ICE CORES AND THE ATMOSPHERE: IMPROVING ICE-CORE INTERPRETATION THROUGH INTENSIVE STUDY OF WEST ANTARCTIC METEOROLOGY

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1. Introduction
The fundamental postulate of ice-core-based paleoclimate research is that a (probably) non-linear but decipherable relationship exists between the large-scale atmospheric circulation that supplies geochemical tracers and moisture to an ice sheet and paleoclimatic proxy records recovered from ice cores and snow pits. Thus, understanding the meteorology and large-scale circulation in West Antarctica becomes a key prerequisite to improving our knowledge of climate change in this region. In current practice, many different ice-core proxies are interpreted as reflections of changes in atmospheric circulation, but with some uncertainty regarding the mechanisms.

Numerous process studies (e.g., Bergin et al. 1995; Dibb and Jaffrezo 1997; Minikin et al. 1998; Sommer et al. 2000; Wåhlin 1996) have been performed to examine the atmosphere-proxy relationship. However, this work has tended to emphasize specific details of the air-snow transfer process, with a focus on Greenland over Antarctica, rather than relating detailed meteorology to the proxy records. The exceptions to this (e.g., Bromwich and Rogers 2000; Kreutz et al. 1999) have yielded important pointers to what might be possible with an improved understanding of the meteorology.

The Antarctic First Regional Observing Study of the Troposphere (FROST) Project (Turner et al. 1999) has shown the utility of focused meteorological observing campaigns. An extended campaign modeled after FROST and focusing on West Antarctica will bring distinct benefits to the meteorological community studying this region. The benefits could be even larger if the meteorological needs of the ice coring community are also considered.

2. Motivation
2.1 Climate Change and Proxy Records
Natural and human-caused climate change are widely acknowledged to be of great societal importance. Advances in our knowledge of the climate system under the auspices of groups such as the U.S. Global Change Research Program (USGCRP), the International Geosphere-Biosphere Programme (IGBP), and the World Climate Research Programmes (WCRP) have been remarkable. Yet the global climate system is inherently complex and the details of its functioning remain poorly understood. This ignorance is due in part to our lack of long-term climate records (e.g., Duplessy and Overpeck 1996). Direct observational and instrumental records are limited both spatially and temporally, extending back approximately 200 years in the Northern Hemisphere and only 30-40 years in the Antarctic, not long enough to characterize natural variability. A vital element of climate-change research thus becomes the development of proxy records of climate variables that can be related to modern observable data. These paleoclimate records from ice cores, ocean and lake sediments, tree rings, and other sources, extend our knowledge both deeper into time and into new spatial regions.

2.2 Ice Cores As Paleoclimate Proxies
Ice cores have been a particularly rich source of paleoclimate proxy data in recent years, providing many new insights into climate from the present back through the last interglacial (ca. 120,000 years ago) and beyond. Ice cores provide information on local climate (snowfall and temperature at a site), regional climate (wind-blown dust, sea-salt, and other materials from beyond the ice sheet), climate in broader regions (through trapped-gas records of carbon dioxide, methane, nitrous oxide and other gases), and even conditions beyond the Earth (concentrations of extraterrestrial dust and cosmogenic isotopes). Ice cores have documented the close tie between greenhouse-gas concentrations and temperature over glacial-interglacial cycles, the common existence of larger, more-rapid climate changes in the past than any experienced by industrial or agricultural humans, and even clean-up of some human-caused pollution (such as the fall of lead concentrations in Greenland snow as the United States phased in unleaded gasoline during the 1970’s) (Ice Core Working Group 1998; Sherrell et al. 2000). Global anthropogenic change from biomass burning during the 19th century agricultural revolution has been seen in ice-core records of NH4+, CO2 and black carbon (soot).
(Holdsworth et al. 1996). Data from the Greenland ice sheet have provided a unique view of atmospheric circulation and chemistry in the northern hemisphere (e.g., Mayewski et al. 1997; O'Brien et al. 1995). Similar work in the Antarctic has shown both the high variability of this region (Reusch et al. 1999) and provided insight into the global nature of the Little Ice Age (Kreutz et al. 1997). The data from the polar regions are also valuable because these areas are usually thought to be more sensitive to climate change (due to ice-albedo feedback effects) than temperate and tropical areas (Peixoto and Oort 1992) and can thus provide unique records of climate.

2.3 West Antarctic Ice Core Interpretation Issues

Ice-core data provide windows on past climates that are critical in understanding and eventually predicting the climate system. Major U.S. efforts are devoted to understanding the time and space variability of climate using West Antarctic ice-core data under the auspices of U.S. ITASE (International Trans-Antarctic Scientific Expedition), WAIS (the West Antarctic Ice Sheet Initiative) and WAISCORES (the WAIS deep ice core project), with important logistical and research investments (Kreutz and Mayewski 1999; U.S. ITASE Steering Committee 1996; WAIS Committee 1995).

Early ice-core data from West Antarctica show large spatial and temporal variability (e.g., Reusch et al. 1999). The "traditional" analysis path, in which ice-core data are examined (by inspection, or by statistical tools including time-series analysis) for relations to possible forcing functions, leaves much of the variance "unexplained". Techniques such as principal component analysis have been successful in identifying the dominant relationships in multivariate data sets, but significant interpretation of the results is still required and identification of noise effects remains subjective.

Some of this unexplained variance is undoubtedly "noise" arising from depositional processes such as snow drifting; however, evidence reviewed below suggests that much of this complexity records the important climatic processes, related to the El Niño-Southern Oscillation (ENSO), position of the Amundsen Sea Low, etc., that these projects seek to interpret. Extracting the signal from the noise is thus central to the success of U.S. ITASE and WAISCORES, and will require analytical tools in addition to those used in previously successful projects such as GISP2.

3. Why West Antarctica is of Interest

3.1 The Importance of West Antarctica

Antarctica plays a vital role in dynamic linkages connecting the complex components of the global climate system (e.g., atmosphere, cryosphere, hydrosphere) (U.S. ITASE Steering Committee 1996). West Antarctica, in particular, may be the most climatologically and glaciologically dynamic area of the continent (WAIS Committee 1995). This sector receives about 40% of the moisture transported into the continent (Bromwich 1988) and has the Antarctic's highest interannual variability, possibly due to an El Niño-Southern Oscillation (ENSO) connection (Bromwich and Rogers 2000; Bromwich et al. 2000; Cullather et al. 1996; Genton and Krinner 1998). Satellite observations indicate that meridional moisture transport is primarily poleward through the Bellingshausen and Amundsen Sea sectors and equatorward in the Weddell Sea sector (Slonaker and Van Woert 1999). Yet the scarcity of climate records keeps this region relatively poorly understood.

Evidence from instrumental records indicates that different parts of the continent are affected by separate components of the atmospheric circulation (U.S. ITASE Steering Committee 1996). The high interior plateau is largely influenced by vertical transport from the upper troposphere and stratosphere. The remainder of the continent is connected more to lower tropospheric transport, such as the cyclonic systems around Antarctica that often move southward over the ice sheet. Central West Antarctica, in particular, is strongly influenced by warm air advecting southward and upslope onto the polar plateau bringing higher concentrations of marine aerosols and a significant amount of the moisture transported to this region (Bromwich 1988; Hogan 1997).

3.2 Meteorology/Climatology Highlights

Thorough introductions to Antarctic meteorology and climatology already include Schwerdtfeger (1984) and King and Turner (1997). Bromwich and Stearns (1993) provides a summary of automatic weather station-based research and an example of the utility of AWS data for short-term forecasting has recently been documented in Holmes et al. (2000). Here a brief overview of some of the more compelling recent results from climate models, from studies of numerical reanalysis data sets (e.g., the European Centre for Medium-Range Weather Forecasts (ECMWF)), and from AWS data sets demonstrates the
importance of West Antarctica in the global climate. Evidence of links to lower latitudes has been discovered in the correlation found between ENSO and moisture convergence in a sector (120° W to 180°, 75° to 90° S) of West Antarctica (Cullather et al. 1996). A study of ECMWF data showed that moisture convergence correlates well with the Southern Oscillation Index (SOI), particularly for the period 1980-90. The nature of this teleconnection to tropical latitudes is unclear and its existence is still debated (Bromwich and Rogers 2000; Bromwich et al. 2000; Genthon and Krinner 1998; Rogers et al. 1999). It may relate to changes in the Amundsen Sea Low as well as other changes in atmospheric circulation over the Antarctic plateau. The SOI also correlates well with deuterium isotopes at Siple Dome (Bromwich et al. 2000). Links such as these help to interpret the ENSO signals being found in Antarctic proxy records (e.g., Legrand and Feniet-Saigne 1991) as well as aid in regional seasonal weather forecasting (Carleton 2000). Another link between the Amundsen Sea Low and West Antarctic climatology appears in glaciochemical records from Siple Dome. In this case, variability in the strength of the low was found to correlate with variability in seasalt concentrations (Kreutz et al. 1999). A link from south to north is seen in the effect atmospheric circulation over Antarctica has on lower latitudes through dramatic seasonal changes in mass balance of the atmosphere (Parish and Bromwich 1997). Variability in the high-pressure system over the plateau results in atmospheric mass transfers over the entire continent with resulting influences on meridional circulation in the southern hemisphere.

3.3 High Spatial Variability
The spatial variability of West Antarctic climate as seen through indicators such as the major ion chemistry and accumulation rates measured in ice cores is high (Reusch et al. 1999). Basic tools such as visual comparisons and linear correlations tell us only that the time series vary widely between sites only ~50 km apart. Higher order tools, such as principal component analysis (PCA), can bring out patterns of coherent overall behavior of species such as seasalt and nssSO4, but they only give an outline of the complete picture at best. A gap remains between the direct record in the ice, which is highly spatially variable, and the PCA results (Reusch et al. 1999). To bridge this gap and to go beyond climatological approaches (e.g., 40 year averages) requires new tools to be developed. Such tools will be essential to extracting all available information from the WAISCORES inland deep core and the U.S. ITASE traverse cores over the coming years.

4. Improving the proxy calibrations
Our ongoing research into improving the calibration of ice-core-based proxies to climate involves two different applications of artificial neural networks (ANNs), one in progress, one planned. ANNs are a powerful nonlinear tool used in, for example, pattern recognition and time series prediction. Numerous sources exist for further information, such as Gardner and Dorling (1998) and Haykin (1999).

4.1 Automatic Weather Station Records
The ANN-based project currently underway (using variants of the multi-layer feed-forward ANN) is attempting to improve the existing database of automatic weather station (AWS) records in West Antarctica. AWS currently provide the only year-round, continuous direct measurements of weather on the ice sheet. As the spatial coverage of the network has expanded year to year, so has our meteorological database. Unfortunately, many of the records are relatively short (less than 10 years) and/or incomplete (to varying degrees) due to the vagaries of the harsh environment. This reduces the usefulness of these data sets, though much has been learned using the AWS data despite these shortcomings (e.g., Bromwich and Stearns 1993; Holmes et al. 2000; Shuman and Stearns 2001). Climate downscaling results from work in temperate latitudes (e.g., Cavazos 1999; Crane and Hewitson 1998; Hastenrath et al. 1995) suggest it is possible to use GCM-scale meteorological data sets (e.g., ECMWF reanalysis products) with ANNs to both fill gaps in the AWS records and extend them back in time to create a uniform and complete database of West Antarctic surface meteorology (at AWS sites). Such records are highly relevant to the improved interpretation of the expanding library of snow-pit and ice-core data sets.

The focus to date has been on Ferrell AWS (77.91° S, 170.82° E), in part because it has one of the longest available records. We use one year of available AWS observations to train an ANN to predict the AWS near-surface temperature and pressure from nearby ECMWF grid point variables (e.g., 500 mbar geopotential height). This intrayear prediction (of observations in the training year) has been very successful (e.g., RMS errors < 2 mbar for pressure). Interyear prediction (of observations from years not in the training set) remains a work-in-progress (e.g., RMS errors are 4-5 mbar).
Figure 1 shows a preliminary reconstruction of Ferrell pressure for the ECMWF period (1979-1993). ANN predictions have been merged with AWS observations to produce a 15-year record. Error bars derive from RMS errors from predictions against available observations. Two full years have been added at the beginning and numerous gaps (some quite long) have been filled. Temperature predictions have not been as successful so far, likely due to the greater complexity of controls on this variable (and higher spatial variability).

Three different ANN architectures have produced similar predictive skill suggesting that our approach is valid but our training methodology needs refinement. Many possibilities exist, among them exploring different predictors, adding time lags, and using features extracted from the GCM data as predictors instead of the data itself (e.g., using principal component analysis results). Additionally, improved GCM- and meso-scale models (thanks, in part, to more extensive data on local and regional meteorology), should also provide improved predictors for further ANN-based prediction.

4.2 **Circulation Feature Extraction**

The second ANN-based project, expected to begin soon, will use self-organizing maps (SOMs) (Kohonen 1990; Kohonen 1995) to extract features of the general regional circulation that can be compared to the recent ice core record. SOM analysis has been called a nonlinear analog of traditional cluster analysis in that the process can identify (physically) related subsets of the data with the advantage of being an unsupervised process requiring no prior specification of categories. (However, this is an imperfect analogy.) Further information on SOMs and their applications in meteorology may be found in Cavazos (2000).
5. Summary

Increasing our knowledge of present-day weather and climate in West Antarctica will bring benefits to both the meteorological and the paleoclimate communities. A deepened observational data set will provide more ground truth for proxy calibrations and will help to improve our forecasting models. Better models, in turn, will provide higher confidence data for those times and places where observational data remain unavailable. ANN-based predictions of missing AWS observations will also advance with better model-derived predictors.

There is no doubt that we have learned a great deal from ice-core-based paleoclimate proxies. There is also little doubt that our interpretations would improve with a better understanding of present-day weather and climate in West Antarctica.

References


Carleton, A. M., 2000: ENSO Teleconnections with Antarctica. Antarctic Weather Forecasting Workshop, Columbus, OH, Byrd Polar Research Center, The Ohio State University, 79-82.

Cavazos, T., 1999: Large-scale circulation anomalies conducive to extreme events and simulation of daily rainfall in northeastern Mexico and southeastern Texas. Journal of Climate, 12, 1506-1523.


Atmospheric and Space Science Series, Cambridge University, 409 pp.