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IceChrono v1: a probabilistic model to compute a common and optimal chronology for several ice cores

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Abstract

Polar ice cores provides exceptional archives of past environmental conditions. Dating ice and air bubbles/hydrates in ice cores is complicated since it involves different dating methods: modeling of the sedimentation process (accumulation of snow at surface, densification of snow into ice with air trapping and ice flow), use of dated horizons by comparison to other well dated targets (other dated paleo-archives or calculated variations of Earth's orbital parameters), use of dated depth intervals, use of Δdepth information (depth shift between synchronous events in the ice matrix and its air/hydrate content), use of stratigraphic links in between ice cores (ice-ice, air-air or mix ice-air links). Here I propose IceChrono v1, a new probabilistic model to combine these different kinds of chronological information to obtain a common and optimized chronology for several ice cores, as well as its confidence interval. It is based on the inversion of three quantities: the surface accumulation rate, the Lock-In Depth (LID) of air bubbles and the vertical thinning function. IceChrono is similar in scope to the Datice model, but has differences on the mathematical, numerical and programming point of views. I apply IceChrono on two dating experiments. The first one is similar to the AICC2012 experiment and I find similar results than Datice within a few centuries, which is a confirmation of both IceChrono and Datice codes. The second experiment involves only the Berkner ice core in Antarctica and I produce the first dating of this ice core. IceChrono v1 is freely available under the GPL v3 open source license.

1 Introduction

Ice cores from polar ice sheets are widely used to infer information on past climates (e.g., Barnola et al., 1987; Dansgaard et al., 1982, 1993; Delmas et al., 1980; EPICA community members, 2004, 2006; Parrenin et al., 2013; Petit et al., 1999; Raynaud et al., 1993). They allow to reconstruct a wide range of climatic parameters, like the local temperature (Jouzel et al., 2007) and precipitation (Parrenin et al., 2007), the aridity of the surrounding continents (Lambert et al., 2008), the global greenhouse gases concentration (Loulergue et al., 2008; Lüthi et al., 2008; Spahni et al., 2005), the solar activity and Earth geomagnetic field (Bard et al., 1997; Raisbeck et al., 2007), etc.

The dating of ice core is essential for the interpretation of the ice core records, but it is a complex task. First, ice cores enclose air bubbles (which become hydrates at ~ 1000 m depth), and these have a younger age than the surrounding ice (Schwander and Stauffer, 1984). Indeed, the top layer of the ice sheet, called the firn, is permeable and the air is only locked-in at its base. We therefore need to derive two age scales, one for the ice matrix and one for the air/hydrates. Second, there is not one unique method to date ice core, but rather a collection of methods which have all their pros and cons.

These methods fall into 4 categories. (1) The modeling of snow accumulation, snow densification into ice and ice flow (e.g., Goujon et al., 2003; Huybrechts et al., 2007; Parrenin et al., 2007). This method is not accurate for absolute dating far from the surface because of poorly known parameters of the models (e.g., the basal melting of ice), but it is generally accurate for event duration. Moreover, this method gives access to other variables useful for ice core interpretation, like the surface accumulation rate (used to transfer concentrations of chemical species in ice into fluxes at surface) or the spatial origin of the ice. (2) The counting of annual layers (e.g., Svensson et al., 2008; Winstrup et al., 2012) is also accurate for event durations, but because the errors are cumulative, the absolute dating can become inaccurate for sections too far from the surface. Moreover, this technique can only be applied when the annual layer thickness is large enough (and therefore not for low accumulation sites and not for sections too deep). (3) The synchronization to another dated paleo-record (e.g., U-Th dated speleothem, calculated Earth orbital parameters, lavas from a volcanic eruption, . . .). This method is generally the most accurate for absolute dating, but it is not accurate for event durations. (4) The synchronization in between ice cores records (Blunier and Brook, 2001; Parrenin et al., 2012b; Raisbeck et al., 2007; Severi et al., 2007;

Svensson et al., 2013) can be done with a variety of parameters, like the volcanic records, the methane records, the oxygen-18 of air bubbles, the dust records, the ice isotopic records, etc. It is not an absolute dating method but rather a relative dating method, but it can help to transfer absolute dating information from one core to the other. We include in this category the synchronization of ice core records in the ice matrix with records in the gas/hydrates phases to deduce the ice-gas depth shift, called the Δdepth (Parrenin et al., 2012a).

A common and optimal chronology for several ice cores can therefore only be reached by a combination of the previously mentioned methods, in the frame of a probabilistic approach. A parallel can be drawn with the problem of calibrating the ^{14}C chronology (Reimer et al., 2013), which is also done by a probabilistic combination of various chronological information. First attempts at combining chronological information in ice cores have done by constraining an ice flow model by independent age markers along one ice core (Parrenin et al., 2001, 2004, 2007). This method had however several limitations. First, the ice flow models were supposed perfect apart from uncertainties related to their poorly known parameters. As a consequence, the resulting confidence intervals were underestimated. Moreover, due to modeling errors, it was not possible to obtain consistent chronologies for different ice cores. A new probabilistic model, called Datice, was therefore developed (Lemieux-Dudon et al., 2010a, 2010b), where modeling errors were introduced on three canonical quantities of the dating problem: the initial accumulation rate, the Lock-In-Depth (LID) of air bubbles and the vertical thinning function (the ratio of the vertical thickness of a layer to its initial vertical thickness when it was at surface). This model has been successfully applied to 4 Antarctic and 1 Greenland ice core (Bazin et al., 2013; Veres et al., 2013) to build the Antarctic Ice Cores Chronologies 2012 (AICC2012).

In this paper, we present IceChrono v1, a new probabilistic model similar in scope to the Datice model but with differences in the mathematical, numerical and programming point of views. We detail how IceChrono works as well as its differences to Datice in the following section. We then apply IceChrono v1 in Sect. 3 on two different experiments.

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The first one is an AICC2012-like experiment and we compare IceChrono v1 results with the Datice results. The second experiment concerns only the Berkner ice core and we produce its first dating. Finally, we conclude and give some perspectives on future developments on IceChrono in Sect. 4.

2 Method

2.1 The forward model

For each ice core denoted by its index k, given three quantities (initial surface accumulation rate, air Lock-In Depth – LID – and vertical ice thinning function), the model computes at any depth z_k the age for the ice matrix χ_k and the age for the air/hydrates contained in the ice ψ_k (which, for simplicity, are assumed unique, we do not consider the age distributions) using the following formulas:

$$\chi_k(z_k) = \int_0^{z_k} \frac{D_k\left(z'_k\right)}{a_k\left(z'_k\right)\tau_k\left(z'_k\right)} \mathrm{d}z'_k, \tag{1}$$

$$\int_{z_k-\Delta d(z_k)}^{z_k} \frac{D\left(z'_k\right)}{\tau\left(z'_k\right)} \mathrm{d}z'_k \approx \int_0^{l(z_k)D_{\mathrm{firn}}(z_k)} \frac{1}{\tau\left(z^{\mathrm{ie}}_k\right)} \mathrm{d}z^{\mathrm{ie}}_k, \tag{2}$$

$$\psi_k(z_k) = \chi_k(z_k - \Delta d(z_k)), \tag{3}$$

where D_k is the relative density of the material (treated as a known time series), a_k is the initial accumulation rate, τ_k is the vertical thinning function (the ratio between the vertical thickness of a layer to its initial vertical thickness when it was at surface), Δd is the Δdepth (the depth shift between synchronous events in the ice and gas phases, taken as dependent on the gas depth, by convention), l_k is the LID (taken as dependent on the gas depth, by convention), D_{firn} is the average relative density of

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the firn when depth z_k was at LID (treated as a known time series, in practice often assumed constant) and z_k^{ie} is the ice equivalent depth:

$$z_k^{\mathrm{ie}} = \int_0^{z_k} D\left(z'_k\right) \mathrm{d}z'_k. \tag{4}$$

The second equation just means that if one un-thins a depth interval between an ice depth and the synchronous gas depth, one gets the initial lock-in depth in ice equivalent. The second member of the second equation is actually an approximation, since I assume that the vertical thinning function at the time of deposition was the same than at present. But the vertical thinning function being usually very close to 1 in the firn, this assumption is almost verified. Apart from that, there is no approximation in these equations but of course there are approximations in the models that give the values of a, l and τ and we will discuss the errors linked to these approximations below.

2.2 The inverse model

Given some background information on accumulation (noted a^{b}), on LID (noted l^{b}) and on vertical thinning (noted τ^{b}), one seeks optimal values of these three quantities to obtain a best fit with age observations. The background information comes from a combination of model and data that are assumed independent from these age observations (e.g., ice flow models can give an estimate of the vertical thinning function, ice δD and δ^{18}O are often used to deduced accumulation rates, firn densification models or δ^{15}N measurements in air bubbles are used to deduce the LID). To this aim, I define logarithmic correction functions on these three quantities:

$$c_k^a = \ln\left(a_k/a_k^{\mathrm{b}}\right), \tag{5}$$

$$c_k^l = \ln\left(l_k/l_k^{\mathrm{b}}\right), \tag{6}$$

$$c_k^\tau = \ln\left(\tau_k/\tau_k^{\mathrm{b}}\right). \tag{7}$$

The logarithm is taken so as to transform so-called Jeffreys variables (with a canonical density of probability being the log-normal) into Cartesian variables (with a canonical density of probability being the normal) (Tarantola, 2005).

2.3 Discretization

The three background quantities a_k^{b}, l_k^{b} and τ_k^{b} as well as the relative density D_k are discretized onto the same fine depth grid: $z_{k,i}$ (i being the index of the node), called the *age equation grid*, which may not be regular. Equation (1) for the ice age is first solved. Then Eq. (2) for the Δdepth is solved which allows to deduce the air age from Eq. (3). When one needs to compute the ice age, air age or Δdepth at depths which are not nodes of the age equation grid (for example when comparing the model with observations, see below), one uses a linear interpolation.

Then, one discretizes the correction functions onto coarser grids, which also may not be regular and which depends on the age for a and l and on the depth for τ: $t_{k,i}^a$, $t_{k,i}^l$, $z_{k,i}^\tau$ (i being the index of the node). For a and l, the corrections function are then transferred onto the depth scale using the background age scale. I note $\boldsymbol{C}_k^a = (c_{k,i}^a)_i$, $\boldsymbol{C}_k^l = (c_{k,i}^l)_i$ and $\boldsymbol{C}_k^\tau = (c_{k,i}^\tau)_i$ the correction vectors. These grids are coarser than the age grid to limit the number of variables to be inverted. Once the correction vectors are defined on these coarser grid, I apply a linear interpolation to get a_k, l_k and τ_k on the age equation grid.

In the following, I will note the discretized model with a “d” exponent.

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2.4 The cost function

Let us write $\boldsymbol{X}$ the vector containing all the correction vectors for all the drillings. In probabilistic terms, one combines different sources of information which are assumed independent (the background and the observations) and one looks for the most probable scenario, i.e. the most probable $\boldsymbol{X}$. In mathematical terms, this corresponds to multiplying the probability density functions (PDF) of the background and of the observations and to looking for the mode of the resulting PDF, which is called the *likelihood function* L. Here, we assume the PDFs are independent multivariate gaussian distributions, which leads to an optimization problem which is far easier to solve numerically. The likelihood function can therefore be written as:

$$L = \exp\left(-\frac{1}{2}J\right) \tag{8}$$

where J, the *cost function*, is the sum of least-squares terms, each corresponding to an independent multivariate gaussian PDF. Maximizing the likelihood function therefore corresponds to minimizing the cost function. In our case, we assume the information on each ice core and on each ice core couple are independent. The cost function can therefore be written as a sum of terms:

$$J = \sum_k J_k + \sum_{k<m} J_{k,m}, \tag{9}$$

where J_k is the term related to ice core number k and $J_{k,m}$ is the term related to the ice core couple (k,m).

J_k itself is written as the sum of independent terms:

$$J_k = J_k^a + J_k^l + J_k^\tau + J_k^{\mathrm{ih}} + J_k^{\mathrm{ah}} + J_k^{\mathrm{ii}} + J_k^{\mathrm{ai}} + J_k^{\Delta\mathrm{d}}, \tag{10}$$

where J_k^a, J_k^l and J_k^τ are the background terms for a, l and τ, J_k^{ih} is linked to ice dated horizons, J_k^{ah} is linked to gas dated horizons, J_k^{ii} is linked to air dated intervals, J_k^{ai} is linked to gas dated intervals and $J_k^{\Delta d}$ is linked to Δdepth observations.

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$J_{k,m}$ is also the sum of 4 independent terms:

$$J_{k,m} = J^{\text{ii}}_{k,m} + J^{\text{aa}}_{k,m} + J^{\text{ia}}_{k,m} + J^{\text{ai}}_{k,m}, \tag{11}$$

where $J^{\text{ii}}_{k,m}$ is linked to ice-ice stratigraphic links, $J^{\text{aa}}_{k,m}$ is linked to air-air stratigraphic links, $J^{\text{ia}}_{k,m}$ is linked to ice-air stratigraphic links and $J^{\text{ai}}_{k,m}$ is linked to air-ice stratigraphic links.

Let us first describe the background terms:

$$J^a_k = \left(\boldsymbol{R}^a_k\right)^T \left(\mathbf{P}^a_k\right)^{-1} \left(\boldsymbol{R}^a_k\right), \tag{12}$$

$$J^l_k = \left(\boldsymbol{R}^l_k\right)^T \left(\mathbf{P}^l_k\right)^{-1} \left(\boldsymbol{R}^l_k\right), \tag{13}$$

$$J^\tau_k = \left(\boldsymbol{R}^\tau_k\right)^T \left(\mathbf{P}^\tau_k\right)^{-1} \left(\boldsymbol{R}^\tau_k\right) \tag{14}$$

where $\mathbf{P}^a_k$, $\mathbf{P}^l_k$, $\mathbf{P}^\tau_k$ are the correlation matrices and where $\boldsymbol{R}^a_k$, $\boldsymbol{R}^l_k$, $\boldsymbol{R}^\tau_k$ are the residual vectors:

$$\boldsymbol{R}^a_k = \left(\frac{c^a_{k,i}}{\sigma^a_{k,i}}\right)_i, \tag{15}$$

$$\boldsymbol{R}^a_k = \left(\frac{c^l_{k,i}}{\sigma^l_{k,i}}\right)_i, \tag{16}$$

$$\boldsymbol{R}^a_k = \left(\frac{c^\tau_{k,i}}{\sigma^\tau_{k,i}}\right)_i, \tag{17}$$

with $(\sigma^a_{k,i})_i$, $(\sigma^l_{k,i})_i$, $(\sigma^\tau_{k,i})_i$ the confidence intervals for respectively the accumulation, the LID and the vertical thinning function. That means the model giving the background scenario for the accumulation, the LID and the vertical thinning function should have

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a quantified error. In practice, the IceChrono model is flexible, and whatever confidence interval vectors and correlation matrices can be prescribed.

The other terms of J_k are simply comparisons to observations, assumed independent, with a given covariance matrix:

$$\boldsymbol{R}^T \mathbf{P}^{-1} \boldsymbol{R} \tag{18}$$

$$\boldsymbol{R} = \left(\frac{m_i - o_i}{\sigma_i} \right)_i \tag{19}$$

where $\boldsymbol{R}$ is the residual vector, $(m_i)_i$ are the model realizations, $(o_i)_i$ are the observations, $(\sigma_i)_i$ are their confidence intervals and $\mathbf{P}$ is the their correlation matrix. These terms are given in more details in the annex. Again, the IceChrono model is flexible, and whatever confidence interval vectors and correlation matrices can be prescribed.

For J_k^{ih} and J_k^{ah}, one prescribes depth, age and error bar of ice and air dated horizons (and optionally a correlation matrix). For J_k^{ii} and J_k^{ai}, one prescribes depth top, depth bottom, duration and error bar of ice and air dated intervals (and optionally a correlation matrix). For $J_k^{\Delta\mathrm{d}}$, one prescribes air depth, Δdepth and error bar of Δdepth markers (and optionally a correlation matrix). For $J_{k,m}^{\mathrm{ii}}$, $J_{k,m}^{\mathrm{aa}}$, $J_{k,m}^{\mathrm{ia}}$, $J_{k,m}^{\mathrm{ai}}$, one prescribes the depth in the first core, the depth in the second core and a confidence interval in years (and optionally a correlation matrix).

2.5 Optimization

This least-squares optimization problem is solved using a standard Levenberg–Marquardt (LM) algorithm. The LM algorithm gives as result the optimized values of the model's input variables vector $\boldsymbol{X}^{\mathrm{opt}}$ as well as an approximate estimation of its error covariance matrix $\mathbf{C}^X$ (it approximates the model by its linear tangent around the solution). Let us write $\boldsymbol{G}(\boldsymbol{X})$ the model vector containing all the variables we are interested in. The optimal model is therefore $\boldsymbol{G}(\boldsymbol{X}^{\mathrm{opt}})$. From the model Jacobian $\mathbf{G}'$ at $\boldsymbol{X}^{\mathrm{opt}}$, one can compute an approximated value of the error covariance matrix for the model as:

$$\mathbf{C}^G \approx (\mathbf{G}')\mathbf{C}^X(\mathbf{G}')^T. \tag{20}$$

2.6 Programming aspects

IceChrono v1 is coded entirely in the python v2 programming language. IceChrono v1 does not only the optimization problem, but it also construct figures to display the results. The core of the code is entirely separated from the experiment set up directory which also contains the results of the run and which is composed of: general parameters files, a directory for each ice core (which contains the parameters and observations for this ice core) and a directory for each ice core couple (which contains the observations for this ice cores couple). Only a basic understanding of python and an understanding of the structure of the experiment set up directory are needed to run IceChrono v1.

The core of the code is about 1000 lines long (including white lines and comments) and is built using an object oriented paradigm. A class exist for the ice core object and does: the initialization of the ice core, the calculation of the model variables, the calculation of the residuals, the calculation of the Jacobian, the calculation of the confidence intervals, the construction of the figures (for ice age, gas age, accumulation, LID, thinning, ice layer thickness, gas layer thickness and Δdepth) and the saving of the results. A class also exist for each ice core couple and does: the initialization of the ice core couple, the calculation of the residuals, the construction of the figures (for ice-ice links, air-air links, ice-air links and air-ice links). The main program is kept simple and straightforward.

I used the LM algorithm as implemented in the "leastsq" function from the "scipy.optimize" library. It does not try to minimize directly the cost function, but rather the residuals vector, each residual being supposed independent from the other and with a unit SD. Inside each term of the cost function, we allow to define a correlation matrix so the residuals can actually be correlated. So I used a change of variable to transform, for each term of the cost function, the residual vector into a vector composed of independent variables with unit SD.

2.7 Comparison to Datice

IceChrono v1 is similar in scope to Datice but there are numerical and programming differences that I will detail below.

First, Datice does not solve Eq. (2) but an approximation of it:

$$\Delta d(z) = l(z) \times \tau(z), \tag{21}$$

that is, τ is assumed constant between the synchronous ice and gas depths.

Second, there is only one depth grid in Datice while the correction functions in IceChrono v1 are discretized on a different, coarser grid than the age equation grid. This allows to reduce significantly the number of variables to be inverted and therefore to decrease the computation time.

Third, in IceChrono v1, I allow for mix ice-gas and gas-ice stratigraphic links in between ice cores, as well as ice and gas dated intervals. This is new with respect to Datice.

Fourth, IceChrono v1 allows correlated errors in observations for every kind of observation, while Datice in its current form allows only correlated errors for dated ice intervals (Bazin et al., 2014).

Fifth, in IceChrono v1, the Jacobian of the model is computed numerically while it is computed analytically in Datice. While a numerical computation of the Jacobian leads to a slower computation time, it leads to a faster development of the model since each time one modifies the formulation of the cost function, the Jacobian calculation part is unmodified.

Sixth, IceChrono v1 is coded in a simple, flexible and straightforward way using the object-oriented python language. It is very simple in IceChrono v1 to modify the parameters of the problem, e.g. the age equation grid and the correction vectors grids. By comparison, IceChrono v1 is about 1000 lines long (including the construction of

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the figures) while Datice is about 30 000 lines long of fortran code (without any figure construction).

2.8 Avaibility

IceChrono v1 is an open source model available under the General Public License v3. It is hosted on the github facility (https://github.com/parrenin/IceChrono). A mailing list exists for general support or discussions (https://groups.google.com/forum/?hl=en#!forum/icechrono).

3 Results and discussion

3.1 AICC2012-like experiment

IceChrono v1 is similar in scope to the Datice model (Lemieux-Dudon et al., 2010a). Datice has been used to build the last official chronology for 4 Antarctic ice cores (EDC, VK, TALDICE, EDML) and one Greenland ice core (NorthGRIP). So I decided to test IceChrono v1 on the same set up, using the same observations and the same definition of the background. Only one aspect is modified: in AICC2012, the background correlation matrices are supposed to have a Gaussian shape. These matrices are numerically very difficult to invert (with a poor conditional state), which is the sign that they are a wrong description of our state of knowledge. I therefore opt for triangular correlation matrices. I performed two AICC2012-like experiments with different resolutions. First, I used regular grids with a time step of 1 kyr for the accumulation and LID correction functions and with 501 nodes for the thinning correction functions (experiment AICC2012-VHR). Second, I used regular grids with a time step of 0.5 kyr for the accumulation and LID correction functions and with 1001 nodes for the thinning correction functions (experiment AICC2012-V2HR).

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Figure 1 compares the AICC2012-V2HR and AICC2012-VHR experiments for the ice age. The differences are minor and do not exceed 30 years. It means that the formulation of the optimization problem in IceChrono v1 is robust to a change of resolution.

Figure 2 compares the resulting chronologies for the EDC ice core using the IceChrono v1 (experiment AICC2012-V2HR) and Datice codes, as well as their confidence intervals. The difference in both chronologies is less than 200 years for the last 600 000 years and less than 500 years all along the record. The confidence intervals also show comparable shapes. I remark a few noticeable differences, though. At 41 kyr, IceChrono v1 confidence interval decreases to ~ 100 years. This is due to the fact that the dating of the NorthGRIP ice core is firmly tied to the GICC05 chronology (Andersen et al., 2006; Svensson et al., 2006) within 50 years and that there exists an ice-ice stratigraphic links between EDC and NorthGRIP using the beryllium-10 peak during the Laschamp event (Raisbeck et al., 2007) with an accuracy of ~ 100 years. By comparison, Datice confidence interval is about 800 years at the beryllium-10 peak, which is not realistic. Also, IceChrono v1 confidence interval tends to 0 at the surface, which is normal since the age at surface is firmly imposed. But Datice confidence interval does not tend to 0. Other differences are minor and might be due to the fact that Datice use an approximated version of Eq. (2).

The fact that IceChrono v1 and Datice agree fairly well in this experiment is a confirmation of both codes, which have been developed independently using different programming languages and different numerical schemes.

3.2 First dating of the Berkner ice core

I now describe an experiment to date the Berkner ice core (Mulvaney et al., 2007). First, I need to describe the background values used. The background accumulation is deduced directly from the deuterium content of the ice using an exponential relationship:

$$a^{\mathrm{b}} = a^0 \exp(\beta \Delta \delta D), \tag{22}$$

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where $a^0 = 0.224$ ice-m year^{-1} and $\beta = 0.0166$. The accumulation covariance matrix is defined by: a uniform variance value of 20 % and with a triangular shape correlation matrix with an across-diagonal length of 4000 year. I use the simulation of a Herron–Langway model (Herron and Langway, 1980) fitted onto the measured density profile at Berkner to get the density profile as well as the value of the LID of 57.4 m, assumed constant through time. We assume a constant firn average relative density of 0.7 (Parrenin et al., 2012a). The accumulation covariance matrix is defined by: a uniform variance value of 20 % and with a triangular shape correlation matrix with an across-diagonal length of 4000 year. The background thinning is deduced using the so-called pseudo-steady assumption (Parrenin et al., 2006):

$$\tau^b = (1-\mu)\varpi + \mu, \tag{23}$$

with $\mu = 2.65\,\%$ being the ratio between melting and accumulation assumed constant through time and with ϖ being the flux-shape function (Parrenin and Hindmarsh, 2007), that I define using a Lliboutry analytical model (Lliboutry, 1979):

$$\varpi = 1 - \frac{p+2}{p+1}(1-\zeta) + \frac{1}{p+1}(1-\zeta)^{p+2}, \tag{24}$$

with $p = 2.07$. The covariance matrix of the thinning function is defined as: a variance, which is assumed linearly related to the ice-equivalent depth z^{ie}:

$$\sigma^\tau = k\frac{z^{ie}}{H^{ie}} \tag{25}$$

where H^{ie} is the ice-equivalent ice thickness and $k = 0.2$. The value of a^0, β, μ and p have been chosen to obtain a good fit with independent age markers along the core.

I now describe the observations used in the IceChrono v1 experiment. Ice dated horizons (Table 1) have been obtained by synchronizing the Berkner isotopic record with the EDC isotopic record onto the AICC2012 age scale. Gas dated horizons (Table 2) have been obtained by synchronizing the Berkner methane record with the EDC methane record onto the AICC2012 age scale. The confidence intervals only take into account the synchronization error, in order to obtain an optimized chronology which is synchronized onto AICC2012.

The ice age (Fig. 3), air age (Fig. 4), accumulation (Fig. 5), LID (Fig. 6) and thinning (Fig. 7) are displayed. Note that these figures are automatically produced by IceChrono v1. The optimized ice and air ages are consistent with the ice and air age markers. The confidence intervals for the ice and air ages first increase during the last 10 kyr and then decrease due to the presence of age dated horizons. The confidence intervals then increase again at the end of the record where there is no dated horizon anymore. The optimized accumulation scenario is close to the background scenario. Accumulation is maximum during the Holocene with values around 0.2 ice-m year^{-1}. There is a high scatter around the mean during the Holocene which is due to the scatter of the deuterium data. The confidence interval during the glacial part is minimum at the LGM with values around 0.01 ice-m year^{-1} and maximum at the end of the record with values around 0.02 ice-m year^{-1}. For the LID, the values cannot be probabilistically distinguished from the background constant value of 57.4 m. There are deviations of less than 20 % at 15, 30, 35 and 50 kyr b1950 (before AD 1950). For the vertical thinning function, the optimized scenario also cannot be probabilistically distinguished from the background scenario. The method however suggests oscillations in the deepest 300 m of the core.

4 Conclusions and perspectives

I developped and made accessible a new open-source probablistic model to produce a common and optimized age scale for several ice cores, taking into account modeling and observation information. The code is similar in scope to Datice but has mathematical, numerical and programming differences: I believe IceChrono v1 is simpler, more flexible and more powerful than Datice. When compared onto an AICC2012-like experiment, IceChrono v1 generally produces similar results than Datice, which is

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a confirmation of both codes. I also applied IceChrono v1 to produce the first dating of the Berkner ice core, sychronized onto the AICC2012 chronology by the mean of the deuterium and methane records. Although primilarily built for ice core dating, IceChrono v1 could well be used to date other paleoclimatic archives like marine cores, lake cores, speleothems, etc.

The flexibility of IceChrono now opens interesting prospectives. The age observations on different cores are not always independent (because the dating methods are the same) and I might allow in the future to take into account correlation of observations in-between ice cores. Instead of relying on external models for accumulation, LID and vertical thinning, I am in the process of integrating and coupling simplified models directly into IceChrono. The determination of stratigraphic links between ice cores or age markers by comparison to a tuning target is a subjective, un-reproducible, task consumming and poorly documented process. I propose to include an automatic synchronization module into IceChrono. Automatic layer counting (Winstrup et al., 2012) could also be included into IceChrono, so that layer counting is guided by other chronological information and also influences the optimal chronology. These developments will be made available in future versions of IceChrono.

Appendix A

Below I describe in details the terms of the cost function which are linked to observations.

$$j_k^{\mathrm{ih}} = \left(\boldsymbol{R}_k^{\mathrm{ih}}\right)^T \left(\mathbf{P}_k^{\mathrm{ih}}\right)^{-1} \boldsymbol{R}_k^{\mathrm{ih}}, \tag{A1}$$

$$\boldsymbol{R}_k^{\mathrm{ih}} = \left(\frac{\chi_k^{\mathrm{d}}\left(z_{k,i}^{\mathrm{ih}}\right) - \chi_{k,i}^{\mathrm{obs}}}{\sigma_{k,i}^{\mathrm{ih}}}\right)_i, \tag{A2}$$

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where $z^{\text{ih}}_{k,i}$ is the depth of the ith ice dated horizon in the kth ice core, $\chi^{\text{obs}}_{k,i}$ is its age, $\sigma^{\text{ih}}_{k,i}$ is its confidence interval and where $\mathbf{P}^{\text{ih}}_{k}$ is the correlation matrix.

$$j^{\text{ah}}_k = \left(\boldsymbol{R}^{\text{ah}}_k\right)^T \left(\mathbf{P}^{\text{ah}}_k\right)^{-1} \boldsymbol{R}^{\text{ah}}_k, \tag{A3}$$

$$\boldsymbol{R}^{\text{ah}}_k = \left(\frac{\psi^{\text{d}}_k\left(z^{\text{ah}}_{k,i}\right) - \psi^{\text{obs}}_{k,i}}{\sigma^{\text{ah}}_{k,i}}\right)_i, \tag{A4}$$

where $z^{\text{ah}}_{k,i}$ is the depth of the ith air dated horizon in the kth ice core, $\psi^{\text{obs}}_{k,i}$ is its age, $\sigma^{\text{ah}}_{k,i}$ is its confidence interval and where $\mathbf{P}^{\text{ah}}_{k}$ is the correlation matrix.

$$j^{\text{ii}}_k = \left(\boldsymbol{R}^{\text{ii}}_k\right)^T \left(\mathbf{P}^{\text{ii}}_k\right)^{-1} \boldsymbol{R}^{\text{ii}}_k, \tag{A5}$$

$$\boldsymbol{R}^{\text{ii}}_k = \left(\frac{\chi^{\text{d}}_k\left(z^{\text{ii, b}}_{k,i}\right) - \chi^{\text{d}}_k\left(z^{\text{ii},t}_{k,i}\right) - \Delta\chi^{\text{obs}}_{k,i}}{\sigma^{\text{ii}}_{k,i}}\right)_i, \tag{A6}$$

where $z^{\text{ii,t}}_{k,i}$ and $z^{\text{ii,b}}_{k,i}$ are the top and bottom depths of the ith ice dated interval in the kth ice core, $\Delta\chi^{\text{obs}}_{k,i}$ is its observed value, $\sigma^{\text{ii}}_{k,i}$ is its confidence interval and where $\mathbf{P}^{\text{ii}}_{k}$ is the correlation matrix.

$$j^{\text{ai}}_k = \left(\boldsymbol{R}^{\text{ai}}_k\right)^T \left(\mathbf{P}^{\text{ai}}_k\right)^{-1} \boldsymbol{R}^{\text{ai}}_k, \tag{A7}$$

$$\boldsymbol{R}^{\text{ai}}_k = \left(\frac{\psi^{\text{d}}_k\left(z^{\text{ai,b}}_{k,i}\right) - \psi^{\text{d}}_k\left(z^{\text{ai,t}}_{k,i}\right) - \Delta\psi^{\text{obs}}_{k,i}}{\sigma^{\text{ai}}_{k,i}}\right)_i, \tag{A8}$$

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where $z_{k,i}^{\mathrm{ai,t}}$ and $z_{k,i}^{\mathrm{ai,b}}$ are the top and bottom depths of the ith ice dated interval in the kth ice core, $\Delta\psi_{k,i}^{\mathrm{obs}}$ is its duration, $\sigma_{k,i}^{\mathrm{ii}}$ is its confidence interval and where $\mathbf{P}_k^{\mathrm{ai}}$ is the correlation matrix.

$$j_k^{\Delta\mathrm{d}} = \left(\boldsymbol{R}_k^{\Delta\mathrm{d}}\right)^T \left(\mathbf{P}_k^{\Delta\mathrm{d}}\right)^{-1} \boldsymbol{R}_k^{\Delta\mathrm{d}}, \tag{A9}$$

$$\boldsymbol{R}_k^{\Delta\mathrm{d}} = \left(\frac{\Delta d_k^{\mathrm{d}}\left(z_{k,i}^{\Delta\mathrm{d}}\right) - \Delta d_{k,i}^{\mathrm{obs}}}{\sigma_{k,i}^{\Delta\mathrm{d}}}\right)_i, \tag{A10}$$

where $z_{k,i}^{\Delta\mathrm{d}}$ is the depth of the ith Δ depth observation in the kth ice core, $\Delta d_{k,i}^{\mathrm{obs}}$ is its duration, $\sigma_{k,i}^{\Delta\mathrm{d}}$ is its confidence interval and where $\mathbf{P}_k^{\Delta\mathrm{d}}$ is the correlation matrix.

$$j_{k,m}^{\mathrm{ii}} = \left(\boldsymbol{R}_{k,m}^{\mathrm{ii}}\right)^T \left(\mathbf{P}_{k,m}^{\mathrm{ii}}\right)^{-1} \boldsymbol{R}_{k,m}^{\mathrm{ii}}, \tag{A11}$$

$$\boldsymbol{R}_{k,m}^{\mathrm{ii}} = \left(\frac{\chi_k^{\mathrm{d}}\left(z_{k,m,i}^{\mathrm{ii},1}\right) - \chi_m^{\mathrm{d}}\left(z_{k,m,i}^{\mathrm{ii},2}\right)}{\sigma_{k,m,i}^{\mathrm{ii}}}\right)_i, \tag{A12}$$

where $z_{k,m,i}^{\mathrm{ii},1}$ and $z_{k,m,i}^{\mathrm{ii},2}$ are the depths in the kth and mth ice cores of the ith ice-ice stratigraphic link in the (k,m) couple of ice cores, $\sigma_{k,m,i}^{\mathrm{ii}}$ is its confidence interval and where $\mathbf{P}_{k,m}^{\mathrm{ii}}$ is the correlation matrix.

$$j_{k,m}^{\mathrm{aa}} = \left(\boldsymbol{R}_{k,m}^{\mathrm{aa}}\right)^T \left(\mathbf{P}_{k,m}^{\mathrm{aa}}\right)^{-1} \boldsymbol{R}_{k,m}^{\mathrm{aa}}, \tag{A13}$$

$$\boldsymbol{R}_{k,m}^{\mathrm{aa}} = \left(\frac{\psi_k^{\mathrm{d}}\left(z_{k,m,i}^{\mathrm{aa},1}\right) - \psi_m^{\mathrm{d}}\left(z_{k,m,i}^{\mathrm{aa},2}\right)}{\sigma_{k,m,i}^{\mathrm{aa}}}\right)_i, \tag{A14}$$

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where $z^{aa,1}_{k,m,i}$ and $z^{aa,2}_{k,m,i}$ are the depths in the kth and mth ice cores of the ith air-air stratigraphic link in the (k,m) couple of ice cores, $\sigma^{aa}_{k,m,i}$ is its confidence interval and where $\mathbf{P}^{aa}_{k,m}$ is the correlation matrix.

$$j^{ia}_{k,m} = \left(\boldsymbol{R}^{ia}_{k,m}\right)^T \left(\mathbf{P}^{ia}_{k,m}\right)^{-1} \boldsymbol{R}^{ia}_{k,m}, \tag{A15}$$

$$\boldsymbol{R}^{ia}_{k,m} = \left(\frac{\chi^{d}_{k}\left(z^{ia,1}_{k,m,i}\right) - \psi^{d}_{m}\left(z^{ia,2}_{k,m,i}\right)}{\sigma^{ia}_{k,m,i}}\right)_i, \tag{A16}$$

where $z^{ia,1}_{k,m,i}$ and $z^{ia,2}_{k,m,i}$ are the depths in the kth and mth ice cores of the ith ice-air stratigraphic link in the (k,m) couple of ice cores, $\sigma^{ia}_{k,m,i}$ is its confidence interval and where $\mathbf{P}^{ia}_{k,m}$ is the correlation matrix.

$$j^{ai}_{k,m} = \left(\boldsymbol{R}^{ai}_{k,m}\right)^T \left(\mathbf{P}^{ai}_{k,m}\right)^{-1} \boldsymbol{R}^{ai}_{k,m}, \tag{A17}$$

$$\boldsymbol{R}^{ai}_{k,m} = \left(\frac{\psi^{d}_{k}\left(z^{ai,1}_{k,m,i}\right) - \chi^{d}_{m}\left(z^{ai,2}_{k,m,i}\right)}{\sigma^{ai}_{k,m,i}}\right)_i, \tag{A18}$$

where $z^{ai,1}_{k,m,i}$ and $z^{ai,2}_{k,m,i}$ are the depths in the kth and mth ice cores of the ith air-ice stratigraphic link in the (k,m) couple of ice cores, $\sigma^{ai}_{k,m,i}$ is its confidence interval and where $\mathbf{P}^{ai}_{k,m}$ is the correlation matrix.

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Table 1. Ice age markers used to date the Berkner ice core. They have been obtained by comparing the deuterium record to its EDC counterpart (Jouzel et al., 2007), the later being dated with AICC2012 (Bazin et al., 2013; Veres et al., 2013).

Depth (m)	Age (yr b1950)	Uncertainty (years)
642	11 948.7	200
652.5	12 904.3	300
655.5	14 673.8	150
669	18 161.3	170
714	35 801	300
719	38 210.1	150
746	46 526.9	180
752.2	48 189.3	150
768	54 051.6	220
775	56 774	250
781	59 689.8	200
791.5	64 276	150
793	64 765.3	150
808.5	71 991.8	300
811.5	73 747.5	170
817	75 817.3	150
820	77 102.6	170
833	84 039.3	170
839	87 883.6	230
850	91 311.7	200

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Table 2. Air age markers used to date the Berkner ice core. They have been obtained by comparing the methane record to its EDC counterpart (Loulergue et al., 2008), the later being dated with AICC2012 (Bazin et al., 2013; Veres et al., 2013).

Depth (m)	Age (yr b1950)	Uncertainty (years)
605	8405.67	200
642	11 543	200
651	12 809.1	200
659	14 694.1	200
695	28 090.5	70
697.5	29 132	70
709.6	32 517.1	100
713.4	34 024.7	50
716.4	35 514.6	150
721.5	38 018.1	100
748.4	46 749.3	50
831	83 234	800
944	105 057.7	700

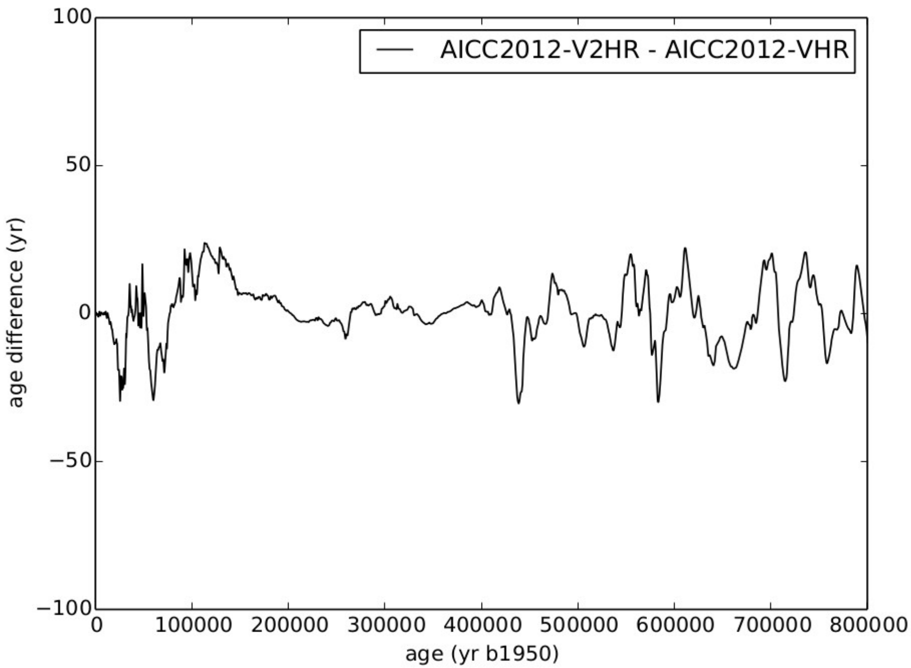

Figure 1. Sensitivity of the AICC2012-like experiment to a change of resolution. The black line is the age difference between the AICC2012-V2HR and AICC2012-VHR experiments (see text).

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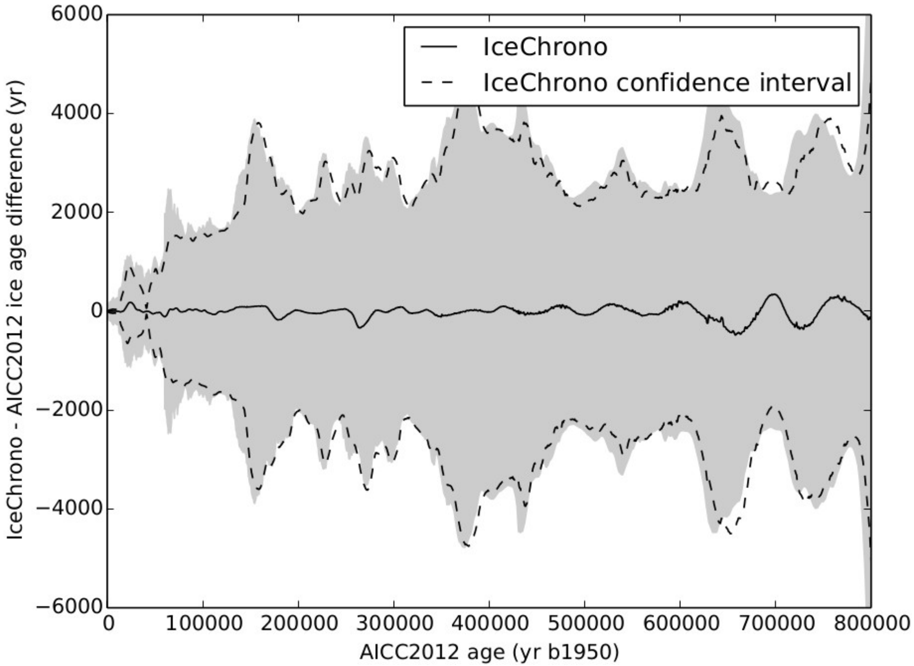

Figure 2. Comparison of IceChrono and Datice chronologies of the EDC ice core in the AICC2012 experiment. IceChrono is the black plain line and its confidence interval is the black dashed line. AICC2012 confidence interval is represented by the grey area.

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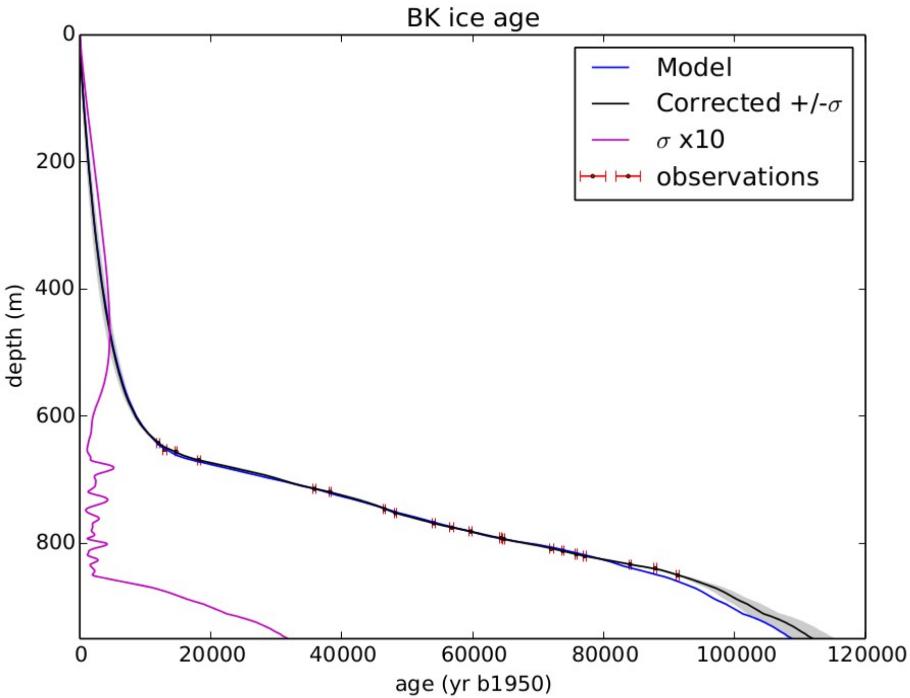

Figure 3. Ice age for the Berkner dating experiment. Background age is the blue line, corrected age is the black line, its confidence interval is the grey area (also enlarged with the pink line), the observations are the red markers with their error bars. This figure has been automatically produced by IceChrono v1.

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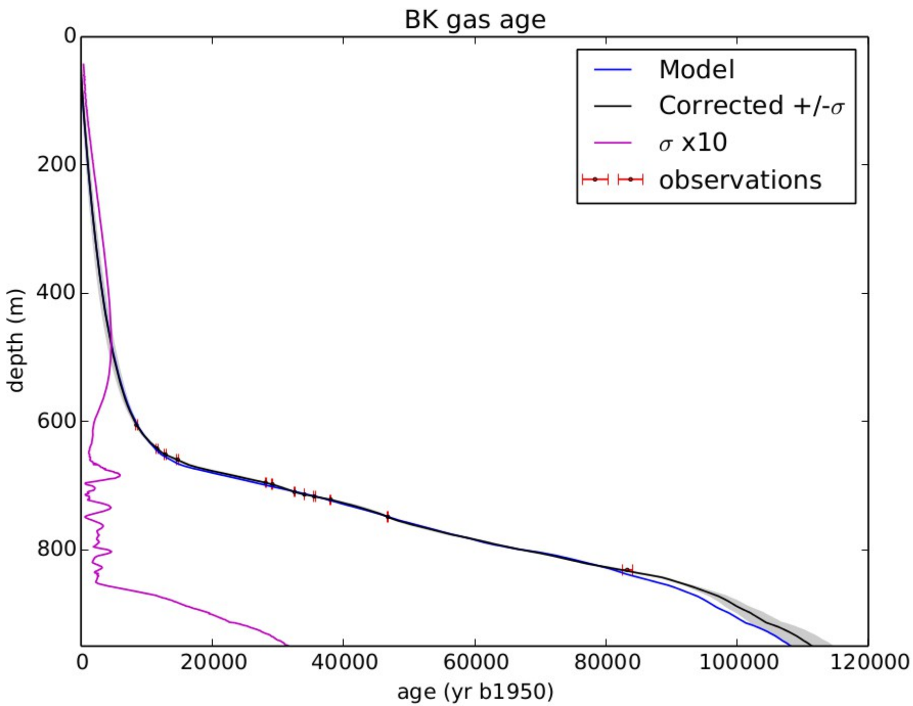

Figure 4. Gas age for the Berkner dating experiment. Background age is the blue line, corrected age is the black line, its confidence interval is the grey area (also enlarged with the pink line), the observations are the red markers with their error bars. This figure has been automatically produced by IceChrono v1.

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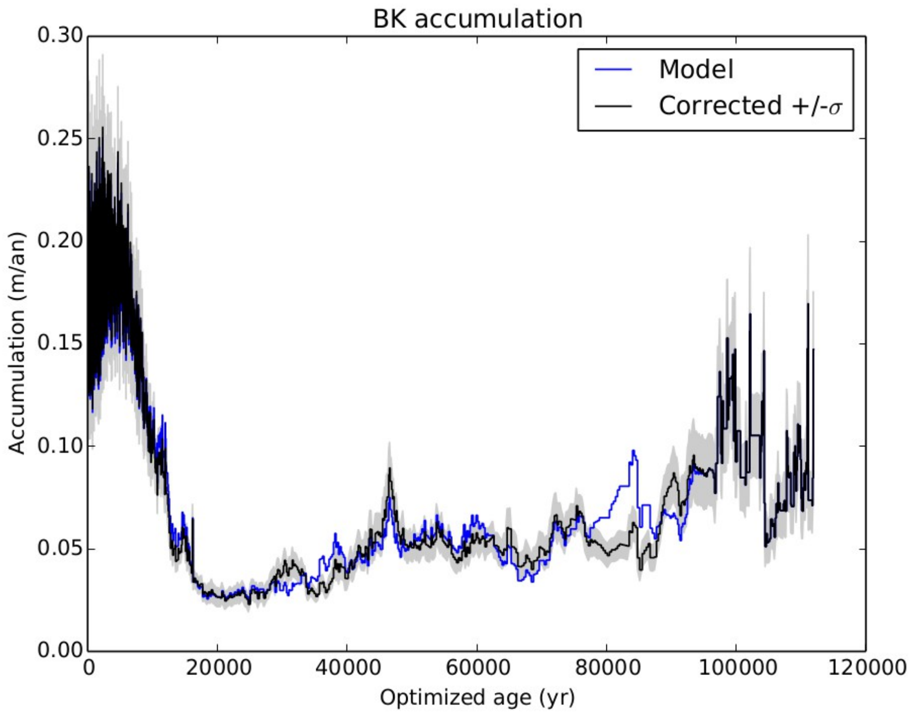

Figure 5. Accumulation for the Berkner dating experiment. Background scenario is in blue, corrected scenario is in black and its confidence interval is the grey area. This figure has been automatically produced by IceChrono v1.

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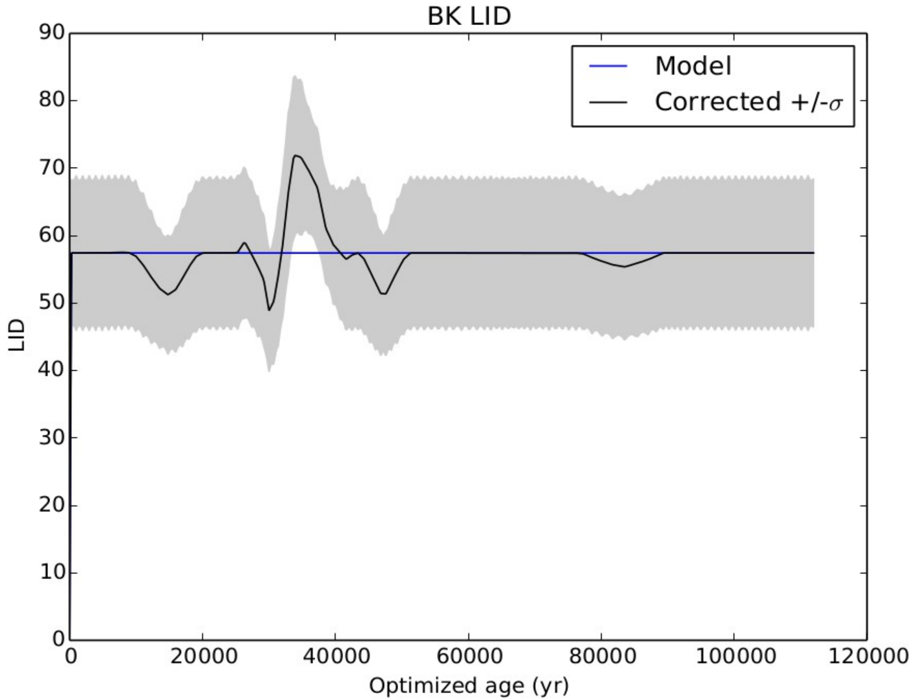

Figure 6. LID for the Berkner dating experiment. Background scenario is in blue, corrected scenario is in black and its confidence interval is the grey area. This figure has been automatically produced by IceChrono v1.

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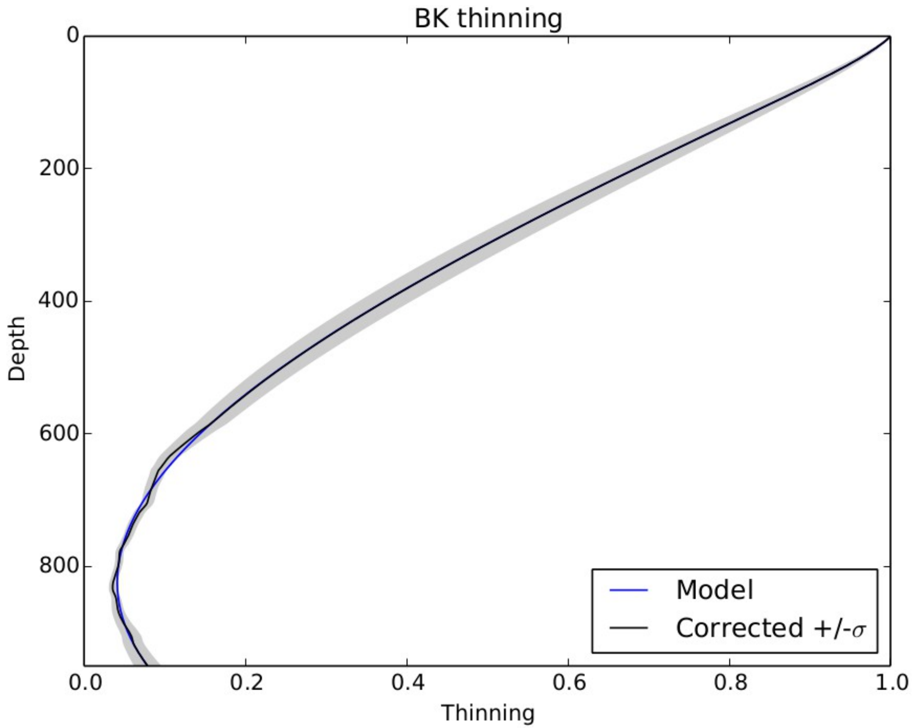

Figure 7. Vertical thinning function for the Berkner dating experiment. The background scenario is in blue, the corrected scenario is in black and its confidence interval is the grey area. This figure has been automatically produced by IceChrono v1.

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