Inter-annual variability in net accumulation reconstructed from three firn cores from the Devon Island Ice Cap, Nunavut

William Colgan, Martin Sharp and Lisa Hryciw

1-26 Earth Sciences Building, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, T6G2E3

UNIVERSITY OF ALBERTA
www.ualberta.ca/~wcolgan

Objectives

This project uses three firn core proxy records to reconstruct both short term (inter-annual) and long term (41 a) net accumulation rates in the high elevation (> 1200 m) western region of the Devon Ice Cap. Trends and variability within the reconstructed net accumulation records are compared with observed mass balance records from the same sector of the Devon Ice Cap and with the Arctic Oscillation Index. The record of the ice content of each annual layer was also examined as a proxy for regional summer temperature and melt.

Methods

Three short ice cores (~20 m) were recovered along a transect extending westwards from the summit of the Devon Ice Cap towards the equilibrium line (Figure 1). The net annual accumulation in each core was calculated using annual layers determined from density measurements on the ice cores and annual layer thicknesses defined by high-resolution anion (Cl^-, SO_4^{2-}, NO_3^{2-} and methanesulphonate (MSA)) stratigraphy. Dating of the core by annual layer counting was verified using in-situ down-borehole ^{137}Cs gamma spectrometry (Dunphy and Dibb, 1994), which allowed the 1963 ^{137}Cs peak due to atmospheric nuclear testing to be identified. The percentage ice content of each annual firn layer was also calculated. The long term (41 a) net accumulation at each site was calculated as the total net accumulation since the deposition of the 1963 ^{137}Cs horizon (c.f. Mair et al., 2005). The dating error is estimated to compound at the approximate rate of ±1 year per 25 years from the present, giving a minimum error of ±1 year between 1978 and 2003 and a maximum error of ±3 years prior to 1953.

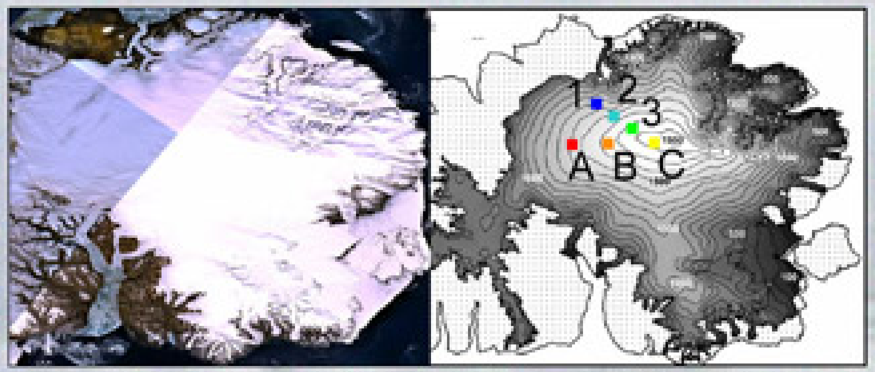

Figure 1 – L: Landsat 7 orthomosaic of the Devon Ice Cap. R: Approximate locations from which cores A (1415 m), B (1630 m) and C (1825 m) were recovered, as well as the locations of three mass balance datasets, identified as 1 (1350 m), 2 (1550 m) and 3 (1750 m), measured by Koerner (1998), to which the core records are compared.

Results

Both the long and short term net accumulation rates are measured in terms of of water equivalent (WE) (Table 1). Long term net accumulation since 1963 increases with elevation from 9.1 m WE in core A to 10.2 m WE in core C. The annual net accumulation rates of the three core records are not significantly different (P>0.05) over their entire record lengths. The three cores exhibit similar amounts of interannual variability as seen by the standard deviation of the annual mean net accumulation.

Core (elevation)	Record Length (span)	Long term net accum. (m WE) ± error	Mean annual net accum. (mm WE a^{-1}) ± SD	Mean annual ice content (% a^{-1}) ± SD
A (1415m)	65 (1938 – 2003)	9.1 ± 0.1	235 ± 82	72 ± 34
B (1630m)	45 (1958 – 2003)	9.2 ± 0.1	224 ± 61	19 ± 22
C (1825m)	49 (1953 – 2002)	10.2 ± 0.1	250 ± 75	12 ± 16

Table 1 – The record length and span, long term net accumulation (net accumulation between 1963 and 2004) and mean annual net accumulation and ice content (calculated annually over the entire record length of each core) of the three cores.

The net accumulation records from the three cores show in-phase temporal variability, with distinct periods of high (1987-1992 and 2000-2003) and low (1980-1986 and 1993-1999) annual net accumulation (Figure 2). The coherence of the three records deteriorates prior to 1980. This may be the result of compounding dating errors or the increasing strength of a forcing that controls mass balance at all three core sites. A significant (P<0.05) 10 to 12 year periodicity is present in the net accumulation records since approximately 1980 according to wavelet analysis (Grinsted et al., 2004; Figure 3). In an attempt to differentiate climatically driven signals from noise, the three net accumulation records were decomposed into two significant principal components (Figure 4; Table 2).

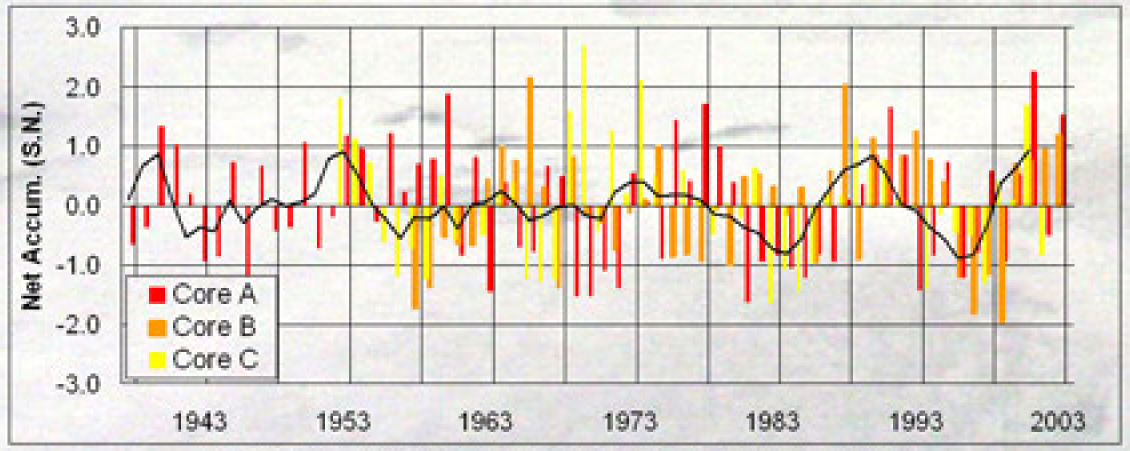

Figure 2 – Reconstructed net annual accumulation (standard normalized) at the three core sites over the period 1938 to 2003. The black line shows the mean annual net accumulation of the three core sites.

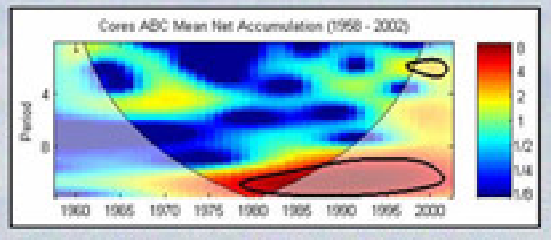

Figure 3 – A 10 to 12 year periodicity in the three core mean annual net accumulation record. Black lines indicate areas of significance (P<0.05).

Core	PC1	PC2
A	-0.55	0.67
B	0.37	0.79
C	0.83	0.09

Table 2 – Net accumulation principal component weightings.

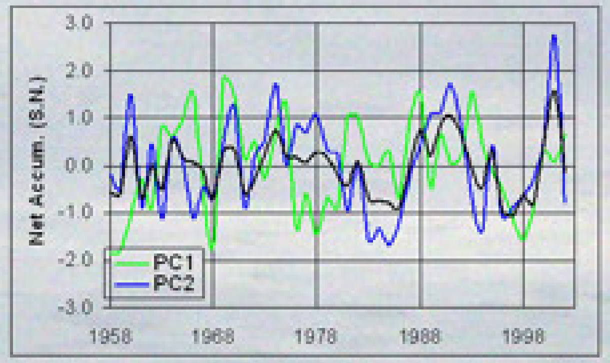

Figure 4 – The first (PC1) and second (PC2) principal components extracted from the three net accumulation records for the period 1958 to 2002. The black line shows the mean annual net accumulation of the three core sites. Principal component loadings on the three records are shown in Table 2.

Running 5-year net accumulation means were calculated for each core and compared to the observed annual mass balance at appropriate elevations (1350 m to 1750 m) in the northwest sector of the Devon Ice Cap over the period 1961 to 1998 (Koerner, 1998; Figure 5). Although good correlation is seen between the three core records over the latter part of this period, the core records were not significantly correlated (P>0.05) with the observed mass balance record. When 5-year running means were used, however, the net accumulation at core B (1630 m) was weakly correlated to the observed mass balance records for both 1650 m and 1750 m (r = 0.32 and 0.35, P<0.05; Figure 5).

This suggests that there may be significant noise in both the mass balance and the ice core records. In the ice core record, this noise could arise from errors in dating, measurements of firn density or core diameter, or from local variations in accumulation rate related to features such as sastrugi. The annual anion concentration peaks are believed to have been correctly identified in the ice cores to within ± two sample intervals, giving an estimated annual net accumulation error of between ±28.4 and ±38.5 mm WE a^{-1}. Cogley et al. (1996) estimate the annual error in a mass balance stake network similar to the one used on the northwest sector of the Devon Island ice cap, to be at least ±100.0 mm WE a^{-1}.

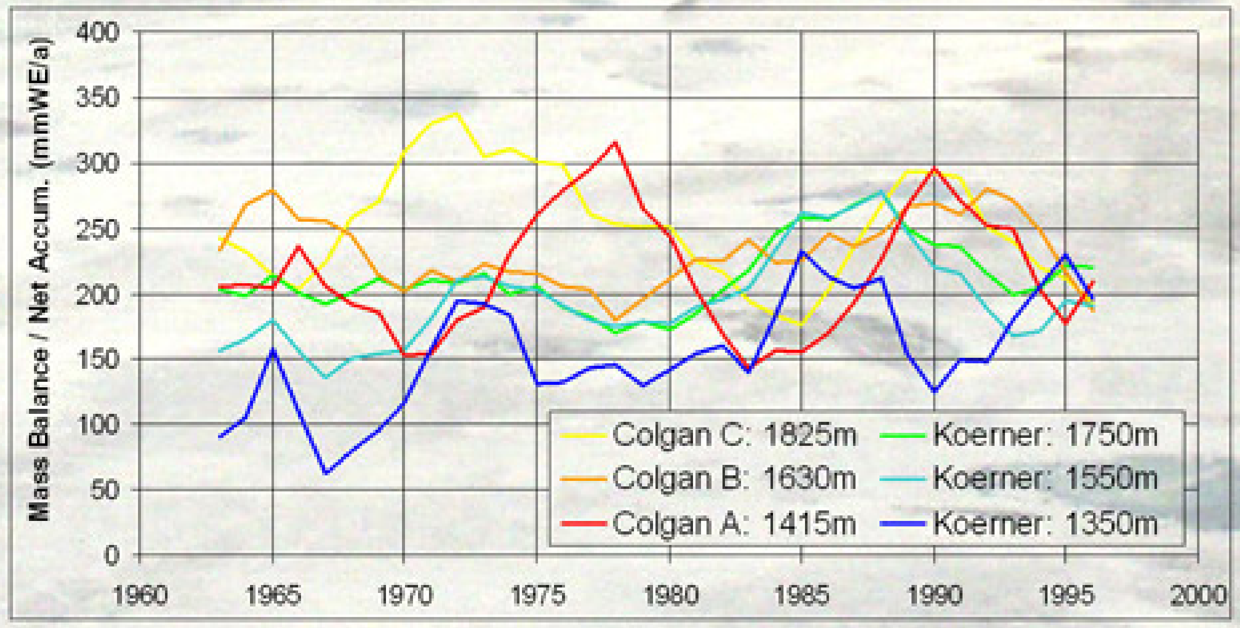

Figure 5 – 5-year running means of the three ice core net accumulation reconstructions and three observed mass balance datasets for the northwest sector of the Devon Ice Cap over the period 1961 to 1998 (Koerner, 1998). The estimated annual error of the cores A, B and C are ±31.2, 28.4 and 38.5 mm WE a^{-1} respectively. The observed mass balance data sets are assumed to have a minimum error of ±100 mm WE a^{-1} according to Cogley et al. (1996).

When examining ice content records, the possibility that meltwater may percolate into, and refreeze in, firn formed in years prior to the year of melt must taken into account (Koerner, 1977). To minimize the possible influence of this process, 5-year running means of ice content and net accumulation were calculated for the three cores. The ice content and net accumulation records for both cores A and B were positively correlated (r = 0.58 and 0.30 respectively, P<0.05), while no significant relationship (P>0.05) was seen in core C (Figure 6). The strength of the core B correlation increases (r = 0.48, P<0.05) when the ice content is lagged one year behind the net accumulation record, suggesting that melt is potentially percolating >1 year at this site. The relationship seen in cores A and B suggests that the summer melt conditions responsible for converting firn into ice are linked to the annual net accumulation.

Ice content can be considered an indicator of summer melt intensity (Koerner, 1977). The records from cores A and B show distinct in-phase warm and cool periods over the last 30 years (Figure 6). Regime shift analysis (Rodionov, 2004), shows significant decreases (P<0.05, cutoff=5) in the ice content of cores A, B and C in 1954, 1960 and 1965 respectively, followed by significant increases (P<0.05, cutoff=5) in cores A and C after 1996 and 1995 respectively.

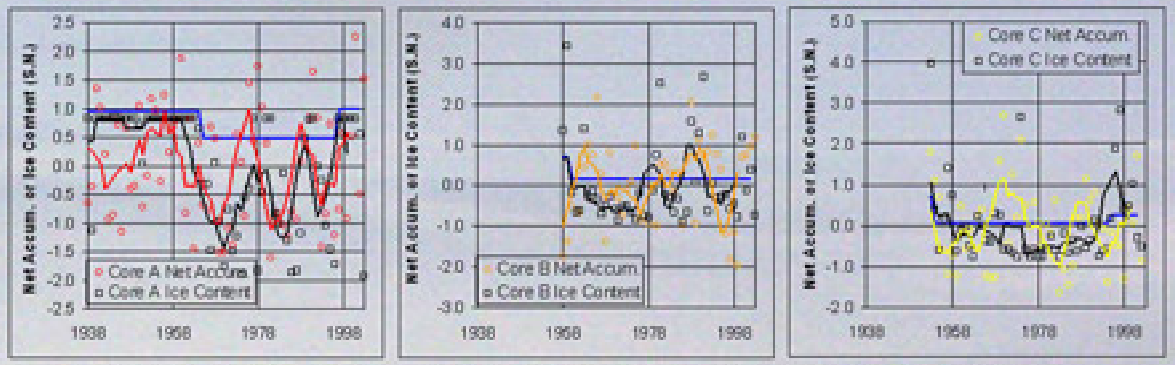

Figure 6 – The standard normalized net accumulation and ice content records from the three cores over the period 1938 to 2003. The 5-year running means of both datasets are shown. The blue lines indicate the ice content regime and significant shifts (P<0.05, cutoff=5) in each plot.

The principal components of the net accumulation records were compared to the seasonal index of the Arctic Oscillation (AO) (the primary EOF of northern hemisphere sea level pressure), using cross-wavelet coherence analysis (Ambaum et al., 2001; Grinsted et al., 2005; Figure 7). PC1 did not show any significant relationships (P>0.05) with the seasonal AO index. PC2 (which reflects net accumulation at cores A and B) however, showed a coherent and significant in-phase relationship (P<0.05) with both the spring (MAM) and fall (SON) AO indices. Given the positive correlation between net accumulation and ice content in these records, this may suggest that positive AO index conditions are associated with both increased snowfall in spring and fall and more intense summer melt.

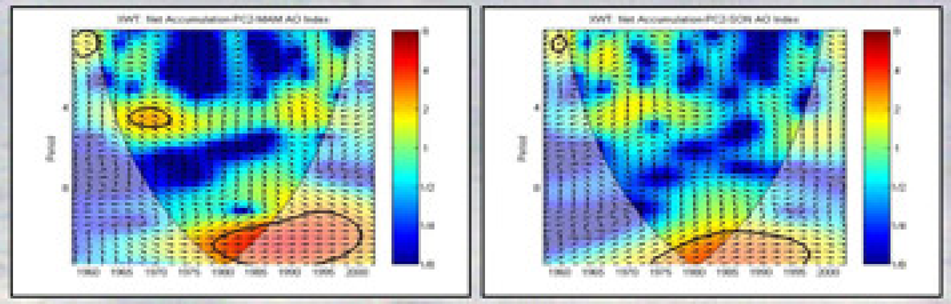

Figure 7 – Cross-wavelet coherence analysis of PC2 and the spring (MAM – L) and fall (SON – R) AO indices. Black lines delineate the significant 10-12 year coherent periodicity (P<0.05) shared by PC2 and the seasonal AO index records. Right-hand arrows in The 10-12 periodicity indicate an in-phase relationship (left-hand arrows would indicate out-of-phase).

Conclusion

The long term net accumulation rates at the three core sites increased with elevation (Table 1), while the annually-resolved records showed distinct periods of high and low annual net accumulation since 1980 (Figure 2), with a significant 10 to 12 year periodicity (Figure 3). This periodicity was also present in PC2 of the net accumulation records. PC2 showed significant in-phase coherence with both the spring and fall AO indices. The ice content records in cores A and B also show distinct in-phase warm and cool periods (Figure 6). At cores A and C, a period of relatively low ice content which had lasted since at least the early 1960s seems to have ended after 1996 and 1995 respectively (Figure 6). The annual ice content and net accumulation records were significantly positively correlated in both cores A and B, but not in core C (Figure 6). It may therefore be that positive AO index years are associated with both high spring/fall snowfall and high summer melt, but that the melt produced refreezes and is not lost from the annual layer.

At the annual scale, no significant correlations were found between the three reconstructed net accumulation records and the observed mass balance data (Figure 5). A 5-year running mean of the core B (1630 m) record, however, correlated weakly with the 15-year running mean of the 1650 m and 1750 m observed mass balances (Figure 5). The weak relationships detected are likely a reflection of errors in the dating of the cores, measurements of core density and diameter, and/or mass balance. They may also indicate a significant element of noise in the records related to the movement of surface features such as sastrugi.

Acknowledgements

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