Spatial variation in the influence of the North Atlantic Oscillation on precipitation across Greenland

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[1] Ice core-derived accumulation records from Greenland have been proposed as proxies for North Atlantic Oscillation (NAO) reconstruction. In a series of single-site analyses, accumulation records from ice cores drilled in western Greenland were found to exhibit the strongest linear association with NAO. In this paper, we expand on these findings by proposing a spatiotemporal statistical model to explore further the relationship between NAO and the accumulation records from 35 firn and ice cores drilled in western and southern Greenland. In particular, we propose a temporal extension of the Bayesian spatially varying coefficient regression model, which is fit using a Markov chain Monte Carlo algorithm. This model readily accommodates the irregular features of the data (i.e., variation in record lengths and irregular spacing among ice core locations) and the serial dependence within individual records. Using our statistical model, we are able to exploit the spatial dependence structure of the derived accumulation-NAO relationship to explore the regional patterns in the strength of this relationship. Our findings support previous work that identified a region in western Greenland where derived accumulation is most correlated with NAO. However, we also identify a region further inland to the east and south where the estimated strength of the linear accumulation-NAO relationship is weaker, but more certain, than in the previously identified region. Thus, our findings can be used to guide decisions regarding where to locate future drilling efforts in Greenland by weighing the trade-off between the potential strength of the accumulation-NAO relationship and its uncertainty.

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1. Introduction

[2] In this paper, we propose a novel Bayesian hierarchical statistical model for exploring spatial variation in the relationship between the North Atlantic Oscillation (NAO), an important climatic phenomenon discussed below, and net annual accumulation across Greenland. This approach allows us to synthesize a large number of ice core-derived accumulation records in order to identify regional patterns in the strength of the accumulation-NAO relationship. As a result, inferences derived from our statistical model can be helpful when selecting specific ice core records to be used for NAO reconstruction and sites for future ice core drilling efforts.

[3] NAO refers to temporal changes in the atmospheric pressure differences between the region of low sea level pressure (SLP) near Iceland and the region of higher SLP in the subtropics. Changes in the strength of this meridional pressure dipole affect the zonal winds across the North Atlantic Ocean and the effects are felt throughout Europe and parts of Greenland [*Hurrell*, 1995]. NAO variability is also linked to changes in storm tracks [*Rogers and van Loon*, 1979; *Hurrell et al.*, 2003], cyclone activity [*Rogers*, 1990; *Serreze et al.*, 1997], precipitation patterns [*Bromwich et al.*, 1999] and sea ice extent [*Deser et al.*, 2000]. As a result, knowledge of the historical behavior of this system provides a context for understanding the implications of current and future climatic trends. NAO is characterized by an index derived as the difference in the mean monthly surface pressure anomalies between Iceland and the Azores. Various meteorological records have been used to construct NAO indexes [*Rogers*, 1984; *Hurrell*, 1995; *Jones et al.*, 1997; *Vinther et al.*, 2003a]. In addition, there have been several attempts to extend NAO indexes further into the past by substituting various climate proxies (e.g., tree rings, corals, ice cores) for the unavailable meteorological records [*Appenzeller et al.*, 1998a, 1998b; *Cook*, 2003, and references therein; *Vinther et al.*, 2003b; *Mosley-Thompson et al.*, 2005, and references therein].

[4] Since precipitation over Greenland is modulated by the NAO, ice core-derived accumulation records from Greenland have been proposed as potential proxies for use in NAO reconstructions. Such records are available for a number of locations throughout Greenland. Some of the

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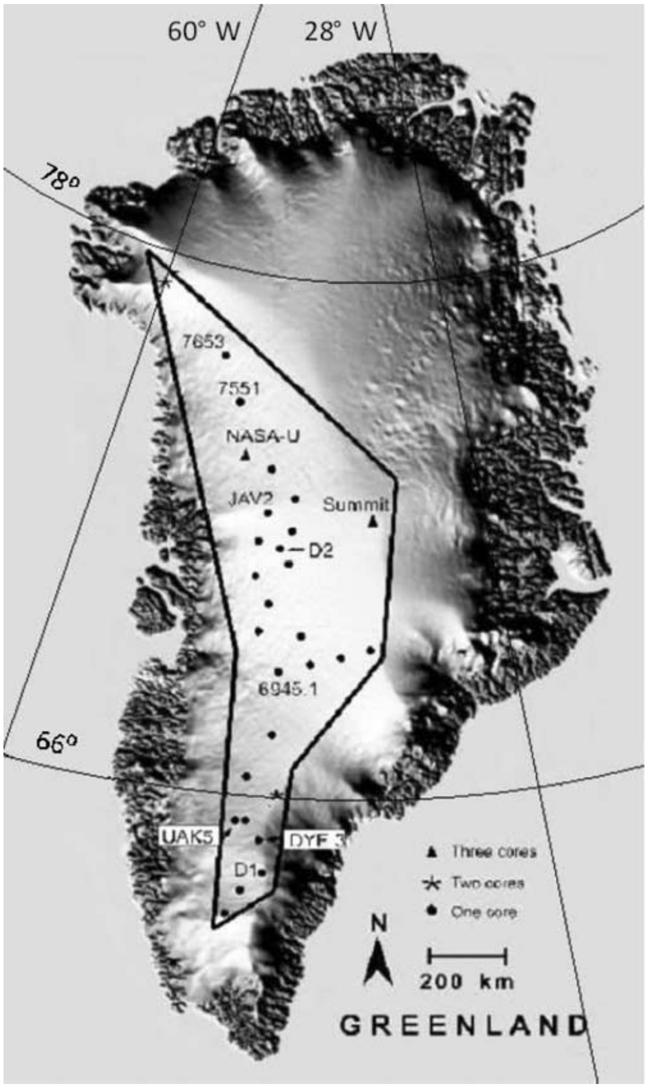

Figure 1. Map of Greenland showing the sites where the cores used in this study were drilled. The Summit region includes three different cores (T2, T5 and GISP2). The black line delineates our study region.

older records (e.g., from Dye 3, see Figure 1) or records derived from cores located in central Greenland have been used for NAO reconstruction, with limited success. On the basis of an analysis of precipitation predicted using the ECMWF ERA-15 reanalysis (http://www.ecmwf.int/research/era/Project/index.html), [*Appenzeller et al.*, 1998a] demonstrated that the strongest correlation (negative) between precipitation and NAO is in the region west of central Greenland. Subsequent work [*Appenzeller et al.*, 1998b] found that the ice core-derived accumulation record from a PARCA (Program for Arctic Regional Climate Assessment) core located in western Greenland (NASA-U, see Figure 1) is more highly correlated with NAO than a composite accumulation record constructed from five cores drilled in the central Greenland (summit) region. Expanding on this finding, [*Mosley-Thompson et al.*, 2005] used five additional PARCA cores located across western Greenland to further explore the spatial and temporal variation in the correlation between derived annual accumulation and NAO. Their analysis demonstrated that the relationship between NAO and accumulation has changed over time, especially as recorded at higher-latitude sites. However, despite these changes, the correlation between NAO and precipitation consistently remains strongest for ice cores drilled in western Greenland.

[5] A limitation of previous attempts to characterize the spatial variation in the relationship between NAO and precipitation over Greenland is that regional patterns were assessed on a site-by-site basis by examining inferences derived from single-core analyses. In these studies, the correlation between NAO and accumulation was computed at each site and then the variation in these single-site correlations over space was interpreted. The fact that NAO and accumulation were correlated at each site does not easily permit formal statistical inferences to be made about spatial patterns in the accumulation-NAO relationship. For example, it is not possible to assess whether the correlation between NAO and accumulation a region, as opposed to at one site, is statistically significant. Another limitation of this approach is that shorter ice cores must be excluded from the analysis since, taken separately, they contain little information. However, given the large number of shorter records available, it is worthwhile to explore whether they can be used in conjunction with the longer records to provide a more detailed description of the spatial patterns in the accumulation-NAO relationship.

[6] Here, we explore the spatially varying relationship between ice core-derived net annual accumulation and NAO using a Bayesian hierarchical model. Our statistical model provides a mechanism for synthesizing the various accumulation records recovered across Greenland in a manner that accommodates the spatial dependence inherent in the accumulation process. Inferences regarding the strength of the linear association between NAO and accumulation at each location are derived using all cores collected at, or near the location of interest. In addition, our Bayesian model readily provides information about the spatial variation in the uncertainty in the accumulation-NAO relationship arising from the differing spatial and temporal coverage of the available ice core records.

[7] We describe the data used in our analysis in section 2. Then, in section 3, we develop a Bayesian hierarchical regression model for exploring the spatial variation in annual accumulation-NAO relationship and present summaries of our inferences in section 4. We conclude with a discussion of our results and propose directions for future research in section 5.

2. Data

[8] In our study, we use an annual (January to December) NAO index [*Hurrell*, 1995], that was obtained from http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#naostatann. This index dates back to 1865 and was constructed from normalized sea level pressures (SLP) between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland.

[9] In addition, we use records of net annual mass accumulation (henceforth annual accumulation) derived from 35 firn and ice cores (henceforth cores), most of which were collected in western and southern Greenland