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Implementation of the Canadian Ice Service Local Iceberg Drift Model

Ivana Kubat and Mohamed Sayed

Technical Report HYD-TR-042

April 2006

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Implementation of the Canadian Ice Service Local Iceberg Drift Model

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ABSTRACT

This report documents the computer code of an iceberg drift model intended for end-users. The computer program keeps track of the dynamics, drift and deterioration of individual icebergs. The code allows the user to access and modify the input and output files. The users can thus incorporate information that may be locally available, which may enhance the accuracy of the forecast. The model also makes it convenient for the user to test various scenarios of environmental forcing and estimate the effect of uncertainties regarding, for example, the iceberg geometry.

TABLE OF CONTENTS

ABSTRACT i
TABLE OF CONTENTS ii
1. INTRODUCTION 1
2. ORGANIZATION OF THE PROGRAM 1
2.1 USER's VARIABLES 2
Run parameters 2
Iceberg initial conditions 2
Environmental variables 3
Material properties 3
3. SUMMARY 4
4. ACKNOWLEGEMENT 4
APPENDIX A 6
APPENDIX B 8

Implementation of the Canadian Ice Service Local Iceberg Drift Model

1. INTRODUCTION

A new iceberg drift, deterioration and calving model was developed by the Canadian Ice Service (CIS) and National Research Council of Canada - Canadian Hydraulics Centre (NRC/CHC). The model is described in detail in the Appendix A. One of the main features of the new model is the utilization of detailed environmental forcing input, such as the vertical profile of water current. The model runs on the CIS main computer system, where it is linked to an ocean model and databases for other environmental inputs. The output of the model has been in operational use by some end users (e.g. Provincial Aerospace Ltd.) to predict the iceberg drift tracks over the Grand Banks. End users have indicated an interest in the development of a version of the model that can be directly operated in a stand-alone mode, without a need to link to the large ocean model and databases at CIS. The idea is that the end user will have the ability to input iceberg and environmental data into the model and could produce the output about the iceberg drift whenever needed. Incorporation of local data and observations (i.e. real-time measurements or user-defined observations of local conditions) would also result in significantly better accuracy that will assist in decision making of iceberg towing. Such model will be advantageous to the end-users as a great tool in predicting the iceberg drift.

The code incorporates an interface that gives the user a flexible ability to introduce the initial conditions, environmental variables, and material properties. The user can also customize the output to provide values of interest in any format and at the required frequency. The input file allows the user to import values of water current, and wind velocities. The user can also specify if the geometry of the iceberg is tabular or non-tabular. For non-tabular icebergs, the user can override default values and specify keel depth and sail height.

The model employs the Canadian Ice Service (CIS) iceberg model, which is included in as library file. That library is linked to Fortran 90 files of the input, output, and user variables. The model, thus, makes use of all the functionality of the CIS model. Drift calculations consider forces resulting from water drag, air drag, wave radiation pressures, and water pressure gradient. Added mass and Coriolis force are considered in the equations. The processes which contribute to mass loss are surface melting due to solar radiation, buoyant vertical convection, forced convection of water and air, wave erosion and calving.

This report documents the code of the Local Iceberg Drift Model. Details of the formulation of the full model are included in Appendix A. Listing of the code of the Local Model is given in Appendix B.

2. ORGANIZATION OF THE PROGRAM

Figure 1 shows the main subroutines of the program. The main program starts the forecast. Definitions of the variables that are employed by the user are included in the "userVariables" file. The input file provides run parameters, initial size and location of the iceberg, water current and wind values, and various properties of ice and water. Default values are included for those properties. The library conducts the calculations that updates the iceberg velocity, position and size. The output file contains Fortran statements that the user can customize to print the required results.

The program consists of four Fortran files and two binary files as follow,

Main.f90
userInput.f90
userOutput.f90
userVariables.f90
localBergLib.lib
variables.mod

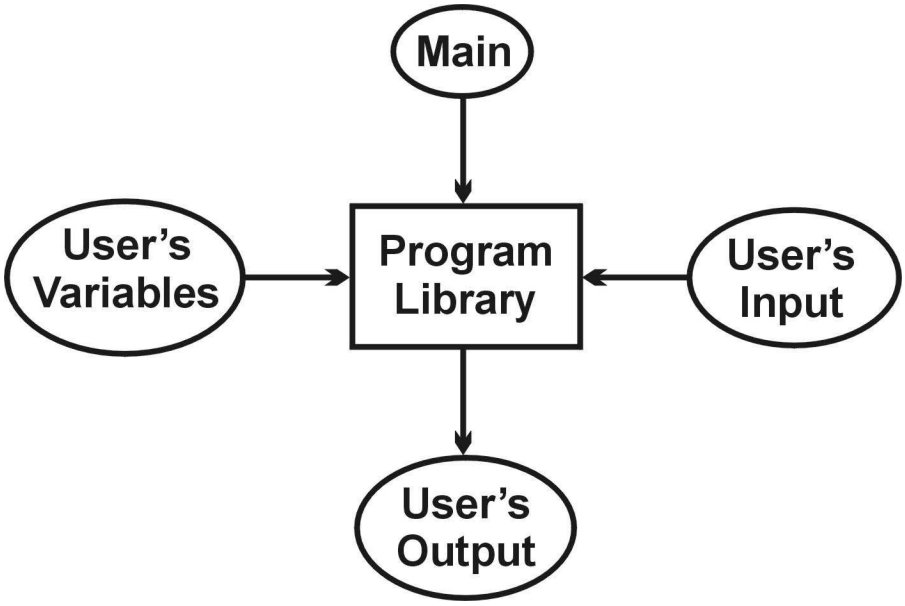

Figure 1: Data flow diagram showing the main subroutines of the program.

2.1 USER'S VARIABLES

The user variables are included in a *module*. It is named **Module userVariables**, and is contained in the file "userVariables.f90". Those variables, which are accessed by the user, consist of:

Run parameters

Name	Type	Description
userNsteps	integer	Number of time steps
userDelt	real	Time step (s)
userPrintFreq	integer	Output frequency (steps)

Iceberg initial conditions

Name	Type	Description
userBergLength	real	Mean length of the iceberg at waterline (m)
userLong	real	Longitude of the iceberg (degrees)
userLat	real	Latitude of the iceberg (degrees)
userU	real	Velocity along the East direction (m/s)
userV	real	Velocity along the North direction (m/s)
userTabularGeometry	integer	1= Tabular, 0= non-tabular geometry
userKeelSailInput	integer	1= yes (must be 1 if Tabular), 0= use default value. This variable determines if the user will override the default values of keel depth and sail height. It should be "1" for tabular icebergs. For non-tabular icebergs, it may be "1" to enter user values, or "0" to use default values.
userKeelDepth	real	If "userKeelSailInput= 1", enter depth (m)
userSailHeight	real	If "userKeelSailInput= 1", enter sail height (m)

Environmental variables

Name	Type	Description
userUwind	real array	Wind velocity along the East direction (m/s) (i.e. East component of wind velocity) - positive towards the East
userVwind	real array	Wind velocity along the North direction (m/s) (i.e. North component of wind velocity) - positive towards the North
userUcur	real array	Water current along the East direction for each layer (m/s) (i.e. East component of water current)
userVcur	real array	Water current along the North direction for each layer (m/s) (i.e. North component of water current)
userWaterTemp	real	Water temperature (°C)
userWaveHeight	real	Height of wind waves (m)
userWavePeriod	real	Period of wind waves (s)

Material properties

Name	Type	Description
userCdwat	real	Drag coefficient of water
userCdair	real	Drag coefficient of air
userRhoice	real	Density of ice (kg/m^3)
userRhoair	real	Density of air (kg/m^3)
userRhowat	real	Density of water (kg/m^3)
userKwater	real	Thermal conductivity of water (W/m/(°C)
userKair	real	Thermal conductivity of air (W/m/(°C)
userNuwater	real	Kinematic viscosity of water (m^2/s)
userNuair	real	Kinematic viscosity of air (m^2/s)
userLatentHeat	real	Latent heat of fusion (J/kg)
userAlbedo	real	Albedo for icebergs

The model includes default values for each variable. These values can be found in the "userInput.f90" file of the program. The user can either use these in case the real-time data are not available or can input his own observed data. In this file user can also specify the time step at which the program is executed (interval at which the calculations are performed), the duration of the run, and output frequency (the interval at which the variables of interest are recorded). In the "userOutput.f09" file the user can specify the values of variables that are of interest to be recorded.

In general the program consists of four Fortran files: mail.f90, userInput.f90, userOutput.f90, and userVariables.f90. The content of these files is listed in the Appendix B.

3. SUMMARY

This report documents the computer code of a Local iceberg drift and deterioration model. The main (global) model, Iceberg Drift model, runs on the Canadian Ice Service (CIS) main computer system. The end-users indicated an interest in having the ability to run the model locally and use their experience, knowledge and real-time data. This would enhance the accuracy of the forecast.

The code allows the user to customize the input and output and use their own observations and data. The full CIS model is packaged in a library that is called by the user. Thus the user has the access to the full functionality of the CIS model, while having flexibility of using locally available information.

4. ACKNOWLEGEMENT

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APPENDIX A

Operational Model of Iceberg Drift

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An Operational Model of Iceberg Drift

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A new iceberg drift, deterioration and calving model has been under development at the Canadian Ice Service (CIS). The model includes several new features, including the utilization of detailed environmental forcing input, and a robust implicit numerical solution method. In particular, the vertical distribution of water current is incorporated in calculations of water drag force on the iceberg keel. The model is also the first to include treatment of calving, prediction of calved ice piece size distribution and deterioration, as well as the drift of calved pieces. This paper gives a description of the drift model formulation as well as verification tests that include comparisons of model predictions with field observations. Additionally, the paper presents the outcome of a parametric study aimed at examining the sensitivity of iceberg drift to input parameters and environmental forcing.

INTRODUCTION

The Canadian Ice Service (CIS) has been developing a new operational model to forecast iceberg drift and deterioration over the Grand Banks region. Offshore developments in that region have led to increasing demands for reliable iceberg drift forecast, and new forecast output concerning, for example, calving and small ice mass populations. The new CIS model deals with the dynamics and drift of icebergs, as well as the deterioration of the icebergs due to various thermal processes and calving. The model also keeps track of calving events, size distributions of the calved bergy bits, and their melt and drift. The calving and deterioration aspects of the model have been presented in the papers of Savage et al. (2000, 2001) and Savage (2002). The present paper focuses on iceberg drift. Particularly examined are the impact of input parameters and environmental forcing on the predicted tracks of icebergs.

Drift of icebergs is modeled by considering the various forces that act on each iceberg, and solving the linear momentum equations. There have been several models that address dynamics of iceberg drift such as El-Tahan et al. (1983), Banke and Smith (1984), Murphy and Anderson (1986), and Bigg et al. (1997). The present drift model builds on such models and incorporates several new features, including a more detailed environmental forcing input. For example, water drag forces are calculated using water current values at 10-m vertical intervals. A detailed description of keel geometry was then needed. Consequently, a parameterization of keel geometry is included in the model, which relates keel areas at 10-m depth intervals to the waterline length of the iceberg. Barker et al. (2004) give details of the analysis of iceberg geometry.

In the present investigation, the role of several input parameters and scenarios of environmental forcing are examined by comparing predicted iceberg tracks to measurements. The observations of Smith and Donaldson (1987) are used here since they are the most reliable and complete dataset available to date. Tests examined the role of water and air drag coefficients, water current input, wind waves, wind drag force, and waterline length of the iceberg. Tests of water current input included a number of cases using values of water current at various depths and average values. In addition, several scenarios of free drift were examined.

The influence of input parameters and variables was established by comparing predicted tracks to observations. Visual inspection of the tracks as well as quantified comparisons were done based on distances between iceberg locations at the end of certain track segments. The conclusions summarize the relative significance of the various parameters and variables. They also establish a basis to guide the choice of environmental forcing and the appropriate procedures for operational use of the model.

GOVERNING EQUATIONS

The equations of the balance of linear momentum which govern the drift of an iceberg can be expressed as:

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

where m and $\vec{V}$ are the mass and velocity of the iceberg, respectively, and $\vec{f}$ is Coriolis force parameter. The terms on the right-hand side of Eq. 1 represent the forces due to air drag, water drag, wave radiation stress, water pressure gradient and added mass, respectively. Equations describing those forces are given below.

The force due to air drag $\vec{F}_a$, is given by:

$$\vec{F}_a=\frac{1}{2}\rho_a C_a A_a|\vec{V}_a|\vec{V}_a \tag{2}$$

where ρ_a is air density, C_a is air drag coefficient, A_a is cross-sectional sail area and $\vec{V}_a$ is wind velocity. Since iceberg velocity

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KEY WORDS: Iceberg forecasting, iceberg drift.

is usually much smaller than wind velocity, the value of the relative velocity is replaced with wind velocity in Eq. 2.

The force due to water drag, $\vec{F}_w$, is given by:

$$\vec{F}_W = \frac{1}{2}\rho_w C_w \sum_k A_w(k)|\vec{u}_w(k) - \vec{V}|(\vec{u}_w(k) - \vec{V}) \quad (3)$$

where ρ_w is water density, and C_w is the water drag coefficient. The keel is considered to consist of layers of 10-m depth. The kth layer has an area A_{wk}. Water current acting on that layer is $\vec{u}_w(k)$. The drag coefficient, C_w, is assumed to be the same for each layer.

The force due to wave radiation stress, $\vec{F}_r$, is calculated as follows:

$$\vec{F}_r = \frac{1}{2}\rho_w C_{wf} g L a^2 |\vec{V}_a| \vec{V}_a \quad (4)$$

where C_{wf} is the wave force coefficient, g is the gravitational acceleration, L is the waterline length of the iceberg, and a is wave amplitude. Eq. 4 follows the usual convention of using wave amplitude. We note that wave amplitude is equal to half the values of wave height, which is commonly used in operational settings. Eq. 4 is used to calculate forces due to wind waves and swell waves. For wind waves, force direction is assumed to coincide with wind direction. For swell waves, the direction is provided as an input to the model.

Pressure gradient in the water causes a force on the iceberg, $\vec{F}_p$, which can be calculated by considering the sum of inertia and Coriolis forces on a volume of displaced water:

$$\vec{F}_p = m\left(\frac{d\vec{V}_{mw}}{dt} + \vec{f} \times \vec{V}_{mw}\right) \quad (5)$$

where $\vec{V}_{mw}$ is the mean water current velocity.

Finally, the added mass is accounted for by writing the mass in Eq. 1 as $(m + m_{am})$. The added mass, m_{am}, is assumed to be a fraction of the mass (considered in the present work as half the mass of the iceberg).

NUMERICAL SOLUTION

Once forces are calculated, Eq. 1 would give the acceleration of the iceberg, $\vec{a}(t, \vec{V})$:

$$\frac{d\vec{V}}{dt} = \vec{a}(t, \vec{V}) \quad (6)$$

Numerical integration of Eq. 6 gives the velocity, which is then used to update the position of the iceberg. Explicit numerical integration has been used in previous models. The approach was based on using the value of the acceleration at a time step, i, to advance to the next time step, $i + 1$. That approach, however, can lead to an unstable solution, particularly as the time step is increased. Thus a method based on the implicit Euler approach is used to update the velocities (see for example Press et al., 1986). In this approach the acceleration at the new time step, $i + 1$, is estimated in advance and used to update the velocities. The resulting solution is stable for relatively large time steps. The approach is briefly described as follows. The implicit form of Eq. 6 can be written as:

$$\vec{V}^{i+1} = \vec{V}^i + \vec{a}^i(t^{i+1}, \vec{V}^{i+1})\Delta t \quad (7)$$

where the superscripts refer to the time step. Eq. 7 can be linearized to give:

$$\vec{V}^{i+1} = \vec{V}^i + \Delta t\left[\vec{a}^i(t^{i+1}, \vec{V}^i) + \left.\frac{\partial \vec{a}}{\partial \vec{V}}\right|_{V^i} \cdot (\vec{V}^{i+1} - \vec{V}^i)\right] \quad (8)$$

where $\partial\vec{a}/\partial\vec{V}$ is a 2×2 matrix of partial derivatives. This matrix involves the terms on the right-hand side of Eq. 1, which contain iceberg velocities (namely water drag and Coriolis force terms). Finally, solving Eq. 8 gives the velocity components:

$$\vec{V}^{i+1} = \vec{V}^i + \Delta t\left[\mathbf{1} - \Delta t \frac{\partial \vec{a}}{\partial \vec{V}}\right]^{-1} \cdot \vec{a}^i \quad (9)$$

Note that solving Eq. 9 requires inverting the matrix: $[\mathbf{1} - \Delta t(\partial\vec{a}/\partial\vec{V})]$. This approach has proved to be very robust and accurate over a wide range of test cases.

DATASET

The measurements of Smith and Donaldson (1987) are used to test the model. These measurements were chosen because they represent the most complete and reliable dataset of iceberg drift and geometry available to date. These measurements have 2 major advantages, which overcome the weakness of other available data. The first advantage is the measurements of water current profiles in the vicinity of the iceberg. The second is the detailed measurements of the geometry of the tracked icebergs. The dataset, however, does not include measurements of waves. The measurements were conducted during 3 voyages of C.S.S. Dawson from 1983 to 1985. The data cover 12 track segments of 7 icebergs. The study covered locations over the Strait of Belle Isle, the southern Labrador shelf, the inner Grand Banks northeast of St. John's and the outer Grand Banks. To measure an iceberg track, the ship followed the iceberg to within 1 to 2 km. The range and bearing to the iceberg were logged at 10-min intervals using S-band Radar. Ship position was also logged. Thus, time series of iceberg tracks were produced. Water current profiles were measured from the moving ship. The measurements were processed to give water current values averaged over 10-min intervals at 10-m depth increments. Wind speed and direction were also measured from the ship, and recorded at 10-min intervals.

Sail cross-sectional areas of each iceberg were measured using traditional survey techniques and photographs from 4 directions. Side-scan sonar profiles of the keel were also used to produce cross-sectional areas of the keels at 10-m depth intervals. Two sets of cross-sectional views were produced, representing the length and width of each iceberg.

Iceberg Geometry

The iceberg drift model contains new parameterization represented by more detailed keel geometry. A formulation for determining keel cross-sectional areas based upon waterline length was developed for this purpose. Detailed description of this work is given by Barker et al. (2004). Waterline length was plotted versus cross-sectional area for each of the vertical sections contained in the Smith and Donaldson (1987) dataset, and the areas were correlated to the waterline length of the iceberg using equation:

$$A_{\text{sail}} = a_0 L + b_0 \quad (10)$$

where A_{sail} is the cross-sectional area of the sail (m^2), L is iceberg waterline length, and a_0 and b_0 are parameters determined by curve-fitting the available data.

In similar manner, the parameters $a_{(k)}$ and $b_{(k)}$ were determined for each 10-m depth layer of the keel by best curve-fitting available data, as:

$$A_{(k)} = a_{(k)}L + b_{(k)} \tag{11}$$

where $A_{(k)}$ is the cross-sectional area of layer k, extending from $(k-1) \times 10$-m depth to $k \times 10$-m depth.

While the largest draft in the dataset of Smith and Donaldson (1987) was 120 m, drafts up to 230 m can be found in the Grand Banks area of Canada (Miller and Hotzel, 1985). Barker et al. (2004) developed equations for drafts up to 160 m. Using their equations, composite icebergs can be created.

TEST RUNS

Two tracks from the observations of Smith and Donaldson (1987) were used for the parametric study. The tracks represent 2 extremes of small and large icebergs, namely icebergs 83-1 and 84-5e. Iceberg 83-1 was observed for 12 h, and iceberg 84-5e for 64 h. Testing started by simulating the drift tracks of those 2 icebergs in order to ensure accuracy of the model. Those tests are referred to as reference cases. Next, a parametric study was conducted by examining changes of predicted tracks to varying certain input parameters and environmental forces. The parametric study examined the following:

- The role of water and air drag coefficients.
- The impact of water current input. Tests cases used mean values of water current (averaged over keel depth), surface current values, and detailed water current measurements at various depths as input.
- The role of wind waves.
- The role of iceberg waterline length.
- The role of wind drag force.
- Several scenarios of free drift, whereby the iceberg follows certain forcing velocities, e.g., surface water current, mean water current, and combination of water currents and wind velocities.

Predicted Drift Tracks (Reference Cases)

The first test simulated the drift of iceberg 83-1. The measured current velocities at 10-m depth intervals and wind velocities were used in the input. The measurements, recorded at 10-min intervals, were interpolated to calculate the input values at each time step. Although iceberg sail and keel areas were measured, the modeled parameterization was used in the tests in order to verify accuracy of the model. Subsequent runs were done using measured sail and keel cross-sectional areas. The results were almost identical to those from runs using modeled sail and keel cross-sectional areas. The second test case simulated iceberg 84-5e. The initial values and parameters of both runs are given in Table 1.

In the case of iceberg 83-1, a waterline length of 58 m was found to give the best fit of the results to measurements. The

Initial Values and Parameters	83-1	84-5e
Iceberg waterline length (m)	58	157
Longitude (degrees West)	55.917	55.917
Latitude (degrees North)	51.567	51.567
Water drag coefficient	1.5	1.5
Air drag coefficient	1.5	1.5
Duration (h)	12	64

Table 1 Initial values and parameters for runs corresponding to observed icebergs 83-1 and 84-5e

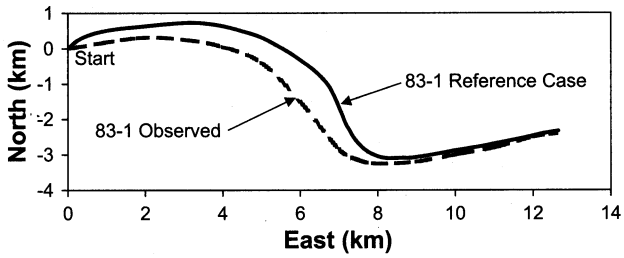

Fig. 1 Predicted and measured iceberg trajectories, Smith and Donaldson (1987), iceberg 83-1

measurements give 66 m and 37 m for the length and width at waterline, respectively. The value of 58 m then falls between the maximum and mean measured values of waterline iceberg dimensions. In the case of iceberg 84-5e, a waterline length of 157 m gave optimal results. The measured length and width at the waterline were 204 m and 136 m, respectively. Thus, the chosen input value of 157 m, which gives the best fit, is a little lower than the mean value of iceberg dimensions at waterline. A detailed examination of the effect of input waterline length is discussed below.

Figs. 1 and 2 show the predicted trajectories of icebergs compared to the observed trajectories. The trajectory of iceberg 83-1 is in good agreement with the measurements. The trajectory of iceberg 84-5e agrees with the observed for the first 48 h. After 2 days the observed track deviates from the modeled track, most likely due to the force of the wind waves. Since the wave height was not recorded during the Smith and Donaldson experiment, wave action was not included in either reference cases. The length of the observed track of iceberg 83-1 was 14.1 km after 12 h; the length of the observed track of iceberg 84-5e was 50.8 km after 64 h. The values of track length were used for determining a quantitative measure of the departure of the forecast track from the observation. This quantitative measure was obtained by calculating the distance between the end points of the observed and predicted (modeled) tracks, ΔL. That distance was then divided by the length of the observed track, L. Because, as mentioned earlier, the modeled and observed tracks of iceberg 84-5e start deviating after 48 h, the length of the iceberg tracks after 48 h was

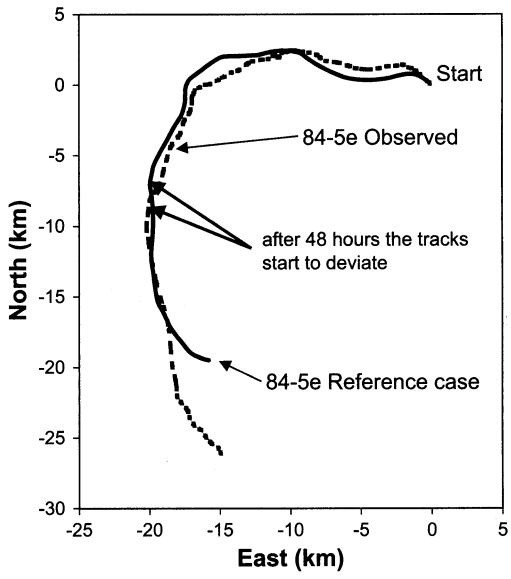

Fig. 2 Predicted and measured iceberg trajectories, Smith and Donaldson (1987), iceberg 84-5e

also compared. The length of the iceberg 84-5e observed track after 48 h was 46.3 km. Although in general the errors are better quantified by considering several points along the track, using the end points appears to be adequate for the present tests.

Water and Air Drag Coefficients

A set of runs was conducted using the above input parameters and variables. The runs used values of water and air drag coefficients of 0.5, 1.0, and 2.0. (The reference case employed a coefficient of 1.5 for both air and water drag.) The resulting drift tracks were very close in all cases. The tracks are not plotted here since they are too close to distinguish from each other.

Water Current and Wind Forcing

Employing detailed vertical distributions of water current is one of the main features of the present model. The impact of input water current on the accuracy of the forecast was examined by conducting runs with the following input water current:

- Measured water current at 10-m depth intervals (reference case).
- Mean (depth-averaged) water current, calculated by giving a weight to each value of water current depending on the area of the keel layer at its depth.
- Surface water current (acting on the top 10-m layer).

The resulting drift tracks are shown in Figs. 3 and 4. The results clearly indicate that using detailed water current profile, or mean water current, gives reasonable agreement with observations. Using surface water current, however, leads to relatively large errors.

Other runs were made using a depth-averaged water current calculated as a mean value of values recorded at all depths (without giving weights proportional to keel areas). The results were very close to those obtained above using weighted mean (depth-averaged) water current.

Another set of runs was conducted to determine the relative importance of water current and wind in drifting the icebergs. One case used only water current in the input but zero wind velocities. Another case used input wind, but with zero values for water current. The resulting drift tracks are compared to the reference cases and observations in Figs. 5 and 6. Obviously, water current

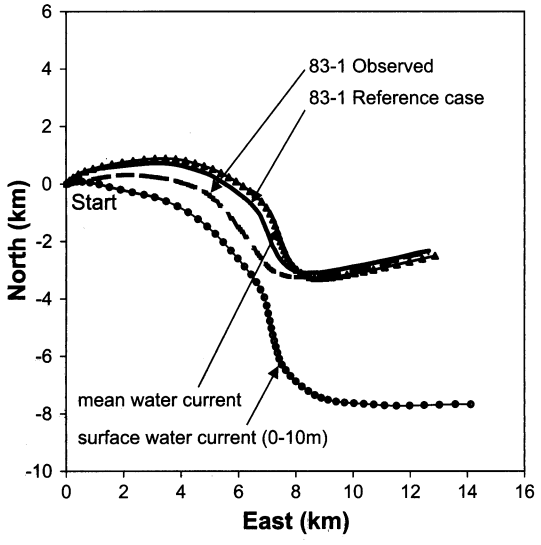

Fig. 3 Sensitivity of iceberg 83-1 drift to surface water current and mean water current (i.e. depth-averaged water current)

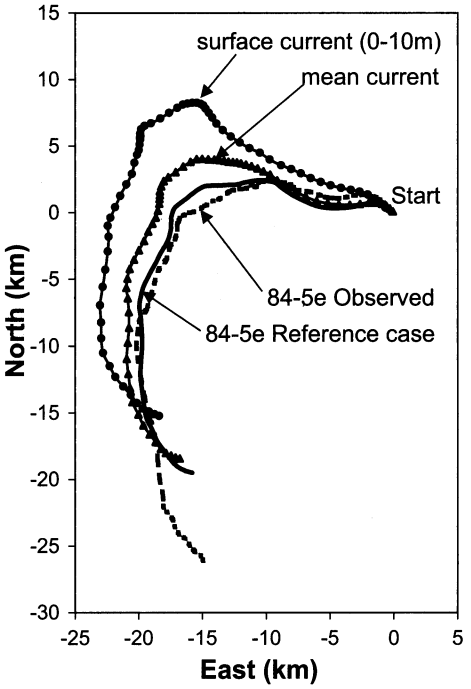

Fig. 4 Sensitivity of iceberg 84-5e drift to surface water current and mean water current (i.e. depth-averaged water current)

has a very significant influence on iceberg drift. Table 2 gives a summary of distances measured between the end of the observed track and the end of the predicted track for iceberg 83-1, and for iceberg 84-5e between the observed and predicted tracks after 48 h as well as between the tracks at the end. The following nomenclature is used in Tables 2~4 in this paper:

ΔL_{12}: distance between end points of observed and modeled tracks of iceberg 83-1

ΔL_{48}: distance between points of observed and modeled tracks of iceberg 84-5e after 48 h

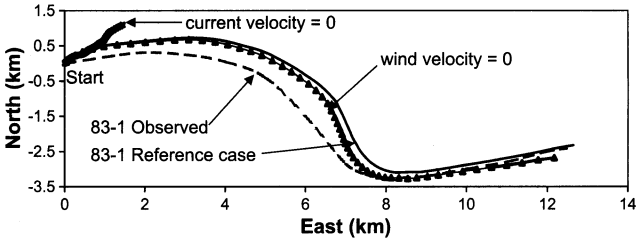

Fig. 5 Sensitivity of iceberg 83-1 drift to zero water current and zero wind force

	83-1		84-5e			
Driving force	ΔL_{12} (km)	$\Delta L_{12}/L_{12}$	ΔL_{48} (km)	$\Delta L_{48}/L_{48}$	ΔL_{64} (km)	$\Delta L_{64}/L_{64}$
reference case	0.087	0.006	2.623	0.066	6.660	0.131
only current (wind = 0)	0.511	0.035	6.722	0.168	18.356	0.361
only wind (current = 0)	11.692	0.810	18.994	0.476	21.276	0.419
mean current	0.285	0.020	4.111	0.103	7.880	0.155
surface current	5.485	0.380	8.869	0.222	11.411	0.225

Table 2 Influence of water current and wind on predicted drift

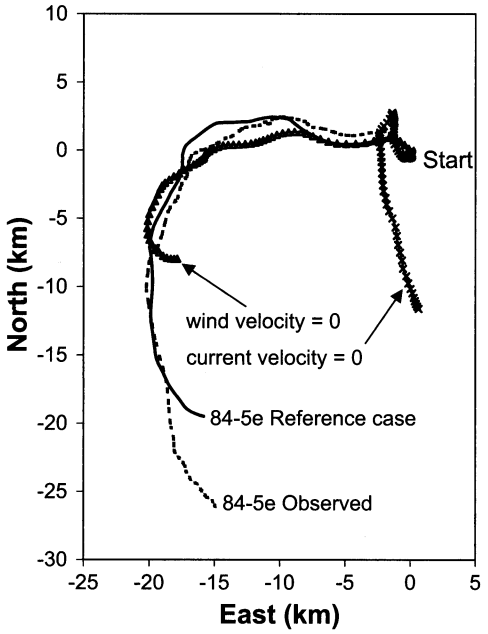

Fig. 6 Sensitivity of iceberg 84-5e drift to zero water current and zero wind force

ΔL_{64}: distance between end points of observed and modeled tracks of iceberg 84-5e

L_{12}: length of whole observed track of iceberg 83-1 after 12 h

L_{48}: length of observed track of iceberg 84-5e after 48 h

L_{64}: length of whole observed track of iceberg 84-5e after 64 h

Further tests used several input water currents to examine the response of the model. Each run was conducted using 1 input water current assumed to act over the entire keel. The value of this current was first taken as that measured for the surface layer (to 10-m depth). The second run used the current measure for the second layer from a 10-m depth to a 20-m depth. Runs proceeded to use currents from each layer in a similar manner. The results showed drastic changes in predicted tracks, which emphasize the significance of input water current.

Waterline Length of Iceberg

The influence of the value of waterline length on predicted drift tracks of the iceberg was tested through several runs. The length was varied between runs, while keeping all other input parameters

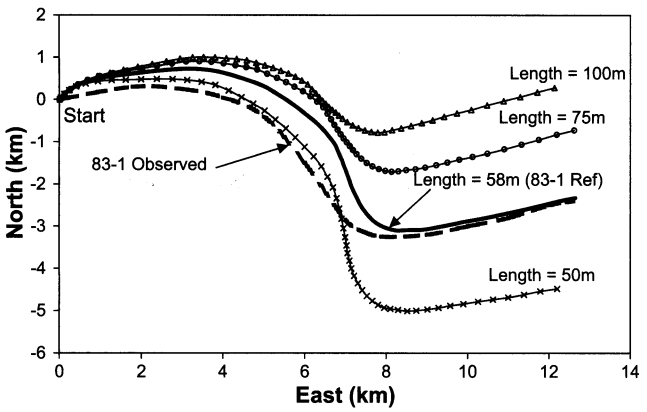

Fig. 7 Sensitivity of iceberg 83-1 drift to iceberg waterline length

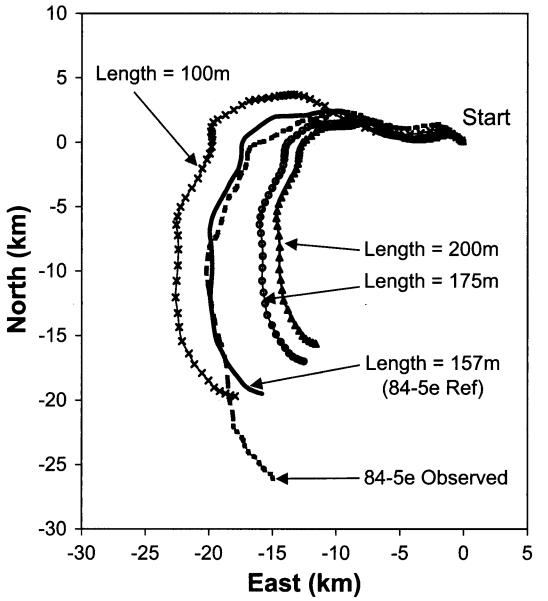

Fig. 8 Sensitivity of iceberg 84-5e drift to iceberg waterline length

and variables similar to the reference cases. Runs for iceberg 83-1 were made using values for waterline length of 50 m, 75 m and 100 m, in addition to the reference case value of 58 m. Runs for iceberg 84-5e were made using values of 100 m, 175 m and 200 m, in addition to the reference case value of 157 m. The results are shown in Figs. 7 and 8. Inspection of the resulting drift tracks in those figures shows that the input waterline length has a significant impact on the results. The values that give the best fit to the observation were close to the mean measured dimension at waterline. Those conclusions are again confirmed by measuring distances between the end of the observed track and the end of the predicted (modeled) track for iceberg 83-1, and for iceberg 84-5e between the observed and predicted tracks after 48 h as well as between the tracks at the end. These results are shown in Table 3.

Waves

Because the data of Smith and Donaldson (1987) do not include measurements of wave conditions, runs examined the role of waves by considering a number of values of wave heights within a plausible range. Only wind waves were considered, and wave period was kept constant at 8 s. Using several values for wave heights was considered sufficient to assess the sensitivity of the forecast to wave action. We note that wave height is used in the present calculations, which is equal to twice the amplitude (Eq. 4).

L (m)		83-1		84-5e			
83-1	84-5e	ΔL_{12} (km)	$\Delta L_{12}/L_{12}$	ΔL_{48} (km)	$\Delta L_{48}/L_{48}$	ΔL_{64} (km)	$\Delta L_{64}/L_{64}$
50	100	2.117	0.147	4.017	0.101	7.082	0.139
reference case							
58	157	0.087	0.006	2.623	0.066	6.660	0.131
75	175	1.673	0.116	5.218	0.131	9.426	0.185
100	200	2.720	0.188	6.564	0.164	11.013	0.217

L: iceberg waterline length

Table 3 Influence of iceberg waterline length on predicted drift

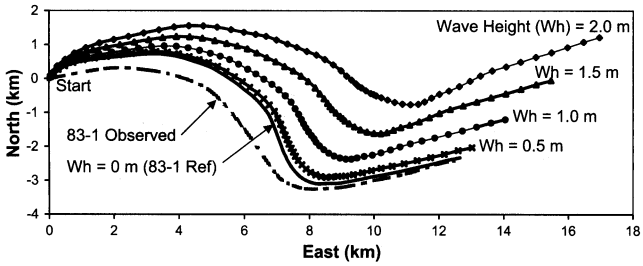

Fig. 9 Sensitivity of iceberg 83-1 drift to wave height (Wh)

Wave heights of 0.5 m, 1.0 m, 1.5 m and 2.0 m were tested. (Wave height of the reference case was 0 m.) Figs. 9 and 10 show the resulting drift tracks for icebergs 83-1 and 84-5e. Those results show that a wave height of 0.5 m had very minor influence on drift. As wave height increased above 0.5 m, the influence on drift became pronounced. Inspection of Fig. 10 also indicates that if wave action were added in the final part of the iceberg 84-5e modeled track, the results would be closer to observation. Table 4 gives the distances between the end points of predicted tracks and observed tracks for both icebergs, and between the predicted and observed tracks after 2 days for iceberg 84-5e.

The present model is intended for operational use in conjunction with wind and wave forecast models. Hence, the present study focuses on sensitivity of the model to various forcing variables, rather than modeling those variables. Although it is possible to generate wave heights by certain standard methods (e.g., using the Pierson-Moskovitz equation), such an effort would not add to the utility of the model. Generating reliable wave information would also require estimates of the appropriate fetch. A more systematic study of wave conditions associated with Smith and Donaldson (1987) observations remains an issue for future investigation.

CONCLUSIONS

The work described in this paper is part of an effort to develop, validate and test a new iceberg drift, deterioration and calving model. The emphasis of this study was to examine the sensitivity

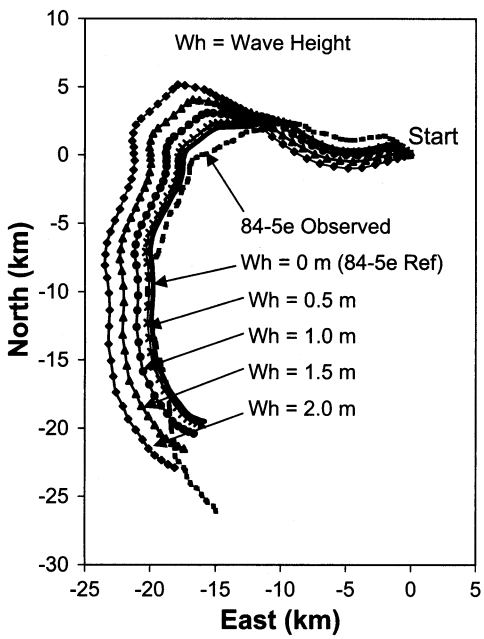

Fig. 10 Sensitivity of iceberg 84-5e drift to wave height (Wh)

Wh	83-1 ΔL_{12} (km)	83-1 $\Delta L_{12}/L_{12}$	84-5e ΔL_{48} (km)	84-5e $\Delta L_{48}/L_{48}$	84-5e ΔL_{64} (km)	84-5e $\Delta L_{64}/L_{64}$
reference case						
0	0.087	0.006	2.623	0.066	6.660	0.131
0.5	0.557	0.039	2.578	0.065	6.473	0.127
1.0	1.876	0.130	0.616	0.066	5.949	0.117
1.5	3.698	0.256	3.010	0.047	5.217	0.103
2.0	5.663	0.392	3.739	0.094	4.502	0.089

Wh: wave height

Table 4 Influence of wave height on predicted drift

of predicted iceberg drift tracks to various input parameters and variables. Test runs examined the role of water and wind drag coefficients, water current and wind forcing, waterline length of the iceberg, and waves. Reliable field observations (Smith and Donaldson, 1987) were used to examine model predictions. The results showed:

- Water current has the most pronounced effect on the forecasts. Using the vertical profile of water current (values recorded at 10-m depth intervals) provided very good agreement between predicted and observed drift tracks. Employing a mean current, averaged over the iceberg's keel depth, yielded relatively small errors (14%) compared to the detailed water current vertical profiles. The percentage was calculated as a distance between tracks divided by the length of the track. Using surface current values (measured over the top 10-m ocean layer), however, gave significant errors (46%). Predicted drift tracks in those cases departed appreciably from observations.
- Waterline length of the iceberg was also found to have a strong influence on drift predictions. This conclusion is to be expected since that length was used to calculate the mass of the iceberg and keel cross-sectional areas. The data used in the comparisons include a length and width for the icebergs, corresponding to the largest and smallest dimensions at the waterline. One of the questions addressed in this study is whether the larger or smaller dimension at waterline should be used as an input to the model. The results showed that using a value between the mean dimensions (of length and width) and the larger dimension (length) give the best fit with observations.
- Waves might have an important role in some cases. This is well demonstrated by modeling the track of iceberg 84-5e. Wave height was not recorded during the experiment, and thus was not used. After 48 h, strong wind force came into effect and caused deviation of the modeled track from the observed one.
- Values of water and air drag coefficients had little effect on the forecasts. The small role of water drag coefficient may appear surprising because water drag force obviously is the main factor affecting drift. The tests showed that the velocity of the iceberg closely follows that of the mean water current (averaged over the keel depth). Thus, the relative velocity between the iceberg and water current is usually small. This, in turn, indicates that the value of water drag coefficient would have a minor effect on the drift.

The results of the present work can be used to guide the operation of the iceberg forecasting models. In particular, it assists in choosing values for input parameters and the type of environmental forcing as well as identifying critical areas for future research. However, operational use of the present model encompasses many issues beyond those considered here. We briefly mention that, for

the operational version of the model, water currents are provided from numerical ocean model forecasts. Detailed profiles are produced, with water current at 10-m depth intervals. Certainly, in the operational context, considerable emphasis is placed on evaluating and ensuring the accuracy of water current forecasts, including wind- and wave-generated currents. Waves, which also play an important direct role on iceberg drift and deterioration, must be generated from numerical forecast models. Clearly, the accuracy of operational iceberg drift forecasts are impacted by the availability and reliability of forecasts from these atmosphere, ocean and wave models. Earlier comparisons of observed and modeled iceberg drift (e.g., Carrieres et al., 2001) have illustrated some deficiencies in forecast driving forces. In addition to ongoing studies of this nature, an evaluation of these driving forces is under way as part of a collaborative effort between the CIS and the International Ice Patrol.

An accurate representation of the iceberg's waterline length, however, may present the greatest challenge. Future work will explore ways to determine better estimates of this variable and how it affects the reliability of operational forecasts.

ACKNOWLEDGEMENTS

The support of the Program on Energy Research and Development (PERD) is gratefully acknowledged.

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APPENDIX B

Fortran Files

File: main.f90

```
!*****************************************************************************
!
! PROGRAM:     Local Iceberg Dynamics and Deterioration (LIDD)
!
! PURPOSE:     The program keeps track of icebergs.
!                                   The program performs the following calculations:
!                                   - iceberg drift
!                                   - iceberg melt
!                                   - iceberg calving
!
! DESCRIPTION:          Methodology of the calculations is given in the paper by:
!                                   I.Kubat, M.Sayed, S.B.Savage and T. Carrieres
!                                   "An operational model of iceberg drift"
!                                   International Journal of Offshore and Polar Engineering
!                                   Vol.15, No.2, June 2005, pp125-131
!
! INPUT FILES:          userInput.f90
!
! OUTPUT FILES:         userOutput.f90
!
! AUTHORS:              Mohamed Sayed
!                       Canadian Hydraulics Centre
!                       National Research Council, Ottawa, Ontario K1A 0R6
!                       E-mail: Mohamed.Sayed@nrc-cnrc.gc.ca
!                       Tel (613)990-6958  Fax (613)952-7679
!
!         AND
!
!                       Ivana Kubat
!                       Canadian Hydraulics Centre
!                       National Research Council, Ottawa, Ontario K1A 0R6
!                       E-mail: Ivana.Kubat@nrc-cnrc.gc..ca
!                       Tel (613)993-7695  Fax (613)952-7679
!
! HISTORY:
! Version       Date            Comment
! -------  ----                 -------
! 1.0           April 2006      Original code.      M. Sayed & I. Kubat
!
!
!*****************************************************************************

        program main

        use variables
        implicit none

        call runProgram

        end program main

!*****************************************************************************
```

File: userInput.f90

```
!*******************************************************************************
subroutine userInput
!
!
! PURPOSE:              - get values of the environmental input at time time step i.
!                               The input consists of water current, wind velocity,
!                               wind waves, and water surface temperature.
!
! DESCRIPTION: The input consists of:
!                               -Wind velocity along the east and north directions
!                               -Current for each time step along (towards) the east and north direction
!                               -Wind wave height and period
!                               -Temperature of surface water
!
!
!
!
!
! AUTHOR: Mohamed Sayed
!
!
! HISTORY:
! Version       Date            Comment
! -------  ----                 -------
! 1.0           April 2006      Original code.     M. Sayed & I. Kubat
!
!*******************************************************************************
        use variables
        use userVariables
        implicit none

        integer i

        !Example test case

        ! Run parameters
        userNsteps= 3390                !Number of time steps
        userDelt= 120                   !Time step (s)
        userPrintFreq= 15               !Output frequency (steps)

        !Initial iceberg variables
        userBergLength= 100             ! Waterline length of the iceberg
        userLong= 55.0                  ! Longitude (degrees)
        userLat= 50.0                   ! Latitude (degrees)
        userU= 0.0                      ! East velocity component (m/s)
        userV= 0.0                      ! North velocity component (m/s)

        !Geometry
        userTabularGeometry= 0  ! 1= Tabular, 0= non-tabular geometry
        userKeelSailInput= 1    ! 1= yes (must be 1 if Tabular), 0= use default value
                                ! This variable determines if the user will override
                                ! the default values of keel depth and sail height
                                ! It should be "1" for tabular icebergs.
```

```
                                ! For non-tabular icebergs, it may be "1" to enter
                                ! user values, or "0" to use default values.

        userKeelDepth= 70.0     ! If "userKeelSailInput= 1", enter depth (m)
        userSailHeight= 10.0    ! If "userKeelSailInput= 1", enter sail height (m)

        !Environmental forcing
        userWaterTemp= 11.9     !Water temperature degrees C
        userWaveHeight= 1.5     !Wind wave height (m)
        userWavePeriod= 9.0     !Wind wave period (s)

        !Current and wind values for each time step. The values could be constant
        !or may be, for example, read from a file. The following loop can be replaced
        !with the user.
        do i= 1, userNsteps
                userUcurrent(i)= 0.5    !East component of water current
                userVcurrent(i)= 0.2    !North component of water current
                userUwind(i)= 5.0       !East component of wind velocity (positive towards the East)
                userVwind(i)= 7.5       !North component of wind velocity (positive towards the North)
        end do

        !Properties (default values are listed below)

        userCdwat= 1.3          !Drag coefficient of water
        userCdair= 1.9          !Drag coefficient of air

        userRhoice= 910.        !Density of ice (kg/m^3)
        userRhoair= 1.3         !Density of air (kg/m^3)
        userRhowat= 1030.       !Density of water (kg/m^3)
        userKwater= 0.562       !Thermal conductivity of water (W/m/degreeC)
        userKair= 0.0241        !Thermal conductivity of air (W/m/degreeC)
        userNuwater= 1.79E-06   !Kinematic viscosity of water (m^2/s)
        userNuair= 1.32E-05     !Kinematic viscosity of air (m^2/s)
        userLatentHeat=3.34E05  !Latent heat of fusion (J/kg)
        userAlbedo= 0.7         !Albedo

end subroutine userInput
!*************************************************************************************
```

File: userOutput.f90

```
!*******************************************************************************
subroutine userOutput(step)
!
!
!  PURPOSE:                - Ouput the results.The subroutine is called at intervals
!                                  defined by the user. The interval between outputsis in seconds is:
!                                  interval = userPrintFreq * userDelt
!
!
!
!
!
!
!
!  AUTHOR: Mohamed Sayed
!
!
!  HISTORY:
!  Version          Date               Comment
!  -------  ----                       -------
!  1.0              April 2006         Original code.      M. Sayed & I. Kubat
!
!*******************************************************************************
        use variables
        use userVariables
        implicit none
        real:: time

        integer, intent(in):: step

        time= step* userDelt

        ! The user can open and close output files and record the values of
        ! variables of interest.

        ! For example:
        ! time     = time from the start of the forecast (s)
        ! userLong = Longitude of the iceberg (degrees)
        ! userLat  = Latitude of the iceberg (degrees)
        ! userU    = East component of iceberg velocity (m/s)
        ! userV    = North component of iceberg velocity (m/s)
        ! userBergLength = Waterline length of the iceberg

        !Example test case

        print *,time, userLong,userLat,userU,userV,userBergLength

end subroutine userOutput
!*******************************************************************************
```

File: userVariables.f90

```
!*******************************************************************************
Module userVariables
!
!
! PURPOSE:              - Declaration of user variables
!
!
!
!
!
!
!
! AUTHOR: Mohamed Sayed
!
!
! HISTORY:
! Version       Date                    Comment
! -------  ----                 -------
! 1.0           April 2006      Original code.     M. Sayed & I. Kubat
!
!*******************************************************************************


        ! Run parameters
        integer:: userNsteps            !Number of time steps
        real:: userDelt                 !Time step (s)
        integer:: userPrintFreq         !Output frequency (steps)

        !Initial iceberg variables
        real:: userBergLength           !Mean length of the iceberg at waterline (m)
        real:: userLong                 !Longitude of the iceberg (degrees)
        real:: userLat                  !Latitude of the iceberg (degrees)
        real:: userU                    !Velocity along the East direction (m/s)
        real:: userV                    !Velocity along the North direction (m/s)
        integer:: userTabularGeometry   !1= Tabular, 0= non-tabular geometry
        integer:: userKeelSailInput     ! 1= yes (must be 1 if Tabular), 0= use default value
                                        ! This variable determines if the user will override
                                        ! the default values of keel depth and sail height
                                        ! It should be "1" for tabular icebergs.
                                        ! For non-tabular icebergs, it may be "1" to enter
                                        ! user values, or "0" to use default values.

        real:: userKeelDepth            !If "userKeelSailInput= 1", enter depth (m)
        real:: userSailHeight           !If "userKeelSailInput= 1", enter sail height (m)

        !Environmental forcing
        real:: userWaterTemp            !Water temperature degrees C
        real:: userWaveHeight           !Wind wave height (m)
        real:: userWavePeriod           !Wind wave period (s)

        !Dimsnsion of the variables below should be equal or larger than the
        !number of time steps "userNsteps".
        real, dimension(20000):: userUcurrent,userVcurrent   !East and North component of water current, respectively
```

```
        real, dimension(20000):: userUwind,userVwind        !East and North component of wind velocity, respectively

        !Properties

        real:: userCdwat,userCdair          !Drag coefficients of water and air
        real:: userRhoice                   !Density of ice (kg/m^3)
        real:: userRhoair                   !Density of air (kg/m^3)
        real:: userRhowat                   !Density of water (kg/m^3)
        real:: userKwater                   !Thermal conductivity of water (W/m/degreeC)
        real:: userKair                     !Thermal conductivity of air (W/m/degreeC)
        real:: userNuwater                  !Kinematic viscosity of water (m^2/s)
        real:: userNuair                    !Kinematic viscosity of air (m^2/s)
        real:: userLatentHeat               !Latent heat of fusion (J/kg)
        real:: userAlbedo                   !Albedo

end module userVariables
```