Reply

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21 January 1991 and 5 June 1991

1. Introduction

In this reply I address issues presented by Makkonen (1989) and Makkonen et al. (1991, referred to as MBM); an earlier discussion of Makkonen (1989) was removed from Overland (1990) at the request of a reviewer. There are clear differences between us on the feasibility of estimating spray delivery from environmental parameters and on the importance of using ship observations relative to deterministic modeling in development of forecast aids. Makkonen et al. make several valid comments that I consider arise primarily from this difference in perspective. These differences notwithstanding, we have a common goal and I welcome this opportunity for discussion on approaches to vessel icing for further development of operational forecasts. The MBM comments can be divided into (1) the NOAA algorithm, (2) observations from the ship *Zandberg*, (3) the paper by Shellard (1974), and (4) miscellaneous.

2. The NOAA algorithm

An issue of Makkonen (1989) and MBM is the formulation of the predictor from Overland et al. (1986, referred to as OPPC). Makkonen et al. and others have proposed the use of the thermodynamic predictor (5′)

$$PR' = C_H \rho_a C_a V_a (T_f - T_a) - C_w \rho_w (T_w - T_f) \frac{dH_w}{dt}. \tag{1}$$

The same notation is used as in MBM, and primes refer to equation numbers in MBM. There are two parts to the icing problem: delivery of spray (i.e., dH_w/dt—water supply per unit surface area of the vessel), and thermodynamic rates of freezing. To my knowledge, it has been virtually impossible to quantitatively estimate spray rate, given the wide range of vessel size, shape, and sea keeping, and the unknown relative motions between real sea conditions, water on decks and surfaces, and the vessel. The approach of OPPC is to formulate (1) as

$$\mathrm{PR} = \frac{V_a(T_f - T_a)}{1 + \Phi(T_w - T_f)}, \tag{2}$$

thus replacing knowledge of dH_w/dt with an estimate of freezing fraction, F,

$$\Phi = \frac{C_w}{L_i F}, \quad F = \frac{\rho_i dH_i/dt}{\rho_w dH_w/dt}, \tag{3}$$

which is at most a few percent. One would expect the icing rate in the numerator of F to increase with wind speed due to thermodynamics, and the spray delivery to increase with wave height and, thus, wind speed in some unknown fashion. Thus, Φ is a weak function of wind speed, probably less than linear. That F may depend on air temperature for constant winds is not disputed. The implication of MBM, i.e., (4′), that OPPC predicts that "icing rate is independent of air and water temperature," is clearly incorrect by reference to the entire predictor (2); Makkonen (1989) chooses to interpret constant Φ and (2) as separate physical statements rather than considering Φ in the context of (2). Our use of constant Φ in (2) is equivalent to truncating an expansion series after the linear term. For an example, let us see the influence of assuming a constant Φ and F relative to a variable Φ and F; let F double for a decrease in air temperature of −12° to −22°C for a water temperature of 3°C. This temperature change increases the predictor value, PR, for variable Φ by a factor of 2.8, compared with a factor of 2.0 for constant Φ or a 40% difference over this 10°C temperature range. This 40% difference in PR value is much less than the order-of-magnitude influence suggested by MBM. Our original OPPC argument stands. We choose to accept that the secondary effect of variable Φ on (2) is not fully modeled, rather than undertaking the nearly impossible task of estimating dH_w/dt.

OPPC uses a categorical technique. Given the uncertainties of the problem, using three icing categories and tuning the algorithm with data allows any algorithm to be less sensitive to the proposed form, shape, and magnitudes of functional dependencies like (2)

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and the neglect of variable Φ. In the development of OPPC, Φ was primarily treated as a statistical parameter, independent of possible physical interpretation, and (2) was found to have skill for an Alaskan dataset for a narrow range of Φ. One should recall that model formulations similar to (1) are extremely crude representations of the entire vessel-icing process. Overland et al. (1986) and Overland (1990) repeatedly emphasize that the OPPC method is to be used only to predict icing categories of light, moderate, or heavy. It is an invalid application of the OPPC method to plot curves such as that labeled "OPPC" in Fig. 1 from MBM. The interpretation of OPPC is that, for the meteorological conditions given for this figure, there is the potential for heavy icing (>2.0 cm hr^{-1}) for sea temperature cooler than 6°C. For MBM to imply that OPPC predicts 6–10 cm hr^{-1} is incorrect. This caveat is stated strongly in OPPC. I concur with the MBM suggestion that different functional forms for the behavior of vessel icing with variable sea temperatures may be more valid than (2). Given MBM's arguments on the shape of (2), it was premature in Overland (1990) to recommend an additional icing category of *extreme,* because this region is beyond the range of the database. However, I stand behind our original OPPC procedure and algorithm, which was to design a categorical procedure combined with the use of observations that would not be overly sensitive to the exact functional form of the predictor.

3. Observations from the *Zandberg*

The important point of the ship *Zandberg*'s observations is that the observed icing rate was so high (>2.0 cm hr^{-1}), given the relatively warm air temperature (−5.5°C) and wind speed (15 m s^{-1}). This is solid observational data. Data for the same atmospheric conditions in the Gulf of Alaska for warmer sea temperatures had much lower icing rates. Regardless of how one can speculate on the influence of ship speed, fetch, and hull design on icing rate, I would consider that the *Zandberg* would have observed greater icing than predicted by the models shown in Fig. 1 of MBM if weather conditions had been 20 m s^{-1} and −10°C air temperatures. The articles of Lee (1958), De Angelis (1974), and George (1975) report icing rates in excess of several centimeters per hour in similar low-sea-temperature locations. Figure 6 from Overland (1990) shows up to 25 cm on a Coast Guard vessel in the Labrador Sea. The approach of OPPC and Overland (1990) is that these reports are the key information that must be accommodated in any icing prediction system.

4. Shellard (1974)

Makkonen et al. (1991) reference Shellard (1974) as their main data source for stating that there is little influence of sea temperature on vessel icing. Shellard (1974, p. 17) states:

> Although there is a tendency for the frequency of heavy icing to be greatest at the lowest sea temperatures and for the average sea temperature to rise slowly with decreasing icing amounts, the number of observations is not sufficiently large to establish a clear relationship. Tables VIII and IX agree in showing that heavy icing can occur with relatively high sea temperatures (4°–7°C) and the evidence seems to refute the idea that sea temperature is an important factor in icing at sea.

In conclusion he states "sea-surface temperature is a factor of limited importance but it cannot be dismissed" (page 26). Shellard (1974) was arguing that icing is not limited only to low sea temperature, i.e., less than 4°–7°C, which is certainly true. Many references quoted by Shellard (1974) indicate sea temperature as a factor. A shortcoming of Shellard's analysis of sea temperature is that his Table IX was not stratified to remove influence of variable wind speed. I do not conclude from Shellard (1974), as MBM, that "icing is relatively *insensitive* to sea-surface temperature," but that Shellard considered his data inconclusive.

5. Miscellaneous comments

A major point of Overland (1990) was to show that the *Zandberg* data is reasonably hindcast by OPPC, which was derived from a much warmer sea-temperature dataset than the *Zandberg* data. Makkonen et al. (1991) make a good point, however, about directly combining all the hourly *Zandberg* data in revising the NOAA algorithm with the Alaska dataset, which were six hourly or greater events. Makkonen et al.'s comments that the *Zandberg* represents only three cases according to OPPC criteria are valid; however, to my knowledge it is the only quality low-sea-temperature dataset. An alternate to what MBM propose is to combine the *Zandberg* data as one composite cold-sea-temperature dataset, with the Alaskan data as one composite dataset. This is close to what was done by combining all the data. The key point, however, is that the addition of the *Zandberg* data was only a minor correction to OPPC. It would be of great benefit to have additional observations for low sea temperatures.

PMEL worked with Mitten on their application of OPPC, and were aware their application of OPPC predictability formulas to the Stallabrass dataset produced negative results, primarily because of lack of skill in the Stallabrass dataset. I would like to gratefully acknowledge the work by Mitten and that he did point out an error in the sorting algorithm; this error did not affect the categorical divisions of light, moderate, and heavy. Extrapolation of data to unrealistic icing rates is a misapplication by Mitten rather than PMEL.

6. Conclusion

Actual icing is so complicated and variable with location on a vessel that the use of models, tunnel tests, quality observations, and other reports are all required for guidance in development of forecast products. There certainly may be little sensitivity of icing rate to change in sea temperature at low sea temperatures, as suggested by the models and laboratory studies documented in MBM. Observational data or Eq. (1) cannot distinguish this fine an effect. I maintain, following Shellard (1974) and others, that the anecdotal evidence indicates greater potential for icing with cold compared to warm sea temperatures. I cannot hypothesize why this sensitivity is not apparent in current-generation icing models. It is unfortunate that there are large differences between different model predictions and scatter rather than systematic errors in model comparison to data (Zakrzewski et al. 1989). However, comparison of these models with anecdotal cases as well as quality observations will advance the field. I have much more optimism that these issues can be resolved than when OPPC was written in 1985.

Vessel icing is a major hazard in northern waters. The resolution of the low-sea-temperature issue has great importance to the safety of operations off of eastern Canada, Sea of Japan, Barents Sea, and in the Baltic. The NOAA algorithm is simple and reliable and is consistent with the level of quality of existing icing data and weather forecasts for input. It provided guidance to icing forecasts for the cold-sea-temperature Bering Sea and the warmer north Pacific during the major January 1989 event, as discussed in Overland (1990). The recommendation of MBM that the categorical algorithm of OPPC not be used, based primarily on the results from models (their Fig. 1) and Shellard (1974), is premature. After MBM's comments, I am not convinced that regions of cold temperatures (<0°C) are as safe as those with >3°C sea temperatures. This is not the operating experience of vessel operators in Alaskan waters. The current NOAA icing algorithm has saved lives.

Acknowledgments. This paper is a contribution to the Marine Services Project at PMEL. I appreciate discussions with C. H. Pease and W. P. Zakrzewski.

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