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Task 4.23 Report on Winterization of Structures in Arctic Regions

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Executive Summary

This report gives an overview about the accretion, environmental prerequisites, risks and the nautical and administrative management of one of the most severe dangers for ships in cold environments, the ice accretion on the superstructure due to sea spray. The risks and effects of icing have been known for a long time from smaller fishing vessels, which are affected by ice accretion during their voyages to and from their fishing grounds. These smaller ships are more likely to be affected by icing due to their smaller size and lower freeboard, masts and rigging and the larger influence on the ships stability. In many cases ice accretion causes the loss of ships and lives. Based on these experiences the appearance of icing came into the focus of mariners and researchers to analyze its accretion and prerequisites for an environmental and ship specific point of view.

Commercial shipping is more and more shifted into remote regions when serving drilling platforms or shipping minerals, liquefied gas and oil. Thus they are exposed to harsh environmental conditions, including stormy winds, low air and sea temperatures and heavy seas. Ships operating in waters with an ice coverage exceeding 6/10 of the total area are minor affected by sea spray icing due to the damped sea state. Thus in regions far off the coast and the ice edge, icing in a zone from 5 to 200 km is more likely to occur. Here, the fetch is sufficient to form higher waves without sea ice diminishing the development of the sea, the sea surface temperature and the air temperature are in general low. Wind, which originates over large ice fields or landmasses, is still cold enough to support ice accretion process without being warmed. At sea the air is warmed due to higher water temperatures. Having a look at sea charts where the locations of icing incidents are marked it becomes obviously, that the potential of icing is high in vicinity of the ice edge. This is preferably caused by cold sea currents, like the Alaskan current in the North Pacific Ocean, originating in icy regions, which comes along with low water and air temperatures. But minor icing incidents have been observed in close vicinity of the ice edge (marginal ice zone) itself.

After 2007 the sea ice extent reached a new minimum extent in September 2011(University of Bremen, Institute of Environmental Physics, 2011). The area of arctic sea ice varies over the year reaching its maximum around March and its minimum around September. As a consequence of the low ice extent the Northwest and the Northeast passages were ice-free in the autumn of 2011 as they were before in 2008. Due to the decreasing amount of multi-year ice and the increasing area of ice-free waters with low temperatures the potential of icing is increasing.

Focusing upon the accretion of ice it becomes obvious that, assuming constant environmental conditions, smaller vessels, like fishing boats or platform supply vessels, are more prone to icing than larger vessels. This is a result of the minor amount of deposited water as a consequence of their diminished behaviour at the wave field and higher freeboard. Thus smaller ships, compared to their total displacement and size, are entirely affected by spray, whereas on larger vessels most of the ice accrues around the forecastle and bow area. The distribution of ice is primarily connected to the wind, the sea state and the heading of the ship as well as the influence of the bow and hull shape, which influences the deflection. Especially on commercial vessels the bow meets the requirements of an economic use, including demands at the vessels area of operation and space for commercial cargo. Spray diminishing bow shapes, as for example the X-BOW® hull line designed by Ulstein, favour the limitation of sea spray formation, but they have to prove its usefulness and icebreaking capabilities under sea ice conditions, especially for vessels which are intended to operate durably under cold climate conditions. Not only bow shapes, also the on deck

construction gives potential for anti- and de-icing solutions. Most of the ice accrues on horizontal surfaces, thus it is essential that water is deflected before deposition. If the water impinges, it has to be removed from the surface as soon as possible before its accretion. In general the exposed areas should be kept as small as possible.

The prediction of vessel icing has been continuously developed further, becoming more precisely due to the implication of the most important factors of ship icing, air and sea temperature, wind speed and the freezing point of sea water. This forecast products, for example those of the National Center for Environmental Prediction (NCEP), are aimed to the commercial fishing industries, because the predictor calculation is based on observations of fishing vessels ranging between 20 to 75 m. Thus the prediction, which can also be used by the commercial shipping, gives a good indication for the extent of icing potential areas, but a conformation for larger vessels and prevailing sea states would be desirable.

The arctic shipping will remain destination-driven and shortcuts for the commercial shipping, especially on the Northern Sea Route (NSR) or Northwest Passage, are not yet economical enough, these future shipping routes face environmental and administrative challenges. But the development of further developed and improved guidelines and mandatory regulations integrates the polar conditions into international framework. Thus the ship operators can be made aware of the risks of icing. As a report of the United States Coast Guard shows, larger vessels start to ice up at the forward part during the night time without being noticed by the officers of the watch or their watchmen. Within the framework of measurements and guidelines to prevent and diminish ice accretion one of the measures should include the alerting of the ship operators with the use of camera and measuring systems at the beginning of ice accretion.

Due to the operation of ships in various economic zones, the vessels have to meet different requirements to comply with. The IMO Guidelines for ships operating in polar waters meet the demands of guidelines on international level, because up to now, no specific mandatory measures beyond those for all open waters have been presented. These rules focus on the construction of ships intended to operate durably in cold climate conditions and prevention of environmental damages.

However, it is questionable whether the recommended value in this context of 30 kg m^{-2} for ice accumulation is sufficient. If the ice accretion is determined according the method of Overland, a 3.75 cm thick ice accumulation would be achieved already within 3 hours under "moderate icing" conditions.

Vessels and marine structures operating in harsh meteorological conditions without sufficient winterization pose a high risk for environmental damages and human disasters.

A minimum stability icing allowance for all kinds of vessels, anti- and de-icing equipment in a sufficient quantity and a well-trained crew, are the basic prerequisites for a safe future of the arctic shipping.

This requires that the standards of classification societies need to be aligned. The classification societies have sufficient experience of the winterization of ships and marine structures. But these are not yet harmonized, what is leading to a different view on the measures, including differences in minimum heating capacities and materials of use. A convention like the 2006 IACS Unified Requirements for Polar Ships (IACS, 2011), concerning the polar class descriptions, structural and machinery requirements could equalize the differences. Harmonized measures are the cornerstone of safe use and international acceptance.

In summary, more and more attention to the future of shipping in cold climate conditions is given, however more cooperation between national and international administrations and authorities is required to reduce the risk potential and to ensure safer operation of ships and marine structures in the harsh environment of waters in the Arctic and Antarctic.

1. Introduction

Global warming is slowly making natural resources – oil, gas, and minerals - more accessible. The ongoing expansion of fishing operations and maritime-traffic in the Arctic, caused by the boundless demand for hydrocarbon resources and raw materials as well as the increasing global trade comes along with new challenges for the shipping and navigation. New transportation routes in ice-covered waters are developed and markets are accessible, especially in the arctic offshore ventures encouraged by the decreasing ice extent in the Arctic.

The operation of offshore structures for exploration and production of oil and gas happens in the Arctic and other ice-covered regions and has specific requirements. on the design and operation of these structures and ships. In particular, the year-round operation of these systems is in terms of "winterization" a great challenge for offshore structures, ships and their crew.

Winterization is primarily focused on the adverse effects and control of snow, freezing, sea spray and atmospheric icing on offshore structures and on board of mobile units and ships. Also material properties in cold temperature have to be considered.

The report focuses on the problems of icing of ships and offshore structures in cold climate conditions. It discusses the physical processes and environmental conditions that lead to icing.

The report describes the types of icing, and introduces measures to prevent the ice accretion. Rules, regulations and standards established by various classification companies provide general principles for vessels and offshore structures for operation in cold-climate environment .The standard code include functions, systems and equipment considered important to the safety of the vessel, personnel and the environment.

2. Formation of sea spray

The accretion of ice on a vessel's superstructure, it´s deck and cargo constitutes a severe hazard to all kind of shipping in cold climate regions. A number of environmental, physical and ship oriented requirements have to interact to let icing occur. In 1968, the United Kingdom Meteorology and Oceanographic Service (MOS) divided the causes of ice accretion on sea going ships into three major categories, categorized by the source of water which deposits on the superstructure.

1. Accretion of freezing rain, evaluated as a minor effecting source due to the insufficient accumulation rates.

2. Sea smoke that belongs to the atmospheric sources of water like freezing rain. In this case the accretion rates are low too.

3. Icing due to freezing sea spray. Initiated by the mechanical rapture of the sea surface due to its contact to the hull or wind, blowing off the waves crests, it is the most severe source of ice accretion due to the high deposition rates of water on the superstructure (*Shellard, 1974*). Statistical analyses of over 2000 icing incidents by *Borisenkov and Panov (1972); Feit (1982)*, as well as studies on wave generated spray and its effects (*Zakrzewski,1986*), clarify that the most common cause of superstructure icing is initiated by the freezing sea spray.

Since there is no clear definition of Northern Hemisphere and Arctic it has to be assumed, that Northern Hemisphere represents all Oceans and Seas north of the Equator. Arctic involves all Seas and Areas northern of the Arctic Circle, 66°33´, and the Arctic Ocean, which is partly or durably covered by ice (*Figure 1*).

According to IMO Guidelines "Arctic ice-covered waters" means those waters which are both:

1. Located north of a line from the southern tip of Greenland and thence by the southern shore of Greenland to Kape Hoppe and thence by a rhumb line to latitude 67º03.9 N, longitude 026º33.4 W and thence by a rhumb line to Sørkapp, Jan Mayen and by the southern shore of Jan Mayen to the Island of Bjørnøya, and thence by a great circle line from the Island of Bjørnøya to Cap Kanin Nos and thence by the northern shore of the Asian Continent eastward to the Bering Strait and thence from the Bering Strait westward to latitude 60º North as far as Il.pyrskiy and following the 60th North parallel eastward as far as and including Etolin Strait and thence by the northern shore of the North American continent as far south as latitude 60º North and thence eastward to the southern tip of Greenland (see *Figure 1*); and

2. In which sea ice concentrations of 1/10 coverage or greater are present and which pose a structural risk to ships.

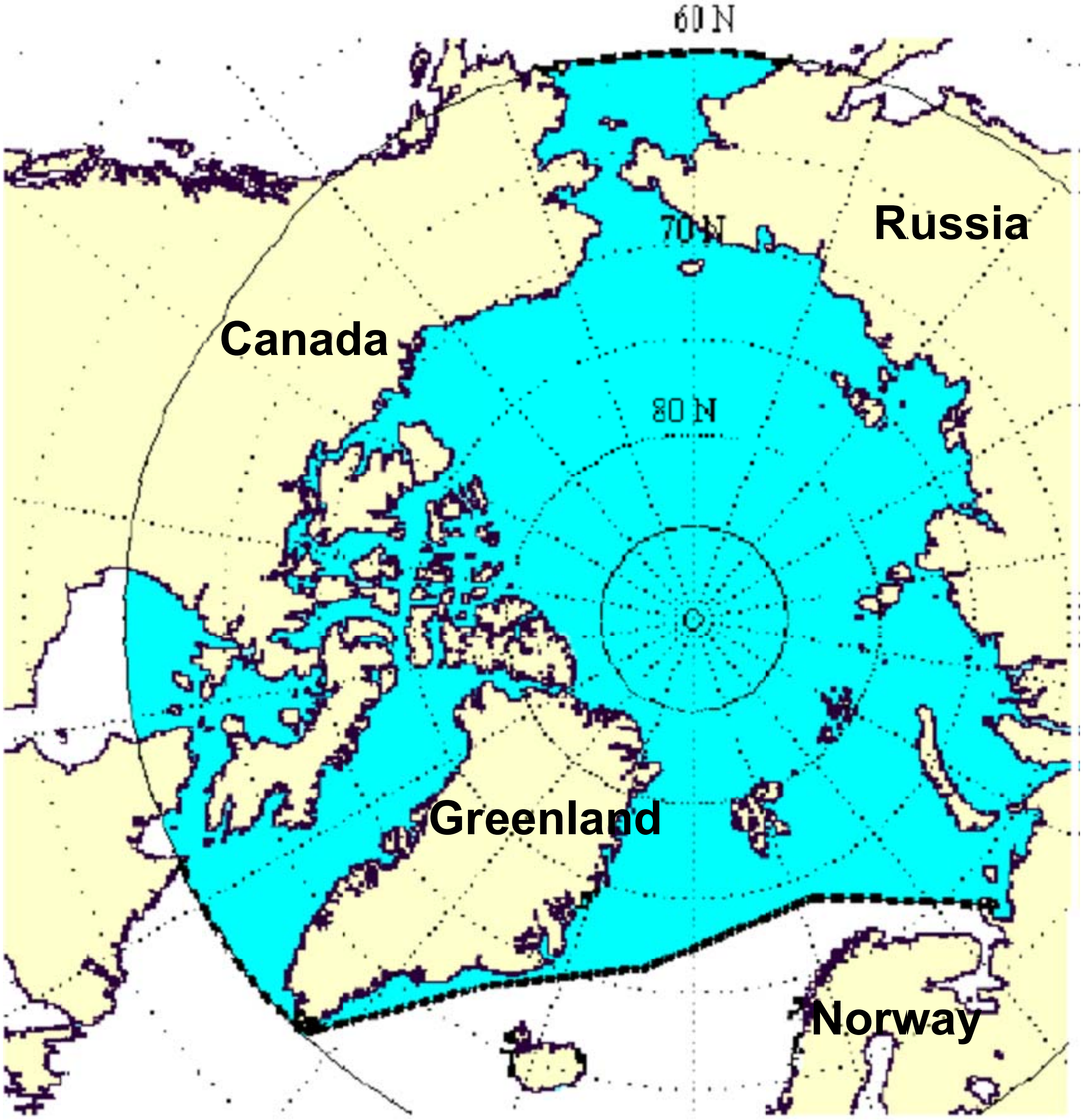


Figure 1 Region of Arctic ice-covered waters according to IMO definition

The percentage frequency of icing occurrence is summarized in *Table 1.* It becomes obvious that in northern cold climate waters nearly 90 % of all documented icing appearances originate from the accretion of sea spray, whereas the occurrence of icing caused by atmospheric sources of water is less than 10 %. This result confirms investigations of *Shekhtman (1968)*, *Shellard (1974)*, where he stated the great danger of icing due to sea spray as a consequence of the abundance of water droplets, asymmetric ice accretion and dense deposition of droplets on the substrate. Two types of spray mechanisms can be differentiated. Those formed by a wave-vessel-interaction or by wind, blowing off the wave´s crests.

Table 1 Percentage frequency of icing occurrence (source: *Borisenkov and Panov, 1972 in Feit, 1987*)

	Spray	**Spray with fog, rain or drizzle**	**Snow**	**Fog, rain or drizzle**
Northern hemisphere	**89.9**	**6.4**	**1.1**	**2.7**
Arctic	**50.0**	**41.0**		**9.0**

2.1 Spray generated by wind

The development of waves is initiated by the resistance between the water surface and the wind at the contact layer. Wind-created waves are assumed to break under deep water conditions, when the depth of the sea is higher than half of the wave's length, overriding a theoretical ratio between height and length from one of seven. Observational records report that waves become unstable at steepness as small as one of ten (*Kotsch, 1977*).

White crests, usually starting to develop from wind force of Beaufort 3 (3.4 to 5.4 m s^{-1}) (*Bock et al., 1989*), appear, when air bubbles rise to the surface after the wave crest has collapsed or is affected by the wind. The wind speed is not high enough to blow of larger amount of droplets of the crests. The formation of airborne spray starts with wind speeds higher than Beaufort 5 (8.0 to 10.7 ms^{-1} (*Zakrzewski, 1986*).

So called "film droplets" are one of two kinds of droplets which comes along with uprising air bubbles. When an air bubble reaches the sea surface, its skin disintegrates into water droplets, with a radius ranging from 0.5 to 50 µm.

"Jet droplets" form when the collapsing whitecap bubble left a cavity, which rapidly fills with water. Thus a jet of water is formed which decompose into droplets within a range of 1 to 100 µm.

Wind, interacting with the waves crests, produces "spume droplets" with a size between 20 to 500 µm. These droplets, which are also called "spindrift", generate the highest volume flux of the wind-generated spray above the sea surface (*Jones & Andreas, 2009*).

In contrast to "film droplets" and "jet droplets", "spume droplets" are not initiated by a breaking wave or rising air bubbles.

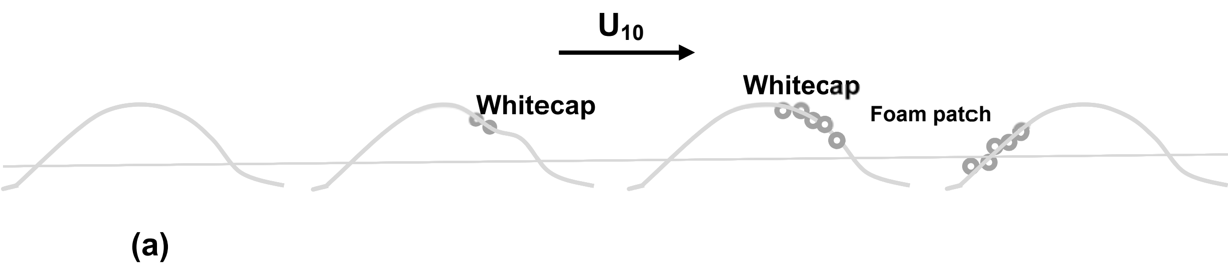
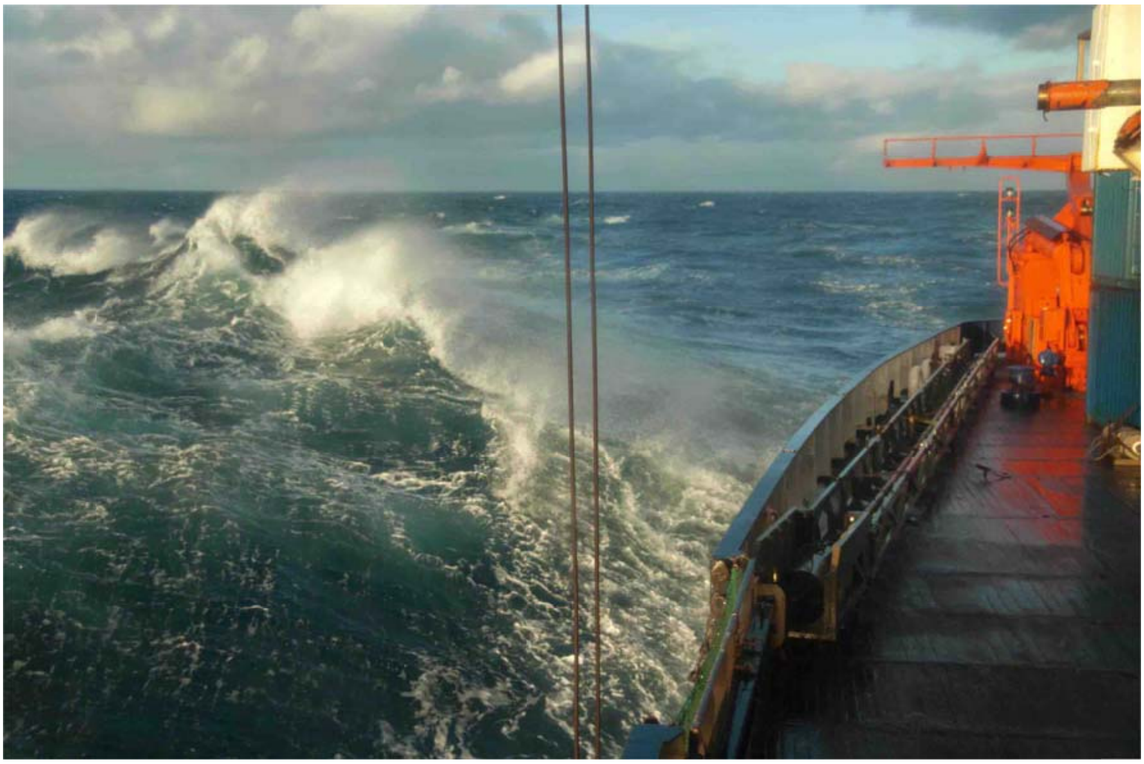


Figure 2 Whitecap formation on wave crests (after *Herbers, 1984*)

The generation of spray takes place at the top of the wave's crests and within the whitecaps, located at the leeward side of the wave as shown in *Figure 2* (*Herbers, 1984*). The amount of whitecap coverage is a function of the wind duration, speed and fetch and the hence resulting wave field as well as, in shallow waters, to the topographic shape of the sea bottom (*Monahan et al., 1983*).

With regard to the wind speed, the coverage by whitecaps at 10 ms^{-1} amounts approximately 1% of the sea surface. At a double of wind speed (20 ms^{-1}), the proportion of whitecaps within the sea surface increases to 10% (*Monahan et al., 1983*).

Even at lower wind speeds whitecaps originate more frequent if waves, propagate away from the bow, interact with the prevailing sea waves, forming steeper crests as they might be formed by wind itself (*Sapone, 1990*) as shown in *Figure 3.*



Source: Alfred-Wegener Institute (AWI), (Photo by S. Fietz)

Figure 3 Bow wave of RV "*Polarstern*" propagates along the vessel

The role of wind-generated spray regarding the precipitation on the vessels substrate has been determined by *Zakrzewski (1986)*. His research shows, that even under violent storm conditions of Beaufort 11 (28.5 to 32.6 m s^{-1}) and 100 nm fetch, the effect of the spray droplets trajectory is not sufficient to initiate a considerable wetting of vessels with a freeboard higher than 2.5 m.

He confirmed the analyses of *Preobrazhenskii (1973)*, who stated that only smaller droplets, carrying less water due to their small diameter of around 30 µm, are exceeding heights of 7 m, when the wind speed is more than 12 m s^{-1}. Droplets of more than 100 µm in diameter need a wind speed of minimum 25 m s^{-1} to reach the same vertical extent. Neglecting the water flux by rain, fog and snow, these result shows, that wave- generated spray is the minor affecting source of water delivery to the superstructure of a vessel.

Thus the influence of wind-generated spray is more important for smaller vessels with a low freeboard or bulwarks in severe strong winds (*Zakrzewski, 1986*). The generation of spray due to wind, tearing up the waves, is smaller compared to the amount of water droplets, released by vessel-wave interaction (*Figure 4 to Figure 7)*.

(source: http://www.cargolaw.com)

Figure 4 Massive waves are crashing into & over the M/V "*Pasha Bulker* "

Figure 5 Coast Guard SAR vessel riding on breaking wave

Figure 6 Coast Guard SAR vessel encounters breaking wave

Figure 7 RV "*Polarstern*" (photo: left) and oil & gas platform "*Troll C*" (*photo:right*) in heavy waves

2.2 Ship-generated spray

The delivery of water to the vessel´s surface is caused by multiple circumstances. Neglecting atmospheric sources like fog, rain drizzle and others, the cause of the wetting event due to the interaction of the ship in the sea and the delivery process of the seawater can be divided into deck wetness and sea spray (*Sapone, 1990*).

2.2.1 Deck wetness

Deck wetness, also known as “green water”, is initiated by the heavy relative motion of the ship´s hull in the current wave field. Pitching down, rotating about the horizontal transverse axis of motion, the distance between the deck edge and the sea surface decreases. Depending on the ship length, freeboard, speed, wave height and the relative heading of the vessel to the sea, this vertical motion can lead to a growing immersion of the deck edge into the sea resulting in overcoming water.

The movement of the environing water surface, which compounds out of the current wave height, the bow wave, generated by the ships displacement through steaming, and a dynamic swell which is a consequence of the up- and downward movement, has to be considered (*Sapone, 1990*).

These three factors determine the height of the current wave field surrounding the vessel. Generally this process itself depends on the wave’s spectrum, marked by height and length, the heading and speed of the ship related to the waves. This results in the vessels period of encounter (T_E), e.g. the frequency that a certain point of the ship is passed by a wave crest.

A superimposed motion of the vessels downward movement and the increasing height of waves will lead to a higher immersion of the hull and thus to a decreasing distance between deck edge and water surface up to the exceedance of the freeboard.

Delivery process of “green water” is highest when the vessels relative movement is in an opposite direction than the waves propagation (*Kent, 1958*). The water which flows above the deck edge, forced by the influence of gravity, is hereby supported by the movement of the wave.

The amount of water flushing over the bulwarks is much smaller when the ship is broadside to the waves caused by the movement of the vessel downwards the waves slope. The “green water” on deck is reduced by the minor relative velocity and the less pitching motion through the waves. Ships with the waves on their beam, assuming slower steaming, have a reduced amount of overcoming water by upswelling water on the side of the ship. The upswelling water at the side which faces the waves, forms a kind of water well through the motion of the vessel downwards the waves slope (“natural lay”). This well calms the sea close to the ship and reduces the overcoming waves. This way, facing the waves is used to minimize the amount of "green water" on deck in heavy storms (*Malanot, 1955; Müller and Kraus, 1988*).

The effect of water, which has been taken on board and led to deck wetness, depends on its temperature and amount, especially the ratio of water which is running off after flooding the deck. Sea water splashing the deck with a temperature higher than 0 °C, may have a limiting effect on the ice accretion at the substrate or causes the washing off of already accreted ice (*Tabata et al. 1963*). The appearance of deck wetness depends on the sea state, size and freeboard of the vessel, her design and on the navigational management (*Shellard, 1974*).

2.2.2 Sea spray

Wave-generated spray has its origin in the relative motion between the waves and the vessels hull. Superimposed waves, forming out of even small ocean waves and the ships divergent waves originate from the slivered water by the stem and are reflected by the hull over the waterline (*Kent, 1958*).

The prerequisite for spray formation is the acceleration of a thin water sheet, a so called spray root, detached from the water surface (*Saunders, 1957*). Initial preconditions of spray roots are initiated at the interface between ship and water (*Figure 8*).

Regions of high pressure, as a consequence of the relative vertical and horizontal motion of the ship in the surrounding water, or discontinuities in the flow of water around the hull initiated by bulwarks, anchors, bow shapes and other protruding obstructions are leading to a forced change in the water flow, results in an acceleration of the water film (*Saunders, 1957*).

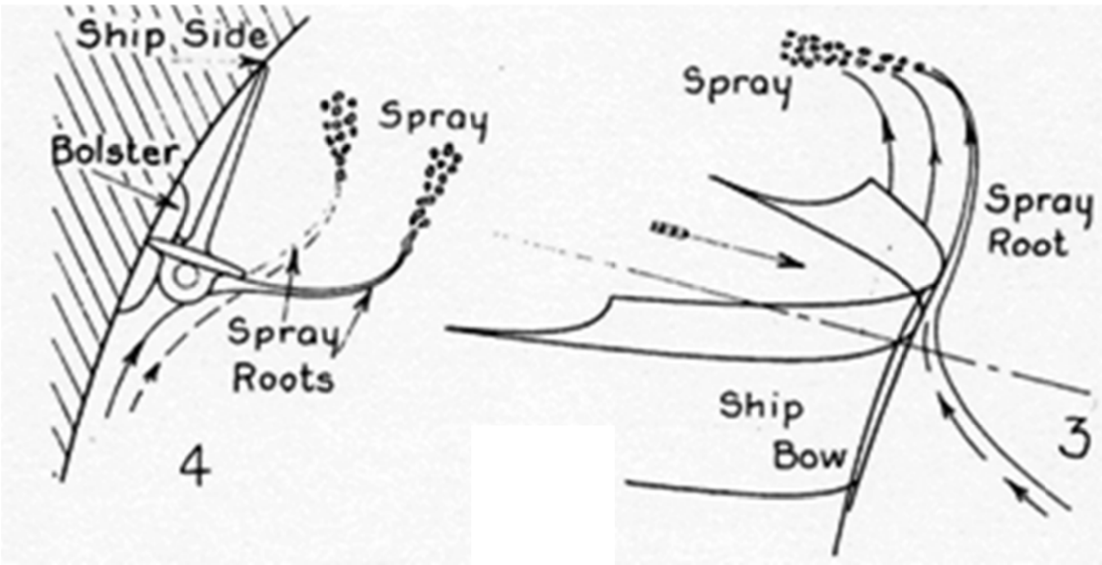


Figure 8 Schematic diagrams of spray-root and spray formation

This process can also be observed on the stem, when, initiated by a strong curvature, the stagnation pressure leads to raising water along the hull and finally in bursting up into spray (*Sapone, 1990*). The so called bow feather, a small uprising water sheet at the stem, delivers a smaller amount of water compared to the before mentioned processes and is best seen under calm sea conditions.

Nevertheless, spray roots are initiated by blunt or protruding surfaces facing into the direction of motion. Depending on their shapes, projecting width and the prevailing velocity of water flow in the contact area, a source of water, which may later on deposits on the surface above the waterline of the ship, is formed (see *Figure 9*).

Figure 9 Sea spray cloud rising at the bow (*left*) and on a cylindrical leg of an oil & gas production platform (*right*)

Especially at low and moderate speeds a smaller but thicker source of spray origins due to the dynamic pressure at the bow. The "Bow-Roll", a small wave before the stem arises at lower speeds. This is marked by a minor vertical extend than a bow feather. Depending on the steepness of the bow at the boundary layer, most of the water rolls forward and staves into the quiet water, approaching from ahead (*Saunders, 1957*)..

Excluding external turbulences and effects the water sheet will maintain its entity. The origination of the water film turning into smaller droplets commences with the influence of external and internal disturbances, such as gravity and wind. The accelerated water begins to rupture into smaller droplets up to the moment where the surface tension of the droplet restricts the forwarding collapse.

At this state the fluid film, which before has been ruptured into irregular formed pieces, now consists of approximately same-sized spherical droplets (*Saunders, 1957*).. As a consequence of the process of disintegration the drop number concentration increases and the mass of each single droplet decreases, which are now more impressionable by the prevailing winds around the vessel.

The size of droplets which are generated in this way ranges from 170 μm to 6100 μm in diameter, with a mean value of 1094 μm (*Ryerson, 1995*). Compared to the droplets originating from wind they are able to carry a higher amount of water per droplet.

A secondary and minor affecting source of spray originates by run-off water, which leaves the deck through scuppers or drops of the edges of objects, which previously have been wetted by a source of water. The hence generated water stream is affected by the prevailing winds and is ripped up (*Ryerson and Gow, 2000*). The amount of spray, which splashes superstructure of the ship, depends on the ships relative velocity and heading, seakeeping performance and geometry as well as environmental factors, like attributes of the wave spectrum, prevailing winds and temperatures, and angle between ship and wave motion (*Overland et al., 1986*).

Thus an accurately prediction of the amount of deposited water on the vessel after a spray event is difficult (see *Section 8.5 Prediction of ice accretion*).

3. Properties of spray clouds

From a thermodynamical point of view, the ice accumulation on the ship structure is a function of prevailing heat fluxes at a certain fraction and the water delivery, which reaches that certain location. This leads to different ice accretion rates under equal environmental conditions relating to the part of the ship (*Ryerson, 1995*). Hereby the mass flux is not only important as a source of water delivery to the substrate, it also affects the thermal energy flow, especially those of latent and sensible heat fluxes.

The spray cloud is characterized by the size distribution of spray droplets, the liquid water content in the air (LWC[1]) and the residence time of the cloud in the air (*Ryerson, 1995*). The properties of the spray cloud are affected by environmental conditions, such as wind speed, its direction and air temperature, which affect their behavior before and after the impingement on a surface.

The concentration distribution of the formed droplets is a function of the height above the water surface and the droplet size, or more precisely, their mass. The created droplets all have the same basic assumption regarding their temperature, which is equal to the sea surface temperature at the moment of splitting-off. Their size at a certain height depends on the influence of gravity and prevailing winds, which affect the droplets. After the water film has been ruptured into smaller, more spherical shapes, the size of the droplets is approximately uniform at the end of the breaking-up process (*Saunders, 1957*).

Investigations of the reactions of droplets with a radius of 100 µm and created from water with a temperature of -1.8 °C (SST[2]) at an air temperature of -10 °C revealed that droplets, at 90 % relative humidity, adopt a temperature below the surrounding air temperature within about 2 seconds. Some smaller droplets reach this state in a shorter time (*Jones and Andreas, 2009*).

Besides the development of the temperature of the droplets exposed to the air temperature, *Figure 10* indicates as well, that the evaporation, reflected in the radius, is up to three orders of magnitude slower compared to the cooling rate (*Jones and Andreas, 2009*). Based on their saline content the droplets will not evaporate entirely.

[1] LWC = liquid water content
[2] SST = sea surface temperature

It becomes obvious, that the spray impact temperature depends on the duration of the droplet on its trajectory and varies over the surface of the substrate (*Zakrzewski et al., 1988*).

This leads to the assumption that spray droplets carry a large amount of water to the substrate with a respectively low temperature. At this, the amount of impinging droplets, their size, the duration of spray cloud impingement and the liquid water content are essential (*Ryerson, 1995*).

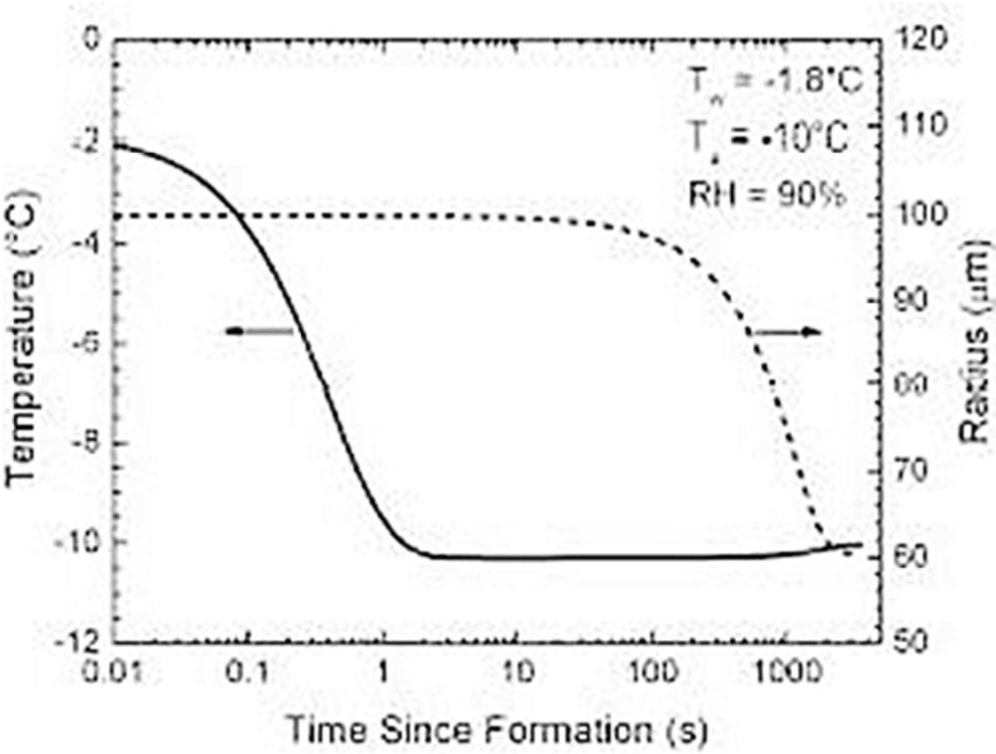


Figure 10 Temperature and radius development of a 100 µm droplet

3.1 Drop number concentration

The amount of available droplets carrying water to the surface depends on the drop number concentration, which indicates the number of droplets contained in an unit volume of spray. During the freezing process they act as nucleating agents, if they are supercooled (*Stallabrass, 1975*), and thus influence the rate of ice accretion on the deposition surface. As a consequence of the higher droplet concentration, the amount of deposited water increases, assuming a constant droplet size, and results in a lower freezing rate, leading to a higher amount of draining water under an unchanged accretion rate. Another fact which comes along with a higher droplet concentration and droplet size is the influence on the atmosphere, especially to temperature and humidity, between the droplets contained in a spray cloud. A higher humidity in a spray cloud, as a result of an increasing droplet concentration, will lead to a faster warm-up than in spray clouds of a lower concentration (*Ryerson, 1995*). Conversely it can be assumed that droplet cooling, initiated by convection and evaporation, will be more intensive, when this process is advantaged by a lower concentration of droplets. Investigations on board of the U.S. Coast Guard Cutter *Midgett* have shown that the droplet concentration of a spray cloud originating from a vessel-wave interaction, which has been determined as about $4.0 * 10^5$ droplets per cubic meter (m^3), exceeds the comparison values of heavy rain or rainstorms several times, but cannot reach the droplet concentration of clouds, which is about $1.0 * 10^7$ to $2.0 * 10^8$ droplets per m^3 (*Pruppacher & Klett, 1978*).

3.2 Droplet size

In addition to the droplet concentration, also the droplet size has to be taken into consideration, to determine the amount of liquid water delivery to the surface as well as the influences of the size onto the droplet trajectory, flight time, collection efficiency, droplet volume, cooling evaporation rate and attributes of the formed ice (*Jørgensen,1982*; *Stallabrass,1975)*. Investigations about the droplet size development in spray clouds originating from a wave-ship-collision were carried out on board of the fishing vessel *Aysberg* by Gashin, documented by Borisenkov and Panov (1972). The thereby logged measurements manifest that droplets, in such a spray cloud, are ranging between 500 μm to 1750 μm in radius, with a mean value of 1200 μm.

The results of the research cruise aboard the *Midgett* reflect the average volume diameter of the observed droplets with 1094 μm, in total ranging from ca. 170 μm to ca. 6100 μm. During the observations it has been detected, that smaller droplets are falling more slowly and are carried further along the ship. This leads to a decreasing droplet size with a further motion of the spray cloud along the ship to the stern, which matches with spray investigation by *Sapone (1975).*

Smaller droplets are more affected by winds, so that they remain aloft longer what results in a further spreading along the ship. They are also supercooled more intensively and are deflected around objects more easily (*Ryerson, 1995*).

3.3 Liquid water content (LWC)

Among the number of attributes characterizing a spray cloud, the liquid water content (LWC) is probably the most important. *Borisenkov and Panov (1972)* published a value for the LWC of 4.6 kg m^{-3} as a result from the investigation aboard the MV *Aysberg.* First steps into the determination of the liquid water content have been carried out by *Katchurin et al. (1974)* who calculated the LWC as a direct function of the wave height, based on tests on ships heading against the waves. *Stallabrass (1980)* refined the formula of *Katchurin* by attaching a coefficient reducing the values calculated by the formula of *Katchurin* to one sixth. Further examinations carried out by *Horjen (1983)* revived the *Katchurin* assumption. He declares the calculated amount by that equation probably reflects the LWC at the height at the wave's crests. He stated that this may lead to the large differences between the anticipated amounts of the formula of *Katchurin et al*. and the observed values by *Borisenkov and Panov (1972)*. But none of the equations took into consideration how the liquid water content may change with a variable high above the mean sea level. In 1983, Horjen applies two new computing methods to the development of the LWC observed within wind generated spray and development which respects the wave height and the height above the sea level on the one hand. On the other hand he implements a factor which considers the wind speed. *Zakrzewski* criticizes the calculation of the LWC based on measurement results of *Borisenkov and Panov (1972)*, because their equation is based on the results of measurements carried out on board of even a single ship. Thus the developed equation cannot be used to determine the vertical distribution of the liquid water content of any other ship, because they have not considered facts like the ship speed and wave height, which have to be taken into consideration (*Zakrzewski, 1986*). He redefines the equation of *Borisenkov* and *Panov* by implementing the wave height and ship speed in relation to the waves.

As a consequence of the refined equation the major aspects of liquid water distribution becomes obvious:

- The LWC does not depend on the ship speed when the ship is heading parallel to the wave crests.
- The LWC increases as a consequence of an increased ship speed for any wave impact angle before the beam (α > 90°, counted from the stern over portside to the bow of the ship).
- The LWC decreases with a vertical expansion of the spray cloud.
- The LWC increases as a result of increasing wind speed.
- The peak values of LWC are reached when the vessel is steaming directly into the waves.

The amount of ice build-up on a substrate per unit of time depends on the mass flux of droplets to the cylinder radius, the liquid water content, the wind speed as well as the collection efficiency and impinging rate (*Minsk, 1980*).

To determine the last mentioned aspect, it becomes necessary to have a short look at the trajectory and stream velocity of the air flow which contains the droplets.

3.4 Collection efficiency

The collection efficiency is defined as the ratio of the water droplets, which are impinging at the accretion surface within a certain time, to the whole mass of droplets, which would have impinged without being deflected (*Minsk, 1980*). The droplet which is embedded into the air stream is influenced at its movement to the accretion substrate by the aerodynamic drag and inertia forces. To estimate the effect of inertia, the mass of the droplet has to be considered. At smaller droplets, the inertia is even low, which results in a small deviation of the droplet trajectory compared to the air stream lines. The inertia increases as a consequence of the growing droplets, which comes along with a higher deviation of their flow trajectory compared to the air flow pattern (*Jessup, 1985*).

The object, which is embedded into the air stream, deflects the air resulting in an air flow around the object (see *Figure 11*). Thus the water droplets, which are influenced by the drag of the air stream, are forced to follow the flow and are deflected from the surface. These results in a minor water collection rate of the substrate compared to an uninfluenced motion of the water droplets towards the accretion surface.

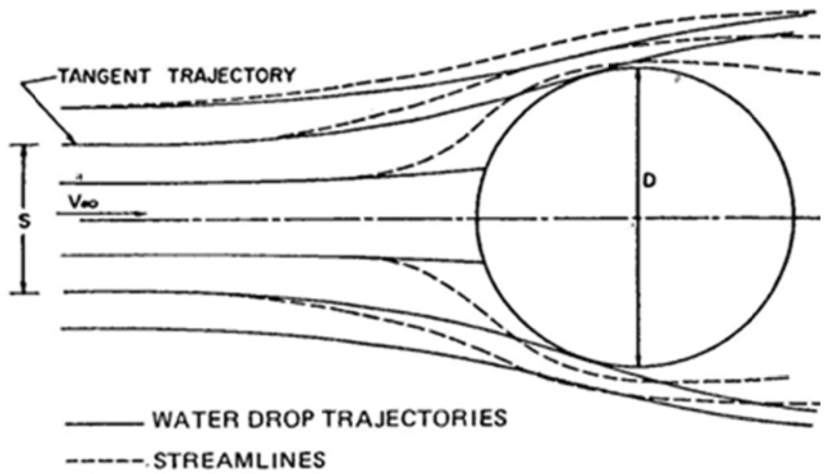


Figure 11 Air flow trajectories around a cylinder (*Minsk, 1980*)

As the figure above shows, the impinging water droplets are deflected from the center stream lines, here denoted as s, limited by the outmost tangential trajectories grazing the cylinder. It becomes obvious, that the collection efficiency depends on the distance between the tangential droplet trajectories (s) and the diameter of the cylinder (D), so that under a constant mass flux the collection efficiency depends on the ratio of s and D (*Stallabrass and Hearty, 1967*). Regarding the diameter of the cylinder, which is embedded into the air stream lines, it is proven, that the greater the cross-sectional area, the smaller is the deposition amount of water under a steady mass flux (*Minsk, 1980*), leading to a higher accretion rate on thin objects. Droplets which are generated by a vessel-wave interaction are bigger than those of clouds or by spindrift, so that inertia forces are assumed to be large enough to dominate the droplet trajectory and make the collection efficiency independent from the shape of the substrate (*Jessup, 1985*).

A Soviet investigation of ice accruement on cylinders has shown that under constant assumptions of cloud droplet radius and cross sectional area, the collection efficiency increases as the wind speed increases (*Jessup, 1985*).

As mentioned above, the collection efficiency constitutes the ratio of the mass of droplets impinging on the cylinder to the total mass of droplets, which would deposit if the droplet deflection is neglected. The number of various factors to determine the accretion rate of ice on a surface is large, which leads to various appearances of ice.

This abstract should give a rough overview about the most important factors. Other factors are not less important, such as the liquid water impinging rate, which describes the ratio of the total mass of impinging water reaching to the surface to the entire area of icing is denominated, expressed in the units of mass per unit area per unit time. In general the air flow, impinging rate and droplet trajectory is much more complex in reality than it appears at a cylinder with a steady accumulation of ice. However, this abstract should describe the complexity of the accretion process. A more detailed view may exceed the basics, which are presented here to give a better insight into the accretion process.

Next to the delivery of water, initiated by the spray droplets embedded into the prevailing air stream, it always has to be kept in mind that another source of water supply has to be considered. Runback water which is not trapped during the formation of ice in its impact area is influenced by gravity and air drag and appears as a source of water at another part of the surface. This either leads to water delivery to before dry areas or forms an additional amount of water at already affected areas (*Jessup, 1985*). This source of fluid water influences the appearances and physical attributes of the accrued ice by thermodynamical and physical effects. Parts of the water film will be influenced by gravity and drop of the surface or become picked up by the air stream. This run-off, as it is called, will leave the surface without accretion but still influences the freezing process due to their transferred heat, which is described in *Chapter 4*. "Thermodynamic processes of the freezing system".

4. Thermodynamic processes of the freezing system

Leading to the thermal energy fluxes, which characterize the icing process, it is essential to enlarge on the thermodynamic composition of the freezing process.

4.1 Freezing system

Four assumptions may be valid or the freezing process (*Jessup, 1985*):

- Liquid water droplets are embedded into an air stream.
- A depositional substrate or surface is exposed to the above mentioned air stream.
- A layer of ice covers this substrate partially or totally.
- A water film covers the accrued ice particles.

The last listed aspect only needs to be considered, when a part of impinging water drains off before freezing. The ice accretion rate contingents on the thermodynamic balance of ice growth and a heat flow away from the accretion substrate, assuming a steady delivery of water to a surface. This equilibrium of heat fluxes is marked by convection of sensible heat, evaporative heat flow and radiative cooling, which are transferring the thermal energy away from the accretion surface. On the other hand, these fluxes are countervailed by the cooling of seawater to the freezing point and thus the initiated formation of ice. This either builds up on the surface or the ice particles are flushed away by run-off water, which carries the heat away by getting cooled before it drains off (*Overland et al., 1986*).

The most common way to describe the process of ice accretion, with view to the thermodynamically processes, is to estimate the accretion on a vertical shape (z-axis), without paying attention to the profile or surface of the location (*Jessup, 1985*). Neglecting the detailed shape of the surface will lead to the assumption that the accrued ice as well as the ice overlying water, which covers this vertical axis, mostly pictured as a rod, with a cylindrical symmetry. For the introduction into the thermodynamic equilibrium at the accretion surface the presentation according to Overland is suitable to visualize the most important aspects.

In the following chapters the aspects of heat fluxes are examined more detailed without taking the calculation of each single value into account. It should give an overview of the dependences of heat fluxes to the prevailing conditions. Detailed investigations determining the specific values can be found in publications by List (1977), Stallabrass (1979), Overland et al. (1986) and Jessup (1985).

4.2 Thermal balance at the icing surface

The thermodynamic processes, which ensure that the impinging water droplets change their phase from liquid to a firm structure and cause an accumulation of ice, dominate the rates of ice accretion on overwater structures.

Focusing on the primary thermal transfer the formation of ice is assumed as a continuous process of heat transfer occurring at the boundary layer between the ship surface and the environmental air. Thus the thermodynamic balance of heat fluxes taking place at the icing surface, disregarding the secondary vessel-specific fluxes like cold soaking, can be described by the balance of heat fluxes formula given in Overland et al. (1986):

$$Q_{lat} + Q_{im} + Q_{ro} = Q_{conv} + Q_{evap} + Q_{rad}$$

Where:

Q_{lat} = latent heat flux originating from freezing a certain fraction of the impinging water, marked by the transition of phase

Q_{im} = heat flux accruing due to the cool down (or heating) of the impinging sea spray to the freezing point of forming ice, which remains accreted

Q_{ro} = heat flux between surface and run-off water, which is not accumulated on the surface

Q_{conv}= heat flux between the boundary layer of between surface and air stream, initialized by the sensible heat flow

Q_{evap} = evaporative heat flux from the outer surface to the adjoining airstream

Q_{rad} = heat flux due to radiative transfer

4.2.1 Latent heat flux Q_{lat}

During the freezing process a latent heat flux, which describes the difference in enthalpy per mole after a transition of phase without changing temperature or pressure (*Potter and Colman, 2003*), will be released at the boundary layer between the outer ice surface and the adjoining air. The value of Q_{lat} is a direct product of the latent heat of the freezing process of saline water, the density of saline ice and the rate of ice formation (*Overland et al., 1986*). The energy which is required to keep the water in a fluid state is released by the freezing process. Thus the accretion surface has a higher temperature compared to the temperature of the impinging water droplets (*Makkonen, 1989*).

4.2.2 Heat fluxes of Q_{im} an Q_{ro}

The water impinging on the surface can be divided into three categories (*List, 1977*):

- Water which freezes to ice and remains on the surface in solid form.
- Water which leaves the surface without freezing.
- Water which will remain on the surface without freezing.

From the thermodynamic point of view, the focus is led to the first two aspects, neglecting the influence of the remaining water which will not convert into ice.

Q_{im} stands for the heat flux from to the impinging water which will permanently remain on the accretion surface and turns into ice. The accrued water initializes a heat flow which detracts thermal energy from the surface while changing its phase from liquid into a solid state. The amount of heat which is removed from the surface is a function of the temperature differences between the surface and the water prior the impingement, the freezing fraction, the amount of deposited water and the specific heat, as a function of the salinity of the spray droplets (*Jessup, 1985*). The greater the temperature differences between deposited water accrued ice and the temperature of the accretion surface, the larger is the amount of transferred heat. To determine the temperature of the impinging water droplets many variables have to be considered, including the sea surface temperature (SST), the air temperature as well as the drop size and the duration how long the drops have been exposed to this environment before impingement. After the first ice has formed it continuously cools down and imbibes the temperature of the surface where it is accrued on. Due to this process further thermal energy is released to the environment.

Q_{ro} describes the heat flux which is initialized by the flowing water, which leaves the surface, in contact with the surface. Regarding the influence of the run-off water which leaves the surfaces before freezing, it has to be assumed that a not negligible fraction of water is shed or lost by bouncing before its deposit (*List et al., 1976*). Hereby the run-off water is divided into three groups:

- The water which leaves the surface has the same temperature before impingement as the substrate, it is running from. Thus no heat exchange will occur during the temporary residence of the water on the substrate because the major assumption for a thermal heat transition, a difference in temperature of two adjoining materials, is not fulfilled.

- Assuming that the shed water has been warmer than the surface or even has 0 °C before the impact, a thermal transposition is initiated. Thus the water carries away heat, what may result in further ice accretion on the substrate.

- The third and last form is marked by water leaving the object, in a partly or completely frozen state. The amount of heat carried away depends on the proportion of formed ice particles and the time before leaving the surface.

Regarding the amount of run-off water it has to be pointed out, that a direct transition of impinging water into crystalline form preferentially comes along with slow wind speeds or a minor content of liquid water, which both leads to higher collection efficiencies (*Zakrzewski, 1986*).

The possibility of water leaving the surface of the accretion substrate is essential for the icing intensity. Increasing the wind speed around the surface will lead to a higher

heat flux of Q_{conv} and Q_{evap} as well as a higher amount of unfreezing water depositing at the substrate. Assuming that the water will accumulate on the surface without run-off this will result in a minor amount of accreted ice, although the heat fluxes of Q_{evap} and Q_{conv} will favor a higher rate of accretion.

As a first consequence of shedding water the icing intensity grows, what explains the higher accretion rate on surfaces without steady water coverage (*List, 1977*).

Regarding the second aspect, the highest amount of thermal exchange will be reached when water which drains off adopts the surface temperature without getting accreted. Thus the maximum of heat transfer results during the cool down of the droplets to the surface temperature.

In the third case, assuming whole ice particles are flushed off by the water, the heat flux is contrarily to the before mentioned cases. This is a result out off the lower temperature of the carted off ice particles in contrast to the water. Thus thermal energy is transferred towards the surface (*List, 1977*).

4.2.3 Convective heat flux Q_{conv}

Convection itself serves as a thermodynamic heat transfer tied to an exchange of particles (*Potter and Colman, 2003*). Regarding the formation of ice, the forced convection either takes place at the boundary layer between air and water or air and ice, what depends on the outermost layer which is in contact to the air. This process follows directly “Newton´s Law of Cooling” (*Jessup, 1985*), which states out, that the rate of changing the temperature of an object is proportional to the difference between its own and the surrounding temperature (*University of British Columbia, 2011*). Applied to the freezing process, the temperature slope between the outermost layer and the air temperature dominates the heat transition, whereas the coefficient of the surface heat transfer (h) has to be taken into account.

This factor reflects the intensity of heat exchange and generally is a function of the specific heat capacity, density of the prevailing fluid, prevailing air streams and the conductivity of the two adjacent mediums (*Pitka et al., 2005*).

4.2.4 Evaporated heat flux Q_{evap}

As well as the above mentioned convective heat flux Q_{conv}, the evaporative heat flow is initiated by the forced convective evaporation of deposited water or the direct transition of ice into vapor, called sublimation (*Jessup, 1985*). Evaporation is assumed when the accretion surface is wet. The amount of evaporated heat generally compounds out of the coefficient of heat transfer (h), the ratio of momentum diffusivity and mass or thermal diffusivity, the latent heat of vaporization or sublimation, the specific heat of air at a constant pressure, the relative humidity, the saturation pressure and the temperature differences (*Jessup, 1985*). The bigger the temperature slope, the higher the heat flux will be. Cooling the surface with impinging droplets due to evaporation and convection is intensified within clouds of a minor drop concentration. This is a result of the higher humidity within a spray cloud of a higher drop condensation which comes along with a warm up of the spray cloud (*Ryerson, 1995*).

4.2.5 Radiative heat flux

The influence of the radiation energy flux is small compared to the before mentioned aspects. The radiative heat flux is initiated by the long-wave radiation of an object which emits thermal energy. Regarding the calculation of the emitted heat flux, the temperature differences between the outermost layer of the accretion surface and air temperature, as well as a constant for the radiated power of an object has to be considered (*Jessup, 1985*).

4.3 Others

A more detailed description of the prevailing heat fluxes at the deposition surface is shown by *Jessup*.

To the before mentioned heat fluxes applied by *Overland et al. (1986)*, *Jessup* added the following heat fluxes, as shown schematically in *Figure 12*.

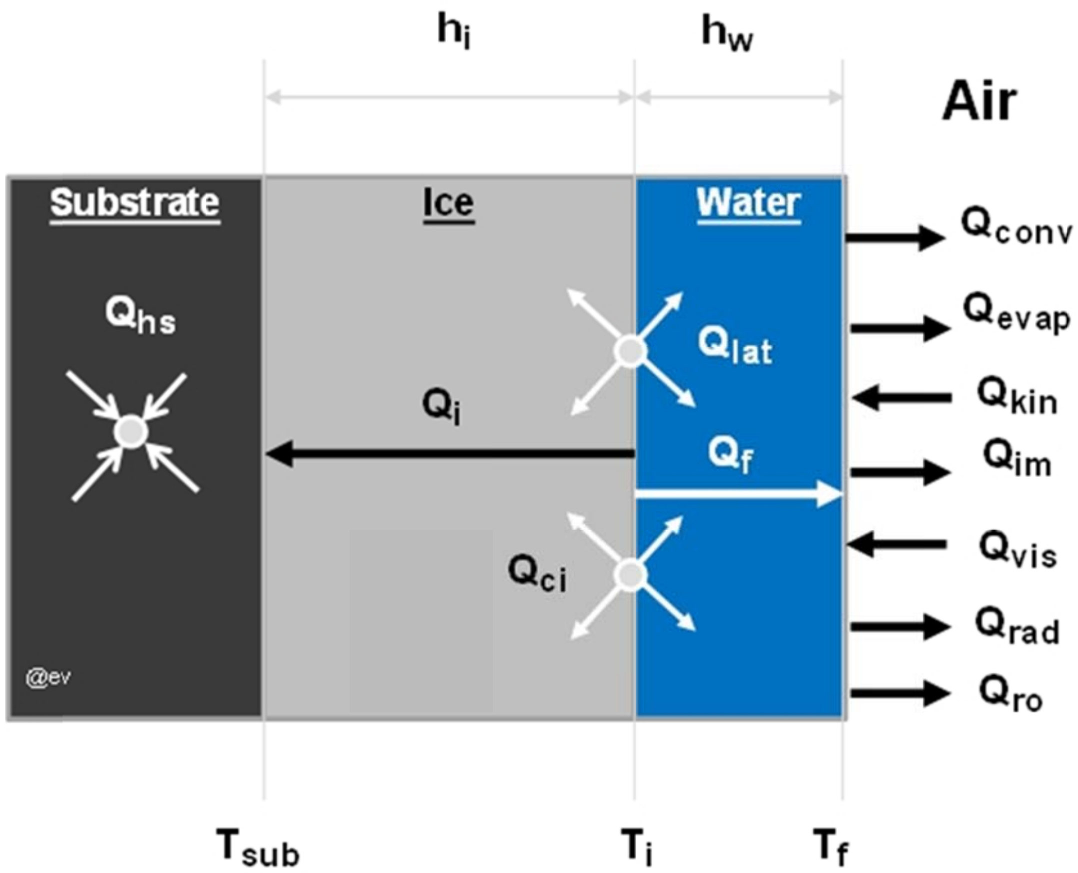


Figure 12 Schematic diagram of heat fluxes, their directions and heat sources at the boundary layer (after *Jessup, 1985*)

Legend of Figure 12:

Q_{evap} = the evaporative or sublimative heat flux from the outer surface to the air stream

Q_{conv} = heat flux from the outer surface to the air stream, caused by forced convective heat transfer

Q_{im} = heat flux from the impinging water

Q_{ro} = heat flux between surface and run-off water, which is not accumulated on the surface

Q_{vis} = heat flux originated from the viscous heating in the boundary layer

Q_{kin} = heat flux initiated by the kinetic energy of the impinging water

Q_{ci} = heat flux released by the newly formed ice in cooling down to the ice surface temperature T_{ice} of the outer ice surface

Q_f = heat flux due to conduction and convection of thermal energy through the liquid film away from the outer ice surface

Q_i = heat flux due to conduction through the ice layer to the surface of the substrate

Q_{hs} = heat flux spent in heating the underlying substrate

T_{sub} = temperature of substrate

T_{ice} = ice surface temperature

T_f = temperature of fluid (water)

Figure 12 is a compilation showing the heat fluxes for the ice accretion with a water film and without. The processes, which take place during the formation of ice on surfaces, exposed to water droplets embedded into an air flow, are numerous as the figure above presents. At the beginning of the freezing process, assuming a sufficiently low temperature, wind and mass flux, the impinging supercooled water droplets are freezing on the impact at the substrate, here the wind-chilled superstructure or hull of the vessel. As a consequence of the solidification latent heat is released, what results in a warming of the unfrozen water and substrate. At the following phase, the solidified and unfrozen deposited water continuously cools down under the release of convection, radiation, evaporative cooling, cooling the substrate and cart off water (*Makkonen, 1989*). The intensity of these processes depend on environmental and ship specific characteristics and vary with the location on board, which leads to different accretion zones at the vessel. At this, the time which is required for the solidification of the water, which deposits on the substrate and then turns into ice, determines the intensity of icing and is a function of the before mentioned heat fluxes.

Another important fact is the characteristic of the spray cloud, which determines especially the mass flux to the surface. Thus, for instance, the sensible heat loss, which increases with an increasing amount of impinging water, is affected (*Blackmore and Lozowski, 1998*).

The here presented basic assumptions of the thermodynamical processes which may take place in a variable manner and intensity, dependent on the mass flux, prevailing temperature, material properties and the vessels characteristic, are essential for the rate of ice accretion and thus dominate each model of icing prediction. For a more realistic evaluation of icing intensities *Jessup* notes that next to the thermodynamically processes, the hydrometeorological parameters which are used to define the state of the environmental conditions like air and sea temperature, wave height, salinity and wind speed are essential to determine the heat fluxes (*Jessup, 1985*).

5. Appearance of ice accumulation

Observations carried out by *Tabata et al. (1963)*, have shown that the formation of ice occurs in different appearances. This is a function of the wind speed and the size, or more precisely, the mass of the droplets (*Tabata et al, 1963*). Researches by the *Canadian National Research Council* (NRC) have investigated the freezing behavior of water droplets impinging on horizontal and vertical cylinders (*Stallabrass, 1980*). These are outlining that regarding the collection efficiency, it is not essential whether the cylinders are exposed to the spray vertically or horizontally.

5.1 Appearance of ice

The accretion of ice is a non-steady process which shows different forms depending on the surface and position of the accretion area. Only the distribution of the accrued ice, due to the influence of gravity, has to be considered. Regarding the accretion of ice, it has been noticed that at the lower part, compared to the midsection of the cylinder, a 10 to 20 % larger diameter develops. On the other hand, this mass is missing at the upper part, where the diameter was 10 to 20 % lower. General statements of these investigations regarding the ice accumulation can be summarized as follows:

- Icing efficiency is increasing as a consequence from decreasing temperature and the minor important influence of the cylinders diameter.
- Ice thickness depends directly on the temperature, whereas the lateral area of the cylinder plays a secondarily role.
- Ice accretion on cylinders of small diameter may exceed the diameter of the cylinder for many times.

Assuming that all other assumptions for the freezing process are complied, small droplets combined with low wind speed lead to the accretion of the water on the surface, when the droplets are captured before further water is impinging.

The accretion takes places at the windward side of the rod (A) whereas the leeward side will remain ice free (see *Figure 14*).

Brine solution, which abstracts due to the icing process, is mostly trapped in the ice layer (*Figure 13*). Brine itself describes a liquid with a higher salt content than the impinging water. It originates from to the freezing process, in which the salt, dissolved in the sea water, is not trapped in the accreted ice due to the lower freezing point and extracts in a fluid. Some of the brine is either running down, blown away by the wind or trapped into the ice as so called salt cells, as is has been described above (*Lundqvist, 1977*).

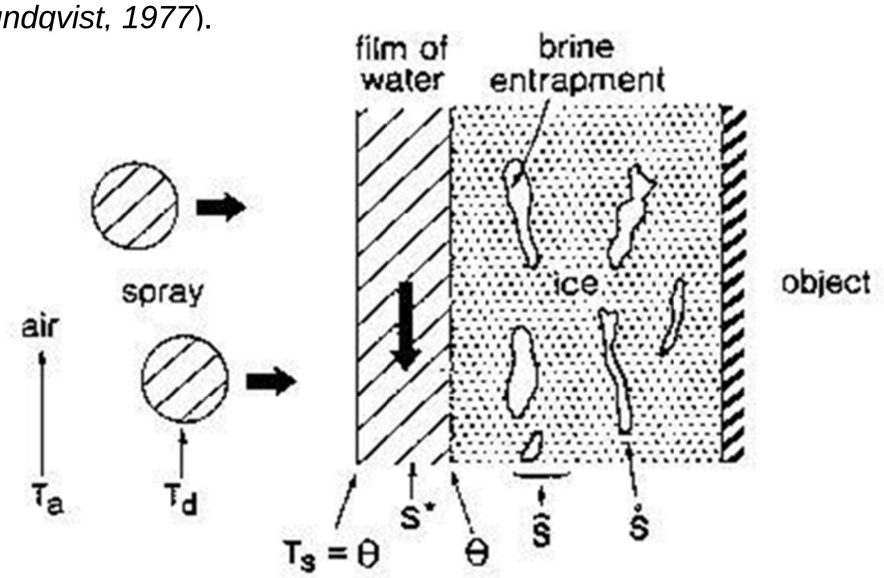


Figure 13 Profile of an iced surface (*Zakrzewski et al., 1988*)

As the above mentioned figure pictures out, brine cells are ice-bounded or flushed away by the water film. Usually the droplet temperature before impingement lies below the air temperature (see *Figure 10*: *Temperature and radius development of a 100 µm droplet*). The temperature of the water film is assumed to be the same as the outermost ice surface temperature (θ).

Increasing the size of droplets as well as the wind velocity leads to an assumed incompleted ice forming process before further water deposits on the surface. Due to the higher water impingement rate R_w, the freezing fraction F decreases under an assumed steady icing intensity R_i. Thus more water is located on the surface than could be formed into ice (*Jessup, 1985*). The thus created odd water is influenced by the air drag and gravity which results in a viscous flow around the cylinder (*Minsk, 1980*). As a consequence a widening-out of the ice formation to the more downward and leeward side of the rod (B+D) takes place (see *Figure 14)*.

Figure C points out that with a further enlargement of the droplet size higher accretion takes place on the side of the rod, because more water runs down the spray exposed part and along the sides before freezing (*Lundqvist, 1977*).

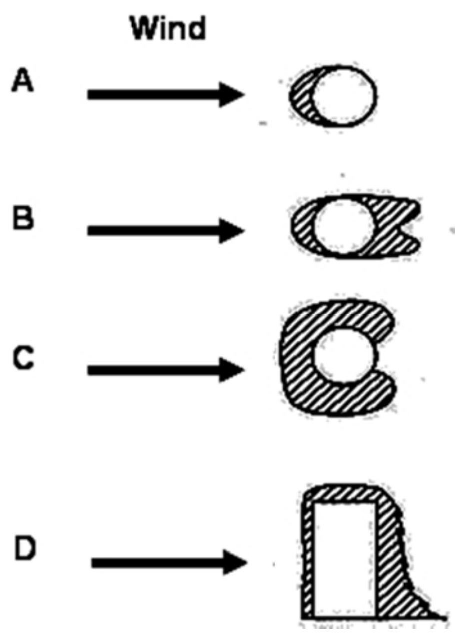


Figure 14 Appearance of ice as a function of wind speed and droplet size (*Lundqvist, 1977)*

5.2 Types of accrued ice

The type of ice which forms at a surface depends on various factors. The freezing fraction F is one of them. This value expresses the freezing efficiency, resulting from the amount of impinging water and the hence generated ice. The freezing fraction F results from the ratio between the icing intensity R_i, which expresses the mass of accreted ice for a local fraction or areal average and the mean liquid water impingement rate R_w.

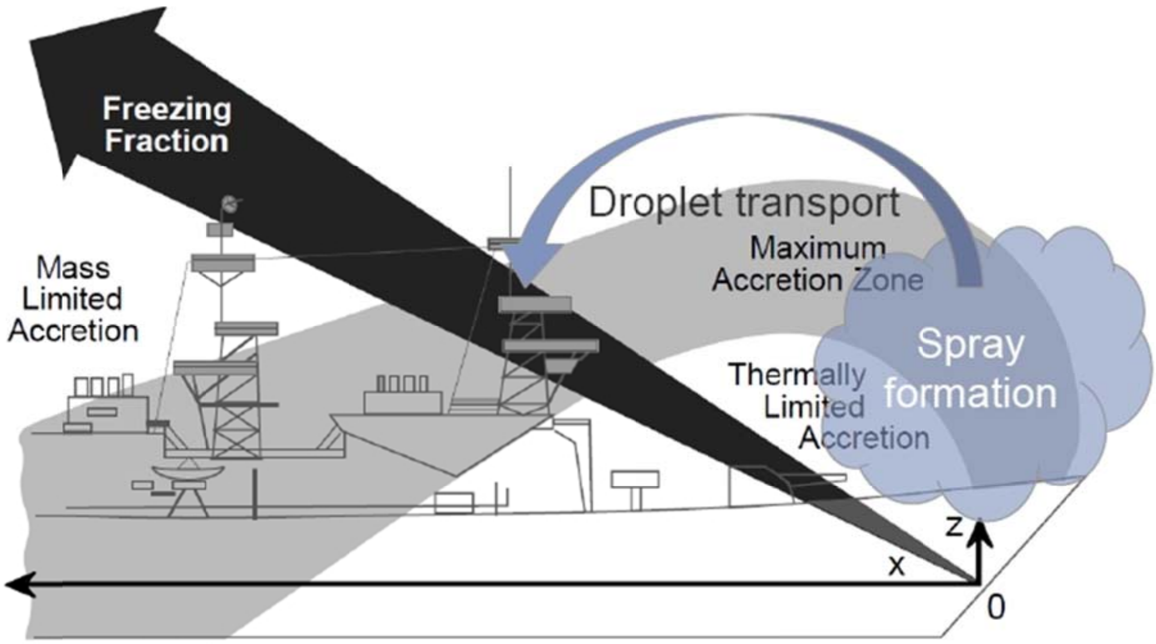
The interaction between the mass flux and heat fluxes determine the ice growth on the superstructure, which varies obviously with the location on the ship (*Ackley, 1985*).

The balance of thermal energy delivered by spray, the atmospheric heat removal and the availability of water, which can be transformed into ice, result in three icing zones which often occur on vessels of all sizes (see *Figure 15*).

(1) The maximum accretion zone appears at locations where the atmosphere is able to remove all the sensible and latent heat of a sufficient rate of deposited water, which is delivered by the spray (*Ryerson and Gow, 2000*). This balance of mass and heat fluxes results in a freezing fraction value of almost 100 %, which means that, neglecting the unfrozen brine trapped in ice, all of the impinging water is transformed into solid ice. The maximum accretion zone often appears at the area around the bow and the forward mooring station, which are primarily exposed to the prevailing relative winds. Next to the bow, the highest accretion rates of ice take place amidships, assuming a smaller fishing vessel, or at any rate aft of the bow, where the water delivery amount is lower than at the forward part of the ship, but the thermal heat removal is still large. Generally the maximum accretion zone occurs at a higher vertical extent at the bow. This is a product of the decreasing spray fluxes at the parts aft of the bow and the lower impingement rate at increasing heights above the deck level (*Ryerson and Gow, 2000*).

(2) A thermally limited accretion zone originates from a higher supply of water to the surface than the atmosphere is able to remove its thermal energy to cause freezing. Under this condition, the ice accretion rate is much smaller than it could be under these circumstances of mass delivery. Primarily affected are bow areas of larger vessels or areas alongside a vessel, not steaming into head seas. But even on smaller fishing vessels a large amount of spray can reach the areas close to the stern. Caused by the fewer accretion rates the formation of ice is suppressed by the higher amount of run-off, if the unfrozen water is able to leave the surface (*Ryerson, 2008*).

(1) The mass limited accretion zone distinguishes from the thermally limited accretion zone by its lower water delivery. However the limiting factor of icing is an insufficient quantity of water, as the atmosphere's ability of heat removal is given (*Ryerson and Gow, 2000*).



$$\text{Location}_{max} = f\,(\text{temp}_{air}, \text{flux}_{spray})$$

Figure 15 Schematic of ship superstructure icing processes. Three principal icing zones are indicated, with the location of maximum ice accretion (Location_{max}) largely a function of spray flux (flux_{spray}) and air temperature (temp_{air}); (after *Ryerson and Gow, 2000*)

The above mentioned three ice accretion zones are dynamic and vary with spray deposition, atmospheric conditions, like relative wind speed and direction, heading and speed of the concerned vessel and prevailing weather conditions (*Ryerson, 2008*). Under these conditions not all types of accretion zones have to occur, so it is possible that just one, two or all three types of zones can be found simultaneously (*Ryerson and Gow, 2000*).

As shown in the *Figure 15* the freezing fraction increases with the distance aft of the bow and with an increasing height above the sea surface. This is the consequence of the decreasing amount of liquid water content LWC within the spray cloud.

Apart from the growth conditions of ice, also the type of formed ice is determined by the freezing fraction F. Neglecting the influence of the salt contained in the water, three categories of F can be distinguished (*Jessup, 1985*):

- When the icing intensity R_i imbibes the value zero, the ratio between R_i and R_W results in a value F = 0 and no ice accretion will occur.
- When R_i deviates from zero, F ranges between a value bigger than zero and smaller than one. Wet ice will grow because the amount of accumulated ice is smaller than the amount of impinging water, which results in an ice covering water film and drain off water. Under these circumstances glaze ice will be formed as a result of the freezing process.
- If the entire mass of water delivery to the surface can be transformed into ice, ice will form dryly without the existence of a water film or draining water. The hence formed ice type is soft rime ice. At the transition between glace ice and soft rime ice the so called hard rime ice forms, which is rather hard than soft rime ice and has a milky to translucent appearance.

Assuming that the value of the freezing fraction relates directly to the temperature of the outermost surface T_S, the freezing temperature of fresh water spray has to be taken into account. There won't be any freezing when the surface temperature is above 0 °C, because ice only accrues on wind chilled cold surfaces. At a temperature of 0 °C the freezing fraction ranges from one to zero. The value of one is reached at temperatures below 0 °C. For the prediction of ice formed from sea water spray, its salinity has to be considered. Thus the determination of the freezing fraction results in a freezing temperature deviating from 0 °C due to the dissolved salt. Under this circumstance another factor has to be taken into account. When ice is formed originating from salty water, a brine solution will develop. Due to the phase transition, the accrued ice has a minor salinity than the impinging water droplets.

5.3 Properties of accrued ice

A number of studies have been carried out since the 1960s on board of Russian fishing trawlers (*Kultashev et al.,1972*), Japanese patrol boats (*Tabata et al., 1963, Ono, 1968; Iwata, 1975*) or in wind tunnels (Gates et al., 1986, Makkonen, 1987) to analyze the accretion and properties of ice. The investigations were emphasized on the brine volume, salinity and porosity and the simulation of the formed ice. The first analyses on board of a larger ship were carried out on board of the U.S. Coast Guard cutter *Midgett* by the *Cold Regions Research and Engineering Laboratory* (CRREL), (*Ryerson, 1995*).

The risk, which lies in the icing, comes along with its properties, like thickness and density resulting in its mass and influence on mechanisms and devices. In contrast to floating sea ice, saline spray freezes much more rapidly, deposits on horizontal as well as on vertical surfaces, forms brine as a result of the freezing process and is flushed by a periodical passage of spray clouds. As a consequence of the prevailing mass and energy fluxes which differ from the location on the vessel, the ice formed from sea spray take various physical and crystalline properties (*Ryerson and Gow, 2000*). Due to the interaction between heat fluxes and mass delivery by sea spray, the accretion of ice on the superstructure is a dynamic process. As described above in the three accretion zones, it becomes obvious that during an icing event the accretion varies with the location at the ship. Usually a number of freezing and melting cycles take place in different areas at the same time. These unsteady growth conditions are reflected in its physical properties and crystalline appearance (*Ryerson and Gow, 2000*).

5.3.1 Ice thickness and density

Only a small amount of information of ice dates is available. One of the most present information has been observed during the research cruise of the U.S. Coast Guard cutter *Midgett* in the Bering Sea. Only small amounts of accreted ice have been recorded with a total weight of about 5300 kg (Ryerson, 1995), assuming a mean density of 0.8 g cm^{-3}.

This stands in contrast to the results from Japanese patrol boats with a size of about 325 metric tons displacement (*Tabata et al., 1963*), where 6 to 25 metric tons of ice have been observed. It underlines that, compared to their size larger vessels are less affected than smaller fishing boats.

The thickness of ice depends on the time of freezing condition and the meanwhile icing intensity at a certain area.

The accretion rate ranges between values less than 0.7 cm/hour for light icing events up to over 3 cm/hour for heavy icing (*DeAngelis, 1974*). On board of the "*Midgett*" a maximal ice thickness of 3.4 cm has been observed on the forecastle deck. The measurements have shown that ice thicknesses on horizontal surfaces are bigger than on vertical surfaces, leading to the assumption that ice accretion varies with the posture of the surface. *Kultashev et al. (1972)* stated that 30 to70 % of the accreted ice is found on horizontal surfaces whereas on vertical surfaces only 15 to 30 % of the ice volume deposits.

Ice thickness on horizontal surfaces, like decks or hatch covers, is thicker than deposits on vertical components, for example bulkheads, with an average ratio of 1.25 : 1 (*Ryerson and Gow, 2000*). Ice accretion from freezing spray can generally exceed an icing intensity of 2 cm/hour and a thickness of more than 25 cm is not uncommon (*Canadian Coast Guard, 1999*).

Due to the vertical position, the brine is able to drain more easily, which results in a lower density so that the accrued ice on horizontal surfaces has a higher weight per volume than ice on vertical surfaces (*Ryerson and Gow, 2000*). The density is most important to determine the ice load on a certain location, when the thickness at this place can be estimated.

Next to the ice load even the strength and adherence to the substrate depends on its density (*Smirnov, 1972*). Densities measured from samples originating from different locations on the ship vary from 0.69 g cm^{-3} to 0.92 g cm^{-3}. During the first measurements the above described difference in horizontal to vertical ice densities due to brine drainage has been observed, however not that significant during the later carried out measurements (*Ryerson and Gow, 2000*).

This values measured by the CRREL agrees with values given by *Kultashev et al. (1972)*, ranging between 0.71 to 0.967 g cm^{-3}, and *Tabata et al. (1963)*, whose results are located between 0.62 g cm^{-3} and 0.94 g cm^{-3}.

As a result of the deposition properties, density and thickness it can be stated, that a respective risk comes from the horizontal surfaces, where the accrued ice shows a larger thickness and a higher density. This results in a higher mass accretion on horizontal surfaces which comes along with a smaller amount of inclusions, like air.

5.3.2 Salinity

The salinity of the sea water of the Bering Sea, where these measurements were conducted, ranges from 32 to 33 ‰ (*National Oceanographic Data Centre, 2011*). At the research cruise of the USCG cutter *Midgett,* measurement results from ice sample indicate a bulk salinity ranging from 7.0 to 25.4 ‰ (*Ryerson and Gow, 2000*), at a reference temperature of 25 °C. Compared to normal sea ice, where the brine returns into the sea, the salinity amount is around 6 to 7 ‰. Thus it is smaller than the salinity amount in consolidated sea spray (*Ryerson and Gow, 2000*).

As mentioned before the salinity of samples, taken on horizontal surfaces, is 8 to 10 % larger than it has been measured within vertical samples. Inaccuracy in measurements results of various durations from the last water impingement due to a spray event. Thus the resulting brine, which is formed within the freezing process, has time to drain from the sample fraction (*Ryerson and Gow, 2000*).

Compared to the results from CRREL[3] which are presented above, *Panov (1972)* observed higher values ranging from 10.3 to 37.5 ‰, for the same sea water salinity. Validation of this assumption is endorsed by *Kultashev et al. (1972)*, who compared the salinity of accrued ice on board of medium-sized fishing vessels and then stated that at a height of three meters above the deck, the salinity varies around 22 ‰, whereas at a height of 0.3 m the salinity increases to 37.5 ‰.

As a consequence of the higher salinity of the accrued ice at the lower parts, its strength has been estimated several times less, compared to the higher parts with a lower salinity (*Kultashev et al., 1972*). The older the ice becomes during the freezing process, the more brine drains, leading to a decreasing salinity of the ice. The decreasing salt content comes along with an increasing hardness and the crystals are increasing in size (*Ryerson, 2008*).

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5.3.3 Porosity

One of the most important attributes of ice formed from saline sea water is the content of ice-bounded unfrozen brine (*Makkonen, 1987*). The part of brine in the total volume of ice is up to 50 %, so that this kind of ice is also called “spongy ice”. Brine drains generally faster during the freezing process and continues flowing even after the first ice has been formed. Due to the separation of the fluid, the density of the ice, in most cases observed on vertically located surfaces, is reduced (*Kultashev et al., 1972*).

Measurements of samples on the USCG cutter *Midgett* where significant differences in air and brine volume content and porosity have been observed between samples from vertical and horizontal surfaces have proved this presumption (*Ryerson and Gow, 2000*).

While extracting these samples, different meteorological surroundings have been observed. The first icing event took place at lower temperatures, which is reflected in the samples, showing higher differences in porosity between vertical and horizontal

[3] CRREL : Cold Regions Research Engineering Laboratory

surfaces. During the second icing event, the temperatures were higher, so that the ice contains a higher proportion of unfrozen water than in the first samples taken.

Samples from horizontal surfaces have shown a higher porosity than those taken from vertical surfaces, because of higher temperatures and a periodical spray deposition (*Ryerson and Gow, 2000*).

Due to the higher temperatures, the pores, which are initiated by the run-off of brine, are either filled with spray or the brine stays trapped in these pores as a result of the moister surface. In general, more brine is trapped in ice pores on horizontal surfaces. On vertical surfaces, more unfilled pores, benefited by the faster drainage of brine, has been observed. These empty pores are later filled up with air, which finally leads to a higher porosity on vertical surfaces than on horizontal surfaces under more dry conditions (*Ryerson and Gow, 2000*).

6. Environmental factors of icing

The environmental conditions affecting the process of sea spray icing are numerous and have to interoperate to let icing occur. The most important environmental prerequisites are the wind speed and its relative direction, the water temperature and the freezing point of sea water, the air temperature and the characteristics of the wave spectrum, e.g. height, period and direction of propagation (*Guest, 2005*). In the following paragraphs the main factors will be described.

6.1 Air temperature

One of the most important conditions to let icing occur, apart from the occurrence of water deposition on the substrate, is a sufficiently low temperature on the freezing surface, especially for the heat dissipation away from the substrate by convection and the cooling by droplets of the deposition surface (*Minsk, 1980*).

For the freezing process of the sea spray itself, the air temperature has to be below the freezing temperature of the water, which forms the droplets. This varies with the salinity of the sea water, whereas the freezing temperature of ocean water with a salt content from 30 to 35 ‰ ranges around -1.8 °C. For instance, due to its lower salinity, the freezing temperature of the Baltic Sea is little below 0 °C (Lundqvist, 1977). At the very beginning of investigations on ice accretion on ships due to sea spray, it has been stated, that icing only occurs within a limited range, marked by an upper and lower limit of temperature. It has been assumed that sea spray, which is exposed to temperatures lower than -18 °C, impinges on the vessels surface in form of small, dry ice crystals (*Shellard, 1974*). These are less dangerous because they do not adhere to the surface, like liquid supercooled drops after their impingement on wind-chilled surfaces would do. During researches on board of Japanese Patrol vessels, light icing has been observed at -1 °C, presupposes a sufficiently strong wind (*Shellard, 1974*). *Shekhtman (1968)* was the first who turns out that -18 °C cannot be assumed as the lowest temperature for icing to occur. In January 1965, where, presumably due to ice accretion, eleven ships got lost during one day in the Bering Sea, the temperature ranged around -23 °C. Later on icing incidents at -29 °C have been observed.

Table 2 Percentage frequency as a result of air temperature (ref.: *Shekhtman, 1968)*

Icing intensity	Air temperature range [°C]				Average temperature [°C]	Number of cases
	+1 to -5	-6 to -13	-14 to -21	-22 and below		
Fast growth	**6**	**52**	**34**	**8**	**-13.3**	**50**
Slow growth	**21**	**70**	**9**	**< 1**	**-8.9**	**302**
No change	**24**	**60**	**16**		**-9.4**	**55**
All cases	**19**	**67**	**13**	**1**	**-9.5**	**407**

The values observed by *Shekhtman* are summarized in *Table 2,* show that at the lower temperatures from +1 to -5 °C fast growing icing occurs rarely. Most ice accretion appears between temperatures from -6 to -13 °C. At this range all three zones of icing intensity (fast growth, slow growth and no change) are most frequent.

Borisenkov and Panov (1972) found icing to be intensified at temperatures below -18 °C leading to a catastrophic amount of ice accumulation within a short of time (*Shellard, 1974*).

This leads to the assumption, that air temperature is one of the most important factors in ice accretion and accretion rates increase with a decreasing temperature over the entire range of sub-freezing temperatures (*Shellard,1974*). The meteorological conditions, especially the combination of low air temperatures and strong winds, benefiting ice accretion, are often observed at the rear of depressions and on the poleward side of the low-pressure system (see *Figure 16*).

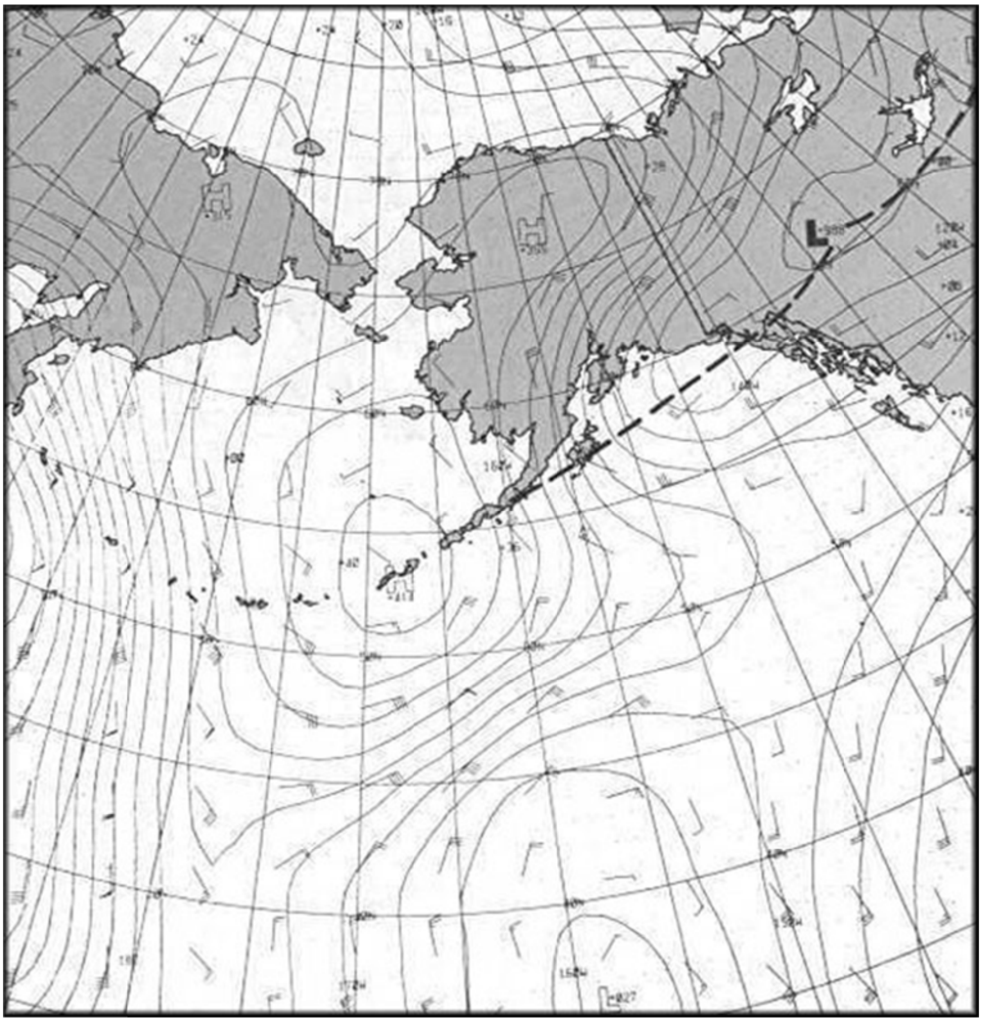

Figure 16 Polar Low in the Northern Pacific as a condition for icing (*P.Guest, 2005)*

Here the zone of the heaviest icing is not right behind the cold front. With some distance to the front, the temperature reaches the lowest values and more steady winds lead to a more developed wave field (*Sukhanov et al., 2006*). Having a look at the annual distribution of icing incidents it has to be stated, that icing is most likely to occur between November and April at the Northern Hemisphere (*DeAngelis, 1974*). Sea spray icing is enhanced during snow fall and in interaction with sea smoke. Because air masses are warmed up by passing warm water areas, the coldest air occurs above cold land masses or ice. Most icing incidents (see *Figure 17* and *Figure 18*) are observed within a belt of 2.7 to 108 nautical miles (5 to 200 km), from the ice edge or land mass, when the wind origins above land masses or ice covered areas (*Kotsch, 1977*). The wind is still cold enough without being warmed by warmer sea surface temperatures. It has to be stated, that even for severe icing the water droplets do not have to be in a supercooled state to accrue on the surface.

Another benefiting effect of low air temperatures on the ice accumulation on the ships is the influence of the temperature on the ships steel. If a ship is exposed to low air temperatures and wind for a longer time, its hull is cooled down due to the windchill and cold soaking. Thus, minor heat has to be transferred through thermodynamic processes before the accumulation of ice can take place.

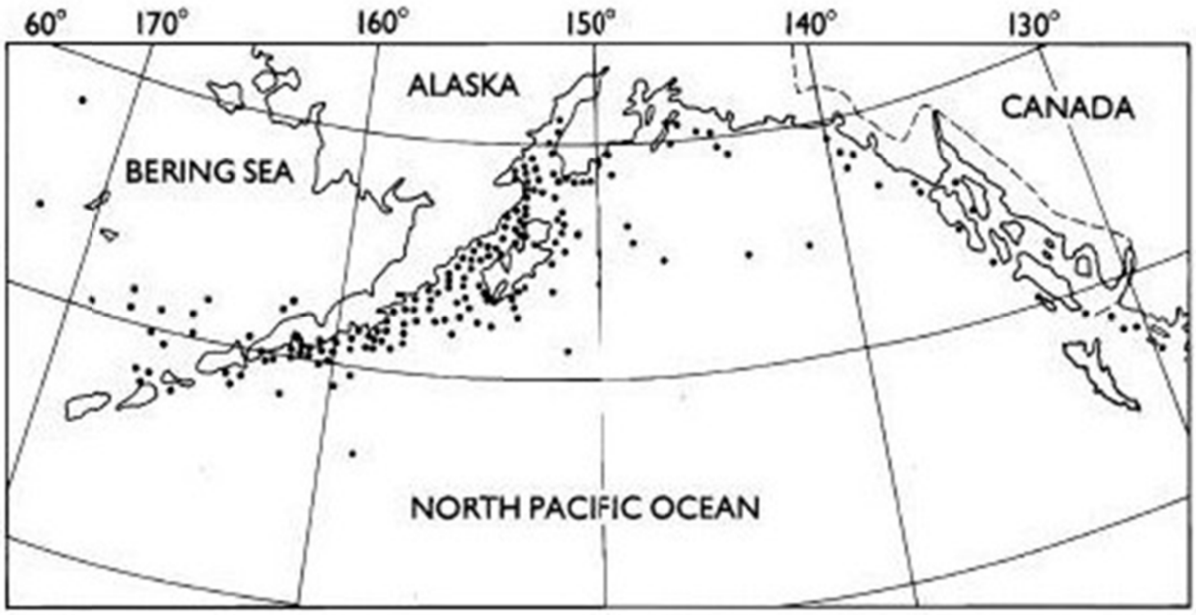

Figure 17 Icing events in Alaskan waters in the period December 1979 to December 1984 (*Pease and Comiskey, 1985*)

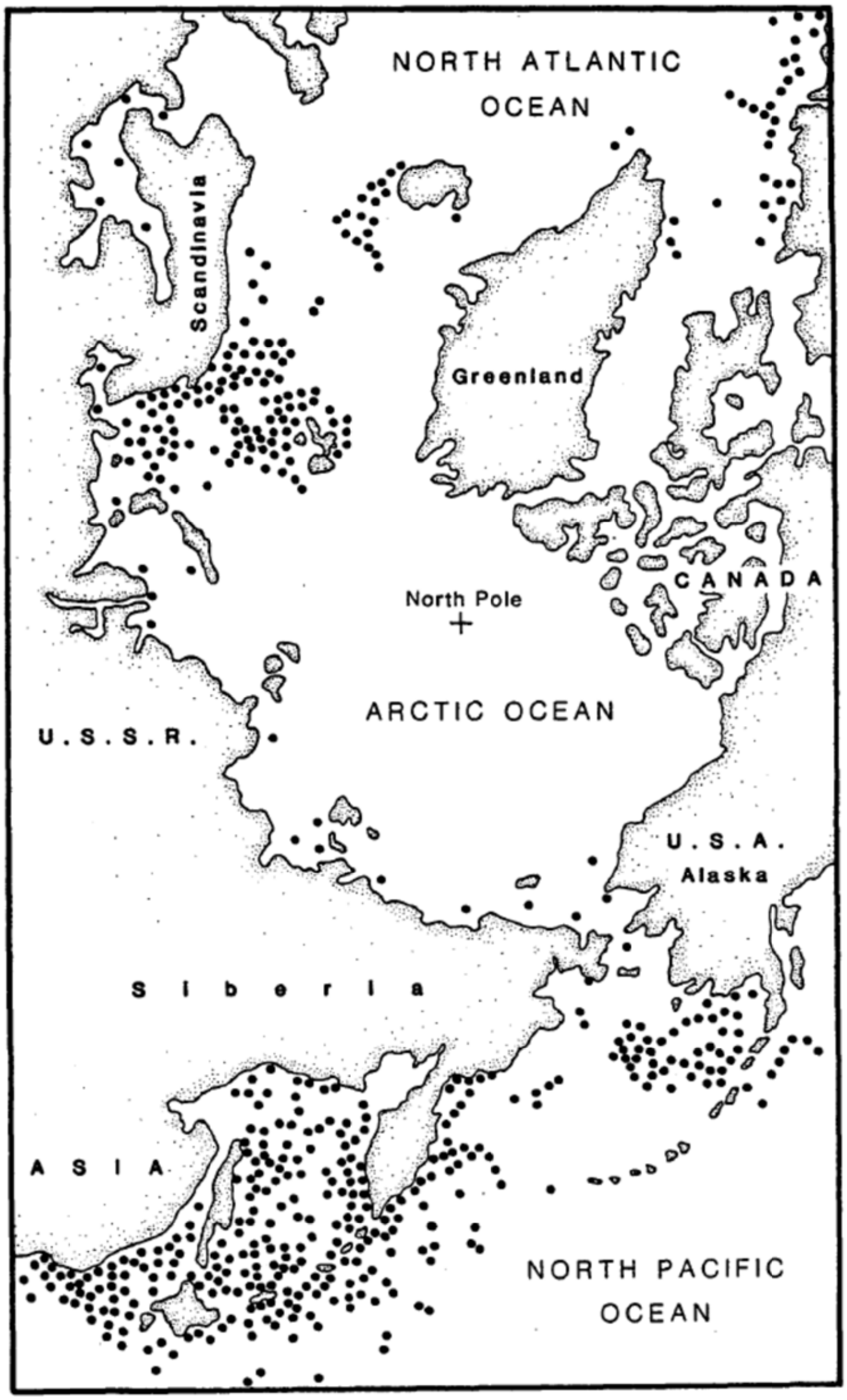

Figure 18 Regions of icing observations (*Panov, 1978; redrafted by ARCTEC Engineering, Inc.*)

6.2 Wind speed

Wind plays an important role in the process of ice accretion, its velocity as well as its relative direction. Prevailing winds, more precise the relative wind as a function of the true winds and the airstream, initiated by the vessels motion, is the main source carrying the spray droplets from the waves crests or the bow spray onto the vessels surfaces.

The amount of ship generated spray depends on the sea state, the speed and heading of the ship in relation to the wave field and certain ship characteristics (*Shellard, 1974*), like length, freeboard and bow shape. Most of the created spray droplets will reach the ships superstructure when the vessel is heading directly into the wind, so that the true wind and the airflow by the ships motion are superimposed (*Tabata et al., 1963*). Contrary to these results *Kultashev et al*. stated that spraying on trawlers is heaviest, when the winds and seas approach from an angle of 30 to 40° off the bow (*Kultashev et al., 1972*). A dangerously asymmetric icing is favored by winds from abeam, where the leeward side of the ship is obviously less affected by ice accumulation than the windward part of the ship (*Ryerson, 2008*).

The influence of the wind speed on the behavior of the vessel in the present wave field depends a lot on its characteristics. Smaller vessels may be more affected by spray icing at lower wind speeds starting from Beaufort four, heading into cross seas with a higher steepness. Contrary larger vessels steaming with low speed with the propagation of the waves spray deposition become apparent from Beaufort force seven to eight appears (*Shellard, 1974*). Obtaining a wind force of six Beaufort (22 to 27 kn) that comes along with waves heights of around three meters, and assuming a sufficient fetch and duration of wind, most small vessels heading into the waves are splashed with sea spray (Minsk, 1980). These values are proved by *Zakrzewski*, who notes 10 ms^{-1} (19,4 kn) as a threshold limit for ice accretion due to sea spray (*Zakrzewski, 1987*). Investigations on ice accretion, carried out in wind tunnels, have shown that the icing intensity intensifies steadily with an increasing wind velocity (*Tabata, 1966*).

Measurements on board of Russian medium sized fishing vessel indicate (*Jørgensen, 1982*) that the icing intensity increases with an increasing wind speed.

This corresponds with the reports of *Shekhtman (1968)* and *Tabata (1966)*, obtained in wind tunnels. In *Table 3* the icing intensity related to wind velocities is summarized.

Table 3 Icing intensity related to wind velocity (*Shekhtman, 1968)*

Icing intensity	Wind speed [kn]					Average speed [kn]	Number of cases
	0 to 2	3 to 10	11 to 20	21 to 29	30 >		
Fast growth	2	4	12	42	40	29	15
Slow growth	1	8	29	43	19	23	303
No change	2	22	39	24	13	17	54

A wind force of five to six Beaufort was found to be the most common lower limit for icing to occur, assuming a sufficiently low temperature. Meeting the requirements of an approximate prediction of icing intensities with respective air and water temperatures and different wind forces, *Mertins (1967)* developed icing prediction diagrams, which are suitable to highlight the relevant role of the wind velocity as shown in *Figure 19*.

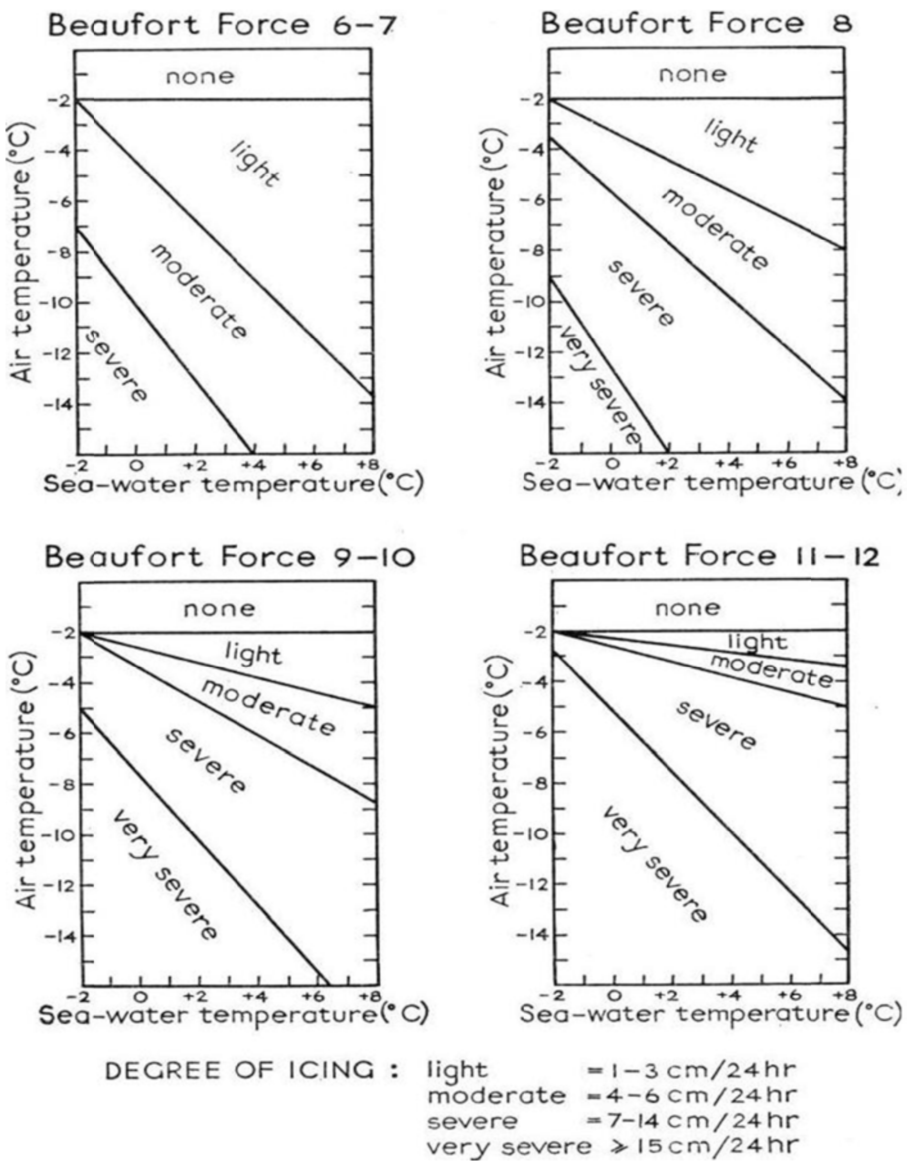

Figure 19 Prediction diagrams as a function of the wind force, air and water temperatures (*Mertins, 1967*)

The degree of icing is divided into five classes, ranging from no icing (class 1) to very severe icing (class 5). Assuming constant conditions of sea surface and air temperature the magnitude of icing increases rapidly with an increasing wind force. The diagrams of *Mertins* do not take into account the vessels characteristics nor more specialized information about salinity or the sea state are taken into consideration. This prediction procedure is acceptable for slow steaming vessels operating in regions where the freezing temperature of the sea water is around -1.8 °C. The application of these diagrams for a prediction at less saline waters would lead to remarkable discrepancies. A minor salt content benefits the formation of ice. For instance, in less saline seas like the Baltic Sea, icing occurs at higher temperatures and lower winds than indicated by the diagrams of Mertins *(Shellard, 1974).* Another fact which has to be considered regarding the winds is their origin. Most spray icing incidents at the Canadian east coast have been observed when strong winter storms gathered with northwesterly winds from cold arctic regions over the Gulf of St. Lawrence, which typically came along with temperatures of around -10 °C, a wind speed of 30 kn and a wave height of 2 to 3 m waves. Under these conditions, the potential of icing is mostly limited by the short fetch and the appearance of ice coverage in this region, which hampers the wave field to intensify (*Canadian Coast Guard, 1999*). For a simplified use, *Wise and Comiskey (1980)* changed the 4 diagrams of Mertins into one, based on the same values of observation (see *Figure 20*).

From the thermodynamic point of view, the wind speed and the air temperature lead the heat flux away from the vessels surface, which means that the higher the wind velocity and the lower the air temperature, the more heat will be lead away from the substrate (*Overland, 1990*). Under a sufficient mass flux this is leads to a higher ice accumulation.

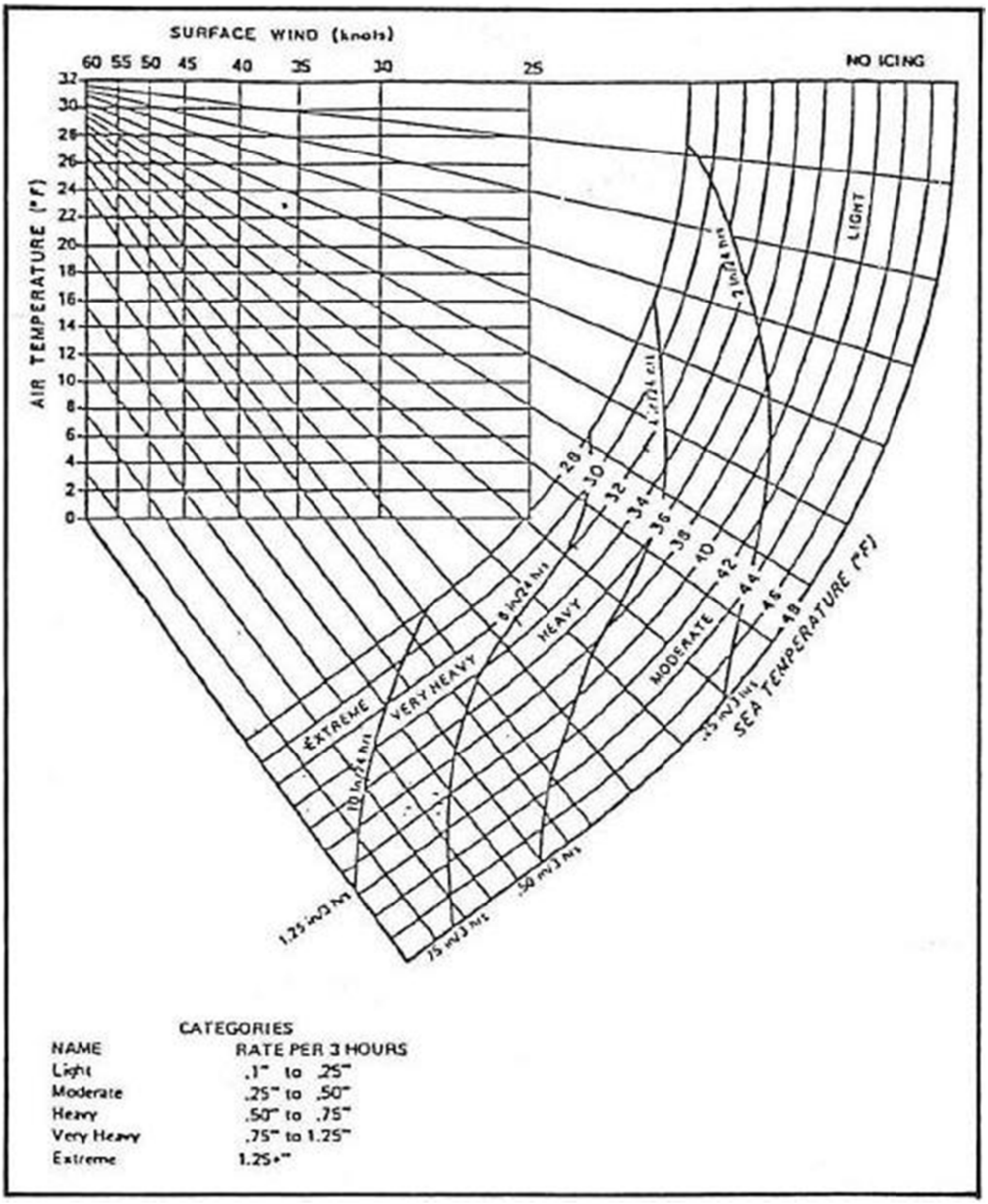

Figure 20 Icing prediction nomogram (*after Wise and Comisky, 1980*)

6.3 Sea surface temperature (SST)

The evaluation from icing incidents, collected by the *Swedish Meteorological and Hydrological Institute* (SMHI), shows that severe icing prevalently occurs at a sea surface temperature (SST) below 2 °C and moderate icing mainly below 4 °C, whereas at SST above 6 °C rarely any icing occurs as shown in *Figure 21*, (*Lundqvist, 1977*). A sea surface temperature of 8 °C is assumed to be the threshold limit to let ice accretion occur (*Shellard, 1974*). Thus, a clear tendency of icing with decreasing sea surface temperatures is visible. The influence of the sea surface temperature is less important on the process of ice accretion, when the velocity of the wind is sufficiently high along with air temperatures below -5 °C, (*Jørgensen, 1982*).

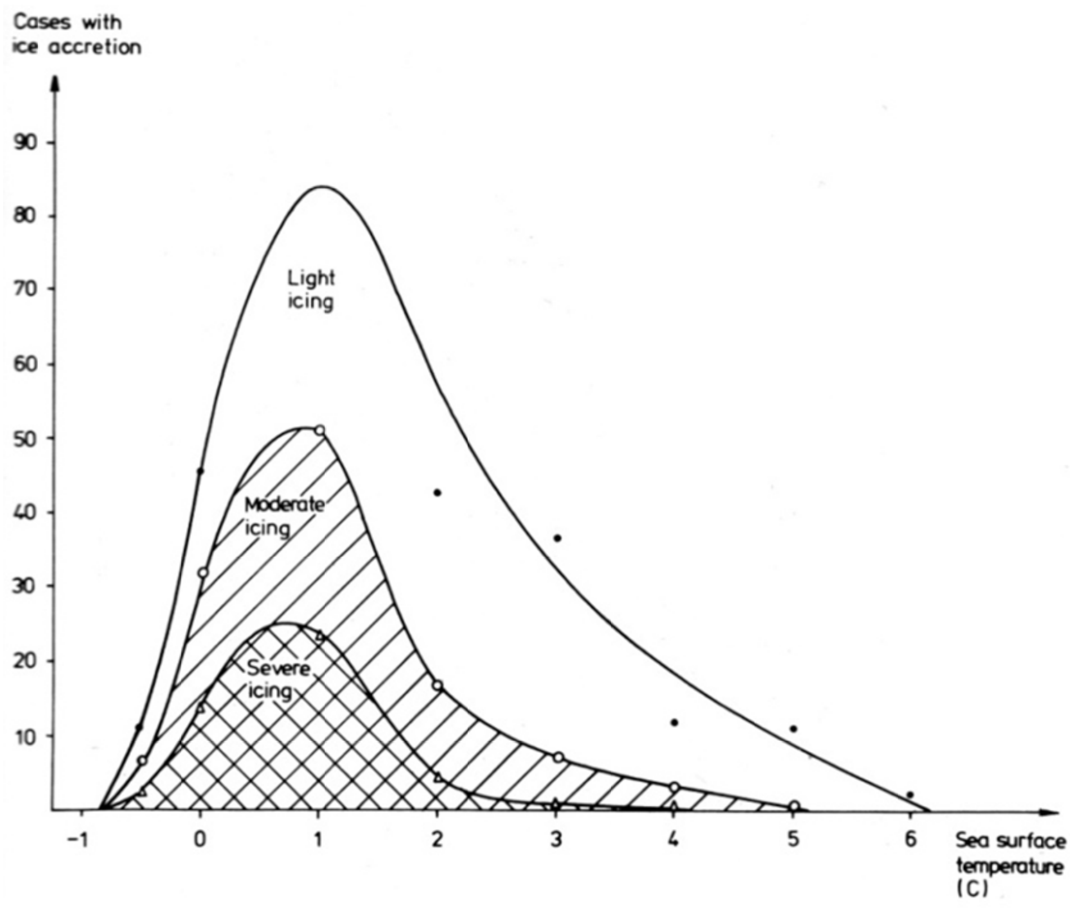

Figure 21 Severity of ice accretion under prevailing SST (*Lundqvist et al., 1977)*

Lower water temperatures favor the accretion process. However, compared to the air temperature and the wind velocity the water temperature plays a minor important role to the intensity of icing (*Shellard, 1974*). During observation of icing on medium-sized fishing vessels, all three icing intensities (severe and light ice accretion and no change of the icing state) have been observed in a range of temperatures from below 0 °C to 6 °C.

Heavy icing has occurred at relatively high sea temperatures above 4 °C. With these measurements, the average temperature in all three categories has been ranged from 1.8 °C for slow growth, to 2.1 °C for no change, what obviously proves the minor affecting role of the SST (*Shekhtman, 1968*).

The limited influence of the sea temperature is assumed with its influence on the temperature of the originating droplets.

The lower the initial temperature during their development is, the more rapidly they are cooled down to or below the air temperature during their flight from the sea surface to the deposition surface on the vessel.

From the thermodynamic point of view, this results in a higher heat removal from the substrate, when the impingement temperature is lower, benefiting a higher accretion rate.

Conversely, a spray temperature above the freezing point of the saline water hinders the ice accretion process due to a minor amount of sensible heat which is removed from the icing surface. The threshold value for the SST varies with the prevailing wind speeds (*Zakrzewski et al., 1988*).

An indirect factor of the sea surface temperature is its influence on large cold air masses. A warmer SST heat up these air masses as they pass over the water. Droplets on its trajectory to the surface of the vessel are less cooled down flying through warmer air than droplets in colder air temperatures (*Shellard, 1974*).

Regarding the formation of wind generated sea spray it can be stated, that colder water has a reduced disposition to the appearance of whitecaps due to the higher viscosity. Under equal meteorological assumptions, warmer water is less efficient in dissipating the energy transferred by the wind, resulting in a higher amount of breaking waves and thus in an increasing number of whitecaps (*Jones and Andreas, 2009*). The accretion of freezing spray is intensively limited when the ice coverage exceeds 50 to 60 % of the total water surface (*Canadian Coast Guard, 1999*) due to the limited spray formation.

6.4 Salinity of sea water

The salinity of the freezing spray influences the freezing temperature of the sea water. This becomes most obvious comparing the freezing point of less saline water, for instance from the Baltic Sea whose salinity ranges from 1 to 2 ‰ in the most northern Bothnian Bay to 20 ‰ in the Kattegat (*Helsinki Commission (n.d.)*), neglecting seasonal fluctuations, with ocean water from the Pacific or Atlantic ocean, where the saline content is about 30 to 35 ‰ (*Kultashev et al., 1972*). As a consequence of the differences in salinity, ice accretion on deck at the minor saline Baltic Sea is observed at air temperatures from -0.5 to -1.4 °C. Compared to more saline ocean sea water, for example from the Barents and Japan Seas, which starts freezing at lower temperatures from -1.4 to -2.2 °C (*Kultashev et al., 1972*). For the prediction of the icing potential assuming an average freezing temperature of -1.8 °C for these areas f is sufficiently precise.

Another fact which has to be taken into consideration is the influence of the difference of salinity on the properties of the accrued ice, especially on its porosity. The formed brine affects the hardness and the adhesion of the accreted ice. This characteristics decrease with an increasing salinity and porosity (*Shellard, 1974*). The so called “spongy ice” has a lower density in contrast to fresh-water ice (*Overland, 1990*), initiated by the entrapments. Compared to the process of atmospheric icing, sea spray droplets cannot sustain the same degree of super cooling during its trajectory to the surface of deposition due to its salinity. Droplets are solidified before the deposition on the substrate at temperatures lower than -29 °C. This temperature is still higher compared to fresh water droplets, which are observed in a supercooled state with temperatures up to -40 °C, if no crystallization nuclei are present to adhere.

6.5 Sea waves

As well as the above mentioned environmental assumptions also the characteristic of the wave field plays a role for the accretion of ice, especially for the spray generation due to the behavior of the vessel in waves (see *Figure 22*). Assuming a constant ship speed, an increasing wave length leads to a higher period of encounter T_E. Thus the angle of pitch, which is a function of the vessels natural pitching period and the period of encounter, is influenced. The angle increases when the period of encounter T_E is equalized to the pitching period of the vessel T_P. This behavior of the ship reaches its maximum due to the limitation of the vessels motion by the resistance of the hull on the water, which mostly depends on the shape of the load water plane (*Kent, 1958*). Due to the pitching behavior of the vessel there is a certain wave length for each ship length which affects the vessel to increase the rotating motion about the horizontal transverse axis.

Figure 22 Vessel encounters a breaking wave

Assuming a constant wave length, the wave height also influences the pitching motion of the vessel. The angle of pitch increases with an increasing wave height as a consequence of the intensified vertical motion (*Kent, 1958*). As well as the more developed motion of the vessel through the waves and the hence intensified vertical motion, which comes along with an increasing spray generation, the vessel gets more affected by wind generated spray, due to the increasing amount of film and jet droplets, initiated by the breaking waves. Assuming wave heights of 1.5 m to 2.5 m, vessels start to generate a significant amount of spray (*Minsk, 1980*), which, at smaller vessels, can affect the entire length of the ship with spray droplet deposition. Wave heights of 2.5 m are corresponding with a wind speed of 10 ms^{-1} for 10 hours (*Overland et al., 1986*). This value depends on the stability and construction characteristics of the ship. Within cross seas, the generation of spray is benefitted by the different propagation and superposition of the waves. Whereas the coverage of the sea surface in ice conditions from 5/10 to 6/10 ice coverage obviously hampers the spray generation (*Zakrzewski et al., 1988*).

7. Vessel characteristics

The potential of icing due to sea spray is regulated by the heat and mass fluxes which occur at the surface of ice accretion. The mass flux of the freezing system is dominated by the ability of the vessel to take over spray on board, assuming meteorological conditions which are benefiting icing, which depend on the characteristics of the constructional and maneuvering properties of the ship.

7.1 Ship length

The relation between the wave lengths and heights in contrast to the ship length plays an important role on the behavior of the vessel in the sea state and thus the amount of generated and overtaken spray (*Overland, 1990*).

Due to their greater length, larger vessels are less likely affected by the encounter of a wave crest, which results in a damped relative motion of the ship in contrast to the wave spectrum leading to a less frequent spray generation (*Ryerson, 1995*).

Focusing on the effect of wave length in relation to the conduct of the vessel in the wave field, it can be stated that under a constant ship speed, the period of encounter increases with an increasing wave length. Hereby the natural pitching period of the vessel, which depends on the ship length, has to be considered (*Kaps, 2006*). When the period of encounter thus is equalized to the pitching period of the vessel, it tends to heavier pitching motions, so called slamming, including an improvement of sea spray generation.

The worst slamming appears, when the natural pitching period of the vessel T_p is superimposed by the period of encounter T_E. At this point the lever of the pitching moment reaches a maximum, when the ship´s speed and specific wave length meet a certain period of encounter (*Kent, 1958*). The thus generated resonance expresses itself by rough slamming of the ships head and aft. The higher the vertical motion of a vessel in a given wave field, the more sea spray appears (*Overland, 1990*). Spray clouds are more likely to cover entire small ships whereas larger ships are covered only partly (*Ryerson, 2000*). As a result of the Pease and Comiskey dataset (1985) of vessel icing in Alaskan waters, it becomes obvious that the number of icing incidents decreases with an increasing ship length (*Pease & Comiskey, 1985*).

Based on the observations by *Brower et al. (1977)*, *Overland (1990)* has developed an overview of reference values (see *Table 4*) for wind speed threshold limits for various ship lengths, underlying the assumption that precipitation of water on deck of all freeboards occurs upon a ratio of significant wave height to ship length of $h_{1/3}$ / L= 0.04. Exceeding this threshold limit of 0.04, the expected wetness on deck depends mostly to the forward speed of the vessel (*Overland, 1990*).

Table 4 Calculated threshold wind speeds for icing for various ship lengths *(Overland, 1990)*

Parameter						
Vessel length [meters]	**15**	**30**	**50**	**75**	**100**	**150**
Signicant wave height $h_{1/3}$ [meters]	**0.6**	**1.2**	**2.0**	**3.0**	**4.0**	**6.0**
Wind speed at 200 km fetch length [meters per second]	**5.0**	**7.4**	**9.8**	**12.5**	**15.0**	**20.0**
Wind speed at 200 km fetch length [knots]	**9.7**	**14.4**	**19.0**	**24.3**	**29.3**	**38.9**

These found threshold values do not include the vessels individual seakeeping behavior or speed, but it becomes obvious that smaller vessels are more likely affected by icing at lower significant wave heights than larger vessels.

7.2 Ship speed

As already stated the vessels natural pitching period is mainly affected by the length of the ship. As well as the length, also the speed affects the behavior of the vessel on the sea state. Assuming a steadily wave period, a change in the ships speed influences the period of encounter T_E, which is a function of the ships heading, and the propagation direction of the waves and their period. Steaming against the waves decreases the period of encounter. Under a large difference from the natural pitching period T_p of the ship to the period of encounter, the ship tends to pitch on her own T_P, which leads to smaller pitching angles (*Kent, 1958*). Dependent on the wave period an acceleration of the vessel can lead to less heavy pitching motions, when the natural pitching period before the acceleration is greater than the period of encounter (*Overland, 1990*). Field studies carried out on board of Japanese patrol vessels, to observe the rate and distribution of accreted ice. These have been recorded while steaming into the waves with different headings and speeds. These observations have shown that heading into the waves with a constant angle of 30° above the bow, the icing intensity decreases perceptibly with reduced speed as shown in *Figure 23* (*Tabata, 1969*). A reduction of speed from 12.5 kn to 10.7 kn implicates a to ten times smaller accretion of ice as a result of the fewer amount of deposited water on the ship.

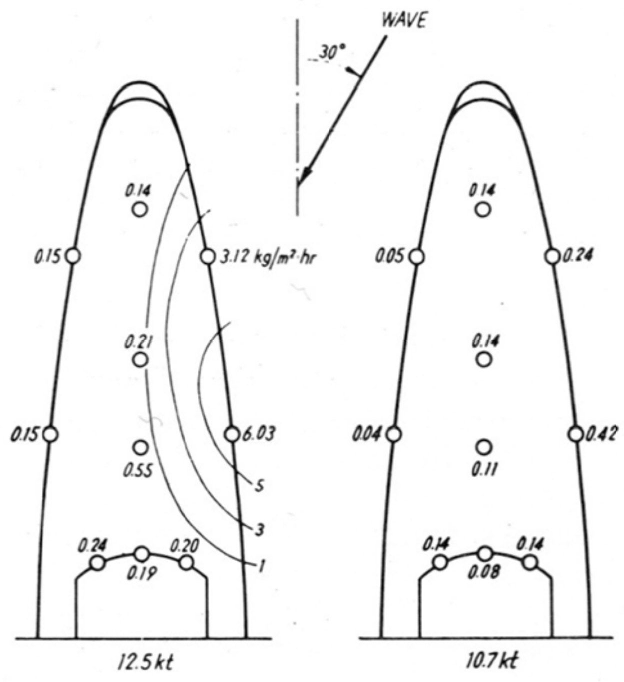

Figure 23 Distribution of icing as a function of heading and speed, including lines of approximate equal accretion rates (*Tabata, 1969)*

Observations on soviet fishing vessels by Panov, Kultashev, Moltjanov et al. (1972) show, that the most intensive spray generation and thus sea spray icing potential occurs at larger angles between heading of the ship and the wave field when the speed increases (see Figure 16). Ice accretion due to sea spray is rarely observed at a vertical extend larger than 16 m above the water surface, except on high speed crafts, where this limit is exceeded due to the high speed steaming of the vessel through the waves (*Minsk, 1980*).

Although the acceleration of speed could minimize the resonance behavior of the vessel, the relative motion between the hull and the waves increases which leads to more dynamic pressurized area around the bow. This high pressure is the reason for the acceleration of water along the hull, which initiates sea spray generation

(*Saunders, 1957*). Having a closer look on the prediction of icing potential, the ships speed as well as the heading has to be considered in determining the relative wind direction and speed affecting the appearance and deposit of the water droplets on the ship (*Stallabrass, 1980*).

7.3 Ship heading

The ships course relative to the propagation of the sea waves plays a significant role in spray generation and herewith establishes the basis of sea spray icing. Field studies on board of Japanese patrol vessels, which had been equipped with icing gauges, distributed about the fore deck, were been carried out to evaluate the icing intensity. During the test phase the patrol ships were steaming against the waves in different angles and various speeds. Results generated from this analyses show, that a smaller icing intensity was documented when the ship headed the waves instead of steaming with an angle between 30° to 60° into the waves (*Tabata, 1969*).
This assumption was confirmed by Soviet observations, which showed that the most intense ice accretion on fishing vessel occurred, when the angle between heading of the ship and the prevailing waves was 30 to 40° (see *Figure 24*), (*Panov et al., 1972*).

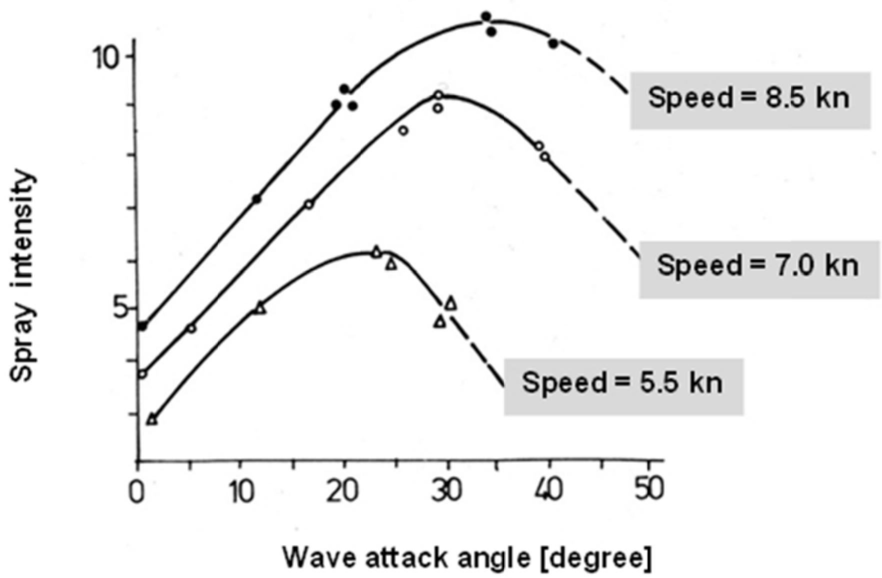

Figure 24 Relation between the intensity of spray and wave attack angle towards the ship and ship speed (after *Lundqvist, 1977)*

This proves that with a lower speed the most spray appears at smaller angles between heading and wave course. A faster vessel reaches the spray maximum and thus the highest mass flux to the superstructure, steaming with higher angles into the waves.

Ice appearance, which is limited to a single side of the ship, poses a higher risk due to the hence generated heeling moment compared to the same mass distributed all over the vessel. On vessels heading downwind, a significant decrease of ice accumulation was observed, even at the stern of the vessels (*Overland et al., 1986*).

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7.4 Bow shape

The form of the hull which is exposed to the water surface influences the sea spray generation during the interaction between the vessel and the waves. Researches on different bow variants and their spray generation behavior have shown, that with an increasing angle at the stem the increased degree of the flare leads to a higher acceleration of the spray away from the hull. The blunt form leads to a more outboard displace of the droplets which results in a minor amount of water which is affected by the prevailing wind and later deposits on the substrate under head wind conditions (*Sapone, 1990*). Next to the amount, the extent of water to the aft has been limited with an increasing flare angle.

Another fact which becomes obvious is, that with an increasing acceleration the amount of smaller droplets grows. These droplets affect the whole ship with a film of water. Compared to larger droplets the amount of deposited water is smaller, because a part of the droplets are brought over the deck without deposition (*Sapone, 1990*).

Apart from the form, also the placement of fixtures assigns the flow around the hull and thus the generation of spray roots. The introduction of a larger and smoother-formed bow variant by *Ulstein*, the so called X-Bow®, achieves a better motion of the bow through the water. This leads, in addition to a more energy-efficient motion in waves, the elimination of slamming and bow impact, also to an obvious reduction of spray generation (*Ulstein, 2011*).

Due to the optimized water flow around the bow a minor amount of spray develops (see *Figure 25*). This leads to decreasing fuel consumption and a minor potential of ice accretion as a consequence of the minor spray deposition on the deck.

Figure 25 Spray generation of different bow types: Ulstein X-Bow® (*left*) compared to a conventional formed bow (*right*)

7.5 Freeboard

Besides the above mentioned characteristics like heading or speed, there is a non-negligible influence of the ship construction properties and handling. Smaller vessels are also more affected by ice accretion due to their smaller freeboard. Thus a higher amount of droplets deposit on board after the spray event has taken place (*Sechrist, et al.,1989*). Ships with a larger freeboard and bow flare are more likely to reflect the spray, which minimizes the spray flux the deck and the superstructure (*Sapone,* *1990*). For vessels heading directly into the waves there is a threshold limit of $h_{1/3}$ / L = 0.04, at which spray deposition on deck and superstructure is found (*Price & Bishop, 1974,* see *Figure 26*). Additionally the ship speed plays an important role, the faster the ship is underway in a given sea state, the more frequent it will be splashed with spray at a certain freeboard-length ratio.

Assuming that a ship acts hydrostatically to waves which are determined by the significant wave height ($h_{1/3}$), the responds of the vessel can be described by its Froude number F_n. This non-dimensional value for the ship speed can be used to determine a threshold limit for a given Froude number F_n to prevent overcoming water in more than 1 of 20 waves (*Overland, 1990*).

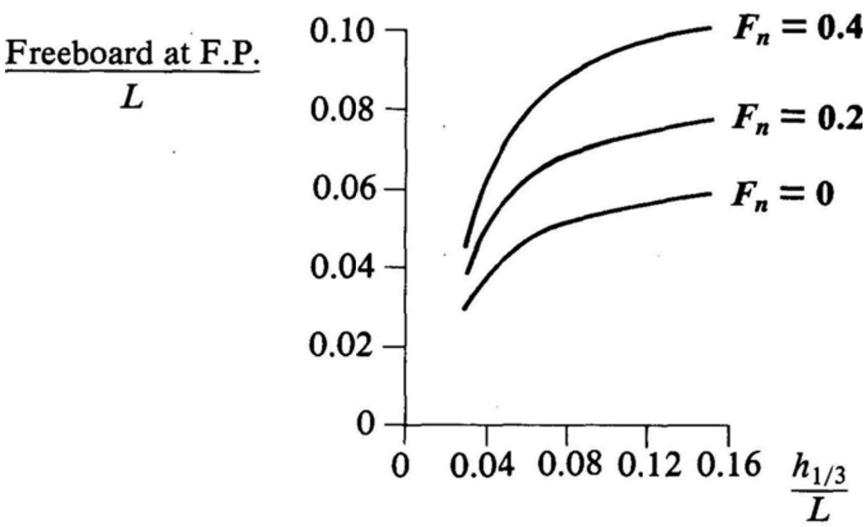


Figure 26 Diagram of non-dimensional limit values of forward speed (*Price & Bishop, 1974)*

Another fact which has to be taken into consideration is the residence time of the water at the ship. The faster the water leaves the superstructure before it freezes, the smaller is the amount of accrued ice. This depends most on the construction of the decks and the arrangement of scuppers. It has to be considered that water draining the deck through the scuppers or over the bulwark, so called deck spray, is creating a secondary source of spray, like a spume fountain.

8. Effects of ice accretion

The accretion of ice on the ships decks and superstructure has various effects. These have to be taken into consideration while operating in areas where the potential of icing is given. In the following chapter the influences of ice accretion on several parts of the ship is constituted.

8.1 Stability and trim

Hazard can result from almost all types of maritime structural icing and the associated dangers by ice accretion particularly on small vessels is great and have resulted over years in significant damage of ships and loss of life. Ice accretion causes an increase in the weight of a vessel and a decrease of freeboard (*Jessup, 1985*). *Shellard* (1974) reported 81 vessels lost due to severe icing in the period 1942 to 1970.

Also the centre of gravity (CoG) can be raised and leads to reduced ship stability. These factors combined with high wind forces and rolling moment can cause a serious heeling angle and can eventually cause the ship to capsize.

Ice accretion also occurs on floating and stationary offshore structures like exploration and production rigs and platforms. The hazards produced on these structures are not as serious as those for small vessels. Nevertheless they can produce a substantial threat to human safety as well as considerable inconveniences for the crew complement (*Jessup, 1985*).

The amount of accreted ice can reach massive dimensions, exceeding hundreds of tons within a few hours. With an increasing weight of formed ice the ship's freeboard reduces, which leads to an increasing draft. Thus the vertical centre of gravity *G* is shifted upwards, closer towards the metacentre *M*. Assuming an uneven distribution of the ice load, *G* moves to the side with the higher weight accumulation. This is often the wind affected part of the ship (*Clark, 2008*). The reduction of the range of dynamic stability is a consequence of the increasing draft and thus results in a minor distance between the centre of gravity *G* and the keel *K.*

In *Figure 27* the influence of ice accretion on the positive stability curve (GZ curve) is illustrated.

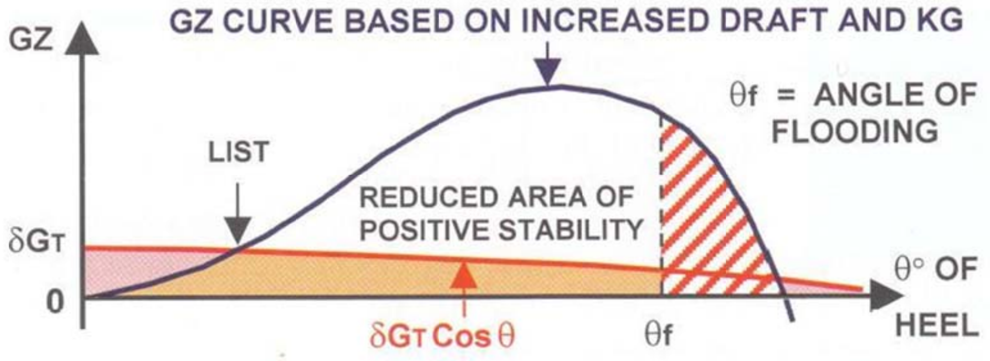


Figure 27 GZ curve under the influence of ice accretion (*Clark, 2008*)

The positive stability curve (*GZ curve*) is reduced in area and range due to the increasing *KG* value and the thus resulting shifted centre of gravity. If the rising centre of gravity *G* exceeds the metacentre *M*, the intact stability, above shown as a graph over the angle of heeling, achieves negative value. This leads to an unstable condition of the ship, which may results in capsizing.

In contrast to the transversal stability, the longitudinal stability is preferable affected by ice accretion at the parts around the bow (*Meteorological Service of Canada, 2002*). As a result of the additional added mass the longitudinal centre of gravity is shifted towards the additional weight. Thus a lever between the centre of buoyancy B and the centre of gravity G develops, which forms a trimming moment towards the added ice.

As a consequence of the accreted ice the sail area increases, which results in a greater influence of the heeling moment due to the wind load (*DeAngelis, 1974*). Especially smaller vessels are affected by the additional weight. Every year ships including their crew get lost due to capsizing after an enormous amount of ice has been accreted.

The substructure, for instance frames, plating and stringers of the deck, should usually not be affected by the ice load. Observations have been made that ice deposition, which become too heavy, start to detach. This endangers the decks structure, especially on tankers and ships with great plain deck areas. Thus the design load of the deck exceeds, causing damage on the plating and structure. Impinging ice poses a higher risk to members of the crew, who operate on deck. Also smaller parts of detached ice can lead to hazardous injuries.

Examples of icing are illustrated in *Figure 28* to *Figure 32.*

Figure 28 Severe icing conditions (source: *Canadian Coast Guard*)

Figure 29 Ice build-up on forecastle (source: *Canadian Coast Guard*)

Figure 30 Crew removing ice from bulwarks (source: *Canadian Coast Guard*)

Figure 31 Severe ice build-up on the forecastle of Russian icebreaker "*Kapitan Dranitsyn*" during voyage in Ob Bay (Russia)

Figure 32 Sea spray icing on a container vessel (source: *Canadian Coast Guard)*

8.2 Deck equipment and cargo

Even smaller amounts of ice restrict the handling of the equipment and the cargo. The deck equipment is locked with ice and thus is not fully operational or accessible to the crew. Ice, which has deposited at the deck, hampers a safe movement of the crew by slippery decks and handrails, locks hatch covers, winches and valves. This influences a safe ship operation (*Kubat & Timco, 2005*). Low temperatures affect fluids, like lubricants and hydraulic oils, which are contained in winches, cranes and davits. These fluids can be frozen or more viscous and thus the equipment is set out of order. Ice accretion on deck also affects the cargo operation. Frozen lashings, ice-covered container fittings, corner castings or inaccessible manifolds hamper the cargo operation (*Sutherby, 1951*). This leads to longer port stays and expansive delays. Icing on anchor windlass is shown in *Figure 33.*

Figure 33 Icing on anchor windlass on board of NOAA ship “*Oscar Dyson” (left)* and Russian icebreaker *“Kapitan Dranitsyn” (right).*

8.3 Watch keeping

At sea accrued ice hampers the steerability, reduces the visibility at the bridge due to frozen windows and the speed due to a hampered maneuverability (*DeAngelis, 1974*). Thus it also affects the navigational watch keeping, which distends to another effect that has to be taken into account. The influence of ice accumulation on communication, signal and ship handling equipment, such as VHF- and radar antennas, tyfon and signal lights can cause severe impairments.

8.4 Safety systems

The ice accretion on safety and firefighting equipment is of particular relevance for the survival in case of emergency. Ice blocked fire mains, nozzles and valves are non-operational, hampering an immediate action in case of fire on board. Rescue boat davits can be locked by ice impeding a safe launch, life rafts are frozen up at their mountings, ice can lock entries to further safety equipment and stores. Escape routes are not accessible and ventilation heads of tanks, where ventilation is required, are closed. Whereas ventilation flaps, which should be able to close, for example the ventilation before CO_2 is released, are not workable. Thus an efficient use of firefighting equipment is impossible.

8.5 Prediction of ice accretion

The accumulation of ice constitutes a high danger to all kinds of shipping in cold climate seas. Thus a precise forecast can contribute to a more efficient operation of the ship and safe lives. But the prediction of vessel icing turned out as a significant difficulty, as a result of the large amount of variables of environmental circumstances and vessel characteristics. Thus only small variations in one of the default values can lead to a totally different forecasted accretion appearance. A large number of different forecasting methods are available, whereas most of them present the relationship between two or more parameters and the thus resulting potential of ice accretion (*Feit, 1987*).

Numerical approaches have been set up to illustrate the processes of icing. These models are based on the three main requirements (*Feit, 1987*).

:

- Liquid water droplets embedded into the air stream surround the ships exposed surfaces.
- Taking the rate of deposition, including collection efficiency and droplet trajectory, into account.
- Thermodynamic processes which are, next to the mass flux, influencing the ice accretion rate the most.

One of the most cited numerical approaches, published by *Stallabrass (1980)*, constitutes that an operational use of his calculation is very difficult due to its complexity. Although his calculation considers the wave height, relative wind speed, the equilibrium temperature of the icing surface, the temperature of the impinging water droplets, the prevailing air temperature and the saturation vapour pressure of moist air at the given air temperature, a practical use is almost excluded.

Compared to numerical calculations, empirical approaches in determining the quantitative potential of icing prove as very useful. These are nomograms which constitute the potential of icing as the relations between the prevailing sea and atmospheric conditions. For instance *Sawada (1962)* figures out the potential of ice accretion from the relation of air temperature and wind speed, neglecting the influence of sea surface temperature or vessel characteristics (*Feit, 1987*).

Further steps into a more precise forecasting have been carried out by *Mertins (1967)* (see *Figure 19*). Based on the observation of more than 400 fishing vessels in the northeast Atlantic, he worked out four charts of icing intensities, whose calculations include the wind speed, the sea surface temperature and the prevailing air temperature. Based on upon these charts, *J.L. Wise and A.L. Comiskey* developed a single chart diagram, including the same parameters as *Mertins* (see *Figure 20*).

A more superior and comprehensive statistical procedure has been developed by *Overland*. He has developed a forecast procedure based on icing incidents, whereas, in contrast to the before mentioned approaches, he included the freezing point of seawater, which depends on its salinity, into the calculation (*Overland et al., 1986*).

Thus three types of icing potential (light, moderate and heavy) are assigned to a value which is the result of the predictor equation, calculated as follows:

$$PR = \frac{U_a * (T_f - T_a)}{1 + 0.4 * (T_w - T_f)} \qquad \left[\frac{m\,°C}{s}\right]$$

Where:

U_a wind speed ($m*s^{-1}$)

T_f freezing point of seawater (°C)

T_a air temperature (°C)

T_w sea temperature (°C)

Light icing (<0.7 cm/hour) is assumed when the result of the predictor is below 20.6, moderate icing (0.7 – 2.0 cm/hour) for a PR ranging between 20.6 to 45.2 and heavy icing (>2.0 cm/hour) for a value above 45.2 (*Figure 34*). Having a look at this equation, it reflects that at very low temperatures a small alteration of the wind speed leads to an explicit change of the icing potential. Equal to this observation, a small change of the air temperature at relatively high wind speed will have the same effect (*Feit, 1987*).

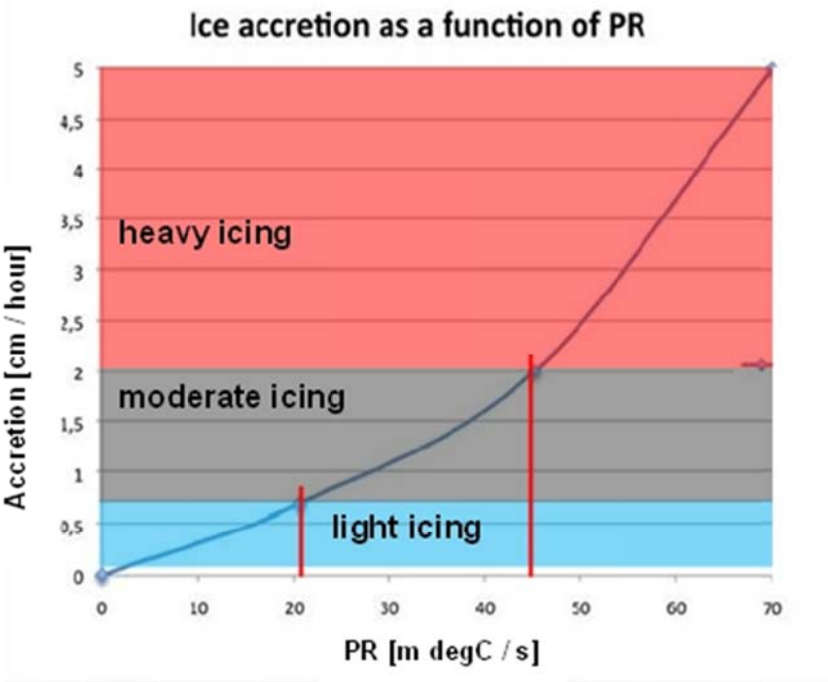


Figure 34 Ice accretion cm/hour as a function of icing index PR, (after *Jacobsen, 2010*)

This calculation procedure should furthermore be adjusted to the prevailing circumstances. For example, for a non-fully developed wave field with waves below 2 m, within a fast moving weather system, which comes along with strong winds, the result of the predictor could be assumed as smaller than calculated. For ships, operating in dry and clear air masses the value should be increased because under these conditions the air is able to remove more heat due to radiation and latent heat than the equation assumes (*Overland et al., 1986*).

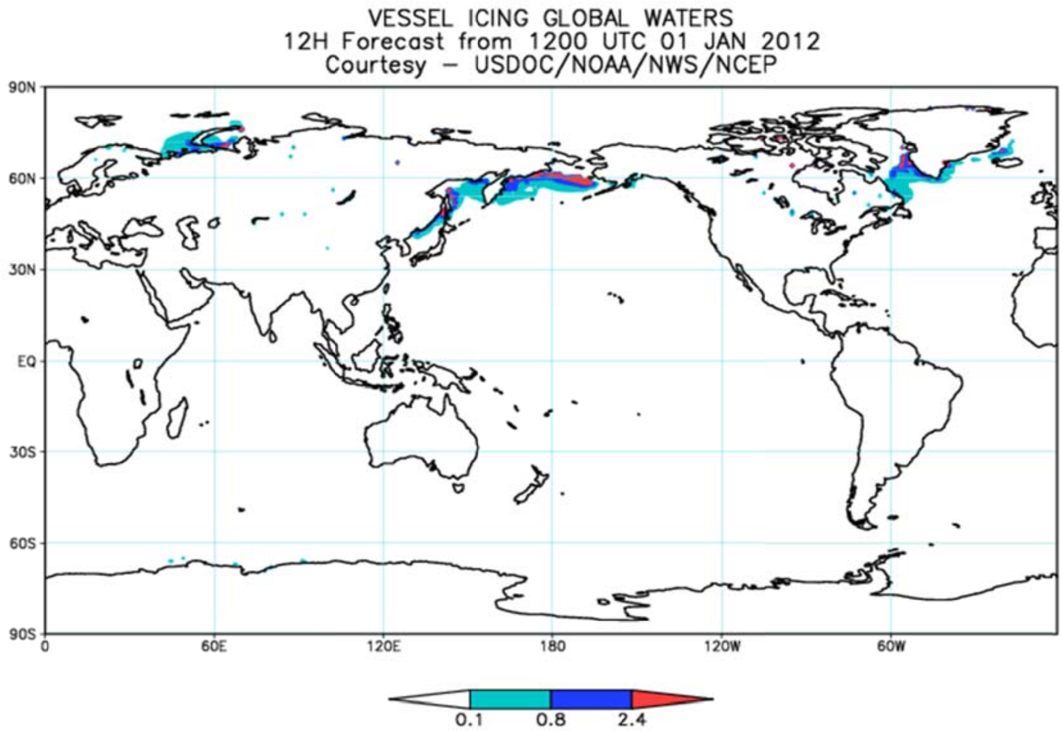
In 1990, Overland reviewed this calculation and proposed to add an additional icing case for extreme icing potential, which is initiated from a PR value of higher than 70.0 (*Overland, 1990*). An icing intensity for extreme icing is not determined. Later on the PR value for extreme icing is commonly denoted with 83.0.To evaluate the accretion rate, a more precise calculation method has been developed, in which the predictor appears as the dependent variable. The predictor (icing intensity) is calculated as follows:

$$IR\ (cm\ h^{-1}) = A(PR) + B(PR)^2 + C(PR)^3$$

Where:

$A = 2.73 * 10^{-2}$
$B = 2.91 * 10^{-4}$
$C = 1.84 * 10^{-6}$

In reference to this method ice accretion charts have been developed, for example those published by the *National Center for Environmental Prediction* (NCEP), (*National Weather Service, 2012*) which illustrates the potential of icing for a certain area for vessels ranging from 20 m to 75 m, steaming into the wind. The colour at the chart (*Figure 35)* denotes areas of light icing in aqua (0.25 to 2 cm / 3 hours), moderate icing in dark blue (2 to 6 cm / 3 hours) and red for heavy icing, exceeding 6 cm of ice accretion within a 3 hour period. But not only the present icing potential, also the extent of icing and the shifting of these areas can be predicted to make mariners more sensitive to the possibility of ice accretion.



http://polar.ncep.noaa.gov/marine.meteorology

Figure 35 Vessel icing global waters

It has to be stated that this forecasting method neither distinguishes the sea state, ice coverage, the area of accretion on the vessel nor its specific characteristics, like freeboard or ship length. The main acceptors of these products are fishing vessels, on whose dates of ice accretion these methods are based. Thus it is also just a method to evaluate the risk of ice accretion, but compared to other methods a more superior one.

The prediction of icing is also transferred on offshore structures. Here the two most cited accretion models are RIGICE and ICEMOD. For these prediction models the verification by investigations on ice accretion has not been fulfilled yet.

Jacobsen presents a diagram of icing index PR as a function of seawater temperature T_W and wind speed U_a at air temperature T_a of – 5 deg C (*Figure 36*) and at air temperature T_a of – 10 deg C (*Figure 37*).

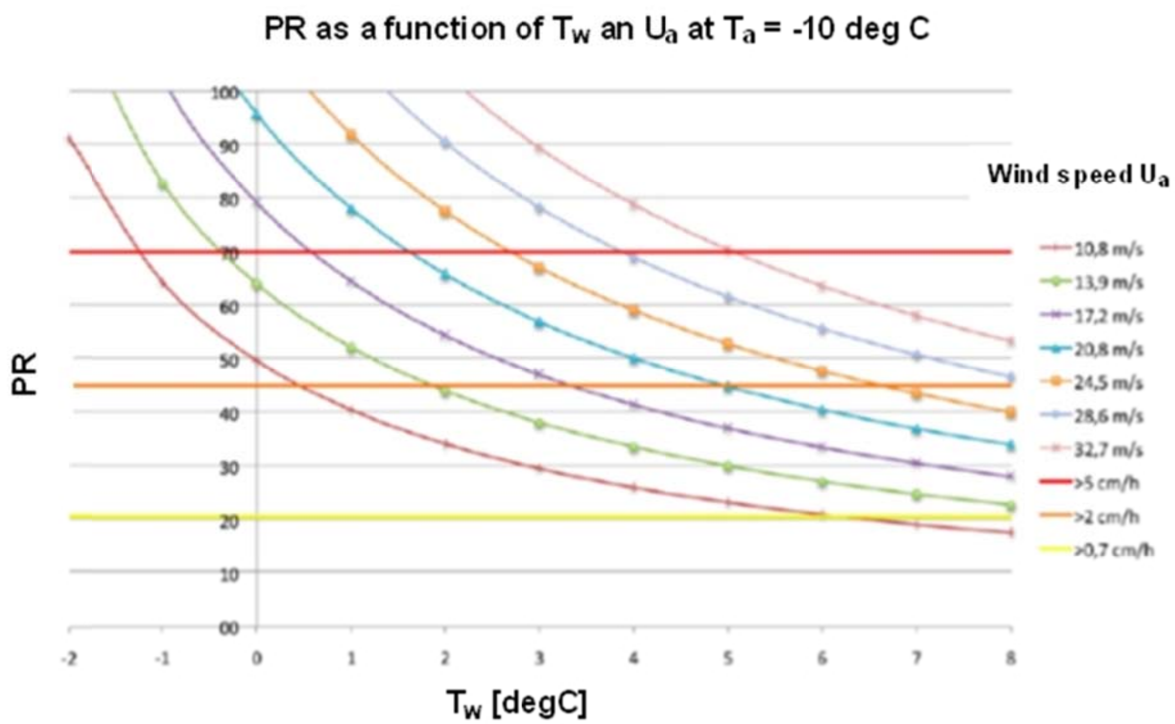


Figure 36 Icing index PR as a function of seawater temperature T_W and wind speed U_a at air temperature T_a of – 5 deg C (after *Jacobsen, 2012*)

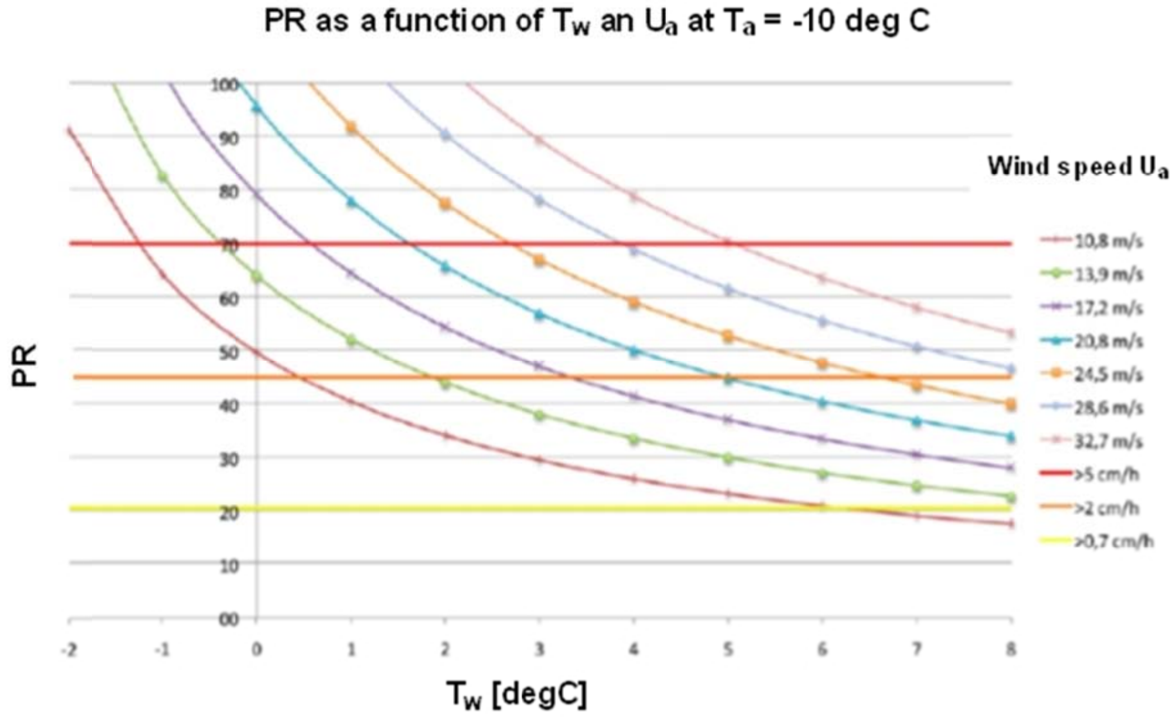


Figure 37 Icing index PR as a function of seawater temperature T_W and wind speed U_a at air temperature T_a of – 10 deg C (after *Jacobsen, 2012*)

The diagram above shows the relationship between the parameters that are used in the ice accretion predictor. The wind speed in each diagram corresponds to the lower limit for Beaufort force 6 to 12. The fixed air temperature T_a of -5 deg C and -10 deg C illustrates the effect of decreasing of decreasing air temperatures. It is obvious that the predictor PR increases significantly as the seawater temperature Tw approaches the freezing point.

The yellow, orange and red horizontal lines are used to denote an ice growth rate of 0.7 cm/hour, 2 cm/hour and 5 cm/hour respectively (*Jacobsen, 2012*).

9. Measures and precautions against ice accretion

Ship navigation, exploration and production in the Arctic, where humans are faced with extreme low temperatures down to -60°C, is in general a difficult undertaking.
At high latitudes and polar regions the extremely low ambient temperatures and high wind speeds create snow and ice conditions that require specific operational considerations. Therefore solutions must be provided for winterization and maintenance of anti-icing and de-icing systems on vessels and structures operating in the Arctic. These systems help provide a safe working environment to ensure the safety of personnel and the operation.
As already mentioned above, in polar and arctic environments ice formation on exposed surfaces of vessels and (offshore) structures creates serious problems impacting the safety of personnel and operations. The ice formation can be caused by sea spray and/or snow, rain and fog with the low ambient temperature.
Anti-icing and de-icing solution and products have been developed for offshore support, supply vessels, icebreakers, semisubmersible drill ships and platforms.
For example trace heating systems and self-regulating heat tapes are designed to ensure that all pipes, vessels, instruments and equipment are adequately protected for operations in low temperatures with cold sea water and high wind.

Four different design philosophies are considered:

- *Anti-icing*: ice and freeze prevention where surfaces will be maintained above freezing under the 'worst case' ambient design conditions.
- *De-icing*: removal of accreted ice in a reasonable and defined period of time.
- *Winterization*: anti-freeze for piping, valves, instruments and equipment containing fluids.
- *Process temperature maintenance*: temperature maintenance of piping, valves, instruments and equipment.

The measures and precautions which are undertaken before entering or while operating in an area with high icing potential, sea ice or low temperatures, are numerous. At this, selections of measures, which are most likely carried out by the vessel or offshore platform operators to diminish the potential of ice accretion or to remove accreted ice are presented.

9.1 Trace heating and self-regulating heat tapes

Trace heating and self-regulating heat tapes systems are specifically designed to facilitate a safe work environment for platforms, escape ways and helidecks. Typical needs for trace heating on FPSO's and FSO's are deck lines for oil, chemical products. Thermon (www.thermon.com) has designed trace heating systems for freeze protection and temperature maintenance of:

- Loading and unloading lines
- Gas / vapor-return lines
- Strip and cleaning lines
- Fuel oil lines
- Storage tanks and vessels
- Deck and tank cleaning lines
- Fire protection lines
- Engine room fuel and drip lines
- Cross-over lines
- Manifolds
- Safety showers

A sustainable and reliable comprehensive range of products has been developed by manufacturer Thermon. The products are available on the market for extreme environmental conditions of offshore support and supply vessels, icebreakers, semi-submersible drill ships and platforms. The products should be in compliance with international industry standards and carry approvals for installation and operation in hazardous (classified) areas.

9.2 Ship handling

The navigational measures which are undertaken to reduce the potential of vessel icing either aim to restrict the amount of generated spray or to achieve a change in the prevailing environmental conditions, which lead to the risk of icing.

The first mentioned aspect comes along with a minor amount of water droplets, which deposit on the superstructure. This can be reached by slowing down (*DeAngelis, 1974*), for instance the reduction of the relative speed between the ship and the wave field (see Figure 15). Thus the pressure gradient at the bow decreases which comes along with a fewer spray generation. An alteration of the heading can have the same result. The direction and speed of the relative wind is changed. The vessel is not steaming furthermore into the waves. This leads to a smaller pressure gradient and a longer period of encounter T_E, which results in a reduced vertical acceleration. A vessel, that is steaming downwinds, in the same direction as the propagation of the waves, runs the risk to broach. The vessel will heavily roll up to the loss of stability. At this heading the amount of spray is less compared to the spray formation, which occurs while steaming into the waves.

One of the most common measure is to leave the open sea. This is done to avoid heavy seas at gathering storms. The vessel seeks shelter close to the ice edge or beyond a peninsula, island or coastline. Here the sea state is less developed due to the minor fetch. This position comes along with an often underestimated risk (*Guest, 2005*). Sea and air temperatures are very low in this position, compared to those further at sea, due to the closer distance to the shore. This can have dangerous consequences in case of a wind shift. Thereby the vessel is exposed to strong winds. These will develop high waves within a short time, due to the sufficient fetch and low temperatures of the air and sea.

The best way to act in dangerous icing conditions is to seek shelter in a port. This measure includes a current icing forecast and its compliance as well as the avoidance of typical weather conditions which are inducing the risk of ice accumulation, such as Polar Lows (see *Figure 38*) during winter time. These cyclones occur with high winds and in areas with low temperatures so that they have a high potential of icing (*Guest, 2005*).

Another way of avoiding conditions that induce icing is to aim for warmer sea currents. Here next to the higher water temperature, usually warmer air temperatures are found (*Overland et al., 1986*).

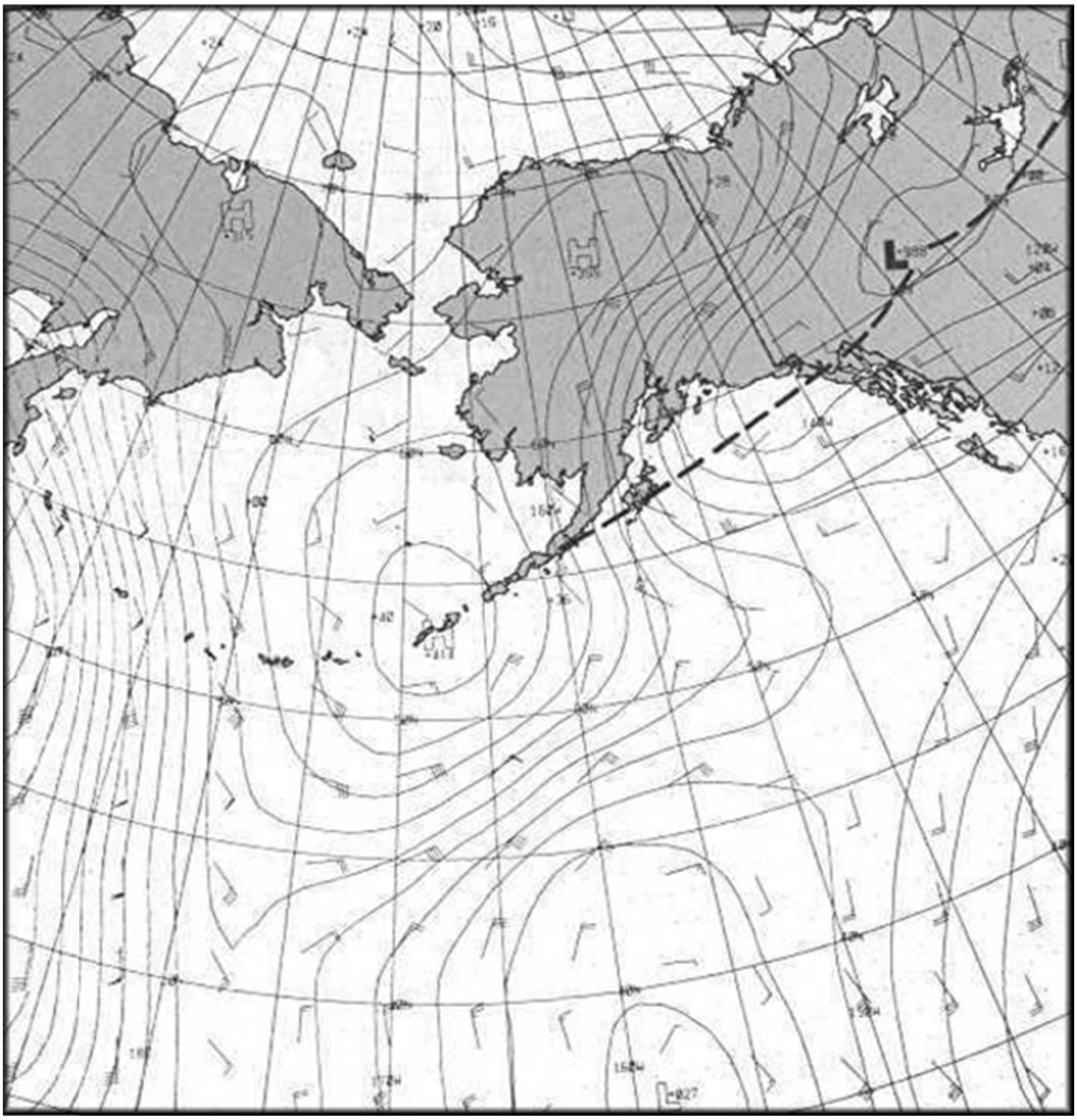


Figure 38 Polar Low in the Northern Pacific benefitting icing conditions (*Guest, 2005*)

9.3 Precaution measures taken by the crew

In case of a current forecast of icing potential for the instantaneous sea area a number of precautions can be taken to minimize the amount of ice formation on deck and to protect equipment from icing. For instance, electrical devices shall be covered by canvas or steel covers, especially switch boxes, electric and air motors at davits, cranes, electric whistles, windlasses and winches. Canvas covers are also used to protect ropes on drums or winded-up ropes on deck, chains or wires. A cleared-up deck is recommended, especially from lashing materials, dirt or spillages. This ensures water to run-off more easily from the decks without ice accretion. Additionally clean decks and scuppers are useful. Special attention should be paid to the lifesaving and fire fighting equipment. The ice should be regularly removed, even when only small amounts of ice have been accreted. Mallets to remove ice and make lifeboats and rafts accessible should be placed in the vicinity. Open lifeboats and embarkation ladders should be covered with a sufficient large tarpaulin. All materials which are used to protect parts from ice accretion should not be made of natural fibres. Natural fibres absorb moisture, which results in a loss of flexibility as well as durability and leads to an additional load of weight. Grease with an attachment of anti-freezing is a helpful measure to avoid the freezing of smaller parts like nuts, hinges, locks, flaps or vents. Ice is easier to remove from grease and keep the parts workable.

For a safe watch-keeping, bridge windows are usually fitted with a heating device, forced ventilation or clear-view screens to prevent ice accumulation. To keep the radar movable, it should be running all the time during icing conditions. Halyards for signal flags should be lowered and signal lights should be switched on also during daytime. Before entering an area of high icing potential, it is a recommended part of good seamanship to lower the anchor a little, just enough to avoid heavy movement of the anchors and at the same time move them and break the accreted ice before use. Under icing conditions the force of band brakes can be strongly limited, thus securing claws are recommended to support the lashings of the brake.

9.4 De-icing tools and equipment

De-icing describes the process of the removal of accreted ice from structures (*Ryerson, 2008*). For immediate actions, taken by a ship´s crew, to remove ice from the deck and the superstructure, usually simplest tools and equipment, for instance baseball bats and wooden mallets, are likely used. In general, wooden tools are favoured, because they are easy to use and not that harmful for operators and the ships structure and equipment, low priced, easy to store and almost everywhere available (*Guest, 2005*). To remove thin ice on plain surfaces, steel-bladed ice scrappers or straight-edged shovels can be useful. Thicker ice layers are favorable removed by spades, hoes and picks. Also snow, which covers passage ways or entrances, has to be removed. For this brooms and snow shovels are preferred. But also pneumatic driven chisels and needle hammers are used to remove the ice due to mechanical steady impacts. Electronic devices, like hot air fans or even hairdryers can be taken to remove ice from smaller areas, parts and frozen devices. Thus the ice is melted to make them moveable again.

The application of steaming or hot water flushing is a fairly simple method for removing ice that has built up on equipment. Advantages are that it is available or can be made available connecting to existing steaming systems or hot water sources onboard. Also it is flexible in the sense that it has flexible hoses and is inflicted by personnel where required.

A disadvantage is that water is added that might again freeze to the critical components. This method is also depending on available power for pumps and hot water and that the hoses at all times are functioning and not clogged by ice (*Torheim and Gudmestad, 2011*).

Infrared radiation

An Infrared radiation method can be used for de-icing. This method is an electromagnetic emission generated in a heat source by rapid vibration and rotation of molecules. It instantaneously provides radiant heat to melt snow and ice without raising the temperature of the intervening air space. This system can be equipped with temperature and relative humidity sensors. Thereby it can automatically be turned on in a situation for potential freeze and snow (*Torheim and Gudmestad, 2011*).

The equipment must be placed so that it does not endanger persons and escape routes always remains free. There are some demands for maintenance of such a system and relatively high power capacity is required.

9.5 Chemicals

Apart from the physical methods of snow and ice removal, a number of chemicals are available for de-icing. These are often used as supplements to the physical way of ice removal. The most common agents are Sodium Chloride (NaCl), Calcium Chloride ($CaCl_2$), Urea ($CO (NH_2)_2$), Ethylene Glycol, Methanol or other alcohol containing de-icers. These agents lower the melting point of the water through the developing brine and can be applied by sprinkling them on deck.

This way, especially areas which have to be safely accessible, like pilot platforms, bridge wings and passage ways, can be cleared effectively from ice. The advantages of chemicals to de-ice surfaces lie within their relatively low costs and their targeted use. Disadvantages become obvious in their corrosiveness to metals and wires and their negative effects on the environment.

The effect of the chemicals is strongly reduced at temperatures below -10 °C using NaCl, up to -32 °C using $CaCl_2$ (*Ryerson, 2008*). This requires a precise careful usage of chemicals, dependent on the prevailing conditions. One of the largest disadvantages in applying chemicals on board of vessels are, that they are frequently washed away and this way their application is difficult to control (*Makkonen, 1984*).

9.6 Coatings

So called “ice-phobic” coatings are used to repel water from the surface and, in case of ice accretion, to minimize the adhesion strength of the ice to the substrate (*Guest, 2005*). Most common phobic coatings are Fluorocarbon penetrating coating (FPC) and Vellox 140. These coatings use the effect of Teflon, Silicon or the Lotus leaf technology. Advantages of coatings lie within their steady effect and their passive nature. No crew member is needed. Even under harshest conditions they act without consuming power and no one has to be exposed to the dangerous conditions on deck.

Furthermore, they are easier to renew subsequently on the surfaces. In contrast to this, they require frequent maintenance and cleaning to maintain their characteristics. Due to the impact of water and ice on the surface, the coating is worn off.

Another disadvantage is their very slippery surface, so that they cannot be safely applied on frequently used passage ways or working areas. An easier way to achieve almost the same effect for a short time is the application of grease, which is limited to smaller parts but can keep them movable and diminish the ice accretion (*Ryerson, 2008*).

9.7 Constructional precaution measures to diminish accretion

Much more effective than the physical or chemical removal of accreted ice is to protect installations and devices durably by constructional measures.

9.7.1 Designs

Design measures are used to prevent the ice accumulation or to drain water before its accretion on the surface. These are preferably installed on vessels which are repeatedly or durably exposed to icing conditions. In comparison to the measures taken by the crew, constructional precautions are very effective and durable. Favored construction attributes are covered areas, for instance closed bridge wings or closed forecastles, to ensure a durable accessibility of the bridge wings and a safer mooring operation. To prevent the mooring station from severe icing, it can also be helpful to use further reaching bulwarks to deflect spray. Bow shapes which are less likely to produce spray can be designed, whereas the profit of a fewer spray generation has to be assessed to the operational use and potential appearance of ice or the loss of usable space.

To guarantee a safe embarkation of life rafts and rescue boats these are installed in a hidden position at the aft or the sides of the vessel, where they are set into the accommodation. Tarpaulins can be installed to improve the prevention of spray droplets reaching the lifesaving equipment (see *Figure 39*).

Figure 39 Tarpaulin installed to protect cranes or rescue boats (*Koren, 2007)*

This method can be transferred to the design of davits, cranes and whole deck arrangements. The smaller the amount of deposition, the smaller the accretion of ice will be. Heat traces can be installed at lifeboat stations to provide safety for personnel (see *Figure 40*)

source: www.thermon.com

Figure 40 Heat trace at muster stations to provide safety of personnel

9.7.2 Installations

Where no coverage is possible or difficult to arrange, a safe accessibility to the deck is an essential task. Gratings with a smaller deposition area are likely to be installed to diminish the ice accretion. The water will easily drain off before freezing. Another method to keep deck areas and passage ways free of ice is to install electronic or steam driven heaters into the floor. Thus the accretion of ice is almost avoided due to the thermal heating (*Figure 41*).

Figure 41 Heating coils to prevent ice accumulation (*Koren, 2007)*

These heating applications can be powered by electrothermal heating due to resistance heating of the cable (see *Figure 42*), known from window heating, hot air and hot water. Apart from the deck also hatches and bulkheads can be kept ice free.

Figure 42 Heating jacket and heating cable for moveable parts and pipes (*ClassNK, 2009)*

Heating jackets and cables are designed for movable parts, hydraulic valves, pipes and flanges and thus guarantee a permanent icing protection.

Warm water is also used in water or steam lances, which are an effective de-icing method. Highly pressurized hot water or steam from boilers is brought to the end of the lance tearing down the ice like a milling machine. Therefore the area which has to be de-iced needs to be accessed to the operating crew member. Another disadvantage of the lance is that more water is brought to the cold surface. This proceeding may strike back with a higher accretion rate of the added water than the amount of removed ice.

Further developments in de-icing systems are more focused on the ice removal from installations, which will be damaged by the influencing forces of traditional mechanical de-icing methods.

Electrical methods tend to cause the melting of ice or to reach the physical disconnection from the underground (*Ryerson, 2008*). Various techniques are proposed

(1) DC-Bias Voltage.

A small voltage of around 2 V DC erodes the ice where it contacts the surface. Thus the adhesion strength of the ice on the substrate is reduced. Using higher voltages of 21 V for 30 to 60 seconds, a reduction of the adherence force up to ten times can be reached (*Courville & Petrenko, 2000*).

(2) Pulse electrothermal de-icing

This system uses short pulses of electric power to heat up thin film heaters close below the substrate. The above accreted ice will melt resulting in a weaker adherence of the ice to the substrate. This method can be used for larger areas for the melting of total ice layers, or for supporting of traditional mechanical methods.

(3) High frequency excitation

This electric method uses high frequency excitation from 60 kHz to 200 kHz. Thus the adhering ice will become dielectric, which causes the ice to heat up and melt. The application of the latter system is favourable at gangways or stairs, but of course not limited to them.

(4) Expulsive de-icing system

This system is designed for aircrafts in flight, but is also designed in versions for ships at sea. The solutions have the potential to keep surfaces ice free with little energy use compared to heating surfaces to melt the ice.

Expulsive de-icing systems like the electro-expulsive de-icing system (EEDS) generate a short, highly accelerated pulse with high amplitudes. Thus the surface which is affected by ice will slightly move, detaching the ice from the ground.

The Electro-Impulse De-Icing (EIDI) system is capable of expelling thin ice, which is sometimes more difficult than expelling thicker ice. However, due to the salinity, the sea-spray ice is softer and the shock effect of an expulse may be partially absorbed. This may reduce the effectivity of the system. This technique can be installed in form of a thin layered material which can take on almost all forms of the structure below.

Reference is made to Innovative Dynamics, Inc. (www.idiny.com):

"Electro Impulse De-Icing is an acceleration based deicer for use on large aircraft, ship and bridge surfaces for general ice protection. The system was developed in collaboration with a NASA Glenn SBIR program. An electromagnetic coil is placed behind the surface skin that induces strong eddy currents in the metal surface. As a

result, strong opposing forces are developed between the actuator coil and the metalskin. This results in a rapid acceleration that sheds and de-bonds ice into the air stream in a very efficient manner (ice layers can be shed as thin as 0.05 inch).
EIDI represents a technically advanced low power de-icing system alternative to electrothermal and bleed air anti-icing systems. IDI's "Icing Onset Sensor" can be added to the basic system to provide an autonomous mode of operation. The IOS detects the initiation of ice accretion (icing onset) and continuously monitors the amount of accumulation. When the accumulation reaches a thickness threshold at which efficient clearing is possible, the sensor commands the deicer to fire. Because the sensor continuously monitors the accumulation, the sensor can determine if the ice was properly shed or if another clearing cycle is required. The sensor continues to monitor accretion and initiate de-icing cycles as required.

The operating principle is shown in *Figure 43*.

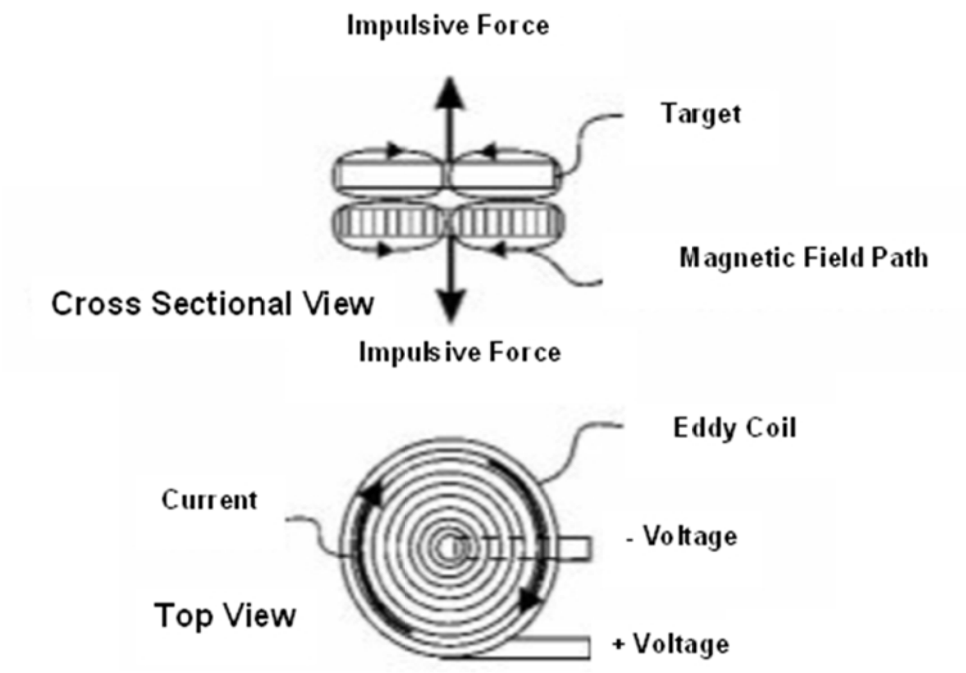


Figure 43 Operating principle of Eddy-Current type actuator (source: *IDI*)

Further developments like millimeter wave technology, infrared heating or piezometric crystals systems are not yet applicable in an economic usable manner.

10. Rules and Guidelines

During the last decades the classification societies and the *International Maritime Organization* (IMO) responded to the increasing amount of shipping in cold climate, with its specific effects and hazards. Numerous rules and recommendations for ships operating occasionally or primarily in cold climate sea areas, where icing conditions have to be expected, exist.

10.1 Classification societies

The former classification rules, which focused on traditional hull design, are nowadays enhanced to polarworthiness, including winterization of the superstructure, equipment and crew (*Chircop, 2008*). The guidelines and regulations presented in this paper represent some current regulations. More information of other classification societies regarding the winterization of ships is available and some of them unfortunately difficult to access. This chapter presents a basic view on guidelines, dealing with the icing issue. In the following paragraphs guidelines of *Det Norske Veritas (DNV), Lloyds Register (LR)* and the *American Bureau of Shipping* (ABS) are presented. These have been developed to reduce or to react at the accretion of ice. Regulations and guidelines from national administrations are not included in these rules and have to be considered while operating in their territorial waters.

10.1.1 Det Norske Veritas (DNV)

The *Det Norske Veritas* (DNV) has integrated winterization rules into its list of guidelines and rules with the inauguration of *Ship Rules Pt.5 Ch. 1 Sec.6,* in January 2006. Their application is intended for ships that operate in cold climate environments. The three class notations, “Winterized Basic”, “Winterized Cold (t_1; t_2)” and “Winterized Arctic (t_1; t_2)” are described. The material design temperature (t_1) should be determined by estimating the daily average air temperature of the area, where the ship is intended to operate. The extreme design temperature (t_2) lies at recommended 20 °C below the mean daily air temperature.

If the air temperature for the operating area cannot be estimated, the extreme design temperature should reflect the material design temperature. Another specialization is made by defining the requirements concerning the accumulation of ice on the exposed ships superstructure. These measurements were divided into anti-icing arrangements (category I) and de-icing arrangements (category II). Category I measures are required to be installed with sufficient power to keep the area or equipment free of ice. These installations are commonly used for navigation, steering, propulsion and communication equipment, radar, navigation lights, if available window wipers, tanks ventilation, anchoring equipment, fire fighting and lifesaving devices and escape routes. For the de-icing of decks, gangways, stairways, superstructures, deck piping and railings, measures of category II are required. According to the guideline these measures have to remove accreted ice from the area or equipment within a reasonable period of time (4 to 6 hours) under icing conditions.

The requirements of “Winterized Basic” are relevant for ships which are designed to operate for shorter times in between their usually routes in cold climate environments, with or without ice coverage. Therefore a material design and extreme design temperature is not necessary. For the approval of this class notation, a number of plans and particulars shall exist. This includes the arrangement of anti- and de-icing equipment for certain areas of application with specified heating capacities, diagrams for their electrical single line distribution and compressed air supply to the main consumers outside the engine space. Plans, where the mechanical de-icing arrangements, hand tools and their location, heating equipment, protective clothing and further ice removal equipment are listed, are required. An anti-icing precaution and de-icing manuals shall be submitted. Minimum requirements regarding the heating power capacity are determined as follows:

- 300 W m^{-2} for open deck areas, helicopter decks, gangways, stairways, etc.
- 200 W m^{-2} for superstructures
- 50 W m^{-1} for railings with inside heating

The minimum electric generator capacity for the heating arrangements is specified with 100 % of electric power, available for anti-icing equipment and 50 % for de-icing installations, as well as a sufficient supply of anti-icing and de-icing installations which are heated by fluids in pipes. Here steam plants or thermal oil heaters have to be designed to deliver 100 % of all power consumption of category I and 50 % of category II equipment. Safeguarding, efficient application and the design for de- and anti-icing facilities, are implied too.

Besides the above mentioned requirements, "Winterization Cold (t_1, t_2)" adds to the requirements of "Winterization Basic" a number of demands to prepare the ship to operate for longer periods in cold climate conditions. This contains additional documentations about the heat balance calculation and further reaching installations, including the de-or anti-icing of mooring equipment and cranes, heating of fire main, foam main, hydraulic oil systems, ballast and fuel oil tanks. The heating power capacity for horizontal surfaces, which are used as walkways or passageways on deck, is increased to a minimum of 450 W m^{-2}.

Compared to the requirements of "Winterization Basic" (see *Table 6*), ships, reaching the class notation of "Winterization Cold (t_1, t_2)" (see *Table 6*), are requested to have specified constructional arrangements. This concerns especially emergency, lifesaving and mooring equipment. Lifeboats shall be placed in a sheltered location, where they are protected from sea spray. Freefall lifeboats are prohibited, unless they are equipped with alternative lowering devices. Anchor windlasses and emergency towing arrangements, if available, shall be inside a forecastle, deckhouse or protected location. This is also relevant for cargo manifolds. To meet the influence of ice accretion, the vessels are required to have a sufficient intact stability, including an assumed value for an additional ice load, which should be introduced into the stability calculation, calculated according to *DNV (2011)* as follows:

$$W = \frac{300}{K}(1 - C) \qquad [\text{Kg m}^{-2}]$$

where:

W Weight distribution over the horizontal area

K Constant value, ranging from 1 to 1.75, representing the freeboard of the ship (K taken from Table C1 K constant)

C Constant value, ranging from 0 to 0.25, representing the ships length ((C taken from Table C2 C constant)

This weight distribution for horizontal surfaces includes the ship length and freeboard and is given in kg m^{-2}. The values for K and C can be found in *Table 5*.

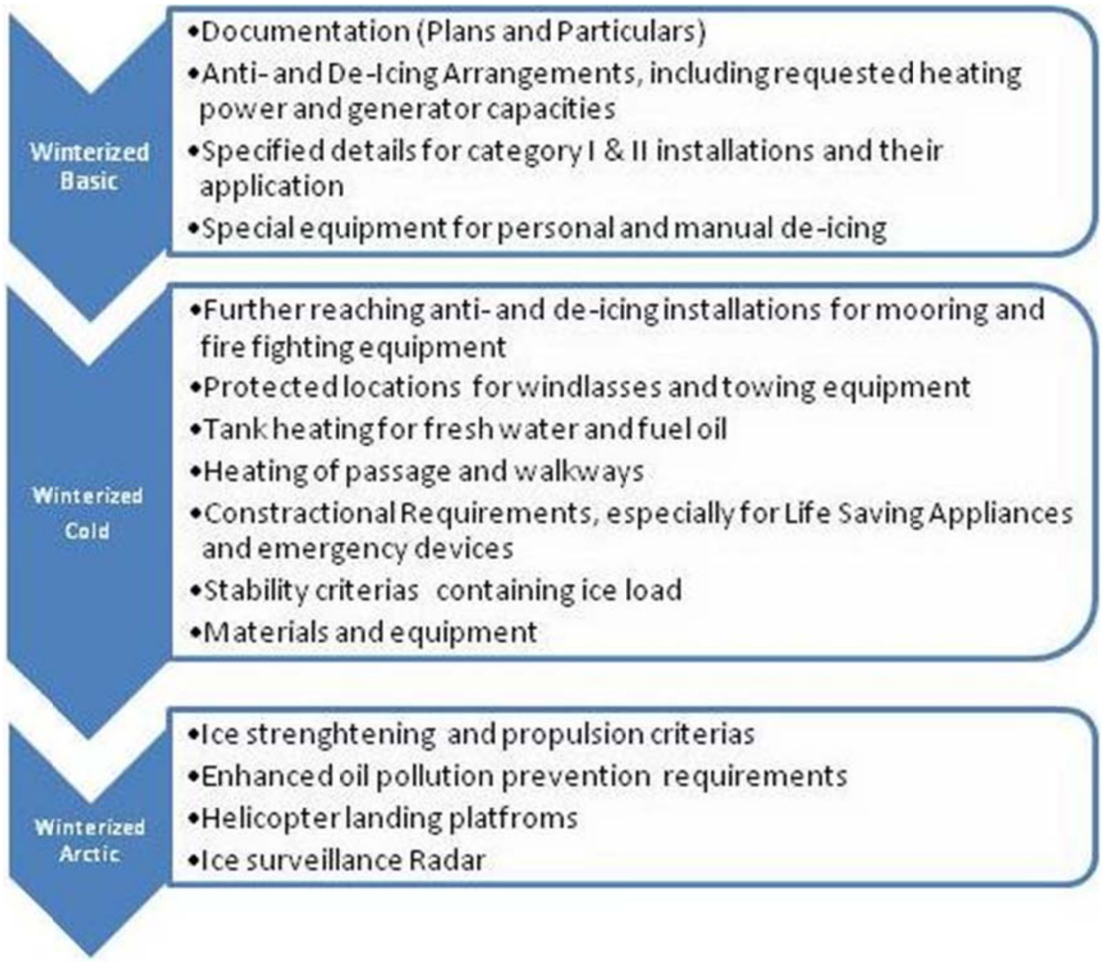
Table 5 Values for the ice load calculation by DNV (*Source: DNV, 2011, Rules for ships pt. 5 ch.1 sec.6, p.85)*

Table C1 K constant	
Summer freeboard	***K***
FB ≤ 2m	**1.00**
2m < FB ≤ 6m	**1.25**
6m < FB ≤ 9m	**1.50**
FB > 9m	**1.75**

Table C2 C constant	
Ship length	***C***
Lpp < 50m	**0**
50m ≤ Lpp < 100m	**0.075**
100m ≤ Lpp < 200m	**0.2**
FB ≥ 200m	**0.25**

Ice on vertical surface has been considered in this calculation. The requirements concerning the prevention or removal of accreted ice are no further increased with the “Winterized Arctic” class notation (see *Table 6*). This is more focused on the strengthening, propulsion and oil pollution prevention. Vessels that meet these requirements are furthermore requested to provide a helicopter landing facility and an ice surveillance radar.

Table 6 Levels of DNV winterization rules (*Richter, 2012*)



10.1.2 Lloyds Register (LR)

In 2008, the *Lloyds Register* has added the *Provisional Rules for the Winterization of Ships* to the existing *Rules and Regulations for the Classification of Ships*, to meet the demand of winterization guidelines and recommendations for ships operating in polar environments.

Vessels which fulfill the requirements are applicable for class notations concerning hull construction (Winterization H (T)) and / or equipment and systems, subdivided into winterization levels A (T), B (T) and C (T), ranging from short transit in cold climates (C) to prolonged operations in very low temperatures (A). The here included average external design air temperature (T) depends on the lowest daily average air temperature, which is assumed to occur in the operational area.

For all design features and installations, a "Winterization Manual" shall be provided, which contains, among others, a list of winterization equipment and arrangements, heating details, trim and stability conditions, arrangements of accommodation, escaping and mooring equipment and details for ice removal measures and their maintenance. A general demand for equipment and systems is to install pipework, components and cables inside a closed space, as far as it is practicable, as well as a safe use of heating equipment. This includes safeguarding and control panels as well. Regarding additional weight of ice accretion, which has to be included in the stability and trim calculation, the following weights of ice have to be integrated into the calculation:

- Winterization C (T): 30 kg m^{-2} for horizontal surfaces
  7.5 kg m^{-2} for vertical surfaces
- Winterization B (T): 60 kg m^{-2} for horizontal surfaces
  15 kg m^{-2} for vertical surfaces
- Winterization A (T): 100 kg m^{-2} for horizontal surfaces
  25 kg m^{-2} for vertical surfaces

The requirement of the *IMO Intact Stability Code* to include a possible ice accretion into the calculation of the stability is herewith more precisely defined for all types of vessels, which are operating in cold climate conditions and not only for fishing vessels (*International Code on Intact Stability (IS-Code), 2008, Annex 2, Ch.6, 6.3*) To take precautions for ice removal and prevention for decks, which are exposed to spray or other sources of water deposition, these have to be provided with gratings, heating devices, checkered plates or coarse-sand containing paint.

De-icing installations and precautions have to be installed in different working and emergency area, like gangways and escape routes. This reaches up to trace heated handrails on stairways and ladders for winterization level A (T). But also anti-icing installations for escape routes, such as heated door frames and suitable door seals, are requested. Beside recommended anti-icing installations a defined number of manual de-icing tools are contained at the provisional rules. Herein included are shovels, hammers or mallets and scrappers, independent of the level of winterization.

All de-icing equipment is requested to be stowed within durably protected and accessible containers, which have to be located at the bow, the stern, port and starboard amidships, on both pilot boarding zones and rescue boats. Water exposed mechanical and electric equipment has to be provided with covers to ease the ice removal. Winterization levels A (T) and B (T) shall be provided with steel covers, as far as they are practicable. At the mooring and anchor winches these heave to be heatable. For winterization C (T) steel covers are requested. Thus the most important safety and ship handling devices should be keep operational.

10.1.3 American Bureau of Shipping (ABS)

“The *IMO Guidelines* define special measures for safety of life and protection of the environment in the Arctic. The Guidelines harmonize different national requirements relating to hull structure, equipment, navigation and operation for different types and sizes of ships that may travel in ice-covered waters. The standards expressed in these guidelines have been developed to deal with additional risks imposed on ships due to harsh environmental and climatic conditions existing in arctic ice -covered waters. These standards are additional to the basic requirements from relevant conventions“(*ABS, 2014*).

IMO Guidelines cover a wide range of issues related to safety of vessels operating in the Arctic region. They are recommendatory rather than mandatory for vessels traveling in the Arctic ice-covered waters and are divided into three principal parts: the design and construction of hull structure and machinery; specific equipment requirements for a low temperature environment, including fire safety equipment, lifesaving appliances and navigational equipment; and operational guidelines, such as operational control, operating manual, training manual, crewing and emergency equipment (*ABS, 2014*).

In 2006, the *American Bureau of Shipping* has published the *Guide for Vessels Operating in Low Temperature Environments* (LTE Guide). Besides the standard classification notations optional notations, including Cold Climate Operation (CCO), Cold Climate Operation-Polar (CCO-POLAR), Cold Climate Operation Plus (CCO +), Cold Climate Operation-Polar Plus (CCO-POLAR +) and DE-ICE are defined. These requirements have been introduced to support the design and operation of ships, which are primarily or occasional operating in ice or low temperatures. Especially the DE-ICE notation is directed to vessels operating occasionally in low temperatures, where they may be exposed to freezing conditions. Vessels with this notation have to be provided with arrangements and installations concerning hull construction, equipment, systems, machinery, safety systems and crew considerations.

Windows, emergency routes, bridge doors and deck areas have to be designed and arranged to keep snow and ice free. Stairs which are exterior are requested to be installed with landings made of grated material. The same material has to be used for operating platforms of deck equipment, which should increase the traction and eases the ice removal. For the CCO-Polar notation heated rails are required for escape routes. Emergency towing installations are usually concerned to ice-class vessels. Vessels with installed de-icing equipment are to be provided even with towing arrangements.

Windlasses for anchors are to be designed to work at the minimum assumed temperature, including heaters for hydraulic oil sumps and electronic motors. For a safe operation on deck, de-icing equipment for hatch covers, ramps and doors is required. For a CCO notation the anti- and de-icing equipment is to be provided with the following minimum heating power capacity:

- 300 W m^{-2} for open deck areas, gangways, stairways, etc,
- 200 W m^{-2} for superstructures,
- 50 W m^{-1} for railings with inside heating.

The low temperature guide addresses various vessel design characteristics and equipment affected by cold temperature extremes as summarized in *Table 7*.
It provides supplemental requirements that are not addressed by existing Ice Class Rules. Vessels designed and equipped in accordance with the requirements of this Guide are eligible for a special class notation, but the application of the requirements is optional.

Table 7 Notations in the ABS Low Temperature Guide for vessel design characteristics and equipment (*source: ABS-Brochure Low Temperature Operations*)

Materials, Welds and Coatings	Suitable materials for low temperatures are mandatory for proper functioning of the hull structure and equipment. This section provides requirements for material classes to be used in the hull's structural members, material grades for the design service temperature, material testing temperatures and alternative requirements for higher strength steels. Coatings requirements, together with additional guidance on coating selections for various parts of the vessel, are listed.
Hull Construction and Equipment	Freshwater, ballast and fuel oil tanks should be carefully placed or fitted with heating equipment to avoid the chance of the tank's contents from freezing or leaking into the environment. The vessel's bow should be designed to reduce the effects of spray from freezing and collecting on the bow area. Bridge wings and deck houses should be specially designed or enclosed to protect equipment and crew. Vessel stability should take into account the effects of ice build-up on the hull.
Vessel Systems and Machinery	The effects of cold air can have unintended effects on systems and machinery. Accordingly, the combustion air system is required to be routed directly to the prime movers to avoid exposing machinery and the crew to the ambient temperature. Additional heating of lube oil may be needed for equipment located in the machinery space. Deck equipment should be provided with heaters for reliable operation. Piping systems need to be provided with gaskets and hoses suitable for low temperatures along with arrangements to drain piping to prevent freezing damage. The heating system should be supplemented with additional heating units and insulation for crew comfort. Firefighting and protection systems components are to be specially located to prevent freezing or provided with heating. In the event of an emergency, the emergency source of power is to be increased to provide heating for selected spaces for crew protection.
Safety Systems	Operations in cold climates require additional equipment to receive weather reports, special radar to make contact with ice and lights suitable for the cold. Life boats should be enclosed and specially designed to operate in the cold. Additional features should be included such as heating and communications equipment. Launching equipment should be designed to avoid the effects of freezing ice. Immersion suits are necessary for crew survival.
Specific Vessel Requirements	Some vessel types require additional consideration for low temperature operation because of special design or operational features.

	Requirements are included for LNG carriers, ore carriers, tankers and support vessels.
Crew Considerations	Working in cold weather can impact the crew unless proper preparations are made to equip the vessel and the crew for operation in the cold, dark and icy conditions. Clothing and work station design requirements are listed in the Guide. The Appendix lists supplemental information addressing human physiological responses to cold, maximum allowable work times, and clothing and personal protective equipment recommendations.
Training and Related Documentation	Training and manning are both important considerations for vessels operating in cold climates as special skills are necessary if they are to be accomplished safely and efficiently. The Guide provides information on the type of training needed as well as the documentation required onboard.
Weather Conditions	Extremely low temperatures, and the associated formation of ice, dominate operations in polar and sub-polar regions. In low temperatures, any precipitation will be in the form of snow, freezing rain, sleet or ice pellets. Visibility in any of these conditions can be very limited and ice build-up can produce a range of hazards. Ice accumulation due to spray is most likely in air temperatures below 2°C, and wind speeds of above 20 knots (10 m/s). It will worsen as wind speeds increase beyond this, and in higher sea states. In very low temperatures, sea ice can form quite rapidly once the water temperature itself falls below 0°C. Ships with little or no ice capability can find themselves at risk if caught in these conditions, which are most likely to occur towards the onset of winter. Most ships can be put at risk by ice movement, which can occur rapidly under high wind or currents. Conditions reported on ice charts or by remote imagery can change quickly, particularly the reported positions of the ice edge and the location of leads through the pack. It is important for mariners to be able to recognize the conditions in which such changes can occur and signs of the proximity of ice. Additional information is provided in the Guide describing the weather conditions likely to be encountered in the cold regions. Vessel Operations Low temperatures require additional tasks to permit equipment to function or to conduct vessel operations. Owners/operators are responsible for operational guidelines and keeping these guidelines updated. The Guide provides guidance on vessel operations related to each section of the Guide addressing design considerations including deck machinery and safety equipment.

Besides the before mentioned classification societies a special attention is paid to the firefighting equipment. This contains occasionally or durably water containing pipes and apparatus. Therefore equipment is to protect from ice build-up on its surface and internal, especially nozzles, hydrants, piping and valves. Portable and semi-portable fire extinguishers are to keep under non-freezing conditions. This is also valid for portable equipment to keep it durably available. Besides the fire fighting equipment also the lifesaving equipment is requested to be provided with anti-and de-icing installations. For instance the lifeboat, heating arrangements are to be installed to keep it accessible and ready for launching.

For manual de-icing measurements a defined number of tools are included, requiring minimum 5 shovels, 5 mallets or hammers and 5 scrapers.

The various installations and equipment are designed to protect areas or installations from water impingement due to covers and constructional arrangement or to ease the removal or prevent the accumulation by heating installations.

The guidelines for the different class notations are intended to assist operation and design for vessels which are constructed to work under cold climate conditions.

These notations are focused on a safe operation of mooring and deck equipment, life saving and firefighting appliances.

Beside the conformities, differences appear in the detailed requests of amount and type of installations or devices, especially manual de-icing tools (ABS, LR) and demands of minimum power capacities (ABS, DNV), if specified.

Recommended calculation values for the computation of the ships stability are given by *Lloyds Register* and *Det Norske Veritas*, which are already implemented in the *IS Code* for the stability calculation of fishing vessels.

10.1.4 Guidelines by the International Maritime Organization (IMO)

The potential of severe accidents and loss of lives, initiated by ice accretion, triggers international reactions to warrant the attention at this issue and ready administrations to enact national requirements concerning the environmental risks. In 2008, the IMO issued the *International Code on Intact Stability* (*IS-Code*).

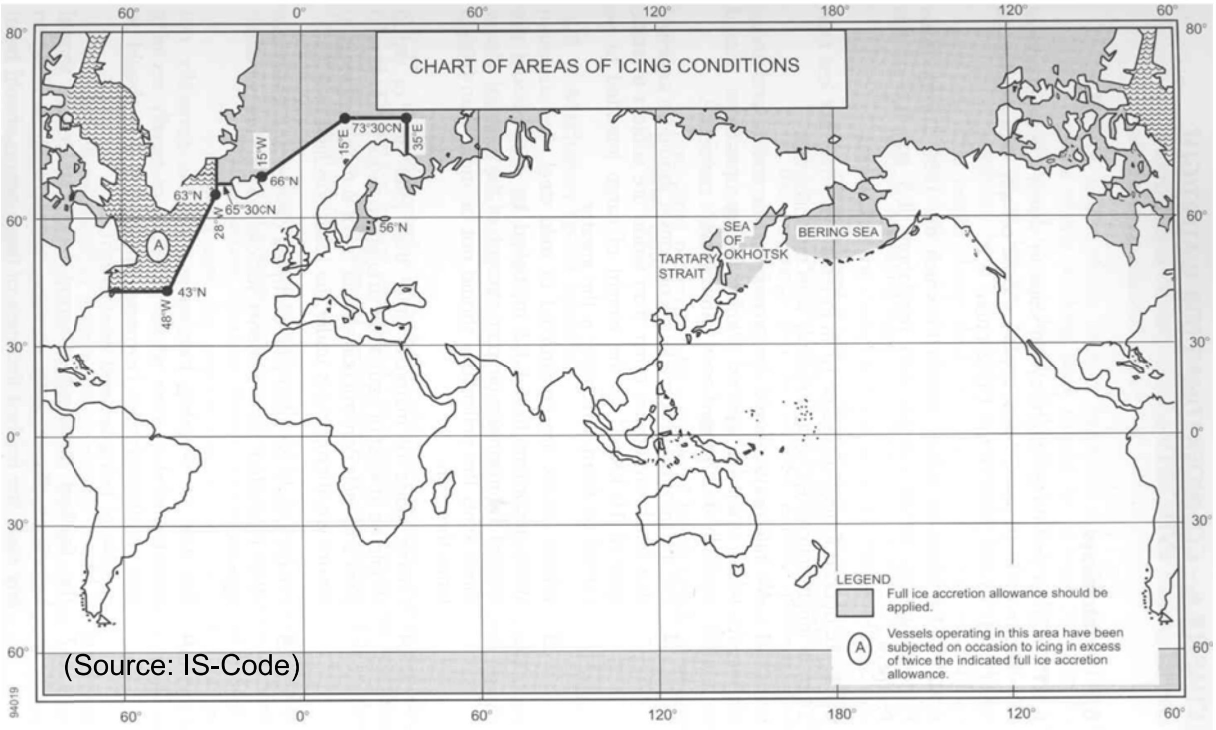
According to the IS-Code, every ship "... operating in areas where ice accretion is likely to occur" is required to integrate the accretion of ice, noted with a sufficiently icing allowance, into the calculation of loading condition (*IS-Code*). More detailed requirements are given for cargo ships, shipping timber on deck, and fishing vessels. Timber cargos tend to absorb water if the impinging water remains liquid after deposition. Thus ice accretion and the additional weight from the absorbed water can affect the ship due to a large amount of additional weight.

Recommendations for the stability analysis of the loading condition of fishing vessels in areas where icing is likely to occur, to determine the icing allowance, is contained in paragraph "6.3.1 Allowance for ice accretion" and is determined as follows:

- 30 kg m^{-2} on exposed weather decks and gangways,
- 7.5 kg m^{-2} on projected lateral area for both sides of the vessel above the water surface,
- "the projected lateral area of discontinuous surfaces of rail, sundry booms, spars (except masts) and rigging of vessels having no sails and the projected lateral area of other small objects should be computed by increasing the total projected area of continuous surfaces by 5 % and the static moments of this area by 10 %" (*IS-Code*).

Precautions in the design of the vessels for the operation in cold climate areas, aim to lower the accretion of ice, should be made. De-icing equipment, like electrical, pneumatic or manual devices, according to the requirements of the flag state or classification society, should be available.

The above mentioned rules shall apply for the areas which are dark marked in *Figure 44.*



(Source: IS-Code)

Figure 44 Icing areas according to IS-Code

The chart in *Figure 44* contains the following areas:

- "... 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

- 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

- all sea areas north of the North American Continent, west of the areas ...” defined in the two before mentioned points
- the Okhotsk and Bering Seas, as well as the Tartary Strait during the icing season
- the Antarctic, south of latitude 60° S (*IS-Code*)

For sea areas, except that in point two, it is recommended to calculate the icing allowance with one and a half to twice of the allowance values to meet the severe icing incidents which often occur in this places. For the area signed by the letter A, described in point two, the values for the analysis of the loading conditions should be more than twice the recommended in *section 6.3.1* of the *IS-Code*.

Further recommendations concerning the design, installations and equipment of vessels operating in cold climates can be found in *Guidelines for ships operating in arctic ice-covered waters* (MSC / Circ. 1056 MEPC / Circ. 399), from 2002, and the more modern *Guidelines for ships operating in polar waters* (Resolution A. 1024 (26)), adopted in 2009. These are developments to exist beyond the SOLAS convention, addressed on operators of ships in Polar Regions with a special focus on maritime safety and pollution prevention. The IMO sub-committee for ship design and equipment is working on a mandatory *Polar Code,* based on the nowadays recommended *Guidelines for ships operating in polar waters* with an envisaged finalization date of 2012 and to be in force in 2014 (*Deggim, 2009*).

Besides the IS-Code the subject of ice accumulation is included in the *International Convention for the Safety of Life at Sea* (SOLAS). In Chapter III, Section VI “Launching and Embarkation appliances”, Regulation 48, the requirement, that “Each launching appliance shall, as far as practicable, remain effective under conditions of icing” is included (*SOLAS, 1997*).

Furthermore, “the master of every ship which … encounters sub-freezing air temperatures associated with gale force winds causing severe ice accretion on superstructures …" is, according to Chapter V "Safety of Navigation", Regulation 2a, obliged to inform ships in the vicinity and coastal authorities about potential icing conditions. Thus adequate warnings to the ships which navigate in this area are recommended.

10.1.5 Publications by national administration and authorities

Besides the international guidelines and regulations, published by the *International Maritime Organization,* a large amount of national recommendations and rules, issued by countries adjoining to sea areas which are likely to be ice covered, like Canada or Sweden, or where harsh conditions and circumstances call for guidelines for ship operators and shipping companies, exist. Relating to sea spray icing these publications contain an overview of the icing problem. An extensive view on the danger of icing is given in the *Ice Navigation in Canadian Waters*, published by the Canadian Coast Guard, which contains (*Canadian Coast Guard, 1999*):

- Accretion of ice accretion,
- Effects and Risks,
- Prediction,
- Icing conditions, including prevalent weather situations,
- Measures to minimize ice accretion and de-icing recommendations and
- Area-specific peculiarities.

This publication is gives a hint that the prediction of ice accretion is difficult because the ship-specific characteristics are not included in the development of icing forecasts.

These manuals generally provide the crew with information, including a summary of present requirements to ships operating in adjoining cold climate areas, refer to reporting schemes, listing points of contacts and warnings (*Canadian Coast Guard, 1999)*. Besides the guidelines for Canadian Waters, these publications can be found, among others, for example for the Swedish territorial seas in "*Winter Navigation*", issued by the *Swedish Maritime and Hydrological Institute SMHI* and *the Swedish*

Maritime Organization (SMHI & Swedish Maritime Administration, 2010) or the *Guidelines for Navigating Ice Covered Seas in Russian Territorial Waters*, issued by *ClassNK (Nippon Kaiji Kyokai),* for ships navigating in Russian waters in the Arctic.

11. Summary and Conclusions

This report gives an overview about the accretion, environmental prerequisites, risks and the nautical and administrative management of one of the most severe dangers for ships in cold environments, the ice accretion on the superstructure due to sea spray. The risks and effects of icing have been known for a long time from smaller fishing vessels, which are affected by ice accretion during their voyages to and from their fishing grounds. These smaller ships are more likely to be affected by icing due to their smaller size and lower freeboard, masts and rigging and the larger influence on the ships stability. In many cases ice accretion causes the loss of ships and lives. Based on these experiences the appearance of icing came into the focus of mariners and researchers to analyze its accretion and prerequisites for an environmental and ship specific point of view.

Commercial shipping is more and more shifted into remote regions when serving drilling platforms or shipping minerals, liquefied gas and oil. Thus they are exposed to harsh environmental conditions, including stormy winds, low air and sea temperatures and heavy seas. Ships operating in waters with an ice coverage exceeding 6/10 of the total area are minor affected by sea spray icing due to the damped sea state. Thus in regions far off the coast and the ice edge, icing in a zone from 5 to 200 km is more likely to occur. Here, the fetch is sufficient to form higher waves without sea ice diminishing the development of the sea, the sea surface temperature and the air temperature are in general low. Wind, which originates over large ice fields or landmasses, is still cold enough to support ice accretion process without being warmed. At sea the air is warmed due to higher water temperatures. Having a look at sea charts where the locations of icing incidents are marked (see Figure 17), it becomes obviously, that the potential of icing is high in vicinity of the ice edge. This is preferably caused by cold sea currents, like the Alaskan current in the North Pacific Ocean, originating in icy regions, which comes along with low water and air temperatures. But minor icing incidents have been observed in close vicinity of the ice edge (marginal ice zone) itself.

After 2007 the sea ice extent reached a new minimum extent in September 2011(*University of Bremen, Institute of Environmental Physics, 2011*). The area of arctic sea ice varies over the year reaching its maximum around March and its minimum around September. As a consequence of the low ice extent the Northwest and the Northeast passages were ice-free in the autumn of 2011 as they were before in 2008. Due to the decreasing amount of multi-year ice and the increasing area of ice-free waters with low temperatures the potential of icing is increasing.

Focusing upon the accretion of ice it becomes obvious that, assuming constant environmental conditions, smaller vessels, like fishing boats or platform supply vessels, are more prone to icing than larger vessels. This is a result of the minor amount of deposited water as a consequence of their diminished behaviour at the wave field and higher freeboard. Thus smaller ships, compared to their total displacement and size, are entirely affected by spray, whereas on larger vessels most of the ice accrues around the forecastle and bow area. The distribution of ice is primarily connected to the wind, the sea state and the heading of the ship as well as the influence of the bow and hull shape, which influences the deflection. Especially on commercial vessels the bow meets the requirements of an economic use, including demands at the vessels area of operation and space for commercial cargo. Spray diminishing X-Bow shapes®, as designed by *Ulstein* , favour the limitation of sea spray formation, but they have to prove its usefulness and icebreaking capabilities under sea ice conditions, especially for vessels which are intended to operate durably under cold climate conditions. Not only bow shapes, also the on deck construction gives potential for anti- and de-icing solutions. Most of the ice accrues on horizontal surfaces, thus it is essential that water is deflected before deposition. If the water impinges, it has to be removed from the surface as soon as possible before its accretion. In general the exposed areas should be kept as small as possible.

The prediction of vessel icing has been continuously developed further, becoming more precisely due to the implication of the most important factors of ship icing, air and sea temperature, wind speed and the freezing point of sea water. This forecast products, for example those of the *National Center for Environmental Prediction* (NCEP), are aimed to the commercial fishing industries, because the predictor calculation is based on observations of fishing vessels ranging between 20 to 75 m. Thus the prediction, which can also be used by the commercial shipping, gives a good indication for the extent of icing potential areas, but a conformation for larger vessels and prevailing sea states would be desirable.

The arctic shipping will remain destination-driven and shortcuts for the commercial shipping, especially on the Northern Sea Route (NSR) or Northwest Passage, are not yet economical enough, these future shipping routes face environmental and administrative challenges. But the development of further developed and improved guidelines and mandatory regulations integrates the polar conditions into international framework. Thus the ship operators can be made aware of the risks of icing. As a report of the *United States Coast Guard* shows, larger vessels start to ice up at the forward part during the night time without being noticed by the officers of the watch or their watchmen. Within the framework of measurements and guidelines to prevent and diminish ice accretion one of the measures should include the alerting of the ship operators with the use of camera and measuring systems at the beginning of ice accretion.

Due to the operation of ships in various economic zones, the vessels have to meet different requirements to comply with. The IMO *Guidelines for ships operating in polar waters* meet the demands of guidelines on international level, because up to now, no specific mandatory measures beyond those for all open waters have been presented. These rules focus on the construction of ships intended to operate durably in cold climate conditions and prevention of environmental damages.

However, it is questionable whether the recommended value in this context of 30 kg m^{-2} for ice accumulation is sufficient. If the ice accretion is determined according the method of Overland, a 3.75 cm thick ice accumulation would be achieved already within 3 hours under "moderate icing" conditions.

Vessels and marine structures operating in harsh meteorological conditions without sufficient winterization pose a high risk for environmental damages and human disasters.
A minimum stability icing allowance for all kinds of vessels, anti- and de-icing equipment in a sufficient quantity and a well-trained crew, are the basic prerequisites for a safe future of the arctic shipping.

This requires that the standards of classification societies need to be aligned. The classification societies have sufficient experience of the winterization of ships and marine structures. But these are not yet harmonized, what is leading to a different view on the measures, including differences in minimum heating capacities and materials of use. A convention like the 2006 *IACS Unified Requirements for Polar Ships (IACS, 2011)*, concerning the polar class descriptions, structural and machinery requirements could equalize the differences. Harmonized measures are the cornerstone of safe use and international acceptance.

In summary, more and more attention to the future of shipping in cold climate conditions is given, however more cooperation between national and international administrations and authorities is required to reduce the risk potential and to ensure safer operation of ships and marine structures in the harsh environment of waters in the Arctic and Antarctic.

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