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An ensemble forecast model of iceberg drift

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ABSTRACT

A study of the application of ensemble techniques to iceberg forecasting has been performed using a numerical iceberg drift model. A simple 'Monte Carlo' approach was used in which variations for each key environmental parameter and iceberg property were sampled randomly to generate 250 ensemble members. The range of variations was estimated to represent the 95% confidence level in the parameter's value. A set of 216 iceberg tracks from the northern Grand Banks region, collected between 2002 and 2007, was used to assess the ensemble performance. While the ensemble mean drift forecast did not improve over the deterministic forecast, the ensemble model is shown to be consistent and the statistical properties of the ensemble provide useful information on the uncertainty inherent in the forecasts.

1. Introduction

The Canadian Ice Service (CIS) is the federal agency in Canada that is responsible for providing operational sea ice and iceberg information. The CIS prepares several products that inform marine interests of areas where ice hazards may be encountered and where they may be more severe. Iceberg products include charts depicting the number of icebergs within a 1° of latitude by 1° of longitude box while text products describe the spatial distribution of icebergs together with a delineation of the iceberg limit. These products are prepared by combining iceberg observations with iceberg drift and deterioration forecasts. Due to the high cost of conducting regular aerial reconnaissance over large geographical areas, a numerical model that simulates the drift and deterioration of icebergs is relied upon heavily to fill data gaps for the periods between observations.

For the CIS operational use, the iceberg model is run automatically every 6 h in order to keep the distribution of icebergs up to date. The original model was developed in the early 1980s (Anderson, 1983; Mountain, 1980) by the International Ice Patrol (IIP) and is referred to as the IIP iceberg model. More recently, a program of iceberg model research has been conducted at the CIS with the goals of improving the quality of forecasts and providing information on the uncertainty in iceberg forecasts. A newer model, referred to as the North American Ice Service (NAIS) iceberg model, has been developed by incorporating more complete parameterization and more reliable numerical methods. An earlier version of the NAIS iceberg model has been described in detail by Kubat et al., (2005, 2007), but a brief overview of the main features is presented here.

The NAIS iceberg model estimates iceberg velocity using the equations for the balance of linear momentum,

$$m\left(\frac{d\mathbf{V}}{dt}+\mathbf{f}\times\mathbf{V}\right)=\mathbf{F}_a+\mathbf{F}_w+\mathbf{F}_r+\mathbf{F}_p+\mathbf{F}_{am}+\mathbf{F}_{si} \tag{1}$$

where m and $\mathbf{V}$ are the mass and velocity of the iceberg respectively, and $\mathbf{f}$ is the Coriolis parameter. The force terms of the right-hand side of the equation are air drag ($\mathbf{F}_a$), water drag ($\mathbf{F}_w$), wave radiation stress ($\mathbf{F}_r$), water pressure gradient ($\mathbf{F}_p$), added mass ($\mathbf{F}_{am}$), and sea ice force ($\mathbf{F}_{si}$). Parameterizations for the forces have been described in detail in Kubat et al. (2005). The implicit Euler method is used to solve the momentum balance equation, giving an estimate of the acceleration at each time step which is then used to update the iceberg velocity (Kubat et al., 2005). Meanwhile, the deterioration of icebergs is modeled using the approach originally developed by White et al. (1980) and updated by Kubat et al. (2007). The reduction in the size of icebergs is important because size affects the drift speed and direction, and because the icebergs must be removed from the system when they have completely deteriorated.

In this paper a preliminary study has been undertaken to assess the feasibility of applying ensemble forecasting techniques to iceberg drift. Ensemble forecasting is a relatively new approach to environmental modeling that uses two or more forecasts valid at the same time. The technique has been widely used in Numerical Weather Prediction (NWP) over the past decade, but has never been applied to operational iceberg drift forecasting. There have, however, been a few studies of iceberg drift forecasting that utilized some aspects of the ensemble method.

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These include Keghouche et al. (2009), who tuned iceberg mass and drag coefficients and found that the observed spread of position errors was of the same order as the forecast error. They suggest that this preliminary result is promising for the viability of an ensemble-based iceberg forecasting system. Keghouche (2010) used an Ensemble Kalman Filter to apply time varying corrections to iceberg position and to optimize model parameters. Lichey and Hellmer (2001) used an ensemble of icebergs to calibrate sea ice strength parameters in a study of Antarctic iceberg drift. Although full ensembles methods have not previously been used for forecasting iceberg drift, they have been applied to the drift of objects in the sea such as drifter buoys (Rixen et al., 2008), containers (Ailliot et al., 2007), pollutants, algae blooms (Vandenbulcke et al., 2009), and search and rescue targets (Breivik and Allen, 2008).

The work carried out on an ensemble forecast version of the NAIS iceberg model, which is presented here, includes the selection of an ensemble technique, the identification of the most important parameters affecting drift, the development of an ensemble model based on these key parameters, and an evaluation of model performance.

2. Ensemble forecasting methods

A history of ensemble forecasting is provided by Lewis (2005). The general approach to ensemble forecasting is as follows. In every ensemble forecast, a 'control forecast' is designated. This is the model prediction from the unperturbed or 'best estimate' initial conditions and is normally run at full (highest) resolution. It is used as a basis for comparison and evaluation of the ensemble forecast. Members of an ensemble forecast are then created by perturbing one or more of the following:

- the initial conditions,
- the model,
- the boundary conditions.

A measure of central tendency of the ensemble is used to produce an 'ensemble forecast' that is, ideally, more accurate than the control forecast. The statistical properties of the ensemble can also be used to identify uncertainties in the modeling process, estimate the decay of forecast skill with increasing forecast lead time, and estimate forecast accuracy.

When applied to iceberg drift/deterioration modeling, ensemble forecasting yields a collection of iceberg positions at a desired forecast period. Fig. 1 shows an example of such an ensemble forecast for iceberg HG03012d (a 55 hour drift track observed on the Grand Banks in April 2003) produced using the techniques described later in this paper. In this case, the deterministic (control) forecast performed reasonably well, but the ensemble forecast, computed as the mean position of the ensemble members, provided a better estimate of the true iceberg position. Moreover, a circle (or other enclosed shape) can be drawn around the position of the ensemble forecast that defines an area in which a certain proportion of the ensemble members lie. If the members of the ensemble forecast are generated appropriately, this contour can provide an estimate of the uncertainty in the forecast iceberg position.

Uncertainties in numerical predictions of iceberg drift, which are suitable for modeling with ensemble forecasting methods, can arise from three different sources. The first is the iceberg drift and deterioration model itself; primarily the model physics, the numerical methods used to simulate those physics, and the specification of initial conditions. The second, and perhaps more important source of uncertainty, is the specification of the environmental driving forces. Currents, winds and waves all play a role in determining where an iceberg drifts. To make a drift forecast, these environmental parameters must also be forecast (and then used to drive the iceberg drift model), and limitations to their accuracy and resolution limit the accuracy of the iceberg forecasts. Third are the uncertainties in the properties of the icebergs themselves. For the ensemble model considered in this paper, only perturbations related to iceberg initial conditions and environmental driving forces have been used to create members of the ensemble forecast.

Numerous perturbation strategies have been developed and many are currently used in ensemble models, both operationally and in scientific studies of meteorological phenomena. No single technique has been shown to be universally superior. The most widely used perturbation strategies are Monte Carlo methods, Lagged Average methods, Breeding of Growing Models methods, and EOF Based methods. Detailed descriptions of the various methods can be found in Leutbecher and Palmer (2008), Sivillo et al. (1997) and Toth and Kalnay (1993). Most of the techniques have been developed for NWP and several have been developed specifically to reduce the demand on computational resources, which can be very high in that application. In the case of iceberg forecasting, the model is relatively simple and requires only modest computational power to run. For our first attempt at ensemble forecasting of iceberg drift, we selected the Monte Carlo method because it can deal with large numbers of parameters (dependent or independent), and is simple to construct. It is, in a sense, a 'brute force' approach because the full model must be run for each ensemble member.

Monte Carlo modeling involves running many trials of a deterministic model with one or more of the model parameters (i.e. the initial iceberg properties and the environmental conditions) selected randomly from pre-defined probability distributions for each trial. The probability distributions are designed to simulate the uncertainty in each parameter. Since the iceberg observations used in this study are from the past, the model predictions are actually 'hindcasts'. However, the techniques are equally suited to real-time forecasts. To avoid repeated changes of the nomenclature, we use the term 'forecast' in both the discussion of ensemble methods and the analysis of the data, but it should be noted that the analyses were performed on past events.

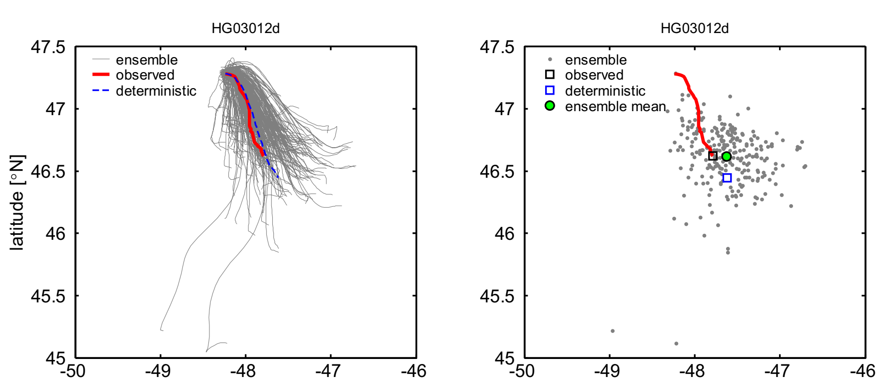

Fig. 1. An example of a 55 hour ensemble forecast for iceberg drift. *Left*: The forecast drift tracks for all ensemble members, together with the deterministic (control) forecast and the observed drift track. *Right*: The final forecast positions for all ensemble members, together with the ensemble mean position, the deterministic forecast position, and the observed position.