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A survey of mesocyclones near the Antarctic Peninsula using digital satellite imagery collected at Palmer Station

JORGE F. CARRASCO[1] and DAVID H. BROMWICH[2]

ABSTRACT

A survey of mesoscale vortices near the Antarctic Peninsula was conducted during August 1989 - February 1990 period. Maximum occurrences of mesoscale vortices occurred in December and the minimum in August. Over the Bellingshausen/Amundsen Sea region most of the vortices tend to move north-eastward, while over the Weddell Sea sector they do not show a preferential direction. The spatial frequency distribution of mesoscale vortices shows a close association with the average position of the northern limit of the sea-ice pack. The highest spatial monthly frequency was found over the western side of the Weddell Sea, in the lee of the Antarctic Peninsula. In the scientific literature a comparison with the spatial frequency distribution for September 1983 - February 1984 showed the highest frequency just to the north of Bellingshausen Sea, indicates interannual variability of mesoscale cyclonic activity on both sides of the Peninsula. This interannual variation is found to be linked to the interannual variability in the large-scale atmospheric circulation.

Key words: mesoscale cyclones, sea ice, cold and warm air advection, synoptic analysis

Estudio de mesociclones en las cercanías de la península Antártica usando imágenes satelitales digitales coleccionadas en la Estación Palmer

JORGE F. CARRASCO[1] y DAVID H. BROMWICH[2]

RESUMEN

Un estudio de vórtices a mesoescala en las cercanías de la Península Antártica fue realizado para el período comprendido entre agosto 1989 y febrero 1990. La máxima ocurrencia de ciclones a mesoescala tuvo lugar en el mes de diciembre y mínima en agosto. Sobre la región de los mares de Bellingshausen y Amundsen la mayoría de los vórtices presentan un desplazamiento hacia el noreste, mientras que en el sector del mar de Weddell las trayectorias no muestran una dirección preferente. La distribución de la frecuencia espacial de los ciclones a mesoescala muestra una relación con la posición promedio del límite norte de la placa de hielo marino. La más alta frecuencia de la distribución mensual de ciclones a mesoescala fue encontrada en el lado oeste del mar de Weddell, a sotavento de la Península Antártica. En la literatura científica se halla una comparación con la distribución espacial mensual observada desde septiembre 1983 a febrero 1984 que muestra la más alta frecuencia ligeramente al norte del Mar de Bellingshausen, indica una variabilidad interanual de la actividad de los ciclones a mesoescala a ambos lados de la península. Esta variación interanual está relacionada con la variabilidad interanual en la circulación atmosférica a escala planetaria.

Palabras clave: ciclones a mesoscala, hielo marino, advección de aire frío y cálido, análisis sinóptico

[1] Dirección Meteorológica de Chile, Casilla 717, Santiago-Chile y Universidad de Valparaíso, Depto. de Meteorología y Física, Valparaíso, Chile.

[2] Polar Meteorology Group, Byrd Polar Research Center and Atmospheric Research program, The Ohio State University, Columbus Ohio 43210, USA.

INTRODUCTION

Early satellite studies of synoptic-scale cyclones for the Southern Hemisphere suggested that the highest occurrence of mesoscale cyclones (diameter less than 1000 km) may occur during the winter season as it was found in the Northern Hemisphere (Carleton, 1979; Carleton and Carpenter, 1990). However, studies carried out during the last decade over the southern polar region have revealed that a large number of mesoscale cyclones can also be observed during the transition to summer seasons (Heinemann, 1990, 1996; Turner and Row, 1989; Turner and Thomas, 1992,1994; Turner *et al.*, 1996, Bromwich, 1991; Carrasco and Bromwich, 1992, 1994, 1996). The consensus from these results is that mesoscale vortices can be found throughout the year with an apparent frequency maximum during the spring-summer period (Turner *et al.*, 1993).

Mesoscale vortices can be observed at any longitude and latitude over the southern polar open ocean, the sea ice and near the coastal margin of the Antarctic continent as well as over the interior. They have frequently been observed over the Ross Sea/Ross Ice Shelf area (Bromwich, 1991; Carrasco and Bromwich, 1994, 1996), and offshore of the Adélie Coast during the winter season (June to August; Fitch and Carleton, 1992; Carleton and Fitch, 1993). These three regions of frequent occurrence of mesoscale cyclones are located offshore from the margin of the continent, near zones where the katabatic winds descend from the high plateau and converge into topographic troughs that dissect the coast, then blowing onto the sea ice (open ocean) or the ice shelf (Parish and Bromwich, 1987, 1991).

Two other regions of frequent mesoscale cyclonic activity have been identified over both sides of the Antarctic Peninsula (Heinemann, 1990; Fitch and Carleton, 1992; Turner and Thomas, 1994; Carrasco and Bromwich, 1996; Carrasco *et al.* 1997; Fitch and Carleton, 1992, Carleton and Fitch, 1993; Carleton and Song, 1997; Turner *et al.*, 1997). Turner and Row (1989) and Heinemann (1990) demonstrated that mesoscale cyclones form over the Weddell Sea, particularly near Halley Station. Turner and Row (1989) suggested that the most likely cause for most of the mesoscale cyclones over the eastern Weddell Sea is the effect of the high Antarctic plateau inland of Halley. No clear role of the katabatic winds was observed. However, the easterly winds associated with most of the mesoscale cyclones indicate a cold air mass descending from the high plateau into the Weddell Sea (Turner and Row, 1989). Lee cyclogenesis mechanisms are likely to be associated with mesoscale formation over the lee (east) side of the Antarctic Peninsula. Heinemann (1990) found that the mean location of the synoptic-scale low pressure associated with mesoscale cyclones over the Weddell Sea sector was over the Bellingshausen Sea or east-northeast of the Weddell Sea. These positions may respectively support lee cyclogenesis over the east side of the Antarctic Peninsula as well as warm air advection into the Weddell Sea, and cold air outbreaks into the Weddell Sea from the interior of the continent (Queen Maud Land).

Lyons (1983) studied the characteristics of intense mesoscale cyclone («antarctic depressions» as he called them) in the vicinity of Drake Passage. He found that intense depressions moved from the Bellingshausen Sea toward the southern tip of South America bringing moderate to severe weather conditions to the area of Tierra del Fuego. The initial northeastward displacement of the systems, and characteristics of their cloud features, indicate that the development of such depressions is caused by a cold air outbreak onto the Bellingshausen Sea area. The same characteristics were found by Turner and Thomas (1994), and by Carleton and Fitch (1993; see also Carrasco *et al.*, 1997). The first pair of authors examined satellite imagery for a six month period (September 1983 to February 1984) that covers spring and summer seasons. They studied the distribution of mesoscale cyclones in the vicinity of the Antarctic Peninsula, including the Bellingshausen and Weddell seas, as well as adjacent areas. They found that the maximum number of mesoscale vortices occurred over the eastern Bellingshausen Sea. Most of them appeared to be of the polar-low type (i.e., an intense subsynoptic-scale marine cyclonic vortex that develops poleward of a polar front) since they developed within cold air outbreaks that usually take place behind synoptic lows, which move from lower latitudes into the Bellingshausen Sea area where they became nearly stationary. Similar results were found by Carleton and Fitch (1993) but for the winter season of 1988 and 1989.

In May 1989 the Antarctic and Arctic Research Center (AARC) of the Scripps Institution of Oceanography installed a satellite receiver at Palmer Station (64° S,65° W: Van Woert *et al.*, 1992) in the Antarctic Peninsula to collect satellite data from the NOAA (National Oceanic and Atmospheric Administration) and DMSP (Defense Meteorological Satellite Program) satellites. Routine collection of these data started in August 1989. The real-time raw digital data are saved on magnetic 8 mm videotapes and periodically returned to the USA and they were archived at AARC. Application of satellite imagery interpretation techniques (e.g., Anderson *et al.*, 1973) are most of the time the only source of in-situ meteorological data that provide information over a vast area of the ocean and the Antarctic continent, since ground observations are scarce or non-existent. This article presents a survey of mesoscale cyclones near the Antarctic Peninsula for August 1989 - February 1990. This was the first period of digital satellite data available from Palmer Station. Although more satellite data are now available for subsequent years, we use this because it provided the opportunity to conduct a pilot study of mesoscale cyclones which, in addition, almost concurs in time and area with a similar study conducted by Turner and Thomas (1994) for September 1983 - February 1984 period, and therefore, some inferences of interannual variability can be explored.

Results from the examination of satellite imagery are shown in Section 2. Comparisons with Turner and Thomas' period and a study of the interannual variability of mesoscale cyclones on both sides of the Peninsula are discussed in Section 3. A case study is presented in Section 4 to illustrate the likely mechanisms involved with me soscale cyclogenesis. A summary and discussion are included in Section 5.

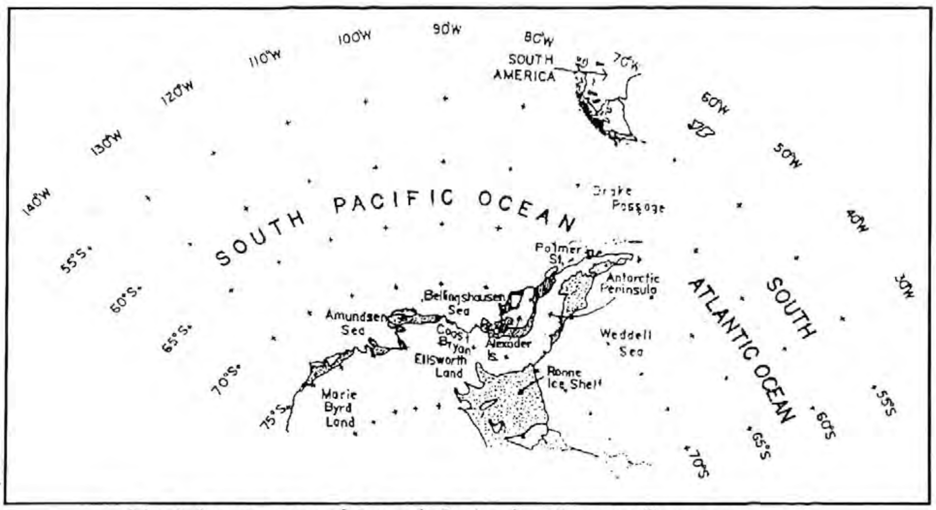

Fig. 1.-Location map of Antarctic Peninsula and surrounding areas.

RESULTS OF THE SATELLITE IMAGERY SURVEY

A survey of mesoscale cyclogenesis around the Amundsen, Bellingshausen and Weddell seas as well as surrounding areas (Figure 1) was carried out based on all the satellite images available for August 1989-February 1990 collected at Palmer Station. The satellite imagery were obtained in the infrared band with a spatial resolution of 3.3 km centered over the station and over the eastern side of the Weddell Sea. This provides appropriate high resolution images which cover large areas surrounding the Antarctic Peninsula, and allow identification of mesoscale cyclones. The identification was based upon the interpreting cyclonic shape of the cloud signature following the general techniques described in the literature dealing with satellite studies of mesoscale cyclones (e.g. Rasmussen, 1981; Forbes and Lottes, 1985; Businger and Reed, 1989; Carleton and Carpenter, 1989; Heinemann, 1990). Figures 2a-c show examples of three well-developed mesoscale vortices near the Antarctic Peninsula.

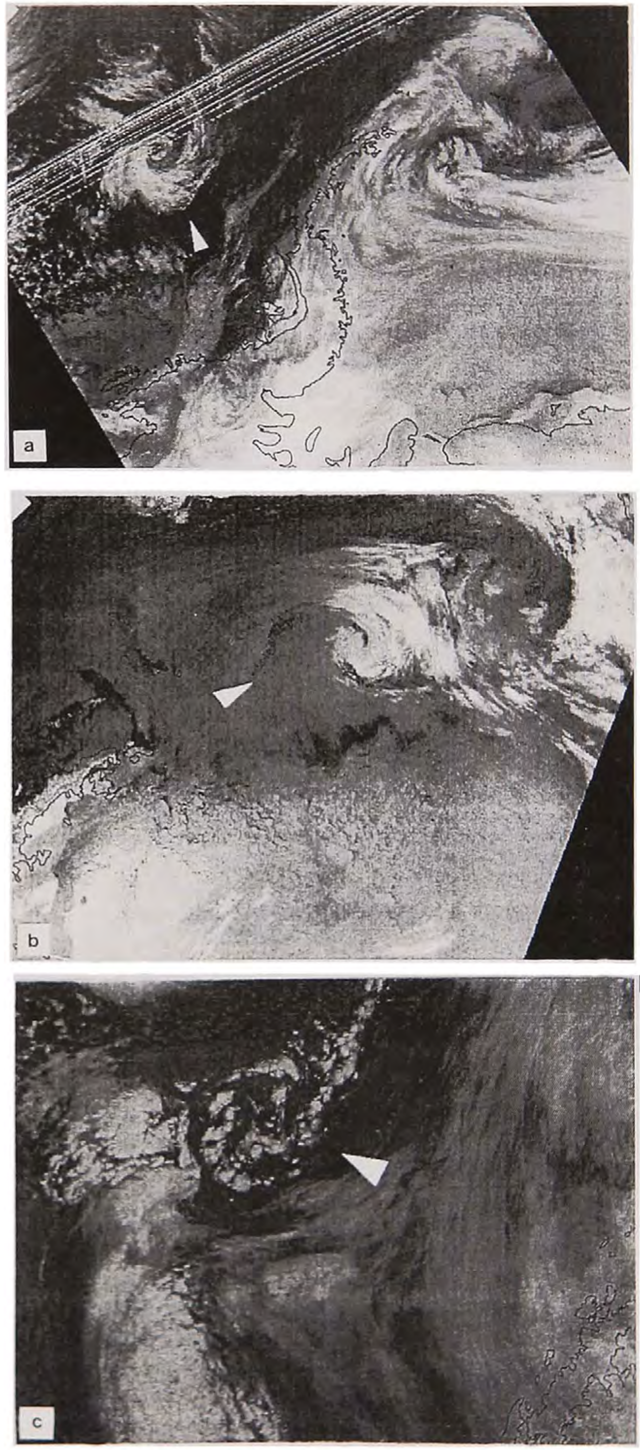

Fig. 2 - Satellite images in the infrared band showing examples of mesoscale vortices observed near the Antarctic Peninsula ((a) and (b) of comma cloud types and (c) a band of convective clouds).

To survey the mesoscale cyclones, the area under consideration was divided in three sectors (see Figure 1): (1) the Bellingshausen region which covers the region from 60° S to the coastline of the Antarctic continent, and to the west of the Antarctic Peninsula up to 110°/120° W, (2) the Weddell Sea region which covers from 60° S to the coastline of the continent and eastward from the Antarctic Peninsula to 20°/10° E, and (3) the continental region poleward of the Antarctic coastline, and includes the Filchner/Ronne Ice Shelf. The division of the study area is based upon the different climatic environments at both sides of the peninsula (Schwerdtfeger, 1984) and the inland area of the continent. All mesoscale cyclones observed on satellite images were counted and plotted on charts. Also, when possible, they were tracked in order to estimate their trajectories.

Column 2 in Table 1 gives the monthly total days for which satellite data were available. There were large gaps in September, October and November of 21, 18 and 12 missing days, respectively. Columns 3, 5 and 7 in Table 1 present the total number of mesoscale cyclones observed within the Bellingshausen, Weddell and Continental regions, respectively. Columns 4, 6 and 8 give the normalized weekly number of mesoscale cyclones observed within the respective regions. This is the total number of mesoscale cyclones on days for which satellite images were available (= analyzable days), expressed as weekly averages. The results showed a weekly maximum of mesoscale cyclonic activity in December over the Bellingshausen (8.3 mesoscale cyclones observed each week) and Continental (5.9) regions, and maximum in January over the Weddell region (17.1). Around 50% of the continental mesoscale cyclones were observed over the Fitchner/ Ronne Ice Shelf. Larger numbers of mesoscale cyclones were observed to the east of the Antarctic Peninsula during December, January and February. The minimum was found in August over the Bellingshausen and Weddell regions, but in November over the Continental region. This indicates that mesoscale cyclones activity either increases toward the summer, and/or the sea ice pack impides moisture and surface fluxes from the underneath ocean for cloud to form in association with mesoscale cyclonic circulations during the winter (Turner *et al.*, 1996). Situation observed over the southwestern corner of the Ross Sea (e.g., Bromwich, 1989; Carrasco and Bromwich, 1996).

TABLE 1

Mesoscale cyclone activity near the Antarctic Peninsula for August 1989 - February 1990 period. Normalized weekly average is the total number of mesocyclones per week of analyzable days

Month	Analizable Day (2)	Number of cyclones (3)	Normalized weekly average (4)	Number of cyclones (5)	Normalized weekly average (6)	Number of cyclones (7)	Normalized weekly average (8)
AUG	28	13	3.3	15	3.8	6	1.5
SEP	9	8	6.2	9	7.0	4	3.1
OCT	13	12	6.5	8	4.3	6	3.2
NOV	18	14	5.4	14	5.4	3	1.2
DEC	26	31	8.3	51	13.7	22	5.9
JAN	29	28	6.8	71	17.1	13	3.1
FEB	25	20	5.6	36	10.0	6	1.7
TOT	148	126	6.0	204	9.6	60	2.8

Figure 3 shows the initial locations of the mesoscale vortices during the study period. Although the results indicate an almost homogeneous distribution of mesoscale cyclones, they tend to cluster close to the coast. Figure 3 also shows large mesoscale cyclone activity over the Weddell Sea and the Ronne Ice Shelf, as well as a few mesoscale cyclones over the plateau of West Antarctica. To examine the distribution of observed mesoscale cyclones, the spatial frequency was calculated. This was determined by dividing the total number of mesoscale vortices counted within a box of 10° longitude and 5° latitude, by the monthly normalized analyzable days. This gives a monthly average frequency distribution of mesoscale cyclones. Figure 4 shows the spatial frequency distribution for August 1989 - February 1990. It can be noted that the largest frequency is located over the Weddell Sea (4.6 to 5.5 mesoscale cyclones per box per 30 days). To the west of the peninsula, the largest frequency is located over the Bellingshausen Sea (2.6 to 3.5 mesoscale cyclones) and to the north of this area. A secondary maximum (2.1 to 2.5 mesoscale cyclones) can be observed over the Amundsen Sea. Figure 5 shows the satellite-observed trajectories of the mesoscale vortices. Most of the mesoscale cyclones were nearly stationary features, and only about 30% of the vortices observed within the Bellingshausen region were tracked. The results suggest that the vortices tend to move northeastward toward the Drake Passage. About 28% and 18% of the vortices were tracked over the Weddell and Continental regions, respectively. No preferred direction of vortex movement was noted over these regions.

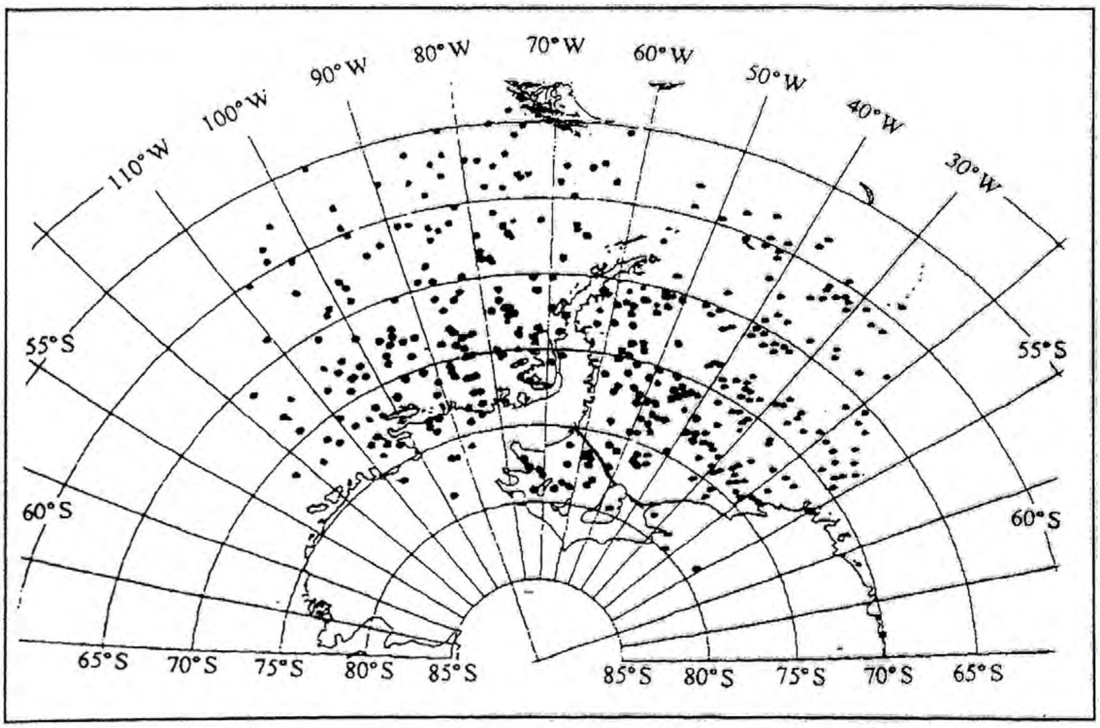

Fig. 3.- Spatial distribution of the initial location of mesoscale cyclones for August 1989- September 1990.

INTERANNUAL VARIABILITY OF MESOSCALE
CYCLONES NEAR THE ANTARCTIC PENINSULA

Comparison between August 1989 - February 1990 and September 1983 - February 1984 periods

Turner and Thomas (1992, 1994) studied mesoscale cyclogenesis over almost the same region and period but for the period/year 1983-84. In order to compare the present results with those obtained by Turner and Thomas, spatial frequencies were calculated from their Figure 2 (reproduced in Figure 6) for the same area of this study, and in the same manner as described above. Figure 7 presents the spatial frequency distribution for 1983-84, where it can be seen that the highest frequency is located to the west and north of the Peninsula. Comparing Figures 3 and 6, it is found that both periods exhibit almost the same mesoscale cyclonic activity to the west of the Antarctic Peninsula. However, over the Weddell Sea 1989-90 presents a larger number of mesoscale cyclones than 1983-84. Part of the difference can be attributed to the fact that Turner and Thomas (1994) used hardcopy (i.e. prints) images with most of them being in the visible band, while, for the present study all the satellite images were obtained in the infrared-digital format (channel 5). These can be displayed on a computer screen, which allows enhancing and zooming of the image for better identification of cloud signatures with an apparent cyclonic shape. despite these differences in data and analysis between the two studies, the contrast is marked over the Weddell Sea, suggesting the greater mesoscale cyclonic activity observed for 1989-90 is real.

Comparison of the spatial normalized frequency distribution for 1983-84 (Figure 7) with that for 1989-90 (Figure 4) reveals that, although both results present almost the same mesoscale cyclonic activity to the west of the Peninsula, for 1989-90 the distribution is more homogeneous and spread out than 1983-84. Also, larger frequencies are located over the Amundsen and Bellingshausen seas for 1989-90. However, a larger frequency can be noted just to the north of Bellingshausen Sea for 1983-84 in contrast with 1989-90 (compare Figures 4 and 7).

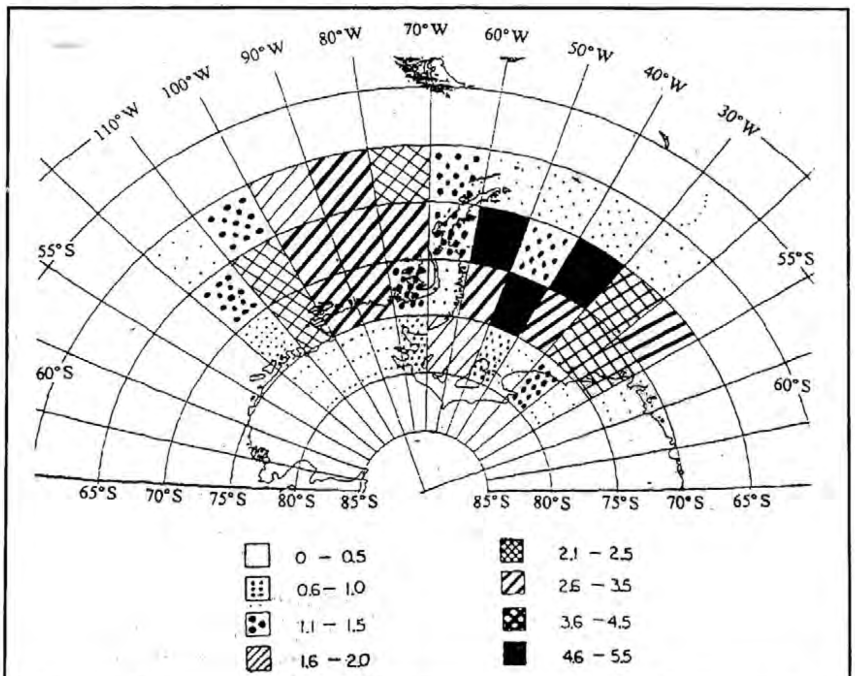

Fig. 4.-Spatial frequency distribution of mesoscale cyclones per 5 latitude x 10 longitude per 30 days, during August 1989 - February 1990 period. Heavy solid line defines area 1, and heavy dashed line defines area 2.

Mean Synoptic-scale Patterns

To investigate whether the interannual variability of mesoscale cyclones found on both sides of the Antarctic Peninsula was associated with the interannual variability of the large-scale atmospheric circulation pattern, the average synoptic-scale environments were calculated from September to February for both periods. Figures 8a and 8b show respectively the mean sea-level pressure for September 1989-February 1990 and September 1983-February 1984 periods. It can be noted that the biggest differences between the two time periods are a deeper low pressure area to the north of Marie Byrd Land, and higher pressure (ridge) over the tip of the Antarctic Peninsula and the Weddell Sea area for September 89-February 90. This low pressure area is part of the circumpolar trough and its variation is indicative of cyclonic activity associated with mature synoptic-scale cyclones that decay near Antarctica (Streten and Troup, 1973; Carleton, 1979). Thus the deeper low pressure center reveals that a greater number of and/or more intense synoptic-scale cyclones decayed to the west of the Antarctic Peninsula mainly offshore from Marie Byrd Land for September 89-February 90. On the other hand, a suggestion of lower pressure over the Weddell Sea for the September 83-February 84 period indicates more synoptic-scale cyclone decaying to the east of the peninsula. This reveals overall two different synoptic-scale environments affecting the peninsula area in both periods. Figure 9 is a Hovmoeller diagram fixed at 67 S displaying the sea-level pressure anomalies for both time periods respect to the 1979-95 climate average. It was obtained through internet from the NCEP/NCAR Reanalysis Project (Kalnay *et al.*, 1996). It shows a slightly lower anomalies to the west of the peninsula (~ 64 W) through out the September 1989-February1990 period, except for December. On the other hand, an overall positive and higher anomalies can be noted to the east of the peninsula for September 1989-February 1990 than September 1983-February 1990 periods. These anomalies confirmed that two different large-scale atmospheric patterns prevailed in both periods.

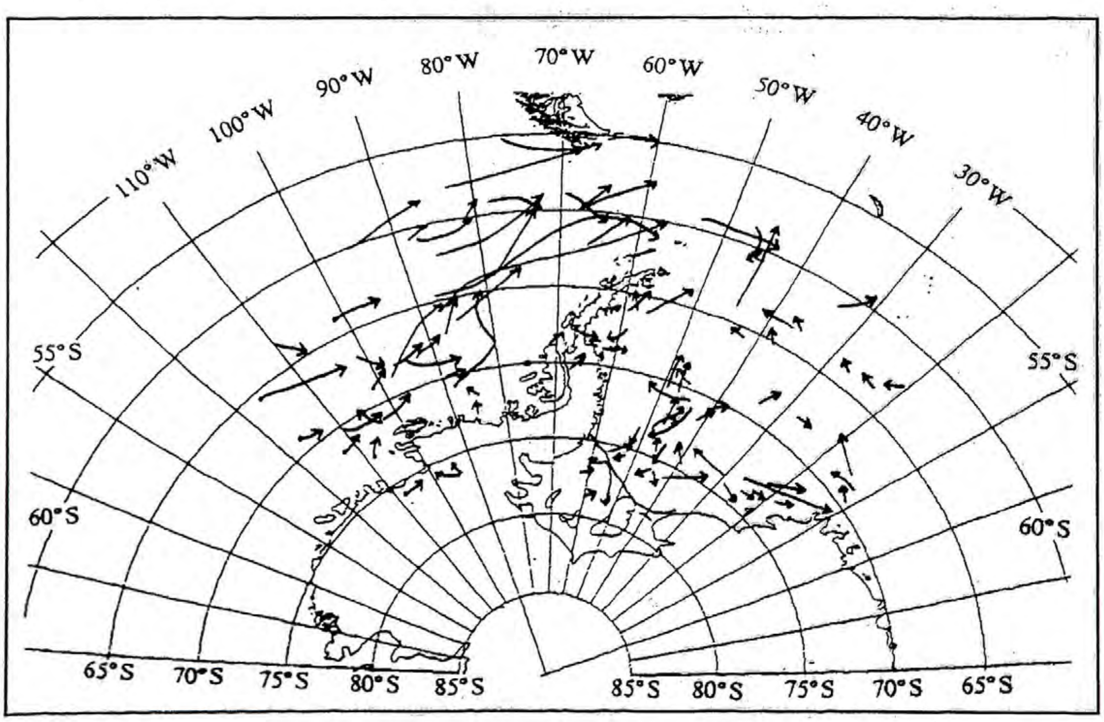

Fig. 5.- Mesoscale cyclone trajectories for August 1989 - February 1990 period.

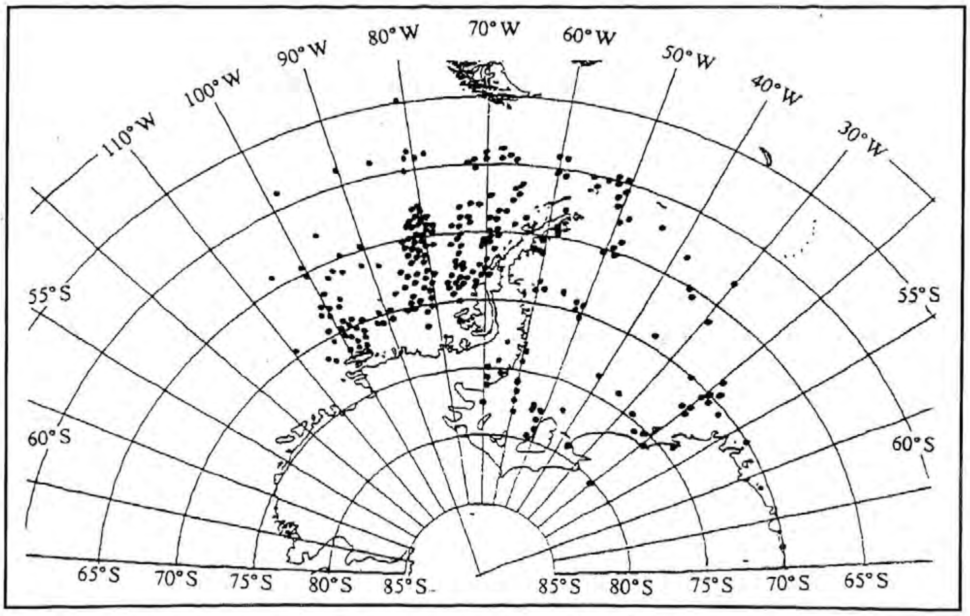

Fig. 6.-Spatial distribution of mesoscale cyclones for September 1983 - February 1984 period after Turner and Thomas (1992).

Figures 8c and 8d are respectively the mean 500-hPa geopotential heights for the September 1989-February 1990 and September 1983-February 1984 periods. Comparison between them reveals a more pronounced upper-level trough over the southeastern South Pacific Ocean (around 110° W) and a slight ridge over the Weddell Sea (50° W) for September 1989-February 1990, indicating an amplification of the wave over the Antarctic Peninsula for this period. This implies that, on average, upper northwesterly winds prevailed across the peninsula for Sep89-Feb90 in contrast with more zonal winds observed for September 1983-February 1984. These overall patterns can be also inferred from the Hovmoeller diagram of the 500-hPa anomalies (not shown). Note that over the Weddell Sea area a trough is resolved by the average analysis on Figure 8d.

No major difference was observed between the 1000-500-hPa geopotential thickness (Figures 8e and 8f) for both periods. Only a suggestion of a slight ridge (trough) over the Weddell Sea can be noted for the Septemeber 1989-February 1990 (Sep83-Feb84) period, which coincides with the northwesterly winds across the peninsula, and suggests warm air advection over the Weddell Sea. The average analyses shown in Figure 8 indicate a colder environment over the Bellingshausen Sea than over the Weddell Sea for September 1989-February 1990 period, while a colder environment prevailed over the Weddell Sea than over Bellingshausen Sea for September 1983-February 1984.

Figure 10 shows the northern limit of the sea-ice extent (hereafter, SIL to refer to the northern edge) at the end of the winter (1 September 1983 and 31 August 1989), and in late spring (1 December 1983 and 30 November 1989) obtained from the Antarctic ice charts (Naval Polar Oceanography Center 1985, 1991). Equatorward (poleward) ice advance (retreat) is linked to southerly (northerly) winds to the west (east) of centers of synoptic-scale cyclonic activity (Carleton 1981, 1992; Streten and Pike, 1980; Cavalieri and Parkinson, 1981). Thus, longitudinal variations of SIL can indicate longitudinal variation in synoptic cyclone activity and cyclone tracks (Carleton, 1992). A comparison of the overall position of the SIL for both periods reveals that, from longitude 60° W to longitude 110° W, the SIL for 1989 was located to the south of its position for 1983. This indicates that a greater frequency of northerly wind components was present in the Bellingshausen

Sea sector for 1989 than 1983, i.e. there was a warmer environment during 1989. This concurs with the stronger pressure gradient and cyclonic circulation shown by the mean sea-level pressure map for September 1989-February 1990 (Figure 8a), and with the location of greater activity of mesoscale cyclones to the west of the Antarctic Peninsula. Conversely, the northern position of the SIL to the west of the peninsula in Septemeber 1983-February 1984 with respect to its position in September 1989-February 1990 indicates more frequent and/or stronger southerly winds over this area implying more frequent and/or stronger cold air masses moving equatorward onto the open ocean over the southeastern South Pacific Ocean. This is in agreement with the indication of more synoptic-scale cyclonic activity over the Weddell Sea area for September 1983-February 1984, which can support southerly winds to the west of the Peninsula. To the east of the peninsula, the SIL does not show a large difference position for both periods.

In summary, the comparatively less mesoscale cyclone activity for September 1989-February 1990 period over the Bellingshausen Sea region and more activity over the Weddell Sea region, can be associated with larger scale patterns favoring more frequent occurrences of northerly flow (warm advection). On the other hand, the comparatively more activity over the Bellingshausen Sea region for October 1983-February 1984, can be associated with larger scale patterns favoring more frequent occurrences of southly winds (cold air outbreaks). Lee cyclogenesis on the east side of the peninsula associated with westerly flow can be another mechanism of mesoscale cyclone formation and therefore the larger activity observed over the Weddell Sea area for September 1989-February 1990.

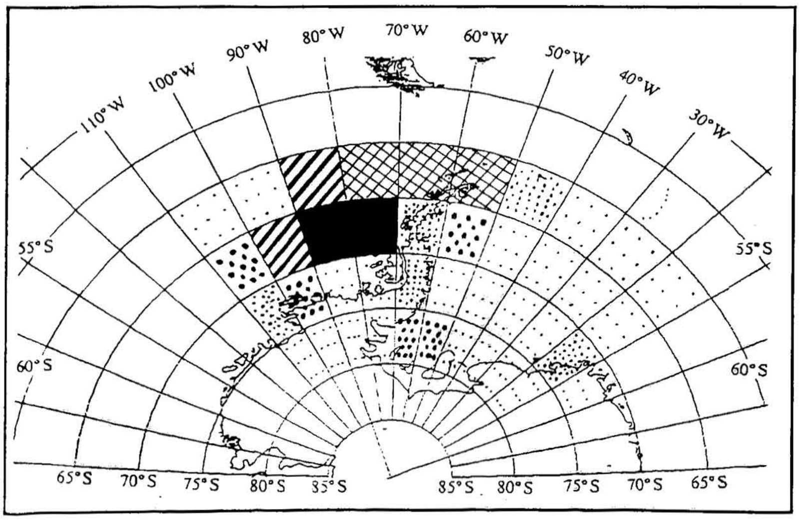

Fig. 7.-Spatial frequency distribution of mesoscale cyclones per 5 latitude x 10 longitude per 30 days, during September 1983 - February 1984 period. Heavy solid line defines area 1, and heavy dashed line defines area 2.

CASE STUDY

To examine the interaction between synoptic- and subsynoptic-scale environments favoring mesoscale cyclone development a case study was conducted based on available operational data. The sequence of satellite images for 1903 and 2054 UTC (universal time coordinate) 24 October (Figures 11a and 11b) and at 0512 and 1903 UTC 25 October (Figures 11c and 11d) show a low cloud signature revealing a subsynoptic cyclone which moved from the northern Bellingshausen Sea (Figure 11a) toward the Drake Passage. The images on 24 October (Figures 11a and 11b) reveal marked development of the cyclone in a period of less than two hours. To the east of this feature, a synoptic-scale cold front can be observed affecting the southern tip of South America and the Antarctic Peninsula.

The Australian Bureau of Meteorology surface analyses between 0000 UTC 23 October and 0000 UTC 26 October show the movement of this front and its vortex along the Pacific coast of West Antarctica. At 0000 UTC 25 October, the surface analysis (Figure 12a) shows the front in a dissipating stage with its associated weak low centered at 70° S, 75° W. At 0000 UTC 26 October (Figure 12b), the frontal system had crossed the Antarctic Peninsula becoming nearly-stationary over the Weddell Sea area where it weakened due to a blocking ridge that developed over the South Atlantic Ocean two days earlier. During this period, the 500-hPa analyses (Figures 12c and 12d) show that an upper-level trough, associated with a tropospheric low, approached the peninsula. At 0000 UTC 25 October, it was located along longitude 80° W with the tropospheric low located over the Ellsworth Land Coast. At 1200 UTC 25 October, the axis of the 500-hPa trough was already located along longitude 72 W (dashed line in Figure 12c), and moved slowly to the Weddell Sea as revealed by the 500-hPa analysis at 0000 UTC 26 October (Figure 12d). Figure 12d also suggests a poleward displacement of the ridge located over the Atlantic Ocean, which concurs with a similar movement at surface (Figure 12b), and with the weakening and subsequent dissipation of the front to the east of the peninsula. From the synoptic-scale environment, it can be inferred that the mesoscale vortex developed within and behind the cyclonic circulation associated with the frontal system, and seems to concur with the traveling upper-level trough.

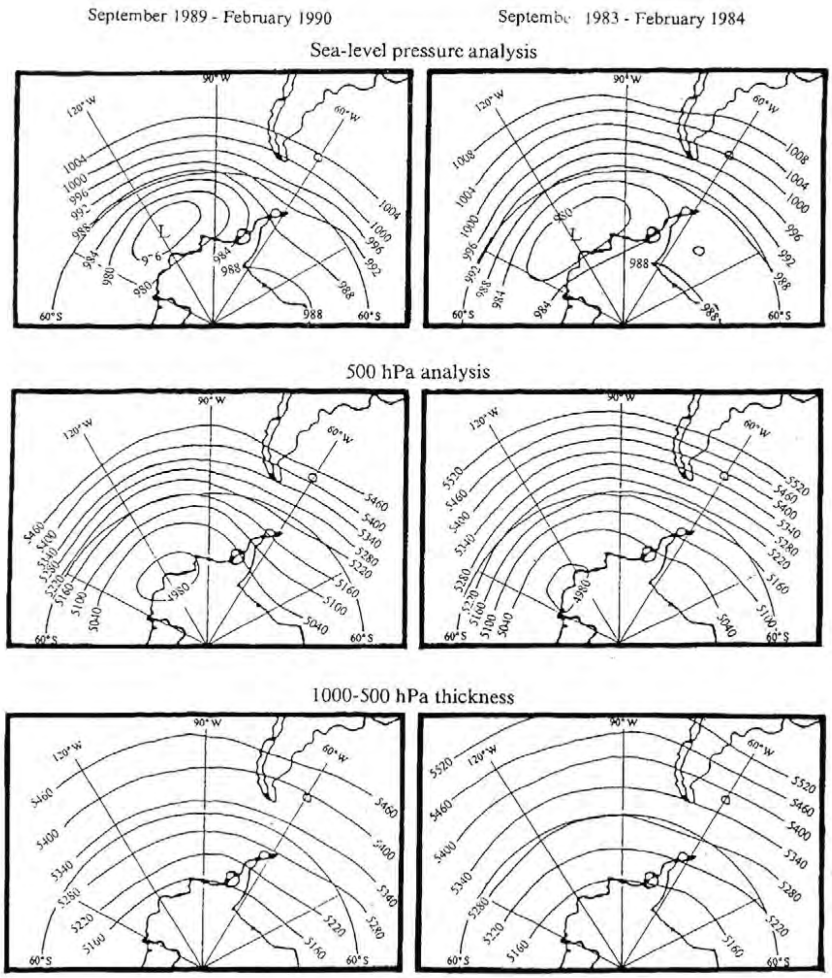

Fig. 8.-A Hovmoeller diagram fixed at 67 S displaying the sea-level pressure anomalies respect to the 1979-95 climate average for both time periods.

The International TOVS (Tiros Observational Vertical Sounders) Processing Package (ITPP-3) developed by the University of Wisconsin, was used to obtain the 1000-500-hPa mesoscale geopotential thickness fields at 2054 UTC 24 October and at 0512 UTC 25 October (Figures 13a and 13b). Although over the southern polar region the TOVS data are quantitatively in error (Lutz *et al.* 1990), qualitatively speaking, they have shown to be able to resolve fairly well the synoptic- and subsynoptic-scale patterns (Turner and Row, 1988; Heinemann, 1990; Carrasco and Bromwich, 1993). The two TOVS 1000-500-hPa thickness fields show a cold tropospheric trough extending from Ellsworth Land into the Bellingshausen Sea sector. This cold trough agrees with the surface and 500-hPa analyses which suggest a polar air outbreak toward the Amundsen and Bellingshausen seas. Note the mesoscale cyclone developed within the cold air near a strong thickness gradient exhibited by these fields.

In summary, a cold air outbreak over the Bellingshausen Sea was shown by the TOVS 1000-500-hPa geopotential thickness field to have occurred behind the synoptic-scale cyclone. This cold air could enhance or create baroclinic zones as the strong thickness gradient and the rapid development of the subsynoptic-scale cyclone suggested. The approach of the upper level trough, as resolved by the 500 hPa analysis, could have advected cyclonic vorticity over the area giving the support for upward motion while the subsynoptic-scale cyclone was located ahead of its axis. The weakening of the vortex suggested by the satellite image at 1903 UTC 25 October, concurs with the position of the trough slightly to the east of the vortex and therefore, the end of the upper-level support.

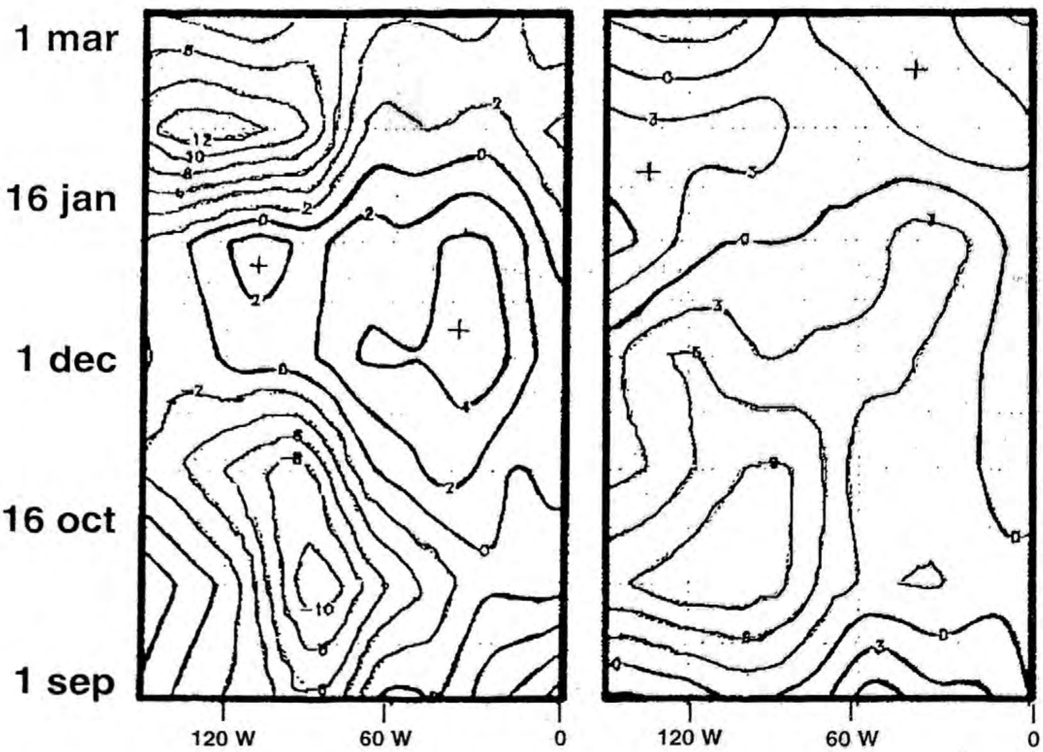

Fig. 9.-Mean sea-level pressure (a and b), mean 500-hPa (c and d) and the 1000-500-hPa thickness (e and f) synoptic-scale analyses for Sep89-Feb90 and Sep83-Feb84 periods

DISCUSSION

A survey of mesoscale cyclones over Bellingshausen/Amundsen Sea was conducted for the August 1989 - February 1990 period, or the end of winter to the end of summer including the time of maximum sea-ice extent (September: Zwally *et al.*, 1983). The results show that, to the west of the Antarctic Peninsula, the maximum mesoscale cyclonic activity occurred in December and the largest spatial frequency of mesoscale cyclones was located over the Bellingshausen Sea and to the north of it. Another smaller frequency maximum was found near the Amundsen Sea. To the east of the peninsula, the peak of mesoscale cyclone activity occurred in January, while the highest spatial frequency was found over the western side of the Weddell Sea. Significant mesoscale cyclonic activity was also observed over the Fitchner/Ronne Ice Shelf (about 13% of the total mesoscale cyclones observed to the east of the peninsula). In subsequent studies of additional years Carrasco and Bromwich (1996; see also Carrasco *et al.*, 1997), Turner et al. (1996) found that the maximum activity occurs in January-February and a minimum in June on both sides of the Antarctic Peninsula; and that the maximum spatial activity occurred offshore of the Filchner/Ronne Ice Shelf, to the north of the Bellingshausen Sea and a secondary maximum near the Amundsen Sea. Only 30% (28%) of the mesoscale cyclones were tracked to the west (east) of the peninsula. This indicates that most of the mesoscale cyclones were nearly-stationary features and/or of short duration. It should be mentioned, however, that the gaps among consecutive images (especially from one day to the next) limited the number of mesoscale cyclones that could be tracked. To the west of the peninsula, the trajectories revealed that vortices tend to move toward the northeast, while no preferable direction was found over the Weddell Sea and continental regions. The same results were found for an additional year studied by Carrasco *et al.* (1997; see also Carrasco and Bromwich, 1996).

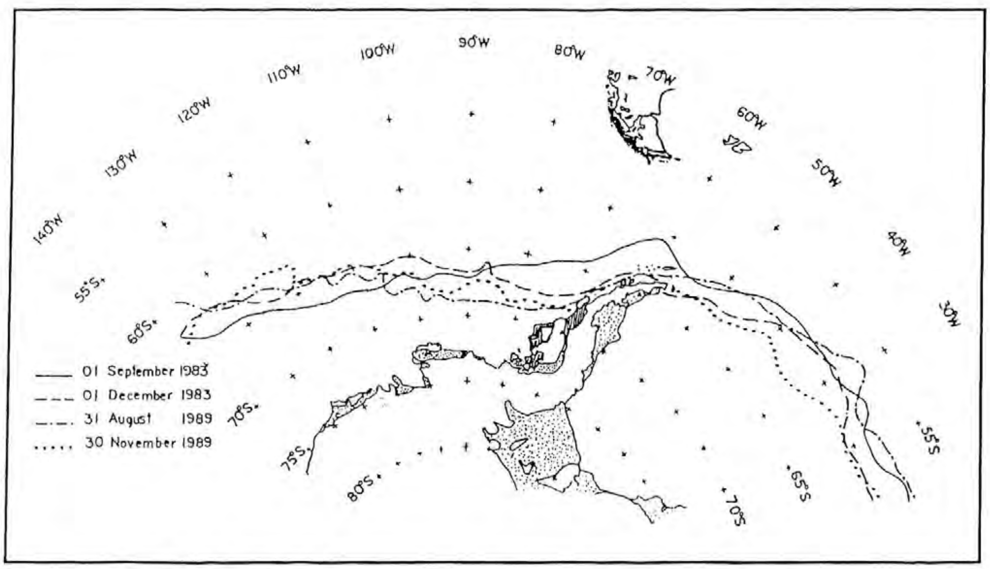

Fig. 10.-Northern limit of the sea-ice extent for 1 September 1983 (solid line), 1 December 1983 (dashed line), 31 August 1989 (dashed-dot line), and 30 November 1989 (dot line).

A comparison with mesoscale cyclonic activity for almost the same seasonal period and area, but for year 1983-84 (Turner and Thomas, 1992, 1994) shows that both periods had similar activity over the Pacific side of the peninsula, but the spatial distribution was different. The 1983-84 period showed (Figures 6 and 7) the largest monthly frequency of mesoscale cyclones to the west of the peninsula with cyclones clustering to the north of the Bellingshausen Sea and over the Amundsen

Sea. Over the southeastern corner of the Pacific Ocean, the maximum frequency was located just to the north of the location for 1989-90. This latitudinal variation is linked to the position of the sea-ice limit (SIL), where the SIL for 1989-90 was located to the south of the SIL for the 1983-84 period. Comparing the overall results in 1983-84 with those obtained in 1989-90, a shift of the maximum frequency from the Pacific to the Atlantic side of the Peninsula was found. The interannual variability of mesoscale cyclones can be linked to the interannual variation of the circumpolar trough in the vicinity of the peninsula. The intensity of the quasi-stationary low pressure offshore of Marie Byrd Land reflects the synoptic cyclonic activity near this area. Thus, the deeper mean synoptic-scale cyclone for September 1989-February 1990 located to the north of Marie Byrd land, indicates more norwesterly flow affecting both sides of the peninsula, and suggesting more warm air advection over the region. This results in more mesoscale cyclone activity over the Weddell Sea region in comparison with the activity observed over the other side of the peninsula. Conversely, the higher activity over the Bellingshausen Sea region for 1983-84 can be associated with more frequent and/or more intense cold air outbreaks to the west of the peninsula. This supports previous findings that indicate that most mesoscale cyclogenesis occurs within cold air masses (Lyons, 1983; Carleton and Fitch, 1993).

A near-surface katabatic wind simulation (Parish and Bromwich, 1987) indicates a katabatic source of cold air in the Amundsen Sea area. The secondary frequency maximum of mesoscale cyclones found in this research and by Turner and Thomas (1992, 1994) and Carrasco *et al.* (1997), suggest that these features may be associated with the katabatic winds coming from the interior of West Antarctica. However, from the present study, no clear linkage can be inferred between katabatic airflow and mesoscale cyclonic activity over the southeastern Pacific Ocean, as it is more clearly found over the Ross Sea/Ross Ice Shelf area (Bromwich, 1991; Carrasco and Bromwich, 1993, 1994, 1996; Galleé, 1994, 1995). The approach of an upper-level trough (e.g., the case study) was linked with the development of the mesoscale cyclone described here, and the establishment or the approach of an upper level ridge was linked with its weakening. This suggests that cyclonic vorticity advection plays an essential role in mesoscale cyclogenesis in this area.

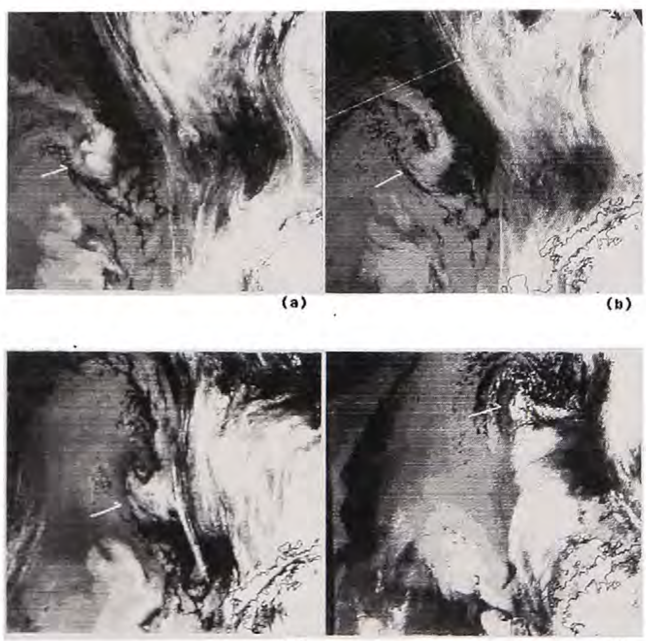

Fig. 11.-Thermal infrared satellite images at (a) 1915 UTC 24 October, (b) 2054 UTC 24 October, (c) 0512 UTC 25 October, and (d) 1903 UTC 25 October 1989.

Previous studies have shown that mesoscale vortices develop within cold air outbreaks (Fitch and Carleton, 1992; Carleton and Fitch, 1993; Turner and Thomas, 1994; Carrasco and Bromwich, 1996). Although no significant difference between the time periods was found in the 1000-500 hPa geopotential thickness, the surface, 500-hPa and SIL analyses indicate that a warmer environment affected the northern tip of the Antarctic Peninsula and the Weddell Sea for 1989-90 period. This suggests that the higher frequency of mesoscale cyclones over the Weddell Sea in Aug 89-Feb 90 can be related to the higher frequency of poleward warm air advection, mainly toward this area. On the other hand, the highest frequency of mesoscale cyclones over the Bellingshausen/ Amundsen Sea region in September 1983-February 1984 is associated with more (less) equatorward (poleward) cold (warm) air advection. This may indicate different mechanisms for mesoscale cyclone formation on both sides of the peninsula.

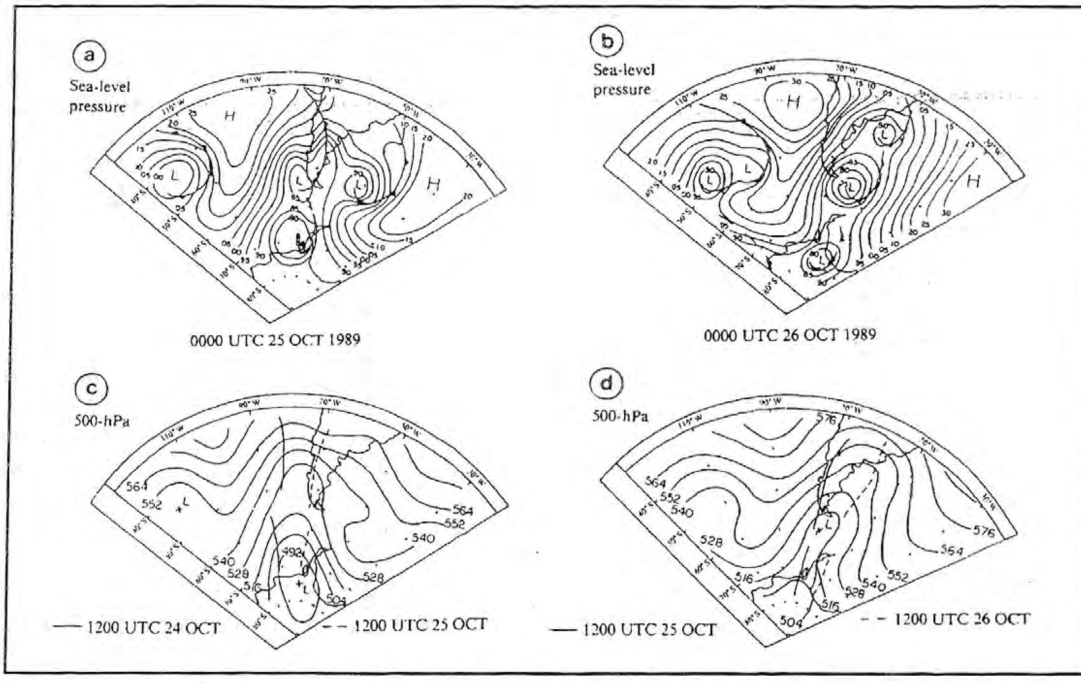

Fig. 12.-Sea-level pressure (a and b) and 500-hPa (c and d) synoptic-scale analyses at 0000 UTC 25 October and 0000 UTC 26 October 1989.

It is speculated that over the Bellingshausen/Amundsen Sea region mesoscale cyclones primarily develop in baroclinic zones within the polar air outbreaks (polar low type), while over the Weddell Sea mesoscale cyclones primarily develop in baroclinic zones formed by cold and warm air advection and/or they are associated with lee cyclogenesis mechanism. Turner and Row (1989) noted that mesoscale cyclones are frequently found in the lee of the Peninsula, and our result for Aug89-Feb90 also places the highest spatial frequency of mesoscale vortices over the western side of the Weddell Sea, downwind of this topographic feature. Note that the 500-hPa pattern for 1989-90 suggests more frequent and/or stronger northwesterly winds across the Antarctic Peninsula than for 1983-84. This pattern may favor lee cyclogenesis which concurs with the highest mesoscale cyclonic activity over the lee side of the Peninsula found in 1989-90 period. It should be mentioned that vortex stretching is another mechanism suggested for mesoscale cyclone formation in the offshore area near Halley Station (75° 36'S, 26 42'W; see Turner *et al.* 1996; Heinemann, 1996; Engels and Heinemann, 1996). It is associated with cold air descending from the antarctic plateau and that moves toward the eastern side of the Weddell Sea.

A meteorological phenomenon that distinguishes the two sides of the Antarctic Peninsula is the cold low-level southerly airflow, which is frequently observed along the east side of the peninsula (barrier winds; Schwerdtfeger 1984). Further studies are needed to determine the effect of such boundary-layer cold air advection upon mesoscale cyclogenesis over the western side of the Weddell Sea.

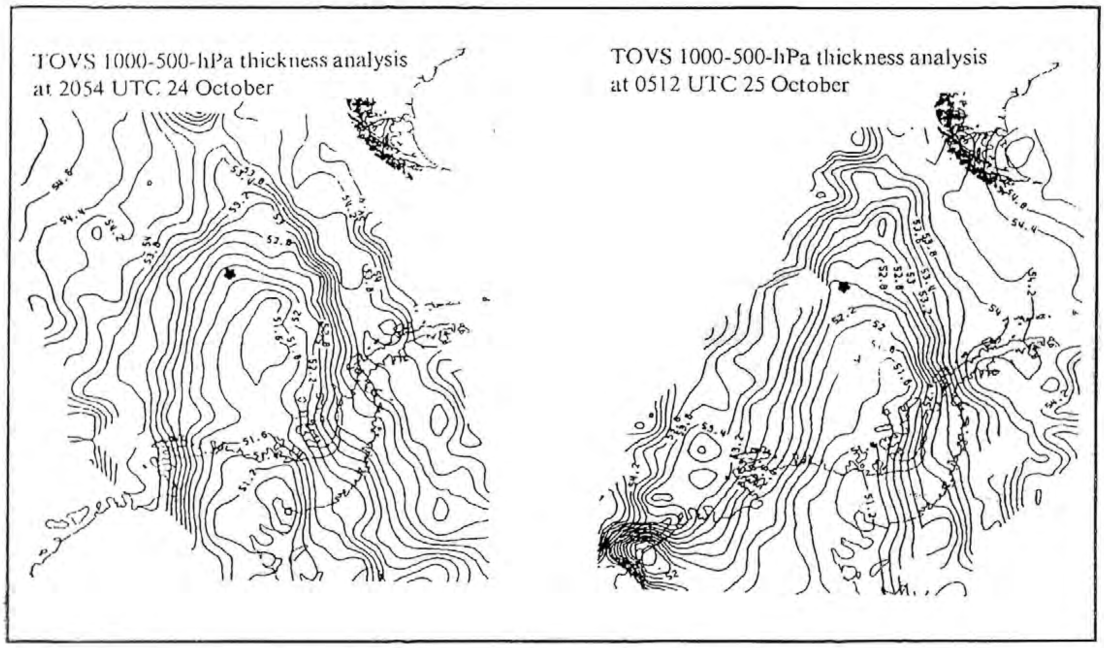

Fig. 13.-TOVS 1000-500-hPa thickness analyses at (a) 2054 UTC 24 October, and (b) 0512 UTC 25 October 1989.

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