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PHENOMENON OF ICING AND A REVIEW OF ICE ACCRETION NOMOGRAMS, MODELS AND CHARTS IN NAVIGATION

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ABSTRACT

The paper presents results of research based on analysis of marine icing nomograms, models and charts using in the sea navigation. The problem of ships icing occurs in specific weather and geographical conditions. Every year numbers of vessels navigate in these areas meet a phenomenon of icing. Ice on decks of ships can be formed from fresh water or sea (salt) water. Ships operating in waters where the phenomime of icing is occurred use for safety navigation icing nomograms and icing charts. Icing charts are created based on icing models.

The main aim of the article is to perform a review of currently used in the sea navigation icing nomograms and icing maps, based on icing models, used in navigation to depict the phenomenon of icing.

Keywords:

icing of ships, icing nomogram, icing model, icing chart.

Research article

INTRODUCTION

The problem of ships icing occurs in specific weather and geographical conditions. Every year numbers of vessels navigate in these areas meet a phenomenon of icing.

Ships traveling through regions were the air temperature is below freezing may acquire thick deposits of ice as a result of salt spray freezing on the rigging, deckhouses, and deck areas [2]. Also, precipitation may freeze to superstructure and exposed areas of the vessels, increasing the load of ice [2]. Icing of ship superstructures and rigs occurs when air temperatures are colder than the freezing point of sea water. Saline spray carried by the wind impacts bulkheads, decks, and rigging. Following three causes of ice accumulation may occur: the first is fog, including fog formed by evaporation from a relatively warm sea surface in a freezing conditions; the second is freezing rain, drizzle or wet snow; the third is sea spray or breaking water over a ship under suitable freezing conditions. Icing is a well-known hazard to traditional operations in high northern and southern waters. Sea spray icing is so far the dominant source for ice accretion on ships.

On small vessels in heavy seas and freezing weather, deck ice may accumulate very rapidly and increase the topside weight enough to capsize the vessel. Accumulation of more than 2 cm per hour are classified as heavy freezing spray [2]. The phenomenon of icing observed on the deck of the Polish Navy Sail Training Ship ORP 'Iskra' on Western and Southern Baltic Sea at February 1996 is presented in fig. 1. This is the example of the sea spray icing.

Fig. 1. Sea spry icing observed on the deck of the Polish Navy Sail Training Ship ORP 'Iskra' on Western and Southern Baltic Sea at February 1996 [photo L. Derlacz]

Below, in fig. 2 is shown the example of icing occurred in Port of Gdynia, not at sea. A large list of MV 'Władysław Broniewski' due to the icing on January 2nd, 1978 in Port of Gdynia occurred by the sea spray throw the breakwater there the vessel was moored. Icing on the deck equipment of the South Korean warship 981 during arriving at Vladivostok on December 22nd, 2014 is presented in fig. 3 [16].

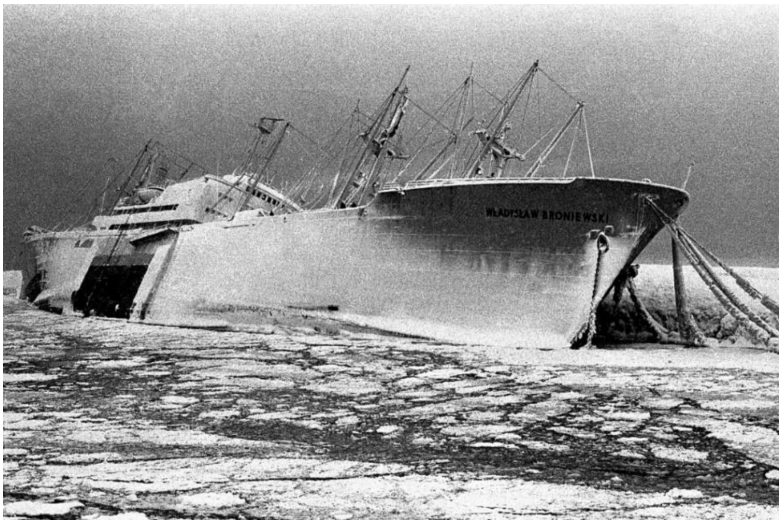


Fig. 2. A large list of MV 'Władysław Broniewski' due to the icing on January 2nd, 1978 in Port of Gdynia [photo Z. Kosycarz]

Fig. 3. Icing on the deck equipment of the South Korean warship 981 arrived at Vladivostok on December 22nd, 2014 [16]

DATA AND METHODS

The main aim of the article is to perform a review of currently used in the sea navigation icing nomograms and icing maps with icing models of vessels used to depict the phenomenon of icing.

Following methods were used to achieve the above aim such an analysis of publications and inference. Implementation of the research was based on the historical material gathers by research institutes and present publications.

The dangers related to icing have been known for centuries. The study and more attention of the icing phenomenon have been started after the third decade of the twenty centuries, when more ships, particularly fishing vessels, started operating in Arctic waters. Due to the icing many ships and their crews were lost in the sea. For example, according the study of T. Sawada from 1968 over a five-year period during the 1960s 19 ships sank in the northern seas of Japan, costing the lives of 296 people. The example from the last year connected with the icing, at about 0610 local time on February 11, 2017, while transiting from Dutch Harbor to St. Paul Island, Alaska, the fishing vessel 'Destination' capsized 2.6 miles northwest of St. George Island, Alaska, and sank several minutes later. 6 crewmembers died [3]. The numerous loss of human lives related with icing increased the necessity of including marine-icing warnings in operational weather forecasts [23].

Overview of icing statistical methods/nomograms and physical models in the operational weather forecasting and the navigation is shown in tab. 1. Only selected statistical methods and physical models are presented for illustrate research achievements in this area of study and modern applications.

Tab. 1. Overview of icing statistical methods/nomograms and physical models in the operational weather forecasting and the navigation

Method/model	Operational weather forecasting (Applied in Countries)	Used in sea navigation
Statistical methods/nomograms		
Sawada (1966)	Japan, Canada	
Mertins (1968)	UK, Denmark, Norway	
Lundqvist and Udin (1977)	Germany, Sweden	
Wise and Comiskey (1980)		

Method/model	Operational weather forecasting (Applied in Countries)	Used in sea navigation
Nomogram for ships of more than 500 dwt in Baltic Sea and the Bay of Bothnia (fig. 5)	Sweden, Finland	X
Nomogram for ships in the Gulf of Alaska and Eastern Bering Sea (fig. 9)	USA	X
Icing nomograms presented in the United Kingdom Hydrographic Office publication *Admiralty. The Mariner's Handbook* (based on fig. 10)		X
Physical models		
Kachurin et al. (1974)		
Stallabrass (1980)		
Overland (1990)	USA, Canada, Norway, Sweden, Japan	
Bleckmore and Lozowski (1993)		
Modified Stallabrass (1994)	Canada, Norway	
Marine-Icing Model for the Norwegian Coast Guard (MINCOG)	Norway	

CHARACTERISTICS OF ICING PHENOMENON

Icing increases the weight and raises the centre of gravity of ships, lowering freeboard and reducing stability, a potentially catastrophic problem, particularly for smaller vessels such as fishing trawlers. Icing also affects personnel and equipment operations, emergency evacuation procedures and communications. Icing of ships would be affected by temperature change, with a potential benefit for navigation in Polar Regions. Structures at the coast at high latitudes may have more sea spray during winter. Light from navigation installations could be reduced by additional sea spray icing [11].

Sea spray icing is a serious hazard for marine operations in high latitude regions. Many ships and lives have been lost when ships sank, or became disabled, after the accretion of ice on decks and superstructures. Large amounts of ice can raise the centre of mass on a ship enough to result in a catastrophic loss of stability [11].

Capsizing, extreme rolling and/or pitching, and topside flooding can occur as a result of the loss of stability and extra weight from the ice burden. The problem is particularly dangerous for smaller ships, such as fishing vessels, because they are more likely to be exposed to sea spray and a relatively smaller amount of ice is required for destabilization. However, as we see in the picture on fig. 2 this phenomenon is dangerous for big ships in specific conditions too. J. E. Overland [20], R. W. Fett and T. L. Kozo [9] and R. W. Fett et al. [8] describe a tragic example of the effects of sea spray icing.

Areas of icing conditions

In the International Code of Safety for High-Speed Craft (2000 HSC Code) in Annex 5 Ice accretion applicable to all types of craft, the following icing areas were defined [14]:

1. The area north of latitude 65°30'N, between longitude 28°W and the West coast of Iceland; north of the north coast of Iceland; north of the rhumb line running from latitude 66°N, longitude 15°W to latitude 73°30'N, longitude 15°E, north of latitude 73°30'N between longitude 15°E and 35°E, and east of longitude 35°E, as well as north of latitude 56°N in the Baltic Sea.
2. The area north of latitude 43°N bounded in the west by the North American coast and the east by the rhumb line running from latitude 43°N, longitude 48°W to latitude 63°N, longitude 28°W and thence along longitude 28°W.
3. All sea areas north of the North American continent, west of the areas defined in subparagraphs .1 and .2 of this paragraph.
4. The Bering and Okhotsk Seas and the Tartary Strait during the icing season.
5. South of latitude 60°S.

A chart to illustrate the areas is presented in fig. 4. During the winter mouths in the Baltic Sea the icing can be occurred in all regions, not only north of latitude 56°N. There are lots examples of icing also from the Gdansk Bay, Southern and Western Baltic.

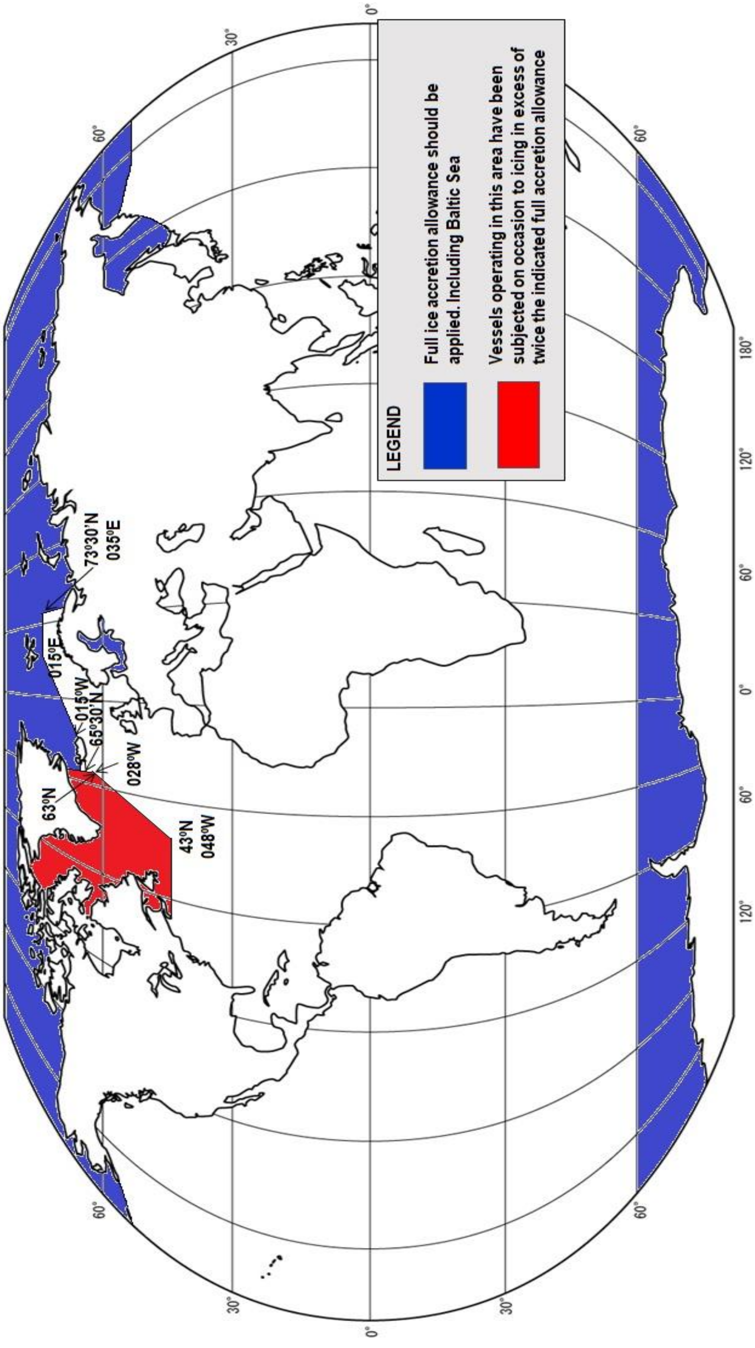


Fig. 4. Chart of areas of icing conditions [own study based on 15]

ICING NOMOGRAMS/STATISTICAL METHODS

In the statistical methods, the icing rate is estimated based on empirical relationships between icing and important input parameters collected from several icing events. While in most of the physical models a continuous icing rate is calculated and the icing is divided into categories based on this continuous icing-rate calculation, the icing output from the nomograms is only categorical [23].

T. Sawada (1962) developed an ice accretion nomogram for use in the Sea of Japan. The graph is based on data obtained by Japanese vessels. It provides icing estimates by three categories: light, moderate or heavy. The graphs do not consider sea temperature and are based on wind speed and surface air temperature [7]. The Sawada's diagram is presented in fig. 5. For example, in weather conditions when the surface air temperature is −10°C and the wind speed 10 m/sec — the icing is moderate.

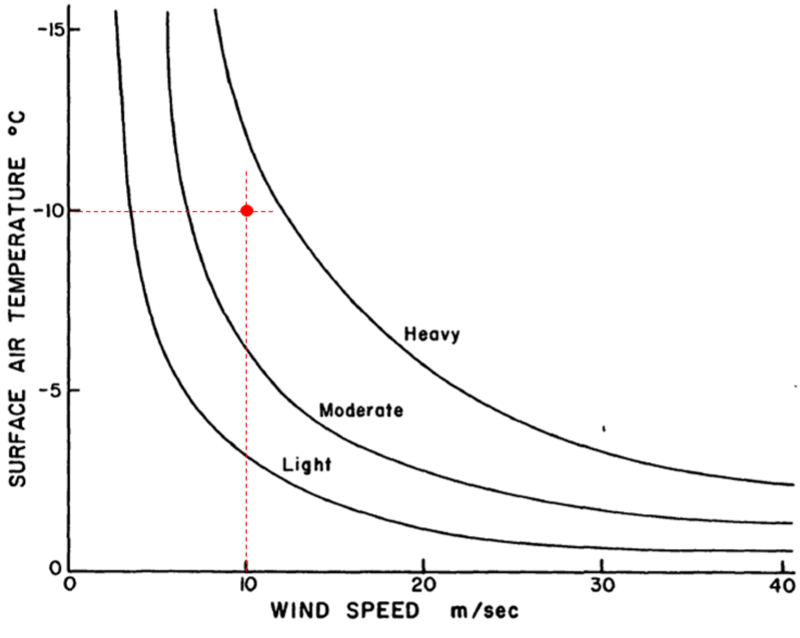


Fig. 5. Sawada's diagram (1962) [7] with an example of the icing calculation

H. O. Martins (1968) studied nearly 400 observations taken by trawlers in the Northeast Atlantic. The study resulted in series of nomograms which provided guidance for forecasting the severity of ice accretion. The charts required sea surface temperature (SST) and based on wind speed and surface air temperature. Martins (1968) has presented icing diagrams on the relation between air temperature, wind and icing rate (fig. 6) [7, 17]. An example of using Martins diagrams (fig.6) is following: windforce 9–10 Bft; air temperature –8.0°C; water temperature +2.0°C. Expected icing to diagrams: severe icing (7–14 cm/24 h).

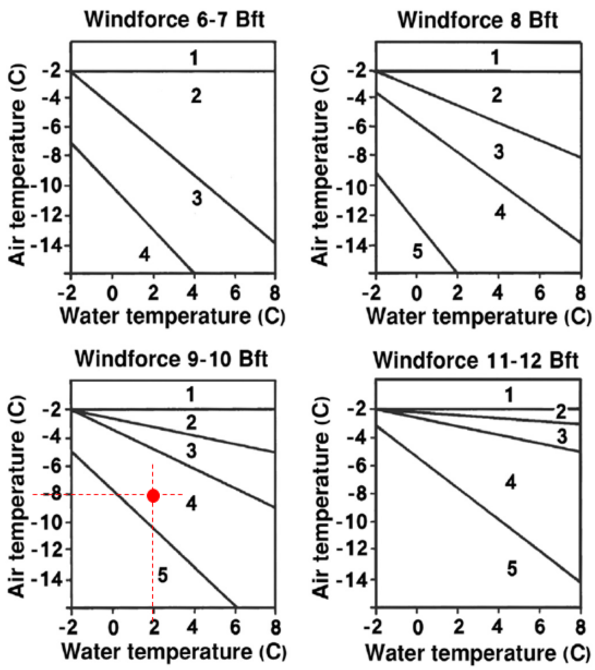


Fig. 6. Martins (1968) charts of icing [17] Degree of icing: 1 — None, 2 — Light (1–3 cm/24 h), 3 — Moderate (4–6 cm/24 h), 4 — Severe (7–14 cm/24 h), and 5 — Very Severe (≥ 15/24 h); wind force in Beaufort scale

Since the middle of the 1960s, ice accretion reports have been collected from ships travelling in the Baltic as part of the research conducted by the Swedish Meteorological and Hydrological Institute (SMHI). The data from these reports have been processed and the relation between ice accretion and meteorological and oceanographic parameters have been studied. The investigation comprises merchant vessels of size typical for the Baltic [17]. The study was provided by Jan-Eric Lundqvist and Ingemar Udin and the result was a nomogram (diagram) presented relation between icing on ships, air temperature and wind speed (fig. 5), there the speed and course of the ships have not been taken into account [17]. The diagram (Lundqvist and Udin, 1977) is nowadays applicable to the conditions in the Baltic Sea and the Bay of Bothnia for ships of more than 500 dwt [24]. Other causes which have an influence on the degree of ice formation is the ships course and speed, the wave height and the temperature of the sea surface.

In the diagram (Lundqvist and Udin, 1977) presented in fig. 5 the data show few cases with icing for wind below 5m/s. Moderate and severe icing have occurred when the winds have exceeded 7 respectively 10m/s. Light icing has been reported for air temperatures as high as 0.0°C and –0.5°C. Moderate and severe icing have occurred with air temperatures below –2.5°C and –4.5°C respectively [17]. For example, in weather conditions when the air temperature is –10°C and the wind speed 10 m/sec — the icing is moderate.

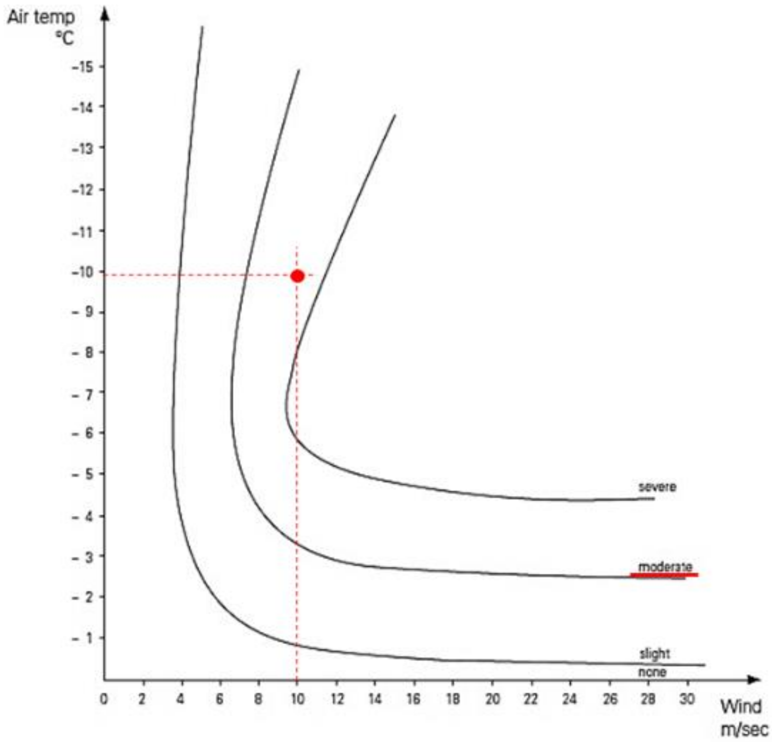


Fig. 7. Icing nomogram (Lundqvist and Udin, 1977) applicable to the conditions in the Baltic Sea and the Bay of Bothnia for ships of more than 500 dwt [24] with an example of the icing calculation

T. Sawada (1966) has also presented a diagram showing the degree of icing related to air temperature and wind. The diagram is based on data from Japanese patrol and fishing boats [17]. The diagrams in fig. 8 shows relation between icing on ships, air temperature and wind speed on the Baltic Sea — solid curves (Lundqvist and Udin, 1977) and on the oceans – dashed curves (Sawada, 1966). The most extreme difference is seen for –6°C and 10 m/sec, where Lundqvist's and Udin's diagram shows severe icing while Sowada's shows light icing [17].

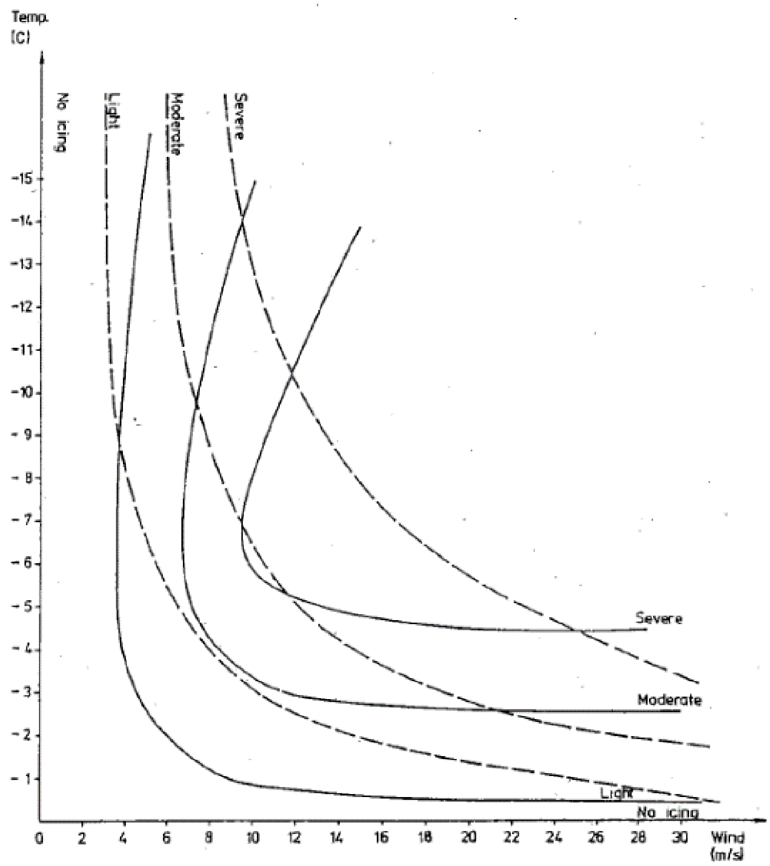


Fig. 8. Relation between icing on ships, air temperature and wind speed. A comparison between Baltic (solid curves) and ocean conditions (dashed curves, after Sawada) [17]

Fig. 9 shows the classification of icing based on the sea surface temperature of the Baltic Sea. As a result, severe and moderate icing happens when the sea surface temperature (SST) is less than +2°C and +4°C, respectively [4]. The diagram shows that severe icing mainly occurs for SST lower than +2°C and moderate icing mainly for SST lower than +4°C. The maximum of cases with ice accretion occur with SST around +1°C. Also, there is no icing when sea surface temperature is higher than +6°C [4].

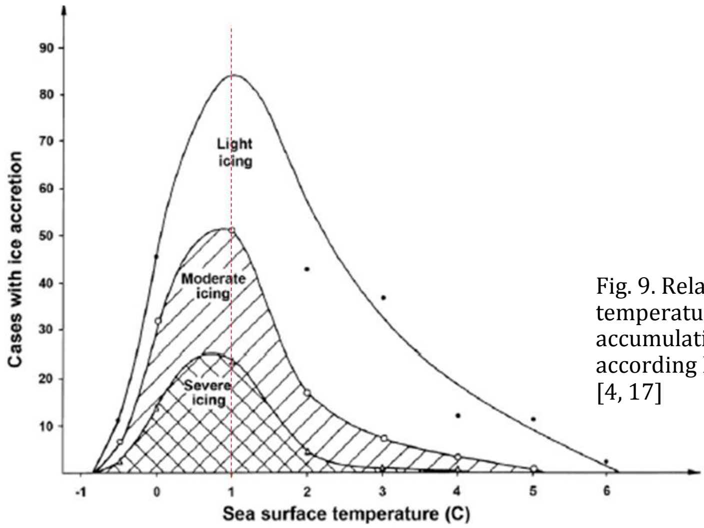


Fig. 9. Relation between sea surface temperature and cases with ice accumulation for the Baltic Sea according Lundqvist and Udin (1977) [4, 17]

J. L. Wise and A. L. Comisky (1980) combined the Martins charts into a single nomogram. The new nomogram was then modified based on climatological differences between the Northeast Atlantic and the Northeast Pacific. In addition, they integrated same 50 quantified icing reports from the northeast Pacific region. The end result was a diagram constructed purely on an empirical basis without recourse to a derived functional relationship between variables [7]. Ice Accretion nomogram prepared by Wise and Comiskey (1980) is presented in fig. 10.

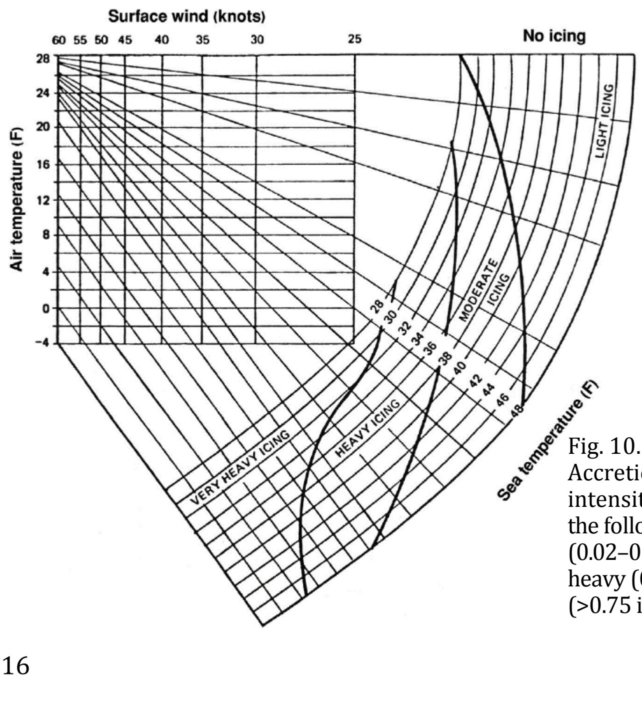


Fig. 10. Wise and Comiskey (1980) Ice Accretion nomogram [4, 6, 7, 15]; icing intensities are defined in terms of the following rates of accumulation: light (0.02–0.2 in./3 h), moderate (0.2–0.3 in./3 h), heavy (0.3–0.75 in./3 h) and very heavy (>0.75 in./3 h)

The diagram in fig. 11 shows the ice accretion nomogram which is recommended for use in the Gulf of Alaska and Eastern Bering Sea [1]. It presents the connection between the degree of ice formation, wind force, the air temperature and the sea temperature. Other factors which have an influence on the degree of ice formation is the ships course, speed and the wave height.

For example, in weather condition when the air temperature is –12°C, the wind speed 15 m/sec and the sea temperature +1°C — the icing is heavy (5 in/24 h or 0.635 in/3 h).

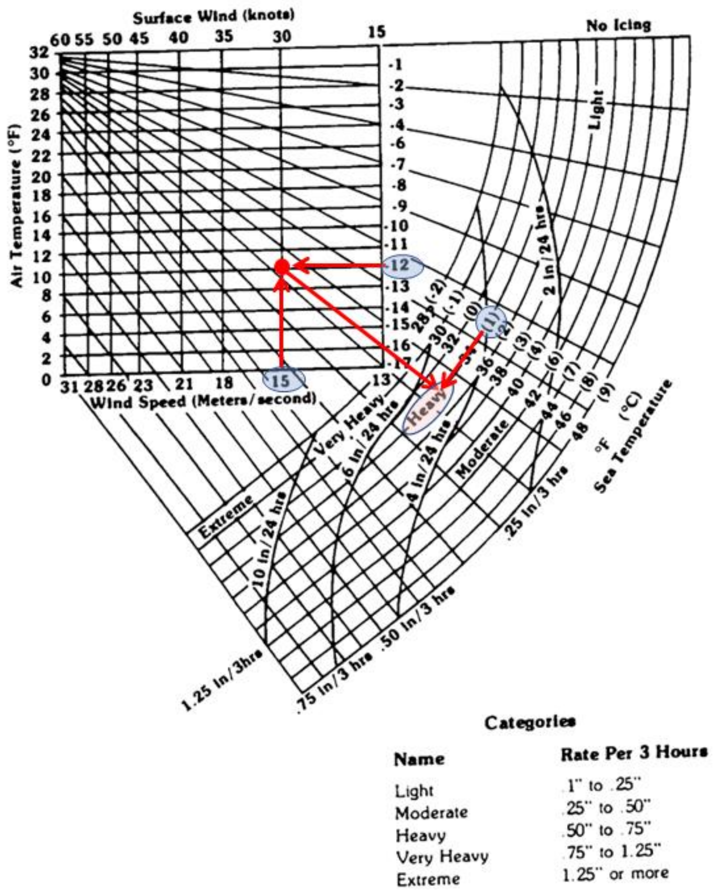
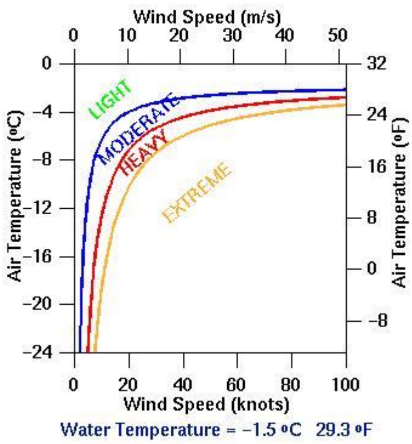
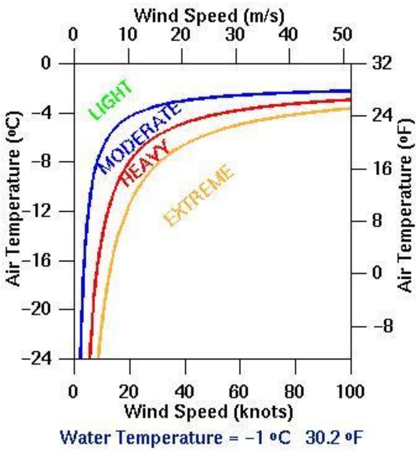


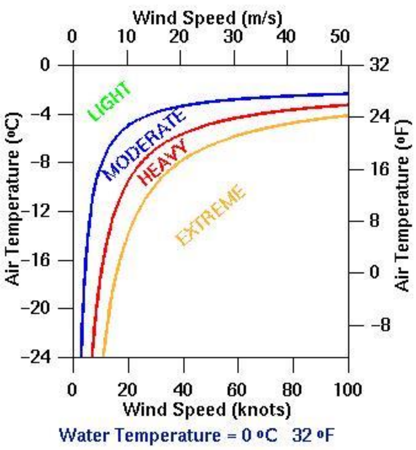
Fig. 11. The ice accretion nomogram recommended for use in the Gulf of Alaska and Eastern Bering Sea [1] with an example of the icing calculation

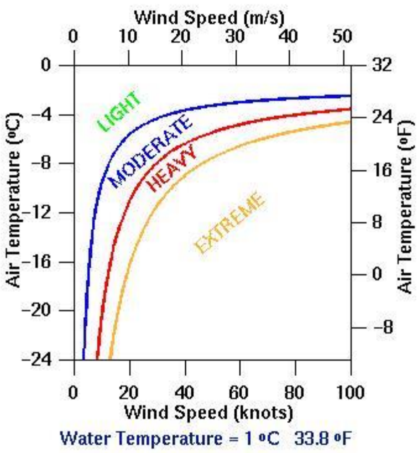
Nomograms presented in fig. 12 have been developed for a quick reference. For the purposes of this study, nomograms are presented only for the water temperatures

–1.5, –1, 0, +1, +2, +4, +6, +7, +8, +10°C. They display sea spray icing potential class as a function of wind speed and air temperature for a given sea temperature. These nomograms are slightly different from the ones found in US Navy because they are based on the most recent work by Overland. The main difference is that the effect of cold sea water is emphasized more in the nomograms shown here. Generally, icing is not a problem at sea temperatures greater than 7°C, and no cases with higher temperatures were considered when the algorithm was derived. Because it may be possible for icing to occur at these higher sea temperatures, they have been included below [11].









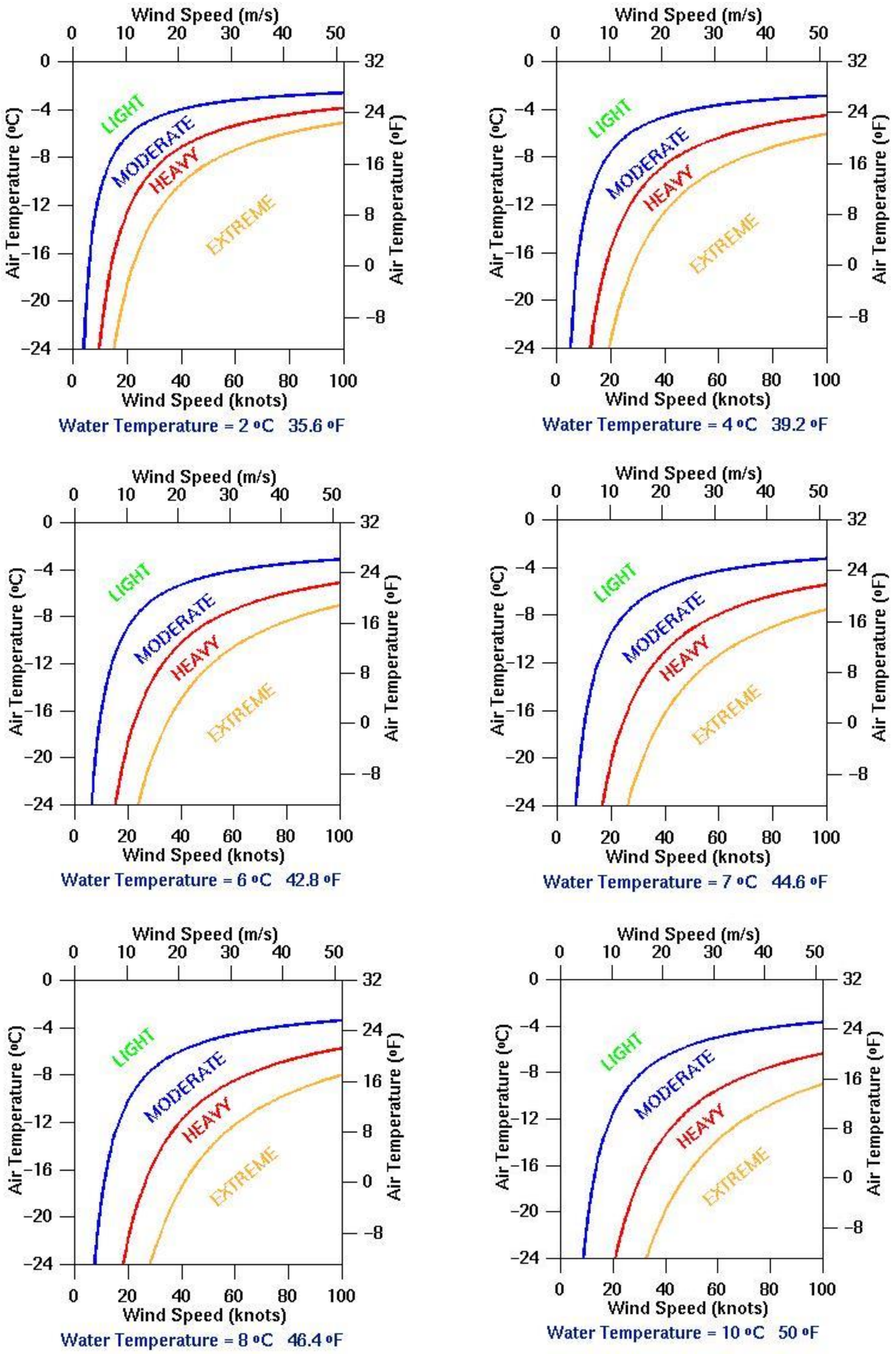


Fig. 12. Nomograms of icing for various water temperature adopted from [11, 22]

Above nomograms based on the Overland algorithms can be used to predict the present icing conditions using parameters measured from the vessel. It can also be used to predict future icing conditions using the predictions of a numerical weather forecast. Use the air temperature and wind speed closest to 10 meters elevation [5].

Nowadays, mainly the following nomograms of icing are used in navigation on board the ships and also during the study of meteorology and oceanography in the Polish Naval Academy:

1. The icing nomogram applicable to the conditions in the Baltic Sea and the Bay of Bothnia for ships of more than 500 dwt (fig. 7) [24].
2. The ice accretion nomogram recommended for use in the Gulf of Alaska and Eastern Bering Sea (fig. 11) [1].
3. Icing nomograms presented in the United Kingdom Hydrographic Office publication *Admiralty. The Mariner's Handbook* (p. 153). The nomograms are based on the work of J. R. Overland, C. H. Pease, R. W. Preisendorfer and A. L. Comiskey. These nomograms show the ice accumulation for slow moving vessels with the wind ahead or on the beam. Icing nomograms are for the following sea water temperatures: +1, +3, +5 and +7°C. Nomograms presented three stages of icing: light, moderate and heavy.

ICING MODELS/PHYSICALS MODELS

The prediction of icing is a complex subject, that takes into account the physical processes. Generally, the icing rate is qualitatively related to ship size, speed, heading, temperature, and sea state.

Two types of models are used to describe icing conditions: empirical and physical. Empirical models use icing observations to determine the severity of icing. Physical models apply theoretical and observational data to generate ice forecasts. Inputs for physical models include sea state and sea surface temperature parameters. Physical models connect icing severity and environmental conditions [10, 12]. Creating a model for forecasting requires observational data. The available data varies depending on the type of vessel, speed, and heading. The models use data from different regions, affecting the calculation of their algorithms. When models have the same inputs and yield different forecasts, it is due to their calibration with observational data and the physics of icing [10, 12].

For the purpose of this article, an analysis of selected icing models was carried out such as models of Kuchurin (1974), Stallabrass (1980), Overland (1990), Blackmore and Lazowski (1993) and modified Stallabrass (1994). The results of analysis are illustrated in tab. 2. The X for each category means the algorithm applies the input directly. If the boxed is not marked, the algorithm applies the variable indirectly or is insensitive to the variable [10, 12, 23].

Tab. 2. Comparison of icing algorithm methodology [10, 12, 25]

Algorithm methodology / Icing model	Thermodynamic equilibrium	Surface film temperature	Sea surface temperature	Spry flux	Wave height
Kuchurin et al. (1974)	X	X	X	X	X
Stallabrass (1980)				X	X
Overland (1990)			X	X	
Bleckmore and Lazowski (1993)	X				X
Modified Stallabrass (1994)				X	X

In fig. 13 is presented the comparison of sea-surface temperature sensitivities for a number of vessel-icing models. The modified Stallabrass (1980) model uses vertical liquid-water content and spray-residence time expressions following Zakrzewski (1986) [18].

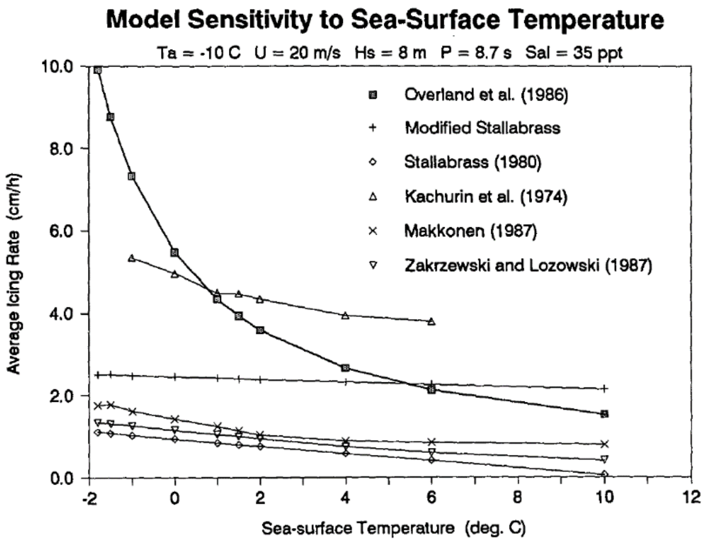


Fig. 13. Comparison of sea-surface temperature sensitivities for a number of vessel-icing models, adopted from [18]

In operational forecasting same of icing models and statistical methods are applied. The overview of icing models and statistical methods apllied in operational weather forecasting shows in tab. 3. In study of E. M. Samuelsen (2018) the overview of icing models applied in operational forecasting also includes personal communication and forecasters in Norway, Sweden, Germany, Canada, the USA and Japan in years 2014–2016 [23].

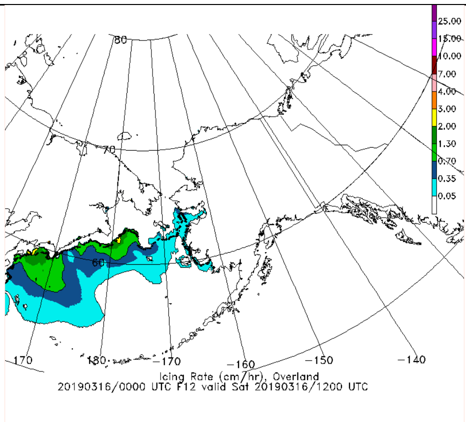
Tab. 3. Overview of icing models and statistical methods applied
in operational weather forecasting, ad [23]

Type of models and methods	Model/method	Applied in
Physical models	Overland	USA, Canada, Norway, Sweden, Japan
	Modified Stallabrass	Canada, Norway
	MINCOG	Norway
Statistical methods/nomograms	Martins	UK, Denmark, Norway
	Lundqvist and Udin	Germany, Sweden
	Sawada	Japan, Canada

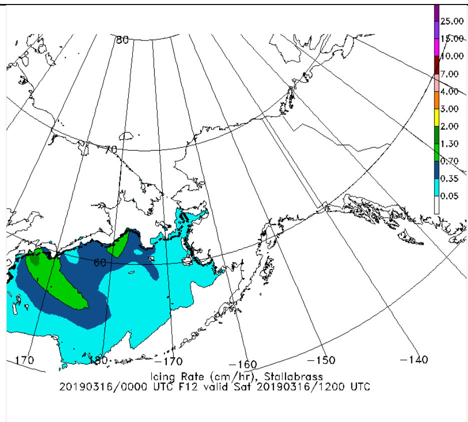
ICING CHARTS

National Oceanic and Atmospheric Administration (NOAA) Ocean Prediction Center online run a superstructure ice accretion service for Alaska and Atlantic which was developed using predictive modelling. The model works on an algorithm relating to wind speed, freezing point of the sea water, air temperature and the sea temperature. The legend of the animation shows the expected amount of ice accretion in cm/hr.

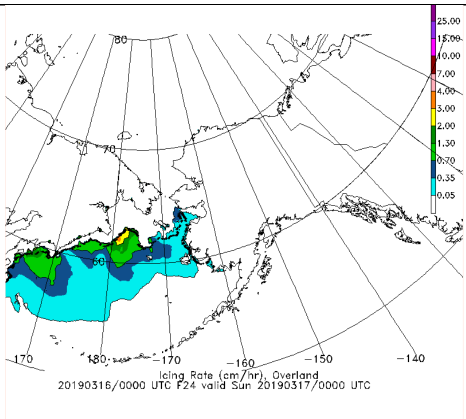
The Icing Rate for Alaska region charts based on the US Modified Overland algorithm and the Canadian Stallabrass algorithm for March 16, 2019 (forecast 12, 24 hours) are presented in fig. 14. The Overland and Stallabrass images depict the forecast ice accumulation rate (in cm/hour) for 12 hours, 24 hours, and 36 hours. The rate is an instantaneous forecast, not cumulative [19].



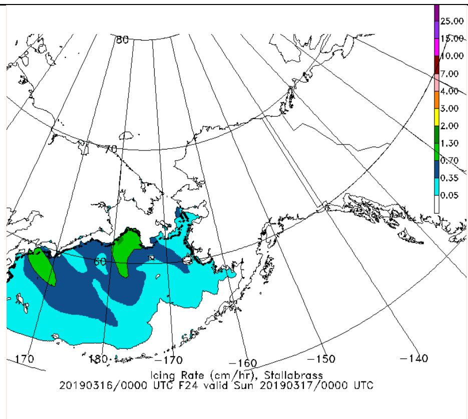
Overland (Forecast 12 hours)



Stallabrass (Forecast 24 hours)



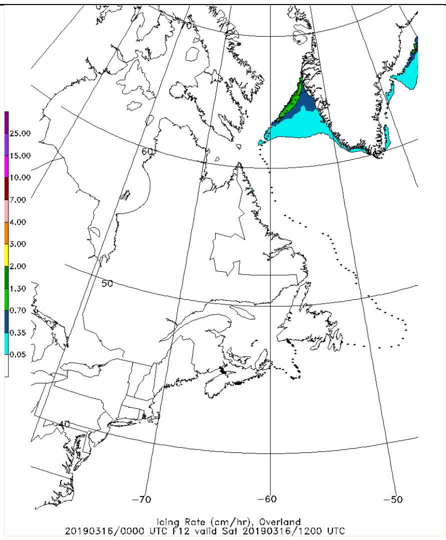
Overland (Forecast 24 hours)



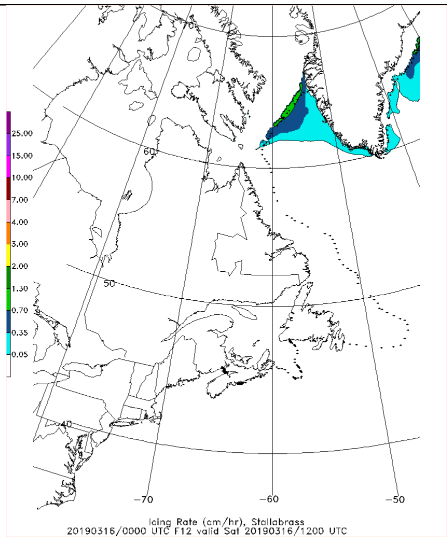
Stallabrass (Forecast 24 hours)

Fig. 14. The Icing Rate for Alaska region charts based on the US Modified Overland algorithm and Stallabrass algorithm for March 16, 2019 (forecast 12, 24 hours) [19]

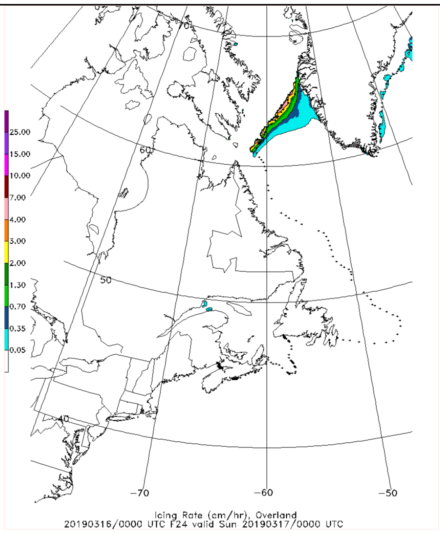
The Icing Rate for North Atlantic Ocean region charts based on the US Modified Overland and Stallabrass algorithms for March 16, 2019 (forecast 12, 24 and 36 hours) are presented in fig. 15. The Overland and Stallabrass images depict the forecast ice accumulation rate (in cm/hour) for 12 hours and 24 hours and the rate is an instantaneous forecast, not cumulative.



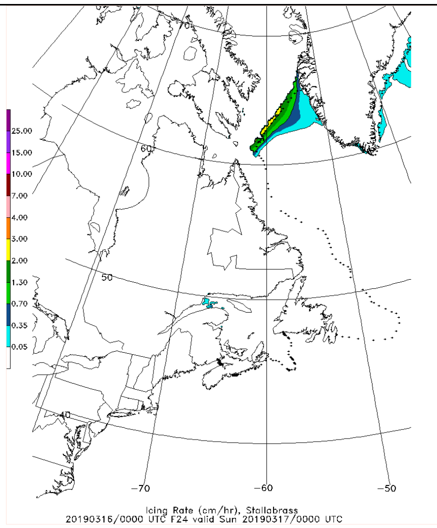
Overland (Forecast 12 hours)



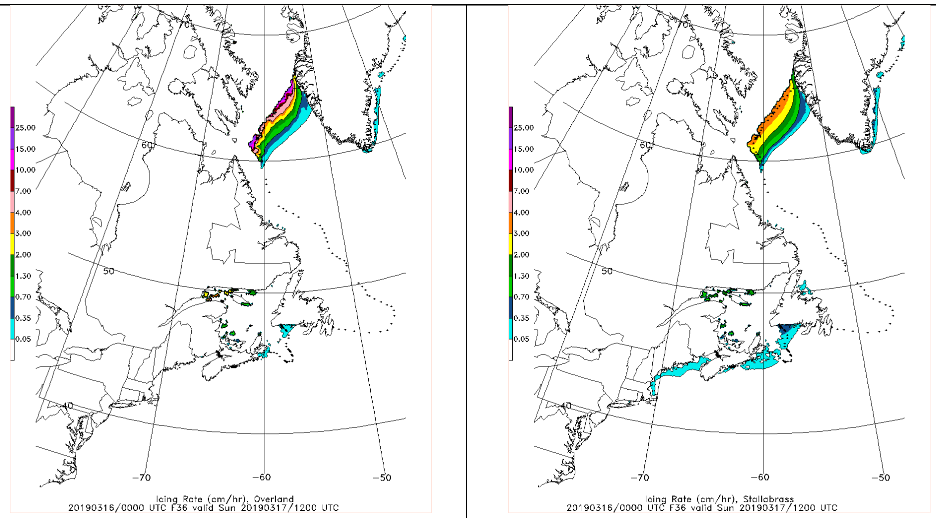
Stallabrass (Forecast 12 hours)



Overland (Forecast 24 hours)



Stallabrass (Forecast 24 hours)



Overland (Forecast 36 hours) | Stallabrass (Forecast 36 hours)

Fig. 15. The Icing Rate for North Atlantic Ocean region charts based on the US Modified Overland and Stallabrass algorithms for March 16, 2019 (forecast 12, 24 and 36 hours) [19]

Currently, the publication of the icing charts is very limited, because these special charts used in the navigation are only issued by the NOAA.

DISCUSSION AND CONCLUSIONS

In the conclusion of the analysis were made of the following generalizations:

1. Sea spray icing has long been a serious hazard to marine vessels, because the ice accumulates over exposed decks and exterior surface of vessel, thereby adding white that may ultimately capsize a vessel [3]. Vessels icing is a severe hazard of high latitude waters (see fig. 4) causing stability and mechanical problems. Necessary conditions for vessel icing are an adequate supply of water to exposed structures on the vessel and air temperatures below the freezing point of sea waters. Forecasting vessel icing is a difficult process due to uncertainty in observational inputs and environmental parameters associated with it [10, 12].
2. The models present solutions to determine ice accretion rates. Each treats the physics of icing differently, causing varying outputs for the same environmental inputs. The value of improving forecasts is to increase vessel safety for operations in

waters where the potential for freezing spray is present. Icing also presents hazards for structures, drilling and production platforms, aircraft, and coastal communities. Forecasting for these is essential for safety purposes. Understanding the meteorological conditions and the algorithms associated with icing are necessary to develop accurate predictions [10].

3. Nowadays, mainly the following nomograms of icing are used in navigation on board the ships and also during the study of meteorology and oceanography in the Polish Naval Academy:
   - the icing nomogram applicable to the conditions in the Baltic Sea and the Bay of Bothnia for ships of more than 500 dwt (fig. 7) [24];
   - the ice accretion nomogram recommended for use in the Gulf of Alaska and Eastern Bering Sea (fig. 11) [1];
   - icing nomograms presented in the United Kingdom Hydrographic Office publication *Admiralty. The Mariner's Handbook* (p. 153). The nomograms are based on the work of J. R. Overland, C. H. Pease, R. W. Preisendorfer and A. L. Comiskey; these nomograms show the ice accumulation for slow moving vessels with the wind ahead or on the beam. Icing nomograms are for the specific sea water temperatures.
4. The publication of the icing charts is very limited, and the examples of charts used in the navigation are charts issued by the NOAA (fig. 14, 15)

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ZJAWISKO OBLODZENIA I PRZEGLĄD NOMOGRAMÓW, MODELI I MAP OBLODZENIA W NAWIGACJI

STRESZCZENIE

W artykule przedstawiono wyniki badań opartych na analizie morskich nomogramów oblodzenia, modeli i map wykorzystywanych w nawigacji morskiej. Problem oblodzenia statków występuje w określonych warunkach pogodowych i geograficznych. Każdego roku wiele statków napotyka warunki powstawania zjawiska oblodzenia. Lód na pokładach statków może być utworzony ze słodkiej lub morskiej wody. Na statkach pływających po akwenach, w których występuje zjawisko oblodzenia, do zapewnienia bezpieczeństwa nawigacji używa się nomogramów i map oblodzenia. Mapy oblodzenia są tworzone na podstawie modeli oblodzenia.

Głównym celem artykułu jest przeprowadzenie przeglądu obecnie stosowanych w nawigacji morskiej nomogramów i map oblodzenia wykonanych na podstawie danych z modeli oblodzenia, używanych na morzu do zobrazowania zjawiska oblodzenia.

Słowa kluczowe:

oblodzenie, nomogram oblodzenia, model oblodzenia, mapa oblodzenia.

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