Introduction

The amount of ice growth and ablation are key measures of the thermodynamic state of the sea ice cover. Measurements from ice mass balance buoys include a time series of snow accumulation and ablation; ice growth; ice surface and bottom melt; and vertical temperature profiles through the snow, ice, and upper ocean. This provides important information about the evolution of ice thickness as well as the surface heat budget and the ocean heat flux. Ice mass balance measurements record winter growth and summer melt, providing insight into the impact of atmospheric and oceanic forcing.

An ice mass balance buoy provides a point measurement of the ice mass balance, defined by a particular combination of snow and ice conditions. Perovich and Richter-Menge (2006) demonstrated how judicious selection of the measurement site facilitates the extrapolation of the data to represent larger regions. The key is carefully selecting a location for the buoy that is representative of the region. For example, undeformed, unponded multiyear ice is the predominant ice type within the perennial zone, and undeformed level ice is the predominant ice type within the seasonal ice zone. Sites that reflect these ice types enable the data to be representative of the largest fraction of the surrounding area, and are targeted during deployment. However, there are limitations to mass balance observations made at these select sites. For example, bare ice sites will not be representative of ponded ice. This could be rectified by deploying a buoy in ponded ice as well (Perovich and Richter-Menge, 2006), or by modeling the additional heat flux to ponded ice nearby inferred from the difference in albedo.

Description of Buoy File Format

Data and metadata from each individual buoy are stored as 5 CSV files: *Position data, Meteorological data, Mass balance data, Temperature data, and Metadata*. In the case where one of these datasets was not collected, due to complications with sensor installment or a complete sensor failure, an empty file is included and the justification is noted in the *Metadata* CSV file.

The *Position data* CSV file includes buoy latitude and longitude in decimal degrees with +/- used to indicate East/West longitude, respectively. The buoy position is determined using several different technologies over the years including Argos (Advanced Research and Global Observation Satellite) Doppler, Iridium Doppler, and GPS. Since the Argos system is opportunistic, meaning the buoys transmit periodic messages that are only successful when an Argos satellite is overhead, Argos-determined position data are reported at an irregular timestep. Iridium and GPS positions are typically recorded every hour.

The *Meteorological data* CSV file includes air temperature (°C) and air pressure (mbar).

The *Mass balance data* CSV file has snow depth, ice thickness, top of ice position, and bottom of ice position (all in meters). The top of ice position always begins at 0.00 m. A negative top of ice position indicates ice surface melt. The ice thickness is simply the top of ice position minus the bottom of ice position.

The *Temperature data* CSV file includes air, ice and ocean temperature profile data (°C) from thermistor string(s). The thermistor at the original ice surface at the time of deployment is at 0 cm.

The *Metadata* CSV file contains information about the individual buoy, its deployment, operation, and a summary of the mass balance statistics, including total ice growth/melt, total snow accumulation/ ablation, and dates of melt/freeze onset during each full growth or melt season that the buoy operated. The mass balance summary statistics only include data when the entire winter growth or summer melt season was observed. Similarly, onset date tables only include data when the freeze-up or melt onset transition time is fully observed. An annual cycle is treated as representing the period from onset of seasonal growth (in autumn) to end of seasonal ice melt (in late summer or early autumn). The ice year denotes the calendar year of the autumn in which seasonal ice growth begins. The sensor functionality table outlines dates and times when the specific buoy sensors were operational for easy lookup. Finally, the file includes processing notes that are specific to that buoy. These include manual data deletions due to faulty sensors, notes on unusual findings, dates that sensors malfunctioned, and potential reasons for those malfunctions. The mass balance summary plot and drift track map are included as PNG files for reference. More detailed information on the *Metadata* CSV file is provided in the Individual Buoy Metadata section below.

Data Collection Intervals

Data were recorded at varying time steps throughout the over twenty years of buoy deployments. The general data collection intervals are summarized here, although some exceptions exist. Time steps on buoys deployed prior to 2003C are not standardized. From 2003C through 2004, positions were collected at 1 hour intervals while meteorological and mass balance data were collected every 2 hours. For buoys deployed from 2005 through 2009, all position data were determined with Argos Doppler and therefore reported at an irregular time step while meteorological and mass balance data continued to be collected every 2 hours. The year 2010 was a transition year with half of the buoys following the time step pattern of the 2005-2009 buoys and the other half collecting at the 2011-2013 intervals. From 2011 to 2013C, almost all of the buoys collected position and meteorological data at 1 hour intervals and mass balance data at 4 hour intervals. Finally, from 2013D through 2016, all meteorological data were recorded at 1 hour intervals, mass balance data at 4 hour intervals, and position data at 1 or 4 hour, with the exception of the SIMB2 buoys (2015I, 2015J, 2015K) that collected all data at a 1 hour interval. The varied data collection and transmission intervals generally arose from constraints on power budgets as technology evolved.

Description of Processing Completed

All buoy data were cleaned and processed in Matlab. The following global outlier thresholds were applied and data outside these bounds were removed.

Temperature values greater than +10 C or less than -60 C.
Barometric pressure values greater than 1100 mbar or less than 850 mbar.
Snow depth greater than 2 m or less than 0 m.
Ice top position greater than 0 m or less than -2 m.
Ice bottom position greater than 0 or less than -5 m.
Ice thickness is calculated from the ice top and bottom position and so ice thickness values were subsequently removed if bad ice top or bottom positions were found.

Additionally, local mass balance outliers were removed with a one-day moving median filter, assuming an exponential distribution and setting a 99% upper tolerance limit.

Faulty thermistor sensor data were removed manually and noted in the processing notes of the buoy's metadata page for reference.

All data gaps 2 days in length or greater were located and noted in the metadata sensor functionality table. All remaining small data gaps (less than 2 days in length) were interpolated. A shape-preserving piecewise cubic interpolation was applied to the meteorological and mass balance data using 2 data points on either side and a linear interpolation was applied to the thermistor data using 1 data point on either side.

Duplicate and faulty position data were also removed manually.

Clean data were written to an Excel file and converted to individual comma-separated values files.

Data Gaps

The Arctic Ocean is a remote and extreme environment. Data gaps inevitably occur due to sensor malfunction or transmission failure. As these buoys are completely autonomous, it is also often difficult to determine the root cause of the data gaps. When possible, reasons are given in the buoy's Metadata CSV file. As detailed in the previous section, as part of the QA/QC process, small data gaps were interpolated and so only data gaps of 2 days in length or greater are present in the final CSV data files.

Individual Buoy Metadata Definitions

Deployment Information

Buoy Type: The buoy type is one of the following: Ice Mass Balance buoy (IMB), Seasonal Ice Mass Balance buoy version 1 (SIMB), version 2 (SIMB2) or version 3 (SIMB3).

The IMB consists of a central canister that contains the data logger, battery, satellite transmitter, and barometer. There are two outlying support structures, attached via umbilical cords. One holds a string of thermistors and the other holds two acoustic sonar rangefinding units, also known as pingers or sounders, positioned above and below the ice. An air temperature sensor is located either on the central canister or on one of the outlying support structures (Figure 1).

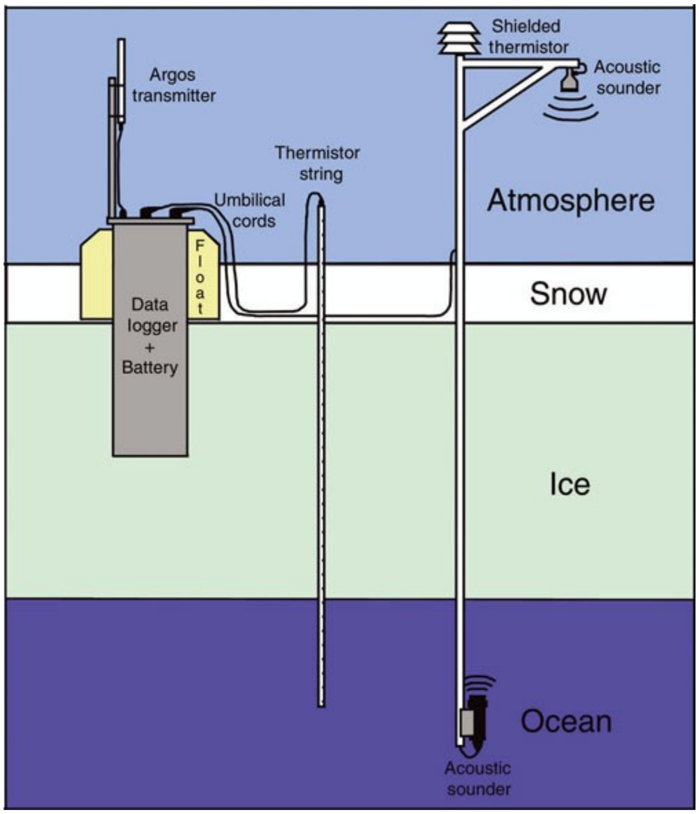

Figure 1. Schematic of an ice mass balance buoy (IMB).

All versions of the SIMB consist of a single hull that encompasses all cables and sensors, allowing for easier deployment and improved durability. A schematic of the SIMB version 1 is shown in Figure 2. The top section contains the transmitter antenna, barometer, air temperature sensor, and downward-looking acoustic rangefinder. The middle section provides buoyancy. The bottom section houses the satellite transmitter, data logger, battery, underwater pressure sensor, and upward-looking acoustic rangefinder. A string of thermistors is attached to the outside of the hull (Figure 2). The SIMB2 is structurally the same as the SIMB but contains an upgraded internal electronics package.

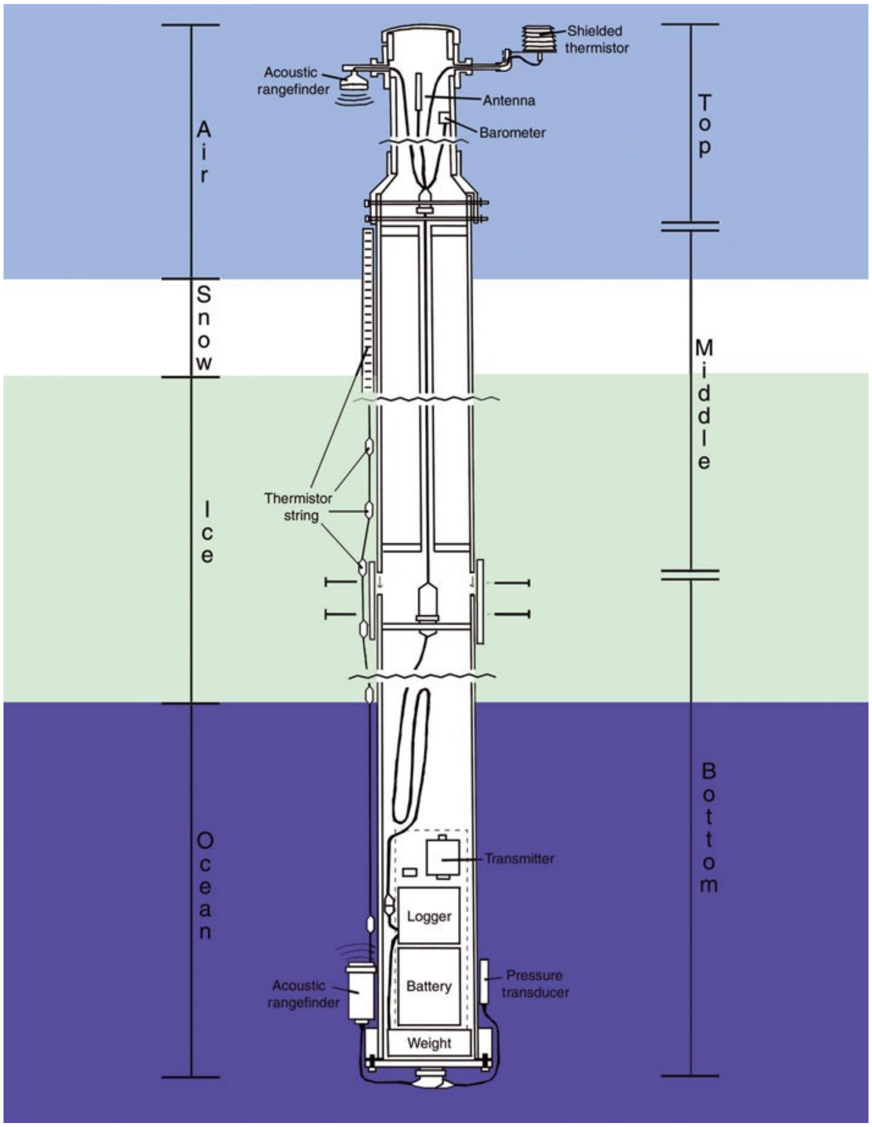

Figure 2. Schematic of a seasonal ice mass balance buoy (SIMB) (Polashenski et al., 2011).

The latest generation of the SIMB, the SIMB3, was designed to be more light weight, less expensive, and more reliable. It is a two-piece, single hull, spar type buoy (Figure 3). It possesses the same core sensor types as the previous versions (acoustic rangefinders, barometer, air temperature sensor, temperature string) but has a higher resolution (2 cm spacing) temperature string. A major advantage is that assembly can be accomplished by just one person and without the use of tools.

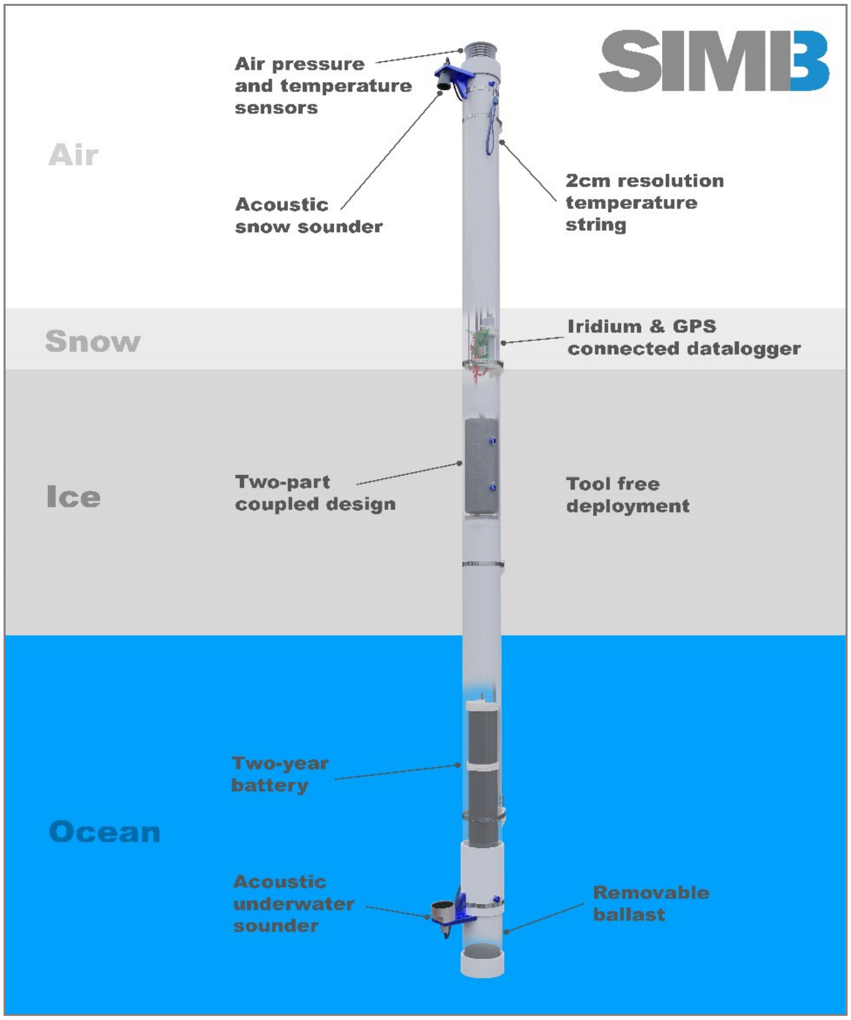

Figure 3. Representation of the SIMB3.

Additional information about the ice mass balance buoy designs can be found in Polashenski et al. (2011) and on the website at *http://imb-crrel-dartmouth.org/instruments/*.

Initial Conditions: The initial ice thickness, snow depth and freeboard are all recorded during deployment and documented here, in units of meters.

Period of Operation: Period of operation refers to the start and end date of the transmitter. Individual sensors may operate for only a subset of this time. See the sensor functionality section for individual sensor start and end dates.

Ice Type: Ice type is categorized into first year, multiyear, or unspecified. First year is ice that has not yet survived a summer melt season while multiyear ice has survived a summer melt season. If the ice type was not noted upon deployment and it is not obvious from the data, it was recorded as unspecified.

Deployment Region: Figure 4 below was used as a reference for defining the Deployment Region documented on the metadata tab.

Figure 4. Map displaying regions of the Arctic Ocean.

Mass Balance Summary Data

The Mass Balance Summary Data table outlines key growth and melt parameters for each full growth/melt season.

Max Ice Thickness is defined as the seasonal maximum ice thickness in April/May. This value is only available if the buoy reports through the seasonal maximum and subsequent melt is observed. The maximum is reported as the average of the readings collected during the 1 week interval centered on the maximum measurement.

Max Snow Depth is defined as the seasonal maximum snow depth in April/May. This value is, again, only available if the buoy reports through the seasonal maximum and subsequent snow melt is observed. The maximum is reported as the median of the readings collected during the 3 day interval centered on the maximum measurement.

Ice Growth is defined as the amount of bottom growth occurring over the entire growth season. Growth is reported as the difference between the minimum and maximum bottom position, where minimum and maximum bottom position are both calculated as a 3 day median centered on the maximum and minimum individual values.

Surface Melt is defined as the amount of ice surface melt occurring over the entire melt season. Melt is reported as the difference between maximum and minimum ice surface position, where maximum and minimum ice surface positions are both calculated as 3 day median centered on the maximum and minimum individual values.

Bottom Melt is defined as the amount of bottom melt occurring over the entire melt season. Melt is reported as the difference between maximum and minimum bottom position, where maximum and minimum bottom positions are both calculated as 3 day median centered on the maximum and minimum individual values.

Onset Dates

The Onset Dates table contains important dates for buoy melt and freeze-up. It is important to note that these dates are best approximations based on the data and the following methods.

Snow Melt is reported as an approximate range of time during which sustained snowmelt begins and is provided in 1/3 month resolution (early, mid, or late of the specified month). The character of melt onset is highly variable and many definitions exist in literature. Here the Snow Melt onset date estimate is determined when snow depth declines below the maximum snow depth from surface rangefinder data and it is then verified that the following decrease in snow depth is sustained.

Ice Surface Melt is defined as the date that the 3 day running average of the surface rangefinder data first reports ice loss.

Ice Bottom Melt is defined as the date that the 3 day running average of the bottom rangefinder data first reports ice loss.

Bottom Growth is defined as the date that the 3 day running average of the bottom rangefinder data first reports ice growth.

References

Perovich, D.K. and J.A. Richter-Menge. 2006. From points to poles: extrapolating point measurements of sea ice mass balance, Annals of Glaciology, 44, 188-192.

Polashenski, C., Perovich, D., Richter-Menge, J., and B. Elder. 2011. Seasonal ice mass-balance buoys: adapting tools to the changing Arctic, Annals of Glaciology, 52(57), 18-26.