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Stability of Vessels in an Ice-free Arctic

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ABSTRACT: One consequence of the declining ice cover in the Arctic is increased areas of open seas. These new open sea areas lead to some challenging aspects related to ship stability. Longer fetch lengths, associated with build-up of larger waves followed by increased conditions for sea spray icing on vessels is one aspect. Open seas in combination with cold atmospheric temperatures is a prerequisite for polar low pressures to occur. Polar lows may represent an additional aspect of increased icing on vessels by heavy snow in addition to extensive sea spray ice accretion.
Over the last decades, different formulas for prediction of sea spray ice accretion rate on ships were developed to form basis for ice accretion warnings. Some of these formulas seem to have certain limitations and appear to be conservative. Important limitations of some formulas are considerations regarding heat flux, relationship between wind and waves, and ice accretion related to Polar lows.
This paper will take a closer look at the accuracy and the realism of different ice accretion formulas and, related to this aspect, we will also discuss whether ship officer candidates receive sufficient maritime education and training (MET) related to realistic ice accretion and ship icing aspects.

1 INTRODUCTION

Marine activities in the Arctic have long traditions. The first ships entering arctic areas were just for exploration purposes, but from the early 17th century to present time, various whale-catching, fishing and seal catch-based activities evolved in the area. The first whale-catching station was established in Smeerenburg on Spitzbergen in 1614.

The marine activities often had to deal with major safety challenges, like encountering sea ice, getting frozen into the ice, remoteness, darkness, poor visibility, long distances, etc. However, one of the major safety challenges these ships had to deal with, and still have to deal with is ship icing (Dyrcz, 2019). This phenomenon occurs in temperatures below subfreezing of seawater where sea spray may, in combination with snow and different atmospheric conditions, freeze on the ship's hull and superstructures, followed by both reduced ship stability and lowering freeboard. During the last 45 years, there has been a motivation for different maritime research to develop better forecasting models for accretion of sea spray icing. Several researchers (Kachurin et al., 1974; Stallabrass, 1980; Overland et al., 1986; Makkonen, 1987; Horjen, 1990; Henry, 1995; Lozowski et al., 2000), all base their calculations on spray flux ice accumulation rate (RW) in kg/m²s, by solving the heat flux equation (Eq. 1) for a freezing surface. The heat fluxes on the right side of the equation contribute to freezing when positive and melting when negative, thus contribute to the heat release due to freezing flux of water (Qf), i.e. ice accumulation, as given on the left side of Eq. 1, (Samuelsen et al., 2015).

$$Q_f = Q_c + Q_e + Q_d \tag{1}$$

where
Q_f - Heat flux released by freezing (W/m²)
Q_c - Convective heat flux (W/m²)
Q_e - Evaporative heat flux (W/m²)
Q_d – Heat flux from incoming water droplets (W/m²)

According to e.g. Samuelsen et al. (2015), this equation has limitations by just taking into account few important heat flux aspects. The importance of implementing relevant and realistic knowledge and understanding about ship icing accumulation aspects in MET is essential for executing proper seamanship in the Arctic. More advanced heat flux equations will be discussed in this paper.

Problems concerning ship icing related to reducing ship stability and lowering freeboard are largely considered for smaller ships like ordinary fishing vessels, crab fishing and seal catcher ships from approximately 10m to 50m length, but there are several examples of ships larger than that, which have been exposed to reduction of stability due to ice accretion. One specific example is the Norwegian coastguard vessel, KV Nordkapp, which went into serious icing conditions between Bjørnøya (Bear Island) and Hopen in February 26-27, 1987, followed by an estimated accumulation of approximately 110 tons of ice in just 17 hours.

This case shows that ice could accumulate rapidly if conditions for icing are present, like sailing into a Polar low. Figure 1 shows pictures of icing of the superstructure of KV Nordkapp (Samuelsen et al., 2015).

Figure 1. Icing on Coast Guard vessel KV Nordkapp on 27 February 1987, Barents Sea (Photo by Prof. S. Løset).

A Polar low is defined as: "Small-scale, intense, short-lived atmospheric low-pressure system (depression) found over the ocean areas poleward of the main polar front in the northern and southern hemispheres. Polar lows can be difficult to detect using conventional weather reports and are a hazard to high-latitude operations", (PWOM, 2019).

An estimation of the stability aspects and an assessment of observed and estimated ice rate of this specific example of a Polar low related ship icing event will be given later in this paper.

Additional ship icing aspects related to Polar lows, individually or in combination with ordinary sea spray ship icing, will also be highlighted.

The consequences of Polar lows could be a severely increased probability of ship icing by: heavy snow, strong wind gusts, thunderstorms, radically dropping temperatures, rising waves, waterspouts, unpredictable conditions etc.

The goal of this paper is to set focus on better and more adequate understanding of state-of-the-art research of different meteorological aspects of ice accretion on ships, and also set focus on to what degree STCW (IMO STCW, 2011) can be used as guidelines for MET schools, with respect to ship stability related to marine icing.

Use of "state-of-the-art" theory in MET schools is one of the prerequisites for executing proper seamanship. Overland et al. (1986) define "potential icing rate" as: "a sustained icing rate by a vessel that is not actively avoiding icing through heading downwind, moving at slow speeds, or avoiding open seas".

Note, however, that this paper will not focus on the underlying causes of how polar lows occur, and in-depth explanations of how ship icing forecasting accumulation algorithms and heat flux equations are structured.

The analytical part of the study is approached by an evaluation of "state-of-the-art" theory about forecasting and accumulation models for ice accretion, then by a discussion of Polar lows influence on ship icing, followed by a case study of how KV Nordkapp was influenced by a Polar low on 27 February 1987. In addition, a document study of the icing related content of STCW (IMO, 2011) and the Polar Code (IMO, 2015) is given.

2 BACKGROUND

Over the last decades sea ice retreats in Arctic have led to opening of new operation areas for increasing maritime activities like cod fishing, shrimp trawling, crab catching, seal hunting, energy harvesting and tourist related activities, etc. This sea ice retreat has also opened for new areas of occurrence of Polar lows due to increasingly open seas along the southern ice edge of the Arctic Ocean, including the Barents Sea, the Bering Sea and the Beaufort Sea (Kolstad and Bracegirdle, 2008). Figure 2 shows the first Polar low satellite image in open sea north of Svalbard.

MET schools offering sea officer education and certification related to the Polar Code must strive to use "state-of-the-art" theory regarding Polar lows, related to where they can occur and the impact these lows have on ship icing. In addition, there are new research-based theories referred to forecasting of accumulation on ship icing that should be included in MET. The importance of having proper relevant understanding of these aspects forms the basis for preventing accidents related to human elements.

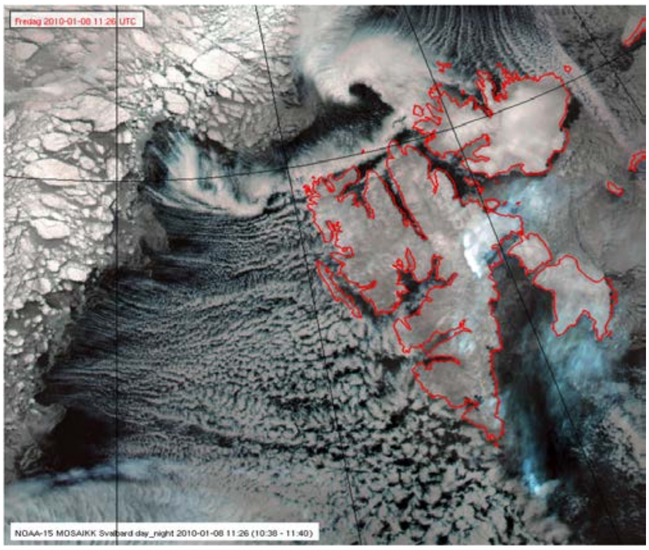

Figure 2. NOAA satellite image, Svalbard 11.26 UTC, 8. January 2010. Image: NOAA/met.no

According to EMSA's analysis of 1170 ship accident events, 60.5 percent were directly attributed to erroneous human actions (EMSA, 2016). Other research shows that 75-96 percent of maritime accidents are directly or indirectly caused by some form of human error (Hanzu-Pazara et al., 2008). However, human elements represent a significant contribution in all ship accidents.

MET schools must therefore strive to provide the students with the best possible basis for exercising their practice. In-depth understanding and knowledge of any subject is a prerequisite for exercising well-executed actions. (Johansen and Batalden, 2018).

Ship icing has caused many accidents and near accidents in polar waters. Raise of the centre of gravity by ship ice accumulated above deck level of vessels has led to reduction of stability followed by severe scenarios like, capsizing, submerging, and the loss of lives (Shellard, 1974).

Examples of recent documented incidents associated with reduction of stability and buoyancy are the following: January 26, 2007, the 75-feet fishing vessel Lady of Grace sank in Nantucket Sound at the east coast of the USA (United States Coast Guard 2008), and January 3, 1999 at the coast of Northern Norway another ship sank, costing the lives of 4 and 3 persons, respectively. The latter incident is revealed by investigating the database of ship accidents from the Norwegian Maritime Authority (2014).

Another concrete recent accident arose on 11 February 2017 offshore Alaska. A crab-fishing vessel with a crew of six suddenly vanished north of St. George Island in the Bering Sea. From the reports of other vessels, it is believed that icing may have been the cause of this accident that led to capsizing, submerging, and the disappearance of the vessel (The Seattle Times, 2017).

From the book "Alaska Shipwrecks 1750-2015" by Captain W. Good and M. Burwell (2018), some relevant icing related accidents are described, like:

- The 58-foot fishing vessel Hunter capsized and sank January 2007 in the Shelikof Strait, location: South Central Alaska 57º 26″ N 156º 01′ W. High winds and freezing sea spray caused heavy icing followed by instability and starboard list. The ship sank in ten minutes. (Good and Burwell, 2018, p. 213).
- The 80-foot steel crab-fishing vessel Rosie G took on water from the stern and sank January 30, 1997 northwest of Cape Cheerful, location Southwest Alaska 53º 52″N 166º 32″W. The Rosie G developed severe ship icing in -40°C followed by a 45° starboard aft list causing serious water ingress. The Rosie G sank by the stern because of severe ship icing (Good and Burwell, 2018, p. 460).
- The 96-foot Lin-J capsized in heavy icing conditions northwest of Saint Paul Island March 18, 1999. There is no further information of the accident, probably because the entire crew was lost (Good and Burwell, 2018, p. 717).

All these accidents are located in Polar waters, but there are examples of severe ship icing further south e.g. on 14 February 1979, North Sea, and west of Thorsminde, Denmark, 6 fishing vessels sank due to ship icing, followed by reduction of stability and buoyancy. The weather conditions for these cases were, eastern breeze, strength 8-10 Beaufort, and the temperature approx. - 8 ° C i.e. perfect conditions for ship icing (sbib.dk, 1979). 15 fishermen were lost on that day.

The accidents presented are just some few documented examples related to ship icing, which shows there may be a potential in strengthen the understanding of this phenomena. In addition, there are near accidents like the KV Nordkapp case, where ships have experienced reduction of stability, without serious consequences. For these cases, accumulated sea ice lead to a rise of the vertical centre of gravity and thus reduced metacentric height (GM) followed by reduced GZ levers.

3 MARINE ICING MODEL

In the physical models for wave-ship-interaction icing the source of water is expressed in terms of a spray flux (Rw). This flux provides an upper boundary on the amount of ice that is accumulated per unit time. In order to derive the rate of ice accretion (Ri) at a certain position of the ship, a surface energy balance is assumed between the heat released from the freezing flux of water (Qf) and the most important heat fluxes from the atmosphere, ocean, and underlying surface (Samuelsen, 2018).

A general full set of heat fluxes per unit area of spray flux ice accumulation (RW) in kg/m²s acting on a plate area is written as (Eq. 2).

$$Q_f = - Q_v - Q_k + Q_c + Q_e + Q_d + Q_r + Q_s + Q_{cond} \qquad (2)$$

where

Q_f - Latent heat released during freezing (W/m²)

Q_v - Viscous/frictional/aerodynamic heating from the air (W/m²) (Makkonen, 1984)

Q_k - Kinetic energy of spray converted to heat in the interaction process (W/m²) (Lozowski et al., 1983)

Q_c - Convective or sensible heat flux from the air (W/m²) (Makkonen, 1987, 2010)
Q_e - Evaporative or latent heat flux from the air (W/m²) (Makkonen, 1987, 2010)
Q_r - Heating or cooling from radiation (W/m²) (Horjen, 1990), (Lozowski et al. 2000)
Q_d - Heating or cooling from the spray (W/m²) (Henry, 1995)
Q_s - Heating or cooling from snow (W/m²) (Horjen, 1990)
Q_{cond} -The conductive heat flux through the ice (W/m²) (Kulyakhtin et al., 2016)

An explanatory illustration of how ice accretion is set in context with the heat flux balance is shown in figure 3.

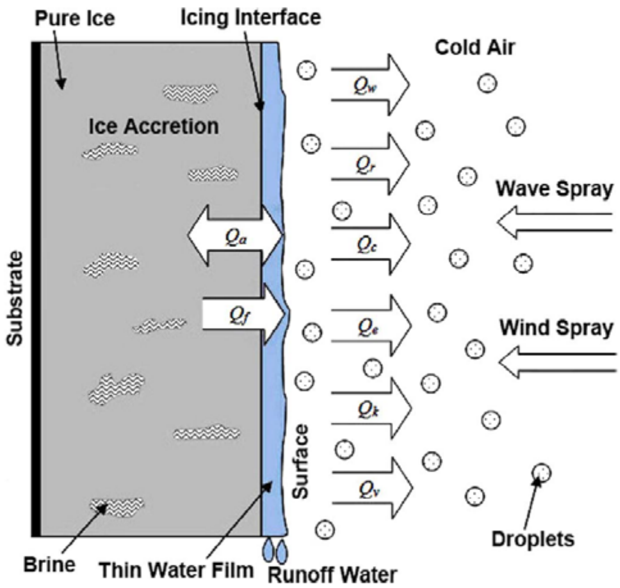

Figure 3. Schematic illustration of the relationship between sea spray icing and heat flux balance (Dehghani-Sanij et al., 2017)

Different researchers take into consideration different combinations of these heat fluxes in their ice rate prediction models. According to Samuelsen (2018), the Modified Stallabrass, Overland and the Marine-icing model developed for the Norwegian Coast Guard (MINCOG) represent the only physically based spray flux icing models applied in operational weather forecasting. The Overland icing rate predictor model (Eq.3) is based on the heat flux equation (Eq. 4) and ends up in a schematic icing class rate, table 1 (Samuelsen, 2018).

$$P_r = \frac{V\left(T_f - T_a\right)}{1 + \Phi\left(SST - T_f\right)} \tag{3}$$

where
Pr= Icing predictor (m/s °C)
V = Wind speed (m/s)
T_f = Freezing point of sea water (°C)
T_a = Air temperature (°C)
SST = Sea Surface Temperature (°C)
Φ = 0.3 °C-1 (Overland, 1990), and 0.4 ºC-1 (Overland et al. 1986)

$$Q_f = Q_c + Q_d \tag{4}$$

Table 1. Icing class and rate based on (Overland, 1990)

PR	<0	0 -22.4	22.4 -53.3	53.3-83.0	>83.0
Icing Class	None	Light	Moderate	Heavy	Extreme
Icing Rates (cm/hour)	0	<0.7	0.7-2.0	2.0-4.0	>4.0

This model is applied as basis for operational weather forecasting (Ekeberg, 2010). A comparison of the applied physically spray flux icing models shows a gap between the Overland and the other models This comparison will be presented later in the paper, (see Figure 9).

4 POLAR LOW CHALLENGES

Ordinary weather is predictable in that both low- and high-pressure systems and different atmospheric conditions can easily be detected by satellite images. This predictability makes it possible for meteorology authorities to predict weather conditions with sufficient accuracy, but this is not applicable for predicting Polar lows. These lows are unpredictable i.e. when and where they occur, what direction they take, strength, duration and atmospheric conditions (Nordeng & Rasmussen 1992). As Polar lows affect the stability of ships, those who sail ships into Polar low areas must have competence and knowledge of these aspects. Figure 4 shows a satellite image of the Polar low that hit KV Nordkapp at February 27, 1987.

Polar lows like the one in Figure 4 will raise to strong northerly winds in combination with heavy snowfall, west of the epicentre. According to Samuelsen (2017), this snowfall may lead to an additional negative effect on ship stability.

Figure 4. Satellite image of the Polar low over the Barents Sea on 27 February 1987. Image imported from the French Wikipedia.

5 THE KV NORDKAPP CASE

The KV Nordkapp case was chosen because of icing caused by the ship sailing into a Polar low, Figure 4, and because of a documented comparison between observed ice rate and icing rates calculated by different icing rate models as presented by Samuelsen et al. (2015). See Figure 9 in the discussion.

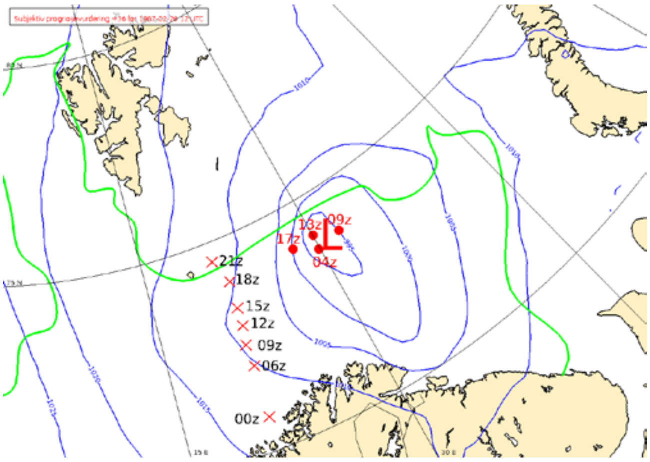

Figure 5. Synoptic situation at 26 and 27 February 1987, and the position of KV Nordkapp (red cross) during the trip when Met-ocean observations were taken. The time of the observation is in UTC/Z (Universal time center/Zulu time). The green line is an approximate position of the ice edge at 26th February (Initial time 1987-02-26 06Z). The red dots mark the approximate position of the Polar low according to satellite image information from 0428z, 0853z, 1243z and 1702z, Samuelsen et al (2015).

Figure 5 shows KV Nordkapp's positions during the voyage, influenced by the weather conditions west of the Polar low epicentre. The air temperature from 06z to 21z was between -12°C to - 20°C. There was wind from north-west between 20 - 30 m/s followed by maximum wave height 7.5m and sea surface temperature (SST) between +3 to -4°C; thus, conditions for ship icing were optimal (Samuelsen et al., 2015).

Samuelsen et al. (2015) present a comparison between Overland, Stallabrass and own test models against observed ice accumulation rate for this specific case, and this will be highlighted in the discussion.

5.1 *Coast Guard vessel KV Nordkapp's characteristics*

The main particulars of the Coast Guard vessel KV Nordkapp are reported in Table 3, and the ship profile is shown in Figure 6.

Table 3. KV Nordkapp`s main particulars

Length over all	105.05 m
Length between perpendiculars	97.50 m
Beam	14.60 m
Depth	7.50 m
Lightweight (Δ_ls)	2785.4 ton
Max operating(Δmax)	3579 ton
Min operating (Δmin)	3239 ton

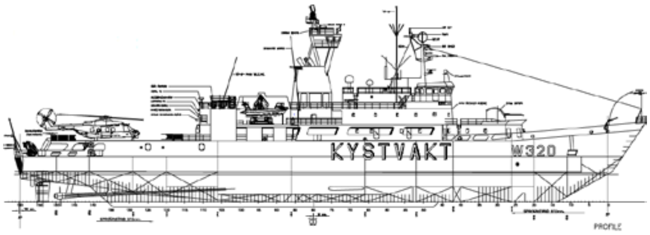

Figure 6. KV Nordkapp's profile from the GA plan.

5.2 *KV Nordkapp's stability reduction*

The calculation of the stability reduction of KV Nordkapp due to icing is based on an estimated weight of 110 ton accumulated ice, Samuelsen et al (2015), at a vertical position above the baseline (VCGice = 11.557m), as shown in Figure 7. VCGice is the average vertical centre of gravity for accumulated ice, as reported by the stability manual of the ship.

The stability manual was originally developed when the ship was built in 1982, but it was redeveloped in 2017 according to the same criteria that can presently be found in the IMO requirements regarding intact and damage stability (IMO, 2008).

Based on information by the Norwegian Navy, KV Nordkapp was stated with loading condition code 2, fully loaded, at departure 26 February 1986. This condition is equivalent to "max operating condition" (Δmax). According to the KV Nordkapp stability booklet, this condition corresponded with the data reported in Table 2 and visualized in Figure 7.

Table 2. KV Norkapp`s loading condition 2 particulars

Displacement (Δ0)	3579 ton
Mean draught (T0)	5.120 m
KG0 (incl. FSC)	6.395 m
KM0	7.532 m
G0M0 (incl. FSC)	1.137 m
KGmax	6.691 m

KGmax (Table 2) corresponds to the maximum KG according to both intact and damage stability requirements.

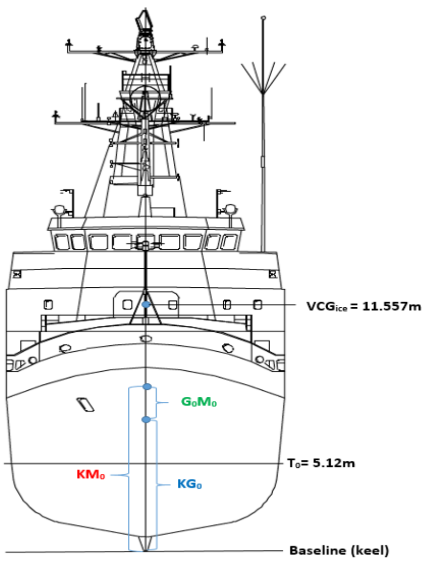

Figure 7. KV Nordkapp from the GA plan of the ship, showing the center of gravity of accumulated ice (VCGice), initial vertical center of gravity (KG0), initial depth (T0),

initial metacentre (KM0) and initial meta-center height (G0M0).

Departure displacement, including the 110-ton accreted ice, became 3689 ton. According to the stability booklet, this increased displacement was followed by a corresponding mean draught Tice 5.273m, KMice 7.464 m and KGmax-ice 6.687m. Based on the following equation (Eq. 5), the center of gravity rises by the accreted icing of 110 ton to:

$$KG_{ice} = \frac{\Delta \times KG_0 + \sum M_{ice} \times VCG_{ice}}{\Delta + M_{ice}} = 6.594\, m \quad (5)$$

KGice ended below KGmax-ice, thus within the stability booklet requirements by (6.687 – 6.549) m = 0.138 m. However, considering also the variation from KM0 to KMice, the ice accretion led to a variation of metacentric height (GM) from 1.137 m to (7.464 – 6.549) m = 0.915m, i.e. a reduction of 1.137 – 0.915 = 0.222 m. The corresponding reduction of the KV Nordkapp stability is visualized by the GZ curve, Figure 8.

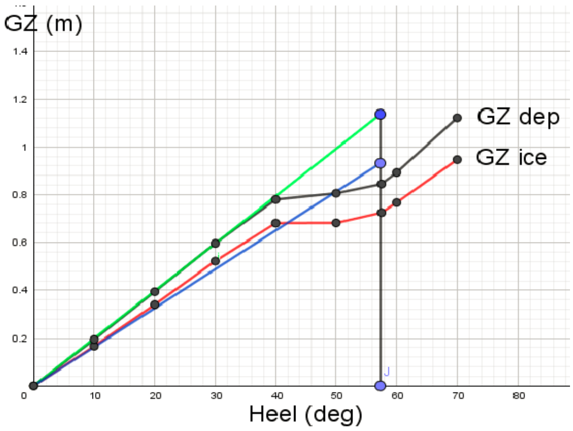

Figure 8. KV Nordkapp`s GZ curve based on departure and ice accreted conditions, February 26 and 27 1986.

6 MINCOG METHODOLOGY

As mentioned in the introduction, several different researchers have tried, for decades, to develop predictions of sea spray ship icing.

Samuelsen (2017) presents a review of the most central research done in this area, as well as a presentation of a new model, the Marine Icing model for the Norwegian Coast Guard (MINCOG). This model is developed on the basis of different data sets derived from observation of 37 ship icing events obtained from the Norwegian Coast Guard. In his thesis, Samuelsen presents the uniqueness of this model by a high level of accuracy compared to currently applied methods.

One of the findings in Samuelsen's research is the importance of not relating wave information with wind parameters in the model because there could be strong winds close to the ice edge, but short fetch lengths for waves to develop (Samuelsen, 2017). Regarding waves, in his research he also found that the nature dictates an upper limit of ship icing from interaction between wave and ship, because high waves rarely coexist with very low temperatures (Samuelsen, 2017). The amount of sea spray related icing also depends on ship type (bow height and shape), and wave characteristics.

Samuelsen (2017) also highlights that inclusion of snow may be an important contribution for ship icing to accumulate, and that this contribution ensues most frequently during cold air outbreaks from the ice and in areas influenced by Polar lows.

The MINCOG heat flux equation (Eq. 6) does not take into consideration the heat fluxes flux components - Qv – Qk +Qs +Qcond (see Eq.2). The reason for this is partly to simplify the equation, but also that the data set showed that the neglected heat fluxes had little impact compared to empirical results.

$$Q_f = Q_c + Q_e + Q_d + Q_r \qquad (6)$$

The effect of snow, Qs, is neglected because of uncertainties related to amount of water accumulation by the snow (Samuelsen and Naseri, 2018). Other research shows that wet snow has low density and weak adhesion during forming. Therefore, wet snow may have limited impact on icing. However, Table 4 shows that the adhesion is strong when the snow is frozen.

Table 4. Typical properties of accreted atmospheric ice (Fikke et al., 2006)

Type of ice	Density (kg/m³)	Adhesion & Cohesion	General Appearance Colour	Shape
Glaze	900	strong	transparent	evenly distributed/ icicles
Wet snow	300-600	Weak (forming) Strong (frozen)	white	evenly distributed/ eccentric
Hard rime	600-900	strong	opaque	eccentric, pointing windward
Soft rime	200-600	Low to medium	white	eccentric, pointing windward

7 THE STCW'S AND POLAR CODE'S REQUIREMENTS TO COMPETENCE

The STCW Standard of competence (IMO, 2011) represents the compulsory minimum requirements for the acquisition of a certificate as an on-duty deck officer on ships with a gross tonnage of 500 or more.

Until the Polar Code (IMO, 2015) had its entry into force in 2017, the requirements of competence regarding ship icing was supposed to exclusively be given by the International Convention on Standards of Training, Certification and Watch keeping for Seafarers, 1978 (IMO STCW, 2011). Tables A/II-1 and A-II/2 in the STCW convention, describe minimum standards of competence for master and officers operating a ship. The only STCW requirement related to ice was a general knowledge about sea ice conditions when planning a voyage i.e. no requirements related to ship icing.

When the Polar Code entered into force, the content was added into the governing STCW Convention followed by additional minimum requirements for training and qualifications of masters and deck officers operating in polar waters, as given in chapter V/section A-V/4. The additional Polar Code related competence requirements became divided into basic training for all officers on-board and an additional advanced training for master and chief mates. The convention then stated that candidates for basic as well as advanced training should have knowledge and understanding of the implications of spray-icing, danger of icing up, precautions to avoid icing up and options during icing up (IMO, 2011).

There are some aspects regarding these requirements that are challenging for the acquisition of competence with respect to Ship icing:

1 The Polar Code is only mandatory for ships operating in polar waters and the definition of “Polar waters” is more a political definition than a meteorological definition and therefore icing events are also likely to occur outside the area of polar waters.
2 The Polar Code is implemented into the STCW convention, but this code is only applicable to ships larger than 24 meters in length. This means the major part of fishing vessels is not regulated under the Polar Code, thus, the Polar Code requirements with regard to icing do not have implications for the training requirements for crew on-board these vessels.

8 DISCUSSION

This paper shows there are still a lot of challenges regarding knowledge and understanding both with respect to the amount of and the consequences of ship icing. To give ship officer students’ relevant understanding of proper prediction of ice accretion, presupposes that the MET schools base their learning on “state-of-the-art” theory, both for the matter of design and operation.

Samuelsen et al. (2015) comparison between real icing rate using the Overland, Stallabrass and own icing rate models show some gaps. According to Figure 9, one can notice that Overland`s estimated icing rates (blue lines) shows large differences with respect to the real icing rate (pink line). It is, thus, questionable that the Overland`s model is applied as both basis for operational weather forecasts and as theory for MET. The T1 model by Samuelsen (2018) and the ModStall model M3 by Stallabrass (1980) correlate well with the real icing rate.

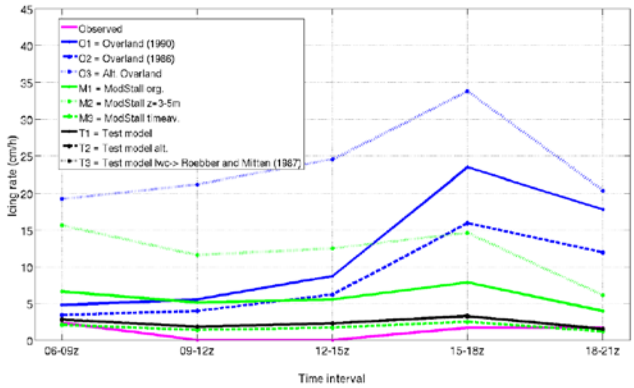

Figure 9. Observed icing rate (pink color) and icing rates from nine different algorithms related to the KV Nordkapp case. Three Overland algorithms (O1, O2, O3) in blue colour, three ModStall algorithms (M1, M2, M3) in green colour and three Test model algorithms (T1, T2, T3) in black colour (Samuelsen et al., 2015).

This outcome is an important reminder for weather forecasters, STCW and for MET schools in developing requirements and curriculum for ship officers’ education. Samuelsen and Naseri (2018) have also revealed other limitations of the Overland model e.g. limited correlation between wind strength and wave height; the upper limit of ship icing caused by high waves rarely coexists with very low temperatures and conditions related to Polar lows.

One challenge regarding the data collection that forms the basis for the MINCOG model is that the data sets are only collected from one type of vessels. Droplets from sea spray that form ship icing will more likely hit the superstructure and upper part of smaller vessels as a consequence of bow height and shape. Because of this aspect, the MINCOG and other ice rating models should be tested and verified for several types and sizes of ships.

With reference to Figure 9, the limitation of the Overland prediction icing rate model results in inaccurate estimates. Bearing in mind the variability in accuracy among the presented prediction icing rate models is important for both weather forecasts and MET. Using the correct model for icing rate prediction is a prerequisite for issuing an accurate and realistic decision supportive ship icing forecasts.

The occurrence of Polar lows in new areas of polar waters is challenging and demands that ship officers be aware of this aspect with reference to Figure 2.

The estimated stability reduction in the KV Nordkapp case was within the maximum required vertical center of gravity (KGmax), regulated by the stability manual. If the ship had continued to sail without action to remove ice, the KGice had exceeded the requirement of the stability manual.

However, an ice accretion of 110 ton, like in the KV Nordkapp case, could easily be actual for smaller ships followed by more severe consequences.

In addition, IMO and other authorities also have developed and implemented the ice accretion allowance regulations discussed by Mintu et al. (2016), see Table 5.

Table 5. Ice Accretion Allowance regulations discussed by Mintu et al. (2016)

IMO Regulations	IMO Polar Code (2015) IMO Intact Stability Code (2015)
Classification Society Rules	ABS (2015) RMRS Rules (2016) DNVGL (2015) Lloyd`s Register (2015)
Offshore Structures Codes	ISO 19906 for Arctic Offshore Structures (2010) NORSOK (2007) Canadian Std. CSA S471 (2004)

For references mentioned in Table 5, see Mintu et al. (2016).

Ship stability is affected by accretion of sea spray icing, atmospheric icing and snow (freezing to ice). Norsok N-003 (Standards Norway, 2017) discusses the accumulation of sea spray ice, atmospheric icing and snow on stationary objects. We should note that the recommendations of Norsok N-003 are as follows:

– North of 70° north on the Norwegian Continental Shelf, a nominal value for thickness of the accumulated icing caused by precipitation may be selected as 20 mm. If the nominal values are applied, an ice density of 900 kg/m3 shall be used. This thickness can be assumed constant from a height of 5 m above sea level to the top of the facilities (Norsok N-003 paragraph 6.7.3).Note that atmospheric icing applies at all surfaces on a vessel, in particular on masts and pipes etc.
– According to Norsok N-003 (Table A5), the expected snow accumulation per day represent 0.8 – 1.0 kPa with an annual probability of exceedance of 10-2 over a horizontal area of 1m2.

Using an approximate horizontal area of KV Nordkapp of 1500 m2, the weight of the accumulated snow using a value of e.g. 0.5 kPa, would be 750 kN (76tf), a substantial weight.

Whether these values should be communicated to the maritime industry as design basis for ultimate stability checks in case of getting into a Polar low situation, should be debated.

The STCW convention requests just an introduction of the theme "Ship icing" for ship officers according to the Polar Code, and the code only applies for larger ships operating in polar waters. This is challenging because all the highlighted shipwreck cases show that hardly none of these ships are regulated by this code.

The loss of 6 fishing vessels west of the coast of Denmark in 1979 also shows the limitations of the code related to occurrence of ship icing outside polar waters.

9 CONCLUDING REMARKS AND RECOMMENDATIONS

The objective of the present work was to set focus on ship icing, and may provide a guideline or a foundation for recommendations of measures for preventing or limiting ship icing. The analysis presented has revealed that the phenomenon of ship icing is one important cause of stability-related accidents due to the reduction of reserve buoyancy and stability. In this respect, the important objective for ship officers is to have competence to enable precautionary measures to avoid such situations. Focus on what MET schools should teach ship officer students related to ship icing aspects is therefore a direct consequence of the objective of this work.

Sufficiently accurate icing rate prediction models have still to be developed and verified to obtain realistic icing forecasts. Some icing rate models seem to be accurate, but they may have to be customized to various types of ships. Prediction of Polar lows is still challenging, and this is probably the most challenging aspect because it is a perquisite for shipmasters to secure their sailing routes in advance to avoid icing conditions. The KV Nordkapp case shows that even larger ships can be affected by severe ship icing, challenging their stability limits in such conditions.

Different technological de-icing solutions have been developed during the last decades. Some of these technologies have been developed for other industries and are later adapted and identified for marine use (Ryerson, 2011). Advanced ships have installed different types of these technologies to prevent ice to accumulate and for removing already accumulated ice like e.g. the Roll to Roll CNT Coating for Electro Thermal Heating (Rashid et al., 2018). Such equipment is expensive, both in procurement and in use, and it is not currently relevant for e.g. fishing vessels, which represent most of the losses due to ship icing.

For fishing vessels, introducing operational measures to minimize ice accretion could be an option. In such cases, avoiding the sea spray impact by manoeuvring the ship for downwind heading leads to a reduction in wave impacts with consequent reduction in the amount of sea spray icing (Guest and Luke 2005).

Based on the number of stability related accidents caused by ship icing, we would recommend that STCW should implement stricter standards for minimum required competence for all ship officers, related to ship icing. These standards should be mandatory in MET schools' curriculums.

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