Antarctic Peninsula mesoscale cyclone variability and climatic impacts influenced by the SAM

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[1] The frequency of mesoscale cyclones in the Western Antarctic Peninsula (WAP) region during 1991–94 is correlated with the Southern Hemisphere Annular Mode (SAM) index, most strongly during winter and spring. Also, during periods of positive SAM index polarity there is a shift in the storm tracks to favor more east-bound trajectories, consistent with strengthening of circumpolar westerlies. The presence of mesoscale cyclones is associated with positive near-surface-air temperature anomalies in the WAP region year-round, largest during winter. **Citation:** Lubin, D., R. A. Wittenmyer, D. H. Bromwich, and G. J. Marshall (2008), Antarctic Peninsula mesoscale cyclone variability and climatic impacts influenced by the SAM, *Geophys. Res. Lett.*, *35*, L02808, doi:10.1029/2007GL032170.

[2] The Antarctic Peninsula is a region that has undergone significant climate change. The WAP region has experienced the largest regional climate warming on Earth over the past half century [*Vaughan et al.*, 2002; *Turner et al.*, 2005] — a 3°C rise in annual mean temperature over the last 56 years, with the greatest warming in austral winter. In addition, a pronounced summer warming in the north-east Peninsula has occurred, which has led to the disintegration of the northern sections of the Larsen Ice Shelf [e.g., *Scambos et al.*, 2003]. There has been a concomitant trend in the Southern Hemisphere Annular Mode (SAM) toward a positive polarity: several modeling studies have suggested that a combination of springtime ozone depletion and greenhouse gas increases are primarily responsible [e.g., *Gillett and Thompson*, 2003; *Marshall et al.*, 2004; *Arblaster and Meehl*, 2006]. The large-scale dynamical change associated with a shift in a polar annular mode toward a positive polarity involves a strengthening and poleward displacement of the circumpolar westerlies [*Thompson and Wallace*, 2001]. This is thought to be responsible for the recent cooling of the Antarctic continental interior [*Comiso*, 2000], while *Marshall et al.* [2006] linked the stronger westerly winds with the collapse of the Larsen Ice Shelf. However, the exact mechanism or combination of mechanisms responsible for the larger WAP warming has yet to be identified [*Thompson and Solomon*, 2002; *Vaughan et al.*, 2002; *Turner et al.*, 2005]. Recent GCM simulations suggest that increased cyclonic activity accompanies the predicted stronger zonal winds over the Southern Ocean [*Lynch et al.*, 2006].

[3] We use data from the U.S. Antarctic Program satellite tracking facility at Palmer Station, Antarctica (64°46′S, 64°04′W), established in 1990 and recording between 2–14 overpasses per day from the NOAA and Defense Meteorological Satellite Program (DMSP) polar orbiters. We analyze global area coverage (GAC, 4-km-resolution) middle infrared images (channel 4) from the NOAA Advanced Very High Resolution Radiometer (AVHRR) and middle infrared imagery of similar resolution from the DMSP Operational Linescan System (OLS). In a typical day, enough overpasses are captured from both spacecraft series in varying orbits to yield contiguous geographic coverage of the Amundsen and Bellingshausen Seas (ABS), the Antarctic Peninsula sector of the continent as far south as the Pole, and the Weddell Sea as far east as the prime meridian.

[4] Satellite images comprising each entire available overpass were inspected manually to identify all polar mesoscale cyclones originating (first sighted) below 55°S following established protocols [*Carrasco et al.*, 1997]. We analyzed data between July 1991 and January 1995, an interval when there was large month-to-month variability in the SAM index [*Marshall*, 2003], such that we obtained samples of roughly equal size under negative and positive SAM polarities in all seasons. We selected for analysis the three months of most negative and then most positive SAM indices for each season, for a total of 24 months from this time period. An additional selection criterion was that satellite imagery was available every day during the month. A total of 7066 images were analyzed, and 77% of the cyclones identified were seen in more than one image, thus showing part or all of their trajectories.

[5] Table 1 gives the number of cyclones [*Carrasco et al.*, 1997], identified during each month under most negative and most positive SAM indices for the period studied, in the ABS and in the Weddell Sea. The cyclone frequency and geographic distribution in our observations are consistent with previous climatological studies covering part of this time period [*Carrasco et al.*, 1997; *Turner et al.*, 1998]. In the ABS, there are noticeably more cyclones under positive versus negative polarities in both winter and spring, while this difference becomes negligible during summer and autumn. We note that in the former seasons there has been little change in the SAM, unlike in the latter seasons [e.g., *Marshall et al.*, 2006]. The most significant result of this climatological assessment occurs when we consider the number of cyclones that originate just west of the Antarctic Peninsula (Figure 1 and the sixth column of Table 1). In the bolded region within Figure 1, there are considerably more

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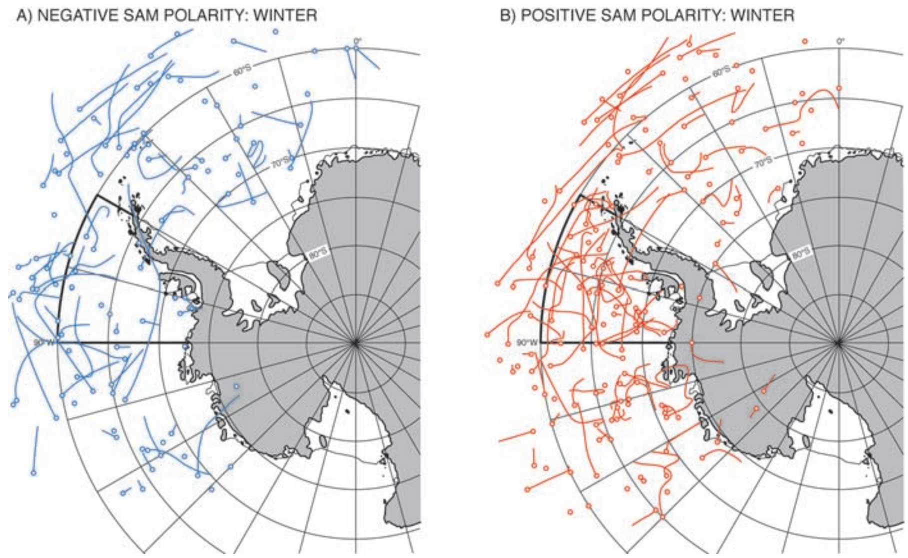

Figure 1. First sighting (circles) and tracks of mesoscale cyclones identified in AVHRR and OLS imagery during three winter months under conditions of (a) most negative SAM polarity (July 1991, June 1992, and June 1994) and (b) most positive SAM polarity (July 1993, August 1993, and August 1994).

cyclones originating under positive versus negative SAM index conditions. This difference is most pronounced during winter and spring, but occurs in all seasons. If we estimate the statistical significance of this result using Poisson statistics evaluated for small event counts [*Gehrels*, 1986], we find that our observed number difference in WAP cyclones during winter is significant at the single-sided 97.5% confidence level, while the difference during spring is significant at the single-sided 90% confidence level.

[6] Using all 24 months, the correlation between originating cyclone frequency and the SAM index is 0.62 (0.67 if we use only winter and spring). Some differences in sample size appear among months in Table 1, due to a steadily increasing number of overpasses tracked between 1991–5, and the correlation between cyclone frequency and sample size is 0.32. We can evaluate the significance of these linear correlations by calculating the probability that they would emerge in completely uncorrelated samples of equal size [*Bevington*, 1969]. These probabilities are 0.0012 for counts in all seasons versus SAM index, 0.017 for winter and spring counts versus SAM index, and 0.127 for counts in all seasons versus sample size. Thus the correlation in cyclone count with sample size is much weaker than that for the SAM index.

[7] For each cyclone appearing in multiple images, we evaluated the overall trajectory as the direction vector between the first and final sighting. Contrasts between the trajectory distribution under positive versus negative SAM polarity give insight into differences in large-scale circulation (Figure 2). For all cyclones in the ABS, the difference between negative and positive SAM index corresponds to a shift in the most probable direction of travel from a southeastward to a more eastward trajectory. For all cyclones in the Weddell Sea, the prevailing trajectory is eastward under all SAM indices, although under negative polarity a secondary maximum appears for northerly headings. If we examine cyclones in the ABS below 65°S, we see that under positive SAM polarity the distribution favors eastward trajectories at the expense of the northerly headings seen under negative polarity. In the Weddell Sea below 65°S, there is little coherence in the cyclone trajectory distribution under negative SAM polarity, but a strong tendency for eastward trajectories under positive polarity. These distributions, which include data from all seasons, are all consistent with stronger zonal winds under a positive SAM polarity.

[8] Mesoscale cyclone activity generally yields an increase in sensible heat flux from the ocean to the lower atmosphere [*Rasmussen and Turner*, 2003]. We therefore attempt to relate cyclone trajectories with near-surface air temperature anomalies. Maintenance of long-term automatic meteorological monitoring equipment is very challenging in the WAP region, due to a cold and corrosive marine environment: however, the University of Wisconsin Automatic Weather Station (AWS) program [*Bromwich and Stearns*, 1993] successfully maintained two AWS in the WAP region throughout much of 1991–95, at Racer Rock (64°04′S, 61°37′W) and Bonaparte Point (at Palmer Station). Of our 24 months analyzed, 22 were covered by consistent 2 m air temperature data from at least one of these AWS. Five-year monthly mean temperatures were computed for each station. During the 22 available months, we identified 63 mesoscale cyclones whose trajectories crossed the northern Antarctic Peninsula such that they were a likely influence on the meteorology sampled by the AWS, and the two AWS together yielded 89 temperature anomaly measurements from the cyclone crossings. For the days that these Peninsula cyclone impacts occurred, the daily average 2 m air temperature was used to compute a temperature anomaly from the five year monthly mean. The monthly averages of these anomalies are shown in Figure 3a. They consistently tend to be positive, most significantly in winter, early spring and late fall. However, if we instead compute the anomalies with respect to just the mean for the

Table 1. Number of Mesoscale Cyclones Detected Between June 1991 (9106) and January 1995, in the Amundsen-Bellingshausen Seas, $N_C(B)$, the Weddell Sea, $N_C(W)$, and Terminating West of the Antarctic Peninsula, $N_C(WAP)$, in All Four Seasons During the Three Months for Each Season When the SAM Index Was Most Negative and Then Most Positive[a]

Date	SAM Index	N_I	$N_C(B)$	$N_C(W)$	$N_C(WAP)$
		Winter			
9206	−3.29	139	15	14	3
9406	−2.71	484	25	10	8
9107	−1.50	117	22	15	4
		740	**62**	**39**	**15**
9308	+3.25	236	35	18	18
9307	+3.07	128	27	9	4
9408	+2.02	435	38	20	14
WIN		**799**	**100**	**47**	**36**
		Spring			
9109	−1.69	196	16	5	3
9111	−0.59	125	16	14	7
9411	−1.73	439	22	12	6
		760	**54**	**31**	**16**
9310	+2.02	409	26	23	9
9110	+1.99	175	19	9	11
9309	+1.95	357	26	10	12
SPR		**941**	**71**	**42**	**32**
		Summer			
9112	−2.59	300	19	11	3
9201	−1.25	189	23	10	9
9401	−0.88	502	24	16	9
		991	**66**	**37**	**21**
9402	+2.23	405	20	16	9
9501	+1.23	396	21	16	8
9412	+0.44	413	21	19	10
SUM		**1214**	**62**	**51**	**27**
		Autumn			
9205	−2.68	170	19	15	7
9405	−1.74	475	26	13	10
9203	−0.01	124	14	13	6
		769	**59**	**41**	**23**
9403	+2.21	449	21	16	10
9304	+1.96	198	22	14	14
9305	+1.80	205	21	13	7
AUT		**852**	**64**	**43**	**31**

[a]These numbers are raw counts, and not corrected for varying number of images; months with satellite data missing during entire days were not analyzed. The SAM index is from *Marshall* [2003], available at http://www.antarctica.ac.uk/met/gjma/sam.html.

month in which they occur, rather than the five year monthly mean (Figure 3b), then the anomalies during late spring and summer are negligible, and the anomalies throughout the rest of the year are generally smaller than when derived from the five year monthly mean. Figure 3c indicates a preference for positive temperature anomalies during positive SAM polarity as opposed to negative polarity (positive temperature anomalies occurring 76% and 56% of the time, respectively). Figures 3b and 3c suggest that the observed temperature anomalies may also be a reflection of the warm air advection conditions accompanying positive SAM polarity [*van den Broeke and van Lipzig*, 2003]. Further work is needed to resolve this issue and to identify the governing mechanisms.

[9] In conclusion, our satellite tracking of West Antarctic mesoscale cyclones over conditions of negative versus positive SAM polarity (1) shows consistency with large-scale zonal wind strengthening associated with a positive SAM polarity, (2) reveals an increase in cyclogenesis (or first sighting) during a positive SAM polarity for winter and

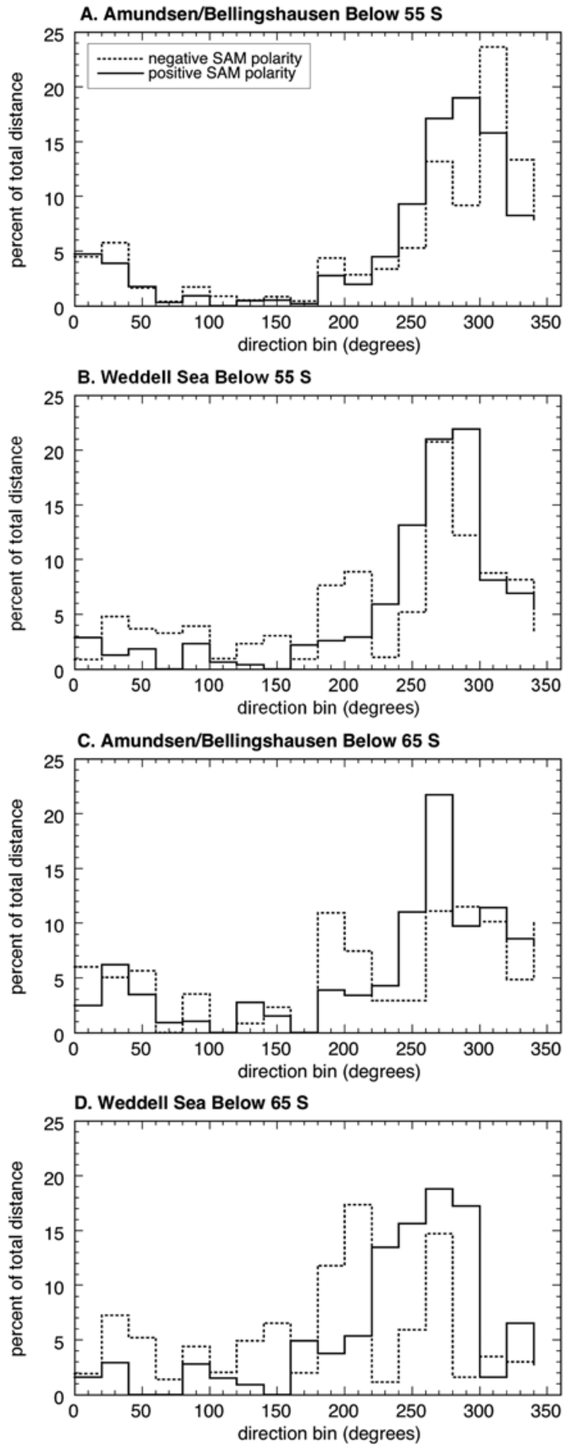

Figure 2. Distribution of mesoscale cyclone trajectories, expressed as the direction from, and as the percent of the total distance traveled by all cyclones considered in all seasons, (a) for the Amundsen and Bellingshausen Seas below 55°S, (b) for the Weddell Sea below 55°S, (c) for the Amundsen and Bellingshausen Seas below 65°S, and (d) for the Weddell Sea below 65°S.

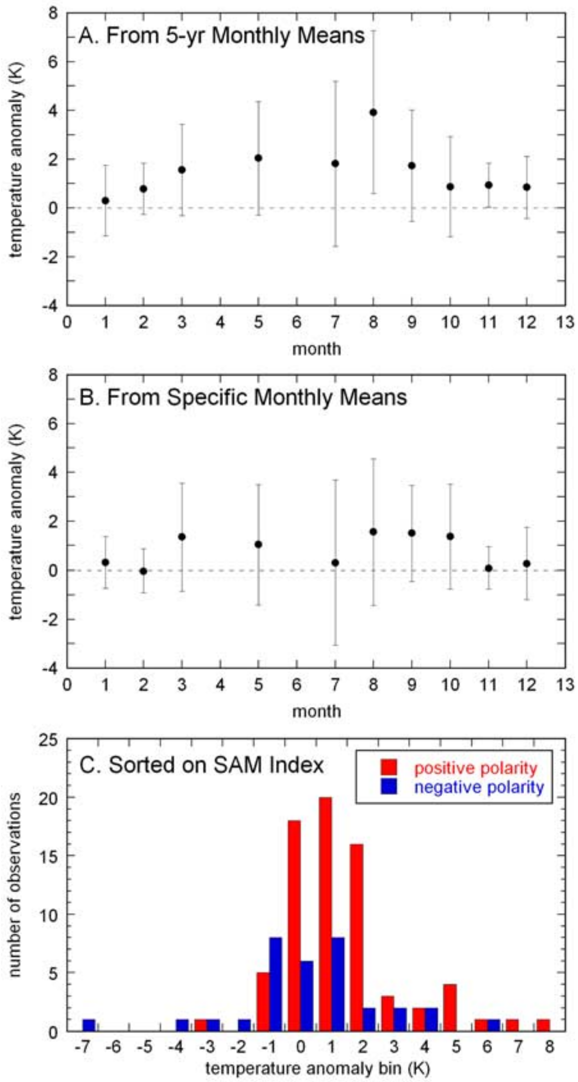

Figure 3. Monthly mean 2 m air temperature anomalies in the presence of mesoscale cyclones impacting the northern Antarctic Peninsula region, determined from AWS data at Racer Rock and Bonaparte Point (Palmer Station), adjacent to the Antarctic Peninsula, average and standard deviation by month, (a) as computed from the five year monthly mean, and (b) as computed from the mean of the month in which they occur. Also shown is (c) the histograms for negative versus positive monthly mean SAM polarity; temperature anomaly bins are of width 1°C and are identified by their midpoints.

spring, and (3) when co-locating WAP cyclone impacts with surface air temperature data, reveals a tendency for positive temperature anomalies in the presence of mesoscale cyclones throughout much of the year except for summer. Mesoscale cyclones may therefore have a significant indirect effect on climate change in the WAP region.

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