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Freezing Spray and Ice Accretion on Vessels: A Comprehensive Summary

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Abstract

Icing threatens the stability of vessels that operate in high-latitude waters. The accumulation of ice on vessels depends on meteorological conditions and vessel design. Meteorological data is input into either the Overland or Modified Stallabrass algorithms which calculate the amount of icing that will occur. Ice coverage in the Arctic region has changed significantly since algorithms were developed in the 1980s. The goal of the National Weather Service (NWS) and the Meteorological Service of Canada (MSC) is to create a cohesive model that determines the icing rate throughout the North American region. A comprehensive overview of vessel icing algorithms that compared their strengths and weaknesses was conducted to lead to the eventual revision and development of a new algorithm. Specifically, ongoing efforts to obtain new observation data from vessels in the North American region will be used to recalibrate the algorithms by relating the model's output to the severity of icing described by the observations. After relating the new observational data, a different Overland predictor value can be derived from the simplified heat balance of ice surface $L_i\rho_i\frac{dH_i}{dt} + C_W(T_w - T_f)\rho_w\frac{dH_w}{dt}$ **[1]**. A constant value, w_0 for the liquid water content equation, $R_w = w_0 * 10^{-3} * H_S * \exp(-\frac{z}{1.8})$, in the Modified Stallabrass algorithm can be calculated with updated data **[2]**. Current observational data applied to the algorithms will reflect the meteorological conditions in the Arctic. Progress made in the understanding of the meteorological conditions and associated augmentations necessary to the development of accurate icing predictions for vessel safety will be reported.

Keywords: Ice accretion, Vessels, Freezing spray

1. Purpose

The goal of this research is to provide a comparative analysis of the algorithms designed to predict vessel icing and highlight improvements for forecasting icing.

2. Introduction

Vessel icing, the accumulation of ice on a ship structure, is a danger to vessels operating in high-latitude waters. Threatening stability, icing can also damage radio and navigation equipment (Guest, 2005). The *Lady of Grace*, a fishing vessel in Nantucket Sound, sank on January 26, 2007 due to ice build-up on the decks (USCG, 2008). On January 29, 1989 the crabbing vessel *F/V Vestfjord* sent a report of heavy icing. *Vestfjord* was unable to act and sank, resulting in the deaths of six crew members (Guest, 2005). These significant examples emphasize the need for accurate forecasting models to predict icing.

The two sources of icing are via fresh and seawater. Freshwater icing is a result of precipitation, fog, and water vapor. The cause of seawater icing is ocean spray. Freshwater icing occurs on high structures: radar, antenna, and masts. Icing from seawater accumulates on the lower areas of vessels (Makkonen, 1984). The main source for ice accretion is seawater spray, enhanced when waves contact the hull of the vessel. The heading, speed, and direction of the vessel in relation to the wave field affect how spray contacts and ices it (Overland, 1986). The icing rate increases the faster a vessel steams into the wind and waves (Guest, 2005).

Accumulation of ice on the vessel depends on meteorological conditions and vessel design. The following conditions promote icing: cold sea temperatures (7°C/ 45°F), below freezing air temperatures (≤ -1.7°C/ 29°F), and strong winds (≥ 18 kts/ 9 m/s). Vessel design characteristics such as length, handling, and freeboard affect total icing as well. The more exposed a vessel is to sea spray, the greater chance the vessel will experience icing (Guest, 2005). As ice accumulates on a vessel, it raises the center of gravity and lowers the freeboard. This decreases the righting arm and heel angle, negatively affecting the stability (Chatterton, 2008). A higher probability of destabilization from icing occurs in vessels with low freeboard and large superstructures (Guest, 2005).

3. Forecasting Icing

Two types of models can be used to describe icing conditions: empirical and physical. Empirical models use icing observations to determine the severity of icing. Physical models apply theoretical and observational data to generate ice forecasts. Inputs for physical models include sea state and sea surface temperature parameters. Physical models connect icing severity and environmental conditions. These characteristics lend credibility to physical models and provide the scientific community reasons to favor them over empirical models (Henry, 1995).

Creating a model for forecasting requires observational data. The available data varies depending on the type of vessel, speed, and heading. Visual estimates typically describe the environmental conditions and ice accumulation, which can introduce error. Datasets require screening and parameters to focus the information for credibility. The models use data from different regions, affecting the calculation of their algorithms. When models have the same inputs and yield different forecasts, it is due to their calibration with observational data and the physics of icing (Henry, 1995).

4. Definitions

4.1. Spray Flux

Spray flux describes the delivery rate of spray (Makkonen et al., 1991). The components of spray flux are liquid water content (LWCLWC), the accumulation of water droplets as they collide with the vessel, and the velocity of the spray cloud relative to the vessel (Henry, 1995). Various approaches model spray flux. Jessup (1985) applies the following assumption to his spray flux equation: droplet velocity is equal to wind speed. Jessup (1985) equates the spray flux to the LWCLWC and wind speed of the spray cloud. Kachurin et al. (1974) state that LWC equals wave height times a coefficient dependent on experimental measurements. Stallbrass (1980) follows this approach, except unlike Kachurin et al. (1974), determines the value of the coefficient from ice accretion rates instead of spray measurements. Blackmore and Lozowski (1993) and Zakrzewski (1986) employ separate methods that include spray delivery time on the vessel, the vessel speed in relation to the phase velocity of the significant wave, and the height the spray impacts the hull of the vessel. Both standardize the coefficient value with LWC observations from the *MFV Narva,* a Soviet vessel in the Sea of Japan. This decreases the accuracy of the spray flux value because the vessel design is a factor in the observed LWC measurements. A final approach from Overland (1990) treats spray flux within a statistical parameter, calibrating the parameter with observed rates of ice accretion (Henry, 1995).

4.2. Sea Surface Temperature

Sea surface temperature (SST) is the temperature of the water closest to the surface of the ocean. The sensitivity of icing to SST is a discrepancy between algorithms (Figure 1). If the algorithms are responsive to changes in SST, the icing forecast will vary because of SST input. Algorithms that are insensitive to SST do not experience variation in icing forecasts because of SST inputs. Overland argues for icing sensitivity to SST because at temperatures >0°C, supercooling combined with small accretion fractions give the strong qualitative dependence of icing rate on sea temperature (Overland, 1990). In addition, for cold SST, the main freezing rate is due to heat transfer: wind speed times air temperature depression but for warmer SST, how the spray washes over the ship has more of an effect (Overland, 2011). The opposing argument from Shellard (1974) describes that the rapid supercooling of droplets makes icing rates less sensitive to sea surface temperature (Makkonen et al., 1991). The supercooling of droplets occurs over the entire range of SST and is not restricted to low temperatures. Shellard's (1974) description of insensitivity to sea surface temperature does not remove the effect of SST from the equation, stating that "sea surface temperature is a factor of limited importance but cannot be dismissed" (Overland, 1991). Sea surface temperature sensitivity's effect on icing depends on the model's response to droplet cooling throughout the temperature range and other parameters (Henry, 1995).

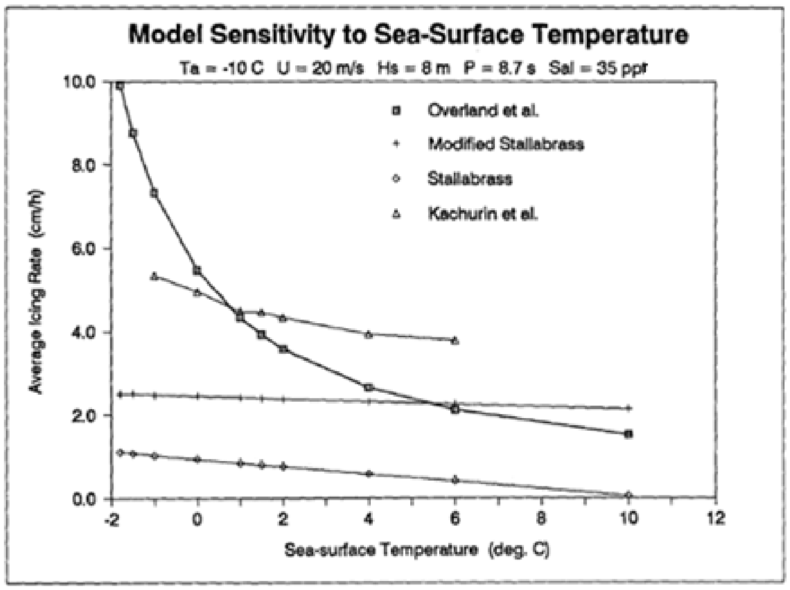

Figure 1. Comparison of sea-surface temperature sensitivities for various vessel icing models. (Makkonen et al., 1991).

4.3. Icing Thermodynamics

The application of icing thermodynamics describes the heat transfer process in the substrate/ice/water-film system and aids in calculating an estimate of the amount of spray that freezes. The distribution of ice on a vessel differs depending on its design. Forecast algorithms determine the ice accumulation rate using an ideal cylinder and relate the theoretical icing rate to observational data. The icing on the cylinder displays a small-scale version of the thermodynamic process that occurs on a vessel. The first coating on the cylinder is a layer of ice, followed by the surface film of seawater. When spraying the cylinder at a certain rate and temperature, energy transfers occur between the water/air, ice/water, and ice/substrate. The spray is either a source or sink for heat, and the latent heat is a source in the system. Summing energy terms and the energy conservation equals the freezing fraction. To simplify the thermodynamic process, icing models apply the following assumptions for the ice/water-film/substrate system: the surface film temperature is the temperature that incident spray immediately cools or heats to and the temperature of the ice layer and surface film equal the equilibrium freezing point. For energy conservation, the heat transfer in the system has to sum to zero. The assumptions for the heat transfer equation are to ignore the insignificant terms, radiational cooling of the icing surface, viscous heating, and spray's kinetic energy. This constructs a heat transfer equation for the icing thermodynamics process (Henry, 1995).

5. Algorithm Analysis

The motivation for evaluating icing models is to explain why the same inputs yield different forecasts. The analysis will illustrate how the algorithms treat the environmental parameters that affect the icing process. Each algorithm for forecasting has characteristics that cause variations in the determination of icing severity.

	Thermodynamic Equilibrium	Surface Film Temperature	Sea Surface Temperature	Spray Flux	Wave Height
Kachurin et al. (1974)	X	X	X	X	X
Stallabrass (1980)				X	X
Overland (1990)			X	X	
Blackmore and Lozowski (1993)	X				X
Modified Stallabrass (1994)				X	X

Figure 2. Comparison of icing algorithm methodology. The X for each category means the algorithm applies the input directly. If the boxed is not marked, the algorithm applies the variable indirectly or is insensitive to the variable. Sources: (Zakrzewski, 1986), (Henry, 1995), and (Hudson, 2011).

6. Kachurin et al. (1974)

Kachurin et al. (1974) is unique because of its thermodynamic equilibrium assumption. The model only applies thermodynamic equilibrium for the water/air system, rather than assuming the water/air, ice/water, and ice/substrate energy transfers are in equilibrium. Because the surface film temperature does not have to equal the freezing point, it enables modeling the transfer of heat from surface film to ice and ice to substrate, building three differential equations with time dependence. Solving these equations makes it possible to ignore substrate heat transfer after a thin ice layer forms. The surface film temperature equation uses the coefficient, which describes the heat transfer between the surface film and ice layer. The coefficient, h_i, poses a problem because it depends on the thickness of water and it is unknown how Kachurin et al. found the thickness making it difficult to use operationally (Henry, 1995).

In addition, the nomogram and digital version are unable to support the range of input values for operational requirements. Even with these restrictions, the modeling form of the algorithm is valuable to understanding the icing process (Henry, 1995).

7. Stallabrass (1980)

Stallabrass's (1980) algorithm parallels Kachurin et al. (1974) ,but has modifications that make it less complicated. The equation for surface film temperature is dependent on the freezing fraction and the seawater freezing point. The following adjustments balance the energy equation: runoff water is negligible, relative humidity is set at 90%, and the temperatures of droplets depend on air temperature, water temperature, and the spray droplets flight time.

Thirty-two icing cases from the Canadian East Coast calibrate the spray flux and droplet flight time equations. Predicted and observed icing rates are used to determine the flux coefficient (Henry, 1995).

Other differences include sensitivity to SST, wave height, and forecasting ability. The equation is not as sensitive as Overland's to changes in SST. Stallabrass (1980) directly applies wave height in the spray flux equation. The algorithm forecasts average icing rates well because the cases are average icing rates from each event (Hudson, 2011).

8. Overland (1990)

The main difference between Overland (1990) and the other algorithms is that it models spray flux within a statistical parameter. The adjustments to the following terms balance the energy equation: droplet cooling, runoff, and evaporative cooling of surface film are negligible, and the equilibrium freezing point of seawater equals the surface film temperature (Henry, 1995).

The parameter that Overland uses does not explicitly apply spray flux because of the variability associated with determining spray flux (Henry, 1995). The observations used for calibration are from Alaskan vessels and the *Zandberg*, a vessel operating in the Labrador Sea. Makkonen et al. (1991) and Hudson (2011) question the quality of Overland's data. Overland uses data from Pease and Comiskey's (1985) 58 separate icing incidents and Zakrzewski et al. (1989) 44 observations from hourly observations taken on board the *Zandberg* during three icing incidents (Makkonen et al., 1991). Overland defends his data stating, "This is solid observational data," comparing *Zandberg's* observations with similar icing rates from Lee (1958), De Angelis (1974), and George (1975) (Overland, 1991).

Other differences include treatment of wave height, input sensitivity, and the forecasting ability. The application of wave height is not direct; it is implied through wind speed. Applying small changes to the values of SST or wind speed can alter the icing forecast, taking it from light to heavy. Overland's algorithm is better at forecasting the maximum icing rate during an incident because the observations that calibrate the predictor are based on observed icing incidents maximum rates (Hudson, 2011). In addition, Overland provides a categorical forecast, whereas the other algorithms outputs are numerical icing rates (Henry, 1995).

9. Blackmore and Lozowski (1993)

Numerous characteristics separate Blackmore and Lozowski's (1993) approach to modeling icing from the other algorithms. The spray cloud surrounding the vessel is treated as a system consisting of entrained air and spray in mechanical and thermal equilibrium. Balancing the spray's thermal energy determines droplet temperature. This allows for the energy equation assumptions: the evaporative and convective cooling of surface film are negligible, surface film temperature equals the equilibrium freezing point, and runoff is negligible. Liquid water content observations from *Narva* are applied to calibrate the coefficient in the spray flux equation (Henry, 1995). Another difference includes the weak sensitivity to SST changes (Henry, 1995).

10. Modified Stallabrass (1994)

The main difference between Stallabrass (1980) and Modified Stallabrass (1994) is the treatment of the spray flux equation. Stallabrass's (1980?) coefficient for the spray flux equation is calibrated with observations from the east coast of Canada and Modified Stallabrass (1994) uses Zakrzewski's (1986) expressions for spray flux and spray-residence time (Henry, 1995 and Makkonen et al., 1991). In addition, the spray flux equation includes spray flux time dependence and the elevation the waves hit above the deck level. The Modified Stallabrass (1994) was derived to increase icing forecast accuracy because Stallabrass (1980) regularly under-predicted icing rates (Hudson, 2011).

Other differences include SST sensitivity and wave height. Changing SST has little effect on the algorithm output. Since wave height is directly applied, the algorithm is sensitive to changes in wave height input (Hudson, 2011).

11. Improving Ice Forecasting

"The issue of forecasting icing rates reappears about every 15 years" (Brown, 2011). The key to improving ice forecasting is to obtain new observations. Currently, the global climate change is causing ice coverage in the Arctic to diminish (Figure 3). The observations for calibrating algorithms are over twenty years old. To recalibrate the algorithms, new data that reflects the current Arctic environment is necessary.

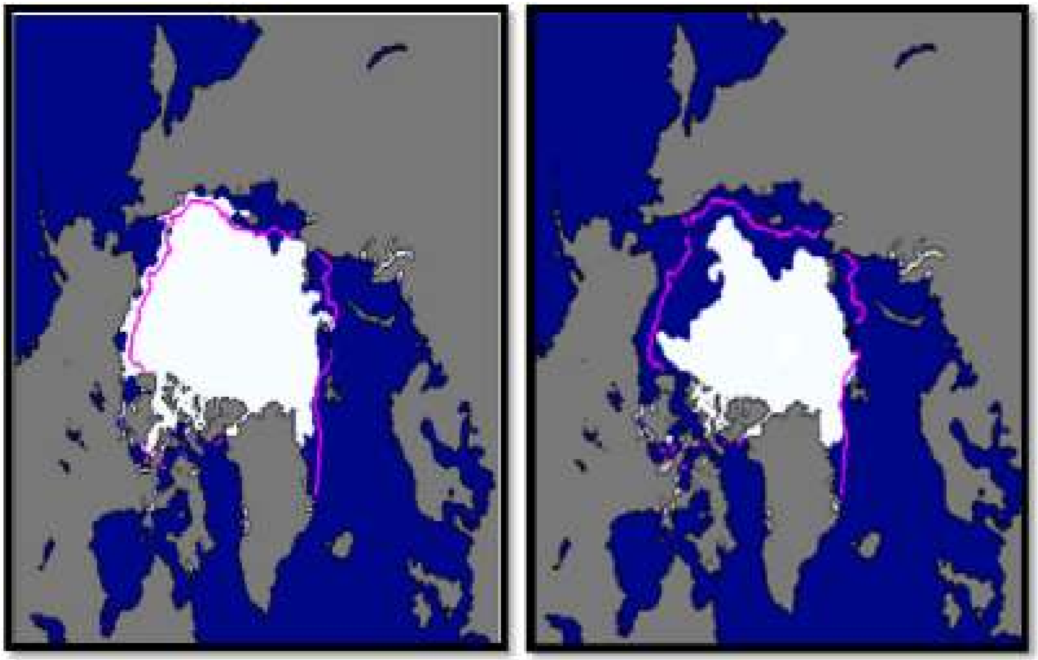

Figure 3. Comparison of sea ice coverage in September 1985 (left) to September 2010 (right). The magenta line represents the median ice edge in September from 1979-2000 (National Snow and Ice Data Center, 2011).

Another problem arises from the application of algorithms based on observations from one region to another. Overland's equation forecasts globally for NCEP ice accretion predictions (NCEP MMAB Global Superstructure Ice Accretion Guidance, 2009). Although it provides an accurate forecast, the dataset is based on observations from Alaskan waters. Ideally, forecasting would use an algorithm calibrated with observations from the prediction region. The National Research Center in Canada has a Marine Icing Database that provides mariners with a form to fill out in the event of an icing incident (NRC Marine Icing Database, 2010). Widespread distribution of this form to mariners could be valuable to icing research. The problem with this approach is mariners may not fill out the forms and even with data verification, the icing measurements will likely be estimates, resulting in questionable data. The best option is to develop an observational system for different vessels in various areas to take icing measurements. The challenge for improving icing forecasting resides in obtaining the resources for observations.

12. Other Icing Hazards

Less ice coverage in the Arctic has led to higher wave heights on average (Young et al., 2011). Ice disrupts wave propagation; with lesser ice extent, waves have a greater distance to propagate. An increase in the fetch combined with high wind speeds causes stronger, higher waves, raising the potential for icing (Figure 4).

The effects of less sea ice are apparent in the recent icing incident in Savoonga, Alaska. The coastal community of Savoonga, Alaska was affected by icing December 25, 2010- January 3, 2011. A combination of cold temperatures, blizzard conditions, and less sea ice, caused ocean spray to freeze on power lines which produced power outages throughout the town (State of the Climate National Overview, 2011).

Icing is not isolated to vessels and coastal communities; it affects structures, drilling and production platforms, and aircraft. Spray icing on drilling and production platforms have specific algorithms to determine icing rates, such as ICEMOD and RIGICE. These platforms need a forecasting system to determine the icing severity to make working conditions safer (Jones et al., 2009). Equipment malfunctions and or added weight from the ice can lead to fatal consequences (Williams, 2004).

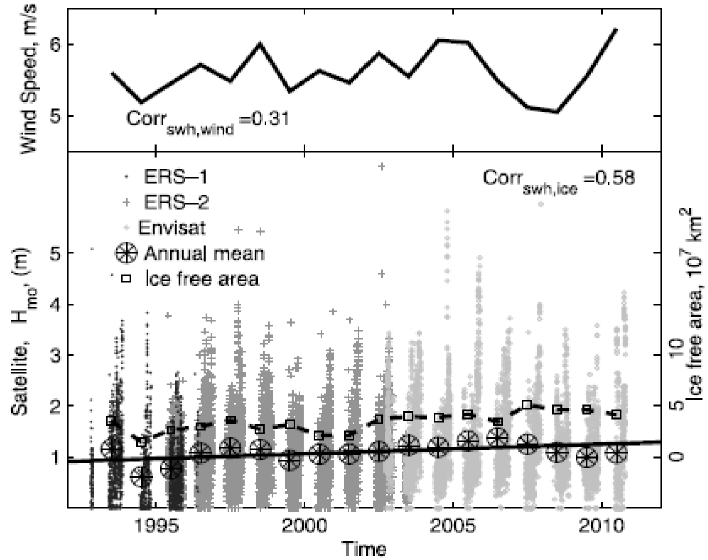

Figure 4. Significant wave height (SWH) for 1993-2010 in southeast Chukchi Sea (Lat 65-74 degrees N, Lon 170-210 degrees E) from May 1 – Nov 1. The straight black line is the SWH mean trend, with a positive increase rate of 0.02 m/year (Francis et al., 2011). Less ice coverage and higher wind speeds have led to an increase in average SWH (Young et al., 2011).

13. Conclusion

Vessel icing threatens operations in high-latitude waters, causing stability and mechanical problems. Forecasting vessel icing is a difficult process due to uncertainty in observational inputs and environmental parameters associated with it. The models present solutions to determine ice accretion rates. Each treats the physics of icing differently, causing varying outputs for the same environmental inputs. The value of improving forecasts is to increase vessel safety for operations in waters where the potential for freezing spray is present. Icing also presents hazards for structures, drilling and production platforms, aircraft, and coastal communities. Forecasting for these is essential for safety purposes. Understanding the meteorological conditions and the algorithms associated with icing are necessary to develop accurate predictions.

14. References

1. Brown, R. D., 2011: Private Communication.
2. Canadian East Coast Ice Engineering Issues, 2010: NRC Marine Icing Database. National Research Council Canada. Available: http://www.nrc-cnrc.gc.ca/eng/ibp/chc/reports/iceengineering.html . (June 2011).
3. Chatterton, M. and J. C. Cook, 2008: The effects of icing on commercial fishing vessels.Worchester Polytechnic Institute, 77 pp.
4. De Angelis, R. M., 1974: Superstructure icing. *Mar. Wea. Log,* **18,** 1-7.
5. Engineering, 2009: General Hydrostatics. BissoMarine. A Available: http://www.bissomarine.com/engineering.html#ghs. (July 2011).
6. Fish, A., 2011: Freezing spray in Alaska waters. NWS Alaska Region Headquarters, Anchorage, Alaska.
7. Francis, O. P., G. G. Panteleev, and D. E. Atkinson, 2011: Ocean wave conditions in the Chukchi Sea from satellite and *in situ* observations. *Geophysical Research Letters*. **38,** 5 pp.
8. George, D. J., 1975: The frequency of weather conditions favourable for ship spray icing on the seas round Iceland during 1972-73 winter. *Mar. Obs.,* 45, 177-185.
9. Guest, P., 2005: Vessel icing. *Mar. Wea. Log,* 49, 1-7.
10. Henry, N. L., 1995: Forecasting vessel icing due to freezing spray in Canadian east coast vessels Part I: Model Physics. Environment Canada: Newfoundland Weather Center, 43 pp.
11. Hudson, E., 2011: Freezing spray forecasting for Canadian Arctic waters. Meteorological Service of Canada: Prairie and Arctic Storm Prediction Centre, Edmonton, Alberta.

12. Jessup, R. G., 1985: Forecast techniques for ice accretion on different types of marine structures, including ships, platforms, and coastal facilities. Marine Meteorological and Related Oceanographic Activities, Report No. 15, WMO, Canada, 90 pp.

13. Jones, K. F. and E. L. Andreas, 2009: Technology assessment and research program, safety and engineering research: sea spray icing of drilling and production platforms. Cold Regions Research and Engineering Laboratory, 63 pp.

14. Kachurin L. G., L. I. Gashin, and I. A. Smirnov, 1974: Icing rate of small displacement fishing boats under various hydrometeorlogical conditions. *Meteorlogiya I Gidrologiya* 3, Moscow, 50-60.

15. Lee, A., 1958: Ice accumulation in the Barents Sea. *Mar. Obs.,* 28, 138-142.

16. Makkonen, L., 1984: Atmospheric icing on sea structures. U.S. Army Cold Regions Research and Engineering Laboratory, 77 pp.

17. ----------, R. D. Brown, and P. T. Mitten, 1991: Comments on “prediction of vessel icing for near-freezing sea temperatures.” *American Meteorological Society*, 565-567.

18. NOAA Environmental Modeling Center, 2009: NCEP MMAB global superstructure ice accretion guidance. NOAA National Weather Service. Available: http://polar.ncep.noaa.gov/marine.meteorology/vessel.icing/. (June 2011).

19. NOAA National Climatic Data Center, 2011: State of the climate national overview: January 2011. NOAA Satellite and Information Service. Available: http://www.ncdc.noaa.gov/sotc/national/2011/1. (July 2011).

20. Overland, J. E., C. H. Pease, R. W. Priesendorfer, and A. L. Comiskey, 1986: Prediction of vessel icing. *J. Climate Appl. Meteor.* **25,** 1793-1806.

21. ----------, 1990: Prediction of Vessel Icing for Near-Freezing Sea Temperatures. *Wea. Forecasting*, **5**, 62– 77.

22. ----------, 1991: Reply to comments on “prediction of vessel icing for near-freezing sea temperatures”. *Weather and Forecasting* **6,** 568-570., 2011: Private communication.

23. Pease, C. H., and A. L. Comiskey, 1985: Vessel icing data in Alaskan waters- 1979-1984 dataset. NOAA Data Report ERL PMEL-14, 16 pp. [Avaliable from the Pacific Marine Environmental Laboratory, Seattle, Washington.]

24. Sea Ice Index, 2011: Daily sea ice images. National Snow and Ice Data Center. Available:http://nsidc.org/data/seaice_index/. (July 2011).

25. Shellard, H.C., 1974: The meteorological aspects of ice accretion on ships. World Meteorological Organization, Marine Affairs Report No. 10, 34 pp.

26. Stallabrass, J. R., 1980: Trawler icing. A compilation of work done at NRC. Mechanical Engineering report MD-56, NRC No. 19372, National Research Council, Ottawa, Canada, 103 pp.

27. USCG (United States Coast Guard), 2008: Report of investigation into the sinking and loss of four crewmembers aboard the commercial fishing vessel *Lady of Grace*. USCG, Washington, D.C.

28. Williams, J., 2004: New forecasts give more icing details. USA Today. Available http://www.usatoday.com/weather/wlzicegf.htm. (June 2011).

29. Young, I.R., S. Zieger, and A. V. Babnin, 2011: Global trends in wind speed and wave height. *Science*. **332,** 451-455.

30. Zakrzewski, W. P., 1986: Icing of ships. Part I: Splashing a ship with spray. NOAA Tech. Memo., ERL PMEL-66, Pacific Marine Environmental Laboratory, Seattle, WA, 74 pp.

31. ----------, and I. Horjen, 1989: The use of ship icing models for forecasting icing rates on sea going ships. *Pro. 10th Int'l. Conf. on Port and Ocean Engineering under Arctic Conditions,* Luleå, Sweden, Vol. III, K.B. E. Axelsson and L.A. Fransson, Eds., Luleå University of Technology, 1454-1467.