Dating Antarctic blue ice areas using a novel ice flow model

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[1] We present a new type of flow model suitable for Antarctic blue ice areas, with application to dating ice for paleoclimate purposes. The volume conserving model uses field data for surface velocities, mass balance and ice thickness along a flow line, with parameterized variation of ice rheology with depth to produce particle trajectories and isochrones. The model is tested on the contrasting Allan Hills Near Western Ice Field and the Scharffenbergbotnen blue ice fields in Antarctica by comparing predicted ages with ages inferred from meteorites and ^{14}C data. During the glacial periods, ice surface velocities at the Allan Hills must have been 25% less, and accumulation rates 50% less than present day values in order to match meteorite ages. In contrast, Scharffenbergbotnen velocities have probably been fairly constant over time due to the atypical valley where it resides. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3210 Mathematical Geophysics: Modeling; 9310 Information Related to Geographic Region: Antarctica. **Citation:** Grinsted, A., J. Moore, V. B. Spikes, and A. Sinisalo, Dating Antarctic blue ice areas using a novel ice flow model, *Geophys. Res. Lett.*, *30*(19), 2005, doi:10.1029/2003GL017957, 2003.

1. Introduction

[2] Blue ice areas (BIAs) are characterized by having exposed ice at the surface due to a negative surface mass balance. Of special interest, are blue ice areas where very localized conditions lead to islands of ablation surrounded by accumulation areas. Many Antarctic BIAs are important stranding surfaces for large numbers of meteorites [*Whillans and Cassidy*, 1983]. The age of the surface ice has been determined by radiogenic and meteorite exposure dating to be typically between 10 thousand to 200 thousand years, though some meteorites have terrestrial ages of more than 2 million years [*Bintanja*, 1999; *Harvey et al.*, 1998]. In high altitude BIAs melting does not occur and the areas should contain ancient ice at the surface in essentially pristine state. This valuable source of paleoclimatic data has not been utilized to date, largely because of difficulties in dating the ice. In this paper we present a modeling approach that requires limited, and usually available input data that can be used in BIAs that have rather complicated flow regimes - as in fact do many of them.

[3] For the purposes of modeling, a useful classification is in terms of whether the ice flow is forced to terminate because of outcropping nunataks (closed type), or whether the flow is free (open type). The closed type must have very old surface ice closest to the nunatak where horizontal ice velocity goes to zero, while the open type will have relatively young surface ice as velocities never go to zero.

[4] First we introduce the flow line model, and then use it to date surface ice on a typical open BIA in West Antarctica and a typical closed BIA in East Antarctica. Modeled ages are compared with radiogenic and meteorite exposure ages, and the effects of changing climate on the ice flow regimes examined.

2. Model

[5] A full three dimensional model is always the best approach for ice sheet modeling, however, the necessary input field data are generally unavailable, or limited in temporal coverage. It is much more practical to use a flow line approach where sparse field data can be most easily incorporated into the model. Traditional flow line models have either been based on the shallow ice approximation [e.g., *Paterson*, 1994] or the full stress equilibrium equations [e.g., *Pattyn*, 2002]. The shallow ice type models have problems in areas such as Scharffenbergbotnen where the flow is not always down slope, bedrock relief is large or the flow is constrained by valley sides. Models based on the full stress equilibrium equations are very good for predicting how the ice reacts to mass balance perturbations. However, these models are not fully constrained to the observed data. Attempts to model flow in specific BIAs have also used approaches based on parameterized ice thickness and divergence terms [*Whillans and Cassidy*, 1983; *Azuma et al.*, 1985; *van Roijen*, 1996]. In this paper we introduce a simple model based on volume conservation and force it with the observed surface velocity, ice thickness and mass balance.

[6] We choose x to be the distance along the flow line, z as the water equivalent height above the bed and y is perpendicular to the flow. The model is formulated using a vertically scaled coordinate $\zeta = z/H$, where H is the water equivalent ice thickness. The velocity components of x, y, z and ζ are U, V, W and ω. The horizontal velocity can be written as

$$U(\zeta) = f(\zeta)U_s \quad \text{and} \quad V(\zeta) = 0,$$

where subscript ‘s’ denote the value at the surface. In this paper we assume that ice is frozen at the bed. Empirically we find a reliable approximation is

$$f(\zeta) = \frac{\tanh(k\zeta)}{\tanh(k)}.$$

The value of f, and hence k should reflect the softening of the ice with depth. The rheological behavior of ice depends on its crystal fabric, impurity content and temperature. In

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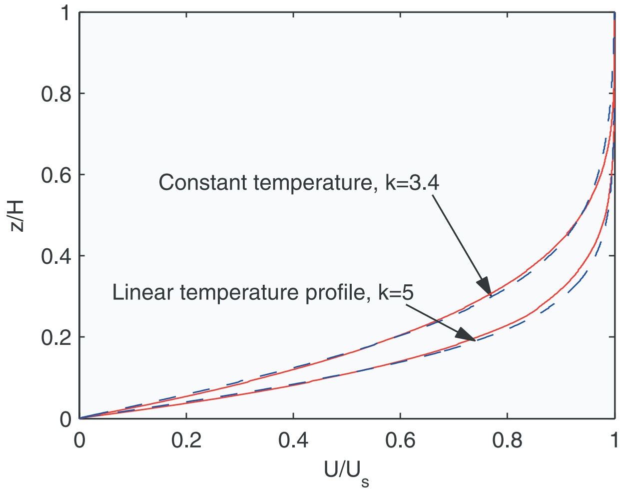

Figure 1. Normalized plot of height above bed against ice velocity. Blue dashed curves are profiles found using the model *f*, red curves are found using the shallow ice approximation using flow parameters based on the compilation of *Paterson* [1994]. The model *f* can approximate a wide range of velocity profiles through an appropriate choice of *k*. The linear temperature profile is for a surface temperature of $-30°C$ and bed temperature of $-10°C$. We chose $k = 5$ to model both BIAs in the paper.

Antarctica changes due to impurities and crystal fabrics seem much less important than those caused by the temperature profile within the ice sheet [*Paterson*, 1994]. The steady state temperature profile in an ice sheet is linear at the equilibrium line, and as we are dealing with slow flow on each side of the equilibrium line a linear profile is reasonable for the whole flow line (Figure 1). Therefore, we write

$$\frac{\partial U}{\partial x} = f(\zeta)\frac{\partial U_s}{\partial x} \quad \text{and} \quad \frac{\partial V}{\partial y} = f(\zeta)\frac{\partial V_s}{\partial y}.$$

From volume conservation of an ice column we get

$$\frac{\partial U_s}{\partial x} + \frac{\partial V_s}{\partial y} = \frac{1}{f_m}\cdot\left(\frac{\partial U_m}{\partial x} + \frac{\partial V_m}{\partial y}\right) = \frac{b}{f_m H},$$

where b is the mass balance and subscript 'm' denote a mean over the entire ice column. The continuity equation assuming incompressibility is written

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \Rightarrow \frac{\partial W}{\partial z} = -\left(\frac{\partial U_s}{\partial x} + \frac{\partial V_s}{\partial y}\right)\cdot f(\zeta).$$

Hence

$$\omega(\zeta) = -\left(\frac{\partial U_s}{\partial x} + \frac{\partial V_s}{\partial y}\right)\cdot\int_0^{\zeta} f(\zeta')d\zeta'$$
$$= \frac{\frac{\partial U_s}{\partial x} + \frac{\partial V_s}{\partial y}}{-k\tanh(k)}\left(\log\left(\frac{1+e^{-2k\zeta}}{2}\right) + k\zeta\right).$$

As input data b, H and U_s are prescribed as functions of x. A Lagrangian integration scheme is then used to calculate particle back trajectories and thus the dating.

[7] This new volume conservation approach with a simple yet realistic velocity profile makes use of all the data typically available. Since the model is so simple, there is basically no room for tuning. We now apply the model to two different BIAs.

3. Allan Hills, Near Western Ice Field (NWIF)

[8] The Allan Hills NWIF (77°S 159°E 2000 m asl) flow line starts on a typical snow accumulation area, passes through the BIA and then continues through downstream snowfields. The flow line, surface velocities, surface elevations and mass balance data (Figure 2) were found from a survey network which was established in 1997 and resurveyed ~2 years later. Ice thickness comes from *Desisle and Sievers* [1991]. Flow is essentially parallel, with little divergence.

[9] Figure 2 shows the particle paths and isochrones along the flow line. It is remarkable that all the surface ice in the BIA was originally deposited within a few km of the equilibrium line. None of the surface ice has been within 150 m of the bedrock. Sensitivity tests with doubled and halved accumulation rates show little difference in surface ages and origin of the ice, whereas changing the surface velocities have a much larger impact.

[10] The modeled maximum age of surface ice is approximately 60 thousand years, using present day mass balance and velocities (Figure 3). For comparison, the maximum terrestrial age of meteorites found on the NWIF is 180 ± 20 thousand years (Kunihiko Nishiizumi, unpublished data). This suggests that accumulation rates and surface velocities have been significantly lower in the past. Deep ice cores and boreholes suggest that surface temperatures

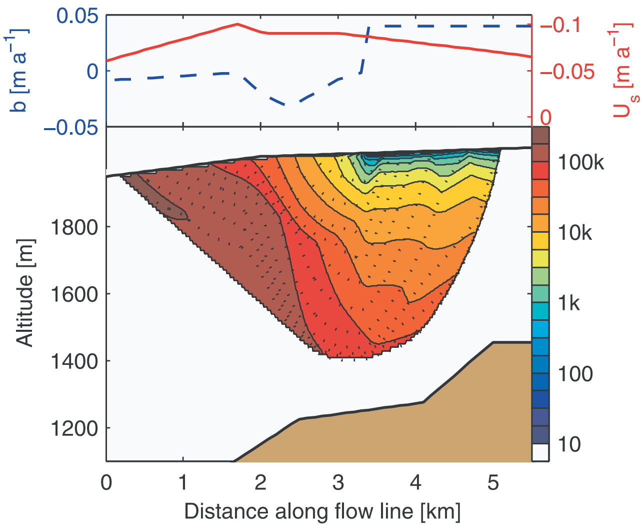

Figure 2. Top: Present day mass balance (dashed blue) and surface velocity (red) along the NWIF flow line. Bottom: Particle paths (dotted lines) and isochrones (colored contours) for the NWIF flow line with accumulation rates 50% and surface velocity 25% of present day values from 11500–115000 and before 125000 years BP.

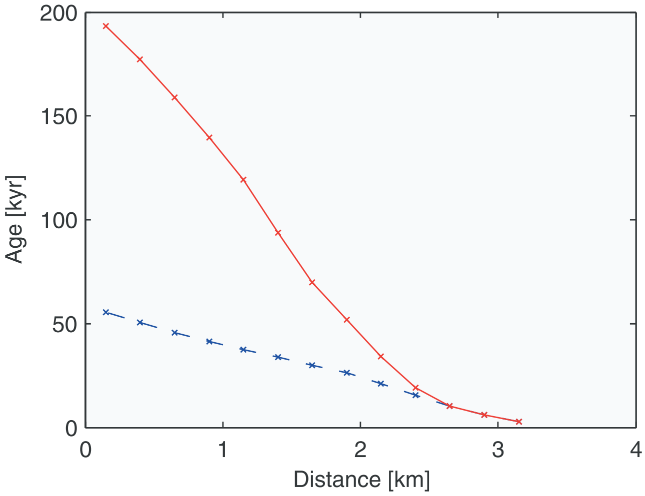

Figure 3. Comparison of surface ages along the NWIF flow line. The dashed blue curve assumes present day accumulation rates and surface velocities (from Figure 2), solid red uses reduced values in the glacial period.

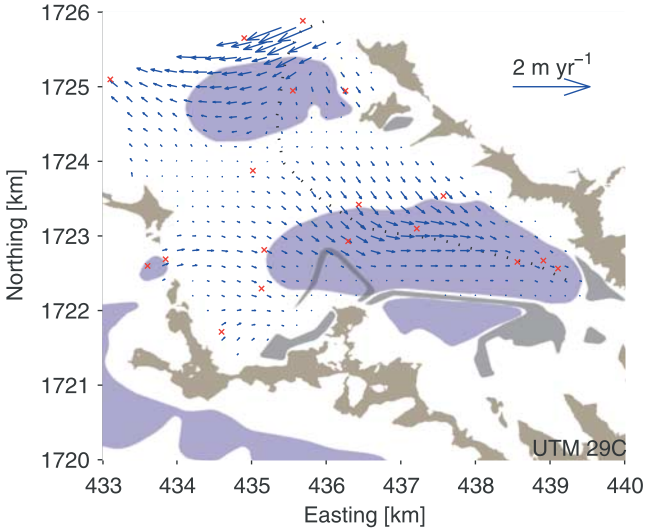

Figure 4. SBB gridded velocity data based on stake measurements (X). The flow line (dotted), the visible extent of BIAs (blue), moraines (grey) and nunataks (brown) are marked.

were about 10–15°C cooler than present, and accumulation rates were about 50% lower during glacial times in Antarctica [*Paterson*, 1994]. Equilibration times for the ice sheet to respond to changes in climate are only in the order of a few thousands of years [*Näslund et al.*, 2000], and a reduction in temperature of the ice sheet by 10°C increases its stiffness by about 3.5 times [*Paterson*, 1994]. Slight changes in ice thickness could result in different surface slopes and thus velocities. As shown in Figure 3 the maximum age of the surface ice changes from about 60 thousand years, using the model with present day velocities and mass balance, to 190 thousand years, by reducing accumulation rates by half and ice velocities to 25% during the glacial periods. Ablation rates are assumed to be constant, which is justified by the similarity between the ablation rates at both BIAs modeled here, despite large differences in surface temperature.

4. Heimefrontfjella, Scharffenbergbotnen (SBB)

[11] SBB (74°S, 11°W, 1200 m asl) is the best-studied blue ice area in Antarctica from a glaciological point of view. The flow line (Figure 4) was picked from gridded surface velocity data [*Sinisalo et al.*, 2003; *van Roijen*, 1996]. Mass balance data (Figure 5) comes from stake observations [*Sinisalo et al.*, 2003], ^{14}C measurements [*van Roijen*, 1996] and radar internal reflections, surface topography from *Sinisalo et al.* [2003] and ice thickness from [*Herzfeld and Holmlund*, 1990].

[12] In contrast to earlier modeling of flow in SBB [*van Roijen*, 1996], it is clear that the ice does not originate from an ice divide at the entrance to the valley (Figure 4), but some comes with the main ice flux from the plateau. The main influx enters through the northern entrance of the valley, with only minor inflows via the shallow and narrow southwestern portal and the eastern end. It is obvious that the valley is most atypical in terms of its low accumulation rate (on the snow covered areas), and very low ice velocities. Wind turbulence inhibits snow accumulation, and since it is a closed BIA, ice flow only just balances net ablation.

[13] The flow line passes over a bedrock high that is an extension of the exposed nunataks along the northeastern side of the valley. Much of the flow from the higher elevation accumulation area does not flow into the valley, but passes across the valley entrance and then to the northwest. The ice that enters the valley diverges as the flow line turns south, and slows considerably. The flow of ice into the valley is regulated by the extent of the divergence, which is heavily influenced by the ice sheet mass balance. During periods of ice sheet thickening (as modeled after the end of the glacial period [*Näslund et al.*,

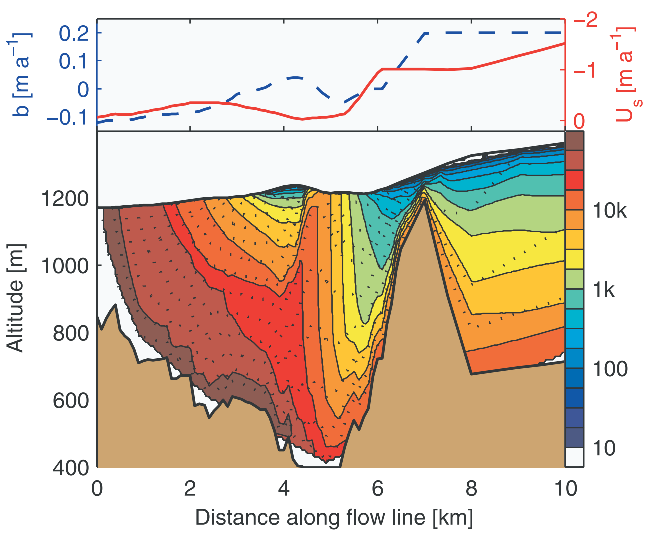

Figure 5. Top: Mass balance (dashed blue) and surface velocity (red) for the SBB flow line. Bottom: Particle paths (dotted lines) and isochrones (colored contours) for the SBB flow line.

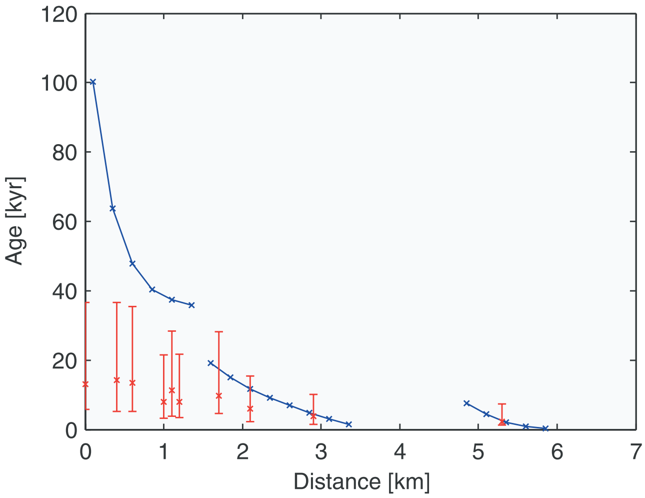

Figure 6. Comparison of surface ages along the SBB flow line (blue line) with ^{14}C ages (converted to calendar years with 1σ error bars, marked in red). The rightmost section of the blue line represent the surface ice in the small BIA, middle section ice in the main BIA originating from the accumulation area inside the valley and the left section ice originating from outside the valley.

2000; *van Roijen*, 1996]), more ice flows into the valley, thereby raising the surface, and eventually inhibiting ice inflow. During periods of thinning, less ice flows into the valley until ablation of the BIA lowers the surface, thereby compensating for reduced influx. In this way the ice velocity inside the valley is not strongly determined by the ice rheology variations caused by changing climate, though the ice flow and accumulation rate outside the valley must be instep with widespread changes. Therefore, in our model, the mass balance and surface velocity fields are left unchanged over time.

[14] Figure 5 shows the particle paths and isochrones along the flow line. Ice from the first 500 m of the flow line (>50 thousand years old) originates from more than 10 km away. The northern small BIA (Figure 4) contains relatively young ice as it is an open-type BIA, and accumulation rates and velocities outside the valley [*Näslund et al.*, 2000] are much higher than within it (Figure 5). The small accumulation area inside the valley supplies ice that is up to 20 thousand years old to the main BIA. The particle paths of the oldest ice nearly reach the bedrock. However, they never come closer than 11 m. It is unclear whether this is close enough to the bed for the ice chronology to have been disturbed. Results from deep ice cores in Greenland [*Taylor et al.*, 1993] suggest that the bottom-most layers are mixed on scales of at least 10 cm.

[15] The most striking result is the discrepancy between the model ages and the ^{14}C ages (Figure 6). Old model ages are an inevitable result of velocities going to zero at the end of the valley. The only way to produce ages comparable to the ^{14}C ages is to make the whole valley an accumulation area in the recent past (~8000 years BP). However, this leads to an essentially constant surface age for the BIA, which is in conflict with observations of dipping radar layers and visible surface bands. This discrepancy may be because of unaccounted ^{14}C processes such as in situ production by muons [*van der Kemp et al.*, 2002] or CO_2 release from organic compounds [*Colussi and Hoffmann*, 2003]. However, a young age could explain the lack of meteorite finds on this BIA.

5. Conclusion

[16] The flow model has the advantage of being both flexible and simple, allowing realistic particle trajectories to be calculated at arbitrary resolution. The model makes use of input velocity, thickness and mass balance data in a self-consistent way. One significant advantage of using measured surface velocities is that the details of the ice rheology do not need to be considered, beyond estimation of the *k* parameter. In practice, it is never possible to know the real variations in rheology along a flow line, so this approach is as good as attempting to model rheology directly.

[17] The model does assume volume conservation - i.e. that the ice thickness does not change with time - this is easy to modify if there is a good reason to suppose that ice thickness has changed. However, consideration of at least the SBB example of a closed type BIA suggests that thickness variations over time are very small. The model does accommodate temporally variable surface velocity and mass balance.

[18] Results for NWIF BIA show that open type areas can contain ice as old as 200 thousand years, which is actually comparable with the oldest ice in SBB. The oldest ice from SBB may be disturbed due to flowing within 11 m of the bedrock, so a better climate record may be available from NWIF and open-type ice fields in general. However, the flow in open-type ice fields is more sensitive to climate change, thus making them harder to date. In contrast to many assumptions regarding accumulation areas for BIAs, the two examples presented here have small local catchments. Short flowlines makes paleoclimate interpretations of records from the BIAs much easier.

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