

Mesoscale cyclone activity over Antarctica during 1991

1. Marie Byrd Land

Jorge F. Carrasco¹

Dirección Meteorológica de Chile, Santiago
Departamento de Física y Meteorología, Universidad de Valparaíso, Valparaíso, Chile

David H. Bromwich and Zhong Liu

Polar Meteorology Group, Byrd Polar Research Center and Atmospheric Sciences Program, Ohio State University, Columbus

Abstract. A 1-year statistical study of mesoscale cyclonic activity over southern Marie Byrd Land, West Antarctica, was conducted using high-resolution satellite imagery collected insitu during 1991 at the U.S. McMurdo and Palmer stations. Results indicate that, on average, one or two mesoscale cyclones can be observed each week over the southernmost part of Marie Byrd Land (Siple Coast and adjacent areas), where cold katabatic winds from the high plateau of East Antarctica and relatively warm katabatic airflows from West Antarctica interact, forming a boundary layer baroclinic zone in the form of a stationary front. The 1991 annual mesoscale cyclone behavior exhibits maximum activity in March and minimum in September. Analysis of the large-scale pattern for these months suggests that the higher activity in March is associated with synoptic-scale conditions that support the cold katabatic drainage from East Antarctica and favor warm air advection into West Antarctica, a situation that can form and/or enhance the boundary layer baroclinic zone. More than half (70%) of the mesoscale vortices observed near Siple Coast were of comma cloud type with an average diameter of about 250 km. Their satellite signature characteristics show that these cyclonic perturbations were stratiform low cloud features, indicating that most of them developed within the lower troposphere, more than likely below 700 hPa, according to a cloud top temperature evaluation.

1. Introduction

Recent satellite-observed studies of mesoscale cyclonic activity over the Ross Sea and Ross Ice Shelf regions of Antarctica indicate that a fraction of the mesoscale cyclones (a cyclonic perturbation whose diameter is less than 1000 km) observed over the ice shelf seems to come from southern Marie Byrd Land (see Figure 1 for geographical locations [Carrasco and Bromwich, 1994, 1996]). This suggests that this area is another source for formation and/or development of mesoscale cyclones, like those near Terra Nova Bay and Byrd Glacier [Bromwich, 1991; Carrasco and Bromwich, 1994]. Little study of mesoscale cyclogenesis over Marie Byrd Land has been conducted, and because of limited insitu observations, their impact is uncertain. Early in November 1992, a team from the Polar Meteorology Group of the Byrd Polar Research Center encountered a severe storm that resulted in sustained winds of 28 m s^{-1} gusting to over 35 m s^{-1} , and blowing snow for 48 hours [Smith and Teeuwisse, 1994]. Subsequent study of this event [Smith *et al.*, 1993; Bromwich and Carrasco, 1995] revealed that the

adverse weather conditions were associated with the development of an intense mesoscale cyclone over southern Marie Byrd Land. This suggests that mesoscale cyclones in this area can generate significant precipitation amounts and/or lead to major drifting snow events.

The simulated and observed surface winds near Siple Coast [Parish and Bromwich, 1986, 1987, 1991; Bromwich *et al.*, 1994; Mather and Miller, 1966] reveal that the airflow over West Antarctica converges into the Siple Coast area (Figure 2), as it does into Terra Nova Bay and Byrd Glacier on the other side of the Ross Ice Shelf. This situation suggests that mesoscale cyclogenesis over southern Marie Byrd Land may occur in the same fashion as near Terra Nova Bay and Byrd Glacier [Bromwich, 1989, 1991; Carrasco and Bromwich, 1993a, 1994, 1996]. That is, the formation of mesoscale cyclones is associated with the presence of a boundary layer baroclinic zone (i.e., stationary front) created by the juxtaposition of cold katabatic air and relatively warm and maritime air affecting the foot of the slope, in this case near Siple Coast. Recently, Bromwich *et al.* [1994] conducted a more detailed simulation of the near-surface wind regime over West Antarctica. Their results indicate that the air descending into Siple Coast not only comes from the plateau of West Antarctica, but also from around the South Pole in East Antarctica (Figure 2). The latter surface airflow reaches the southern side of Siple Coast, and the Gould and Amundsen coasts at the bottom of the Ross Ice Shelf. The potential temperature near South Pole is similar to that on the

¹Previously at Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus.

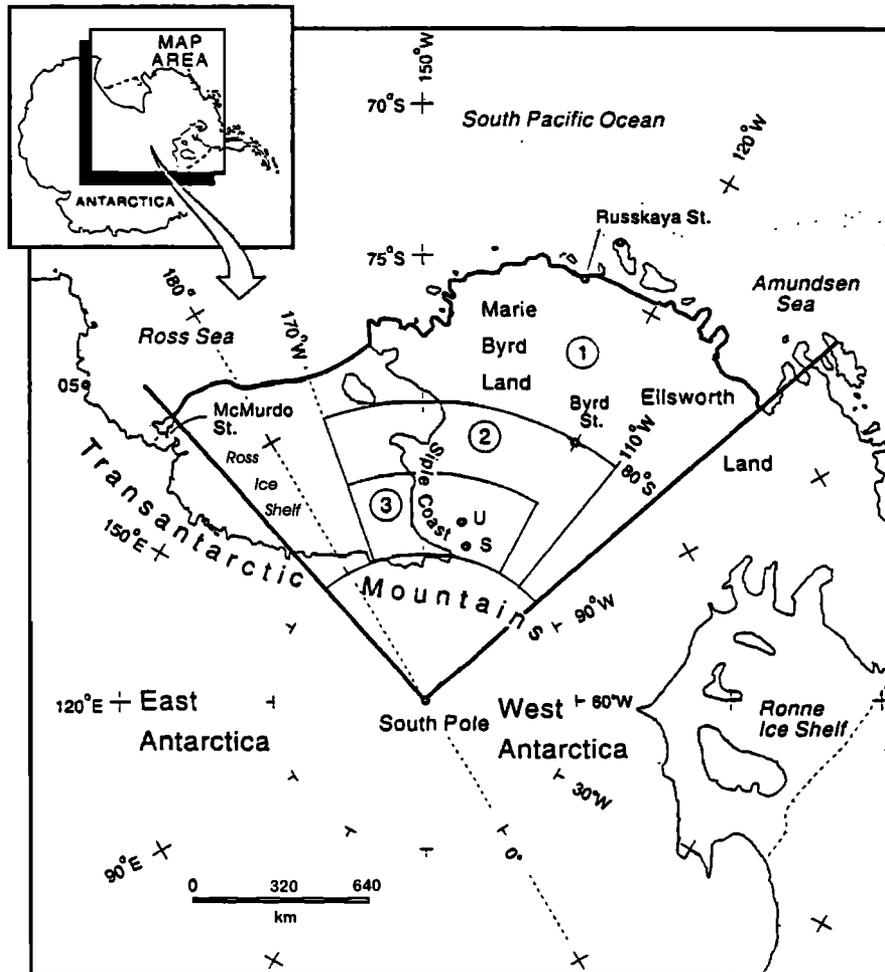


Figure 1. Location map showing the main geographical locations in Antarctica. Bold lines enclose the area most frequently covered by the satellite information. Area labeled 1 defines the area bounded by the 100°E and 170°E longitudes (two bold lines), and the coastline of Marie Byrd Land/Ross Ice Shelf front and the 85°S parallel. Area labeled 2 identifies the area delimited by longitudes 110°W and 170°W, and latitudes 80°S and 85°S. Area labeled 3 denotes the area enclosed by 120°W, 170°W, 82.5°S and 85°S. U and S are Upstream B and South Camp, respectively.

ice shelf but colder than in the interior of Marie Byrd Land [Radok, 1973]. Therefore cold katabatic air descending from East Antarctica toward southern Marie Byrd Land and Siple Coast may interact with the much warmer katabatic air over West Antarctica creating a boundary layer baroclinic zone in the interior of Marie Byrd Land.

Bromwich and Liu [1996] and Liu and Bromwich [1997] studied the behavior of the surface winds and temperatures as well as their profiles at two temporary stations (Upstream B and South Camp; U and S in Figure 1, respectively) deployed near Siple Coast during the early austral summer of 1992 (November 8 to December 8). Their composite analysis of the vertical structure of the boundary layer indicates that the confluence zone is composed of cold katabatic airflow from East Antarctica that extends to about 500 m above the surface, with overlying warmer katabatic airflow from West Antarctica that extends 500-1000 m in height above the cold East Antarctic drainage flow (see Figure 3); above this is easterly synoptic flow associated with the time-averaged low in the Amundsen Sea. Because katabatic drainage from East Antarctica is associated with colder air masses than the

drainage from West Antarctica, Bromwich and Liu's results suggest that a significant low-level temperature gradient zone forms over southern Marie Byrd Land, where the katabatic air masses from East and West Antarctica are horizontally adjacent. Mesoscale cyclogenesis can occur in association with this low-level baroclinic zone [Bromwich and Carrasco, 1995]. Figure 4 depicts the inferred formation of the baroclinic zone based on the results of numerical model simulation of the katabatic winds (Figure 2 [Bromwich et al., 1994]), and the composite analysis of Bromwich and Liu [1996] and Liu and Bromwich [1997]. The stippled area represents the boundary layer baroclinic zone, (i.e., the low-level front) formed by the juxtaposition of the West Antarctic (warm) and East Antarctic (cold) katabatic winds and therefore where a strong temperature gradient zone can form. Enhanced warm and probably moist air advection into West Antarctica associated with synoptic-scale features (dotted arrow) may enhance the katabatic boundary layer baroclinic zone, favoring mesoscale cyclogenesis even more. That such events happen frequently is suggested by the fact that about 40% of the water vapor falling as snow on Antarctica enters

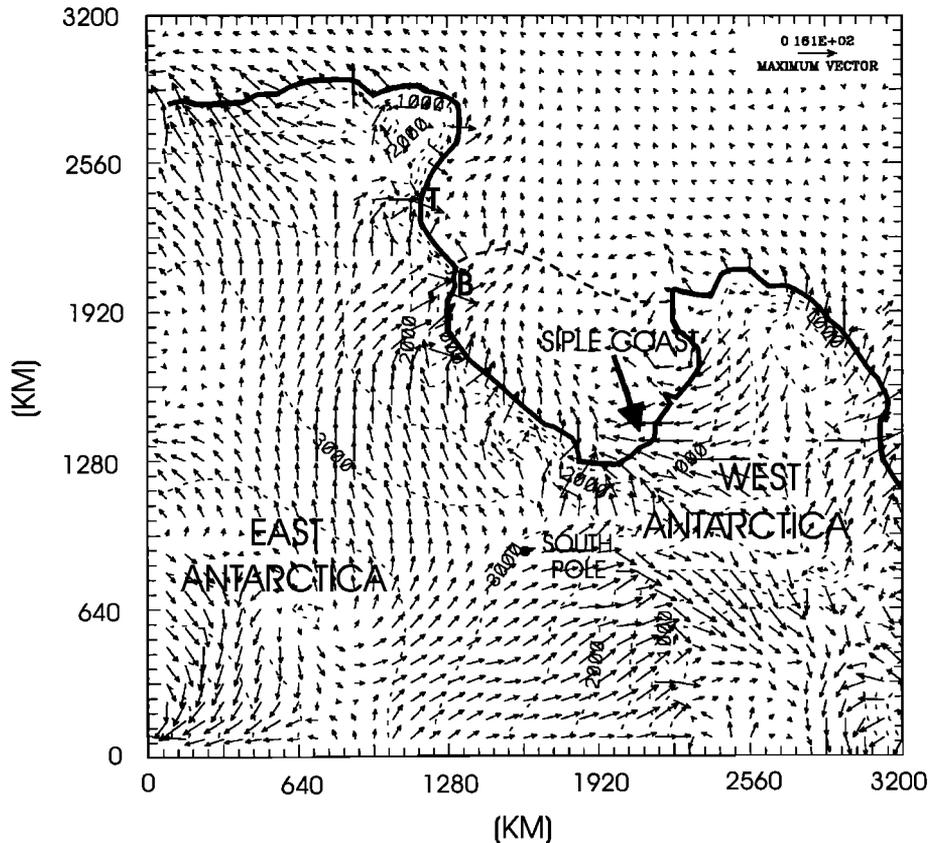


Figure 2. Near-surface winter winds over part of the Antarctic continent showing the confluence of katabatic winds near Siple Coast as simulated by Bromwich *et al.* [1994]. T and B locate Terra Nova Bay and Byrd Glacier. Dashed lines are elevation contours in 500-m increments. Dashed line to the north of the "Siple Coast" label marks the seaward edge of the Ross Ice Shelf.

the continent through the West Antarctic sector [Lettau, 1969; Bromwich *et al.*, 1995]. Conservation of potential vorticity associated with incipient mesoscale cyclones that descend toward the flat Ross Ice Shelf may be another mechanism that

favors and/or supports the development of mesoscale cyclones. Unfortunately, the lack of appropriate data inhibits analysis of this situation.

A 1-year survey (1991) of mesoscale cyclonic activity over southern Marie Byrd Land and surrounding areas was conducted using meteorological satellite imagery recorded insitu at McMurdo and Palmer stations. The main objectives were to describe the spatial and temporal variations, to identify cyclogenesis and cyclolysis areas and to infer the role of mesoscale cyclones in the climate of West Antarctica. Results are solely based on satellite images because no surface observations were available over southern Marie Byrd Land. The selection of the year was based on the good temporal coverage of satellite imagery in comparison with other years. Because only 1 year was analyzed, results may be representative for only this particular year. The following section presents the results of the survey, and in section 3 the synoptic-scale pattern over the south polar region associated with mesoscale cyclonic activity is presented. Discussions and conclusions are given in section 4.

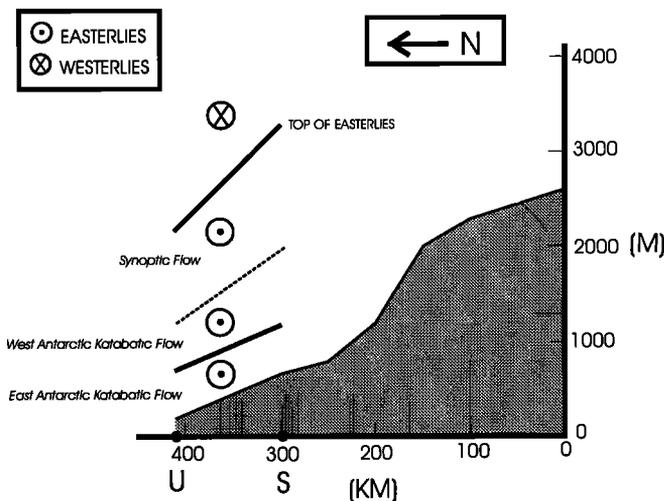


Figure 3. Vertical section across the confluence zone near Siple Coast showing the warmer katabatic flow from West Antarctica overlying the colder katabatic flow from East Antarctica. Open circles denote easterlies, and solid circles westerlies [adapted from Liu and Bromwich, 1997], both perpendicular to the north-south oriented cross section.

2. Satellite Survey and Analysis

2.1. Procedure

In 1987 the Arctic and Antarctic Research Center (AARC) at Scripps Institution of Oceanography installed a satellite receiver at McMurdo Station [Van Woert *et al.*, 1992]. Since then, real-time polar-orbiting satellite imagery from National

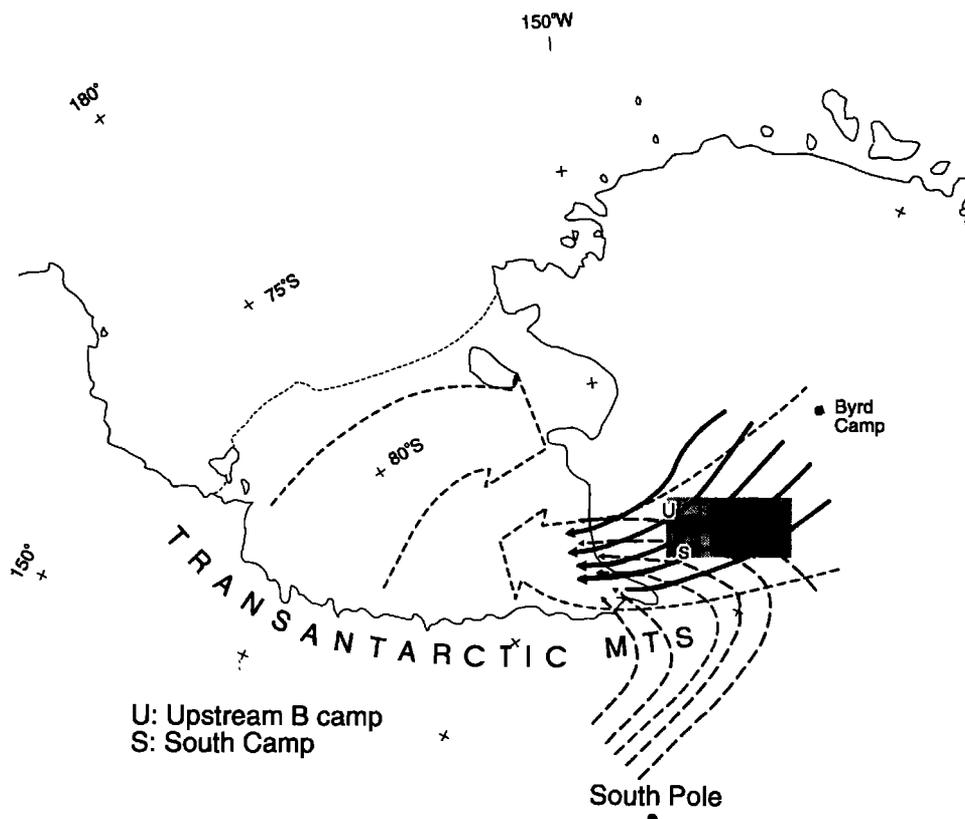


Figure 4. Schematic illustration of the katabatic winds near Siple Coast, West Antarctica. The streamlines of the near-surface winds from West Antarctica (solid lines) are undercut by the near-surface winds (dashed lines) from East Antarctica. Stippled area denotes the boundary layer baroclinic zone. Dashed arrow over West Antarctica illustrates the warm air advection that may enhance the baroclinic zone. Dashed arrow over Ross Ice Shelf shows cold air advection noted by *Bromwich and Carrasco* [1995].

Oceanic and Atmospheric Administration (NOAA) and Defense Meteorological Satellite program (DMSP) spacecraft are routinely collected and shipped to the AARC, where they are archived. A second satellite receiver system was installed at Palmer Station (65°S, 64°W) in May 1989. Copies of the original raw digital satellite data collected at both stations during 1991 were obtained on 8 mm video tapes and processed on a workstation using the TeraScan Software Package developed by SeaSpace. The advanced very high resolution radiometer (AVHRR), onboard the NOAA spacecraft, provides satellite images at 1.1 km resolution at nadir in five channels, from the visible (0.58-0.68 μ m) to the thermal-infrared (11.50-12.50 μ m). For the purpose of this research, the satellite images were processed in the infrared format (channel 5) with a spatial resolution of 3.3 km centered over southern Marie Byrd Land. This resolution is appropriate for identification and tracking of mesoscale cyclones, and allows coverage of the surrounding areas. The capabilities of zooming and/or enhancing the digital images on the computer screen facilitate identification of the mesoscale vortices. Once these features were identified for the first time (initial appearance), they were plotted on a chart in order to obtain their spatial distribution through the year. Mesoscale vortices that appeared on more than one image were counted only once but were tracked to determine their trajectories.

For a detailed study of mesoscale cyclonic activity over Marie Byrd Land, the region was divided into three zones.

Figure 1 shows the area of interest. The solid thick lines enclose the area most frequently covered by satellite information and therefore for which the results are most representative. Area 1 encloses all of Marie Byrd Land and most of the Ross Ice Shelf. Area 2 reduces the analysis to the southern half of Marie Byrd Land and southeastern Ross Ice Shelf, where the katabatic winds occur (Figure 2). Finally, Area 3 only encloses the southernmost part of Marie Byrd Land and the very bottom part of the Ross Ice Shelf near Siple Coast, where the katabatic wind confluence zone is located and where the juxtaposition of katabatic winds from East and West Antarctica is most likely to occur. Note that the above division zooms up on Siple Coast.

Monthly and seasonal evaluations of mesoscale cyclonic activity were conducted. For the latter, the year was arbitrarily divided into five periods to represent the summer, winter, and transition seasons. Thus late summer corresponds to January and February, the second half of the south polar summer; autumn transition includes March and April and represents the change from summer to winter; winter season extends from May to August; spring transition includes September and October and corresponds to the change from winter to summer; and finally, early summer incorporates November and December.

Identification of the mesoscale vortices was based upon the cyclonic appearance of the vortical cloud, following the general techniques used and described in previous satellite-observed studies of these features in both the northern and

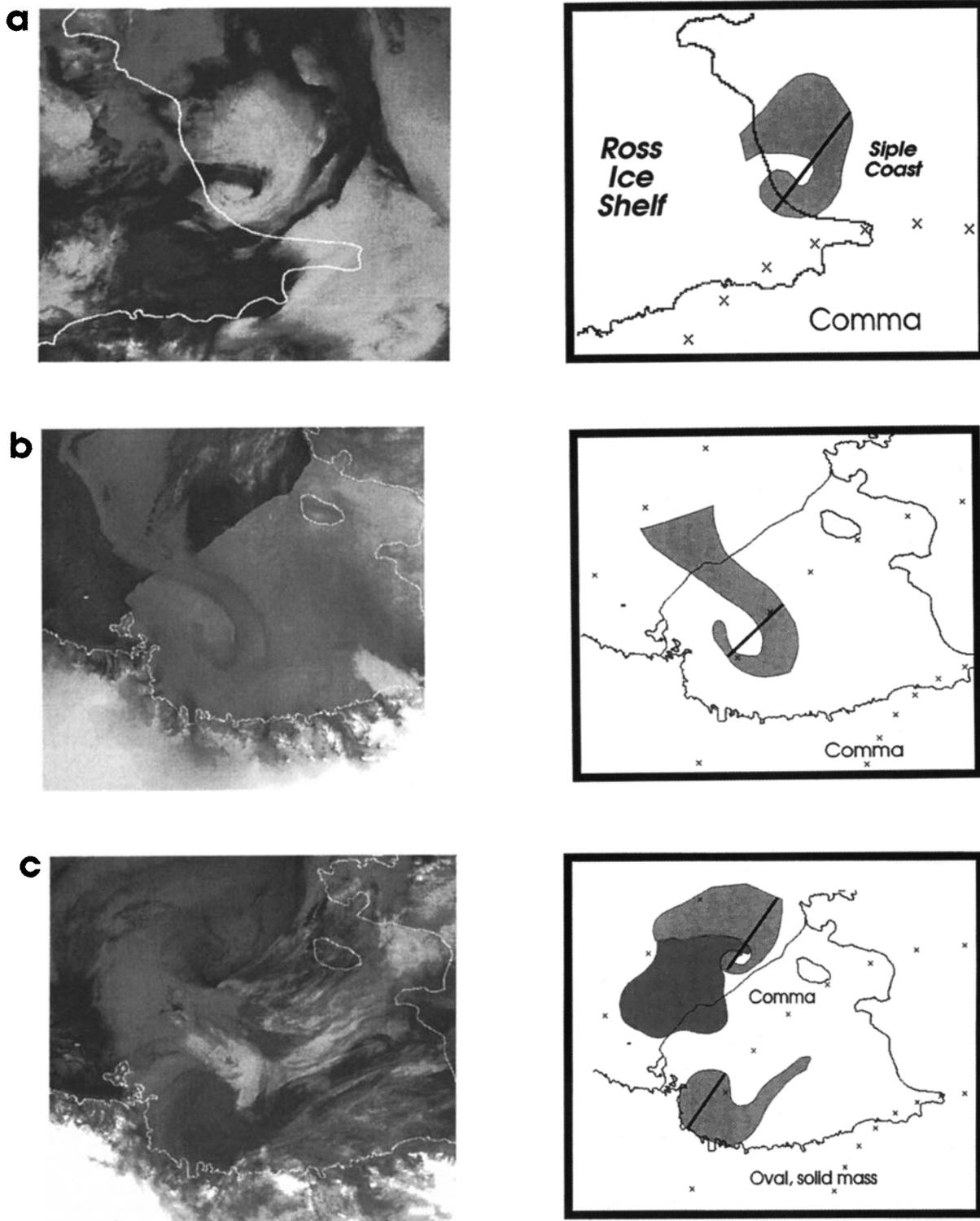


Figure 5. Infrared satellite images along with the corresponding schematic illustrations showing examples of the common types of mesoscale vortices observed over southern Marie Byrd Land and Ross Ice Shelf regions (a) at 0324 UTC January 16, 1989, (b) at 0623 UTC November 11, 1991, (c) at 0707 UTC June 21, 1991, (d) at 0559 UTC November 13, 1991, (e) at 0908 UTC November 14, 1991, (f) at 0612 UTC May 4, 1991, and (g) at 0602 UTC June 9, 1991. All images have a resolution of 3.3 km apart, from Figure 5a, which is 1.1 km. The lines in the sketches illustrate how the diameters were measured: (a) 235 km; (b) 254 km; (c) 347 km (comma), 267 km (oval, solid mass); (d) 694 km; (e) 430 km; (f) 414 km; and (g) 138 km.

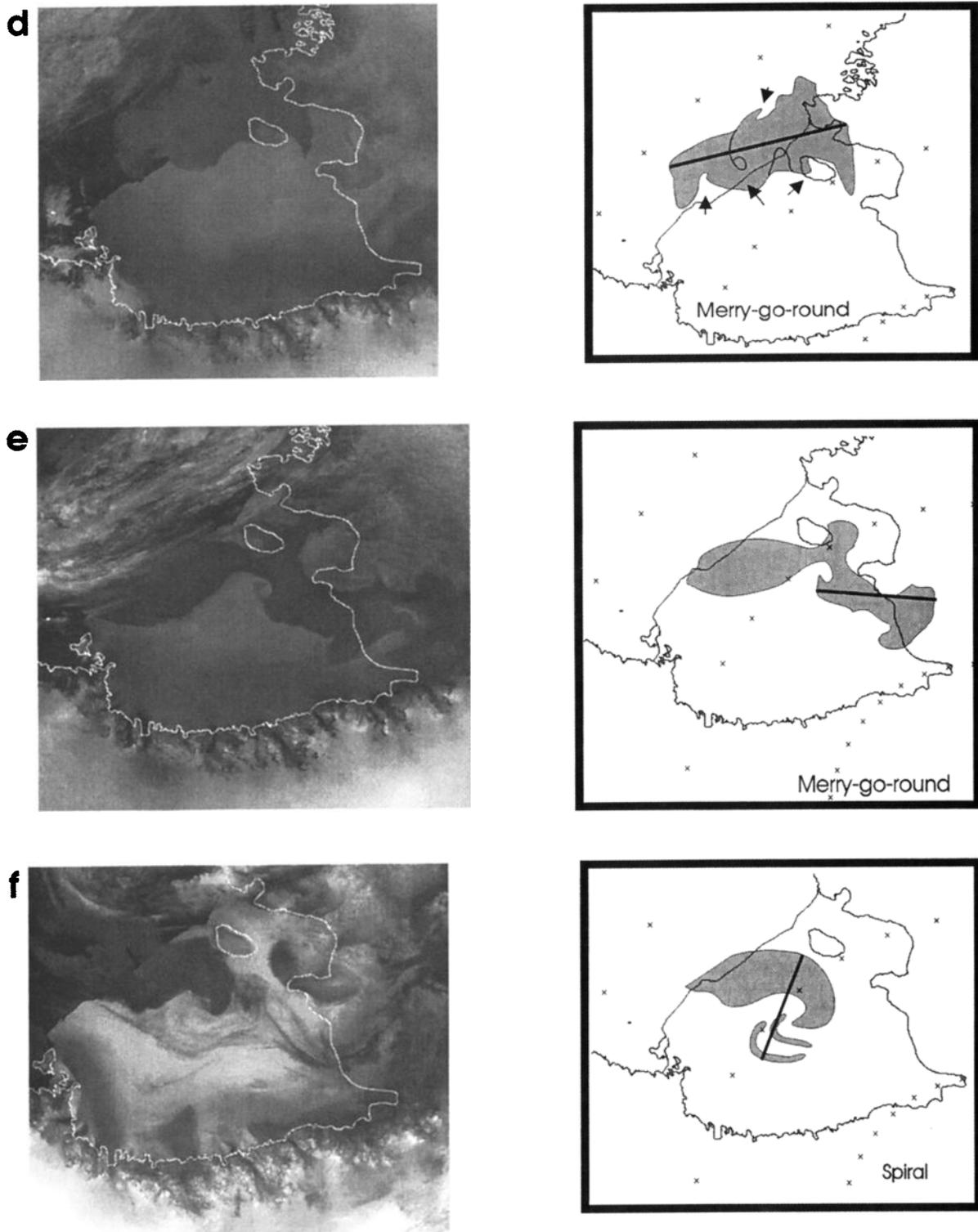


Figure 5. (continued)

southern hemispheres [e.g., *Rasmussen*, 1981; *Lyons*, 1983; *Forbes and Lottes*, 1985; *Carleton and Fitch*, 1993; *Carrasco and Bromwich*, 1994]. Figures 5a-5g show examples of mesoscale vortices that illustrate the pattern recognition used here.

2.2. Survey Results

Column 1 in Table 1 indicates the availability of satellite data for 1991. Overall, at least one satellite image was

available for 272 days (75% of the time; analyzable days). January was the month with fewest data, only 13 analyzable days. Days with no satellite coverage are randomly distributed throughout the remainder of the year. Column 2 in Table 1 (see also Table 2) shows the total monthly number of mesoscale cyclones observed throughout the year in each area. About 50% (71) of the total annual mesoscale cyclones (141) observed in Area 1 were located within Area 2. Of the total in Area 2, about 48% were concentrated within Area 3

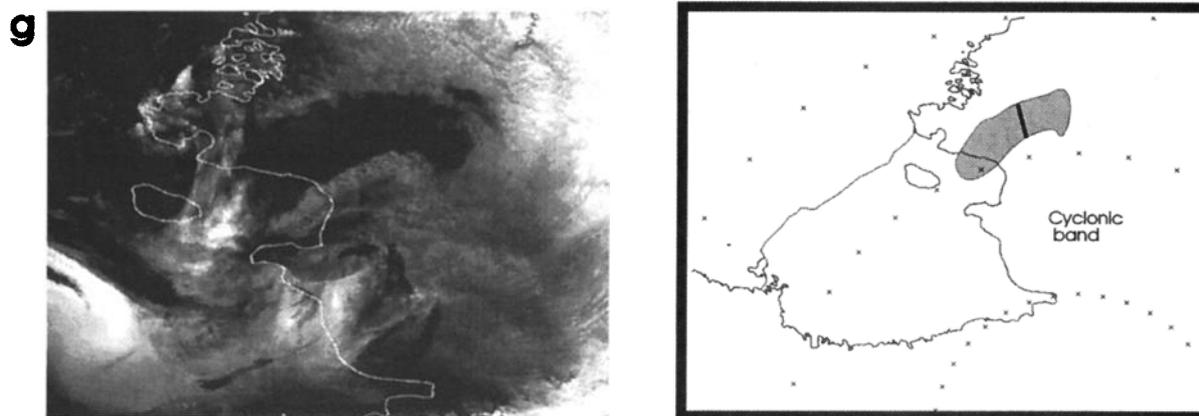


Figure 5. (continued)

(constituting 24% of the number in Area 1). This suggests that the mesoscale cyclonic activity tends to be concentrated over southern Marie Byrd Land. Figure 6 shows the spatial distribution of the initial appearance of the mesoscale vortices (mv) observed in 1991. Note that the mesoscale vortices cluster in southern Marie Byrd Land near Siple Coast. Because of the distortion of the area on a polar stereographic projection, the annual distribution of mesoscale cyclones was normalized to a fixed area (unit area = 10^4 km²). Table 2

summarizes the annual results. Once again, Area 3 arises as the most active one (2.0 mv per unit area), confirming the larger activity near Siple Coast, especially when compared with the activity outside of Area 3 (0.8 mv per unit area). Using Area 3 as unit area, it can be seen that while 34 mv per year were observed in Area 3, 14.7 mv per equivalent Area 3 were observed outside Area 3.

Figure 7 shows the trajectories of all mesoscale cyclones observed in 1991. Because of large gaps between

Table 1. Mesoscale Cyclonic Activity Over Marie Byrd Land and Ross Ice Shelf Within Areas 1, 2, and 3 According to Purely Satellite Imagery Examination During 1991

Month	Analyzable Days (1)	Number of Mesoscale Cyclones (2)			Equivalent Weekly Frequency (3)			Percent of Mesoscale Cyclones Tracked (4)
		Area 1	Area 2	Area 3	Area 1	Area 2	Area 3	
Jan.	13 (42%)	6	1	1	1.4	0.2	0.2	33
Feb.	18 (64%)	25	10	5	9.7	3.9	1.9	56
March	20 (65%)	20	14	10	7.0	4.9	3.5	65
April	26 (87%)	21	9	4	5.7	2.4	1.1	48
May	18 (58%)	8	4	3	3.1	1.6	1.2	43
June	23 (77%)	11	3	3	3.3	0.9	0.9	33
July	31 (100%)	11	7	2	2.5	1.6	0.5	55
Aug.	26 (84%)	10	4	1	2.7	1.1	0.3	90
Sept.	27 (90%)	1	0	0	0.3	0.0	0.0	100
Oct.	17 (55%)	8	5	2	3.3	2.1	0.8	100
Nov.	30 (100%)	13	10	3	3.0	1.2	0.7	84
Dec.	23 (74%)	7	4	0	2.1	1.2	0.0	29
Annual	272 (75%)	141	71	34	3.6	1.8	0.9	62

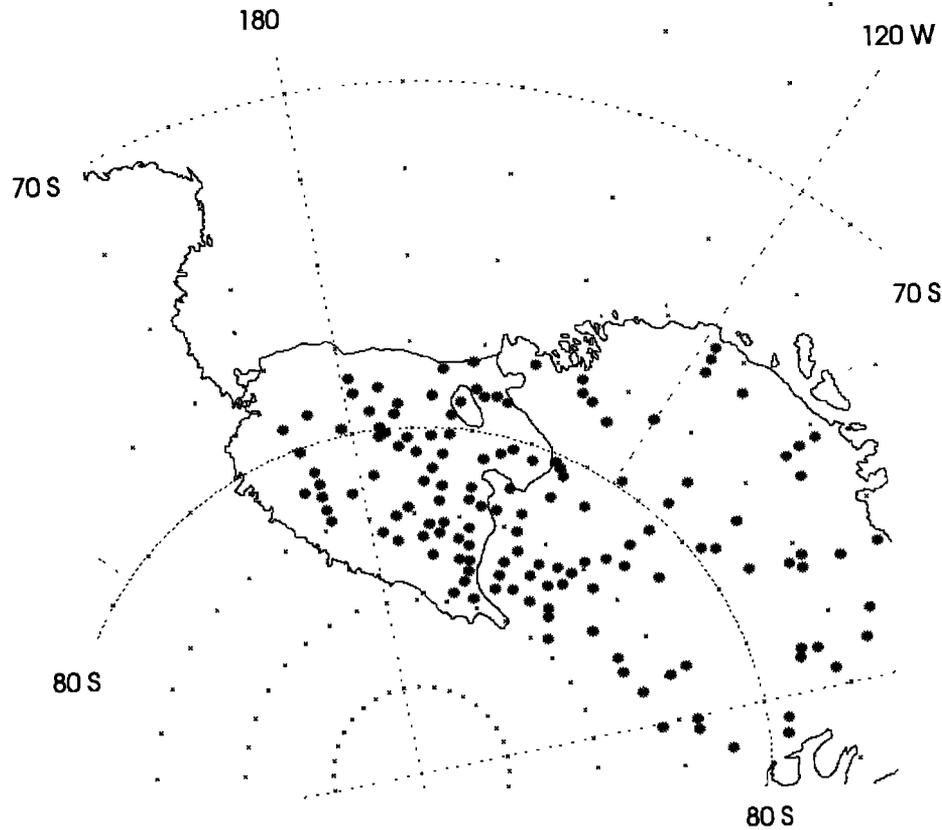


Figure 6. Annual spatial distribution of the initial appearance of mesoscale vortices observed on satellite images (dots) during 1991.

consecutive satellite images, only slightly more than half of the observed cyclones were tracked (column 4 in Table 1) from their initial detection to the point where they were last observed. At least one third of the trajectories were obtained from two consecutive satellite passes, a time interval of about 101 min. The average time interval was about 4 hours. That

is, on average, three to four consecutive satellite images were used to track the mesoscale cyclones. This suggests that their average lifetime was at least 5–6 hours. It can be seen that the trajectories indicate that many mesoscale vortices moved northwestward from near Siple Coast to the Ross Ice Shelf. This concurs with results obtained by Carrasco and

Table 2. Annual Summary of Mesoscale Cyclone Activity Within Areas 1, 2, and 3 for 1991 According to Satellite Imagery

	Within Area 1	Within Area 2	Within Area 3	Outside Area 3	Outside Area 2
Annual number of mesoscale vortices	141	71	34	107	70
Equivalent weekly average	3.6	1.8	0.9	2.7	1.8
Annual number of mesoscale vortices per unit area (10^4 km^2)	1.0	1.5	2.0	0.8	0.7
Annual equivalent number of mesoscale vortices per unit area (10^4 km^2)	1.3	1.9	2.8	1.1	1.0

Annual number of mesoscale cyclones per equivalent Area 3, but outside Area 3: 14.7; within Area 2: 24.6; and outside Area 2: 13.0.

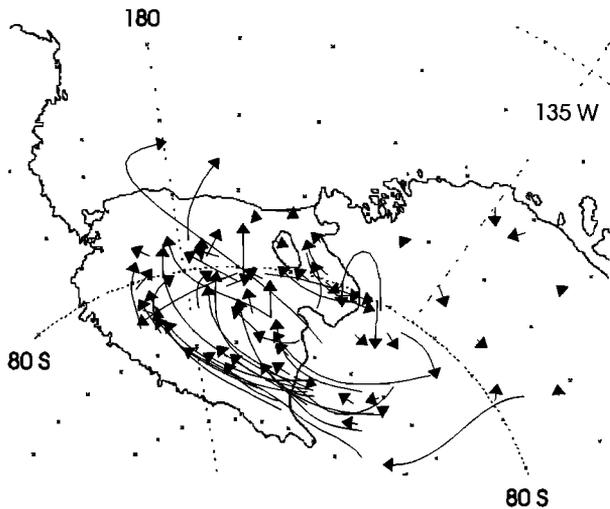


Figure 7. Trajectories of mesoscale vortices observed on satellite images during 1991.

Bromwich [1994, 1996] for 1988 and 1991, confirming that southern Marie Byrd Land is another source of mesoscale cyclones and that the northwestern side of the Ross Ice Shelf is a cyclolysis area. Other trajectories reveal the southeastward movement of mesoscale cyclones toward and over Marie Byrd Land, another area of frequent mesoscale cyclone dissipation. Of the mesoscale vortices tracked from Area 2 (46), 41% (19) were decaying features, as observed from their initial detection to the subsequent satellite image(s) while 46% (21) of them showed some degree of development. About 13% (6) did not exhibit any change. Considering only the mesoscale vortices tracked from Area 3, 64% (14) of the total (22) showed some degree of development and 27% (6) some degree of dissipation.

Column 3 in Table 1 indicates the monthly equivalent weekly frequency of mesoscale vortices within each area. This was calculated by dividing the total number of mesoscale cyclones by one-seventh of the analyzable days. This yields an unbiased weekly average of mesoscale cyclones observed through the examination of satellite images. On average, one (two) mesoscale cyclone was observed each week over southern Marie Byrd Land within Area 3 (2) during 1991. In terms of seasonal behavior within these two areas (Figure 8), a maximum frequency was noted during the autumn, and a minimum during spring. The maximum weekly frequency occurs in March, and the minimum in September (Table 1). Only one mesoscale cyclone was observed within the study region in September, and none within Area 3 in December.

2.3. Satellite Characteristics of Mesoscale Vortices

To study the characteristics of the mesoscale cyclones, the shape and brightness of the vortical-cloud signature were noted on the satellite images. The comma cloud, spiral form, merry-go-round, solid oval mass, and single shallow band [Forbes and Lottes, 1985] were the common types identified. Table 3 gives the description of each type adapted from Forbes and Lottes [1985] and examples are displayed in Figures 5a-5g. Table 4 shows the annual results of the type of vortices observed in the study region. It can be seen that about 63% of the total mesoscale vortices within Area 1 were

identified as comma-cloud features. About 27% of these features were located within Area 3. Of the total mesoscale vortices observed within Area 3 (34 mv), 70% of them were comma cloud types. Both spiral and merry-go-round forms account for only 12% of the total within Area 1 and neither was observed within Area 3. No clear seasonality was revealed for any type, although a higher percentage of comma-cloud features occurs in early and late summer. The maximum mesoscale activity in autumn concurs with a relatively small fraction of comma-cloud types.

The diameters of the vortices were measured from edge to edge of the vortical cloud. Examples in Figure 5 illustrate how this was done. In general, spiraliform vortices are almost symmetric, and their diameter can be easily measured once the cyclonic cloud is identified (Figure 5f). For comma clouds the diameter was measured from the rear edge to the front edge of the vortical cloud (Figures 5a-5c). The diameter for merry-go-rounds was given by the longest distance from edge to edge that includes all the vortical clouds (Figures 5d and 5e). For solid, oval mass the diameter was measured from edge to edge of the cyclonic cloud mass (Figure 5c), while for the single cyclonic band the diameter was given by the widest part of the cloud band (Figure 5g). Table 4 gives the annual average diameter for each type. The average diameter for all the mesoscale vortices was 279 km. Comparing this with the results obtained by Carrasco and Bromwich [1996] over the Ross Sea and Ross Ice Shelf in 1991, it can be noted that the average diameter near Siple Coast (238 km) is similar to the diameter found over the Ross Ice Shelf (247 km) but larger than those near Terra Nova Bay (200 km) and near Byrd Glacier (195 km). Similar results are

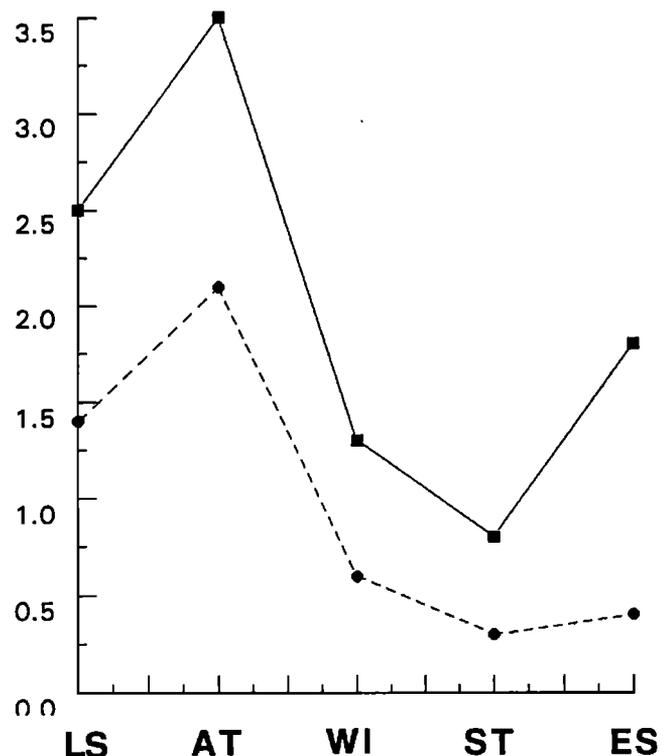


Figure 8. Seasonal variation of equivalent weekly frequency of mesoscale vortices within Areas 2 (solid line) and 3 (dashed line). LS, late summer; AT, autumn transition; WI, winter; ST, spring transition; and ES, early summer.

Table 3. Description of the Cloud Pattern Associated With West Antarctic Mesoscale Vortices Observed on Infrared Satellite Imagery

Type	Description	Example
Comma cloud	Front-like shape	Figures 5a-5c
Spiral form	Two or more cloud bands spiral into a common center	Figure 5f
Merry-go-round	Ring of mesoscale vortices	Figures 5d-5e
Oval, solid mass	Cyclonic-cloud mass with no apparent vortical center	Figure 5c
Single cyclonic band	Cyclonic-cloud band with no apparent vortical center	Figure 5g

found when comparison is done with the mesoscale cyclone survey carried out for 1988 [Carrasco and Bromwich, 1994].

The depth of the vortical cloud was qualitatively estimated because no concurrent radiosonde data are available over Marie Byrd Land. For this, the brightness of the vortical cloud was noted. In infrared satellite images, low (middle/high) cloud appears as dark or gray (white or light) tones; therefore dark (white) vortical cloud identified shallow (deep) vortices. Throughout the survey all the mesoscale vortices were of low clouds (shallow clouds). Two tones were distinguished, dark (almost black on the satellite image) and gray. About 62% (38%) of the total mesoscale vortices observed within Area 1 were dark (gray). A limited random survey of the cloud-top temperatures (CTT) associated with mesoscale vortices was conducted to obtain a quantitative estimate of the vertical extent of the mesoscale vortices. It is assumed that most of the clouds (except cirrus) are nearly blackbodies, implying that their emissivity is close to 1. The

average CTT was compared with climatological temperature profiles (11-year average 1972-1982) at McMurdo Station. CTT for dark clouds ranged between -16 and -24°C from summer to winter, which correspond to 790 hPa and 890 hPa, respectively. CTT for gray vortical clouds was about -29°C year-round, which climatologically corresponds to 570 hPa in summer and 720 hPa in winter. The CTT evaluation indicates that the majority of the mesoscale cyclones were limited to the lower troposphere, more than likely below 700 hPa. Of the total observed within Area 1, about 14% of them that developed during the early and late summer seasons could have exceeded the 700-hPa level.

3. Synoptic-Scale Pattern

To analyze the synoptic-scale circulation accompanying the presence of mesoscale cyclones within Area 3, the numerical digital analyses from the Australian Bureau of

Table 4. Annual Summary of the Satellite Classification of Mesoscale Vortices Observed Over Marie Byrd Land and Ross Ice Shelf Within Area 1, and Near Siple Coast Within Area 3

Type of vortex	Area 1			Area 3		
	N	P	d	N	P	d
Comma cloud	89	63	257	24	70	253
Spiraliform	9	6	386	0	-	-
Merry-go-round	9	6	451	0	-	-
Oval, solid mass	19	14	281	5	15	271
Single shallow band	15	11	129	5	15	133
Total/average	141		279	34		238

N, number of mesoscale vortices; P, percentage of mesoscale vortices with respect to the total number observed in the respective area; and d, diameter in kilometers.

Meteorology were used to construct averages and anomalies of the sea level pressure, 700-hPa and 500-hPa heights, and the 1000-500-hPa thickness for cyclonic days (days for which a mesoscale cyclone was observed on satellite imagery within Area 3) and noncyclonic days (no mesoscale cyclone was observed). Calculations were conducted for each season of 1991 because the mesoscale cyclones are not equally distributed throughout the year. Overall, the results for all fields for cyclonic days show positive anomalies with respect to the seasonal averages over Marie Byrd Land. Figures 9a and 9b are the sea level pressure and 500-hPa height differences between cyclonic and noncyclonic days for the autumn transition, which are presented as an example of the synoptic-scale patterns that are more or less the same as those obtained for the other seasons (shaded areas indicate where the differences are statistically significant). As with the

anomalies, the pressure and the 500-hPa geopotential height for cyclonic days over Marie Byrd Land and the Ross Ice Shelf are higher than for noncyclonic days. This indicates that mesoscale cyclogenesis near Siple Coast occurs, in principle, in conjunction with a warmer synoptic-scale environment. The analyses show a strong negative center offshore from Marie Byrd Land (around 60°S), reflecting the synoptic-scale circulation that prevails over this area on cyclonic days. This environment can support warm air advection into the interior of West Antarctica in association with passing and/or decaying synoptic-scale cyclones. In addition, it may favor katabatic drainage from East Antarctica, as discussed next.

Murphy and Simmonds [1993] studied katabatic wind events at Casey Station (66°S, 110°E) using a general circulation model. Their synoptic-scale pattern associated with simulated katabatic events at Casey is similar to that found for cyclonic days (Figure 9), that is, a wavenumber four pattern around Antarctica. This intriguing coincidence may indicate that katabatic wind drainage from the Antarctic plateau is a continental-scale event. Observations and simulations of the several katabatic confluence zones around Antarctica should clarify this situation.

Because the survey revealed that the maximum and minimum cyclogenetic activity within Areas 2 and 3 occurred in March and September, a comparison of these 2 months is performed. The monthly mean synoptic-scale pattern for these two 1991 months provides insight into the synoptic-scale environment favoring or inhibiting mesoscale cyclogenesis. Figures 10a-10d present the Australian mean sea level pressure and 500-hPa geopotential heights analyses for March and September 1991. Comparison between both sea level pressure charts (Figures 10a and 10c) indicates that the pressure gradient across the Ross Ice Shelf and Marie Byrd Land was weaker during March. In September, the 500-hPa low was located above the low at the surface (Figures 10c and 10d), indicating that a barotropic environment affected Marie Byrd Land; in March the 500-hPa low was centered over the western Ross Ice Shelf, to the west of the low at the surface (Figures 10a and 10b). The southwestward tilt of the vertical axis of the low in March indicates a baroclinic environment over Marie Byrd Land, a condition that favors cyclogenesis. The different synoptic-scale environment for the 2 months suggests that warm air advection toward southern Marie Byrd Land was likely to have been more frequent and/or stronger during March.

On the other hand, the mean potential temperature measured by the automatic weather station (AWS) at South Pole (Clear Air [*Keller et al.*, 1993]) in March (−31.9°C) was colder than in September (−29.6°C; see Figure 11 for reference). The long-term (1986-1992) monthly mean potential temperature in March is −29.4°C, and in September is −32.8°C. The potential temperature difference between Byrd Station (West Antarctica) and South Pole (East Antarctica) in March (17.4°C) was higher than its long-term monthly mean (15.6°C), while in September it was slightly lower (13.1°C compared to 13.5°C). The colder environment in March than in September at South Pole suggests stronger and/or more frequent katabatic airflow from East Antarctica to southern Marie Byrd Land. This indicates that the baroclinic zone formed by the juxtaposition of katabatic winds coming from East and West Antarctica [*Bromwich and Liu*, 1996] was stronger and/or more frequent in March.

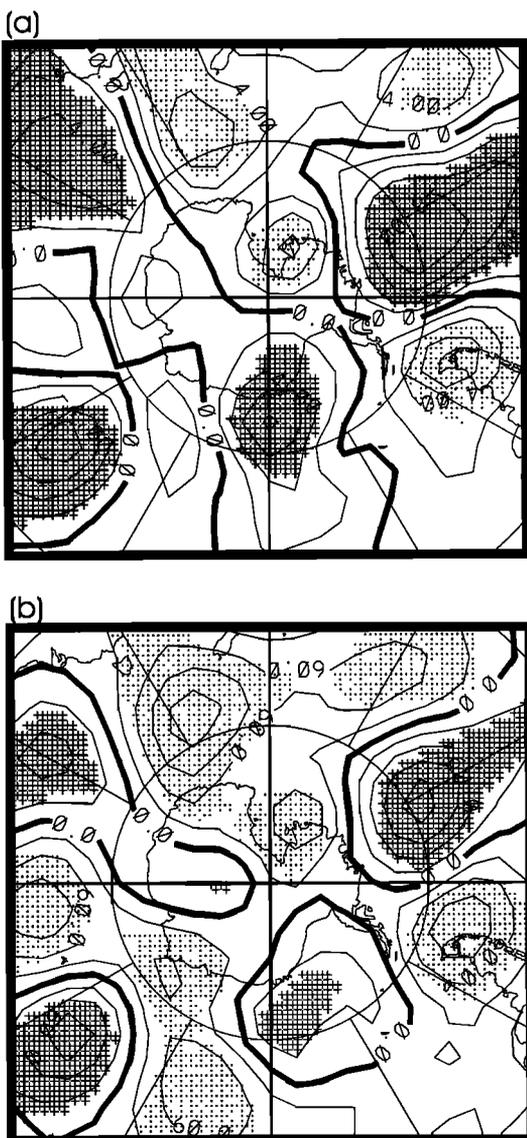


Figure 9. Australian (a) sea level pressure and (b) 500-hPa geopotential height differences between cyclonic and noncyclonic days for autumn transition (March and April). Contour interval is 2 hPa in Figure 9a and 30 gpm in Figure 9b. Stippled and crossed areas indicate that positive and negative differences, respectively, are statistically different from zero at the 95% confidence level.

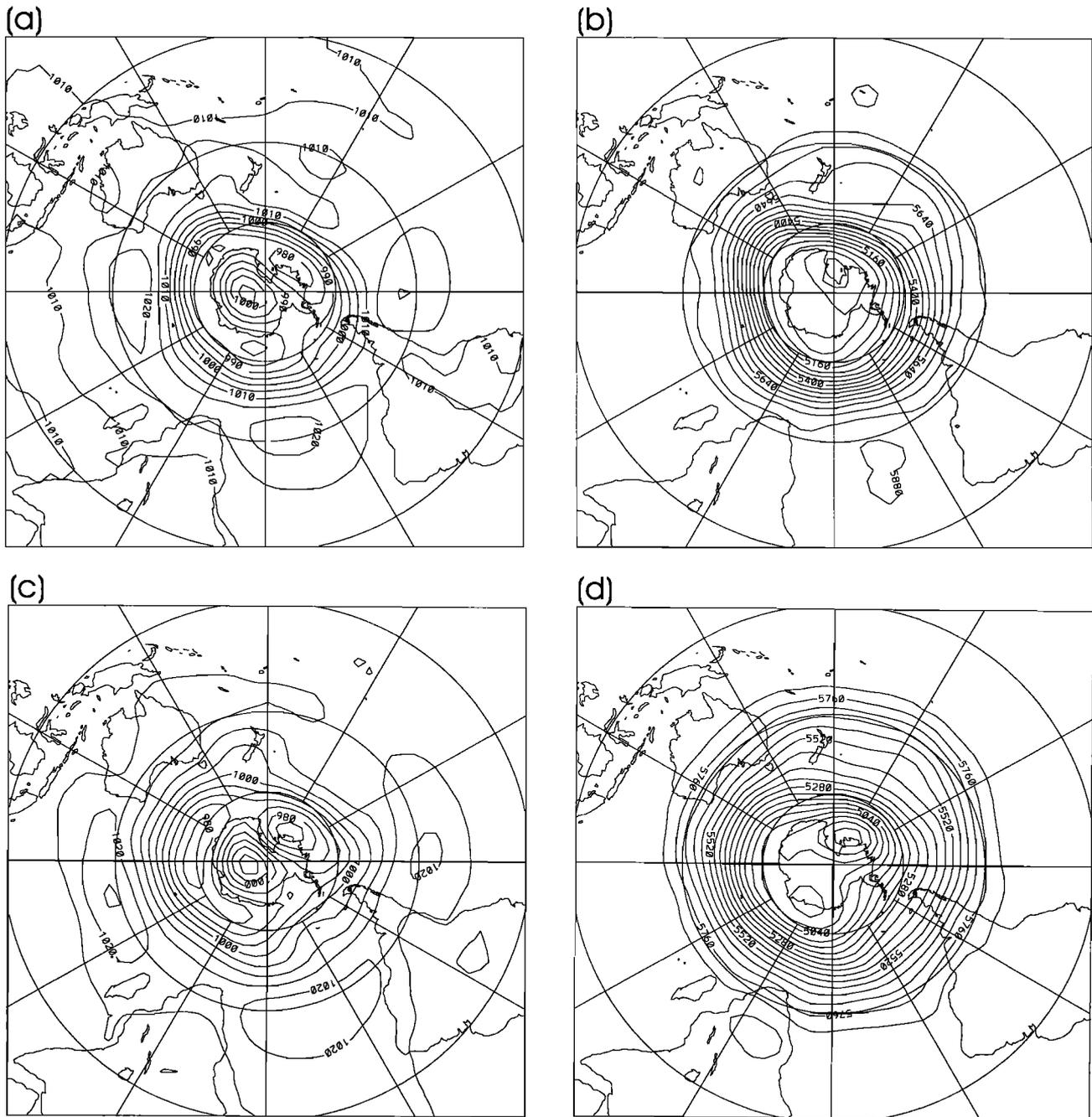


Figure 10. Australian sea level pressure and 500-hPa analyses for (a and b) March and (c and d) September 1991. Contour interval in Figures 10a and 10c is 5 hPa. Contour interval in Figures 10b and 10d is 60 gpm.

Unfortunately, no winds were recorded in September at Lettau AWS (82.6°S, 174.3°W) on the southeastern Ross Ice Shelf, which is a key station for evaluation of katabatic wind propagation from Siple Coast area. However, a comparison of the average wind velocity between cyclone days (days for which a mesoscale cyclone was observed on satellite imagery within Area 3) and noncyclone days (no mesoscale cyclone was observed) during March did not reveal a significant difference between them. This indicates that the formation and/or development of mesoscale cyclones over southern Marie Byrd Land is not necessarily associated with the propagation of katabatic winds onto the Ross Ice Shelf. This

concurs with the fact that the stronger pressure gradient in September is associated with a minimum mesoscale cyclone activity over the southern Marie Byrd Land despite the more favorable geostrophic support for propagation of katabatic winds from Marie Byrd Land.

Bromwich et al. [1992, 1993] and *Carrasco and Bromwich* [1993b] found that the northwestward propagation of the katabatic winds across the Ross Ice Shelf is, on average, supported by a synoptic-scale sea level pressure field (and 500 hPa) similar to that resolved for September 1991 (Figure 10c). A barotropic environment with a low centered offshore from Marie Byrd Land is more likely to support the

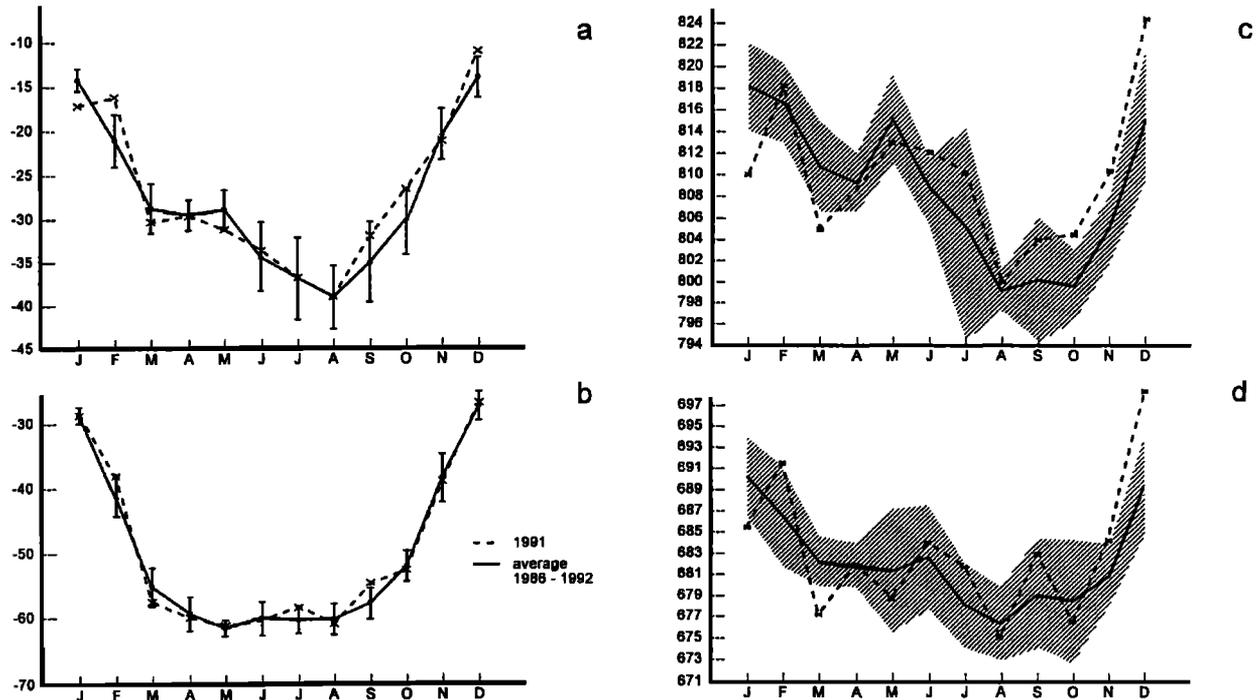


Figure 11. Annual cycle of monthly mean air temperatures and station pressures (solid lines) at Byrd (panels a and c, respectively; 1984-1992) and at Clean Air AWS, South Pole (panels b and d, respectively; 1986-1992) along with the monthly values (dashed lines) during 1991. Shadow areas in Figures 11c and 11d define ± 1 s.d., as do the bars in Figures 11a and 11b.

northwestward propagation of the katabatic winds. A baroclinic troposphere (or less barotropic) affecting southern Marie Byrd Land (like in March), where a low-level thermal wind exists, is more favorable for mesoscale cyclogenesis. In summary, two aspects seem to be simultaneously present over southern Marie Byrd Land in March, which were not during September nor the rest of the year; they are warm air advection and more frequent and/or stronger katabatic winds descending from East Antarctica. Note (see Table 1) that 50% (71%) of the mesoscale cyclones observed within Area 1 (2) during March were found within Area 3, indicating that for this month the spatial distribution of mesoscale vortices was more concentrated near Siple Coast than during the rest of the year.

To infer whether or not the seasonal (or monthly) behavior of mesoscale cyclones found in 1991 may apply to other years, the 1991 monthly means of the air temperature and station pressure at Byrd and Clean Air (South Pole) AWS are compared with the long-term (1984-1992) monthly means in Figure 11. It can be seen that the monthly mean temperatures (Figures 11a and 11b) follow the climatological trends, and most of the months fall within the ± 1 standard deviation (s.d.) band. However, an abrupt cooling occurred from February to March at both sites. On the other hand, the station pressure variability in 1991 at both locations (Figure 11) generally falls within the expected year-to-year variability (as given by the 1 s.d. calculations) except for January, March, November, and December (and October at Byrd AWS). However, a maximum in February followed by an abrupt pressure decrease toward March does not concur with the climatological trend at both stations. From this, it can be inferred that the maximum frequency of mesoscale cyclones

near Siple Coast in March and/or autumn transition in 1991 may not be applicable to other years and, probably, neither is the result for January. It is suggested that the maximum frequency of mesoscale cyclones over southern Marie Byrd Land usually occurs during the late austral summer. It decreases during winter, reaching a minimum toward the end and/or the beginning of the spring transition. It is important, however, to mention that the above behavior was based solely on satellite imagery analysis, which means that in order for a mesoscale vortex to be observed it needs either the moisture to develop a cloud signature, or to steer surrounding clouds into its cyclonic circulation; therefore, many mesoscale cyclones may be missing from the satellite analysis, as has been found over the Ross Ice Shelf [e.g., Carrasco and Bromwich, 1996].

4. Discussion and Conclusions

A survey of mesoscale cyclones over southern Marie Byrd Land and adjacent areas has been carried out for the calendar year of 1991. Therefore the analysis is valid only for this year although some intra-annual results may apply to other years. It was found that the mesoscale cyclonic activity was higher near Siple Coast (within Area 3) than elsewhere within the study region. On average, one (or two) mesoscale cyclone can be observed each week within Area 2 (3); however, a marked seasonality was found in this year. A maximum (minimum) equivalent weekly frequency occurred in March (September), which is the transition period between summer and winter (winter and summer). The large-scale pattern suggests that enhanced katabatic winds blowing from near South Pole, East Antarctica to southern Marie Byrd Land, and

stronger and/or more frequent poleward warm air advection into West Antarctica were associated with the greater mesoscale cyclonic activity in March. The annual number of mesoscale vortices per unit area (10^4 km^2) near Siple Coast (Area 3) was 2.0, which was much higher than elsewhere within the study region, and confirms the greater mesoscale cyclonic activity in this area. This value, however, is lower than the activity observed near Byrd Glacier and Terra Nova Bay found in 1988 [Carrasco and Bromwich, 1994] and in 1991 [Carrasco and Bromwich, 1996].

Trajectories of the mesoscale cyclones also confirmed southern Marie Byrd Land as a source of these features. They also showed that the majority of the mesoscale cyclones were last observed over the central or northern part of the Ross Ice Shelf, confirming this region as a cyclolysis area, as indicated previously by Carrasco and Bromwich [1994, 1996]. The relatively high fraction of mesoscale cyclones showing some development in Area 3 with respect to Area 2 can be associated with the position of the boundary layer baroclinic zone, which is over the southernmost part of Marie Byrd Land, near Siple Coast, as inferred from the integrated analysis of the studies by Bromwich and Liu [1996], Liu and Bromwich [1997], and Bromwich et al. [1994]. Some easterly and south-southeasterly trajectories toward or over Marie Byrd Land also confirm this as another cyclolysis area, probably for mesoscale cyclones forming and/or developing near Terra Nova Bay and Byrd Glacier [Bromwich, 1991; Carrasco and Bromwich, 1994, 1996]. The overall trajectory of the mesoscale cyclones concurs with the average synoptic-scale geostrophic circulation associated with the semi-permanent surface synoptic-scale cyclone located to the northeast of the Ross Ice Shelf. This suggests that most of the mesoscale cyclones (at least those which were tracked) are steered by the lower tropospheric circulation. If some mesoscale cyclones which form over southern Marie Byrd Land move westward onto the Ross Ice Shelf before being first detected on satellite imagery, this can explain the high concentration of vortices on the ice shelf just to the west of Siple Coast (Figure 6).

Unfortunately, the gaps between consecutive satellite images impede study of the cloud evolution and of the duration of the mesoscale vortices. However, identification of the initially observed cloud signatures indicates that more than a half of the mesoscale vortices were of comma-cloud type. Similar results were found over the Ross Sea and Ross Ice Shelf area for 1988 and 1991 [Carrasco and Bromwich, 1994, 1996]. Carleton and Carpenter [1989] and later Carleton and Fitch [1993], who carried out a similar mesoscale survey but during winter months (June-September and June-August, respectively) and mainly over the sea ice and open ocean, found that comma-cloud vortices dominate in the southern hemisphere. The present results and those of Carrasco and Bromwich [1994, 1996] confirm that comma-cloud vortices are the dominant type, not only over the ice sea and open ocean, but also near the coastal areas and over the interior of West Antarctica. The average diameter of the comma-cloud vortices was about 250 km, which is larger than that found near Terra Nova Bay and Byrd Glacier areas during 1988 and 1991. It is close to the average diameter found for the mesoscale cyclones observed over the Ross Ice Shelf. The fact that the katabatic winds converge into narrower topographic troughs (glaciers) near Terra Nova Bay and Byrd Glacier than Siple Coast, may account for the

difference in diameter. The different physical characteristics of the katabatic airflow descending from East Antarctica (drier and colder) compared to that from West Antarctica may also account for the smaller diameter of the mesoscale cyclones near Terra Nova Bay and Byrd Glacier as well as the larger mesoscale cyclonic activity. All the mesoscale vortices observed over West Antarctica were stratiform low-cloud features, indicating that most of them developed within the lower troposphere, more than likely below 700 hPa, as confirmed by the CTT analysis.

The seasonal behavior of mesoscale cyclone formation was based solely on satellite imagery and must be viewed with caution. More likely, the baroclinic zone formed by the juxtaposition of both katabatic drainage flows is a year-round feature, and it should be weaker during the summer due to a weaker inversion layer over Antarctica [Schwerdtfeger, 1970]. This may indicate that many mesoscale cyclones during winter are not detected because of the lack of moisture (and cloud) in the interior of West Antarctica. On the other hand, they are probably weak features that undergo significant development only when supported by the synoptic-scale environment. Warm air advection that enhances the preexisting baroclinic zone seems to play an important role in this regard [Bromwich and Carrasco, 1995], as has been found near Byrd Glacier and Terra Nova Bay [Carrasco and Bromwich, 1993a, 1994, 1996].

The annual spatial pattern of snowfall over Antarctica shows that maximum values are concentrated along the coastal slopes of the continent with small amounts in the interior. Coastal precipitation is primarily associated with passing and/or decaying synoptic-scale storms that rapidly weaken and dissipate when they move onto the high plateau of the Antarctic continent. Therefore, while organized storm clouds from synoptic-scale cyclones or fronts are the source for snowfall accumulation in coastal areas, it is believed that the semicontinuous fall of ice crystals from cloud-free skies becomes the dominant type of precipitation over the interior [Bromwich, 1988]. Although this is true most of the time over East Antarctica, the comparatively low elevation of West Antarctica and its geographical location with respect to the synoptic-scale circulation may result in the precipitation over the interior of West Antarctica being associated with synoptic-scale events.

The present results along with those reported by Carrasco and Bromwich [1994] indicate that mesoscale cyclones may contribute to the annual precipitation over the Marie Byrd Land and Ross Ice Shelf areas. The annual accumulation map [Giovinetto and Bentley, 1985] shows that precipitation is higher over the southernmost part of Marie Byrd Land and all along the east side of the Transantarctic Mountains. The orographic effect of the steep mountains upon the airflow moving toward it is the primary mechanism for snowfall generation along the mountains. Circulation toward the Transantarctic Mountains can be caused by passing and/or decaying synoptic-scale lows over the Ross Sea [Vickers, 1966], so that winds from the northeast quadrant may affect the Marie Byrd Land and Ross Ice Shelf regions. The overall trajectories of the mesoscale cyclones indicate that these features can be partly responsible for the snowfall along the Transantarctic Mountains. Northerly and northeasterly winds on their east side take place when they move northwestward onto the Ross Ice Shelf. On the other hand, for the case studied by Bromwich and Carrasco [1995; see also Smith and

Teeuwisse, 1994], drifting snow was the major weather event associated with the mesoscale vortex, indicating another role of these features. Further studies are needed to accurately determine the impacts of mesoscale cyclones. The deployment of an AWS network over southern Marie Byrd Land early in 1995 provides surface observations throughout the year. These data along with the continued collection of high-resolution satellite information at McMurdo and Palmer stations, and the operational numerical model products, will permit detailed studies of individual cases as well as derivation of mesoscale cyclone climatologies.

Acknowledgments. This research was sponsored by the Office of Polar programs of the National Science Foundation via grants OPP-9117448, OPP-9218949, and OPP-9417983 to David H. Bromwich. The satellite imagery was obtained from Robert Whritner of the Arctic and Antarctic Research Center at Scripps Institution of Oceanography (NSF grants OPP-8815818 and OPP-9414276). Automatic weather station data were provided by Charles R. Stearns at the University of Wisconsin-Madison (NSF grants OPP-8606385, 8818171 and 9015586). Byrd Polar Research Center contribution 1035.

References

- Bromwich, D.H., Snowfall in high southern latitudes, *Rev. Geophys.* 26(1), 149-168, 1988.
- Bromwich, D.H., Subsynoptic-scale cyclone developments in the Ross Sea sector of the Antarctic, in *Polar and Arctic Lows*, edited by P.F. Twitchell, E.A. Rasmussen, and K.L. Davidson, pp. 331-345, A Deepak, Hampton, Va., 1989.
- Bromwich, D.H., Mesoscale cyclogenesis over the southwestern Ross Sea linked to strong katabatic winds, *Mon. Weather Rev.*, 119, 1736-1752, 1991.
- Bromwich, D.H., and J.F. Carrasco, An investigation of an intense mesoscale cyclone over southern Marie Byrd Land, West Antarctica, in *Fourth Conference on Polar Meteorology and Oceanography*, pp. 238-243, Am. Meteorol. Soc., Boston, Mass., 1995.
- Bromwich, D.H., and Z. Liu, An observational study of the katabatic wind confluence zone near Siple Coast, West Antarctica, *Mon. Weather Rev.*, 124, 462-477, 1996.
- Bromwich, D.H., J.F. Carrasco, and C.R. Stearns, Satellite observations of katabatic wind propagation for great distances across the Ross Ice Shelf, *Mon. Weather Rev.*, 120, 1940-1949, 1992.
- Bromwich, D.H., J.F. Carrasco, Z. Liu, and R.-Y. Tzeng, Hemispheric atmospheric variations and oceanographic impacts associated with katabatic surges across the Ross Ice Shelf, Antarctica, *J. Geophys. Res.*, 98, 13,045-13,062, 1993.
- Bromwich, D.H., Y. Du, and T.R. Parish, Numerical simulation of winter katabatic winds from West Antarctica crossing Siple Coast and the Ross Ice Shelf, *Mon. Weather Rev.*, 122, 1417-1435, 1994.
- Bromwich, D.H., F.M. Robasky, R.I. Cullather, and M.L. Van Woert, The atmospheric hydrologic cycle over the Southern Ocean and Antarctica from operational numerical analyses, *Mon. Weather Rev.*, 123, 3518-3538, 1995.
- Carleton, A., and D.A. Carpenter, Satellite climatology of "polar air" vortices for the Southern Hemisphere winter, in *Polar and Arctic Lows*, edited by P.F. Twitchell, E.A. Rasmussen, and K.L. Davidson, pp. 401-413, A Deepak, Hampton, Va., 1989.
- Carleton, A., and M. Fitch, Synoptic aspects of Antarctic mesocyclones, *J. Geophys. Res.*, 98, 12,997-13,018, 1993.
- Carrasco, J.F., and D.H. Bromwich, Mesoscale cyclogenesis dynamics over the southwestern Ross Sea, Antarctica, *J. Geophys. Res.*, 98, 12,973-12,995, 1993a.
- Carrasco, J.F., and D.H. Bromwich, Satellite and automatic weather station analyses of katabatic surges across the Ross Ice Shelf, in *Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations, Antarct. Res. Ser.*, vol. 61, edited by D.H. Bromwich and C.R. Stearns, pp. 93-108, AGU, Washington D.C., 1993b.
- Carrasco, J.F., and D.H. Bromwich, Climatological aspects of mesoscale cyclogenesis over the Ross Sea and Ross Ice Shelf regions of Antarctica, *Mon. Weather Rev.*, 122, 2405-2425, 1994.
- Carrasco, J.F., and D.H. Bromwich, Mesoscale cyclone activity near Terra Nova Bay and Byrd Glacier, Antarctica during 1991, *Global Atmos. Ocean Syst.*, 5, 43-72, 1996.
- Forbes, G.S., and W.D. Lottes, Classification of mesoscale vortices in polar airstreams and the influence of large scale environment on their evolution, *Tellus, Ser. A*, 37, 132-155, 1985.
- Giovinetto, M.B., and C.R. Bentley, Surface balance in ice drainage systems of Antarctica, *Antarct. J. U.S.*, 20(4), 6-13, 1985.
- Keller, L.M., G.A. Weidner, and C.R. Stearns, Antarctic automatic weather station data for the calendar year 1991, 356 pp., Dep. of Atmos. and Ocean. Sci., Univ. of Wisconsin-Madison, 1993.
- Lettau, B., The transport of moisture into the Antarctic interior, *Tellus*, 21, 331-340, 1969.
- Liu, Z., and D.H. Bromwich, Dynamics of the katabatic wind confluence zone near Siple Coast, West Antarctica, *J. Appl. Meteorol.*, 36(2), 97-118, 1997.
- Lyons, S.W., Characteristics of intense Antarctic depressions, in *First International Conference on Southern Hemisphere Meteorology*, pp. 238-240, Am. Meteorol. Soc., Boston, Mass., 1983.
- Mather, K.B., and G.S. Miller, Wind drainage off the high plateau of Eastern Antarctica, *Nature*, 209, 281-284, 1966.
- Murphy, B.F., and I. Simmonds, An analysis of strong wind events simulated in a GCM near Casey in the Antarctic, *Mon. Weather Rev.*, 121, 522-534, 1993.
- Parish, T.R., and D.H. Bromwich, The inversion wind pattern over West Antarctica, *Mon. Weather Rev.*, 114, 849-860, 1986.
- Parish, T.R., and D.H. Bromwich, The surface windfield over the Antarctic ice sheets, *Nature*, 328, 51-54, 1987.
- Parish, T.R., and D.H. Bromwich, Continental-scale simulation of the Antarctic katabatic wind regime, *J. Clim.*, 4(2), 135-146, 1991.
- Radok, U., On the energetics of surface winds over the Antarctic ice cap, *Energy Fluxes over Polar Surfaces, Tech. Note 129*, pp. 69-100, World Meteorol. Organ., Geneva, Switzerland, 1973.
- Rasmussen, E., An investigation of a polar low with spiral cloud structure, *J. Atmos. Sci.*, 38, 1785-1792, 1981.
- Schwerdtfeger, W., The climate of the Antarctic, in *World Survey of Climatology*, vol. 14, edited by S. Orvig, pp. 253-355, Elsevier, New York, 1970.
- Smith, S.R., and S. Teeuwisse, Whiteout!, *Weatherwise*, 47(5), 54 and 50, 1994.
- Smith, S.R., J.F. Carrasco and Z. Liu, A case study of a Siple Coast mesoscale cyclone, *Antarct. J. U.S.*, 28(5), 283-285, 1993.
- Van Woert, M.L., R.H. Whritner, D.E. Waliser, D.H. Bromwich, and J.C. Comiso, ARC: A source of multisensor satellite data for polar science, *Eos, Trans. AGU*, 73(6), 65, 75-76, 1992.
- Vickers, W., A study of ice accumulation and tropospheric circulation in western Antarctica, in *Studies in Antarctic Meteorology, Antarct. Res. Ser.*, vol. 9, edited by M.J. Rubin, pp. 135-176, AGU, Washington, D.C., 1966.

D. H. Bromwich and Z. Liu, Polar Meteorology Group, Byrd Polar Research Center, 108 Scott Hall, 1090 Carmack Road, Ohio State University, Columbus, OH 43210-1002. (e-mail: bromwich@polarmet1.mps.ohio-state.edu)

J. F. Carrasco, Dirección Meteorológica de Chile, Casilla 717, Santiago, Chile. (e-mail: clima@meteochile.cl)

(Received January 10, 1996; revised February 28, 1997; accepted March 21, 1997)