Instruments and Methods

Rapid techniques for determining annual accumulation applied at Summit, Greenland

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ABSTRACT. We have determined accumulation histories by identifying annual-layer horizons in records obtained by three independent methods: (1) glaciochemical analysis on a core, (2) density profiling in the borehole from which the core was taken, using the neutron-probe (NP) technique, and (3) borehole optical stratigraphy (BOS), again in the same borehole. We also used three different techniques for determining density to convert annual-layer thickness to accumulation: (1) gravimetric measurements on core samples, (2) measurement of density using NP and (3) a simple empirical model based on regional climatology. The result is nine different accumulation time series, three of which are completely independent. The chemical-analysis- and NP-derived accumulation time series are correlated, and the ∼70 year means are in agreement. The BOS-derived accumulation ∼70 year mean is slightly lower, probably due to a combination of the empirical density model's underestimate of the density profile and the misidentification of sub-annual events in the shallow part of the borehole as annual horizons.

INTRODUCTION

Determination of the mass balance of polar ice sheets is of critical importance in the assessment of current, past and future climate conditions. Measuring accumulation at the surface of a glacier or ice sheet is one of the most important means of determining the mass input to the system. Traditionally, net accumulation (precipitation minus evaporation) is measured in several different ways, depending on the desired length and resolution of the record.

Annual accumulation rates are determined from ice cores by identifying annual markers and determining the mass between them. One accepted method is to analyze the core for chemical species which are deposited at rates which vary seasonally (e.g. Taylor and others, 2004) and use the chemical data to identify the annual horizons. Although chemical analysis is possible in the field, this technique normally involves returning the core to a laboratory for analysis, a process which can be expensive and time-consuming.

Recently, new, relatively rapid techniques of identifying annual markers using borehole instruments have been developed (Hawley and others, 2003; Morris and Cooper, 2003; Hawley and Morris, 2006). In this paper, we compare accumulation rates derived using the well-established method of chemical analysis with these new methods in order to determine how well the new methods can characterize the mean and temporal variability of the accumulation rate.

METHODS

Field location

'Summit' is a year-round research station located near the summit of the Greenland ice sheet, at ∼72.58° N, 38.47° W. The mean annual temperature at Summit is −31°C (Alley and Woods, 1996) and the mean accumulation is ∼23 cm a^{-1} (water equivalent; Meese and others, 1994). Summit is situated in the dry snow zone, and rarely sees any melt. Annual layers were identified in the deep Greenland Ice Sheet Project 2 (GISP2) core, collected ∼1 km from Summit (Alley and others, 1997). Our annual-layer analysis comes from a location ∼1 km from Summit where a 30 m core (known as 'Katie') was collected on 7 June 2004, and sent to the laboratory for analysis in October 2004. We also profiled the borehole with a neutron-probe density-profiling system on 8 June 2004, and using borehole optical stratigraphy on 9 June 2004.

Measurements

Glaciochemistry measurements

Sigg and others (1994) described an early continuous-flow melter system. In our experiment, we measured a much broader spectrum of elements and chemical species on the Katie core using the continuous-flow analysis with trace elements dual system (CFA-TED; McConnell and others, 2002, 2007). In this method, consecutive longitudinal samples of ice core (∼3 cm by ∼3 cm cross-section) are melted and the meltwater is split into three regions by ridges engraved on a heated melter head. Melt from the innermost region (∼10%) is pumped to two high-resolution inductively coupled plasma mass spectrometers (HR-ICP-MS) and an optical emission spectrometer (ICP-OES) for measurements
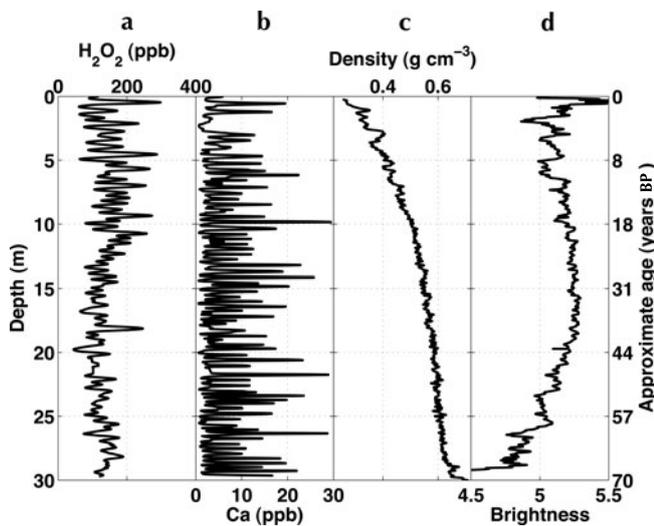
Fig. 1. The chemistry, density and optical profiles. Panels show: (a) H_2O_2, (b) Ca^{2+}, (c) density from the neutron probe and (d) brightness from borehole optical stratigraphy (units arbitrary). Also shown on the right-hand axis is the approximate age in years before 2004, based on annual layering identified by the three techniques.

of ~30 seasonally varying soluble and insoluble elements and isotopes related to sea salts (e.g. sodium), continental dust (e.g. aluminum, calcium, iron, strontium, rare earth elements), volcanism (e.g. sulfur) and industrial pollution (e.g. lead). Melt from the middle region (~20%) is pumped to a series of flow-through spectrophotometers, fluorimeters and other instruments for hydrogen peroxide and other soluble compounds (e.g. nitrate and ammonium ions). The potentially contaminated outer 70% of meltwater is discarded. The depth resolution of CFA-TED measurements is determined primarily by dispersion in the continuous-flow system and is estimated as 1 cm for the Katie core.

Neutron-scattering density probe
The neutron probe used in this experiment forms part of the ice geophysical logging system (IGLS) described by Morris and Cooper (2003). It contains an annular source of fast neutrons around a cylindrical detector of slow neutrons. The fast neutrons lose energy by scattering in the snow, and the count rate of slow neutrons arriving back at the detector is related to snow density. Morris (2008) has derived a theoretical calibration equation, consistent with empirical data, which relates count rate to density, the diameter of the hole which is being profiled, and the degree of centralization of the probe within it. Random errors in the density result from the random emission of neutrons by the radioactive source and are minimized by using a long counting period. For example, for a counting period of 64 s (which allows 56 cm of snow to be profiled at 1 cm intervals in 1 hour) the error in density is <2% for a centred probe in a 5 ± 0.25 cm access hole. For a borehole with a 12 cm diameter, known to ~5% accuracy, the error in density rises to 6%; this can be reduced by using calipers to determine the diameter more precisely.

As the neutron probe is winched slowly upwards, the count rate is measured over time intervals of 100 ms. After the probe has traveled 1 cm, the average count rate is determined from these individual measurements and recorded. The

length of the detector is 13.5 cm, but the count rate is most influenced by the density at the center of the detector. Hence the smoothing effect is similar to a low-pass filter with ~6.5 cm cut-off.

Changes in winch speed, perhaps because of increasing cable length, may change the length of time spent moving through 1 cm, and hence the precision of the density measurement, but the smoothing length will not be affected. The depth is measured to the center of the neutron detector, and no offset was applied for this analysis. Figure 1 shows the complete neutron-probe log of the borehole used in this study, collected on 8 June 2004, 1 day after drilling; despite the smoothing it is possible to see significant variation in density on the 1 m scale.

Borehole optical stratigraphy
Borehole optical stratigraphy (BOS) has been developed as a technique for simple and rapid measurement of vertical strain in a borehole by repeat measurements. The equipment and processing involved in creating a BOS profile are described in detail by Hawley (2005). In essence, the measurement uses a borehole video camera to obtain a video log as a proxy for the results obtained by visual stratigraphers on a core. The borehole probe is a downward-looking, wide-angle video camera connected to the surface via a three-conductor cable which carries both video signal and power. A portable digital video camcorder is connected at the top of the hole for viewing and recording the log. The depth of the camera is measured with an optical encoder mounted on the shaft of the pulley over which the cable runs down the hole. This depth is then displayed in the upper-left corner of the video screen. In post-processing, an annulus of pixels around the borehole wall is sampled and the mean intensity of those pixels calculated. At the same time the depth is read from the frame using optical character recognition. The end product of the BOS process is a log of intensity vs depth. The depth is measured from the snow surface to the top of the down-hole tool, and no offset has been applied in this analysis. Figure 1 shows a complete log of the borehole used in this study, collected on 9 June 2004, 2 days after drilling.

Identifying annual layers
Glaciochemical method
We used a range of seasonally varying elements and chemical species to date the Katie core, including tracers of sea salts, continental dust, marine biogenic emissions and industrial pollution. Previous studies have shown that H_2O_2 concentrations in near-surface snow at Summit are strongly seasonal and consistent from year to year. Concentrations are determined by the atmospheric concentration and temperature-dependent partitioning between the gas and ice phases (McConnell and others, 1998), with exchange between the atmosphere and snow continuing near the surface until the snow is buried (McConnell and others, 1998). The annual minimum in surface snow H_2O_2 concentration consistently occurs around the winter solstice (unpublished data), when atmospheric concentrations are low because cold air temperatures and nearly complete darkness lead to low absolute humidity and little incident solar radiation (McConnell and others, 1998). As in other studies of Greenland snow accumulation (McConnell and others, 2000; Hanna and others, 2006; Banta and McConnell, 2007), we assigned 1 January to the annual winter minimum

in H_2O_2. Thus, accumulation for each calendar year is defined using the length between annual winter minimums.

Although not required for ice-core studies in areas of moderate accumulation such as Summit, we confirmed the annual dating in three ways. First, we matched spikes in sulfur-associated volcanic fallout measured in the Katie core with well-known volcanic eruptions such as El Chichón, Mexico (1982) and Pinatubo, Phillipines (1991). Second, we compared a number of the high-resolution glaciochemical profiles from Katie with similar profiles from an array of Greenland ice cores, some from regions with higher accumulation, and confirmed chemical variations between cores at sub-annual to multi-annual timescales. Third, we compared the accumulation record from the Katie core with simulated snowfall from European Centre for Medium-Range Weather Forecasts (ERA-40) reanalysis. This showed close correspondence in temporal variability (Pearson's correlation coefficient: $r = 0.40$; Student's t-test probability: $p < 0.004$; number of observations: $n = 44$), despite the fact that an ice-core accumulation measurement includes both regional accumulation and local deposition-noise components from wind redeposition and sastrugi (Banta and McConnell, 2007).

Neutron-probe method

The density profile shown in Figure 1c exhibits a trend of general densification with depth, with decimeter- to meter-scale fluctuations. At the smaller scale, peaks in density form near the surface during the summer, as warmer temperatures promote more rapid densification. This enhances the annual variation between the low-density hoar formed in late summer/autumn and the higher-density snow, compacted by wind, deposited in winter, spring and early summer. The neutron-probe (NP) annual layer is defined as the length between successive peaks in density.

Near the surface it is relatively easy to identify annual layers by eye, although in years when the accumulation is abnormally low a peak may be extremely small or missing entirely. As in the chemical method, it is useful to have data from a number of sites so that missing, or extra, peaks can be identified. At greater depths there is more opportunity for error. The mean accumulation rate derived from the upper layers is used to help distinguish the 'true' annual horizon from possible alternatives.

Borehole optical stratigraphy method

Hawley and others (2003) showed that annual layers could be detected using BOS. The optical brightness is backscattered radiation that depends primarily on density and grain size, so is expected to readily characterize annual layers. Peaks in optical brightness correspond to the higher-density, finer-grained winter wind-slab. The optical brightness and density are highly correlated in the upper 15 m at Summit (Hawley and Morris, 2006). Peaks in brightness were determined by eye, with an a priori idea of the size of an annual layer based on long-term mean accumulation rates and densification models. The BOS annual layer is defined as the length between successive peaks. From comparison with the NP and chemistry peaks it becomes clear that, in the shallow region of the record, some peaks were picked as annual horizons that were, in fact, sub-annual layers caused by weather events such as large storms.

Density

Once annual horizons are determined by any method, density is required to determine the accumulation. In parallel with our three independent methods of determining annual layers, we used three different methods of characterizing the density profile, which allows each layer-counting method for determining accumulation to be evaluated as a stand-alone measurement.

Gravimetric method

In the laboratory, we cut rectangular longitudinal samples from the core for chemical analysis. To measure volume, we used calipers to make two or three measurements of the rectangular cross-sectional dimensions in each ∼1 m long sample. We used a meter rule to measure the length of the sample. The mass of each sample was determined just before analysis on the melter system with an electronic balance. We fitted the density measurements of the 31 samples with a seventh-order polynomial. The density at the depth of each chemical species sample is determined from this polynomial to get a continuous profile of chemical concentration vs water-equivalent depth.

Neutron-probe method

The neutron probe records a density profile at 1 cm intervals in the borehole, as described above. We used this detailed profile to determine a water-equivalent depth profile.

Simple empirical model

Since BOS does not record the density and, in principle, can be used in a borehole from which no core was recovered, we needed an independent means of estimating a density profile for the purposes of calculating annual accumulation series. Since measurements may not be available, we turned to models. Densification is a function of the overburden pressure, among other things, and thus is linked to accumulation. Therefore any model which calculates the density profile at a site requires as a model input an estimate of the accumulation at the site. As such, the use of a density model in the determination of accumulation rates has a potential for circularity, in that we must specify an estimate of accumulation in order to determine annual accumulation series. As can be seen from the resulting BOS-derived accumulation series, however, the mean of the annual series is significantly different from the accumulation estimate used as a model input. In addition, as can be seen in the discussion of differences between accumulation rates that follows, the density used for conversion between annual-layer thickness and accumulation rate has far less of an impact on the resulting accumulation series than does the method for choosing annual layers.

Many investigators have modeled firn densification over the years, with increasing complexity and fidelity (e.g. Alley, 1987; Arthern and Wingham, 1998; Zwally and Li, 2002). Modern density models can predict seasonal changes in density based on temperature changes. Because of the aforementioned reduced impact of the density used in the conversion from layer thickness to accumulation, we used one of the simplest available, the empirical model developed by Herron and Langway (1980), to characterize the density in the upper regions of the firn. The model is based on empirical relationships between mean annual temperature, mean accumulation rate and density profiles from many glaciological regimes. The required model inputs are the
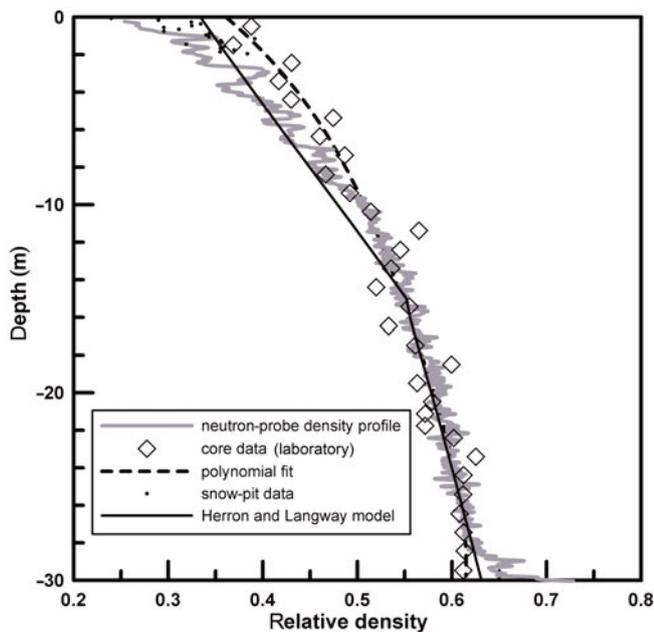
Fig. 2. Densities used in this work. The gravimetric densities for the Katie core were measured in the laboratory by weighing square columns cut from the core. A polynomial fitted to the gravimetric values is also shown. The NP density profile is shown by the gray curve. Within ∼30 cm of the upper boundary the density is underestimated because fast neutrons are lost to the air; similarly near the lower boundary the density is overestimated because fast neutrons are reflected from the bottom of the borehole. Otherwise, the NP data are a good fit to the gravimetric values. Snow-pit data are from the pits reported by Burkhart and others (2004), and were used in the determination of the Herron and Langway (1980) modeled density profile.

temperature at 10 m depth, which approximates the mean annual temperature, mean annual accumulation rate and density of the initial surface snow. We used $-31°C$ (Alley and Woods, 1996), $0.23 \, m \, w.e. \, a^{-1}$ (Meese and others, 1994) and $0.33 \, g \, cm^{-3}$ (unpublished snow-pit data), respectively. This density profile can, in turn, be used to generate a water-equivalent depth profile for determining accumulation rates. The density profiles are shown in Figure 2.

Accumulation rates

Given a set of annual-layer locations and a set of water-equivalent depth profiles, annual accumulation rates are simply the difference in water-equivalent depth between annual horizons. For each method of identifying annual layers, we calculated accumulation using each method of determining water-equivalent depth. The resulting nine accumulation series are shown in Figure 3.

DISCUSSION
Comparison of identified layers

As can clearly be seen from the upper two rows of Figure 3, the long-term mean and variability in the six accumulation histories are in agreement, indicating that NP-based layer picking achieves similar performance to glaciochemical analysis. In the three BOS-based accumulation series in the bottom row, however, there is a clear trend toward lower accumulation in the most recent years which is not present in the other series. Though this could be due to annual horizons missed in the glaciochemical and NP profiles, a more plausible scenario is that some peaks picked in the upper part of the BOS profile are due to sub-annual processes, such as particularly large storms or warm periods causing additional 'layers' between successive annual horizons. These storm-event markers may disappear with further compaction, which would explain the close agreement between all three records at greater depths. It is worth noting that, although some peaks in the shallow region were misidentified, only four additional peaks were identified as 'annual layers' in the BOS record, compared to the chemical record.

In addition, the chemistry-based and density-based methods allow a greater confidence in identifying annual markers because both methods have also been used at higher-accumulation sites. The layer patterns at these higher-accumulation sites, which are more clearly defined, can be traced to our Summit site (e.g. Banta and McConnell, 2007). Thus these methods benefit from the analysis of several cores and boreholes in the region, whereas the BOS-based method was only used directly at our study site.

Also apparent in Figure 3 is that the annual fluctuations in accumulation are not identical between the three layer-identification methods. This is not surprising, as the processes that define a peak in one record are not necessarily correlated with the processes that define a peak in another record, as was demonstrated by Anklin and others (1998) for multiple chemical records on Greenland cores. For instance, the peak in density may occur at a given time in one year, but be phase-shifted in the next. Likewise, the couplet defining the BOS annual horizon may take different forms in successive years. These differences result in different derived accumulation rates.

Table 1. Pearson's *r* correlation between accumulation series in each row of Figure 3. The trend has been removed from the series in row 3. Each row in the table represents the method of choosing layers, and each column compares accumulation series resulting from two density estimates. In all cases correlation is very good, indicating that the location of annual horizons is of greatest importance. H & L indicates Herron and Langway (1980) density profile

Correlation, *r*	Gravimetric/NP	Gravimetric/H & L	NP/H & L
H_2O_2	0.9717	0.9800	0.9931
Neutron probe	0.9829	0.9889	0.9961
BOS	0.9960	0.9981	0.9972

Table 2. Pearson's *r* correlation between accumulation series in each column of Figure 3. Note that the trend has been removed from the series in row 3. Each row in the table represents a method of estimating density, and each column compares accumulation series resulting from two sets of annual layers. Correlation is clearly not as good between annual-layer methods (within columns of Fig. 3) as between density methods (within rows of Fig. 3), as indicated in Table 1

Correlation, *r*	H_2O_2/NP	H_2O_2/BOS	NP/BOS
Gravimetric	0.2032	0.1312	0.0087
Neutron probe	0.2141	0.1635	0.0354
H & L	0.2031	0.1520	0.0256
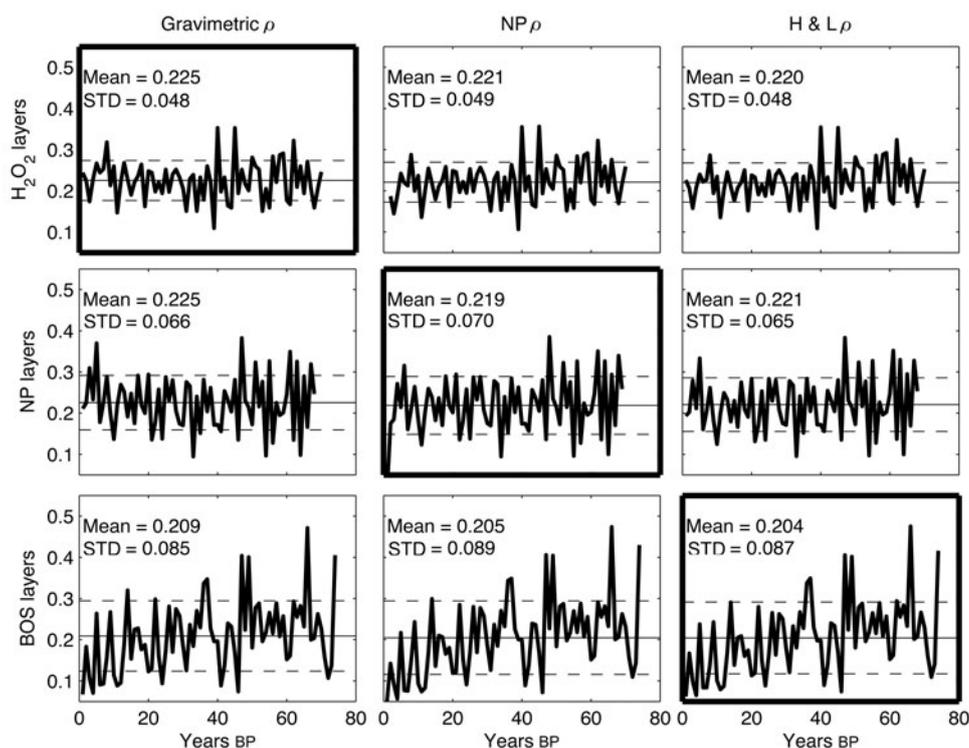
Fig. 3. Accumulation histories for nine combinations of dating and density methods. The rows represent different methods of determining annual layers, and the columns represent the different methods of determining water-equivalent depth. The three panels with bold frames on the diagonal from upper-left to lower-right show each method's independent estimate. The mean and standard deviation (STD) are indicated by a light solid horizontal line and a light dashed horizontal line, respectively. Note that the differences are dominated by the method of determining layering, rather than the method of determining density (i.e. there is more variability between the rows than between the columns; see Tables 1 and 2).

In spite of these differences, the chemistry-based and density-based accumulation records show significant correlation ($r = 0.38$, $p = 0.001$, $n = 68$) when filtered with a fourth-order Butterworth filter with a cut-off of 3 years, showing that both series capture the same longer-period fluctuations. Similarly, the deepest 34 years of the BOS-based accumulation series correlates well ($r = 0.35$, $p = 0.04$, $n = 34$) with the chemistry-based series.

The upper two series in Figure 3 do not exhibit a trend. The statistics of each complete series are given in each panel, and Figure 4 shows histograms of each series. It can be inferred that the NP- and chemistry-based methods produce statistically indistinguishable accumulation time series. The variability of the NP-based series is slightly higher, probably due to the variability of the timing (in the year) of the annual density peak. This variability is even greater in the BOS-based series, also probably due to the temporal variability of the conditions that create the BOS annual horizon.

Comparison of density profiles

While the variability between the rows of Figure 3 highlights the differences in picking annual layers, the uniformity of the columns indicates that the choice of density profile for determining water-equivalent depth has a relatively small effect on the estimated accumulation time series. Indeed, while there are some slight differences (e.g. the Herron and Langway density profile underestimates density, through some of the firn column as shown in Figure 2, leading to lower mean accumulations in column 3), the mean and

standard deviation differences between adjacent columns are insignificant. Cross-correlations between the series in adjacent columns and between the series in adjacent rows are shown in Tables 1 and 2. The row-wise correlations are all very high, and the column-wise correlations are low, indicating that choice of annual-layer location is the important factor when determining accumulation time series.

CONCLUSIONS

We have determined nine accumulation time series from a core and corresponding borehole at Summit, Greenland, based on three independent methods (glaciochemical analysis and gravimetric density, NP profiling for annual layers and density, and BOS for annual layers with an empirical density model). The accumulation time series produced by NP, while displaying slightly different variability, is the same as the glaciochemically derived series when looking at long-term means and multi-year trends. The BOS-derived time series is distinctly different in the shallower sections of the profile, where it is likely that sub-annual events (storms, for example) were misidentified as annual. For a rapid, field-based determination of accumulation history, the NP approach performs well. Though the present BOS analysis for Summit leaves significant room for improvement, at other locations (e.g. Hawley and others, 2003) the identification of annual layers with BOS has given a good result. Future profiling systems that integrate the NP and BOS instruments might achieve better performance than either could alone.
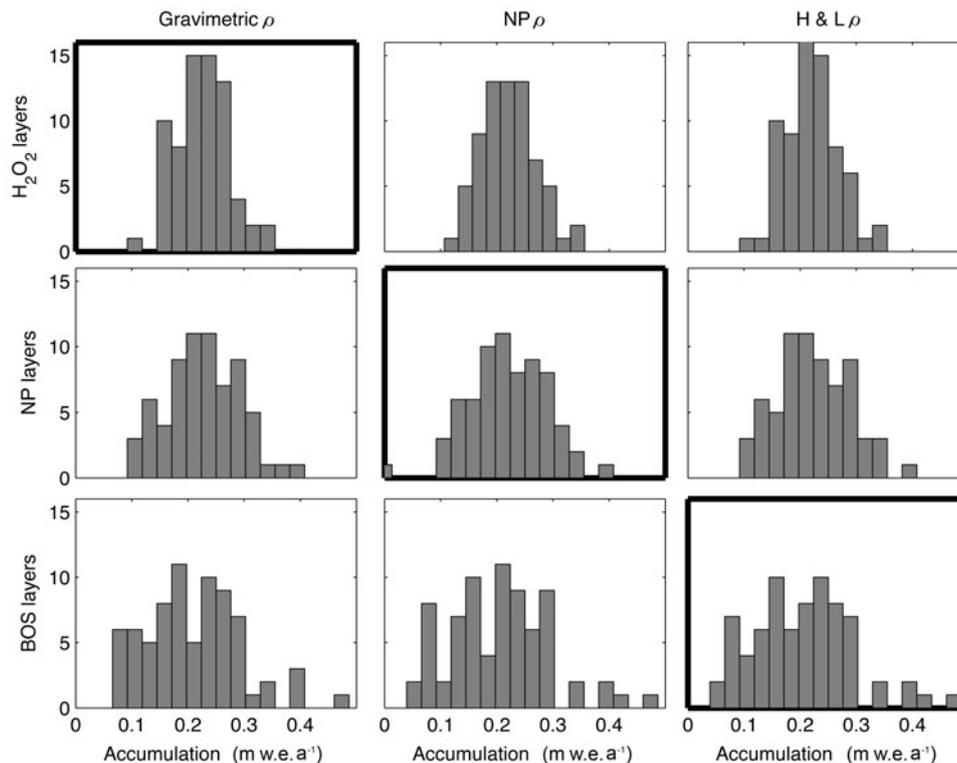
Fig. 4. Histograms of the nine accumulation histories shown in Figure 3. The rows represent different methods of determining annual layers, and the columns represent different methods of determining water-equivalent depth. The three panels with bold frames on the diagonal from upper-left to lower-right show each method's independent estimate. Note that the distribution for the H_2O_2 and NP rows is very similar, though the NP distribution is flatter, and the BOS distribution shows more lower values. This suggests that some sub-annual events in the shallow section of the profile have been misidentified as annual events.

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