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MODELING THE ENSO MODULATION OF ANTARCTIC CLIMATE IN THE LATE 1990S WITH POLAR MM5

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1. INTRODUCTION

Perhaps the most well known signal of climate variability is the El Niño-Southern Oscillation (ENSO), a pattern of warm and cold sea-surface temperature (SST) anomalies in the central and eastern equatorial Pacific with coupled atmospheric changes. The atmospheric component is monitored by the normalized pressure difference between Tahiti (17.6^o S, 149.6^o W) and Darwin (12.4^o S, 130.9^o E) that is called the Southern Oscillation Index (SOI). In recent years, the relationship between ENSO and Antarctica has become a topic of intense research as scientists try to understand the surprising, and occasionally conflicting, climate changes taking place.

Vaughan et al. (2001) remind us that our current knowledge of the mechanisms and spatial distribution of climate change is limited, and we can only predict *large-scale* variations with some degree of confidence. It is important that we first expand our knowledge at the regional scale in order to truly understand global signals. It is desirable to model the atmosphere with higher spatial and temporal variability than is currently obtained with analyses and reanalyses products and general circulation models. In the high latitudes, this will allow the proper representation of processes over and around polar ice sheets (e.g., ice crystals in clouds, sea ice thermodynamics, katabatic winds).

Here, simulations from the Polar MM5 are used to examine interannual variability over the Antarctic for 3 years in the late 1990s (July 1996-June 1999). The Polar MM5 is a version of the Pennsylvania State University / National Center for Atmospheric Research (NCAR) fifth generation mesoscale model (Grell et al. 1994), adapted by the Polar Meteorology Group at the Byrd Polar Research Center for high-latitude applications (e.g., Bromwich et al. 2001, Cassano et al. 2001). This period is chosen because it spans a strong El Niño episode (negative SOI; ~Mar 1997-June 1998) followed by a moderate La Niña (positive SOI; ~July 1998-June 1999). For convenience, henceforth, "El Niño" refers to July 1997-June 1998 and "La Niña" refers to the July 1998-June 1999. The model has demonstrated good skill in extensive validations over Greenland and Antarctica (Cassano et al. 2001, Bromwich et al. 2001, Guo et al. 2003), and captures atmospheric variability at diurnal, synoptic, seasonal, and annual timescales. This study gives, for the first time, a comprehensive depiction of interannual variability over Antarctica in the late 1990s. A complete version of this paper is online (www-bprc.mps.ohio-state.edu/PolarMet/pmm5.html).

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2. MODEL CONFIGURATION AND EVALUATION

The Polar MM5 version 1 (henceforth, PMM5) is based on the nonhydrostatic version 2 of MM5 (Dudhia 1993, Grell et al. 1994). A description of the polar modifications available in PMM5 is given by Bromwich et al. (2001) and Cassano et al. (2001). The model domain (Fig. 1) is a polar stereographic projection consisting of 120 grid points in orthogonal directions centered at the South Pole, with a horizontal resolution of 60 km. The top pressure is set at 10 hPa with a rigid lid upper boundary condition. A total of 32 sigma levels are used in the vertical; seven are located within the lowest 400 m of the atmosphere. The model topography over the Antarctic continent is interpolated from a modern 5-km resolution digital elevation model for Antarctica (Liu et al., 1999), the so-called RAMP DEM. The regions spanned by the Ronne/Filchner Ice Shelf and Ross Ice Shelf are manually identified from climatic maps. The surface height and land use type for both ice shelves are set to 50 m and permanent ice, respectively.

The 2.5° horizontal resolution European Centre for Medium-Range Weather Forecasts (ECMWF) Tropical Ocean – Global Atmosphere (TOGA) surface and upper air operational analyses are used to provide the initial and boundary conditions for the model atmosphere. In addition, the 1.125° ECMWF/TOGA global surface analyses are used to specify the initial surface temperature, SST, and deep soil temperature. The daily polar gridded sea ice concentration data with 25-km horizontal resolution obtained from the National Snow and Ice Data Center are used to identify the sea ice surface type and its fractional coverage at each model grid. The PMM5 produces short duration (36 h) simulations of the atmospheric state over Antarctica from July 1996 through June 1999. The model is initialized with the 00 UTC ECMWF/TOGA analyses for each preceding day, with the 12 –36 h PMM5 forecasts used for data analyses (the first 12-h are discarded to account for spin-up).

Data obtained from the University of Wisconsin Antarctic Meteorological Research Center (AMRC) (http://amrc.ssec.wisc.edu) automatic weather stations (AWSs) are used to examine the quality of PMM5 simulations of surface pressure, temperature, and winds. Radiosonde data from manned stations, archived by the British Antarctic Survey (BAS) (http://www.antarctica.ac.uk/met/), are used to examine the quality of PMM5 simulations of 500-hPa geopotential height, temperature, dew point, and wind speed. The locations of these stations are shown in Fig. 1. The model skill is generally very good at capturing atmospheric variability on monthly timescales. At the surface, the correlations (averaged over all sites) are 0.97 (pressure), 0.73 (temperature) and 0.77 (wind speed). There is a systematic cold temperature bias in the winter months. This has been noted in other evaluations of PMM5, and is probably caused by deficient simulated wintertime cloud cover (Guo et al. 2003a. At 500 hPa, the correlations (averaged over all sites) are 0.96 (geopotential height), 0.86 (temperature), 0.68 (dewpoint), and 0.76 (wind speed). A slightly negative (~15 m) geopotential height bias is largely attributable to the cold bias at the surface.

Monthly mean surface (skin) temperatures inferred from Advanced Very-High Resolution Radiometer (AVHRR) digital satellite imagery and provided by the National Aeronautics and Space Administration's Goddard Space Flight Center are used to evaluate the spatial distribution of the PMM5 surface (2 m) temperatures over Antarctica. An extensive description and validation of this dataset is given in Comiso (2000). The two datasets are compared for the mean surface temperature from July 1996-June 1999 (not shown). Qualitatively, they are remarkably similar, and PMM5 captures many of the detailed spatial features present in the Comiso (2000) dataset. As described above, there is a cold bias in the PMM5 data, which is most evident over the continental interior.

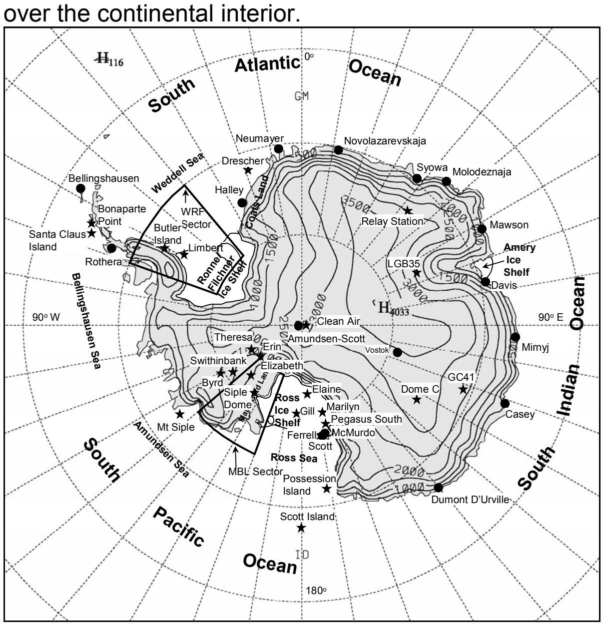

Fig 1. Map of PMM5 model domain showing model topography at 500-m intervals. Names and locations of AWS (stars), manned stations (circles), and sectors over which time series are extracted are shown.

Monthly cloud frequency fields inferred from AVHRR and obtained from University of Wisconsin's Cooperative Institute for Meteorological Satellite Studies are used to evaluate the spatial distribution of the PMM5 clouds over Antarctica (not shown). Further details on the dataset and algorithms can be found in Key (2002, and references therein). The percent change in cloud frequency between La Niña (DJF 1998-99) and El Niño (DJF 1997-98) for the PMM5 is compared with those inferred from the AVHRR satellite radiances (not shown). Similar features are resolved in both; the largest anomalies appear to reflect a wave number 2 pattern encircling the continent. During the El Niño episode, more clouds are present over the Ross Ice Shelf and West Antarctica, the South Pole, and East Antarctica from ~30°-90° E. Fewer clouds are present over the Ronne/Filchner Ice Shelf, the Antarctic Peninsula, and over East Antarctica from ~90°-140° E. In addition, fewer clouds are generally present over the entire Southern Ocean surrounding Antarctica.

In conclusion, the PMM5 appears to be accurately capturing the monthly variability from July 1996 to June 1999. The pressure and geopotential fields are especially well simulated, indicating that the synoptic variability is well represented. The best performance is in the free atmosphere where the effects of terrain are minimal.

3. RESULTS

Figure 2 shows the July 1997-June 1998 (El Niño) minus July 1998-June 1999 (La Niña) surface pressure anomaly over the PMM5 domain. Station observations are plotted for comparison to modeled fields, and are generally in good agreement. It is noteworthy that the blocking pattern in the Bellingshausen Sea is a nearly equivalent barotropic feature, extending upward throughout the troposphere. This blocking feature implies enhanced onshore flow over West Antarctica from approximately 90°-150° W and offshore flow over the Antarctic Peninsula and Weddell Sea regions during the El Niño episode. The most prominent low-pressure anomalies are over the Ross Sea/Ice Shelf and to the northeast of the Weddell Sea, centered at ~15° W, implying enhanced cyclone activity or cyclone intensity in these areas during the El Niño episode.

Figure 3 shows the MAM 1997 (El Niño) minus MAM 1999 (La Niña) surface temperature anomaly. The autumn months are chosen because they reflect the strongest interannual variability in surface temperature throughout the study period. Note that MAM 1998 is not used because it occurs during the abrupt transition of the SOI from negative to positive, and thus does not show significant variability. The most prominent feature is the warmer temperatures over the Ross Ice Shelf and Marie Byrd Land during the El Niño episode, due to enhanced onshore flow during March and May 1997. Over the Ronne/Filchner Ice Shelf and in the Weddell Sea, cooler temperatures are observed for the same period. Large warm anomalies are also present near Novolazarevskaja (~15° E) and between Mirnyj and Casey (~100° E), and a large cool anomaly is to the east of Dumont D'Urville (~150° E). The observations in Fig. 2 indicate that PMM5 is capturing the spatial distribution and sign of the anomalies with good skill over most of the model domain. Over the Weddell Sea and Antarctic Peninsula, the magnitude of the observed versus modeled anomalies are in good agreement. The PMM5 appears to be overestimating the magnitude of the negative anomaly over the interior of East Antarctica from ~10°-70° E. The magnitude of the positive anomaly over the interior of East Antarctica from ~70°-140° E is also somewhat overestimated, and this “tongue” of warm air should perhaps extend further eastward and inland according to the observations at Dumont D’Urville, Dome C, and LGB35. The most marked differences between observed and modeled values are in the large positive anomaly over the Ross Ice Shelf. The observations indicate that this anomaly definitely exists, but perhaps is about +5 K at its maximum, compared to about +11 K in the model. This discrepancy is related to the treatment of the ice shelves as 2-m thick sea ice in the ECMWF/TOGA data (that provide the initial conditions), and is examined in detail in the complete online version of this text (it is shown to affect only near-surface temperatures during the cold months).

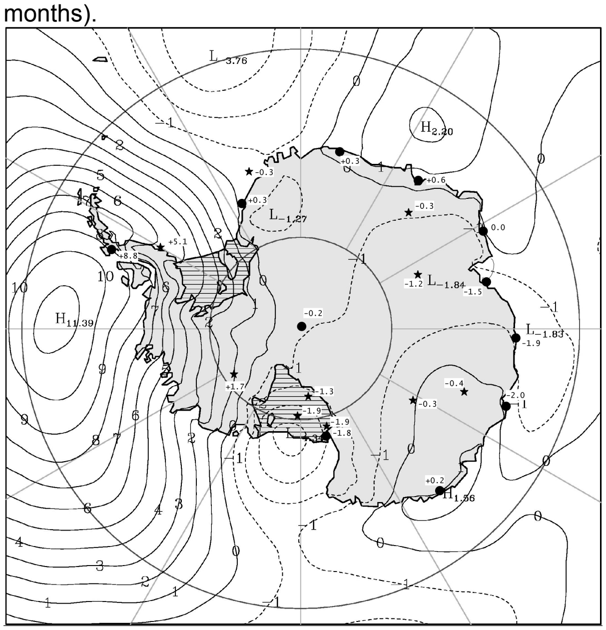

Fig. 2. July 1997-June 1998 minus July 1998-June 1999 PMM5 surface pressure anomalies. Observed anomalies are given in the white boxes next to stations indicated. (contour interval = 1 hPa; negative contours are dashed).

Figure 4 shows the percent change in PMM5 precipitation between La Niña (DJF 1998-99) and El Niño (DJF 1997-98), respectively. Over the continental interior, where fewer clouds and less precipitation occur, this method better reflects the variability than anomalies. The summer months are chosen because they display strong interannual variability over the Antarctic dipole region (Yuan and Martinson 2000). This appears to be due to the magnitude and location of the blocking feature in the Bellingshausen Sea, which is oriented most favorably for anomalous flow into (out of) the Marie Byrd Land (Weddell Sea) region during DJF 1997-98 (DJF 1998-99), and visa versa. Enhanced summer precipitation occurs over the Ross Sea/Ross Ice Shelf and Marie Byrd Land extending inland to South Pole during the El Niño episode, in excess of 400% more than the La Niña summer over much of the area. Decreased precipitation occurs over the Ronne/Filchner Ice Shelf and Coats Land, in excess of 400% less than the La Niña summer in some areas. Other large minima are located along the East Antarctic coastline near the Amery Ice Shelf (~70°E) and Dumont D’Urville (~120°-150° E). Few observations are currently available for comparison to the PMM5 simulations; it is anticipated that accumulation data from the International Trans Antarctic Scientific Expedition will be available in the future. However, comparisons (not shown) indicate these precipitation trends correspond closely to the cloud trends in the areas of highest variability, which are shown to be in broad agreement with observed (from manned stations) and satellite-inferred clouds.

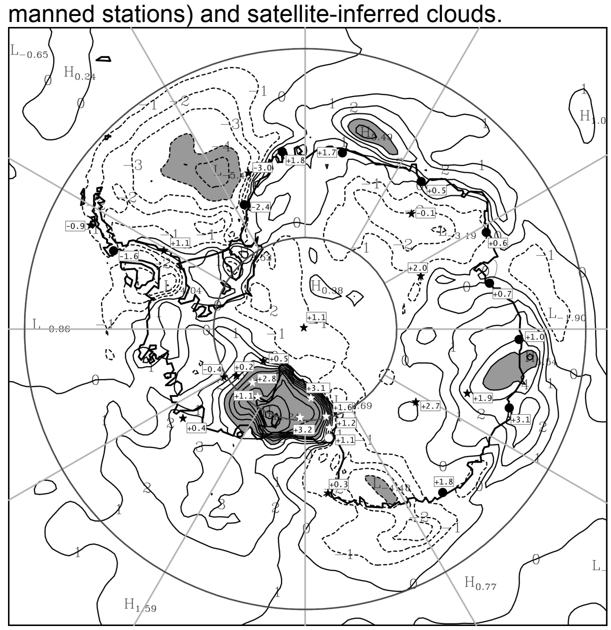

Fig. 3. MAM 1997 minus MAM 1999 PMM5 surface temperature anomalies. Observed anomalies are given in the white boxes next to stations indicated. (contour interval = 1 K; areas with change > |4 K| are shaded; negative contours are dashed).

Although not shown here, the temporal march of the seasonal anomalies from July 1996-June 1999 of several variables averaged over the Marie Byrd Land (MBL; 130°-160° W, 75°-85° S) and Weddell Sea-Ronne/Filcher Ice Shelf (WRF; 40°-70° W, 70°-80° S) sectors (Fig. 1) are calculated. These areas are chosen because they are regions of generally high interannual variability of nearly opposite sign in the model output, as demonstrated in Figs. 2-4. This relationship is strongly modulated by ENSO and consistent throughout the 3-y period, and is present in the surface temperature, meridional wind, cloud, precipitation, and net heat flux fields. Other authors have noted this regional phenomenon in sea ice, surface pressure, and surface temperature (e.g., Yuan and Martinson 2000, Kwok and Comiso 2002).

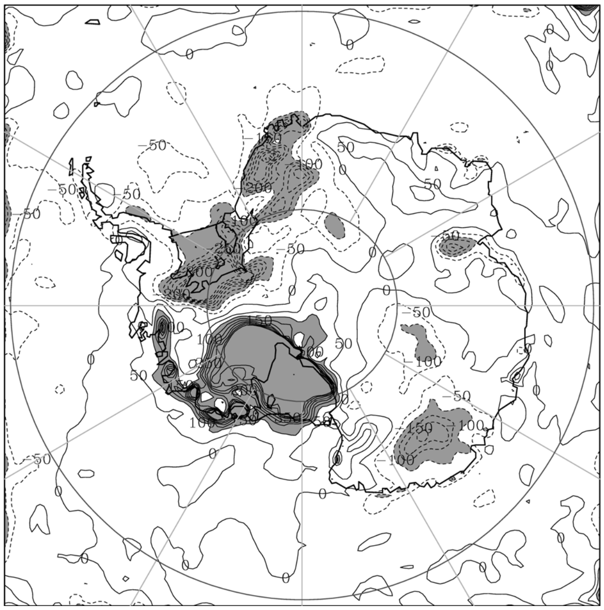

Fig. 4. Percent change in PMM5 precipitation between La Niña (DJF 1998-99) and El Niño (DJF 1997-98). (contour interval = 50%; areas with change > |100%| are shaded; negative contours are dashed).

4. CONCLUSIONS

The Polar MM5 is employed to examine the strong El Niño-Southern Oscillation (ENSO) modulation of Antarctic climate for July 1996-June 1999. This provides a more comprehensive assessment than can be achieved with observational datasets by using a regional atmospheric model adapted for high-latitude applications (Polar MM5). The most pronounced ENSO response is observed over the Ross Ice Shelf-Marie Byrd Land and over the Weddell Sea-Ronne/Filchner Ice Shelf. In addition to having the largest climate variability associated with ENSO, these two regions exhibit anomalies of opposite sign throughout the study period, which supports and extends similar findings by other investigators. The dipole structure is observed in surface temperature, meridional winds, cloud fraction and precipitation. The ENSO-related variability is primarily controlled by the large-scale circulation anomalies surrounding the continent, which are consistent throughout the troposphere. When comparing the El Niño / La Niña phases of this late 1990s ENSO cycle, the circulation anomalies are nearly mirror images over the entire Antarctic, indicating their significant modulation by ENSO. Large temperature anomalies, especially in autumn, are prominent over the major ice shelves. This is most likely due to their relatively low elevation with respect to the continental interior making them more sensitive to shifts in synoptic forcing offshore of Antarctica, especially during months with considerable open water. The Polar MM5 simulations are in broad agreement with observational data, and the simulated precipitation closely follows the European Centre for Medium-Range Weather Forecasts Tropical Ocean - Global Atmosphere precipitation trends over the study period. The collective findings of this work suggest the Polar MM5 is capturing ENSO-related atmospheric variability with good skill and may be a useful tool for future climate studies.

Acknowledgments

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References

Bromwich, D.H., J.J. Cassano, T. Klein, G. Heinemann, K.M. Hines, K. Steffen, and J.E. Box, 2001: Mesoscale modeling of katabatic winds over Greenland with the Polar MM5. *Mon. Wea. Rev.*, **129**, 2290-2309.

Cassano, J.J., J.E. Box, D.H. Bromwich, L. Li, and K. Steffen, 2001: Verification of Polar MM5 simulations of Greenland's atmospheric circulation. *J. Geophys. Res.*, **106**, 13,867-13,890.

Comiso, J.C., 2000: Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements. *J. Climate*, **10**, 1674-1696.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State - NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.*, **121**, 1493-1513.

Grell, G.L., J. Dudhia, and D.R. Stauffer, 1994: *A description of the fifth-generation Penn State / NCAR mesoscale model (MM5)*. NCAR Tech. Note NCAR/TN-398+STR.

Guo, Z., D.H. Bromwich, and J.J. Cassano, 2003: Evaluation of Polar MM5 simulations of Antarctic atmospheric circulation. *Mon. Wea. Rev,* **131**, 384-411.

Key, J., 2002, The Cloud and Surface Parameter Retrieval (CASPR) System for Polar AVHRR Data User's Guide. Space Science and Engineering Center, University of Wisconsin, Madison, WI, 62 pp.

Kwok, R., and J.C. Comiso, 2002: Southern Ocean climate and sea ice anomalies associated with the southern oscillation. *J. Climate*, **15**, 487-501, 2002.

Liu, H., K.C. Jezek, and B. Li, 1999: Development of an Antarctic digital elevation model by integrating cartographic and remotely sensed data: A geographic information system based approach. *J. Geophys. Res.*, **104**, 23199-23213.

Vaughan, D.G., G.J. Marshall, W.M. Connolley, J.C. King, and R. Mulvaney, 2001: Devil in the detail. *Science*, **293**, 1777-1779.

Yuan, X., and D.G. Martinson, 2000: Antarctic sea ice extent variability and its global connectivity. *J. Climate*, **10**, 1697-1717.