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Variability of accumulation in northwest Greenland over the past 250 years

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Abstract. During summer 1996, a 120-m firn and ice core was drilled to determine annual accumulation rates at a northwest Greenland site (GITS, 77.1392°N, 61.0422°W, 1910 m elevation). Annual layers were identified in the core using multiple parameters: δ^{18}O and concentrations of dust, hydrogen peroxide, ammonium, calcium and nitrate. Using all parameters together to define annual layers resulted in a 251-year record with a dating uncertainty of one year within that period. Annual accumulation over the period of record averaged about 0.37 m water equivalent. Comparing this record with four other multi-century long records from the west central and northwest portion of the ice sheet shows many periods when decadal-scale fluctuations in accumulation at the different sites are in phase. Overall variations in accumulation in this portion of the ice sheet were ± 8-9% per decade, versus ± 25% for individual cores. Annual accumulation at GITS showed a significant correlation with a 12-month North Atlantic Oscillation index (Pearson's $R = -0.32$ with a significance level of $> 99\%$), though the correlation was slightly lower than for two cores roughly 350 and 700 km south.

1. Introduction

Accumulation estimates for the Greenland ice sheet have been based on point measurements made at over 250 locations, over a period of more than 70 years [*Ohmura and Reeh*, 1991]. The variability of ice sheet accumulation over time is of particular interest for studying changes in the mass balance of the ice sheet. However, the natural variability over space and time is superimposed upon the long-term trends, making them difficult to decipher.

1.1. Methods

In summer 1996, 120-m and 21-m ice cores were drilled at the Greenland Ice Sheet Training Facility (GITS, 77.1392°N, 61.0422°W, 1900 m elevation) using a 100-mm (4-in) electromechanical drill, Figure 1. The cores were about 30 m apart. For both cores we established uninterrupted records for six different physical or chemical parameters that exhibit seasonal variations: dust, δ^{18}O, hydrogen peroxide, ammonium, calcium and nitrate. Analytical methods were described previously [*Anklin et al.*, 1998].

1.1.1. Statistical model

A sensible way to analyse trends and seasonalities in geophysical time series is the development of a structural model in state space form. Following this approach, the monthly mean tropospheric ozone concentrations Y_t at JFJ are modeled as a linear combination of a stochastic trend component μ_t, a stochastic seasonal component s_t, k intervention components $w_{i,t}$, and an irregular component ϵ_t.

Stochastic Trend: The stochastic trend component is recursively defined as a local level μ_t with disturbance η_t and a local slope β_t with disturbance ζ_t

$$\begin{aligned} &Y_t\mu_t + s_t + \sum_{i=1}^{k}(x - x_0)\cos\Theta + (y - y_0) \\ &\quad \lambda_i w_{i,t} + \epsilon_t \ . \end{aligned} \tag{1}$$

The stochastic trend component is recursively defined as a local level μ_t with disturbance η_t and a local slope β_t with disturbance ζ_t

$$\begin{aligned} \mu_t &= \mu_{t-1} + \beta_{t-1} + \eta_t \\ \beta_t &= \beta_{t-1} + \zeta_t \ . \end{aligned}$$

The seasonal component consists of 12 monthly levels which summarise to a disturbance ξ_t, allowing the seasonal pattern to evolve with time

$$s_t = -\sum_{i=1}^{11} s_{t-i} + \xi_t \ .$$

All disturbances are normally distributed, independent white noise processes with zero means and constant variances

$$\begin{bmatrix} \epsilon_t \\ \eta_t \\ \zeta_t \\ \xi_t \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_\epsilon^2 & 0 & 0 & 0 \\ 0 & \sigma_\eta^2 & 0 & 0 \\ 0 & 0 & \sigma_\zeta^2 & 0 \\ 0 & 0 & 0 & \sigma_\xi^2 \end{bmatrix} \right) .$$

Interventions may be easily incorporated in the model. A structural break, for instance, in which the level of the series shifts up or down can be modeled by a step intervention variable which is zero before the event and one afterwards.

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2. Kalman Filter

Suppose that the temporal growth of the state vector from t_{k-1} to t_k can be expressed by

$$\mathbf{x}_k^f = \mathbf{F}(\mathbf{x}_{k-1}^a, \mathbf{w}_k + \mathbf{q}_k) \tag{2}$$

Under the assumption that the acoustic tomography data $\mathbf{y}_k$ available for the data assimilation are linearly related to the state vector $\mathbf{x}_k$, the following observation equation is given

$$\mathbf{y}_k = \mathbf{E}_k\mathbf{x}_k + \mathbf{e}_k \tag{3}$$

where $\mathbf{E}_k$ is the observation matrix which provides a relationship between the prognostic model variables and measurement data. The

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Figure 1. Here is a caption for a single column figure. Here is a caption for a single column figure.

$\mathbf{e}_k$ is the measurement error assumed to have zero mean and the known covariance matrix $\mathbf{R}_k$. The measurement data of the acoustic tomography are the travel times from one acoustic station to another.

3. Discussion

There is a good match between the 10-year running mean accumulation from the GITS core and that from a 1977 core that was only about 2 km away with a correlation coefficient of 0.46 for the triangular filtered data and 0.50 for the ten-year running means, Figure 2. However, it should be noted that annual layers in the 1977 core were based on a single annually varying parameter (δ^{18}O), resulting in greater uncertainty in the dating of that core.

1. We estimated the current distance of the subsolar magnetopause from the Earth (D_S) and radius of the magnetopause crossection at the terminator (R_S) using the prediction of the magnetopause model [*Shue et al.*, 1997].
2. We scaled the INTERBALL-1 X_{GSE} coordinate with respect to D_S and its distance from the Sun-Earth line with respect to R_S.
3. We scaled the INTERBALL-1 X_{GSE} coordinate with respect to D_S and its distance from the Sun-Earth line with respect to R_S.
4. Using these relative coordinates and the S66 model, we determined for each measurement the predicted value of the magnetosheath flux, FCC_{pr} (predicted flux compression coefficient). We fixed values $M_A = 8$ and γ = 5/3 as parameters of the model.

3.1. Measurement Errors

We neglected several effects in computation of the ion number flux from the Faraday cup currents: current of alpha particles, contribution of high-energy electrons and changes of ion flux direction. These effects were broadly discussed in *Zastenker et al.* [1999b] with the conclusion that they cannot explain the disagreement between observations and S66, Table 2.

Table 1. Summary of Correlations Between Ice Cores and NAO Indices[a]

Site	Time Span	12-Month Period	Pearson's R	Spearman Rank Order
GITS[a]	1865-1995	Feb-Jan	-0.316	-0.298
Camp Century	1865-1974	Jul-Jun	-0.320	-0.298
Nasa-U	1865-1994	Sep-Aug	-0.353	-0.342
Milcent	1865-1966	Jun-May	-0.410	-0.494

[a] Algorithms from numerical recipes.

[b] Data supplied by NASA Moffat.
Table References:
Information from GITS, and Camp Century.

3.2. Magnetosheath Cross-Section

We have adjusted the "dimensions" of the magnetopause in accordance with the S97 model. After our scaling, the position of the bow shock in the S66 model is a little nearer to the Earth than that determined from the Formisano empirical model [*Formisano*, 1979]. This corresponds with a note in *Song et al.* [1999b] that the observed bow shock is, as a rule, located outside of the gasdynamic prediction.

Interventions may be easily incorporated in the model. A structural break, for instance, in which the level of the series shifts up or down can be modeled by a step intervention variable which is zero before the event and one afterwards.

4. Conclusions

Using multiple dating parameters to define annual layers resulted in a 251-year record for the 120-m GITS core, with a dating uncertainty of one year within that period. Multi-century long records from five sites show many periods when fluctuations in decadal accumulation at the different sites are in phase. Accumulation during the decade of the 1980s was the lowest in the last 200 years while that during the 1960's and 1970's was well above average.

Appendix A: Title Here

An example appendix with a title.

Appendix B

An example of an appendix without a title. The actual spread in measured phase due to satellite motion can be estimated by

$$\phi = \frac{360 V_s t \cos\theta}{\lambda} \tag{B1}$$

where V_s is the satellite velocity, t is the integrated measurement time, θ is the angle between the spacecraft velocity and the cylindrical axis of the helix, and λ is the helix wavelength.

Figure 2. The accumulation records for the three cores in northwest Greenland are compared to two older cores from central Greenland, and to the Camp Century core. Camp Century and Milcent were based on *Claussen et al.* [1988], with data from the NOAA Paleoclimate Program's International Ice Core Data Cooperative (www.ngdc.noaa.gov/paleo/icecore/greenland/gisp/gisp.html). GISP2 was based on *Meese et al.* [1994], with data from The Greenland Ice Cores CD-ROM, 1997 (Available from the National Snow and Ice Data Center, University of Colorado at Boulder, and the World Data Center-A for Paleoclimatology, National Geophysical Data Center, Boulder, Colorado). Graphs are 10-year running means, normalized to their period of record since 1800 A.D. Heavy line on GITS graph is accumulation record for the Camp Century core.

Table 2. Evidence on Missing M2 During the 1990's

		Panel A Regression A				Panel B Regression B			
			Error				Error		
				Cumulative				Cumulative	
Year	Actual M2 Growth	Predicted M2 Growth	Level Growth	(billions)	Percentage	Predicted M2 Growth	Level Growth	(billions)	Percentage
1990Q4	4.0	6.4	−2.3	−71	2.2	6.5	−2.4	−80	2.4
1991Q4	3.0	3.6	−0.5	−91	2.7	3.3	−0.3	−92	2.7
1992Q4	1.8	6.4	−4.5	−257	7.5	5.9	−4.0	−239	6.9
1993Q4	1.4	4.8	−3.4	−392	11.2	5.0	−3.6	−381	10.9
1994Q4	0.6	3.0	−2.4	−489	13.9	2.6	−2.0	−464	13.2
1995Q4	3.8	3.5	0.3	−495	13.6	4.2	−0.4	−500	13.7
1996Q4	4.5	3.9	0.5	−495	13.0	4.0	−0.4	−505	13.3
Mean Error (1990–1996)			−1.78				−1.78		
RMSE			2.52				2.40		

The predicted values are generated using the regressions reported in Table 1. Regressions are estimated from 1960Q4 and dynamically simulated from 1990Q1 to 1966Q4. *RMSE* is the root mean squared error, which is of particular interest in this context.

Appendix C: Journal Abbreviation Reference

`\aj`	*Astron. J.,*
`\apj`	*Astrophys. J.,*
`\apjl`	*Astrophys. J.,*
`\apjs`	*Astrophys. J. (Supp.),*
`\aap`	*Astron. Astrophys.,*
`\bams`	*Bull. Am. Meteorol. Soc.,*
`\bssa`	*Bull. Seismol. Soc. Am.,*
`\eos`	*Eos Trans. AGU,*
`\epsl`	*Earth Planet. Sci. Lett.,*
`\gca`	*Geochim. Cosmochim. Acta,*
`\gjras`	*Geophys. J. R. Astron. Soc.,*
`\grl`	*Geophys. Res. Lett.,*
`\gsab`	*Geol. Soc. Am. Bull.,*
`\jatp`	*J. Atmos. Terr. Phys.,*
`\jgr`	*J. Geophys. Res.,*
`\jpo`	*J. Phys. Oceanogr.,*
`\mnras`	*Mon. Not. R. Astron. Soc.,*
`\mwr`	*Mon. Weather Rev.,*
`\pepi`	*Phys. Earth Planet. Inter.,*
`\pra`	*Phys. Rev. A,*
`\prl`	*Phys. Rev. Lett.,*
`\pasp`	*Publ. A. S. P.,*
`\qjrms`	*Q. J. R. Meteorol. Soc.,*
`\rg`	*Rev. Geophys.,*
`\rs`	*Radio Sci.,*
`\usgsof`	*U.S. Geol. Surv. Open File Rep.,*
`\usgspp`	*U.S. Geol. Surv. Prof. Pap.,*
`\astap`	*Astron. Astrophys.,*
`\apjlett`	*Astrophys. J.,*
`\apjsupp`	*Astrophys. J. (Supp.),*

Glossary

Adiabatic invariants: Geomagnetically trapped charged particles execute three basic motions according to three adiabatic invariants.

Auroral electrojets: High-latitude current flow concentrated inside the auroral oval and carrying a total current of $\sim 10^6$ A.

Notation

A	Surface area, m^2;
$T_{i,\mathrm{bulk}}$	freezing temperature of water to ice under bulk conditions, K.;
$\Delta T_{i,\mathrm{pore}}$	depression in freezing temperature of ice inside a pore, below bulk freezing temperature, K.;
μ^0	chemical potential of a substance in the standard state, J mol^{-1};
$\Delta H_{f,i}$	specific enthalpy of fusion of ice, J kg^{-1}.

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Anklin et al. [1998], *Hammer* [1977]

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