Sources of uncertainty in ice core data

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1. Background

Ice cores provide unique contributions to the reconstruction of past climate. At the highest latitudes and altitudes, they are generally the only proxy data archives available. They contain both climate proxy information and climate-forcing proxy information (e.g. the cosmogenic isotope proxy of solar variability). Furthermore, they are archives of a great variety of atmospheric species, for which they are not proxies but are direct records of these species (among them aerosols and greenhouse gases, and of course snow accumulation).

Ice core records are best known for the information they provide on millennial and longer timescales. Their potential use for shorter timescale climate and climate forcing reconstruction (e.g. annually resolved-reconstructions of the last millennium) remains to be fully exploited. The primary hindrance has been an insufficient number of records either to quantify or to improve the signal to noise ratio. This has now largely been addressed through efforts to obtain multiple new ice core records from both Antarctica and Greenland, as well as in the Andes, Northwestern North America, and Asia. Results from these efforts sufficient signal in the records, even at very high (<annual) resolution, to capture the spatial structure of important climate fields. Examples include methanesulfonic acid (MSA) as a proxy for sea ice (Abram et al., 2007), water stable isotope ratios (δ^{18}O) for temperature (Schneider and Noone, 2007); sea salt for atmospheric circulation (Fischer et al., 2004; Kreutz et al., 2000); and snow accumulation (Monaghan et al., 2007; Hanna et al., 2006).

A handful of quantitative high-resolution reconstructions, notably of surface mass balance and temperature on the Antarctic (Monaghan *et al.*, 2007; Schneider *et al.*, 2006) and Greenland ice sheets (McConnell *et al.*, 2000,Vinther *et al.*, in review), has recently been obtained from spatial networks of ice cores. The uncertainties in these reconstructions, however, have not yet been well quantified. A fundamental challenge to quantifying the uncertainties is presented by the paucity of primary instrumental climate data in the generally remote regions where ice cores are obtained; in the Antarctic, this is limited essentially to the last 50 years (Steig *et al.*, in review). This means that there is very little data to work with in establishing verification statistics, for example. This suggests a strong need to identify and quantify uncertainties in ice core data *a priori*, to establish norms for representing those uncertainties, and to conduct research aimed at reducing them. With the wealth of data now available, it should be possible to make significant progress in each of these areas. Below, I summarize current understanding, and make some recommendations for progress.

2. Sources of uncertainty in ice core proxies.

Timescale uncertainty is an obvious source of error in ice-core based reconstructions. In general, for ice core timescales based on counting of seasonal cycles (in δ^{18}O, sulfate, etc.), uncertainty will increase with depth (i.e. time) in an ice core. However, near volcanic marker horizons of independently-known age (e.g. the Tambora erurption of 1815) this uncertainty will be reduced. The magnitude of the uncertainty depends on the degree of ambiguity in identifying seasonal markers, and the likelihood of missing layers; both are functions of snow accumulation rate and, to a lesser extent, location. In general, where snow accumulation rates are <10 cm (ice equivalent)/year, identification of annual layers begins to be problematic. Steig *et al.*, (2005) emphasized the need to distinguish absolute accuracy from relative accuracy. In the 200-year-long U.S. ITASE ice cores from West Antarctica, they showed that while the absolute accuracy of the dating was ±2 years, the relative accuracy among several cores was <±0.5 year, due to identification of several volcanic marker horizons in each of the cores. In this case the cores can be averaged together without creating additional timescale uncertainty, since any systematic errors in the timescale would affect all the cores together.

Diffusion uncertainty: Migration of geochemical signals occurs in polar ice cores primarily in the upper ~60 – 80-m-thick firn layer; in glaciers experiencing summer melt, migration may be much faster and persist to much greater depths. For cold firn, migration is essentially by molecular diffusion below the upper ~10 m. *Diffusion uncertainty* is important to the extent that the characteristic length of diffusion exceeds the characteristic depth-resolution at a proxy is being used. A typical cumulative diffusion length for δ^{18}O over the depth of the firn layer is ~7 cm. Diffusion will thus reduce the amplitude of the seasonal cycle, but not the amplitude of interannual-variations, in an ice core with annual snow accumulation >>7 cm/year. The influence of diffusion can be quantified using models of vapor diffusion, which depend primarily on temperature and snow accumulation rate (Cuffey and Steig, 1998). Vintner et al. (in review) suggest that the best way to address diffusion in reconstructions is to artificially diffuse the ice core data so that all of the data are equally diffused; in their high resolution Greenland cores, they were able to take this approach and yet retain enough of the seasonal signal to meaningfully separate winter and summer data. With the exception of δ^{18}O, however, rates of diffusion are not well established for other species (e.g. MSA; Mulvaney *et al.*, 1992) where it may be important. An obvious alternative is to simply average samples over greater lengths of time, but in many cases this may need to be more than a year. For some species (e.g. sulfate) diffusion is in any case negligible.

Sampling uncertainty: Snowfall may not be continuous, and therefore may be biased by snowfall occurring during a particular season, or during a particular storm. Quantifying this uncertainty can probably best be done by evaluating the mean and variance of snowfall events in observational data sets and models. It may also be possible to address seasonal sampling uncertainty through the use of multiple geochemical species that have different seasonal behavior. For example Steig *et al.*, 2005) calculated the time-varying phase relationship between δ^{18}O and sulfate in West Antarctic cores and found their phase varied by no more than 1 month, suggesting that large variations in seasonal snowfall were unlikely for these cores. Addressing how this magnitude of uncertainty translates into uncertainty in a reconstruction, however, remains to be explored.

Spatial uncertainty. The amount and chemical composition of the snowfall can vary considerably over short distances, due to local micrometerological effects (e.g. due to snow dunes). In general, the degree of spatial variance is reduced when greater time averages are considered. Quantifying this uncertainty requires obtaining multiple ice cores from nearby locations.

Uncertainties in physical relationships. Fundamental to the use of any paleoclimate proxy is the assumption that relationships between variables do not change over time. Ice cores differ from many other proxies in that many of the key parameters of interest (e.g. aerosol loading) are recorded essentially directly – that is, they aren't really proxies. The main source of uncertainty is this case is the relationship between what is measured in the ice itself, and the original concentration of the species of interest in the overlying atmosphere. Well known examples include so-called "reversibly deposited" species such as nitrate, but this also pertains to δ^{18}O (Neumann *et al.*, 2005,Waddington *et al.*, 2002), and also to snow accumulation (insofar as it is used as a measure of precipitation). Quantifying these uncertainties has been the goal of combined atmospheric and snow sampling campaigns (e.g. at Summit, Greenland), but remains a challenge.

3. Strategies to reduce and represent uncertainties in ice core proxies

The ice core research community, through its International Partnerships in Ice Coring Sciences (IPICS) initiative, has recognized the need to "contribute ice core data of sufficient quality to significantly enhance quantitative climate reconstruction and climate modeling studies" (IPICS, 2008) and has emphasized the importance of increasing the spatial density of ice cores in order to achieve this goal. Obtaining multiple ice cores from the same general location is a basic way to both quantify and reduce the uncertainties in ice core proxy data. We can expect that with the efforts supported by IPICS, the availability of very well-dated (and cross-dated) high-resolution ice cores will continue to grow. Among the strategies being employed are the routine use of high-frequency snow radar, which allows for the following of stratigraphy from site-to-site, permitting cross-checking of the age assigned to specific layers (Steig *et al.*, 2005; Spikes *et al.*, 2004); the identification of volcanic marker horizons at high resolution (often the age is known to a within a specific season of a specific year) (Dixon *et al.*, 2004); and the development of new measurements that yield specific information, for example, on the degree of post-depositional change in the ice chemistry (Blunier *et al.*, 2005).

Of the five sources of uncertainty discussed in the previous section, three of them (timescale uncertainty, spatial uncertainty, sampling uncertainty) can be readily represented by including Monte-Carlo simulations of the influence on the reconstruction that results. Incorporating "timescale wiggle" into such calculations is straightforward and should probably be adopted routinely.

Quantitatively representing the effects of possible changes in the relationships between the proxy variables measured, and the climate variable they are supposed to represent, is far more problematic. A case in point is the relationship between sea ice and MSA, which is often supposed to arise from the greater production of MSA in water stratified by melting sea ice. Abram *et al.* (2007) concluded that at least in one location, the "…relationship is most likely due to variations in the strength of cold offshore wind anomalies ... which act to synergistically increase sea ice extent while decreasing MSA delivery to the ice core sites." Beside purely empirical studies (e.g. statistical calibration/verification residuals), the only way to address this kind of uncertainty is with process-based studies – in particular, coordinated measurements in the atmosphere and snow to better understand air-snow transfer relationships – combined with the incorporation of ice core proxy variables into atmospheric models. In particular, the inclusion of ice core proxies, in addition to the water isotopes, should be encouraged in the modeling community (e.g. Field *et al.*, 2006, for ^{10}Be). To the extent that ice core observations can be shown to validate these model predictions (an exercise that is just beginning to be realized), uncertainties can be quantified by conducting model runs to examine the sensitivity of the resulting proxies to various changes in climate; Schmidt *et al.* (2007) provides a useful example.

4. Recommendations

Many of the goals of this workshop are shared by the IPICS community and were discussed at a recent meeting of IPICS and in the Science Plan for the "IPICS 2000 Year Array". One issue that was discussed was the question of data archiving. Ice core data is currently stored in multiple locations, and in different formats. It would be highly beneficial to improve the norms for doing this. It is not clear that a single database containing both ice core and non-ice core data makes sense, due to the rather different requirements (e.g. multiple variables measured at different resolutions).

One of the outcomes of this workshop should be the express support of the IPICS efforts, and encouragement of efforts to gather duplicate records. Because of the expense involved with ice coring there remains resistance to obtaining duplicate (let alone multiple) records; yet this seems to be essential both for quantifying and reducing uncertainty. Encouragement for more process-based studies and ice-core-specific modeling work is also desirable.

References Cited

Abram, N. J., Mulvaney, R., Wolff, E. W., and Mudelsee, M. Ice core records as sea ice proxies: An evaluation from the Weddell sea region of Antarctica. *Journal of Geophysical Research* **112**, doi:10.1029/2006JD008139 (2007).

Blunier, T., Floch, G. L., Jacobi, H.-W., and Quansah, E. Isotopic view on nitrate loss in antarctic surface snow. *Geophys. Res. Lett*. **32**, L13501 doi:10.1029/2005GL023011 (2005).

Cuffey, K. M. and Steig, E. J. Isotope diffusion in polar firn: Implications for interpretation of seasonal climate parameters in ice core records, with emphasis on central Greenland. *J. Glac*. **44**, 273-284 (1998).

Dixon, D. et al. A 200 year sulfate record from 16 antarctic ice cores and associations with southern ocean sea-ice extent. *Annals of Glaciology* **39**, 155-166 (2004).

Field, C. V., Schmidt, G. A., Koch, D., and Salyk, C. Modeling production and climate-related impacts on 10 be concentration in ice cores. *Journal of Geophysical Research* **111**, D15107 doi:10.1029/2005JD006410 (2006).

Fischer, H. et al. Prevalence of the Antarctic circumpolar wave over the last two millenia recorded in Dronning Maud Land Ice. *Geophys. Res. Lett*. **31**, L08202 doi:10.1029/2003GL019186 (2004).

Hanna, E. et al. Observed and modelled Greenland ice sheet snow accumulation, 1958-2003, and links with regional climate forcing. *Journal of Climate* **19**, 344-358 (2006).

IPICS et al. The IPICS 2000 year array: Ice core contributions to quantitative assessment of recent climate forcing and climate variability. Science and coordination plan. International Partnerships in Ice Core Sciences (2008).

Kreutz, K. et al. Sea level pressure variability in the Amundsen sea region inferred from a west antarctic glaciochemical record. *Journal of Geophysical Research* **105**, 4047-4059 (2000).

McConnell, J. R. et al. Changes in Greenland ice sheet elevation attributed primarily to snow accumulation variability. *Nature* **406**, 877-879 (2000).

Monaghan, A. J., Bromwich, D. H., Chapman, W., and Comiso, J. C. Recent variability and trends of antarctic near-surface temperature. *Journal of Geophysical Research* **in press** (2007).

Mulvaney, R. et al. The ratio of msa to non-sea-salt sulphate in Antarctic Peninsula ice cores. *Tellus* **44B**, 295-303 (1992).

Neumann, T. A., Waddington, E. D., Steig, E. J., and Grootes, P. M. Non-climate influences on stable isotopes at taylor mouth, Antarctica. *J. Glac*. **51**, 248-258 (2005).

Schmidt, G. A., LeGrande, A. N., and Hoffmann, G. Water isotope expressions of intrinsic and forced variability in a coupled ocean-atmosphere mode. *J. Geophys. Res*. **112**, D10103 doi:10.1029/2006JD007781 (2007).

Schneider, D. P. and Noone, D. Spatial covariance of water isotopes in ice cores during 20th century climate change. *Journal of Geophysical Research* **112**, D18105 doi:10.1029/2007JD008652 (2007).

Schneider, D. P. et al. Antarctic temperatures of the past two centuries from ice cores. *Geophys. Res. Lett.* **33**, L16707 doi:10.1029/2006GL027057 (2006).

Spikes, V. B. et al. Variability in accumulation rates from gpr profiling on the west antarctic plateau. *Annals of Glaciology* **39**, 238-244 (2004).

Steig, E. J. et al. Antarctic temperatures since the 1957 International Geophysical Year. *Nature* **in review**, (2008).

Steig, E. J. et al. High-resolution ice cores from US ITASE (West Antarctica); development and validation of chronologies and estimate of precision and accuracy. *Annals of Glaciology* **41**, 77-84 (2005).

Vinther, B. M. et al. Climatic signals in multiple highly resolved stable isotope records from Greenland *Quaternary Science Reviews* **in review** (2008).

Waddington, E. D., Steig, E. J., and Neumann, T. A. Using characteristic times to assess whether stable isotopes in polar snow can be reversibly deposited. *Annals of Glaciology* **35**, 118-124 (2002).