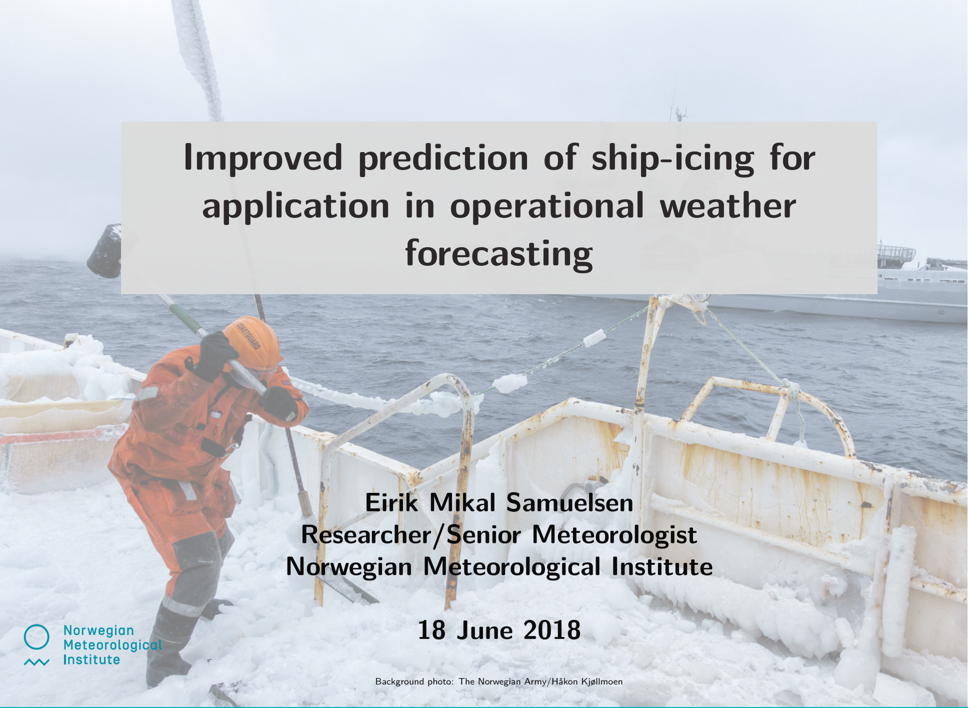

Improved prediction of ship-icing for application in operational weather forecasting

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Researcher/Senior Meteorologist
Norwegian Meteorological Institute

18 June 2018

Norwegian Meteorological Institute

Background photo: The Norwegian Army/Håkon Kjøllmoen

Ship icing = ice accumulation on ships

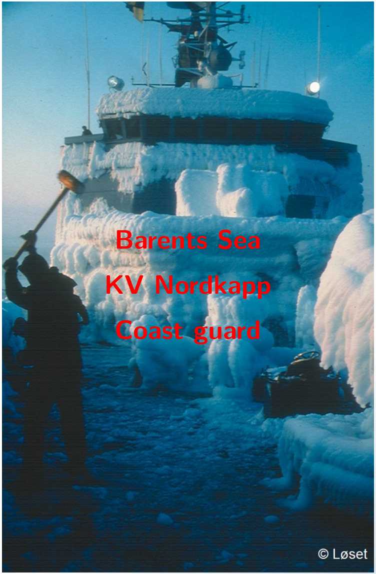


Photo: Sveinung Løset

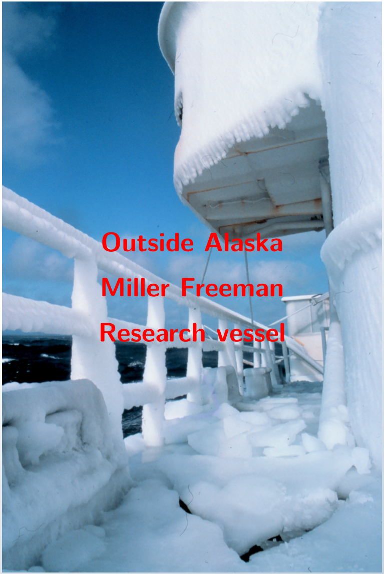


Photo: Captain R. A. Pawlowski, NOAA. Source: Wikimedia Commons.

Different types of ship icing

- Marine/Sea-spray icing (saline water)
  - Wave-ship-interaction icing
  - Wind-driven icing (ripping-off droplets from wave crest)
- Atmospheric icing (fresh water)
  - Snow
  - Freezing rain
  - Supercooled fog
- Combination of both saline and fresh-water icing

Freezing temperature dependent on salinity:

$$T_f = -54.1126\left(\frac{S_b}{1000 - S_b}\right), \text{ for } S_b \in [0, 124.7] \text{ ppt}$$

$$T_f = -2.0\ ^\circ\mathrm{C}, \text{ for } S_b = 35 \text{ ppt}$$

$$T_f = -7.1\ ^\circ\mathrm{C}, \text{ for } S_b = 117 \text{ ppt}$$

Risk factors

- Small ships
  - 100 ships capsized 1942-1970 (Sawada, 1968; Shellard, 1974)
  - N-Norway 1999 (3), Eastern USA 2007 (4), Alaska 2017 (6)
- Large ships
  - Slippery decks
  - Slippery ladders
  - Slippery handrails
  - Disabled life boats
  - Hamper radio communication
- De-icing with heat
  → energy consuming

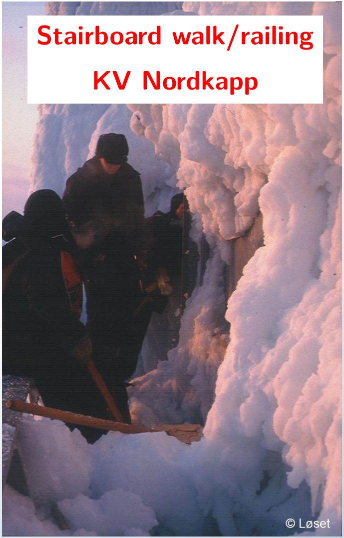
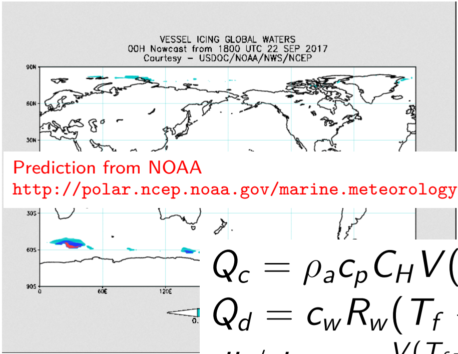
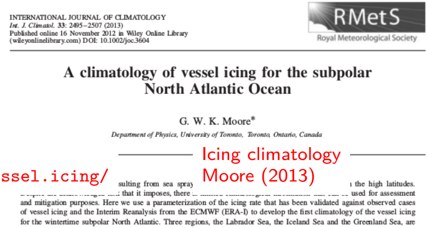


Photo: Sveinung Løset

Overland (1990): the most applied model



Prediction from NOAA
http://polar.ncep.noaa.gov/marine.meteorology/vessel.icing/


INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. 33: 2495–2507 (2013)
Published online 16 November 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3604

RMetS Royal Meteorological Society

A climatology of vessel icing for the subpolar North Atlantic Ocean

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... sulting from sea spray ... the high latitudes. ... that it imposes, there ... used for assessment and mitigation purposes. Here we use a parameterization of the icing rate that has been validated against observed cases of vessel icing and the Interim Reanalysis from the ECMWF (ERA-I) to develop the first climatology of the vessel icing for the wintertime subpolar North Atlantic. Three regions, the Labrador Sea, the Iceland Sea and the Greenland Sea, are

Icing climatology
Moore (2013)

$$Q_c = \rho_a c_p C_H V(T_f - T_a)$$

$$Q_d = c_w R_w(T_f - \mathrm{SST}) = \frac{c_w}{0.06} R_i(T_f - \mathrm{SST})$$

$$dh/dt \propto \frac{V(T_f - T_a)}{1 + 0.3(\mathrm{SST} - T_f)} \quad \text{Accuracy?}$$

20 to 75 met

PPR = Icing Predict
$\mathbf{V_a}$ = Wind Speed (m s^{-1})
$\mathbf{T_f}$ = Freezing point of seawater
$\mathbf{T_a}$ = Air Temperature (ºC)
$\mathbf{T_w}$ = Sea Temperature (ºC)

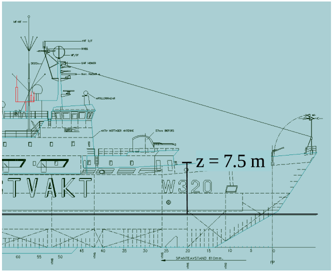
Peter Guest, Naval Postgraduate School
http://www.met.nps.edu/~psguest/polarmet/vessel/predict.html

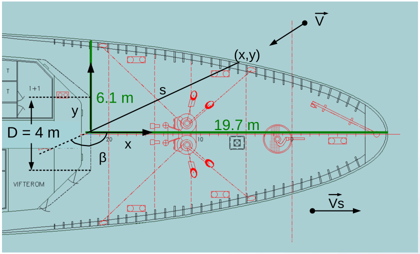
The following table shows the expected icing class and rates for 20 - 75 meter vessels that are steaming into the wind.

Table 2
Icing Class and Rate

PPR	<0	0-22.4	22.4-53.3	53.3-83.0	>83.0
Icing Class	None	Light	Moderate	Heavy	Extreme
Icing Rates (cm/hour) (inches/hour)	0	<0.7 <0.3	0.7-2.0 0.3-0.8	2.0-4.0 0.8-1.6	>4.0 >1.6

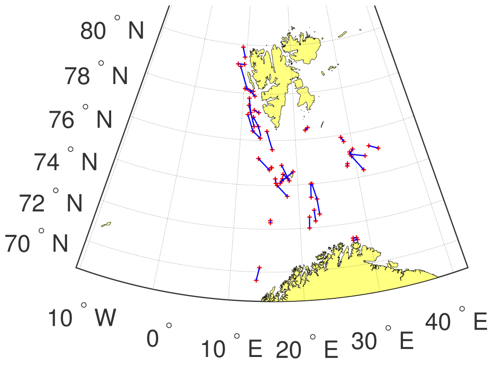
KV Nordkapp icing data





Above view/side view KV Nordkapp.

37 icing events



Median values obs:

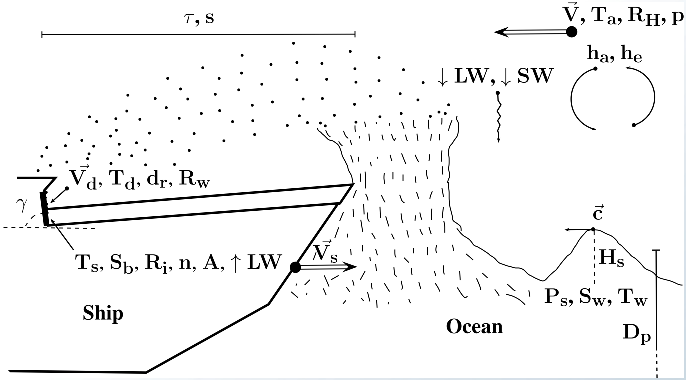
$\mathbf{T_a = -10.2\ ^\circ C}$

$\mathbf{V = 15.4\ m\ s^{-1}}$

$\mathbf{H_s = 3.0\ m}$ (vis.)

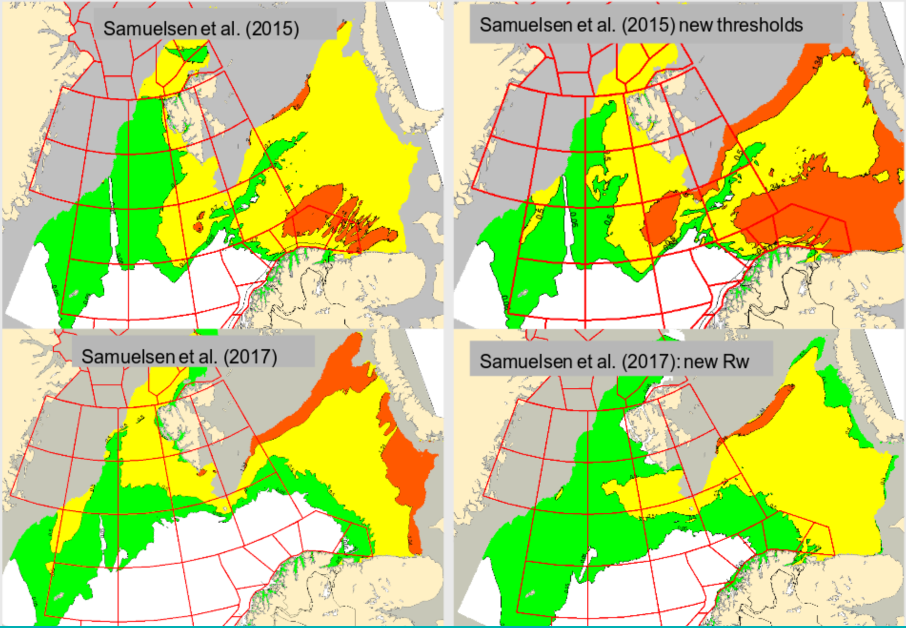
Model dev.: wave-ship-interaction icing

- Spray flux (R_w) $\rightarrow$ empirically derived and adj. for ref. ship
- Heat balance at a specific position of the ship ($Q_f = \sum_{i=1}^{N} Q_i$)
- Icing flux ($R_i = nR_w$)



Sketch of wave-ship-interaction icing process

Model calculations March 2018



Verification of icing rates

- Physics-based models:
  1. Overland (1990), $n = 0.06$ (const)
  2. Over bulk2 (C_H, $n = 0.5$, $Q_{e,r}$)
  3. Mod. Stall. (Stallabrass, 1980; Henry, 1995).
  4. MINCOG (Samuelsen et al., 2017)
- 3 nomograms (Mertins (1968), Lundqvist and Udin (1977), and Sawada (1962))

Verification of icing rates

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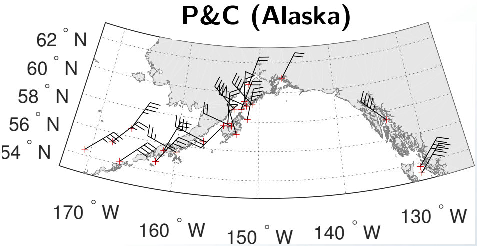
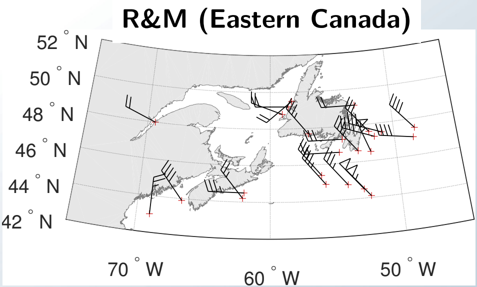
  4. MINCOG (Samuelsen et al., 2017)
- 3 nomograms (Mertins (1968), Lundqvist and Udin (1977), and Sawada (1962))
- 3 data sets applied:
  - KVN (Samuelsen et al. (2017))
  - P&C (Pease and Comiskey, 1985)
  - R&M (Roebber and Mitten, 1987)



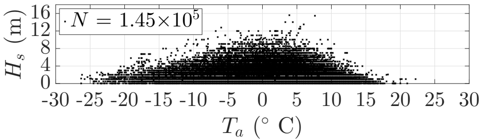


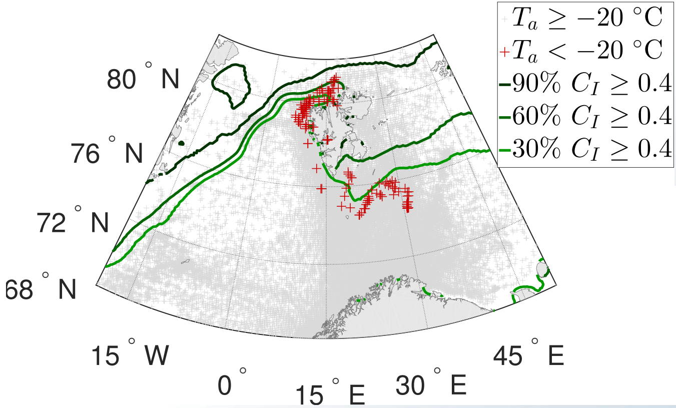
Categorical verification

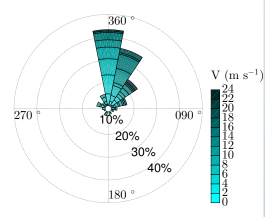
Modelname	KVN with no-icing ($N = 67$)				All data ($N = 114$)			
	PC	HSS	PSS	GMSS	PC	HSS	PSS	GMSS
				New category definition				
Ref. (unif.)†	**0.34**	**0.11**	**0.13**	**0.19**	**0.32**	**0.09**	**0.09**	**0.14**
Ref. (obs.)††	0.42	0.13	0.13	0.14	0.37	0.10	0.10	0.10
Over	0.21	0.05	0.07	**0.28**	0.25	0.07	0.08	**0.22**
Over bulk 2	0.30	0.07	0.08	**0.22**	**0.42**	**0.16**	**0.15**	**0.24**
ModStall	0.19	0.05	0.06	**0.26**	0.25	**0.10**	**0.12**	**0.29**
MINCOG	**0.40**	**0.17**	**0.18**	**0.30**	**0.45**	**0.20**	**0.20**	**0.26**
Mertins	**0.34**	**0.14**	**0.16**	**0.39**	**0.37**	**0.18**	**0.19**	**0.32**
LU	0.18	0.02	0.03	**0.26**	0.21	0.03	0.03	**0.20**
Sawada	0.19	0.04	0.04	**0.28**	0.27	0.09	**0.10**	**0.24**

MINCOG best for most scores.
Mertins quite good with new def. derived from distribution of icing-rate observations

High H_s and low T_a rarely coexist



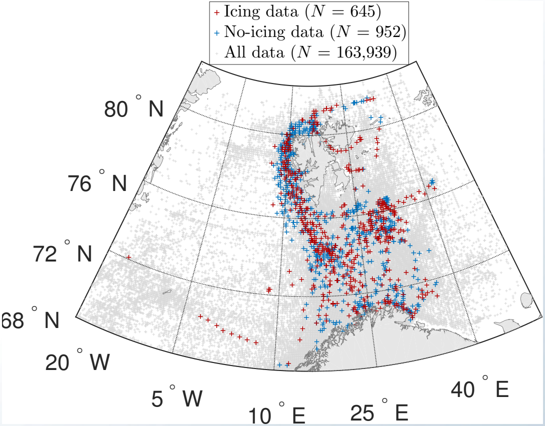




145,000 ship observations (1976-2007)

Weather situation during icing

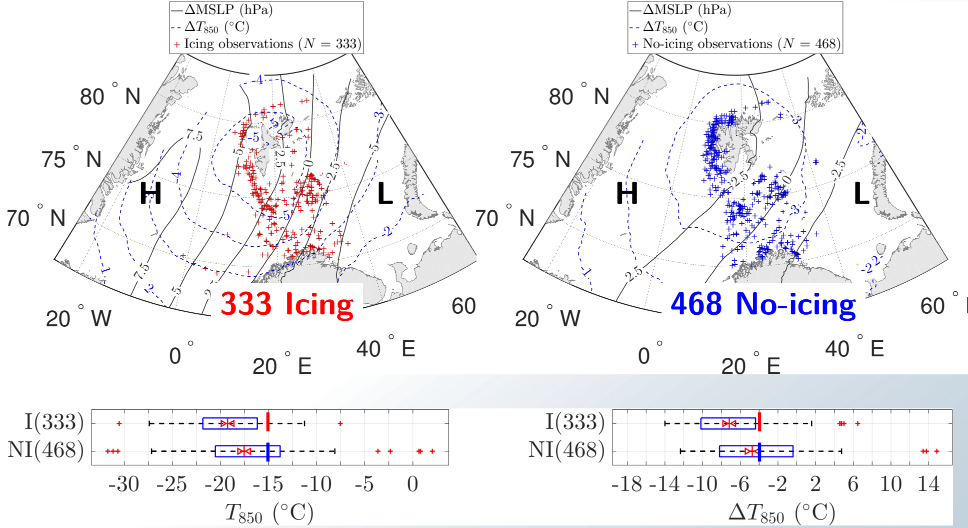
- Uncertainties in wave-ship-interaction icing modelling
- More general approach: large scale weather ↔ icing/no-icing (R_S)
- Simple model from upper-air parameters for long-term predictions



x Icing events, x No-icing events, x All ship observations

Anomaly maps: mean(Obs. − monthly mean)

ΔMSLP and ΔT_{850}



Questions?

Background photo: The Norwegian Army/Håkon Kjøllmoen

References I

Borisenkov, Y.P., Zablockiy, G.A., Makshtas, A.P., Migulin, A.I., Panov, V.V., 1975. On the approximation of the spray-cloud dimensions (In Russian), in: Romanova, L.I. (Ed.), Trudy Arkticeskogo. Antarkticheskii Nauchno-Issledovatelskii Institut, Gidrometeoizdat Leningrad. volume 317, pp. 121–126.

Defraeye, T., Blocken, B., Carmeliet, J., 2010. CFD analysis of convective heat transfer at the surfaces of a cube immersed in a turbulent boundary layer. International Journal of Heat and Mass Transfer 53, 297–308. URL: http://www.sciencedirect.com/science/article/pii/S0017931009005109, doi:10.1016/j.ijheatmasstransfer.2009.09.029.

Gulev, S.K., Hasse, L., 1998. North Atlantic wind waves and wind stress fields from voluntary observing ship data. Journal of physical oceanography 28, 1107–1130. URL: http://dx.doi.org/10.1175/1520-0485(1998)028<1107:NAWWAW>2.0.CO;2, doi:10.1175/1520-0485(1998)028<1107:NAWWAW>2.0.CO;2.

Henry, N.L., 1995. Forecasting Vessel Icing Due to Freezing Spray in Canadian East Coast Waters. Part I: Model Physics. Technical Report. Environment Canada, Newfoundland Weather Centre.

Horjen, I., 2013. Numerical modeling of two-dimensional sea-spray icing on vessel-mounted cylinders. Cold Regions Science and Technology 93, 20–35. URL: http://www.sciencedirect.com/science/article/pii/S0165232X13000773, doi:10.1016/j.coldregions.2013.05.003.

Horjen, I., Loeset, S., Vefsnmo, S., 1986. Icing hazards on supply vessels and stand-by boats. Technical Report. Norwegian Hydrotechnical Labratory.

References II

Kulyakhtin, A., Tsarau, A., 2014. A time-dependent model of marine icing with application of computational fluid dynamics. Cold Regions Science and Technology 104–105, 33–44. URL: http://www.sciencedirect.com/science/article/pii/S0165232X14000962, doi:10.1016/j.coldregions.2014.05.001.

Lundqvist, J., Udin, I., 1977. Ice accretion on ships with special emphasis on Baltic conditions. Research Report 23. Winter Navigation Research Board, Swedish Administration of Shipping and Navigation, Finnish Board of Navigation.. Norrköping, Sweden.

Mertins, H.O., 1968. Icing on fishing vessels due to spray. Marine Observer 38, 128–130.

Moore, G.W.K., 2013. A climatology of vessel icing for the subpolar North Atlantic Ocean. International Journal of Climatology 33, 2495–2507. URL: http://dx.doi.org/10.1002/joc.3604, doi:10.1002/joc.3604.

Overland, J.E., 1990. Prediction of vessel icing for near-freezing sea temperatures. Weather and Forecasting 5, 62–77. URL: http://dx.doi.org/10.1175/1520-0434(1990)005<0062:POVIFN>2.0.CO;2, doi:10.1175/1520-0434(1990)005<0062:POVIFN>2.0.CO;2.

Pease, C.H., Comiskey, A.L., 1985. Vessel icing data in Alaskan waters-1979-1984 dataset. NOAA Data Report ERL PMEL-14. Pacific Marine Environmental Laboratory.

Roebber, P., Mitten, P., 1987. Modelling and measurement of icing in Canadian waters. Technical Report. Canadian Climate Centre, Atmospheric Environment Service.

References III

Rohsenow, W.M., Choi, H.Y., 1961. Heat, mass, and momentum transfer. Prentice Hall.

Samuelsen, E.M., Edvardsen, K., Graversen, R.G., 2017. Modelled and observed sea-spray icing in Arctic-Norwegian waters. Cold Regions Science and Technology 134, 54 – 81. URL: http://www.sciencedirect.com/science/article/pii/S0165232X16303275, doi:https://doi.org/10.1016/j.coldregions.2016.11.002.

Sawada, T., 1962. Icing on ships and the forecasting method.(In Japanese). Snow and Ice , 12–14.

Sawada, T., 1968. Ice accretion on ships in northern seas of Japan. J. Meteorol, Soc. Japan 46, 350–354.

Shellard, H.C., 1974. The Meteorological Aspects of ice accretion on ships. Technical Report 10. World Meteorological Organization. Marine Science Affairs Report.

Stallabrass, J.R., 1980. Trawler icing - A compilation of work done at N.R.C. Mechanical Engineering Report MD-56. National Research Council Canada.

Teigen, S.H., Hansen, E.S., Roth, J.C., 2015. Marine icing severity in the Barents sea, in: Proceedings of the 23rd International Conference on Port and Ocean Engineering under Arctic Conditions, Norwegian University of Science and Technology, Trondheim. pp. 1–7. [Available online at http://www.poac.com/Papers/2015/pdf/poac15Final00148.pdf. Accessed 29 June 2017.].

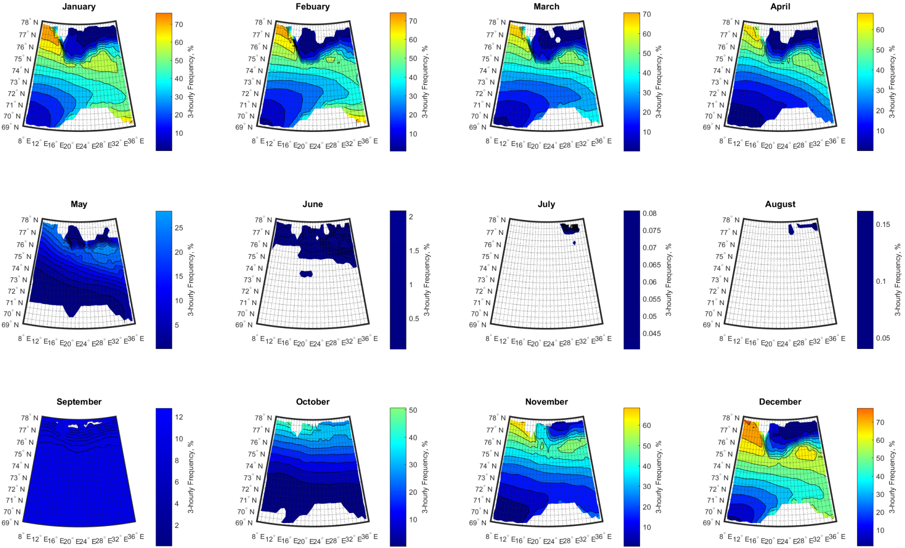
Zakrzewski, W.P., 1987. Splashing a ship with collision-generated spray. Cold Regions Science and Technology 14, 65–83. URL: http://www.sciencedirect.com/science/article/pii/0165232X87900450, doi:10.1016/0165-232X(87)90045-0.

Supporting information

Societal impacts

- Increased traffic in northern areas may increase the necessity of accurate ship-icing predictions
- Safer travels
- Economical beneficial with more accurate icing predictions
- Calculate icing potential by using T_{850}, ΔT_{850} in Global Climate Models to find possibility of icing in northern area in future scenarios

Icing freq. 1980s (Naseri and Samuelsen, unpubl.)



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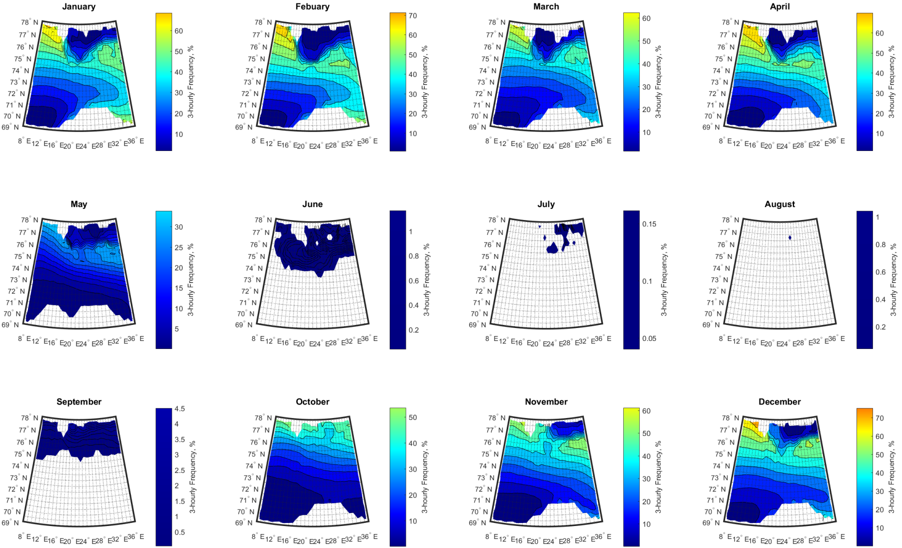

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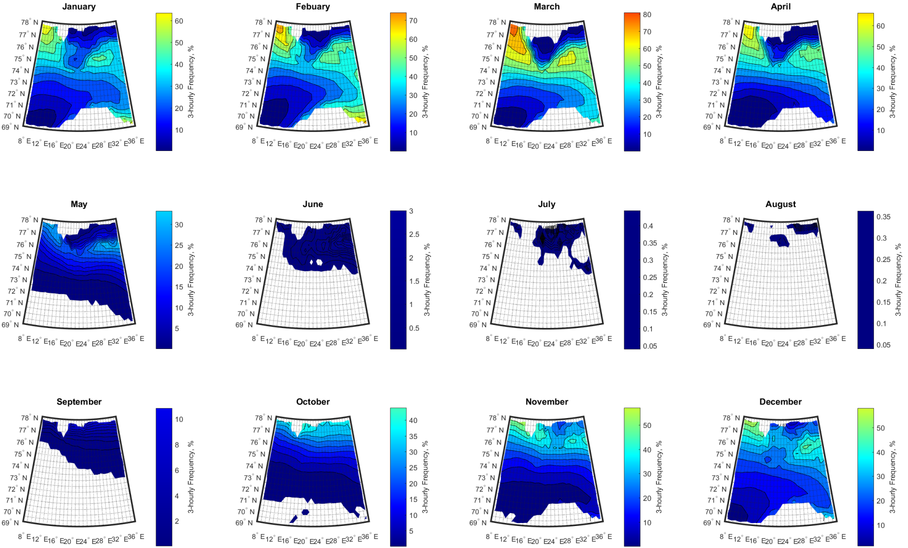
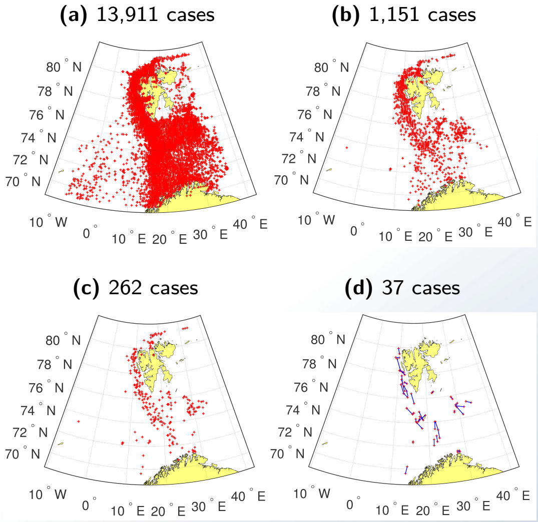


Calculation of icing rate

- $z = 6.5$ to 8.5 m
- $L = 105$, but position only 6.1 to 19.7 m from gunwale/perimeter
- $D = 4$ m
- Icing rate calculated from E_S data:
  - $\frac{dh}{dt} = \frac{E_S(t_2) - E_S(t_1)}{t_2 - t_1}$
- Trajectory model for droplet/spray speed
  - $\frac{d\vec{V}}{dt} + \frac{3}{4}\frac{C_d}{d_r}\frac{\rho_a}{\rho_w}|\vec{V}_d - \vec{W}_r|(\vec{V}_d - \vec{W}_r) - \vec{g}(1 - \frac{\rho_a}{\rho_w}) = 0$
  - Mathematical expression for s through elliptical shaped body fit of gunwale (MATLAB)

Screening of KV Nordkapp data



a) All obs. (1983-2000) b) Icing registered c) Subj. icing rate d) Selected cases

Screening details

- $\Delta t \leq 9$ h
- $C_I < 0.4$, $I_S = 1$, 3, or 5 in end position (spray icing)
- Mean ship speed (V_s) and heading (D_{ir}) $\rightarrow$ from position data assuming constant heading
- $\beta = |D_{\mathrm{ir}} - D_D| \in \langle 90{,}180]^\circ$
- $V_s \neq 0$
- Observed SST, SVIM SST, and NORA10 SST were compared. SVIM and OBS were most similar.
- H_s, P_s from Gulev and Hasse (1998).
  - $H_s = \sqrt{H_{\mathrm{ws}}^2 + H_{\mathrm{sw}}^2}$ for $|D_D - D_W| < 30^\circ$, otherwise $H_s = \max\left(H_{\mathrm{ws}}, H_{\mathrm{sw}}\right)$
  - $P_s = \max\left(P_{\mathrm{ws}}, P_{\mathrm{sw}}\right)$ for $|D_D - D_W| < 30^\circ$, otherwise $P_s = P_{H_s(max)}$
  - Multiplying P_s with some correction constants

Spray flux from Borisenkov et al. (1975) data

$$R_w = (\vec{V_d} \cdot \vec{n_1}) l_{\text{wc}} N t_{\text{dur}}$$

$$l_{\text{wc}} = 6.36 \times 10^{-5} H_s V_r^2 \mathrm{e}^{(-0.55z)} \quad \text{39 m fishing boat}$$

Other parameters adjusted for large ship

$$\frac{d\vec{V_d}}{dt} + \frac{3}{4}\frac{C_d}{D}\frac{\rho_a}{\rho_w}|\vec{V_{\text{rel}}}|\vec{V_{\text{rel}}} - \vec{g^*} = 0, \quad \text{Traj. model for KV Nordkapp}$$

$$\vec{n_1} = [\sin\gamma, 0, \cos\gamma] \quad \gamma \text{ tilt angle of plate}$$

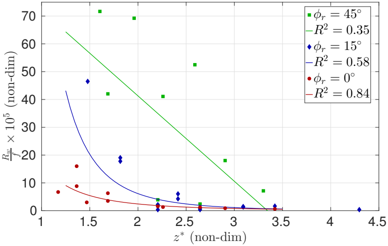
$$N = \frac{V_r}{4\lambda}, \quad \text{Spray frequency large ship}$$

$$t_{\text{dur}} = 0.1230 + 0.7009\frac{V_r H_s}{V}, \quad \text{New expr. from USCGC Midgett}$$

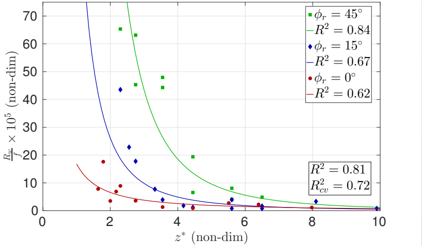
Spray flux from Horjen et al. (1986) data

- $R_w = f_1 A \left(z^*\right)^B \cos\phi_r$
- Spray data from Endre Dyrøy (64 m) updated with wave data from MET database:
  - $z^* = \frac{2z}{H_s} - 1$
  - $f_1 = \frac{g\rho_w H_s^2}{\lambda V^2} V_{gr}$
  - A, B empirical constants adjusted for 3 relative headings (ϕ_r)

Horjen (2013) fit



New fit



Additional information

- $h_{\rm ax} \rightarrow$ CFD modelling of cubes, Defraeye et al. (2010)
- $h_{\rm ay} \rightarrow$ Laboratory experiments over a flat plate in a turbulent flow, Rohsenow and Choi (1961)
- SW from diffuse radiation taken into account. Has an effect in April. Applying a view factor based on the angle of the plate.
- LW - instead of using T_{2m}, I have applied reanalysis data. Temperature and humidity decreasing strongly with height (lower values).
- $h_e = \left(\frac{\mathsf{Pr}}{\mathsf{Sc}}\right)^{0.63} \frac{\epsilon L_v}{c_p p} h_a$
- $\mathrm{Pr} = 0.715$, $\mathrm{Sc} = 0.595$, $L_v = 2.5 \times 10^6$ (increasing for lower temperature, decreasing for salinity)

Defining no-icing events

- Not reporting icing information does not guarantee no icing
- Paper II $\rightarrow$ 41 no-icing events:
  $E_S(t_2) - E_S(t_1) = 0$ cm (whole cm only)
- Paper III $\rightarrow$ 30 no-icing events:
  as II $+ R_S = 0$
- Predicted no-icing events for $\frac{dh}{dt} < 0.05$ cm h^{-1}
- Paper IV:
  More general approach. No-icing events only for $R_S = 0$ for 17 ships.

Categorical icing-rate verification

Paper I and II (Overland (1990) boundaries):

- No icing:
  $x < 0.05$ cm h^{-1}
- Light:
  $x \leq 0.70$ cm h^{-1}
- Moderate:
  $0.70 < x \leq 2.00$ cm h^{-1}
- Severe:
  $x > 2.00$ cm h^{-1}

Paper III (new boundaries):

- No icing:
  $x < 0.05$ cm h^{-1}
- Light:
  $x \leq 0.50$ cm h^{-1}
- Moderate:
  $0.50 < x \leq 1.34$ cm h^{-1}
- Severe:
  $x > 1.34$ cm h^{-1}

Multi-categorical verification scores

- In order to condense the information in the contingency table
- Need to look upon several scores to not exclude too much information
- Percent Correct (PC):

$$\mathrm{PC} = \sum_{i=1}^{4} p\left(y_i, o_i\right)$$

Not equitable - does not consider the effect of hitting correctly by chance

Pred.\Obs.	N	L	M	S
OBS N	**11/78**	5/78	0	0
OBS L	20/78	**14/78**	2/78	0
OBS M	10/78	7/78	**5/78**	1/78
OBS S	0	2/78	1/78	**0**

Multi-categorical verification scores

- In order to condense the information in the contingency table
- Need to look upon several scores to not exclude too much information
- Heidke Skill Score (HSS):

$$\mathrm{HSS} = \frac{\mathrm{PC} - \sum_{i=1}^{4} p(y_i) p(o_i)}{1 - \sum_{i=1}^{4} p(y_i) p(o_i)}$$

Probability of randomly hitting the diagonal element for each category

$i = 1$

Pred.\Obs.	N	L	M	S
N	**11/78**	5/78	0	0
L	20/78	**14/78**	2/78	0
M	10/78	7/78	**5/78**	1/78
S	0	2/78	1/78	**0**

$$p(y_1, o_1) = 11/78 \qquad = 0.141$$
$$p(y_1) \times p(o_1) = 16/78 \times 41/78 \qquad = 0.108$$

Multi-categorical verification scores

- In order to condense the information in the contingency table
- Need to look upon several scores to not exclude too much information
- Peirce Skill Score (PSS)

$$\text{PSS} = \frac{\text{PC} - \sum_{i=1}^{4} p(y_i) p(o_i)}{1 - \sum_{j=1}^{4} p(o_j)^2}$$

Uses sample climatology in the denominator instead

$i = 1$

Pred.\Obs.	N	L	M	S
N	**11/78**	5/78	0	0
L	20/78	**14/78**	2/78	0
M	10/78	7/78	**5/78**	1/78
S	0	2/78	1/78	**0**

$$p(y_1, o_1) = 11/78 \qquad = 0.141$$

$$p(y_1) \times p(o_1) = 16/78 \times 41/78 \qquad = 0.108$$

$$(p(o_1))^2 = (41/78)^2 \qquad = 0.276$$

Multi-categorical verification scores

- In order to condense the information in the contingency table
- Need to look upon several scores to not exclude too much information
- Gandin-Murphy Skill Score (GMSS)

$$\mathrm{GMSS} = \sum_{i=1}^{4} \sum_{i=j}^{4} p\left(y_i, o_j\right) s_{ij}$$

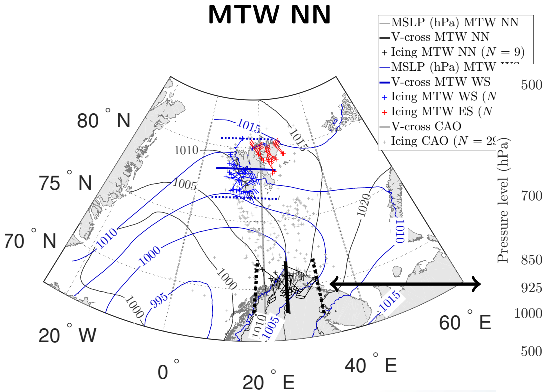
Generate symmetric scoring matrix for all elements based on sample climatology

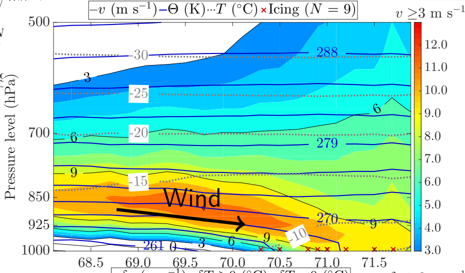
Pred.\Obs.	N	L	M	S
N	**11/78**	5/78	0	0
L	20/78	**14/78**	2/78	0
M	10/78	7/78	**5/78**	1/78
S	0	2/78	1/78	**0**

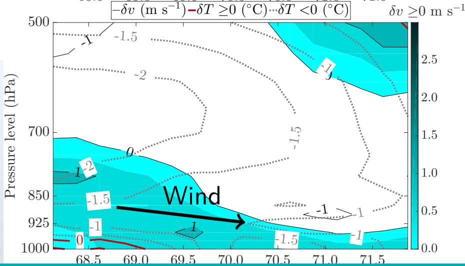
Higher weight to elements close to diagonal for rare events even for misses

Pred.\Obs.	N	L	M	S
N	**0.349**	−0.286	−0.662	−1.000
L	−0.286	**0.417**	0.040	−0.297
M	−0.662	0.040	**2.929**	2.592
S	−1.000	−0.297	2.592	**28.592**

Vertical cross sections

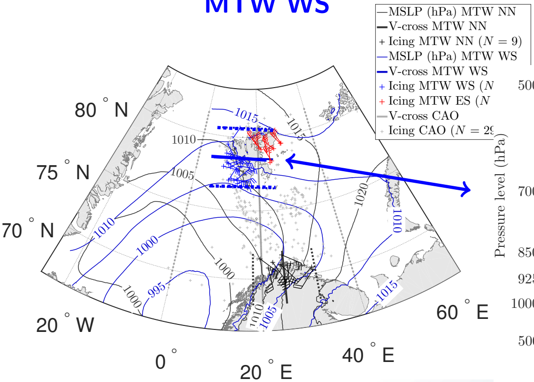


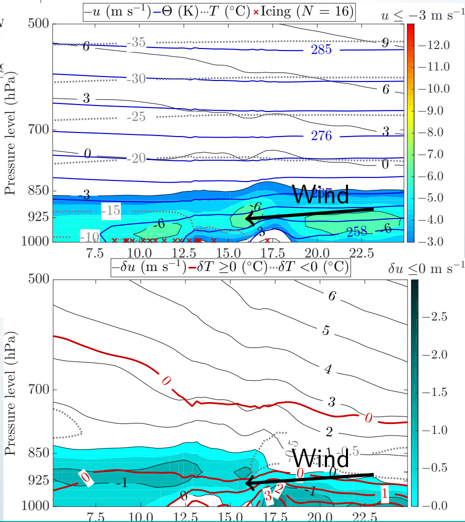




Vertical cross sections

MTW WS





Vertical cross sections