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Surface ablation model evaluation on a drifting ice island in the Canadian Arctic

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ABSTRACT

A 4-week micro-meteorological dataset was collected by an automatic weather station on a small ice island ($0.13\ km^2$) adrift off Bylot Island (Lancaster Sound, Nunavut, Canada) during the 2011 melt season. This dataset provided an opportunity to identify the environmental variables and energy fluxes that contribute most to surface ablation during the melt season, as well as test previously developed surface melt (ablation) models. Surface ablation was estimated using energy fluxes calculated using the bulk aerodynamic approach (EB_{AWS}) and three existing surface ablation models. These models included a simple solar radiation model developed for iceberg use (CIS-IB), a more sophisticated energy-balance model developed for ice island use (CIS-II), and a temperature index melt (TIM) model based on an assumed relationship between air temperature, time, and surface ablation. The models were driven by our measured micro-meteorological data (optimal forcing) or regional environmental forecast data from the Global Environmental Multiscale (GEM) Model, which is used for operational iceberg modeling. The sensible heat flux contributed most to the ice surface's available melt energy (47%), followed by net radiation (38%) and the latent heat flux (30%), while the subsurface heat flux removed 15% of available energy. When cumulative surface ablation was predicted with these calculated energy fluxes (EB_{AWS}), observed surface ablation was under-predicted by 38%. Results illustrate the decreased performance of the melt models when run with GEM data versus *in-situ* micro-meteorological data, which is optimal for model input but not available for operational modeling. The CIS-II model under-predicted cumulative surface ablation by 5.7% (RMSE = 1.2 cm) with observed micro-meteorological data and over-predicted cumulative surface ablation by 35% when run with GEM model data. This is likely a result of the GEM model wind speed being 57% greater than that recorded on the ice island. Since surface ablation plays a greater relative role in overall deterioration of ice islands than traditional icebergs due to morphological differences (size, surface structure), it must be accurately represented in operational ice island deterioration models. The costs and benefits between parsimonious TIM models and skilled energy-balance models are weighed here for operational modelers to consider, along with the complications caused by the use of the regional environmental data input provided by the GEM model for operational modeling efforts.

1. Introduction

One consequence of Arctic climate change is an increased frequency in break-up events of ice shelves and floating glacial tongues. These events, in turn, create drifting ice islands (large tabular icebergs) that are hazards to navigation and infrastructure (Mueller et al., 2008; Peterson, 2005). Ice islands have been increasing in occurrence off the east coast of Canada (Peterson, 2005) and in the Arctic Ocean (Copland et al., 2007). These ice masses present serious risks to shipping and resource extraction infrastructure (McGonigal et al., 2011; Peterson, 2011) due to their extreme mass and unique shape, in particular their small drafts (depth below waterline) which allow for drift into shallow waters that support industrial activity (Ballicater Consulting Ltd., 2012). The deterioration mechanisms and drift patterns of ice islands are poorly understood since they have been relatively uncommon in Canadian Arctic and East Coast waters until recently (Rudkin et al., 2005). There is a need to improve the ability to monitor and model ice island deterioration and drift as they are increasingly observed in waters rich in natural resources where exploration and development and increased ship traffic are likely to become more common (Peterson, 2011; Prowse et al., 2009). Operational iceberg modeling is currently conducted in Canada by the Canadian Ice Service (CIS-Environment Canada) to predict iceberg locations on analysis charts. These are available from the North American Ice Service for

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East Coast waters south of 60°N latitude. With natural resource extraction and shipping transportation activity expected to increase in the Arctic (Prowse et al., 2009; Smith and Stephenson, 2013), it is important that these models are also validated for use in these northern waters. The CIS has developed drift and deterioration models for icebergs (Kubat et al., 2005; Kubat et al., 2007) and ice islands (Ballicater Consulting Ltd., 2012; Crocker et al., 2013) which are intended for operational use. This study is the first validation of these models with *in-situ* data north of the Arctic Circle.

Dimensional output from operational deterioration models may be used as input for subsequent ice island drift modeling, therefore it is important for the former to have high model skill for accurate drift forecasting. Surface ablation is one process that contributes to an ice island's deterioration (Ballicater Consulting Ltd., 2012; Kubat et al., 2007; Savage, 2001); which, in the case of ice islands and this study, is calculated as the surface melt affecting the horizontal above-water surface. It was found to contribute a relatively low amount (2.8%) to the total observed deterioration in previous studies on traditional, non-tabular icebergs (Savage, 2001). However, Crocker et al. (2013) state that surface ablation will have a larger effect on the overall deterioration of ice islands due to their extensive horizontal surfaces. For example, an ice island with a 2 km waterline (a proxy measurement for size and mass in Kubat et al., 2007; Ballicater Consulting Ltd., 2012), is predicted to lose approximately 10% of its mass via surface ablation (Ballicater Consulting Ltd., 2012). This increases to approximately 30% for an ice island with a 10 km waterline (Ballicater Consulting Ltd., 2012). An example of the mass loss by surface ablation for an ice island is provided by Halliday et al. (2012) who document the surface ablation observed for PII-A, a product of the 2010 Petermann Glacier calving event (Johannessen et al., 2011). This ice island was visited twice between June and July 2011 when adrift off the coast of Labrador. The average surface ablation ($n = 4$) was 1.7 m over 35 days resulting in an average daily surface ablation of 4.9 cm d^{-1} (Halliday et al., 2012). Based on an estimated extent of 62 km^2 (Halliday et al., 2012), this equates to a mass loss through surface ablation of 9.6×10^4 tons over the 1-month period. This is 60% of the total mass loss due to thickness change (surface and basal ablation), which was equal to 16×10^4 tons.

An ice island research project was initiated by the CIS and ArcticNet, a Network of Centres of Excellence of Canada, in 2011 to gather data for the purpose of evaluating the existing iceberg and ice island deterioration models. A comprehensive 4-week micro-meteorological dataset, including surface ablation, was recorded for a small ice island unofficially named Berghaus as it drifted off the north and east coast of Bylot Island.

The objectives of this study are twofold; first, to identify the environmental variables and energy fluxes which control surface ablation during the melt season for this ice island and second, to compare the prediction accuracy of surface ablation model outputs by model type (inter-model comparison) as well as by environmental data input source (intra-model comparison). The optimal input data, collected by an automatic weather station (AWS) installed on an ice island, should lead to more accurate model output in comparison to model runs forced with regionally forecasted Global Environmental Multiscale (GEM) Model data, which is utilized at the CIS for operational modeling.

It is hypothesized that a relatively sophisticated energy-balance (EB) surface ablation model will show the greatest skill for ice island surface ablation modeling, while a simpler temperature index melt (TIM) model may prove attractive due to limited meteorological input data needed, acceptable forecast accuracy and computational ease. Calibrating and/or modifying existing surface ablation models, specifically for use in operational ice island deterioration modeling, is a first step in improving the knowledge of the overall ice island deterioration processes. The results of this study form the basis of recommendations for surface ablation modeling within a complete ice island deterioration model.

2. Methods

2.1. Study site

Petermann Ice Island (270 km^2) calved on 5 August 2010 from the Petermann Glacier of northwest Greenland (81°N, 61°W) (Johannessen et al., 2011). Berghaus, a 0.13 km^2 fragment (Fig. 1) most likely from the original Petermann Ice Island, was accessed on 30 July 2011 from the CCGS *Amundsen*. Berghaus was located off the northwest coast of Bylot Island in Lancaster Sound (74°06′N, 81°12′W) at the time of the survey (Fig. 2). Thickness, recorded with ice penetrating radar, varied from 124.5 to 131.2 m and freeboard was estimated between 18 and 25 m. The maximum length and width of the ice island fragment were 260 m and 460 m, respectively, and mass was estimated at 12×10^9 kg (Forrest et al., 2012).

Rapid deterioration of Berghaus ended AWS data transmission within 4 weeks of initial survey. The station last reported from 73°29′N, 75°07′W, 200 km from where it was installed at the start of the study. Based on hourly position reports, the ice island drifted 560 km over the 4 weeks and its looping drift track is illustrated in Fig. 2.

2.2. Data collection and correction

The AWS was installed on Berghaus on 30 July 2011 and was supported by a tripod atop of vertical wooden posts drilled into the ice to an approximate depth of 2.7 m (Fig. 3). Data were collected every 60 s and averaged hourly for the 4-week observation period. A Campbell Scientific Inc. (Lincoln, NE) CR3000-XT recorded data which were transmitted by an Iridium L-Band modem. The AWS was equipped with a Kipp and Zonen (Delft, Holland) NRLite2 net radiometer (Q^*), two Kipp and Zonen CMP-3-L pyranometers (reflected shortwave radiation ($K\uparrow$) and incoming shortwave radiation ($K\downarrow$)), a shielded Rotronics (Bassersdorf, Switzerland) HC2-S3-L hygrometer/thermistor (relative humidity (RH_o) and air temperature ($T_{a\text{-}o}$) at an initial height of 1.8 m above surface), an RM Young (Traverse City, MI) Marine 05106-10-L anemometer (wind speed (u_o) and direction at an initial height of 2.4 m above the surface), an RM Young 61302 V barometer (air pressure (P)), a Hemisphere (Scottsdale, AZ) V101 GPS (position), five Campbell Scientific 109B thermistors (ice temperature (T_i)) at initial depths of 10 (T_{i1}), 60 (T_{i2}), 110 (T_{i3}), 160 (T_{i4}) and 210 (T_{i5}) cm below the ice surface, and a Campbell Scientific SR50A sonic ranger (distance to surface/surface ablation). The subscript 'o' denotes observational data which were modified for modeling analyses and explained further below.

An accurate measurement of the surface temperature (T_s) was not recorded during data-collection. T_s was assumed to equal 273.15 K, the temperature of melting ice, as per Hay and Fitzharris (1988), Ishakawa et al. (1992) and Ballicater Consulting Ltd. (2012). It is likely that this is a valid assumption as T_a was >273.15 K for the entirety of the study period. The midpoint value between 273.15 K (the temperature of melting ice and the maximum possible temperature of the ice surface) and the temperature recorded by the uppermost T_i that was still encased in ice (representing the lowest possible ice surface temperature) was used to represent the uncertainty of this assumption. T_s was utilized in the calculation of: (1) outgoing longwave radiation ($L\uparrow$), (2) the sensible and latent (turbulent) heat flux densities (Q_H, Q_E), and (3) the correction of air temperature ($T_{a\text{-}o}$) to a standard 2 m height (more information to follow below). The maximum possible error in $L\uparrow$, Q_H, Q_E, and available melt energy (Q_M, which utilizes Q_H and Q_E in its calculation) due to the use of T_s was calculated by substituting the mid-point temperature described above for T_s in each respective calculation. The difference between the results calculated with T_s and the mid-point temperature is the derived uncertainty in these flux magnitudes. The uncertainty is presented as an average percent difference.

The observations of $T_{a\text{-}o}$, RH_o, and u_o, were the meteorological conditions used to calculate Q_H and Q_E. These observations were corrected to