NOTES AND CORRESPONDENCE

Comments on "Prediction of Vessel Icing for Near-Freezing Sea Temperatures"

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1. Introduction

Overland (1990) recently presented an update to a ship-icing prediction algorithm that is used operationally by NOAA. The predictor used to estimate the severity of potential spray-icing conditions is derived from the simplified heat balance of the icing surface (Eq. 2a in Overland (1990); for notation, see Appendix)

$$L_i\rho_i \frac{dH_i}{dt} + C_w(T_w - T_f)\rho_w \frac{dH_w}{dt} \approx C_H\rho_a C_a V_a(T_f - T_a), \quad (1)$$

by assuming that

$$\Phi = \frac{C_w}{L_i} \frac{\rho_w \frac{dH_w}{dt}}{\rho_i \frac{dH_i}{dt}} \quad (2)$$

is a constant. Solving dH_i/dt from Eq. (1) and neglecting the physical constants then gives a severity index, PR, defined by

$$PR = \frac{V_a(T_f - T_a)}{1 + \Phi(T_w - T_f)}. \quad (3)$$

Overland et al. (1986) and Overland (1990) then used vessel-icing data and statistical analysis to find a representative value of the constant Φ. A value for Φ of 0.4 was obtained by Overland et al. (1986), while Overland (1990) obtained a slightly lower value of 0.3 when vessel-icing data from the east coast of Canada were included in the analysis.

2. Problems with the Overland algorithm

Makkonen (1989) criticized this approach on the basis that it assumed Φ was a constant, when in fact this was not the case. However, these criticisms were dismissed by Overland (1990) as being incorrect, because the freezing fraction was "defined as a ratio which is slowly varying." The illogical nature of this assumption becomes readily apparent if we consider icing situations with similar wind speeds. The spray flux dH_w/dt is then largely invariable, and differences in dH_i/dt are caused by air and water temperature. According to Eq. (2), Φ is then inversely proportional to the icing rate dH_i/dt. The "constant" Φ is thus critically dependent on the factor ($dH_i/dt \approx PR$) that is supposed to be predicted. That the empirical data and Eq. (1) show an order of magnitude change in dH_i/dt, and consequently in Φ, due to temperature effects, demonstrates the invalidity of the assumption of a constant Φ.

The unsound nature of the assumption of a constant Φ can be seen even more clearly by noting that Eq. (2) with a fixed Φ results in

$$\frac{dH_i}{dt} = k\frac{dH_w}{dt}, \quad (4)$$

where k is a constant. Thus, assuming that Φ is a constant is analogous to assuming that the icing rate is *independent* of air and water temperature. Such an assumption contradicts the final result of Eq. (3), where the predictor PR depends on T_a and T_w. In other words, while Overland et al. assume in Eq. (1) that the icing rate is determined by the heat balance, they simultaneously assume, by setting Φ constant, that it is not.

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Instead of deriving an incomplete solution for dH_i/dt using a contradictory assumption, dH_i/dt should be solved directly from Eq. (1). This results in the predictor

$$PR = C_H \rho_a C_a V_a (T_f - T_a) - C_w \rho_w (T_w - T_f) \frac{dH_w}{dt}. \quad (5)$$

Observed icing data could then be used to find the statistically optimal value of dH_w/dt, or to calibrate the model by finding a reasonable function relating the spray flux, dH_w/dt, to wind speed, V_a.

A manifestation of the above theoretical deficiencies is the strong water-temperature sensitivity displayed by the Overland et al. (1986) algorithm. A comparison of the algorithm with a number of other models that solve the heat balance from Eq. (1) clearly shows the different response (Fig. 1). Overland (1990) goes to great pains to justify this response by mentioning a "supercooling hypothesis" and noting "observational support for the existence of extreme icing at low sea temperatures." However, there is more convincing observational evidence (see Shellard 1974) that icing is relatively *insensitive* to sea-surface temperature. This insensitivity was a feature of the time-dependent icing model of Horjen and Vefsnmo (1987), and pulsed-spray, saline-water wind tunnel experiments recently completed at the University of Alberta (Brown et al. 1990) showed very little dependence on water temperature over the range of −2.0° to +4.0°C. In fact, as Shellard (1974) points out, it is the rapid "supercooling" of droplets that makes icing rates less sensitive to sea-surface temperature, contrary to the arguments of Overland (1990).

It is also believed that Overland (1990) did not correctly use the data of Zakrzewski et al. (1989) to verify and update his algorithm. First, the data were collected while the *Zandberg* was operating close to the ice edge, which had a major impact on reducing the sea state (this can be clearly seen in the data, where sustained wind speeds of 30 knots only produced mean wave heights of around 1.0 m). Vessel speed was also very low during the first icing event (<2.5 knots). The data therefore clearly violate one or more of the key assumptions used in the derivation of the Overland et al. (1986) algorithm—namely, that vessels are "not actively avoiding icing through heading downwind, moving at slow speeds or avoiding open seas." Second, Overland (1990) used all 44 icing observations from Zakrzewski et al. (1989) as independent icing observations in a pooled comparison with the Pease and

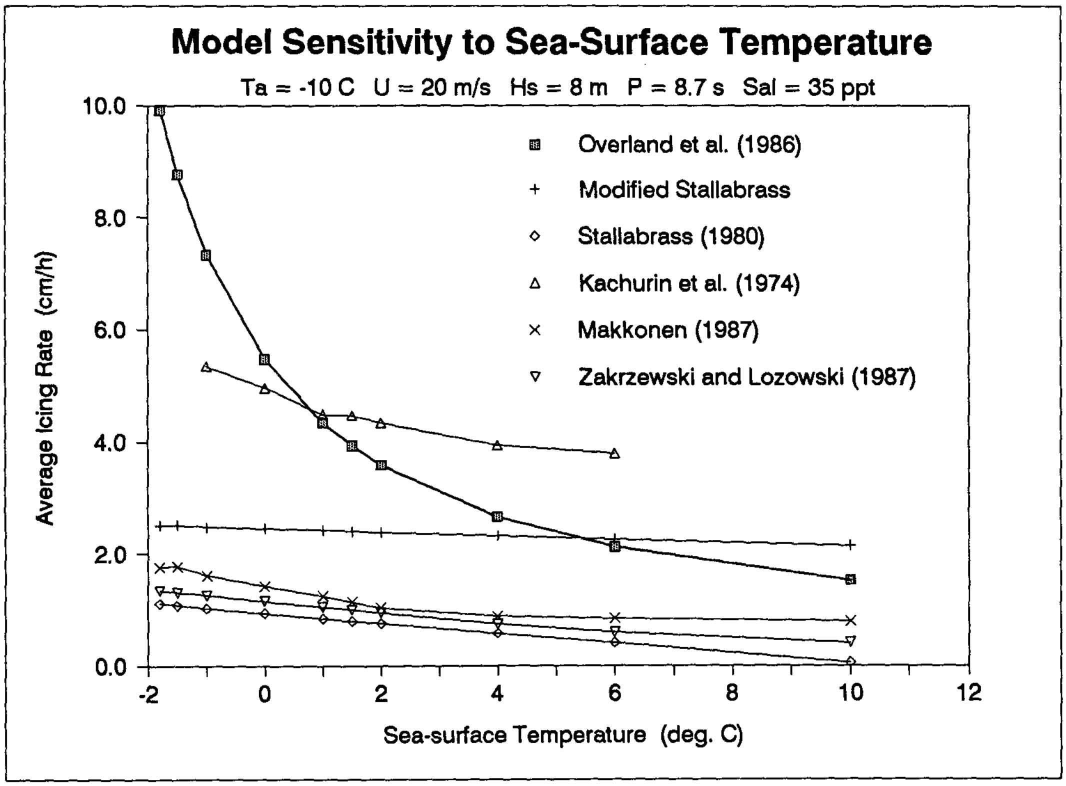

FIG. 1. Comparison of sea-surface temperature sensitivities for a number of vessel-icing models. The modified Stallabrass (1980) model uses vertical liquid-water content and spray-residence time expressions following Zakrzewski (1986).

Comiskey (1985) data, the latter being obtained from 58 separate icing events. This is inconsistent, because the Zakrzewski et al. (1989) data were *hourly observations,* taken during only three separate icing events. To be consistent, Overland should have computed the maximum and event icing rates from the Zakrzewski et al. (1989) data. This would have yielded an additional three points, hardly sufficient data to warrant additional calibration of the algorithm, or the conclusion that the algorithm is valid for low sea-surface temperature conditions.

When attempting to apply the Overland et al. (1986) categorical analysis technique to an icing dataset from the east coast of Canada, Roebber and Mitten (1987) were unable to replicate the results published by Overland et al. (1986) for the Pease and Comiskey (1985) dataset. A subsequent review of the software used by Overland et al. (1986) revealed several errors that affected the calculation of potential and absolute potential predictability. In addition, an error in a sort routine for computing class median values had a significant impact on fitting the polynomial to describe the continuous icing rate. For example, the median predictor and icing-rate values for the heavy-icing class were computed by Overland et al. (1986) as 71.40 and 4.1 cm h^{-1}, respectively, while the correct values were determined to be 75.175 and 3.025 cm h^{-1}. When these correct values were fitted with a third-degree polynomial to generate a continuous icing rate, following Overland et al. (1986), it gave physically unrealistic icing rates for high predictor values, i.e., the icing rate *decreased* for predictor values greater than 200. Roebber and Mitten (1987) therefore recommended that a second-degree polynomial of the form

$$IR\ (\mathrm{cm\ h^{-1}}) = a_0 + a_1 PR + a_2 PR^2, \qquad (6)$$

where

$$a_0 = 0.1982$$

$$a_1 = 3.070 \times 10^{-2}$$

$$a_2 = 1.996 \times 10^{-4},$$

be used. Overland was made aware of these problems at the time, but has not acknowledged them in subsequent papers.

The authors do not deny there is a need for a robust icing procedure for forecasting vessel icing, and the categorical procedure applied in Overland et al. (1986) is an excellent way to deal with the uncertainties inherent in vessel-icing data. However, it is argued that any simplified vessel-icing approach should, as a minimum, be based on the correct physics of the icing process and display reasonable sensitivity to the main icing parameters. Therefore, we do not recommend that the algorithm presented by Overland et al. (1986) and updated in Overland (1990) be used for operational vessel-icing forecasting.

APPENDIX

Notation

V_a = wind speed
T_f = freezing point of seawater
T_w = sea-surface temperature
T_a = air temperature
dH_i/dt = icing rate
dH_w/dt = spray delivery rate
$\rho_a\ \rho_i\ \rho_w$ = density of air, accreted ice, and seawater
L_i = latent heat of freezing for accreted spongy ice
$C_a\ C_w$ = heat capacity of dry air and seawater
C_H = transfer coefficient for sensible heat flux

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