A Cyclone Climatology of the Canadian Climate Centre General Circulation Model

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ABSTRACT

The cyclone event climatology is presented for a five-year simulation by the Canadian Climate Centre general circulation model. Winter season results are given for the extratropical regions of both the Northern and the Southern hemispheres and the results are compared to an event climatology based on five years of observed data.

In the Northern Hemisphere, classification of the simulated and the observed 1000 mb lows as a function of central height shows that the model has a deficiency of weak cyclones and an excess of intense cyclones while the number of cyclones of medium intensity is well simulated. The geographical distribution of the cyclone events shows that those features of the observed climatology which are thermal in nature, such as a preference for lows to form and move over relatively warm underlying surfaces, are reasonably well simulated, but the topographical features such as lee cyclogenesis and the avoidance of high terrain by lows are poorly simulated.

The Southern Hemisphere also shows a deficiency of simulated cyclones, although less pronounced than the Northern Hemisphere. The number of weak and strong cyclones are well simulated, and the paucity of Southern Hemisphere lows results from a deficiency of cyclones of moderate intensity. The observed climatology, which is nearly free of mountain influences, is well simulated and only a few minor problems are evident, such as a poor simulation of the winter cyclogenesis in the lee of the Andes and a tendency for model cyclones to be present over high terrain.

1. Introduction

Cyclones are important features of the observed climate. In the extratropics, much cloud and precipitation is associated with low pressure systems. Consequently, it is important for general circulation models (GCM) to simulate their behavior correctly, especially to assess the results of climate change experiments on a regional basis.

Observational studies of cyclones show that they are not uniformly distributed over the earth's surface but tend to occur in preferred geographical regions. Petterssen (1956) used once-daily analyses for the period 1899 to 1939 to determine the frequency of cyclone centers in 100 000 km^2 areas during winter and summer for the extratropical Northern Hemisphere. Klein (1957) used data for the same 40-yr period to determine the number of days with cyclones for all 12 months in five degree by five degree latitude–longitude quadrangles. These studies also showed that cyclones tend to occur in highly elongated zones or "storm tracks." It was also observed that lows tended to move over relatively warm underlying surfaces and that cyclones had a life span of four to five days. The effect of topography was also evident since lows were observed to avoid high terrain and that the lee of mountains was a favored area of cyclogenesis.

A Southern Hemisphere cyclone climatology was produced by Taljaard (1967) who used the data from the International Geophysical Year (July 1957 to December 1958). These results were somewhat different in character from those of the Northern Hemisphere. The main feature of the Southern Hemisphere climatology is a circumpolar zone of high cyclone frequencies surrounding Antarctica during winter, summer, and the intermediate seasons. During the winter two principal storm tracks originating in midlatitudes merge with the circumpolar maximum. One of these originates between Australia and New Zealand and the other over South America.

Subsequent cyclone studies have tended to be regional in scope. Zishka and Smith (1980) and Whittaker and Horn (1981), for example, showed that cyclone frequencies over North America decreased significantly during the period 1950–77; and in the Southern Hemisphere, an investigation of cyclogenesis in the lee of the Andes by Chung (1977), based on the sea level pressure analyses of the Argentinian Meteorological Service for the year 1973, revealed three favored areas of lee cyclogenesis at 25°, 31° and 55°S.

The behavior of cyclones in numerical forecast models has also been studied in some detail. Leary (1971) examined the 36-h sea level pressure forecasts produced by the six-layer primitive equation model of

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the National Meteorological Center (NMC) for the 1969/70 winter season. Her results showed that cyclones over the oceans were not forecast deep enough and that those forming to the lee of the Rocky Mountains were forecast too deep. Model cyclones were also observed to intensify less rapidly and dissipate more quickly than those of the real atmosphere. Also evident from this study was the fact that forecast lows tended to move too slowly and that rapidly deepening storms tended to move to the left of the forecast track. Silberberg and Bosart (1982) studied systematic cyclone errors in the NMC LFM-II (limited-area fine mesh) model during the period 1 October 1978 to 1 May 1979. Their results also showed that cyclones were not forecast deep enough over the oceans and too deep to the lee of the Rocky Mountains. The phase speeds of the lows in October and November were underforecast, in March and April they were overforecast, and no systematic speed errors were evident in December, January and February.

A recent study by Akyildiz (1985) examined the behavior of cyclones in the European Centre for Medium Range Weather Forecasts (ECMWF) 1.875 by 1.875 degree grid-point model and the triangular 63 wave spectral model during the 1983/84 winter. In the grid-point model, lows moved too slowly and their deepening and filling rates were underestimated. In the spectral model, the systematic slowness was evident only for rapidly moving cyclones. The rate of deepening was reasonably well forecast but the rate of filling was still underestimated. For both forecast models, the horizontal scale of cyclones in the early stages of development was too small and for mature cyclones it was too large.

Manabe and Terpstra (1974) presented Northern Hemisphere cyclone trajectories for a 45-day winter period from a simulation by the GFDL GCM described in Holloway and Manabe (1971). Their results showed a major storm track originating south of Japan and extending to the Gulf of Alaska. There was a second major storm track along the east coast of North America to Greenland, western Europe, and northeast of the Caspian and Aral Seas where the lows dissipated. The cyclogenetic areas off the east coast of Asia and to the lee of the Rocky Mountains appeared to be reasonably well simulated, but the strong cyclogenetic area in the Mediterranean was absent.

There appear to be no global studies of the behavior of cyclones in GCMs in the literature, and this paper hopes to fill this void by presenting a winter cyclone climatology for both the Northern and the Southern hemispheres for a five-year simulation from the Canadian Climate Centre (CCC) GCM.

2. Analysis

There are two methods used to obtain cyclone frequencies or "event" climatologies. The first of these counts the number of cyclone tracks which cross unit areas, or in many cases latitude–longitude quadrangles, and the second records the number of low centers found in a unit area in a given time period.

The method which counts tracks enumerates a low only once in a given unit area, hence slowly moving or quasi-stationary lows are not multiply counted and fast moving lows will be counted in each unit area along its path. This method is very labor intensive because the trajectories of every low over a period of time must be extracted before proceeding with the counting of the tracks. However, in doing so, one has the advantage of being able to eliminate those lows which are not relevant, such as thermal lows and lows caused by reduction to sea level over high terrain.

The second method of producing cyclone frequencies counts the number of lows in each unit area. As a result, slow moving lows can be enumerated many times in a given unit area and rapidly moving cyclones will not necessarily be counted in all unit areas along its path. It is very straightforward to extract such an event climatology using a computer, but it must be remembered that all lows including spurious ones will be included.

Most cyclone studies have used latitude–longitude quadrangles as the "unit areas" or analysis boxes. Since the area of a quadrangle is a function of latitude, the extracted raw cyclone frequencies were usually area-normalized when the results were presented. This procedure has been criticized by Zishka and Smith (1980) and Hayden (1981) who recommend that the presentation of cyclone frequency results be done in terms of the raw values even though this would bias the results. The authors felt that the area-normalized results were also biased and that it would be preferable to display the raw frequencies. An additional bias in the cyclone track counting method is described in Taylor (1986) who showed that the number of cyclone events depends on the orientation of the cyclone trajectories in the analysis boxes.

For this study, the second approach is used mainly because it can easily be done on a computer. The problem of lows "skipping" analysis boxes is a sampling problem which is controlled by using a relatively long period of five years to smooth the frequency maps. Another advantage of this method is that it does multiply count slow moving cyclones and thereby provides a better measure of cyclonic activity and, hopefully, cloudiness and precipitation in each grid box. The climatology is produced using a polar stereographic projection and since its grid boxes have a relatively weak dependence on latitude, area-normalized results will be given.

The cyclone climatology is extracted for the Northern Hemisphere winter (December, January, and February) and the Southern Hemisphere winter (June, July, and August) from five years of simulated data from the CCC GCM (Boer et al., 1984) operating in an annual cycle mode sampled once per day. The model's 1000 mb height fields, which had been archived as triangular 20 wave arrays of spherical harmonic coefficients, were synthesized on a hemispheric polar stereographic grid with a spacing of about 440 km at 60 degrees latitude. A low event at a grid point is defined as the occurrence of a height lower than each of the four surrounding points. The total number of events for the two hemispheres was determined for the five-yr simulation period. The raw event statistics were area-normalized by the square of the chart's map scale factor, making the unit area approximately 200 000 km^2.

Because the choice of grid type, analysis box size, sampling interval and length of record influence the results, it was decided to repeat the analysis for a five-year period from observations. The 1000 mb height field analyses from the ECMWF/WMO dataset for the years 1980 to 1984 were interpolated to the same polar stereographic grid used for the model results in order to make the subsequent analyses identical.

3. Results

Table 1 displays the number of lows north of 30°N and the number of lows south of 30°S from the model and observations as a function of central height for five winters. These results show that during the five seasons the model exhibits fewer lows in total than are observed. In the Northern Hemisphere, the results as a function of central height show that the model had too many deep cyclones and that the paucity of model lows is concentrated in the weak low categories. Most of the spurious lows counted by the analysis procedure will appear in the weak low classes; it is not clear whether the model deficiencies in these categories result from too few relevant cyclones, too few spurious lows, or both. In the Southern Hemisphere, there is less difference between the number of simulated and observed lows than was evident in the Northern Hemisphere results.

A statistical test was made to determine if the number of simulated lows differs significantly from the number of observed lows. Three categories are used: a weak low category with central heights above 0 m; a medium category with central heights between −300 m and 0 m; and a strong low category with central heights below −300 m. The mean number of lows and the standard deviation over the five seasons are calculated, and the following t-statistic is computed for each category and the total number of lows:

$$t = (\bar{x}_o - \bar{x}_m) \bigg/ \left\{ \left(\frac{1}{n_o} + \frac{1}{n_m} \right) \times \left[\frac{(n_o - 1)s_o^2 + (n_m - 1)s_m^2}{n_o + n_m - 2} \right] \right\}^{1/2} \qquad (1)$$

TABLE 1. Total number of simulated and observed cyclone events as a function of the central height for five winter seasons for the Northern Hemisphere between 30°N and the North Pole and for the Southern Hemisphere between 30°S and the South Pole.

	Northern Hemisphere		Southern Hemisphere	
Central height	Model observations	Ratio	Model observations	Ratio
Over 200 m	50 201	0.25	1 9	0.11
100 to 200 m	653 1654	0.39	264 358	0.74
0 to 100 m	1676 2510	0.67	938 772	1.22
−100 to 0 m	1354 1733	0.78	1178 1099	1.07
−200 to −100 m	1102 1034	1.07	1534 1785	0.86
−300 to −200 m	530 365	1.45	1151 1538	0.75
−400 to −300 m	181 64	2.82	439 541	0.81
−500 to −400 m	30 15	2.00	67 52	1.29
Below −500 m	2 2	1.00	9 8	1.13
Total	5578 7578	0.74	5581 6162	0.91

TABLE 2. Computed t-values for the difference between the number of simulated and observed lows as a function of central height. Values over 3.4 are significant at the 1% level.

Central height	Northern Hemisphere	Southern Hemisphere
Over 0 m	8.5	0.8
−300 to 0 m	1.6	4.3
Below −300 m	4.1	0.8
Total	9.0	4.3

where $\bar{x}$ is the mean number of lows per season in each category, s its standard deviation, and n the number of seasons. The subscript o refers to observations and the subscript m refers to the model. The t-values are displayed in Table 2. For $n_o = n_m = 5$ values over 3.4 are significant at the 1% level. The results show that total number of simulated lows in both hemispheres, the number of weak lows in the Northern Hemisphere, the number of medium lows in the Southern Hemisphere, and the number of strong lows in the Northern Hemisphere are significantly different from the observed number of lows.

The geographical distribution of total cyclone events is given in the following figures. Even though these figures display events equatorward of 30 degrees, they were not used in compilation of the preceding statistics.

Figures 1 and 2 display the total number of Northern Hemisphere cyclone events per 200 000 km^2 during the five-yr period from observations and the model respectively. Comparison of Fig. 1 to the previous studies of Petterssen (1956) and Klein (1957) shows reasonable agreement indicating that the simple analysis procedure used in the present study is yielding reliable results. It is readily apparent upon comparison of Figs. 1 and 2 that the model has simulated too few lows which is also indicated by Table 1.

The observations show a large area of cyclone activity in the northern Pacific with a maximum in the Gulf of Alaska, and two major storm tracks. The first originates to the west of Kamchatka and ends in the Gulf of Alaska, and the second and somewhat stronger one begins in southern Japan and also ends in the Gulf of Alaska. (The contour with a value of 20 in the middle of the shaded area in the Pacific has not been mislabeled; there is a minimum in this area.) The model results show a similar pattern in the north Pacific, but the maximum cyclone frequency occurs near Kamchatka and the more southerly storm track is much weaker than observed.

Over North America, the observations show a maximum of cyclonic activity in the favored cyclogenetic areas in the lee of the Rocky Mountains. From this region a broad band of high events extends eastward across southern Canada and the northern United States with the maximum activity located over the Great Lakes and Hudson Bay. The model results show few cyclone events and consequently little cyclogenetic activity to the lee of the Rocky Mountains. There is a small region in the northern United States with a weak storm track extending to the Great Lakes. The most prominent model storm track over North America is a continuation of the storm tracks in the Gulf of Alaska along the north coast of Canada to Hudson Bay. The observed results do not show such a track implying that very few cyclones move inland from the Gulf of Alaska and along the Arctic coast to Hudson Bay. The spurious event maximum off the coast of Baja California is the surface reflection of upper cold lows which are frequently present in this area during winter.

The major observed cyclonic activity over the Atlantic Ocean is found off the east coast of North America, both coasts of Greenland, northern Scandinavia, and the northern coast of the U.S.S.R. There is a lesser area of cyclone events over and to the west of the British Isles. A similar behavior is seen in the model results. Lows in the model tend to be farther off the east coast of North America and there is no splitting of the storm track along the two coasts of Greenland. The cyclone areas to the north of Scandinavia and the U.S.S.R. are poorly defined, and there is an event maximum over the high terrain of Norway and Sweden where the observations show an expected minimum.

In Europe, the major area of cyclonic activity is found in the Mediterranean with centers of maximum events near Italy and Cyprus and a storm track extending northeastward into the western Soviet Union and another extending eastward towards the Caspian Sea. The model fails to show any significant cyclonic activity in the lee cyclogenetic area in the Gulf of Genoa but does simulate the storm tracks running eastward from a center near Cyprus.

Over the land mass of Asia, the model and the observations show little organized cyclone activity. The most striking features occur over mountainous terrain and are assumed to result from extrapolation below the surface.

A few individual model cyclones were followed throughout their life spans, and the period of time between genesis and lysis was observed as typically about ten days in contrast to the four or five days reported by Klein (1957). This inordinately long life of simulated cyclones was a result of their slow dissipation rate. As mentioned previously, a similar behavior was found in the ECMWF forecast models by Akyildiz (1985).

Figures 3 and 4 show the Southern Hemisphere cyclone event climatologies for winter from observations and the model, respectively. The most prominent feature in the observations is the ring of high events surrounding Antarctica. The number of events is not uniformly distributed in the ring, and the highest number of cyclones is found on the Indian Ocean side of Antarctica, with a secondary maximum occurring in the quadrant between the dateline and 90°W. Between South America and the Prime Meridian, the circumpolar ring becomes quite broad, suggesting a storm

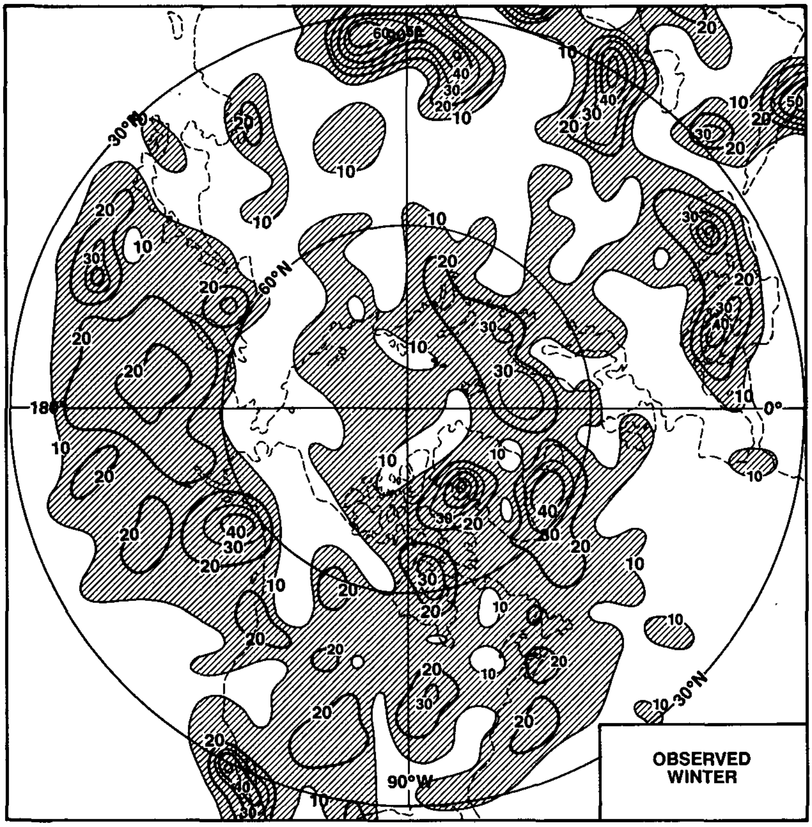

FIG. 1. The total number of lows per 200 000 km^2 for five Northern Hemisphere winters (December–February) during the period from 1980 to 1984 using the once-daily analyses of the ECMWF/WMO dataset.

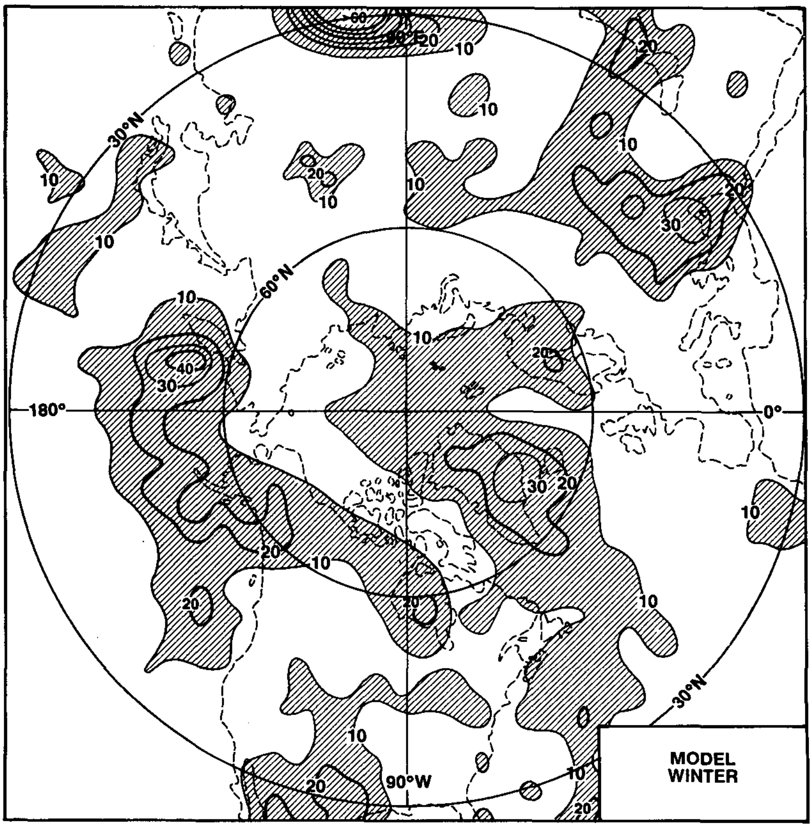

FIG. 2. As in Fig. 1 except for five winters simulated by the GCM.

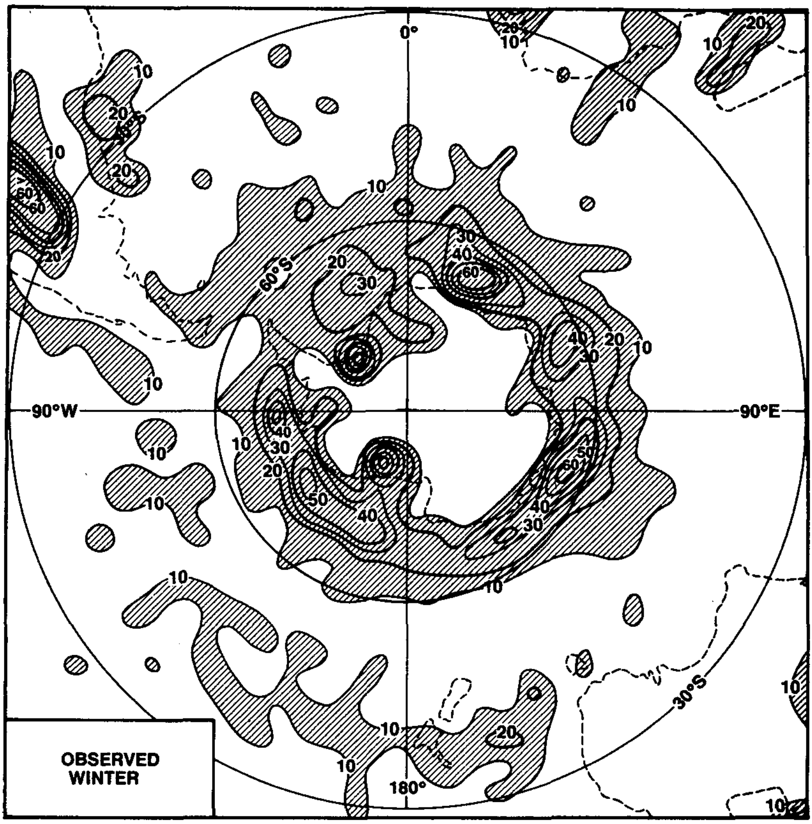

FIG. 3. As in Fig. 1 except for the Southern Hemisphere winter (June–August) as observed.

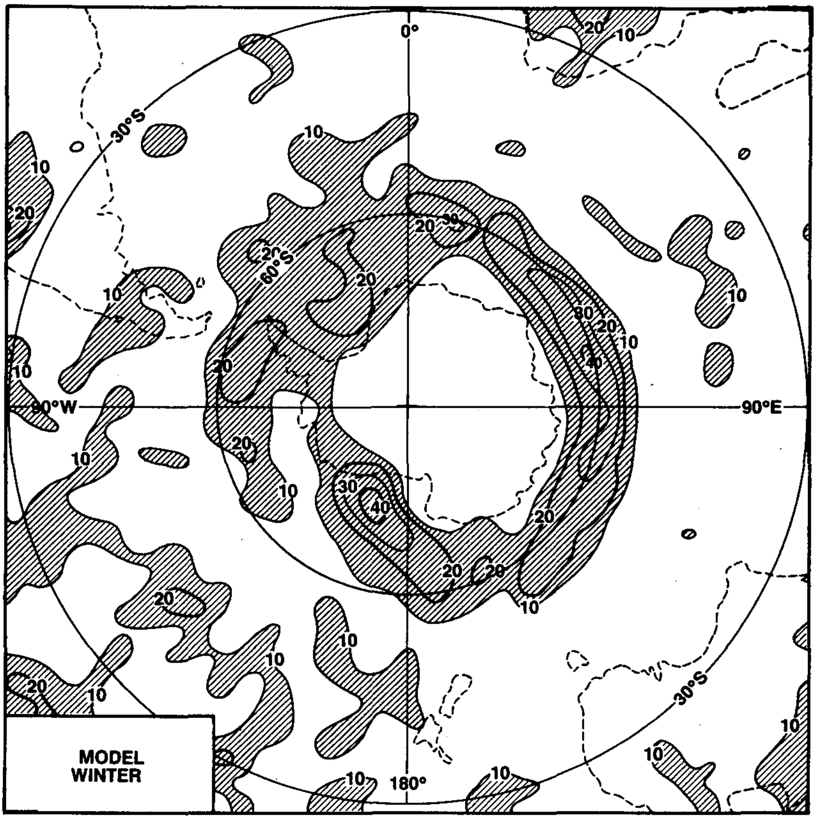

FIG. 4. As in Fig. 2 except for five Southern Hemisphere winters simulated by the GCM.

track in the southern Atlantic Ocean which begins in South America and merges with the polar ring. There is a maximum in the number of events in the Tasman Sea with a storm track extending to the east and merging with the circumpolar maximum. A similar view of the Southern Hemisphere was given in Taljaard (1967) except that the South American storm track begins farther north around 30°S where Fig. 3 has a maximum but no obvious associated storm track.

Figure 4 shows that the model has been quite successful in simulating the geographical distribution of the event climatology. There is a nonuniform circumpolar ring with the largest number of events on the Indian Ocean side and another maximum in the sector between the dateline and 90°W. The ring is broadest east of South America and there is evidence of an Atlantic storm track originating over South America. A storm track extends eastward from New Zealand but the event maximum in the Tasman Sea is absent. In addition, there is little cyclogenetic activity in the lee of the Andes as expected from the results of Chung (1977). Although not so pronounced as in the Northern Hemisphere, there is a tendency for model cyclones to be present over high terrain as shown by the events over the southern Andes and the southern Antarctic Peninsula where few cyclones are observed.

4. Summary and conclusions

The winter season event climatologies of the CCC GCM for the Northern and Southern hemispheres have been determined from a five-year simulation. In the Northern Hemisphere, the simulations have too few weak lows and too many intense lows when compared to observations. The model simulates well those characteristics of the event climatology for which thermal influences are important including oceanic storm tracks and the concentrating of cyclones over large inland bodies of water. The model has problems simulating those features of the event climatology which are topographical in nature. Observed lee cyclogenesis areas such as those east of the Rocky Mountains and in the Gulf of Genoa are essentially absent in the model. The simulated cyclones also tend to traverse mountain ranges which block observed cyclones.

In the Southern Hemisphere, the model also produces too few lows in total resulting from a deficiency of medium intensity lows. The number of strong and weak lows is well simulated. In general, the features of the event climatology are well reproduced by the GCM.

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