Mesoscale cyclone activity over Antarctica during 1991

2. Near the Antarctic peninsula

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Abstract. A survey of mesoscale cyclogenesis near the Antarctic peninsula has been carried out for 1991 based on digital satellite imagery collected at Palmer Station. Slightly higher cyclonic activity was found over the Bellingshausen Sea sector (BSS) than in the Weddell Sea sector (WSS). Both sides were characterized by a pronounced formation maximum in summer and a minimum in winter. Comma clouds were the dominant vortex type, and their average diameter was around 370 km. Trajectories show that many vortices in the BSS move northeastward toward the Drake Passage, with some of the most well developed moving north-northeastward to the southern tip of South America, bringing severe weather conditions to that area; little systematic motion was noted over the WSS. The fraction of mesoscale cyclones with middle and/or high cloud on the west side of the Antarctic peninsula was much higher than on the east side. These numerous and deep mesoscale cyclones are a consequence of the frequent outbreaks of cold air associated with synoptic-scale cyclones that move cold air northward over the relatively warm Bellingshausen Sea, with convective instability resulting. This happens much less often in the WSS, where low-level baroclinic instability and vortex stretching are the dominant formation mechanisms and air-sea interaction is usually much less vigorous due to the stabilizing influence of the extended sea-ice cover.

1. Introduction

The Antarctic peninsula is a mountain barrier that extends northward from the base of the continent (Ellsworth Land) to about 63°S. It has a length of about 1300 km, and an average width of 70 km to the north of 69°S (Figure 1). The peaks of the mountains have elevations that range from more than 2000 m to nearly 800 m at the tip of the peninsula [Schwerdtfeger, 1984]. These steep mountains, averaging 1500 m in elevation, separate the southern Pacific and Atlantic Oceans, and act as a formidable barrier to the airflow [Parish, 1977]. The north/northwesterly winds over the Bellingshausen Sea-side bring relatively warm and moist air to the western side of the peninsula, while the southerly winds over the Weddell Sea-side bring cold air from the continent and generate a continental climate [Schwerdtfeger, 1970; Parish, 1977]. The steep mountains and the nearly permanent cyclonic surface circulations that affect both sides of the peninsula result in distinct climatic environments on each side.

One of the first studies of subsynoptic-scale vortices (those whose diameter is less than 1000 km) near the Antarctic peninsula was by Lyons [1983], who investigated the characteristics of intense Antarctic depressions (his terminology) in the vicinity of Drake Passage. He found that these depressions can undergo intense development as they move northeastward from the Bellingshausen Sea area within a cold air outbreak, bringing moderate and severe weather conditions to the southern tip of South America. Later, Fitch and Carleton [1992] and Carleton and Fitch [1993] studied mesoscale cyclogenesis over the South Pacific sector during the winter months (June - August) of 1988 and 1989. Their results revealed that mesoscale cyclonic activity was associated with lower 1000 to 500-hPa geopotential thickness than the seasonal average (winter mean 1988-1989), indicating that these features developed within cold air outbreaks as previously indicated by Lyons [1983].

On the other hand, Turner and Row [1989] examined satellite imagery and operational hand-drawn analyses constructed by meteorologists at the U.K. Meteorological Office during the September 1983 to August 1984 period. They analyzed the occurrence and trajectories of mesoscale vortices over the Weddell Sea area. A total of 170 mesoscale vortices (mv, hereafter) were detected throughout the period with a maximum during spring (September - November; 50 mv) and autumn (March-May; 48 mv). However, more than half (94) of the observed features entered the Weddell Sea sector from the west and were in a mature state, indicating that their formation and initial development occurred somewhere to the west of the Antarctic peninsula. Heinemann [1990], who studied six January-February periods...
from 1983 to 1988, also demonstrated that mesoscale cyclones are often observed over the Weddell Sea sector. In addition, he noted that these features were usually associated with a synoptic-scale low located over the Bellingshausen Sea or to the east of the Weddell Sea. These positions may support southward warm air advection into and cold air outbreaks over the Weddell Sea sector, respectively.

Turner and Thomas [1992] used hard copy satellite imagery to carry out a study of mesoscale activity occurred over the Bellingshausen Sea than over the Weddell Sea sector during their study period; this was also true of the summer period (December 1983 to February 1984) studied in more detail by Turner and Thomas [1994]. This spatial activity pattern contrasted with that found by Carrasco and Bromwich [1992, 1993], who examined practically the same region using digital satellite data but for the period of August 1989 to February 1990. The latter authors noted that the greater activity for their period was over the Weddell Sea sector. This suggests that there may be interannual variability in the location of the maximum mesoscale cyclonic activity near the Antarctic peninsula. Also, their mesoscale cyclone trajectories showed that these features tend to move northeastward from the Bellingshausen Sea to the Drake Passage [Carrasco and Bromwich, 1992]. No preferred direction was noted for the movement of mesoscale vortices observed over the Weddell Sea sector.

Here, a survey of mesoscale vortices near the Antarctic peninsula is presented. It was based solely on satellite imagery collected at Palmer Station (65°S, 64°W [Van Woert et al., 1992]) during the calendar year of 1991. The selection of this year was based on the good coverage in comparison with other years, which had large data gaps. The results are intended to represent this particular year, although some inferences can be drawn for other years by comparison with published analyses. The main objectives of this survey are to describe the spatial and temporal (monthly and seasonal) distribution of mesoscale cyclones on both sides of the Antarctic peninsula, as well as their satellite-observed characteristics, and to analyze the synoptic-scale circulation accompanying mesoscale cyclone formation. The paper is organized as follows: section 2 describes the results of the survey; section 3 deals with the synoptic-scale analysis; and the final section presents some discussion and conclusions.

In a recent study similar to the present effort, Turner et al. [1996] used satellite imagery from Rothera Station for the period of March 1993 to February 1994 to evaluate the annual cycle of mesoscale cyclone activity on both sides of the Antarctic peninsula. The emphasis was on establishing the cyclone characteristics and less on the synoptic-scale circulation accompanying mesoscale cyclogenesis. Repeated contrasts are made between their results and those obtained here.

2. Satellite Analysis

2.1. Survey of Mesoscale Vortices and Their Spatial and Temporal Distribution

Figure 1 shows the area under consideration and the main geographic features. The dashed box encloses the area covered by the satellite images. All mesoscale cyclones
Figure 2. Infrared satellite images along with the corresponding schematic illustrations showing examples of mesoscale vortices observed near the Antarctic peninsula (a) at 2153 UTC February 2, 1991, (b) at 0012 UTC February 27, 1991, (c) at 1132 UTC February 19, 1991. All images have a resolution of 1.1 km. The lines in the sketches are the diameters (a) 283 km, (b) 597 km, and (c) 278 km.
within this area but south of 50°S were considered in this survey. To study mesoscale cyclogenesis on both sides of the Antarctic peninsula, the area was divided into the Bellingshausen Sea sector (BSS) and the Weddell Sea sector (WSS). However, all mesoscale cyclones observed over the Filchner/Ronne Ice Shelf and over the continent were counted separately. They correspond to the continental sector (CS). Over the Drake Passage, the division follows the northern curvature of the peninsula until 50°W and then northward at this longitude.

The procedure for identification of mesoscale vortices around the Antarctic peninsula is similar to that previously described by Carrasco et al. [this issue]. Figures 2a-2c show some examples of mesoscale vortices on both sides of the peninsula that illustrate the pattern recognition used here. Monthly and seasonal evaluations of the mesoscale cyclone activity were performed. For the latter, the year was divided into five periods according to the annual march of the monthly mean temperature on both sides of the peninsula [Schwerdtfeger, 1984, Figure 3.13, p. 81]. These are late summer (January and February), autumn transition (March to May), winter (June to August), spring transition (September and October), and early summer (November and December). This division provides a better depiction of the seasonal behavior of mesoscale cyclones and facilitates the synoptic-scale analysis.

Column 1 in Table 1 indicates the total number of days for each month for which at least one satellite image was available (called analyzable days); most of the time, more than three images were available, mainly during the second half of the year. The difference between the number of analyzable days on both sides of the Antarctic peninsula occurs because sometimes the available image(s) cover one side but not both. Overall, periods when imagery was not available were randomly distributed throughout the year. On average, satellite imagery was available for about 80% and 82% of the total days in 1991 for the BSS and WSS, respectively. January was the only month with a significant number of missing days, and therefore results for this month and the late summer season must be viewed with caution, especially for the BSS. Column 2 in Table 1 shows the total number of mesoscale vortices observed each month on both sides of the peninsula. A total of 264 and 192 mv were counted over the BSS and WSS, respectively. Except for January, the number of cyclones decreases toward the winter in both regions. Over the continental sector, 45 mv were observed, most of them during the austral summer season (see column 4 in Table 1). Of this total, 24 mv were over the

<table>
<thead>
<tr>
<th>Month</th>
<th>BSS Analyzable Days (1)</th>
<th>WSS</th>
<th>Number of Mesoscale Vortices (2)</th>
<th>BSS</th>
<th>WSS</th>
<th>Equivalent Weekly Frequency (3)</th>
<th>BSS</th>
<th>WSS</th>
<th>Number of Mesoscale Vortices (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>10</td>
<td>17</td>
<td>11</td>
<td>13</td>
<td>7.7</td>
<td>5.4</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb.</td>
<td>22</td>
<td>23</td>
<td>26</td>
<td>16</td>
<td>8.3</td>
<td>4.9</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>24</td>
<td>27</td>
<td>29</td>
<td>15</td>
<td>8.5</td>
<td>3.9</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>24</td>
<td>24</td>
<td>26</td>
<td>12</td>
<td>7.6</td>
<td>3.5</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>20</td>
<td>23</td>
<td>17</td>
<td>8</td>
<td>6.0</td>
<td>2.4</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>24</td>
<td>23</td>
<td>17</td>
<td>12</td>
<td>5.0</td>
<td>3.7</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>27</td>
<td>23</td>
<td>6</td>
<td>9</td>
<td>1.6</td>
<td>2.7</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug.</td>
<td>26</td>
<td>28</td>
<td>22</td>
<td>10</td>
<td>5.9</td>
<td>2.5</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sept.</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>10</td>
<td>5.6</td>
<td>2.3</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct.</td>
<td>30</td>
<td>31</td>
<td>25</td>
<td>23</td>
<td>5.8</td>
<td>5.2</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov.</td>
<td>27</td>
<td>25</td>
<td>26</td>
<td>18</td>
<td>6.7</td>
<td>5.0</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec.</td>
<td>27</td>
<td>27</td>
<td>35</td>
<td>46</td>
<td>9.1</td>
<td>11.9</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>291</td>
<td>301</td>
<td>264</td>
<td>192</td>
<td>6.4</td>
<td>4.5</td>
<td>45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BSS, Bellingshausen Sea sector; WSS, Weddell Sea sector; CS, continental sector.
Figure 3. Annual spatial distribution of the initial appearance of mesoscale vortices observed on satellite images near the Antarctic peninsula during 1991.

Filchner/Ronne Ice Shelf. Figure 3 shows the spatial distribution of the initial appearance of mesoscale vortices observed during 1991. It can be seen that the mesoscale cyclones are almost homogeneously distributed. To overcome the areal distortion of this type of map, an equivalent areal distribution was calculated. For this, the entire area was divided into boxes of 5° of latitude and 10° of longitude. Then the number of mesoscale cyclones in each box was converted to a fixed area (= 10⁵ km²). In addition, to account for the missing days, the results over the Bellingshausen (Weddell) Sea were corrected by a factor of 1.254 (1.213), which corresponds to the total days of the calendar year divided by the total analyzable days for each side of the peninsula. This gives an equivalent areal and annual count of the initial appearance of mesoscale cyclones over the entire region; therefore comparison of both sides is possible. Column 3 in Table 1 gives the monthly equivalent weekly frequency of mesoscale vortices on both sides of the Antarctic peninsula. This was obtained by dividing the number of mesoscale cyclones for the given month by one-seventh of the analyzable days. This calculation yields an unbiased weekly average of the mesoscale cyclones throughout the year. As noted previously, the mesoscale cyclonic activity decreases during the winter in both sectors. The monthly weekly frequencies suggest a maximum frequency toward the end of the summer (February and March) over the BSS, but once again, results for January may be misleading. Figure 5 graphically shows the results in terms of the seasonal breakdown. In this case the weekly frequency was adapted according to the total analyzable days in each season. Larger activity occurred over the BSS except for early summer, specifically in December (the same is true in July). In summary, the annual equivalent weekly frequency indicates that about 7 (5) mesoscale vortices can be observed each week within the BSS (WSS).

The trajectories of the mesoscale cyclones that were tracked (about 48% and 36% of the total in the BSS and WSS, respectively) during the year are shown in Figure 6. They reveal the preferential eastward movement toward the Drake Passage for the majority of the tracked vortices in the BSS. Note that some of the trajectories show a north-northeastward orientation from the northern Bellingshausen...
Sea to the southern tip of South America. Lyons [1983] had already found this preferential direction for mesoscale vortices originating near the Bellingshausen Sea. Few mesoscale vortices were tracked near the west coast of the Antarctic peninsula, but many trajectories aim toward this region. No preferential direction was observed over the Weddell Sea sector, although northeastward trajectories seem to dominate to the south of 70°S. None of the mesoscale cyclones crossed the Antarctic peninsula, indicating that it acts as a true barrier for these perturbations. The location of the final appearance of the mesoscale vortices on the satellite images (arrow heads) suggests that they often decay near and over the peninsula, and over the southern tip of South America. Many of the mesoscale vortices that passed through the Drake Passage probably dissipated to the north of the Weddell Sea.

2.2. Characteristics of the Mesoscale Cyclones

The type, depth, and diameter of the mesoscale vortices were analyzed based on the cloud pattern recognition and interpretation of meteorological satellite imagery. Overall, the common types observed throughout the survey on both sides of the peninsula were comma cloud; spiraliform; merry-go-round; oval, solid mass; and band or mass of convective clouds. Table 3 of Carrasco et al. [this issue] gives the description of each type except the last one. Band or mass of convective clouds are defined as cumulus and/or cumulonimbus clouds clustered to form a single band or mass, and are illustrated by Figure 2c. Examples of a comma and spiraliform are presented in Figures 2a and 2b. The depth of the vortical cloud was qualitatively estimated by evaluating the brightness of the vortical cloud; the concurrent radiosonde data from both Bellingshausen and Weddell Sea areas were not available for this study. On thermal infrared satellite imagery that are displayed on a black to white scale, low clouds appear in dark or gray tones, while middle and high clouds appear white. Therefore dark (white) clouds identify shallow (deep) vortices. In addition, a limited random survey of the cloud-top temperatures (CTT) associated with the vortices was conducted to obtain a quantitative estimate of the vertical extent of the mesoscale vortices. It was assumed that
most of the clouds (except cirrus) behave as blackbodies, implying that their emissivity is close to 1. The average CTT was then compared with the climatological temperature cross-sectional diagram for summer and winter along longitude 100°W from Crutcher et al. [1971].

The diameter of each mesoscale vortex was measured from edge to edge of the vortical cloud as illustrated in Figure 2. For comma clouds the diameter was given by the distance from the front edge to the rear edge of the vortical cloud. Spiraliform features are almost symmetric in shape, and their diameter was easily measured once identified. Even though merry-go-round features are formed by two or more mesoscale vortices whose individual diameters are less than 100 km [Turner et al., 1993a], the diameter for merry-go-round features was here determined as the greatest length of the peripheral edge that enclosed all the vortical clouds. For the oval, solid mass the diameter was measured from edge to edge of the cyclonic cloud. The diameter for band or mass of

Table 2. Annual Summary of the Satellite Classification of Mesoscale Vortices Observed Over the Bellingshausen Sea and the Weddell Sea Sectors Within the Areas Defined in Figure 1

<table>
<thead>
<tr>
<th></th>
<th>Bellingshausen Sector</th>
<th>Weddell Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Comma cloud</td>
<td>166</td>
<td>63</td>
</tr>
<tr>
<td>Band or mass of</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>convective clouds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiraliform</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>Merry-go-round</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Oval, solid mass</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>264</td>
<td>110</td>
</tr>
<tr>
<td>Continental sector</td>
<td>45</td>
<td>0</td>
</tr>
</tbody>
</table>

N, number of mesoscale vortices; P, percentage of mesoscale vortices with respect to the total number observed in the respective area; h, number of mesoscale vortices that had middle/high cloud associated with them; d, diameter in kilometers.
convective cloud types was given by the zonal distance from edge to edge that included all the clouds either forming a band of cumulus, or grouping into almost a single mass.

Table 2 shows the annual summary of the types of mesoscale cyclones observed throughout the year on both sides of the Antarctic peninsula. On both sides, around 65% of the total mesoscale vortices were of comma cloud type. The average diameter for these features was 353 and 346 km over the BSS and WSS, respectively. Band or mass of convective cloud (oval, solid mass) type was the second most frequent type over the BSS (WSS). Overall, about 42% of all the mesoscale cyclones within the BSS had white cloud (i.e., middle and/or high cloud) associated with them, indicating that these were deep cyclones. Table 3 gives the total number and weekly frequency of these cyclones in terms of season. As previously indicated, the overall mesoscale cyclonic activity decreases during the winter. However, deep cyclones exhibit a winter maximum, with the result that the fraction of them with respect to the total is greatest during this season. This implies that even though the actual number of mesoscale cyclones is less in winter, more of them become deep features; as shown below, this is because of more frequent outbreaks of cold air over the relatively warm Bellinghausen Sea. CTT evaluation of the deep BSS cyclones indicates a mean temperature of about -37°C in winter, which corresponds to pressure levels that range between 470 and 420 hPa from 65°S to 55°S in winter. On the other hand, only 6% of the mesoscale vortices showed some middle/high cloud associated with them over the WSS, indicating that the majority of them were shallow features. This reveals that the mesoscale cyclonic activity over the BSS is driven and/or supported by different mechanisms than on the other side of the polar front. This may be another indication of the different mechanisms associated with mesoscale cyclonic activity on both sides of the peninsula. During summer, the mean CTT of the deep BSS cyclones was also -37°C, which corresponds to pressure levels of 420 and 350 hPa from 65°S to 55°S. For clouds that appear dark on satellite images, the CTT indicates a mean temperature about -6°C and -9°C for summer and winter, respectively. These correspond to pressure levels that range between 860 and 720 hPa in summer, and 850 and 740 hPa in winter from 65°S to 55°S. Clouds that appear in gray tones have a mean CTT about -21°C in both summer and winter. This corresponds to pressure levels that range between 620 and 530 hPa, and 650 and 580 hPa from 65°S to 55°S, respectively.

Table 3. Total Number and Equivalent Weekly Frequency of Mesoscale Vortices Observed Over the BSS That Showed Middle/High Cloud Associated With Them

<table>
<thead>
<tr>
<th>Period</th>
<th>Number of Middle/High Mesoscale Vortices</th>
<th>Equivalent Weekly Frequency</th>
<th>Ratio of Middle/High to All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late summer</td>
<td>15</td>
<td>3.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Autumn</td>
<td>18</td>
<td>1.9</td>
<td>7.4</td>
</tr>
<tr>
<td>Winter</td>
<td>33</td>
<td>3.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Spring</td>
<td>21</td>
<td>2.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Early summer</td>
<td>23</td>
<td>3.0</td>
<td>7.9</td>
</tr>
<tr>
<td>Annual</td>
<td>110</td>
<td>2.6</td>
<td>6.4</td>
</tr>
</tbody>
</table>

This corresponds to pressure levels that range between 620 and 530 hPa, and 650 and 580 hPa from 65°S to 55°S, respectively.

Band or mass of convective cloud has long been identified as a distinctive feature on satellite images (called PVA masses = cyclonic vorticity advection). They are made up of cumulus and cumulonimbus clouds that cluster to form a single mass and are usually found to the rear of a cyclone or of a major frontal band within the cold air, where convection is well developed. They identify localized upward motion that can be associated with a diffusent thermal trough in the thickness field (1000-500 hPa). Note that 36 of the 37 band or mass of convective cloud types over the BSS had white tones, indicating that they were deep features. The comma cloud term used here refers to the shape of the cloud signature on the satellite image. However, it has been also used to describe the type of vortex that forms and/or develops behind the polar front. This may be the final stage of development of band or mass of convective cloud type features, or what has been called "organized PVA" [Guymer, 1983]. Anderson et al. [1973] defined a comma-shaped cloud as "a moving convective vortex to the rear of a polar front (that) produces a cloud mass or grouping of cloud elements ahead of the center that assumes a characteristic shape, that of comma." If we consider the band or mass of convective cloud and comma-cloud features to be the same type of mesoscale cyclone but at a different stage in their development, then about 50% of their total (203) had high cloud associated with them. This is in marked contrast with the 5% observed over the WSS, indicating again that different mechanisms are associated with the formation and/or development of mesoscale cyclones on both sides of the peninsula. About 25% of all the tracked cyclones (127) over the BSS showed some degree of development from their initial appearance to the next image(s), while only 8% of the total (73) developed over the WSS. About 39% and 27% of the tracked vortices observed in the BSS and WSS, respectively, were dissipating while the rest of them (36 and 65%) did not show any distinguishable change. This may be another indication of the different mechanisms associated with mesoscale cyclonic activity on both sides of the Antarctic peninsula.
Figure 7 shows the annual distribution and trajectories of all deep convective and comma types observed within the study area, whose diameter was greater than or equal to their respective annual averages. This filters out all small features, leaving only those that may be considered to be significant mesoscale cyclones. A total of 57 (out of 100 deep cyclones) of these mesoscale vortices were observed over the BSS, but only four (out of seven deep cyclones) over the WSS. It can be seen that most of them cluster to the northwest of the Antarctic peninsula. About 68% (40) of the total were tracked. Of these, 45% (18 out of 40) showed a degree of development, while 43% (17 out of 40) showed some dissipation. Most of the significant mesoscale vortices moved northeastward toward the Drake Passage. The annual equivalent weekly frequency of significant mesoscale vortices was 1.4, being highest (lowest) during the spring (autumn) season (1.8 and 0.9 mv per week, respectively).

From this survey, the exact location of mesoscale cyclogenesis is uncertain. Back extrapolating the trajectories suggests that many vortices over the BSS entered the study area from the west, indicating that their formation and/or initial development took place somewhere over the open Southern Ocean. Examination of significant mesoscale vortices indicated that about half of them showed some degree of development as they approached the Drake Passage or the southern tip of South America. This, along with the fact that the maximum annual equivalent activity was found just to the west of Drake Passage, suggests a cyclogenesis area to the north of Bellinghausen Sea, probably around the northern edge of the sea ice (compare Turner and Thomas [1994] and Turner et al. [1996]).

The trajectories over the WSS suggest that many of the mesoscale vortices formed within the study area, even though only 8% of the tracked systems showed some degree of development. This indicates that the mesoscale vortices over the WSS are usually weaker than those over the BSS. The two areas of greater activity to the north of the Ronne Ice Shelf can be associated with lee cyclogenesis to the east of the peninsula [Turner and Row, 1989], and the other to the north of Coats Land (near Halley Station) with cold air outbreaks onto the Weddell Sea [e.g., Turner et al., 1993b] and associated vortex stretching [Engels and Heinemann, 1996]. The Filchner/Ronne Ice Shelf is another cyclogenesis area, with formation likely to be associated with katabatic such as occurs over the Ross Ice Shelf [Turner and Thomas, 1994; Turner et al., 1996; Bromwich, 1991]. The few mesoscale cyclones that showed eastward movement over the northern Weddell Sea indicate that some of these features had their origin on the other side of the peninsula.

3. Synoptic-Scale Pattern and Mesoscale Cyclones

To analyze the synoptic-scale pattern associated with mesoscale cyclones on both sides of the peninsula, averages and anomalies for the sea-level pressure, the 700-hPa and 500-hPa geopotential heights and 1000 to 500-hPa geopotential thickness were calculated using the numerical analyses produced by the Australian Bureau of Meteorology. Because mesoscale vortices may be observed simultaneously on both sides of the peninsula, cyclonic days for the BSS (WSS) correspond to days for which a mesoscale cyclone was observed on satellite images within the BSS (WSS), but none was observed within the WSS (BSS). This isolates all the cyclonic days in each sector, and therefore results may better reflect the synoptic-scale environment associated with mesoscale cyclones on each side of the peninsula but not on both. Calculations were carried out seasonally to overcome, in part, the asymmetric distribution of mesoscale cyclones throughout the year. The left panels in Figures 8a to 8e (9a to 9b) are the sea level pressure anomalies for late summer, autumn transition, winter, spring transition and early summer associated with mesoscale cyclones over the BSS (the WSS), respectively. The anomaly patterns for the other fields (i.e., 700-hPa and 500-hPa heights and 1000 to 500-hPa thickness) are similar to those displayed in Figure 8 for the BSS (Figure
Figure 8. Sea level pressure anomalies for cyclonic days over the Bellingshausen Sea sector in relation to the seasonal mean (left panels, contour interval of 1 hPa) along with the t-test (right panels) applied to the anomalies for (a) late summer, (b) autumn, (c) winter, (d) spring, and (e) early summer. In the right panels, shading means statistically significant (better than 95% confidence level using a two-tailed t-test); negative values are denoted by crosses, and positive values are stippled.
Figure 9. Same as Figure 8, but over the Weddell Sea sector.
9 for the WSS); therefore discussion in terms of the pressure anomalies also applies. The t-test applied to the pressure anomalies (right panels in Figure 8 for the BSS, and in Figure 9 for the WSS) indicates that they are statistically significant (better than 95% confidence level using a two tailed t-test) for the winter but generally not for the rest of the year. The anomalies for the other fields are statistically significant for all seasons around the areas where maximum and minimum anomalies occur.

Negative departures (lower pressures than the seasonal average) over the BSS are resolved for cyclonic days in all seasons, except late summer and spring, which show negative anomalies centered to the north of the Weddell Sea. Differences can be noted throughout the year in relation to the extent, intensity, and location of the negative anomaly areas affecting the BSS. Thus in winter the area of maximum negative anomalies is centered over the Drake Passage (Figure 8c) and is larger than in the other seasons. This center concurs with that of maximum concentration of mesoscale cyclones shown in Figure 4, as well as with the period of highest fraction of deep mesoscale vortices (Table 3). In spring a small positive anomaly area is located over the Drake Passage. This is despite the fact that during this season more significant mesoscale vortices were observed.

Over the WSS, the anomaly pattern is more variable. Negative anomalies occur in late summer, autumn, and spring seasons, while winter and early summer show significant positive anomalies. From this analysis, no synoptic-scale pattern that persistently favors mesoscale cyclogenesis over the WSS was found. The fact that the trajectories of mesoscale cyclones do not show a preferential direction may be a reflection of this situation.

To gain more insight into the synoptic-scale environment associated with mesoscale vortices, differences between cyclonic days and non-cyclonic days (no cyclone was observed on satellite images within the selected sector) were constructed for both the BSS and WSS. This procedure filters out the missing days for which the presence or absence of mesoscale cyclones is unknown. The difference of thickness fields along with the results of the t-test is presented in Figures 10a to 10e for the BSS, and in Figures 11a to 11e for the WSS. Overall, it can be seen that a colder environment (negative differences) for cyclonic days dominates in both sectors (except early summer in the WSS). This further confirms the results described above over the BSS. Note that a warmer environment (positive differences) dominates over the WSS for cyclonic days on the other side of the peninsula. Likewise, while over the WSS a colder environment accompanied mesoscale cyclogenesis, a warmer one was present over the BSS. From these analyses, the results over the WSS for winter are opposite to those obtained by taking the anomalies with respect to the seasonal average.

In principle, the location of negative pressure anomalies identifies regions of more frequent and/or stronger synoptic-scale cyclones, while the positive anomalies suggest the dominance of anticyclonic circulation in the areas where they are resolved. Thus the negative centers observed over the BSS and WSS can be interpreted as an indication of more equatorward (poleward) airflow occurring on the west (east) side of these centers and, conversely, for the positive centers.

The overall patterns resolved by the 1000 to 500-hPa geopotential thickness field indicates that mesoscale cyclones occur within cold air masses, and they are generally consistent with the advection patterns inferable from Figures 8 and 9.

4. Discussion and Conclusions

A survey of mesoscale cyclones near the Antarctic peninsula has been carried out for the calendar year of 1991. Even though only one or two images were analyzed for many days, the images were randomly distributed during the day and throughout the year; therefore the results from this sampling are representative and provide insight as to the mesoscale cyclonic activity around the peninsula. Results reveal that the mesoscale cyclonic activity was slightly higher over the Bellingshausen Sea sector than over the Weddell Sea sector. On average, about seven and five mesoscale vortices were observed each week within these respective areas. A maximum (minimum) equivalent weekly frequency occurred during the summer (winter) seasons on both sides of the Antarctic peninsula, as found previously by Turner et al. [1996]. The annual equivalent frequency of mesoscale vortices per unit area suggests two preferential areas over the BSS, one to the north and northeast of the Bellingshausen Sea and the other over the Amundsen Sea; the latter probably forms in association with the persistent katabatic winds that blow offshore in the vicinity of 110øW [Parish and Bromwich, 1986]. Over the WSS, two zones of greater activity were also noted, one offshore from Coats Land (about 200 km from the coast) and the other on the lee side of the peninsula (to the north of the Ronne Ice Shelf). The annual frequency in these two locations is slightly greater than the activity observed over the BSS. In a previous survey carried out between August 1989 and February 1990, Carrasco [1992] and Carrasco and Bromwich [1993] noted a similar spatial distribution on both sides of the Antarctic peninsula. That is, a relatively homogeneous distribution of mesoscale vortices over the BSS with a suggestion of slightly higher activity over and to the north of the Bellingshausen Sea. Over the WSS, higher frequency on the lee side of the peninsula and to the north of the Ronne Ice Shelf was also noted. In addition, the spatial distribution of mesoscale cyclones for the September 1984 to February 1985 period [Turner and Thomas, 1992; Carrasco and Bromwich, 1993] showed similar results over the BSS, but less activity over the WSS.

The annual spatial distribution obtained by Turner et al. [1996] for March 1993 to February 1994 provides the best comparison with the 1991 pattern shown in Figure 4. There is a broad similarity between the two spatial distributions, with the Turner et al. [1996] formation frequencies being 50-100% higher than found here. In the WSS both analyses resolve maxima over the Filchner/Ronne Ice Shelf, the central Weddell Sea, and the eastern Weddell Sea. The latter two centers are found between 70ø and 75øS in 1991 and between 65ø and 70øS in 1993-1994. In the BSS both analyses resolve a formation maximum to the northwest of the Antarctic peninsula in roughly the same location. In the western part of the BSS, large differences between the two analyses are found, both structurally and in magnitude. The formation maximum at 72øS, 105øW in Figure 4 is located to the northeast by Turner et al. [1996] near 67øS, 95øW with a formation frequency twice as large as in 1991. The northward shift of this BSS center by about 5ø matches the northward shift of the two WSS centers mentioned above; these three
Figure 10. Differences of the 1000 to 500-hPa geopotential thickness between cyclonic and noncyclonic days over the Bellingshausen Sea sector (left panels, contour interval of 10 gpm) along with the t-test (right panels) applied to the differences. Shading means statistically significant (better than 95% confidence level using a two-tailed t-test); negative values are denoted by crosses and positive values are stippled.
Figure 11. Same as Figure 10, but for the Weddell Sea sector.
centers constitute the primary zone of mesoscale cyclone formation in the study area. Some of the differences between the analyses can be attributed to differing imagery characteristics with the temporal resolution of Turner et al. [1996] being much superior to that used here (about 5 times better) but having a much poorer spatial resolution (8 km hardcopy versus 3 km digital here). Turner et al. [1996] perform a more complete correction for the temporally varying satellite coverage across the observational domain, which results in analysis differences around the edges of the area evaluated. The much better temporal resolution of Turner et al. [1996] likely primarily explains their greater formation frequencies because of the short vortex lifetimes found by these authors (50% of their vortices had lifetimes of 1-6 hours). The shift in the primary axis of mv formation on both sides of the peninsula from 70øS and 75øS in 1991 (Figure 4) to 65-70øS in 1993/94 must be a consequence of interannual variability of the atmospheric circulation. Turner et al. [1996] associate this mv formation axis with the circumpolar trough; inspection of the mean sea level pressure charts for these 2 years (not shown) shows a northward shift of the circumpolar trough axis by an average of 3ø latitude, confirming the hypothesis of Turner et al. [1996].

Trajectories of the mesoscale vortices confirm results previously found by Carrasco [1992] and Carrasco and Bromwich [1992] that many vortices observed to the west of the peninsula move northeastward toward the Drake Passage. This is also true for significant mesoscale cyclones, implying that the southern tip of South America (Tierra del Fuego) and the northern tip of the Antarctic peninsula can be affected by severe weather conditions, as found previously by Lyons [1983]. The much higher fraction of deep and significant mesoscale vortices over the BSS with respect to the WSS indicates that different mechanisms support mesoscale cyclogenesis on both sides of the peninsula. The synoptic-scale pattern for cyclonic days over the BSS during the winter indicates that mesoscale cyclones formed and developed within cold air outbreaks associated with synoptic-scale cyclones. This cold air moves equatorward from the Antarctic continent over the much warmer and moister environment of the open ocean over the southeastern South Pacific Ocean. Sensible and latent heat fluxes from the ocean into the boundary layer can develop convection in the cold air mass, triggering and enhancing mesoscale cyclonic perturbations. These results confirm earlier work by Fitch and Carleton [1992] and Carleton and Fitch [1993].

Wiin-Nielsen [1989] used a simple three-level baroclinic model to represent the basic thermal structure of the atmosphere. The lower layer (1000-700 hPa) had a nearly adiabatic lapse rate, and the upper layer (700-100 hPa) a more stable lapse rate. His results demonstrated that this basic state is baroclinically unstable with a wavelength of a few hundred kilometers within the subsynoptic scale. This thermal structure may occur over the open ocean to the west of the peninsula when a cold Antarctic air mass has been modified to an almost adiabatic lapse rate by air-sea interaction. Strong air-sea interaction can result in convection and thus vertical development. The large number of deep mesoscale vortices over the BSS is indicative of this process. On the other hand, a baroclinic zone can be found at the edge of the sea ice created by the cold temperatures over the ice and the warm temperatures over the open ocean [e.g., Heinemann, 1996a]; for a slightly different situation, see the work by Tsuboki and Wakahama [1992]. Therefore baroclinic instability and convective instability of second kind (CISK) are the most likely mechanisms for cyclogenesis over the BSS (compare Sardie and Warner [1983]) and can be assisted by upper level forcing. One or more mechanisms may be active during the lifetime of individual mesoscale cyclones. These physical characteristics of the atmosphere may also occur over the WSS adjacent to and north of the sea ice boundary as individual case studies have suggested. Heinemann [1996b] studied a mesoscale vortex that underwent intense development over the eastern Weddell Sea. The formation and development of the mesoscale cyclone took place near the edge of the sea ice, and its baroclinic structure was associated with a cold air outbreak. The sensible heat flux from the ocean was about 300 W m-2 during the genesis stage. During the intense development of another mesoscale vortex over the Weddell Sea studied by Turner et al. [1993b], a cold air outbreak descending from the interior of Antarctica (Queen Maud Land) was once again associated with mesoscale cyclone formation and intensification. However, the much lower percentage of deep mesoscale vortices in the WSS indicates that convective processes are inhibited by the sea ice implying that baroclinic instability is a primary cause for cyclogenesis. Heinemann [1996c] and Engels and Heinemann [1996] conclude that the mesoscale cyclones forming along the eastern side of the Weddell Sea are caused by a combination of two mechanisms: baroclinic instability of boundary layer fronts generated by katabatic winds and by vortex stretching of synoptic easterly airflows blowing down from Queen Maud Land. Lee cyclogenesis on the east side of the peninsula is the other mechanism for mesoscale cyclogenesis associated with the effect of the mountain barrier upon the westerly airflow [Turner and Row, 1989].

The fact that the synoptic-scale pattern associated with mesoscale cyclones over the WSS is not as clearcut as in the BSS, also indicates that more than one mechanism supports cyclogenesis in this sector. Individual case studies have shown that deep vortices in this sector [Turner et al., 1993b; Heinemann, 1996b] are associated with the approach of an upper level trough (as resolved at the 500-hPa level) that brought cyclonic vorticity over the incipient mesoscale vortex. The shallowness characteristic of the mesoscale cyclones in the WSS suggests that this upper level support is not as frequent as it is over the BSS.

Unfortunately, the gaps between consecutive satellite images impede study of the cloud evolution and of the duration of the mesoscale vortices, as done by Turner et al. [1996]. However, identification of the initially observed cloud signatures indicates that about 65% of the mesoscale vortices were of comma-cloud type. The dominance of this type of perturbation was also found by Turner and Thomas [1994] and Turner et al. [1996] for this area and by Carrasco and Bromwich [1994, 1996] for the Ross Sea and Ross Ice Shelf area. 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 over the southern hemisphere. The present results and those of Turner and Thomas [1994], Turner et al. [1996], and Carrasco and Bromwich [1994, 1996] confirm that comma-cloud vortices are the dominant type over the south polar region.
The average diameter of all vortices was about 370 km which is larger than that found for the same period over the Ross Sea and Ross Ice Shelf (267 and 247 km, respectively), especially of those near Terra Nova Bay (200 km) and Byrd Glacier (195 km) [Carrasco and Bromwich, 1996]. This is also true when comparing with the results obtained in these areas but for 1988 [Carrasco and Bromwich, 1994]. By comparison, Turner et al. [1996] obtained average vortex diameters for the study area in 1993-1994 of around 530 km. This is 43% larger than the 370 km found here and probably results from a combination of differing diameter definitions and interannual variability.

Most of the mesoscale vortices observed over WSS were straitform low cloud features in appearance, indicating that they developed within the lower troposphere, more than likely below 700 hPa, as confirmed by the CTT analysis. Much greater vertical development was typically observed in the BSS as a consequence of the limited sea ice cover and vigorous air-sea interaction.

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