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Modelled and observed sea-spray icing in Arctic-Norwegian waters

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A B S T R A C T

Hazardous marine icing is a major concern for ships operating in Arctic waters during freezing conditions. Sea spray generated by the interaction between a ship and ocean waves is the most important water source in these dangerous icing events. Although there exist several data sets with observations of ice accretion in conjunction with meteorological and oceanographic parameters, these data sets often have shortcomings and only a few are obtained in Arctic-Norwegian waters. In this study, icing rates from a large coast-guard vessel type, the KV Nordkapp class, are used for verification of a newly proposed Marine-Icing Model for the Norwegian COast Guard (MINCOG). Ship observations, NOrwegian ReAnalysis 10km data (NORA10), and wave data based on empirical statistical relationships between wind and waves are all applied in MINCOG and the results are compared. The model includes two different empirically-derived formulations of spray flux. It is found that in general the best results for different verification scores are obtained by using a combination of observed atmosphere and ocean-wave parameters from the ships, and wave period and direction from NORA10, regardless of the spray-flux formulation applied. Furthermore, the results illuminate that wave parameters derived from formulas based on empirical relationships between the local wind speed and significant wave height and wave period, compared to those obtained from observations or NORA10, considerably worsen icing-rate predictions in Arctic-Norwegian waters when applied in MINCOG.

1. Introduction

Icing at sea can be a hazardous phenomenon which under the most dramatic circumstances may cause capsizing and the loss of lives. According to Stallabrass (1971), 40 Canadian fishermen died due to icing in the 1960s. Icing on ships can be divided into sea-spray icing, where wave-ship-collision-generated sea spray is reckoned as being the most important water source in dangerous icing events (Lozowski et al., 2000; Stallabrass, 1980; Zakrzewski, 1987), and into atmospheric icing where the water source is either fog, typically Arctic sea smoke, rain/drizzle or snow (Stallabrass, 1980). Icing can also be a result of a combination of both. From the 1960s to the 1980s there was extensive work in different countries trying to collect icing data for use in prediction of dangerous icing events. The data were used either to create statistical relationships between different environmental parameters and observed icing rates, e.g. Mertins (1968), or as input to wave-ship-collision-generated freezing sea-spray algorithms, e.g. Stallabrass (1980). Overland et al. (1986) on the other hand, use a combination of both. Brown and Roebber (1985) estimate that around 7000 questionnaire responses from the USA, Canada, Japan, the former Soviet Union, Sweden and Germany were used to collect icing data. Unfortunately little of these data have been made accessible for use.

An article review has revealed that 516 cases of ice accretion are available from the east coast of Canada and Alaska. For the east coast of Canada 3 papers include the following numbers of icing events: 39 cases in Stallabrass (1980), 45 cases in Zakrzewski et al. (1989) and 307 cases in Roebber and Mitten (1987). The Alaskan data are only published in Pease and Comiskey (1985) and 58 of them were selected and applied in Overland et al. (1986). In addition, Zakrzewski and Lozowski (1989) have collected 115 cases by

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Abbreviations: NORA10 , NOrwegian ReAnalysis 10 km hindcast archive (Reistad et al., 2011); MINCOG , Marine-Icing Model for the Norwegian COast Guard; USCGC , United States Coast Guard Cutter; MFV , Medium-sized fishing vessel; nm , Nautical miles; WMO , World Meteorological Organization; SVIM , Nordic 4 km ocean model hindcast archive (Lien et al., 2013); ERA40 and ERA-Interim , European Centre for Medium-Range Weather Forecasts Reanalyses (Dee et al., 2011. Uppala et al., 2005); CFD , Computational Fluid Dynamics, N10, HYBRID1, HYBRID2, ZAKR; HORJEN , Different sources for model-input (see Section 3.2); PC , Proportion Correct; HSS , Heidke Skill Score; PSS , Pierce Skill Score; GMSS , Gandin-Murphy Skill Score; N , No icing; L , Light icing; M , Moderate icing; S , Severe icing.

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Nomenclature

A	Albedo of freezing surface
BIAS	Mean error: $\frac{1}{n'}\sum_{i=1}^{n'}(P_i - O_i)$,$n'$ number of events, P_i predictions, O_i observations
C_d	Drag coefficient
C_I	Ice concentration (code/fraction)
c	Wave-phase speed (m s^{-1})
c_g	Wave-group speed (m s^{-1})
c_p	Specific heat capacity of air (1004 J kg^{-1}°C^{-1})
c_w	Specific heat capacity of sea water (4000 J kg^{-1}°C^{-1})
D	Freezing plate width (4 m)
D_D	Wind direction (°) **
D_W	Wave direction (°) **
D_{ir}	Ship direction (°) **
D_p	Water depth (m)
d_r	Droplet diameter (2.0 mm)
E	Collection efficiency
E_S	Ice-accumulation thickness (cm)
e_s	Saturation vapour pressure (hPa)
g	Gravitational acceleration (9.81m s^{-2})
g^*	Effective gravitational acceleration of droplet (m s^{-2})
$\frac{dh}{dt}$	Icing rate (cm h^{-1})
h_a	Heat-transfer coefficient (W m^{-2}°C^{-1})
h_{ad}	h_a for droplet cooling (W m^{-2}°C^{-1})
h_e	Evaporative heat-transfer coefficient (W m^{-2} hPa^{-1})
h_{ed}	h_e for droplet cooling (W m^{-2} hPa^{-1})
H_s	Significant wave height (m)
H_{sw}	Swell-wave height (m)
H_{ws}	Wind-wave height (m)
I_S	Icing cause (code)
k^*	Interfacial distribution coefficient (0.3)
k_a	Thermal conductivity of air (0.023 W m^{-1}°C^{-1})
L_{fs}	Latent heat of freezing of saline water (J kg^{-1})
L_f	Latent heat of freezing of fresh water (3.33×10^5 J kg^{-1})
L_v	Latent heat of vaporisation (2.5×10^6 J kg^{-1})
l_{wc}	Liquid water content in spray (kg m^{-3})
↓↑LW	Incoming and outgoing longwave radiation (W m^{-2})
MAE	Mean absolute error: $\frac{1}{n'}\sum_{i=1}^{n'}\lvert P_i - O_i\rvert$
MASE	Mean absolute scaled error: $\frac{\mathrm{MAE}}{\frac{1}{n'-1}\sum_{i=2}^{n'}\lvert O_i - O_{i-1}\rvert}$
n	Freezing fraction
$\vec{n}_1$	Normal vector towards freezing plate
N	Spray frequency (s^{-1})
N_N	Total cloud cover (oktas)
Nu	Nusselt number
Nu$_d$	Droplet Nusselt number
Pr	Prandtl number (0.715)
P_s	Significant wave period (s)
P_{sw}	Swell-wave period (s)
P_{ws}	Wind-wave period (s)
p	Air pressure at mean sea level (hPa)
Q_c	Convective heat flux (W m^{-2})
Q_{cd}	Convective heat flux for droplets (W m^{-2})
Q_{cond}	Conductive heat flux (W m^{-2})
Q_d	Heat flux from incoming water droplets (W m^{-2})
Q_e	Evaporative heat flux (W m^{-2})
Q_{ed}	Evaporative heat flux for droplets (W m^{-2})
Q_f	Heat flux released by freezing (W m^{-2})
Q_r	Radiative heat flux (W m^{-2})
R^2	Coefficient of determination
R^2_{cv}	Leave one out cross-validated R^2
Re	Reynolds number
Re$_d$	Droplet Reynolds number
R_i	Ice accretion flux (kg m^{-2} s^{-1})
R_S	Visually estimated icing rate (code)
R_w	Spray flux (kg m^{-2} s^{-1})
R_H	Relative humidity of air (fraction)
R_R	Accumulated water-equivalent precipitation (mm)
S_b	Salinity of brine (‰)
Sc	Schmidt number (0.595)
S_i	Salinity of ice (‰)
S_w	Salinity of sea water (‰)
↓↑SW	Incoming and reflected shortwave radiation (W m^{-2})
s	Distance from freezing plate to gunwale (m)
T	Collection time of spray (s)
T_{850}	Air temperature at 850 hPa (°C)
T_a	Air temperature at ship level (°C)
T_d	Droplet temperature (°C)
T_f	Freezing temperature of sea water (°C)
T_s	Freezing temperature of brine (°C)
T_w	Sea-surface temperature (°C)
t_{dur}	Time duration of spray cloud (s)
t_{int}	Time interval between a collision between a ship and waves (s)
Δt	Time difference between two E_S-observations (h)
$\vec{V}_d$	Droplet velocity in coordinate system following ship
$\vec{V}_{\mathrm{rel}}$	Relative velocity between droplets and wind
$\vec{V}$	Absolute wind velocity
V	Absolute wind speed (m s^{-1})
V_r	Relative speed between a ship and an oncoming wave (m s^{-1})
V_{gr}	Relative speed between a ship and wave groups (m s^{-1})
V_s	Ship speed (m s^{-1})
V_V	Visibility (code)
$\vec{W}_r$	Wind velocity in coordinate system following ship
W_r	Relative speed between a ship and wind or wind speed in coordinate system following ship (m s^{-1})
W_W	Present weather (code)
$\vec{x}$	3D position vector in coordinate system following ship
z	Height above sea level (6.5–8.5 m)
z^*	Non-dimensional height above significant waves ($z^* = \frac{2z}{H_s} - 1$)
α	Angle between a ship and waves (°)
β	Angle between a ship and wind (°)
γ	Tilt angle between the freezing plate and the horizontal (85°)
ϵ	Ratio of molecular weights of water and air (0.622)
λ	Wave length (m)
ν	Kinematic viscosity (1.2×10^{-5} m^2 s^{-1})
ρ_a	Density of air (1.3 kg m^{-3})
ρ_i	Density of ice (890 kg m^{-3})
ρ_w	Density of sea water (1028 kg m^{-3})
σ	Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
τ	Droplet flight time (s)
ϕ_r	Heading relative to wind in coordinate system following ship (°)

** defined in wind-direction notation, i.e. azimuth of incoming direction.

translating Russian papers from the 1970s. Common to most of these data sets are that cases from different ship types are merged together. Due to variations in bow shape and ship size, spray characteristics and spray icing resulting from collisions between ship and wave, may