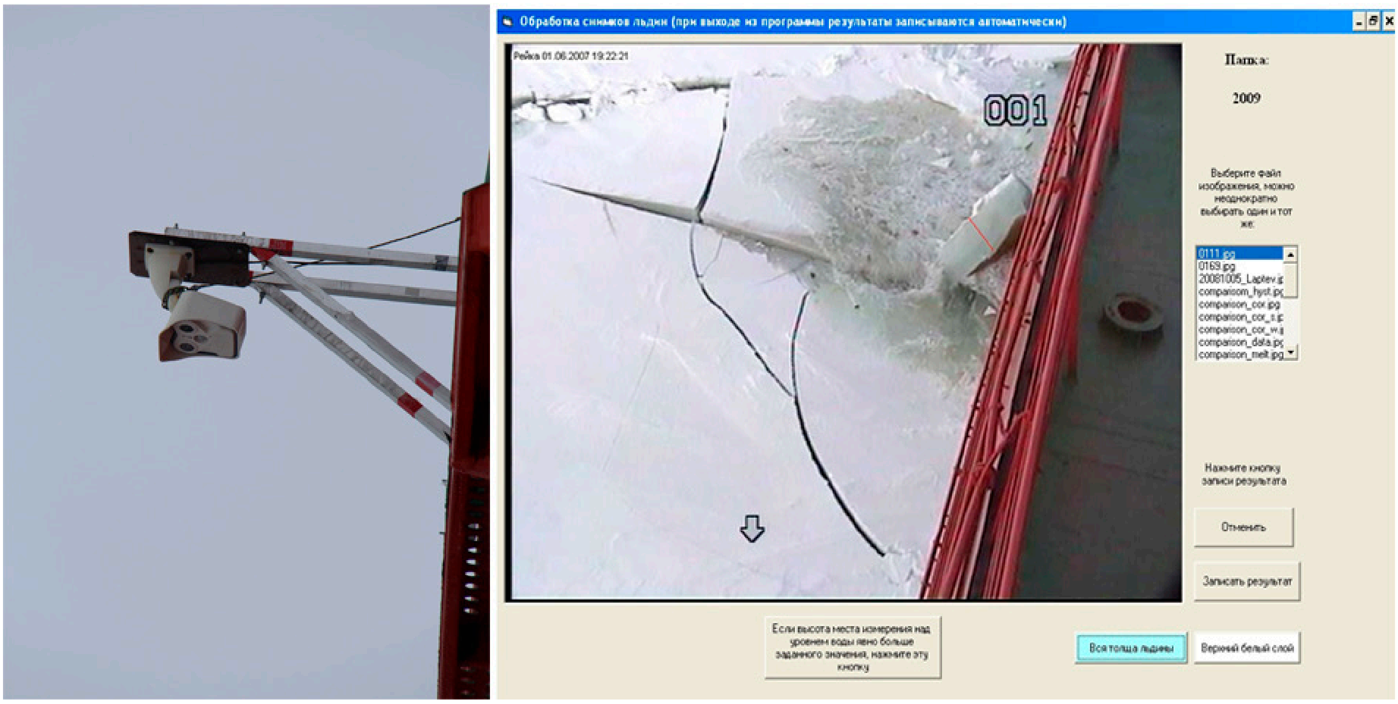

Figure 4 – Ship-based TV-system (left) mounted on the side deck of the ship for along-track recording of sea ice overturnings, and interface of the software for processing of images and estimating of sea ice thickness and snow depth.

icing, low temperatures). The AARI specialists develop currently the computer-assisted methods of ice and snow thickness measuring by images and upgrade the video monitoring system itself.

Main results of sea ice thickness measurements in the Arctic Seas

1. *Moored sonars*. The results of processing data sets observed with moored sonars can be found in the works published at the late 1990s-early 2000s [22-25]. In 1990-1996 the highest mean thickness in April-May in the Fram Strait near 79° N was 3.27 m and the lowest mean value was 2.25 m in September [22]. Monitoring of the interannual variability during the period 1990-2011 reveals decrease in mean level sea ice thickness from 3 m in 1990s to 2.2 m in 2008-2011. Minimum values of sea ice thickness were indicated in 2005-2006 [25]. In the eastern part of the Beaufort Sea a small decrease of ice thickness (by 2%) was recorded for the period 1991-2013 [23]. According to sea ice thickness buoy data from the Arctic basin in the area of the Beaufort Gyre ice draft had been gradually decreased by 0.5 m from 2005, when maximum values were detected, to 2012 [24].

2. *Electromagnetic systems EM-31 and EM-bird*. EM-systems have been actively used for sea ice thickness measurements since 2001. The most covered areas by EM-measurements are located in vicinity of Svalbard [12, 26-28] and in the Canadian Arctic Archipelago [29-32]. A number of sea ice thickness measurements in the area to the north of Svalbard with strong impact of warm Atlantic waters indicate change in sea ice thickness in April-May from 2.4 m in 2009 [12] to 1.8 m

in 2011 [27] and 1.7 m in 2015 [26]. In May 2011 and April 2015 sea ice thickness measurements with EM-bird were carried out along the Northwest Passage [31]. Mean thickness of level sea ice was 1.8-2 m over the large part of the Passage. Multi-year ice more than 3 m thick was found in Viscount-Melville Sound, McClintock Channel and Byam-Martin Channel. The authors were not able to monitor interannual variability of sea ice thickness because of absence of similar earlier measurements in this area; however, the results showed that thickness was 0.4-0.6 m less than observed during expeditions in 1950-1989 [32]. Thus, based on the obtained results and analysis of average air temperatures in this area, the authors [31] suggested a certain decrease of ice thickness along the Nortwest Passage, though large amount of multiyear and deformed ice still challenged navigation.

3. Ice drilling. Data from polar stations in the Kara Sea, Laptev Sea, East Siberian Sea and Chukchi Sea for the period 1936-2000 are summarized in monographs [33, 34]. According to the data from the Kara Sea the maximum thickness of landfast ice has increased from 1936 till the late 1960s before it began to decline by the end of the 20th century. Average values were 1.65 m in 1936-1957, 1.81 m in 1958-1983 and 1.74 m in 1984-2000. No significant changes in landfast ice thickness during "warm" and "cold" periods were observed in the eastern seas of Siberian Shelf. Mean values were 1.99 m in 1936-1957, 2 m in 1958-1983 and 1.97 m in 1984-2000. The study [35] analyses the interannual variability of landfast ice thickness till 2009. Thus, since 1940 till 1973 mean landfast ice thickness has increased from 1.83 to 1.96 m in the areas with the largest extent of landfast ice (north-western part of the Kara Sea, western and eastern parts of the Laptev Sea, western part of the East Siberian Sea), following the negative trend of air temperature above ocean surface. In 1973-2009, when trend of air temperature has shifted to positive one, mean landfast ice thickness started to decline (from 1.95 to 1.80 m). In monographs [36, 37] data sets from a large number of polar research stations are analyzed separately for each sea. Mean landfast ice thickness at the period of maximum landfast ice extent was estimated over total record for each station (time series from a station opening till 2012 in the Barents and south-western part of the Kara Sea and till 2015 in the north-eastern part of the Kara Sea, Laptev and East Siberian Seas) and separately over the period 2000-2012 or 2000-2015, respectively. Analysis of mean values over total record and over the early 2000s shows that landfast ice mean thicknesses were 1-11 cm less in 2000-2012 as compared to the total period of observation in the Barents Sea and 4-7 cm less in the Kara Sea. Landfast ice mean thicknesses over the period 2000-2015 were 7-16 cm less as compared to those of the total record in the north-eastern part of the Kara Sea, 0-4 cm in the Laptev Sea and 4-16 in the East Siberian Sea.

Landfast ice thickness measurements in the Hopen meteorological station (Svalbard) are carried out since 1966. Maximum sea ice thickness of approximately 1.5 m was observed in winter seasons 1967/1968, 1976/1977, 1987/1988 and 1997/1998. Ice thickness has a declining trend of landfast ice thickness -0.11 m per decade. During 2000-2007 landfast ice thickness was less than 1 m [38]. However, later observations in 2008-2011 in the area with stable landfast ice south of Barentsburg showed growth of landfast ice thickness in Green Fjord. After ice-free period in 2005/2006 mean ice thickness has increased from 5-10 cm in 2007 up to 74 cm in 2011 and maximum thickness has increased from 10 cm in 2007 up to 91 cm in 2011 [39].

Seasonal and interannual variations of landfast ice thickness at the research stations in the Canadian Arctic Archipelago during 1950-2014 are presented in papers [32, 40, 41]. Mean values of maximum landfast ice thickness during the specified period were 2.11 m at Cambridge Bay, 2.02 m at Resolute, 2.27 m and 1.98 at Eureka and Alert, respectively. In average, landfast ice thickness at these sites has declined for 4.5 cm per decade during 1957-2014 [40].

In 1971-1975 and 1977-1980 sea ice thickness near the Queen Elisabeth Islands was measured during ice drilling for hydrophone mounting by the seismic service. Results of data processing are shown in paper [42]. Thus, mean ice thickness in drilling holes was approximately 3 m in 1971-1974 and slightly more since 1975, i.e. from 3 to 4.6 m in 1978.

Main results of sea ice thickness measurements in the Arctic Basin

The results of observed and measured sea ice thickness are of particular interest in the context of continuing discussion on magnitude and causes of ice decline in the Arctic Basin over the several decades (see annual IPCC reports https://www.ipcc.ch/).

Estimations of changes of sea ice thickness in the Arctic Basin are presented in several papers published at the late 1990s-early 2000s and based mainly on measuring sea ice draft along the submarine routes [43-49]. The estimations are ambiguous.

Generalization of data acquired on 12 submarine voyages between 1958 and 1992 [45] reveals no significant change in sea ice thickness in the vicinity of the North Pole, and the study [49] shows no changes in sea ice thickness from 1991 to 1996 based on data from 6 submarine cruises along 150°W.

However, more complete integration of submarine data over the Arctic Basin in the study [46] demonstrates that the overall mean thickness decreased by 42% by the mid-1990s against the mean value 1958-1977. The paper [48] also shows sea ice thinning between mid-1980s and early 1990s according to the data on springtime submarine cruises during 1976-1994.The authors suggest that this thinning is caused by decreased proportion of multi-year ice and increased proportion of thinner first-year ice.

The study [43] introduces estimations of changes in the Arctic ice thickness derived from satellite data between 1982 and 2003. It is reported that mean ice thickness in January increased from 1982 to 1988, decreased from 1988 to 1996 and increased again from 1996 to 2003 mainly in the central Arctic Basin. The results in [44] show no sea ice thinning in the Arctic Basin during 1993-2001 according to the data derived from satellite altimeter measurements.

Integration and comparison of the Arctic ice thickness data for the period 1958-2008 is given in the study [50] (submarine data for the periods 1958-1976, 1993-1997 and satellite data ICESat 2003-2008). Relative to submarine records for the periods 1958-1976 and 1993-1997, the ICESat data (2003-2008) show that ice thickness has decreased by 1.6 m or 53% and by 0.2 m or 12%, respectively. Besides, the papers [50, 51] indicate significant decrease in mean ice thickness from ICESat (2003-2008) induced by a substantial decline of multiyear ice extent in the Arctic.

Later studies analyze data obtained at the beginning of the 21th century which induce definite thinning of the Arctic sea ice. The study [52] analyze sea ice thickness measurements obtained with electromagnetic (EM) instruments in the Fram Strait at the end of summer season from 2003 to 2012. Mean sea ice thickness has decreased by more than 50% during this period. The most significant thinning was indicated between 2003 and 2008. The paper [53] integrates several data sources (submarine data, EM-data and buoy data) and presents error assessments of existing sea ice thickness measurement techniques. The data indicate that the annual mean ice thickness in the central Arctic Basin has decreased from 3.45 m in 1975 to 1.11 m in 2013 which means a 65% decline. Sea ice changes results in seasonally ice-free areas in a considerable part of the Arctic. The year 2007 may be considered to be a tipping point when proportion of first year ice in the Arctic overpassed 50% [54].

In view of ambiguous estimates of changing Arctic sea ice thickness new estimates based on new data sources are needed. Dedicated ship-based measurements along the long-distance shipping routes may serve as such new data sources. Since the middle of the 20th century to the present days AARI has collected numerous unique ship-based visual data, as well as video-monitoring data since 2004. However, no integrated analysis has been done yet on sea ice thickness distribution and changes based on all available data. AARI's data compilation in the data base 'STK-LED' is currently in progress [55].

Important parts of the data base are observational data along the routes to the North Pole. The nuclear icebreaker 'Arktika' was the first to navigate to the circumpolar Arctic in August 1977 [56], the next was the nuclear icebreaker 'Sibir' in spring 1987 [57]. Navigation to the North Pole has become regular since 1990. Lighter ice conditions in the Arctic made it possible for ice-strengthened vessel 'Akademik Fedorov' to navigate independently in the high latitudes [58]. Since 1990s (with break at early 2000s) the AARI specialists have conducted dedicated ship-based visual ice observations during navigation to the North Pole. Since 2009 visual observations have been supplemented by ice thickness measurements with TV-system [58-61]. Figure 5 represents map of all expeditions which used TV-system.

During the first cruises to the North Pole in 1977 and 1987 only visual ice observations were carried out. Comparison of data on sea ice thickness distribution along the shipping routes in August 1977 and 2005, as well as in May 1987 and 2006 is given in the study [62]. Mean first-year ice thickness along the track from ice edge in the Laptev Sea to the North Pole in August was 1.2 m in 1977 and 1.19 m in 2005, the same estimates of old year ice thickness were 2.38 m and 2.25 m, respectively. In the period of maximum ice cover in the Arctic in May mean first-year ice thickness along the route to the north-west of Franz Josef Land archipelago was 1.38 m in 1987 and 1.23 m in 2006, mean old-year ice thickness was 2.56 m and 2.4 m, respectively.

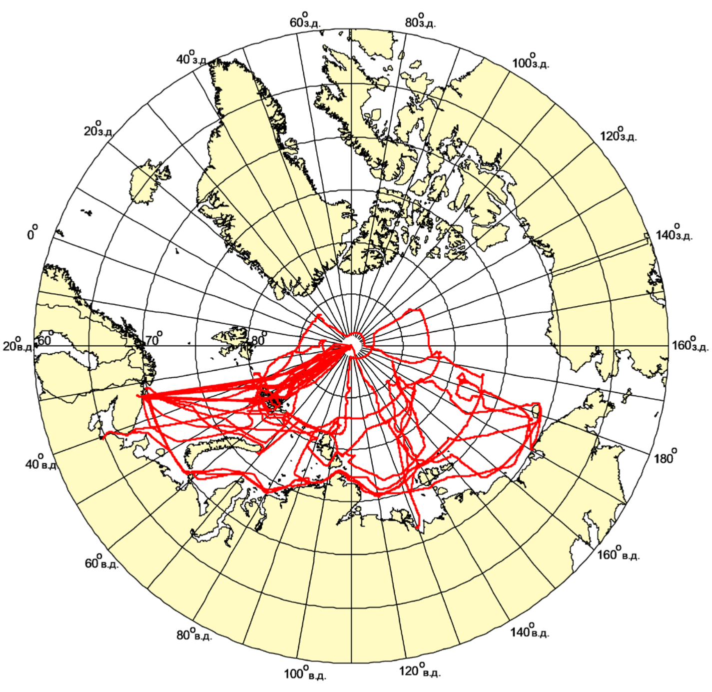

Figure 5 – High-latitude shipping cruises providing ship-based TV observations in 2004-2019.

Results of ice thickness measurements in the Arctic Basin during the navigation of nuclear icebreaker 'Rossiya' to the North Pole in August 1990 are shown in paper [63]. Measurements were conducted by video recording and making images of overturned ice manually from screen without using a software, which made it impossible to obtain a statistically significant amount of data and to assess its accuracy. Average ice thickness in 1990 along the 90°E in the area between 81°N and 90°N was 2.5 m. In 2004-2019 the TV-system was used in high-latitude expeditions in the Arctic Basin onboard the research vessel 'Akademik Fedorov' and nuclear icebreakers [17, 18]. The study [18] presents measurements of drifting level ice thickness derived from TV-system along the route between Franz Josef Land and the North Pole in summertime (July-August). The measurements were conducted in 2006-2009. The amount of data is more than 55 000 ice thickness measurements. The comparison of ship-based visual data obtained in 1990s before the current Arctic warming with data collected in 2006-2009 indicates following:

1. During 2006-2009 mean sea ice thickness has decreased along the shipping routes from Franz Josef Land to the North Pole as compared to 1990s. Maximal decline by 34% in July and 42% in August was recorded in 2007.

2. Mean sea ice thickness in summertime remained the same in 2008 and 2009 as compared to summer season 2007.

3. Largest change in thickness for the period 2006-2009 was up to 21% for first-year level ice. Old level ice has decreased by 7-13%.

4. Using of the video monitoring system (TV-system) allows to collect extensive data on sea ice thickness along the shipping routes crossing the Arctic Basin. This technique is an advanced direction for automation of ship-based ice thickness observations. The results of ship-based observations along the route from Franz Josef Land to the North Pole in summertime 2018 are shown in paper [61]. Mean level ice thickness in 2018 has notably decreased compared to the measurements in 1991-1996 and 2006-2011. Mean thickness of old ice was almost 2.5 m in 1991-1996 and 2.25 m in 2006-2011. In 2018 the significant decline of old year ice thickness to 1.6 m was observed. Mean first-year ice thickness has decreased from 1.5 m in 1991-1996 to 1.25 m in 2006-2011 and reaches its minimal values 0.9 m in 2018.

Conclusions

Maximal coverage by sea ice thickness data in the Arctic Basin nowadays is provided by acoustic sounding form submarines as well as by dedicated ship-based visual observations together with simultaneous TV ship observations from board of ice class vessels and icebreakers. Sonars on submarines measure ice draft, including keels of ice ridges, which prevent unambiguous estimation of level ice thickness. At the same time the new opportunities are appeared for underway ship-based measurements from ice class vessels and icebreakers due to increased navigation in the Arctic Basin. An advantage of visual ship observations is the unified methodology of measurements proceeding which allows to compare data from different years in different regions, though disadvantage is visual kind of observations which required experienced ice observer and discontinuity of measurements as it is impossible for ice observer to estimate every overturned ice floe near the ship board. Besides, captains try to navigate in thinner ice which has an impact on ice thickness distribution along the ship route. However, TV-system allows to compensate the disadvantage of visual observations and improves significantly the accuracy of measurements.

Sea ice thickness measurements presented in this review were obtained in various areas of the Arctic in different seasons, by different techniques and with different time periods of generalization and, consequently, are not adequate to estimate unambiguously a climate and interannual variability of sea ice thickness in the Arctic. Nevertheless, late AARI researches confirmed by ship-based observations indicate that revealed changes in sea ice thickness are mainly driven by changes in the atmosphere dynamic processes rather than thermodynamic processes due to climate change. Dynamic processes in the atmosphere are associated with changes in atmospheric circulations providing advection, hummocking and diverging of ice cover. Calculations based on approximation of vector fields of resulting ice drift over long-time periods show that in case of a low residual ice cover in the seas to the east of Severnaya Zemlya the circumpolar area which is usually covered by old ice is progressively (within 1-2 years) covered by first-year ice 1.5-2.5 m thick due to ice drift. Thereby the significant sea ice thinning is indicated which has been replaced by inherent ice cover in a several years [34, 64, 65].

Acknowledgements

This paper covers one of scientific activities of Frolov Sergey Viktorovich (1962-2021), who was the head of the Ice Navigation Research Laboratory of AARI since 2000. Sergey Viktorovich Frolov was an expert of the highest level in the fields of analysis of ice and hydrometeorological processes development, calculating optimal navigation routes in the freezing seas, developing the basic principles of the Hydrometeorological Support of Navigation in the Arctic. He participated in numerous Arctic expeditions, including 13 Russian expeditions to the North Pole, 7 high-latitude expeditions onboard icebreakers and vessels for establishing and evacuation of drifting stations «North Pole» (SP-27, 28, 29, 33-40), 3 ultra-early cruises along the Northern Sea Route, 5 expeditions on the establishment of border of the Continental Shelf of Russia. For his high professional skill Sergey Frolov was awarded the Order «For Merit to the Fatherland» of the 1st grade, the Order «For Merit to the Fatherland» of the 2nd grade, a Certificate of Appriciation from Rosgidromet, the badge «The Honours Polar Explorer», the badge «Honorary Worker of Hydrometeorological Service of Russia». The article is published with profound gratitude for coordination, wisdom and fruitful scientific ideas of Sergey Viktorovich Frolov.

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