Uncertainty of Dating Ice at the Byrd Ice Core, Antartica

Gutowski et al.

1. Abstract

Data from radar-sounding surveys of West Antarctica are used to determine the age of observed radar horizons near the Byrd ice core, Antarctica [Gow, 1968]. We emphasize inclusion of uncertainty in radar- and ice-related sources of uncertainty. We present a new chronology of the Byrd ice core which takes into account theoretical and measurement uncertainties in depth and age of prominent layers observed in the ice.

2. Introduction

Annual layers within ice sheets have long been recognized as an invaluable resource for understanding changes in ice dynamics over time. Information imbedded in these layers – including their chemical composition and their position – provide climate proxies on both millennial and shorter, annually-resolved scales. Intrinsic to this, is the ability to assign a date to internal ice layers that allow for a picture of the underlying dynamics to emerge. Such information is pertinent to problems ranging from the development of large-scale ice sheet models coupled to general circulation models to understanding fundamental ice physics to tracking the mass balance of land ice over time.

Ice cores provide a useful resource for extracting data from annual layers, particularly young ones, because these layers can often be differentiated by eye in a core sample. However, the resulting measurements are inherently localized and depend on the quality and completeness of the core sample as it is recovered.

Increasingly, radar echo sounding has provided a method to obtain information about ice layers over large areas. These operations can be executed more quickly and less expensively while providing a wealth of valuable data. By comparing these data to that of nearby ice cores, it is possible to determine an age-depth relationship for observed layers. This relationship can then be used to understand how ice has flowed throught large regions of ice sheets such as Greenland and Antarctica over the course of thousands of years.

This information is particularly relevant to studies of sea-level change; by understanding how ice is flowing, it is possible to constrain mass balance calculations and therefore track ice melt. Correlating these features to paleoclimate could lead to a predictive strategy for estimating sea-level rise.

Despite the advancement in our understanding of ice physics, however, there has yet to be a thorough review of the uncertainties associated with depth estimations of radar echo surveys. While there are several existing ice core chronologies that incorporate estimations of age uncertainties, they are largely incomplete. Although underdeveloped, uncertainty estimations are at the crux of predicting future sea level changes. Without proper uncertainty quanitification, predictions are generally useless in matters of decision-making. The community is in need of robust, probabilistic measures of uncertainty pertaining to questions of sea-level rise.

In this case, uncertainties can be assigned to both the depth of layers and their corresponding ages. There is inherent uncertainty in both the radar sampling of layers and the myriad of techniques used to determine relative ages of ice layers and then correlate them to absolute chronologies using known climatic events. Here, we employ a stochastics, Bayesian approach to derive an ensemble of age-depth relationships for the Byrd ice core which take into account uncertainties from radar and dating techniques.

3. Data

The radar echo sounding data was obtained in December 2004 as a part of the AGASEA project. The flight line passed 870 m from the Byrd ice core site. The plane was travelling at 67 m/s and was 550 m above the ground. It had a slight -0.37° roll and was travelling due east. The data includes radar times (the time it takes for a radar pulse to leave the plane, reflect off a layer, and return to the detectors) in microseconds. The data was collected with a 15 Mhz bandwidth. The ten unique layers we include here were hand chosen using GeoFrame for having some of the strongest reflection amplitudes.

Volcanic data was used to quantitatively compare our calculated age-depth relationship to the age of layers in the Byrd ice core. The volcanic chronology was developed using the electrical conductivity method [Hammer et al., 1994]. We used a representative subset of dated volcanic events to cover an age range from 709 BP to more than 18000 BP. These events correspond to a depth range of 97.8 m to 1890 m below the 1968 surface on the Byrd ice core Gow [1968].

Density data was used to account for the varying density of ice in the upper part of the ice sheet. This was necessary to properly calculate the depth of each radar-detected layer we used (see Section 4 for more on this). We obtained our data from the original analysis of the ice core presented by Gow [1968].

4. Sources of Uncertainty

There are many sources of uncertainty inherent to the way in which data is collected, analyzed, and understood. We have included the following sources of uncertainty.

4.1. Uncertainty in depth of radar-detected layers

As mentioned previously, layers are selected by hand using the program GeoFrame. This program allows a user to select strong reflectors from a radargram and trace them along a flight path. However, there is a fundamental limit to how accurately the depth of these layers can be tracked given the resolution of radar timing and, in turn, the sampling rate. The sampling rate might be anywhere from 5ns to 20ns, so we assume a resolution of 10 ns when picking the reflection from the surface of the ice sheet and for each internal layer. We can then treat the two cases of surface and internal layers separately.

To put this uncertainty into units of depth, we scale the time by the velocity of the electromagnetic wave involved. For example, we assume the e/m wave travelled to the surface with a velocity of c, the speed of light, but then slowed to the velocity of electromagnetic radiation in ice, which we assume to be 1.69 x 10^8 m/s (reference?) before reaching the internal layers. This results in a 1σ depth uncertainty of 0.3 m for the surface and 0.17 m for the internal layers. We also consider the fact that the uncertainty picking the surface represents a systematic error – it will be the same for each of the internal ice layers. However, the uncertainties of each internal layer will not necessarily all be the same, so they should be modeled as random within the bounds described above.

The radar data used for this study was taken using a radar pulse with a 15 MHz bandwidth. The limitation of a finite bandwidth means that an even an infinitesimally thin layer of ice will appear in the survey to have a finite width. To account for this effect, we assume a 1σ depth uncertainty of 5.63 m. This is obtained from considering both the bandwidth frequency and the velocity of electromagnetic radiation in ice. This uncertainty is applied as a random error for each of our selected layers. See Section 5 for additional discussion about how all of the sources of uncertainty were included.

4.2. Uncertainty in determination of age

Each year fresh snow accumulates on the top of the ice sheet, burying the previous season's snowfall. As layers of ice descend into the ice sheet, the layers become thinner, as air from the surface is squeezed out and gravity compacts the ice. This thinning makes it increasingly difficult to distinguish one layer from another at depth while in shallow regions, it maybe be possible to simply count layers by eye and therefore determine the age of those layers.

The uncertainty associated with determining ages for ice layers is a function of depth; -delta age

-landmarks like 10Be, CH4, F

-ecm method accuracy

-correlation with bc89?

5. Method

-firn offset

-depth correction from 1968

1. determination of depth from radar times

2. use metropolis algorithm to invert for accumlation and ratio of surface to basal velocity based on volcanic dating (calculate cost based on this)

3. use schwander model to calculate ages (include assumptions)

We used an ice model adapted from Schwander et al. [2001] to determine the age of internal ice layers near the Byrd ice core drilling site in Antarctica. The age was determined assuming an average time-varying accumulation, ice flow, and layer depth near the ice core. We separated this process into two distinct parts.

First, we use a metropolis algorithm to assign an age to each meter of depth at the Byrd ice core. We invert for a piecewise accumulation function over the depth of the core and for a parameter that describes to the ratio of surface ice velocity to bed ice velocity. We include the age uncertainties described in Section 4.2. By comparing to the age and depth of known volcanic events, determined using the electrical conductivity method (ECM; Hammer et al. [1994]), we

Next, we utilized a radar uncertainty model to determine depth from available radar reflection horizons near the Byrd ice core. Our basic approach calculated distance based on the speed of light in ice and the time it took for the radar pulses to return to leave and return to the aircraft. This method assumes that there is no basal melting and that the density throughout the ice depth is constant. For simplicity, we assume throughout this work that there is no basal melting, though we know that is not the case [Gow, 1968]. We correct for varying density in the firn layer using a correction presented by Dowdeswell [2004]. Ice density was tracked throughout the ice by Gow [1968], and we apply these measurements to the Dowdeswell et al. correction:

Below the firn layer (64 m, ref:Physics of Glaciers), a constant correction of 6.9 m is applied.

6. Results

7. Discussion

8. Conclusion

9. References

References

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