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APPLICATIONS OF NEURAL NETWORKS IN WEST ANTARCTIC METEOROLOGY AND CLIMATOLOGY

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Joint interpretation of surface-based meteorological and forecast reanalysis data from West Antarctica using a suite of nonlinear tools provides an improved climatology for this poorly known region and reveals important changes in spatial coherency between inland and ice-shelf sites

1. INTRODUCTION

A deeper understanding of regional meteorology in the Antarctic is required for improved interpretations of the ever-growing body of ice-core-based paleoclimate records from this region. Benefits would also accrue in related areas such as operational forecasting at McMurdo and global change research. Artificial neural network (ANN) techniques offer new approaches to improving our record of surface observations and our understanding of the regional atmospheric circulation, two keys to this important problem.

Apart from a small number of mostly coastal manned stations, the only source of continuous, direct measurements of near-surface weather on the West Antarctic ice sheet and Ross Ice Shelf is the network of automatic weather stations (AWS) managed by the University of Wisconsin-Madison and begun in 1980. Unfortunately, the AWS are widely and non-uniformly distributed, record only a few basic measurements, and are subject to instrument failures that may go for months without repair due to limited opportunities for service. The records are also relatively short with many stations in place only since the late 1980's/early 1990's. This makes it difficult to use these highly valuable records for comprehensive climatological studies. Recent work with ANN-based methods has shown a way around some of these problems.

With 6-hourly GCM-scale upper air data from the ECMWF 15-year reanalysis (ERA-15) as predictors (e.g., 500 mb geopotential height, 850 mb temperature advection) and the available AWS temperature and pressure data as targets, multilayer feed-forward ANNs were trained to predict the missing AWS observations from the forecast data (Reusch and Alley, 2002). Using this technique, we have developed complete 15-year temperature and pressure records (1979-93) for six West Antarctic AWS: Siple, Byrd, Lettau, Marilyn, Elaine and Ferrell (Figure 1, Table 1). Errors for temperature prediction are approximately equal to those from a satellite-based methodology but with no exposure to problems from surface melt events or sensor changes (Reusch and Alley, 2002; Shuman and Stearns, 2001).

With complete 15-year records from six sites covering ~90° of longitude, it is credible to do detailed climatological studies of, for example, interannual and spatial variability. The spatial pattern of temperature anomalies and principal component analysis suggests significant differences both between the ice shelf and ice sheet sites and between the two ice sheet sites. The records also allow us to put these AWS sites into context with respect to ENSO.

Self-organizing maps (SOMs), a second ANN technique, have proved useful for analysis of synoptic-scale circulation in temperate latitudes (Hewitson and Crane, 2002). The use of SOMs allows development of synoptic climatologies with an arbitrary number of smoothly transitioning climate states, in contrast to traditional synoptic classification techniques. Results from SOM analyses are applicable both to the ice-core interpretation problem and to studies of global change. SOM-derived maps of synoptic variables such as 700 mb temperature and geopotential height can be compared to ice core data to examine the relationship

Table 1. AWS Locations

Station	Latitude	Longitude	Elevation (m)	Date Installed	Distance[1] (km)
Byrd	80.01° S	119.40° W	1530	February 1980	11.5
Elaine	83.13° S	174.17° E	60	January 1986	71
Ferrell	77.91° S	170.82° E	45	December 1980	49.5
Lettau	82.52° S	174.45° W	55	January 1986	8.3
Marilyn	79.95° S	165.13° E	75	January 1987	6.1
Siple	75.90° S	84.00° W	1054	January 1982[2]	103.9

1. Distance to the nearest ERA-15 gridpoint.
2. Siple AWS was removed in April 1992.

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between the proxy and the atmosphere. Climate change can be studied by looking at how state transitions evolve over time. We anticipate new insights and improved ice-core interpretations from application of SOMs to the West Antarctic atmosphere.

Predictive ANNs can also be used to directly relate the atmosphere to the ice core proxies by training the ANN to predict ice core data from atmospheric data. The relative contributions of each predictor can provide new insight to the atmosphere-ice core relationship. This is an area of ongoing and future research.

2. METHODOLOGY

2.1 *Data*

Automatic Weather Station Data: The main source of direct meteorological data in West Antarctica is the network of AWS maintained by the University of Wisconsin-Madison since 1980 (Lazzara, 2000). All stations provide air temperature and pressure, wind speed and direction; some stations also have relative humidity and the 3.0-0.5 m (above nominal snow surface) temperature difference. Data were selected to match ECMWF time-steps from the three hourly quality-controlled archive for each AWS. Two geographic categories are present (Figure 1): ice sheet (Byrd and Siple, 1000 m above sea level or higher) and Ross Ice Shelf (the rest, less than 100 m above sea level). All sites in this study are within the south/southeast Pacific sector of West Antarctica (Table 1).

Gridded Meteorological Data: ERA-15 is our source for GCM-scale meteorological data at 2.5° horizontal resolution for the period 1979-1993 (ECMWF, 2000). Potential problems have been noted with the ECMWF (re)analysis data over Antarctica, stemming in part from the flawed surface elevations used in these models (Genthon and Braun, 1995). Elevation errors exceeding 1000 m exist in some areas of Queen Maud Land and the Antarctic Peninsula (e.g., Figure 3, Genthon and Braun, 1995). Topography in West Antarctica is generally better but errors from outside our study area will still have an influence on the reanalysis data. There are also issues related to the treatment of the Ross Ice Shelf as seasonal sea ice rather than ~500 m thick floating ice. Nonetheless, evaluations of several operational products (e.g., 1998; Bromwich et al., 1995; 2000; Cullather et al., 1998) suggest that the ECMWF analyses are still the best available data sets for Antarctica despite these issues.

Ice-core Data: Four shallow cores from central West Antarctica (Reusch et al., 1999) provided high-resolution glaciochemical and annual accumulation data for comparison with the ERA-15 data. Each core was originally sampled at high resolution (continuously every 3 cm or 10-12 samples per year) to capture the annual signals in the major soluble ions of atmospheric chemistry: Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^- and SO_4^{2-}. Annual averages of the chemistry time series were created for this study. See Reusch et al. (1999) for full details of methodology and dating.

2.2 *Artificial Neural Networks*

At the simplest level, artificial neural networks (ANNs) are a computer-based problem solving tool inspired by the original, biological neural network – the brain. Because of their ability to generate non-linear mappings during training, ANNs are particularly well-suited to complex, real-world problems such as understanding climate (Elsner and Tsonis, 1992; Tarassenko, 1998). Meteorological examples include an improved understanding of controls on precipitation in southern Mexico (Hewitson and Crane, 1994), prediction of summer rainfall over South Africa (Hastenrath et al., 1995) and northeast Brazil (Hastenrath and Greischar, 1993), and extreme event analysis in the Texas/Mexico border region (Cavazos, 1999).

The ANN-based methodology used to develop the records for the six AWS sites is essentially the same as described in Reusch and Alley (2002). Two refinements (using more input data and adding insolation as a predictor) were tried but had no appreciable affect on predictive skill. Due to different elevations (Table 1), the same pressure levels could not be used at all six sites, but this did not affect the ANN training methodology. We have used the MATLAB® Neural Network Toolbox (Demuth and Beale, 2000; Haykin, 1999) for the AWS predictions.

Three ERA-15 variables from the middle troposphere (700 mb) were used in the SOM-based analyses: temperature (T), geopotential height (Z) and specific humidity (q). The analyses required that the ERA-15 data first be resampled to an equal area grid. We used both 250 km and 125 km versions of the National Snow and Ice Data Center EASE-Grid (Armstrong and Brodzik, 1995). Grid-scale means and standard deviations were then calculated on annual, semiannual and seasonal time-scales for each variable from the regridded data. Because T, Z and q have widely different mean values, each variable was standardized to avoid scale problems in the SOM. The SOM analyses were then performed on the six variables (mean and standard deviation of T, Z and q) combined using SOM-PAK software (Kohonen et al., 1996). Each SOM analysis produces a classification of input records (calendar years) grouped by the similarity of their meteorological data (with one or more years per group). AWS and ice core data from each group were then compared for similarity within and differences between groups and as a predictor for the SOM classification.

3. RESULTS

3.1 *Seasonal Anomalies*

Seasonal temperature anomalies can be quite large and range from –6.1 °C up to 7.8 °C (Figure 2). The extreme minima tend to occur in fall while extreme maxima occur in winter (thus creating an issue for annual anomaly calculations). The 1980 annual warm anomaly is predominantly due to abnormal warmth in the austral winter of that year with additional contributions from a warm fall. The evolution of this anomaly is fairly similar at all sites. The 1988 annual warm anomaly is also related to abnormal winter warmth but in this case the additional contributions come from a warm spring. Only Siple does not show a strong warm anomaly in this timeframe. The four ice shelf sites also have a strong single-season (fall) warm anomaly in 1983. It does not appear in the annual anomalies due to cold anomaly offsets in other seasons. Cold anomalies appear at all sites in fall (1982, 1987 – weak at Ferrell), winter (1986), and spring (1981 – weak at Byrd, 1986 – except Siple). The ice sheet sites and Marilyn also have cold anomalies in summer 1981 and winter 1983. Thus the 1982 annual cold anomaly appears to be at both the ice shelf and ice sheet sites but is hidden at the latter by offsetting warm/neutral seasons. In contrast, the 1983 ice sheet annual cold anomaly is distinct and only present at those sites. This implies different behaviors, with respect to temperature, between the ice sheet and ice shelf sites. Marilyn also appears to have characteristics of both domains (also suggested by the ERA-15 prediction statistics).

3.2 *Trends and Correlations*

A thorough linear regression analysis of the complete temperature time series, including sliding windows of varying lengths, reveals essentially no statistically significant trends at all six sites. (Statistical significance based on α=0.05 confidence intervals.) Lettau does have a warming trend (0.06 °C/yr) in 6-hourly data but it disappears over longer averaging periods. When subannual periods are examined on a year-to-year basis (e.g., winter-to-winter), statistically significant warming trends appear at three sites during the austral summer season. Siple, Lettau and Marilyn have summer season warming trends of 0.18-0.25 °C/yr. At monthly resolution, warming is present in January at all 3 sites (0.25-0.27 °C/yr) but only at Siple and Marilyn in December (0.27 and 0.3 °C/yr) and February (0.14 and 0.26 °C/yr). Marilyn also shows warming in October and November (0.31 and 0.48 °C/yr, respectively). The explanation for the directions and locations of these trends remains speculative. The distance between Siple and the two ice shelf sites (1777 and 2221 km for Lettau and Marilyn, respectively) and the lack of a trend at Byrd suggests there may be two processes involved. And while Lettau and Marilyn are both on the Ross Ice Shelf, they are ~ 450 km apart and in potentially quite different geographical conditions. Regardless of a satisfying physical explanation, it appears that summer temperatures are increasing over time at three distinct West Antarctic AWS sites.

Inter-site correlation analysis, also performed over a variety of sliding window sizes, yielded a time and space varying pattern of coherence. At the yearly level, there is a general downward trend in the number of significant correlations in almost all comparisons of temperature. With interseasonal data, Siple and Byrd are disconnected from the ice shelf sites and each other during summer and to varying degrees in the other seasons. Siple also separates from Byrd in the spring.

There are hints of a behavioral difference between the early (1980's) and later (1990's) portions of the records but distinct change points remain elusive. Correlations appear to degrade as more later-record data is included in sliding windows but the change is quite gradual.

3.3 *Multivariate Analysis*

Principal component analysis (PCA) of the joined temperature records readily shows the dominance of the annual cycle (nearly 80% of the variance is found in the first component, PC1). A PCA after removing the annual cycle has two significant components with 51% and 17% of the variance, respectively. The ice shelf sites are most influenced in PC1 with 60-65% of their variance. PC1 also affects the ice sheet sites to a lesser extent (Siple at 20% and Byrd at 35%). PC2 is dominated by the ice sheet sites suggesting a separate behavior for Siple and Byrd relative to the ice shelf sites. This may be related to a differing ENSO influence between the ice sheet and Ross Ice Shelf.

PCA of the joined pressure records (annual cycle removed) also has two significant components. In this case, PC1 has nearly 80% of the variance. Byrd (70%) joins the ice shelf sites (86-94%) in PC1 with a smaller loading on Siple(35%). PC2 (15%) is dominated by Siple (58%) and some influence from Byrd (16%). Siple thus appears to behave somewhat differently for pressure. Otherwise, the pressure pattern resembles the associations seen in the temperature PCA.

3.4 *Preliminary SOM Results*

Early results from SOM analysis of annually, semi-annually and seasonally averaged 700 mb geopotential height, temperature and relative humidity are promising. In general, geopotential height maps show expected features (e.g., the climatological low in the Amundsen Sea region) and significant changes on interannual and interseasonal timescales. The 1980 and 1988 warm anomalies identified in the AWS records are seen as a part of a distinct synoptic state with a significant warm anomaly over nearly the whole of West Antarctica. Attempts to predict the SOM classifications from the corresponding AWS and ice core data using small ANNs have been quite successful. Unfortunately, the limited amount of input data makes it difficult to assess the validity of these predictions. Further work will attempt to address this problem. We also plan to continue studying the relationships between the SOM-based climatology and the AWS and ice-core data. As the methodology matures, we plan to add new ice core data sets (e.g., Siple Dome) to the analysis.

4. SUMMARY

ANNs provide a potentially powerful tool for repairing and extending the AWS surface meterological record in West Antarctica. They also offer a new way to study the synoptic climatology and investigate how it relates to the ice core proxy record. Results from the AWS work have been encouraging in many respects and a full analysis of these records will be even more rewarding. Early results from the SOM-based work are promising as well. The potential benefits to the ice coring community towards improved interpretations of paleoclimate proxies are but one reason of many to continue.

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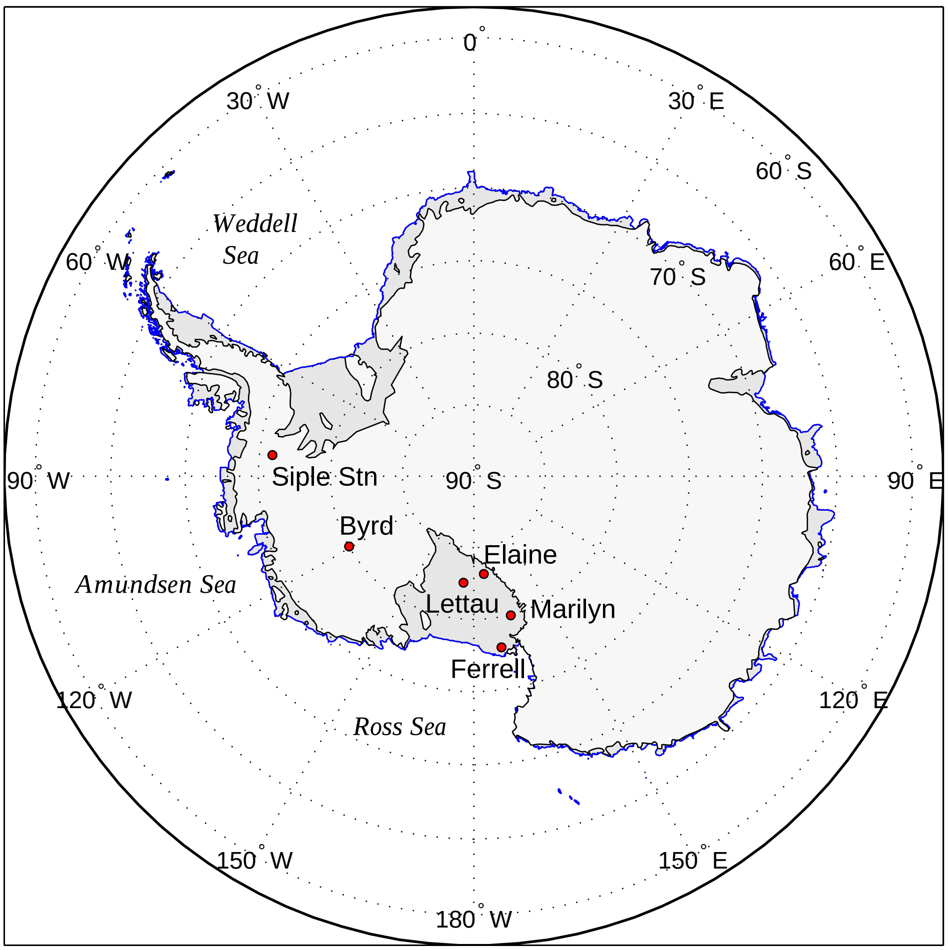

Figure 1. AWS sites of this study. Exact site coordinates, elevations and history are presented in Table 1. Fifteen year (1979-1993) temperature and pressure records for each site were created with the assistance of artificial neural network-based methods.

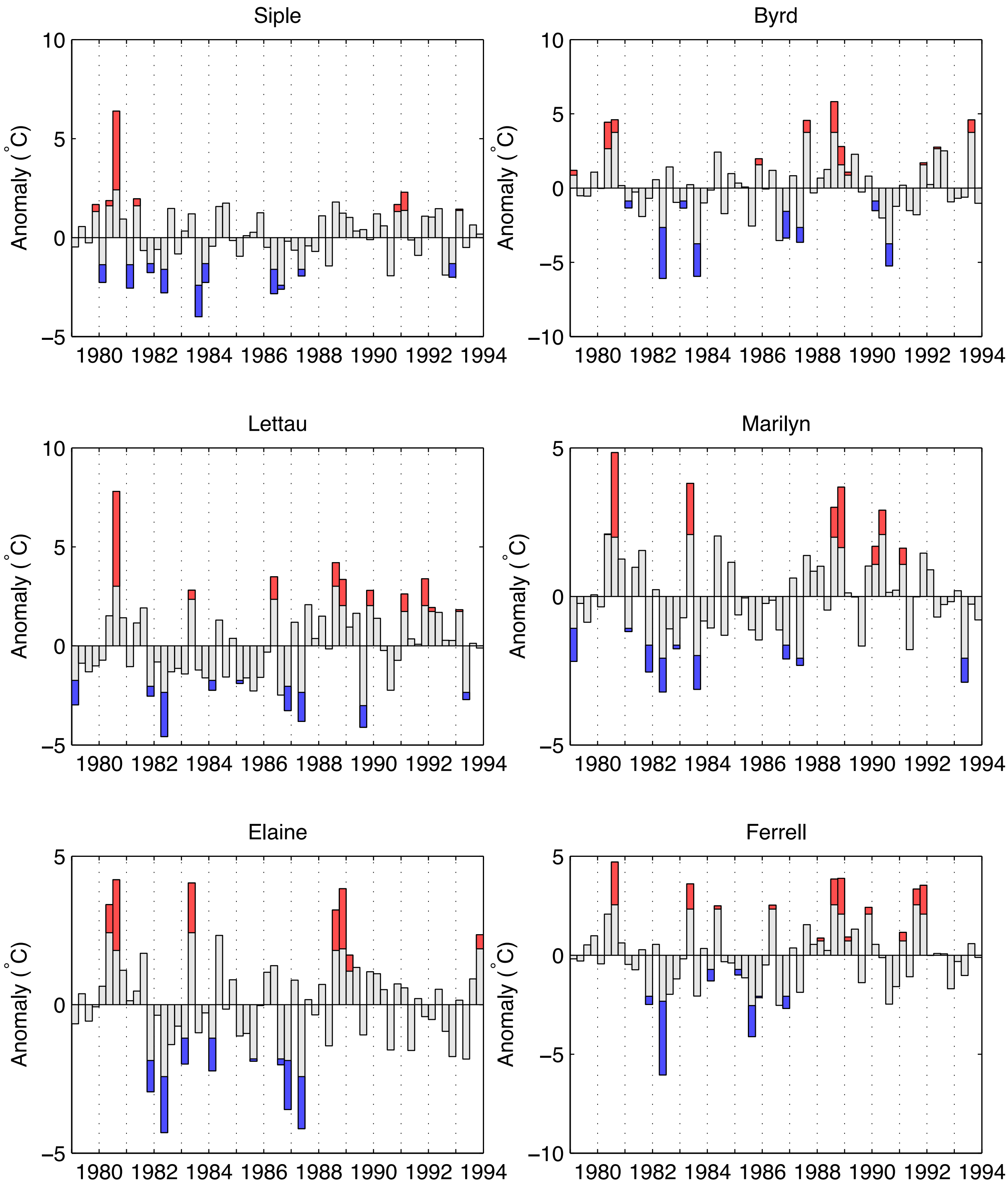

Figure 2. Seasonal temperature anomalies by site. Temperatures more than one standard deviation for the season are shown in red and blue for warm and cold anomalies, respectively. Each year is made up of the four austral seasons in the order summer, fall, winter and spring.