Mean Southern Hemisphere Extratropical Cyclone Behavior in the 40-Year NCEP–NCAR Reanalysis

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(Manuscript received 16 November 1998, in final form 31 March 1999)

ABSTRACT

This paper presents a new climatology of Southern Hemisphere (SH) extratropical cyclones. This has been compiled by applying a state-of-the-art cyclone tracking scheme to the 6-hourly National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalyses spanning the period 1958–97. The results show there to be, on average, between 35 and 38 cyclonic systems per analysis (depending on season), with the greatest density [exceeding 6×10^{-3} cyclones (deg lat)$^{-2}$] found south of 60°S in all seasons and in the Indian and west Pacific Oceans in autumn and winter. For the most part, there is a net *creation* of cyclones (i.e., cyclogenesis exceeds cyclolysis) north of about 50°S, and a net *destruction* to the south of this latitude. Having said this, the most active cyclogenesis takes place south of 45°S. The NCEP–NCAR reanalyses indicate that most SH cyclogenesis occurs at very high latitudes, and the axis of the maximum lies on, or to the south of, 60°S. This is in agreement with the deductions of many modern studies of SH cyclone behavior. The region is also host to even greater levels of cyclolytic activity.

The authors consider measures of the importance and influence (e.g., for eddy fluxes) of cyclonic systems. It is suggested that the ''depth'' of a system (the pressure difference between the center and the ''edge'' of a cyclone) is a relatively bias-free and useful measure of a cyclone's status and effect on the circulation. The greatest climatological depths are seen to lie at about 60°S, well to the north of the circumpolar trough and of the region of greatest cyclone density. The mean lifetime of cyclones that last at least 1 day is just over 3 days. Those that are located between 50° and 70°S (at their half-lifetime) endure, on average, almost one day longer than all other systems. The mean track length of winter systems is 2315 km, which reduces to 1946 km in summer.

The significance of the work presented here lies in a number of factors. First, the climatology has been derived from 40 yr of analysis, a period longer than any considered heretofore. Further, the (re)analyses used can be regarded as one of the best representations of the global atmosphere. The availability of these analyses at 6-hourly intervals means that the uncertainties with tracking of cyclones are greatly diminished. Finally, it has been compiled using one of the most sophisticated and reliable automatic cyclone finding and tracking schemes. This climatology of SH extratropical cyclones is arguably the most accurate and representative set yet assembled.

1. Introduction

It has been appreciated for a long time that extratropical cyclones are associated with ''weather'' over the globe. Hence the study and documentation of the behavior of these systems is important for a wide range of human pursuits. Such systems also play a central role in the maintenance of global climate and are responsible for a large proportion of the poleward transport of heat and moisture effected by the atmosphere. They also play a pivotal role in the angular momentum budget of the atmosphere and, in particular, are primarily responsible for maintaining the westerlies against their surface frictional sink (Peixoto and Oort 1992).

The distribution of extratropical cyclones is known to be determined by a number of factors, including the distribution of land masses and sea surface temperatures gradients, and the location and orientation of baroclinic zones. These conditions are rather different in the two hemispheres, and hence it is not surprising that the distribution of cyclones contrast significantly. In the Southern Hemisphere (SH), which is the focus of our work here, many climate variables, including cyclone density, display more zonal symmetry than do their Northern Hemisphere (NH) counterparts. The NH winter climatology exhibits large-amplitude standing waves (induced by continentality and topography) and these are responsible for a significant poleward energy transport. By contrast, in the SH the fluxes effected by these are small (van Loon 1979; Peixoto and Oort 1992), which serves to underline the importance of transients disturbances in the maintenance of climate in that hemisphere.

The study of cyclones and cyclogenesis has experi-

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enced a remarkable renewal of interest in recent times due to the emergence of new theoretical problems and new approaches to diagnose these phenomena (Mass 1991; Joly et al. 1997; Turner et al. 1998). There have been a number of significant papers that have examined the behavior of cyclones over the SH. Taken chronologically, these reflect a steady improvement in our fundamental understanding of these systems, the quality of the analyses from which they were obtained, and the techniques that have been used to identify systems. Among the literature we confine ourselves to citing the works of Lamb and Britton (1955), Taljaard (1967), Streten and Troup (1973), Carleton (1979, 1983), Kep (1984), Leighton (1992), Jones and Simmonds (1993a, hereafter JS), Sinclair (1994, 1995, 1997), Simmonds and Murray (1999), and Simmonds et al. (1999).

The results from these works (and particularly the early ones) should be regarded with some degree of caution for two basic reasons. First, the studies were undertaken with early satellite mosaics and meteorological analyses that covered a limited period (although it should be mentioned that the Carleton studies were based on five winters) or used ''operational'' analyses. Use of the latter means in practice that the analyses are not of temporally uniform quality and will obviously be more reliable as the system that produces them becomes more accurate. Second, a wide range of techniques has been used to identify and track cyclones from sequential analyses and it is sometimes difficult to assess the reliability and veracity of such schemes.

In this work we present a new climatology of SH extratropical cyclones that has been constructed paying explicit regard to the points raised above. The analyses that we use are the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996) 6-hourly reanalysis set covering the 40-yr period 1958–97. These analyses were obtained by assimilating past data into a frozen state-of-the-art analysis/forecast model system. The database was enhanced with many sources of observations that were not available in real time for operations, and the product can be regarded as one of the most complete, physically consistent meteorological datasets. [Having said this, it should be borne in mind that in the first decade or so of the reanalysis period no satellite data were available for the vast expanses of the Southern Ocean. We shall address cyclone variability over the period of the analyses in a companion paper (Simmonds and Keay 2000).] The four-decade period covered by these analyses makes them particularly useful for our task. We also make use of the recently refined [in light of data collected during the First Regional Observing Study of the Troposphere (Turner et al. 1996a) and other new insights] Melbourne University cyclone finding and tracking scheme (Simmonds and Murray 1999; Simmonds et al. 1999). This represents one of the best and most robust automatic cyclone tracking schemes available. The use of these two enables us to assemble what is probably the most reliable climatology of SH cyclones yet obtained.

2. The NCEP–NCAR data

The full details of the NCEP–NCAR project and the dataset are given by Kalnay et al. (1996). In using the analyses in the SH one should be cognisant of the problems that may be associated with the misallocation of bogus data. Between 1979 and 1992 the Australian surface pressure bogus data (PAOBS; see, e.g., Seaman et al. 1993) were incorrectly shifted by 180° longitude before being assimilated. To give guidance to the meteorological community NCEP–NCAR have rerun short periods of reanalysis with the aim of quantifying some of the effects of the PAOBS problem (for further details, see the NCEP Web site at http://wesley.wwb.noaa.gov/paobs/paobs.html). Their examination of the results led to the conclusions that the SH mid- and high latitudes were most affected, and the winter months by more than the summer months. The assessment also showed that the differences decrease rapidly as the timescale increases from synoptic to monthly. For our climatology of cyclonic systems in the SH we needed to be sure that the initial reanalyses (I) were appropriate for our purpose. As part of this assessment we examined the temporal standard deviation of the difference between the mean sea level pressure (MSLP) of the I and corrected (C) analyses for the month of July 1979 over the SH (Fig. 1). The root-mean-square difference (rmsd) tends to show largest values in the region of the circumpolar trough. About half of this region displays values in excess of 4 hPa. Values of this magnitude may appear to be cause for concern, but it should be remembered that the SH displays its greatest daily temporal variability over this domain (e.g., Jones and Simmonds 1993b). We have conducted other assessments to assure ourselves that the I analysis set is appropriate for our climatological purpose. One of these was an exhaustive examination of cyclones identified and tracked in the two analysis sets in this month. We confine ourselves here to showing the tracks of all SH cyclones (with a minimum lifetime of 24 h) in the I and C analyses (Figs. 1b,c). It can be seen that there are differences between the tracks in the two sets of analyses. However, the overall structure of the plots is very similar, and significant discrepancies are very few. During this month the mean number of SH cyclones per analysis differed by less than 0.3 in the two sets, which represents less than 1% of the mean number of cyclones (37). We should also note that in spite of these differences, the assessment undertaken by NCEP–NCAR showed that the rmsd between the I and C analyses to be much smaller that the rmsd between C and the European Centre for Medium-Range Weather Forecasts operational analyses. The NCEP–NCAR assessment found that in regional (i.e., synoptic scale) case studies ''sizeable differences occur from time to time, primarily in the eastern

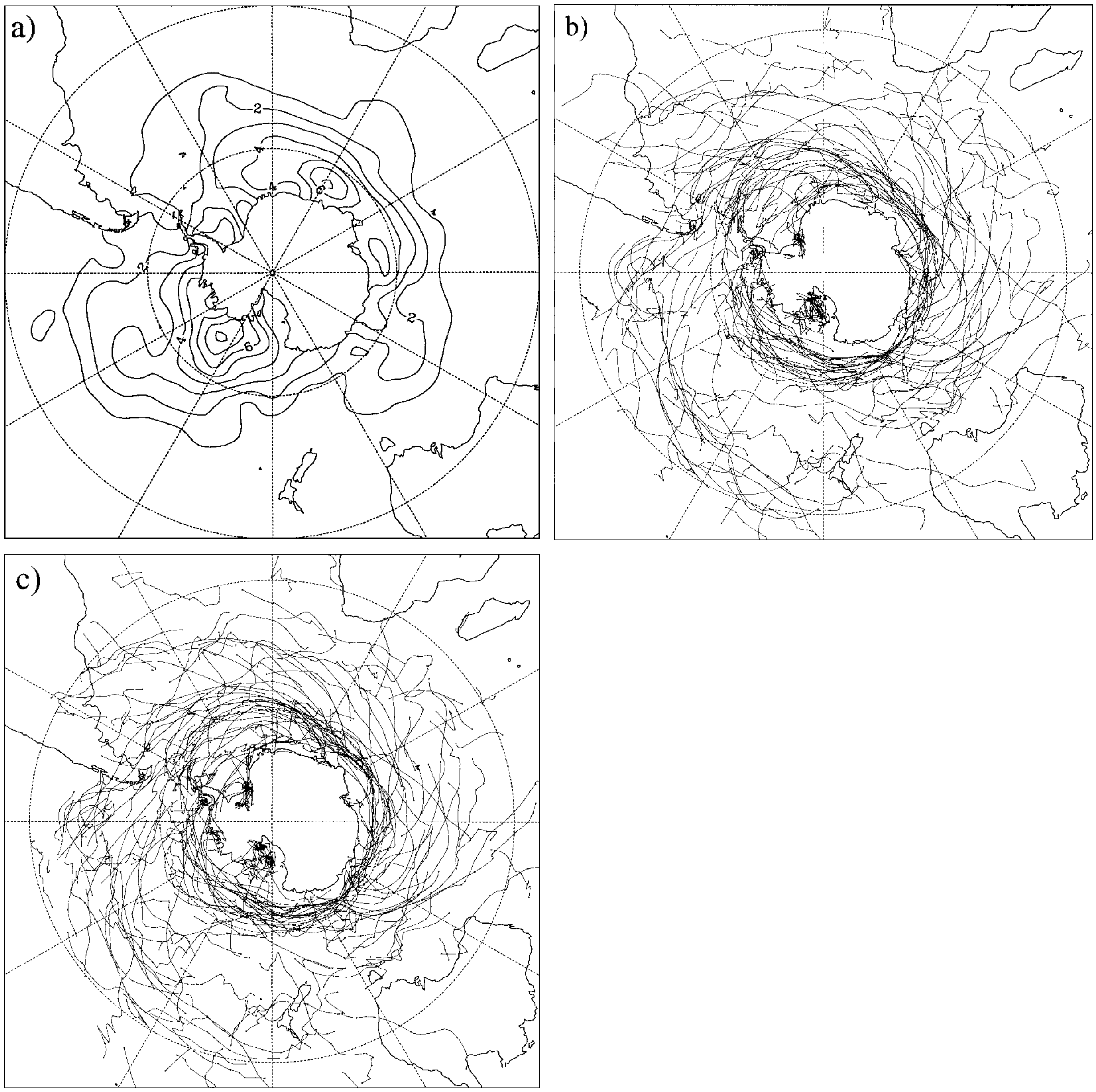

FIG. 1. (a) Temporal standard deviation of the difference between the MSLP of the initial reanalyses (I) and corrected analyses (C) for Jul 1979 (the contour interval is 1 hPa). Tracks of all SH cyclones (with a minimum lifetime of 24 h) in Jul 1979 in the (b) I and (c) C analyses.

ocean basins.'' However, we are content that our climatologies are not unduly influenced by these events. The above observations lead us to believe that a climatology based on the I analyses is quite reliable and robust.

3. Cyclone tracking scheme

The cyclone tracking scheme used here was based on that of Murray and Simmonds (1991), but with the refinements discussed in Simmonds and Murray (1999) and Simmonds et al. (1999). Only a broad outline is given here.

In the original scheme latitude–longitude data were transformed by bicubic spline interpolation to a polar stereographic array centered on either the North or South Pole. The low-finding routine begins by searching this array for a grid point maximum of the Laplacian of pressure, $\nabla^2 p$. The position of the associated pressure minimum is then located by iterative approximation to the center of the ellipsoid of best fit to the pressure surface, which is defined by a bicubic spline function fitted to the array data. If a closed center cannot be found or does not lie within a very small distance, the routine also searches for an ‘‘open depression.’’ The Laplacian of the pressure in the vicinity of the center ($\nabla^2 p_c$) can be taken to be a measure of the strength of the system and systems that fail to reach a specified minimum strength are normally excluded.

Tracking was accomplished in a three-stage process in which 1) a subsequent position is predicted for each cyclone, 2) a probability of an identification between the projected cyclone and each cyclone present at the new time is reckoned, and 3) a matching is made that maximizes the calculated probabilities of association between the projected and new positions, allowing the tracks to be extended by one analysis period.

The refined scheme used here has taken advantage of improvements in the ‘‘screening’’ procedure, techniques to avoid considering spurious lows over topography, refinements to the ‘‘steering’’ of MSLP systems, and a modification of the ‘‘probability of association’’ calculation. Full details of these improvements are given in Simmonds and Murray (1999) and Simmonds et al. (1999).

Among the raft of important statistics that the new automated scheme can produce are measures of strength and influence of the features. In attempting to understand the behavior and formation of cyclonic systems and their role in weather and climate it is important to be able to quantify the ‘‘strength’’ of these systems and their influence in climate maintenance. For example, a given region may be host to a large number of cyclonic systems but if they are relatively weak their influence may be less than those over an area that is host to fewer but more intense systems. In quantifying the strength of a system, one must remember that the background (climatology) MSLP upon which cyclones are placed varies considerably over the SH. In an attempt to take this into account, Simmonds and Wu (1993) considered the ‘‘relative’’ central pressure of lows, which was taken as the difference between the mean central pressure of the lows and the climatological mean pressure at a given location. This statistic is useful but does have some drawbacks in that it is biased against regions that have a high frequency of cyclones.

One measure of intensity that does not suffer from this problem is the Laplacian of the pressure field calculated at the center of the system ($\nabla^2 p_c$). One should bear in mind, however, that this measure has an implicit dependence on scale. For example, a cyclone of a specified depth will assume a greater intensity ($\nabla^2 p$) as its horizontal scale is reduced. Obviously a scale can be reached at which the Laplacian is large, but the system is physically insignificant. Hence other measures, including the ‘‘depth’’ (D) and ‘‘radius’’ (R) are needed to be able to assemble a complete picture. All these concepts are related. This can be most easily be seen for the idealized case of an axially symmetric paraboloidal depression of radius R on a flat field. The depth is seen to be given by

$$D = \frac{1}{2}\frac{\partial^2 p}{\partial r^2}R^2 = \frac{1}{4}\nabla^2 p R^2. \qquad (1)$$

(This expression, incidentally, makes explicit the scale bias inherent in using $\nabla^2 p$ as the sole measure of intensity.) The depth of a system so defined is of obvious interest in itself. However, as the above expression makes clear it is also proportional to the product of $\nabla^2 p$ and the ‘‘area’’ of the cyclone. This parameter then reflects the importance of a cyclone in the circulation, without being biased by scale. Another way of seeing this is to consider the eddy meridional transport of any quantity, χ, ($\overline{v'\chi'}$), affected by a cyclone. This is related, in part, to the longitudinal integral of the meridional wind from the center to the edge of the cyclone, $\int_0^R v'\,dx$, where x is distance to the east measured from the center of the cyclone. Using geostrophy this can be shown to be proportional to $p(x = R) - p(x = 0)$, that is, the depth.

In the more common case of nonaxially symmetric systems it is useful to retain the depth and radius concepts, and there a number of ways in which these can be determined (e.g., Williamson 1981). Our method consists in finding first a number of points that together bound the cyclonic region, which in the first instance can conveniently be defined as the region surrounding the $\nabla^2 p$ maximum in which $\nabla^2 p$ is positive. For a depression with contours of monotonic curvature, the perimeter points may easily be found by searching outward along radial lines. However, it frequently happens that two centers will exist within a single region of positive $\nabla^2 p$; in this case it is sensible to take the cyclonic domain of a particular center as being limited to the area in which the $\nabla^2 p$ surface slopes up or down towards the center, that is, it belongs to its ‘‘catchment.’’ Sinclair (1997) has determined cyclonic domains in this way and has located the divides as the points at which the gradient of the (geostrophic) vorticity $[(1/(\rho f))\nabla^2 p]$ surface changes sign along the radial search lines. However, it is possible for radii from two neighboring centers to cross and for $\nabla^2 p$ to continue increasing along both lines after having done so. Recognizing this, Sinclair adjusted the areas so neighboring domains do not overlap, but the domains shown in his Fig. 5 indicate that in such cases the adjustment has only been made to one of the areas and in such a way as to cut short search radii before crossing radii from the neighboring depression; this results in one domain being too large and the other too small. Another objection to the use of radial search lines is that it may not be able to ‘‘see’’ the outer parts of a cyclonic domain that curves away from its center.

The rigorous determination of a cyclonic region that we have instituted performs searches along a suitable number of paths radiating from the cyclonic center and following the directions of maximum (negative) gra-

TABLE 1. Mean number of cyclones per analysis.

	DJF	MAM	JJA	SON
SH	34.9	37.2	37.7	37.3
10°–30°S	8.1	5.8	3.6	6.0
30°–50°S	9.3	10.3	12.0	10.9
50°–70°S	14.5	16.4	16.6	15.4
70°–90°S	2.2	4.0	4.2	3.6

dient; this process is similar to defining the boundaries of a water catchment. These paths are not difficult to follow, but they do diverge more or less strongly as one proceeds away from the cyclone center, and in a manner that cannot be predicted before the search has commenced. In order to achieve a roughly constant density of perimeter points, it is necessary to advance the search points outward along maximum gradient trajectories to a new ring of contiguous points and allow for the interpolation of new search points in ring segments that have become larger than a critical length. Having found the boundary of the cyclonic domain, its area may be evaluated, and hence a notional radius may be reckoned, being that of a circle of area equal to that of the polygon. A depth can also be calculated for a depression of any shape by taking the areal average of $\nabla^2 p$, and using this in Eq. (1).

4. Climatology

We present firstly some gross statistics of the counts of SH cyclones. Table 1 shows that just in excess of 37 systems per analysis are identified in the SH in winter (JJA) and in the two intermediate seasons, while 10% fewer are observed in summer (DJF). When broken up by latitude bands, in all seasons the greatest number of systems is found in the subantarctic belt 50°–70°S, while the second greatest frequency is observed in the belt immediately to its north (30°–50°S). The vast majority of SH systems are found in the two midlatitude belts. In the annual mean 43% and 29% (a total of 72%) reside in these bands. The cyclone numbers display seasonality, with the maximum in both belts being found in winter and the minimum in summer. The seasonality is stronger in the tropical belt (10°–30°S), with the maximum occurring in summer, reflecting predominantly the frequent occurrence of heat lows in the northern parts of Australia.

a. System density

The density of systems [the mean number per analysis found in a 10^3 (deg lat)^2 area] in the four seasons is presented in Fig. 2. In summer (part a) in the Atlantic and Indian Ocean sectors the greatest cyclone densities exceed 4×10^{-3} cyclones (deg lat)$^{-2}$ near 60°S, while in the Pacific the axis of the maxima lies somewhat farther south. In autumn (Fig. 2b) the axis of the highest density moves south, and the region just off the coast of east Antarctica is host to densities in excess of 6×10^{-3} cyclones (deg lat)$^{-2}$. Local maxima are also seen next to the Siple Coast, off Coats Land, in the Bellingshausen Sea and in Prydz Bay. These last features are also observed in winter (Fig. 2c), during which time the density of systems in the immediate subantarctic region reduces somewhat and the line of highest values moves back toward the north. In lower latitudes one of the more interesting characteristics is the split in the Tasman Sea–New Zealand sector, where low densities are found between 45° and 55°S, and higher values are found to the north and south. The area of the SH that experiences cyclone densities greater than 2×10^{-3} cyclones (deg lat)$^{-2}$ is the greatest in this season. In particular, this isoline rapidly shrinks by the spring season, and the number of systems in the subantarctic maximum assumes more modest proportions (Fig. 2d).

b. Cyclogenesis

In summer, there is seen to be considerable genesis over Australia (associated for the most part with heat lows) and in the lee of New Zealand and of the Andes (Fig. 3a). These regional features are superimposed on a general southward increase in cyclogenesis. Most regions south of 45°S experience genesis rates in excess of 0.5×10^{-3} cyclones (deg lat)$^{-2}$ day^{-1}. The axis of maxima is found on, or to the south of, 60°S and extrema are found over the northern part of the Antarctic Peninsula, off Victoria Land, and the Siple Coast, as well as in the southern part of the Weddell Sea. Figure 3b shows that the pattern in winter is rather similar (except for the obvious absence of heat lows over Australia), but the level of cyclogenetic activity in increased. A minimum of cyclogenesis is apparent at about 45°S across much of the Pacific and Atlantic Oceans, while a maximum is observed in the Indian Ocean.

c. Cyclolysis

The distribution of summer cyclolysis shown in Fig. 4a, when taken in conjunction with the analogous cyclogenesis map, indicates that a significant proportion of the systems born over southeast Australia are mobile and move elsewhere before terminating. There is little cyclolytic activity off the east coast of Argentina, over Graham Land, or over New Zealand. Hence the large number of systems that were formed in these regions (Fig. 3a) are transported downstream by the westerlies. The greatest cyclolytic activity is found just off the Antarctic coast. Maxima are seen near 20°E and 120°E, and these are areas of only modest cyclogenesis. The Bellingshausen Sea is also a favored location for cyclones to end their trajectory. Broadly similar remarks may be made for the winter season (Fig. 4b), except that the level of cyclolytic activity in the Bellingshausen and Amundsen Seas are considerably enhanced.

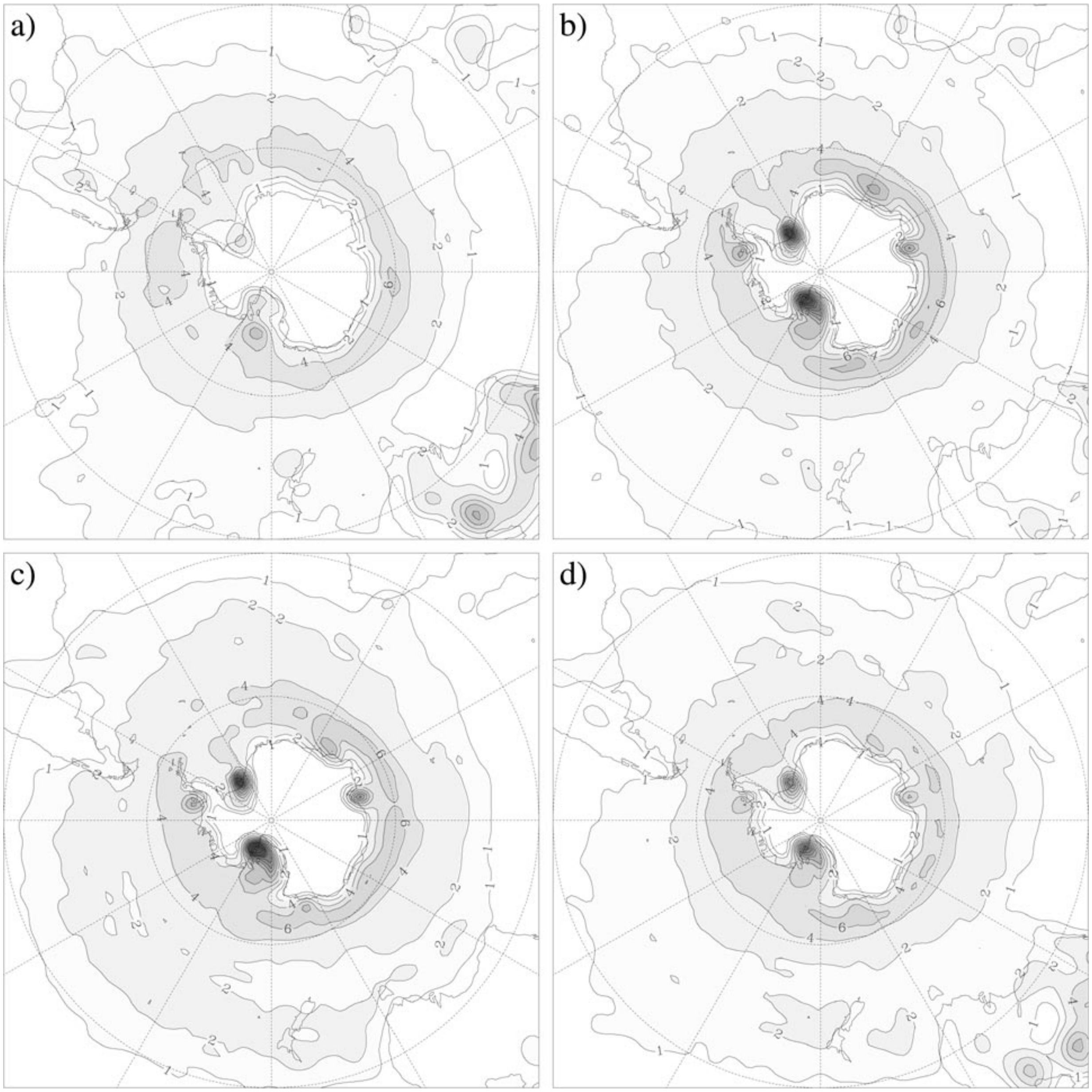

FIG. 2. System density [the mean number found in a 10^3 (deg lat)^2 area] in (a) DJF, (b) MAM, (c) JJA, and (d) SON. The contour interval is 2×10^{-3} (deg lat)$^{-2}$. An additional isoline at 1×10^{-3} (deg lat)$^{-2}$ has been included in the plots.

d. Difference between cyclogenesis and cyclolysis

A revealing picture of the relationship between the above two statistics can be obtained by considering the geographical structure of the *difference* between the genesis and lysis rates. In both summer and winter (Figs. 5a,b) the excess of genesis over lysis off the east coast of Argentina, over Graham Land, and over New Zealand is clearly evident, as it is over most of Australia in summer. Both seasons also exhibit excesses over, and to the south of, southern Africa and off across the Indian Ocean all the way to Australia. Cyclolysis exceeds generation in the narrow sector between 90°W and the South American coast. Aside from regional features, for the most part genesis exceeds cyclolysis north of about 50°S in both seasons, while the converse is true south of this latitude. We stress, however, that while the higher southern latitudes are cyclone ''graveyards'' in this mean sense, we have seen there is significant levels of genesis in the subantarctic regions.

e. Strength of cyclonic systems: Intensity, depth, and radius

We discussed earlier the use of the Laplacian of the pressure field calculated at the center of a system ($\nabla^2 p_c$)

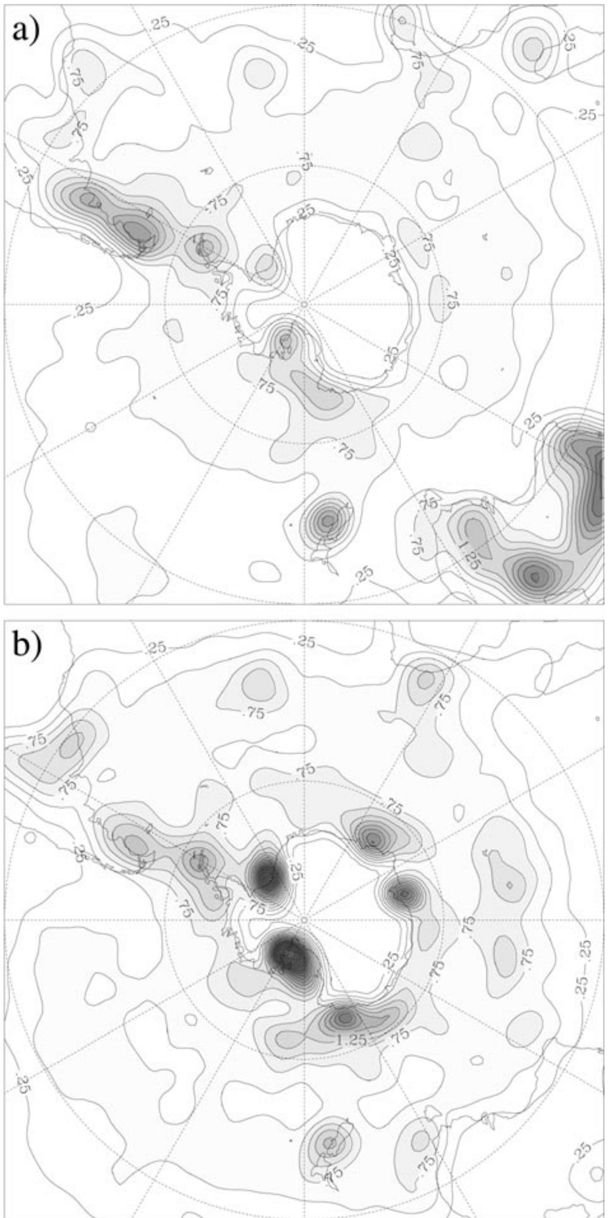

FIG. 3. Cyclogenesis density in (a) DJF and (b) JJA. The contour interval is 0.25×10^{-3} cyclones (deg lat)$^{-2}$ day^{-1}.

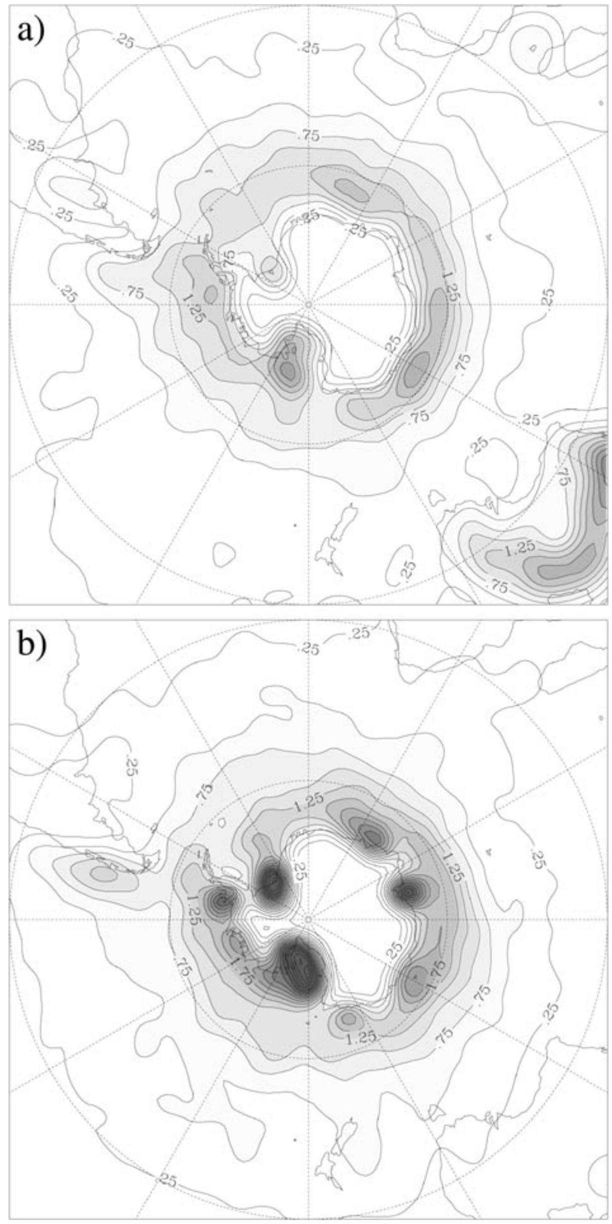

FIG. 4. Cyclolysis density in (a) DJF and (b) JJA. The contour interval is 0.25×10^{-3} cyclones (deg lat)$^{-2}$ day^{-1}.

as a measure of intensity. When defined this way the most intense systems in summer (Fig. 6a) are seen to lie on a fairly zonally symmetric axis at about 55°S, somewhat to the north of the regions of maximum density (Fig. 1a). The region through the Drake Passage is one of diminished intensity as are the regions immediately off the Antarctic coast. Figure 6b shows that the systems are more intense in winter, with the most intense found immediately off the Antarctic coast, particularly in the Indian Ocean sector, and to the north of the Ross Sea. (The apparently very high values over Antarctica in the latter part of the figure have little meaning due to the infrequency of systems there.)

The mean radius of systems (R) is presented in Fig. 7. In summer (Fig. 7a) the largest systems are found near 60°S, with longitudinal maxima in the Atlantic Ocean and in the eastern parts of the Indian and Pacific Oceans. Marked minima are observed in the vicinity of the land masses. This last feature is also apparent in winter (Fig. 7b), but the distribution in this season differs from that in summer in that the largest systems are now found considerably farther north (at about 45°S) in the Pacific. Local maxima are found in the Tasman Sea and to the south of Perth. In both seasons the radius of systems shows a diminution over the sea ice zone and the coastal regions. The climatology of the summer

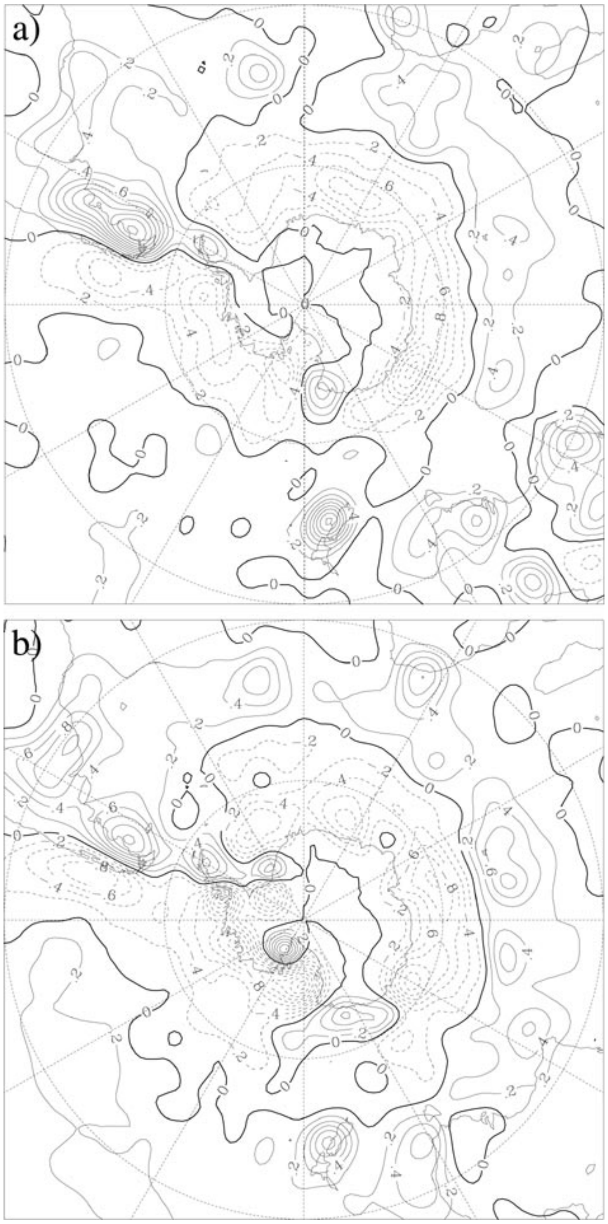

FIG. 5. Difference between cyclogenesis and cyclolysis density in (a) DJF and (b) JJA. The contour interval is 0.2×10^{-3} cyclones (deg lat)$^{-2}$ day^{-1}.

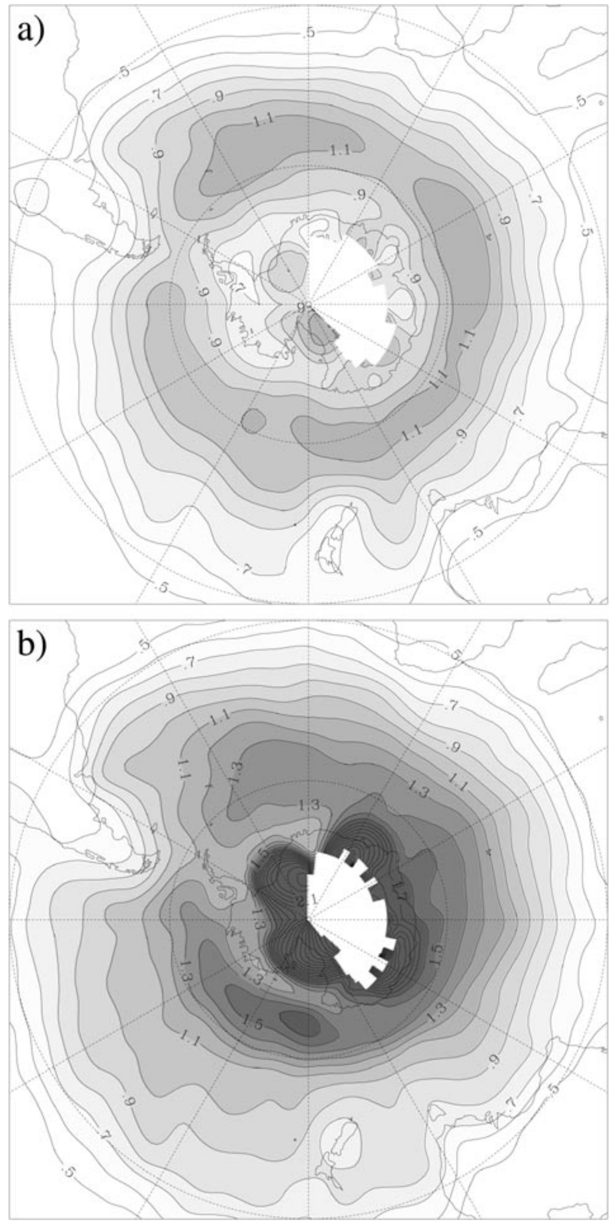

FIG. 6. Mean Laplacian of the pressure field calculated at the center of the each cyclone in (a) DJF and (b) JJA. The contour interval is 0.25 hPa (deg lat)$^{-2}$.

mean cyclone depths (Fig. 8a) exhibits less structure and a steady increase with latitude to a belt of maxima close to 60°S. The depth exceeds 8 hPa over significant portions of the Atlantic and Pacific Oceans at this latitude. The mean depths are everywhere greater in winter (Fig. 8b), and the axis of the greatest depth has shifted south. Mean cyclone depths in excess of 10 hPa are observed off Wilkes Land and in the coastal region at about 30°E.

The relationship between these last three quantities for individual systems [Eq. (1)] suggests that it may be fruitful to compare their climatologies. In doing this one does not expect (1) to hold for the *mean* charts because, among other reasons, there is considerable temporal covariance between the parameters. This having been said, there are a few general observations that may be made with safety. As seen earlier, the depth of systems in summer shows a much greater increase with latitude (to the maximum at 60°S) than does the Laplacian. This can now be seen as due to the fact that the mean radius steadily increases to a maximum at a similar latitude. The longitudinal structure of the measures in this region of high cyclone numbers can also be understood with similar arguments. The depth maxima centered to the north of Thurston Island and of Queen Mary Land (Fig. 8a) owe their existence to coincident structures in the radius field (Fig. 7a), rather than to any features in the distribution of the Laplacian (Fig. 6a). Similar reasoning can be followed for the relationships in winter. For example, the region to the north of the Ross Sea has been seen to be a region of large Laplacian, whereas the depth exhibits a relative (in the longitudinal direction) minimum at that location. Figure 7b shows that the radii of systems in this vicinity are rather small.

f. Track duration and length

Another characteristic of cyclones that is important for understanding their role in weather and climate is their duration. Extratropical cyclones are intimately tied up with the index cycle, which dictates their natural timescale. However, the variation of the Coriolis parameter, the location of the continents, the location of sea surface temperature gradients, and the location of baroclinic zones means that these timescales would be expected to vary across the SH.

We show in Fig. 9a a histogram of the distribution of track duration of all winter SH cyclones that have a lifetime of at least 24 h. The distribution is strongly skewed and (almost) monotonically decreases with increased track duration (over 40% of the cyclones considered last less than 2 days). This general structure is also reflected in the other three seasons, as well as when the data are stratified into latitude belts. The first row in Table 2 shows for the four seasons the mean duration of all of these SH cyclones. The average duration is a little over 3 days and displays very little seasonal variation. The body of the table shows a breakdown of the durations into four latitude bands, each 20° ''wide'' (a cyclone track is allocated to the latitude band in which it was located halfway through its life). It will be seen that the systems that are in the 50°–70°S latitude band at the halfway time in their lives last, on average, almost 1 day longer than all other systems. The longevity of cyclones in this subantarctic region shows only a modest seasonality, varying from 3.69 days in summer to 3.57 in winter. A little more seasonality is seen in the 30°–50°S belt, with systems in winter lasting some 12% longer than their summer counterparts (2.92 as opposed to 2.60 days). More still is reflected for the tropical figures, reflecting the presence of summer heat lows discussed earlier.

Figure 9b shows a frequency histogram of the distance between the genesis and cyclolysis points of all SH winter systems that last at least 24 h. About 7% of all such systems travel less than 500 km and approximately 30% travel between 500 and 1500 km. The plot shows a steady decay in frequency at the longer translation distances, but a significant proportion of the systems travel in excess of 5000 km. As might have been expected, the longest mean track length occurs in winter

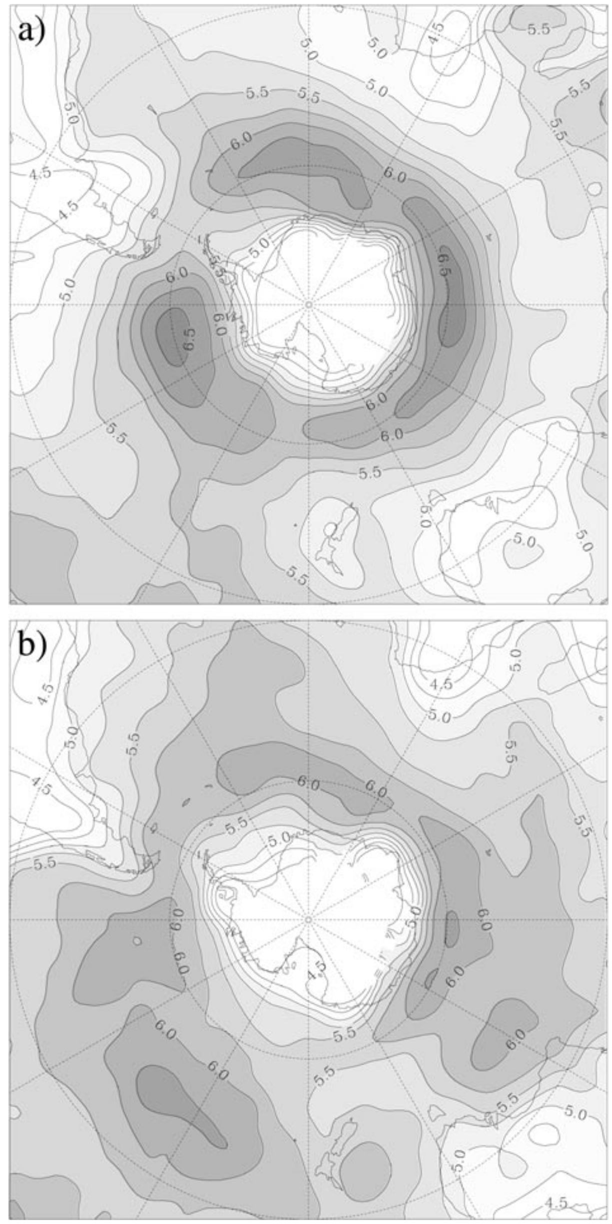

FIG. 7. Mean radius of cyclones in (a) DJF and (b) JJA. The contour interval is 0.25 deg lat.

(2315 km), while the shortest is found in summer (1946 km).

5. Discussion

The climatologies presented here exhibit similarities to those of earlier compilations but also show some interesting differences. This may be exemplified for the case of the Jones and Simmonds (1993a) climatology, which was compiled from 15 yr (1975–89) of the Australian dataset. For the most part, the system density and level of cyclogenetic activity found here significantly exceed those documented by JS. We have made the point

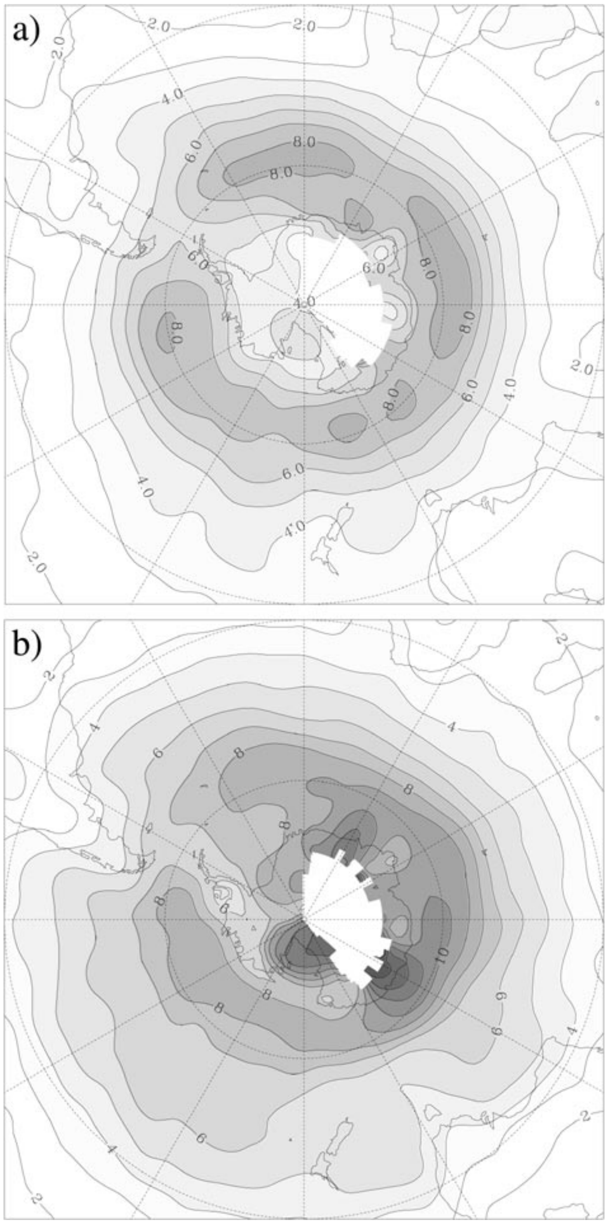

FIG. 8. Mean depth of cyclones in (a) DJF and (b) JJA. The contour interval is 2 hPa.

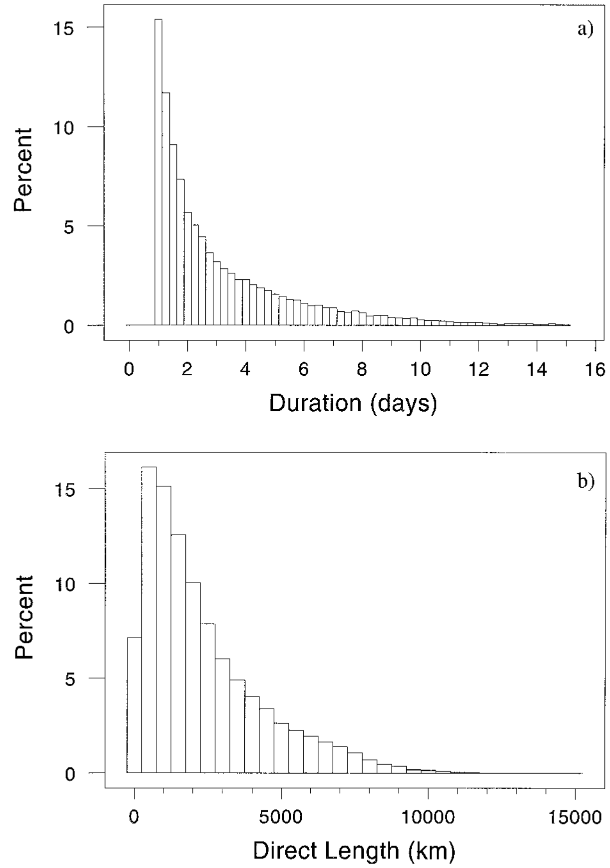

FIG. 9. Frequency distribution of two statistics of all winter SH cyclones with a lifetime of at least 24 h. (a) Cyclone duration (binned in 6-h boxes), and (b) distance between genesis and lysis points (binned every 500 km).

in this paper that as the quality of analyses improves, a more reliable appraisal of the synoptic structure emerges. Hence is not surprising that in the NCEP–NCAR set, being of higher quality and resolution than the Australian data, one would expect to ''find'' more systems. In both summer and winter the present compilation finds twice as many systems in the midlatitudes than JS, and the density is typically 2×10^{-3} (deg lat)$^{-2}$ in the latter season. Note, however, that the system density is not greater everywhere and, in particular, the density of summer systems to the east of Australia north of about 30°S is larger in the JS compilation. A feature of great interest in a broad region around New Zealand is the pronounced axis of maxima at about 40°S in winter and spring (Figs. 2c,d). The structure of this feature revealed in the present analysis is very similar to that presented by JS, save that the number of systems is about double that revealed in the earlier study.

Into the high latitudes, the results obtained with the NCEP–NCAR data display less zonal asymmetry. For example, the maximum identified off Byrd Land, particularly marked in winter, by JS is not present in the new compilation. This may be due to recent climate changes that have been documented in this sector of the subantarctic region (e.g., King 1994; Cullather et al. 1996; Simmonds et al. 1998).

TABLE 2. Mean cyclone track duration (in days) of cyclones that have been tracked for at least 24 h. A cyclone track is allocated to the latitude band in which it was located halfway through its life.

	DJF	MAM	JJA	SON
SH	3.05	3.09	3.12	3.02
10°–30°S	2.62	2.35	1.93	2.08
30°–50°S	2.60	2.80	2.92	2.87
50°–70°S	3.69	3.60	3.57	3.61
70°–90°S	2.18	2.62	2.57	2.34

It is important to satisfy ourselves that the enhancement of the number of systems in the analyses is a more accurate representation of actual atmospheric character. In this context we note that the overall behavior (including genesis, density, movement) of systems identified by our algorithm in the Antarctic Peninsula region bears great similarity to those revealed in the detailed observational study of Turner et al. (1998).

Our results show that the high southern latitudes and the subantarctic regions are host to high cyclone density and strong cyclogenetic activity, findings somewhat different from those of Sinclair (1995, 1997). He found that winter ''track density maximizes between 50 and 60°S in the Atlantic and Indian Oceans sectors, and south of 60°S in the Pacific'', whereas our comparable density plot (Fig. 2c) shows the maxima everywhere farther south. His results also show much smaller genesis rates in the immediate vicinity of Antarctica than those we present here. Part of the reason for these differences is that Sinclair displays the track density of vorticity extrema, while we present system density of pressure minima. Of perhaps more importance is the fact that Sinclair chose to delete from consideration any system that moves a total distance less than 10° of latitude, with a view to eliminating cyclones caused by local orographic effects because ''their contribution to the weather and climate is likely to be small.'' However, our results appear quite consistent with the satellite-based analyses of Carleton and Fitch (1993) and Turner et al. (1998) and the theoretical analyses of Mechoso (1980), Kottmeier (1986), Berbery and Vera (1996), and others, who have indicated strong baroclinicity in the environs of the Antarctic coast. King and Turner (1997) comment that recent studies have shown that the subantarctic trough region exhibits developments on the meso- and synoptic scales more frequently than had been previously thought.

We have referred above to the importance of clearly defining the terms that are used in discussing cyclone behavior. We have discussed various measures of the ''importance'' of a cyclone and have suggested that the depth is a reliable measure of its influence. Our results indicate that the cyclone density is highest in the subantarctic trough region, whereas the axis of maximum depth tends to lie to the north of this. This is consistent with the remarks of King and Turner (1997), who comment that the depressions in the trough region, while exhibiting low surface pressure consistent with their location, are not especially active. It is also in accord with the mean total cloud cover at high southern latitudes in the SH, which might be taken as a nonbiased proxy measure of cyclonic activity. Both surface-based (Warren et al. 1986, 1988) and satellite (Rossow 1993) climatologies show maxima near 60°S.

Our study has revealed significant cyclone numbers in the Antarctic Peninsula region, in the southern part of the Weddell Sea, and in the Ross Sea (especially in the Siple Coast area), but we have seen the mean radii of these to be modest (Fig. 7). These locations of these features tend to coincide with areas of frequent mesocyclone activity (e.g., Carleton and Fitch 1993; Turner and Thomas 1994; Turner et al. 1996b; Bromwich 1997; Carrasco et al. 1997a, b). From a limited number of case studies we have performed, it appears that the NCEP–NCAR reanalyses are able to represent at least some of the larger mesocyclones in these domains.

In closing it is salutary to compare our findings with the depression frequency distributions estimated by Lamb and Britton (1955). Their Fig. 3, derived from Naval Weather Service charts drawn for the summers and autumns of 1947 and 1948, show the highest depression frequencies near or to the south of 60°S, with longitudinal maxima upstream of the peninsula, near 20°E, 90°E, off George V Land and in the Ross Sea. These features, identified over four decades ago, have counterparts in the modern summer and autumn climatologies presented here. Lamb and Britton also indicated the ''main depression tracks'' in their figure, and from these it may be deduced that they believed the region south of 60°S to be one of significant cyclogenesis.

6. Concluding remarks

We have presented a new climatology of SH extratropical cyclones. This is arguably the most reliable such climatology yet assembled being, as it is, based on 40 yr of 6-hourly NCEP–NCAR reanalyses and compiled using one of the most sophisticated and reliable automatic cyclone finding and tracking schemes. [An issue of which we must be cognisant in studies of this nature is the possible effects of changing data quantity and quality on the climatologies. This question is addressed in a companion paper (Simmonds and Keay 2000), but we should comment here that the effect is determined not to impact the results in any appreciable way.] Our study identifies about 37 systems per analysis in three of the seasons and approximately 35 in summer. When stratified by 20° wide latitude bands the greatest number of systems is found in 50°–70°S in all seasons. The axis of greatest system density is found south of 60°S in all seasons and values exceed 6×10^{-3} cyclones (deg lat)$^{-2}$ in the Indian and west Pacific Oceans in autumn and winter. The structure is similar in summer, but the density is less. In the midlatitudes there is a split in the cyclone density in the western Pacific most marked in winter.

The distribution of cyclogenesis assumes its largest values south of 45°S and our results confirm the findings of earlier studies in that in all seasons the greatest cyclogenetic density occurs at very high latitudes, with the axis of the maximum lying on, or to the south of, 60°S. This region is also the location of the greatest cyclolytic activity. Broadly speaking, the rates of cyclogenesis exceed those of cyclolysis north of about 50°S in all seasons, while the opposite holds south of this latitude. While there is a *net* destruction of cyclones south of 50°S, as we have said above, this region is one of the greatest cyclogenesis. Our results have also shown that the cyclones generated off the east coast of Argentina, over Graham Land, and over New Zealand are mobile and are seen to be transported downstream by the westerlies. The Bellingshausen Sea is a favored location for cyclones to end their trajectory.

We have commented on the desirability of defining a quantitative index of the strength or influence of a cyclonic system. In the literature there is considerable ambiguity associated with terms such as intensity and strength. We have considered as measures the Laplacian of the pressure field around a low, the depth, and the radius of systems. These indices are interrelated and each has been seen to have their drawbacks, but it is suggested here that the mean cyclone depth is one of the best measures of cyclone influence. The greatest climatological depths are seen to lie at about 60°S, well to the north of the circumpolar trough and the region of greatest cyclone density.

It has been shown that the mean lifetime of cyclones (which last at least 24 h) is just over 3 days, while the cyclones that find themselves between 50° and 70°S halfway through their lives last, on average, almost 1 day longer than all other systems. The distance travelled by systems shows a broad distribution and a sizeable fraction systems travel in excess of 5000 km. The mean track length is 2315 km in winter and 1946 km in summer.

In closing, we comment that this work represents another step in the Lagrangian analysis of cyclone behavior in the SH. The automated Lagrangian analysis of cyclone behavior has a history much shorter than the Eulerian analysis of ''storm tracks.'' Blackmon et al. (1977) were among the first to document zones of eddy activity in terms of the variability exhibited in various frequency bands. Trenberth (1991) performed a comprehensive Eulerian analysis of a number of SH variance and covariance fields; he found them to bear a distinctive relationship to the storm track, but he found the latitude of their maxima to be displaced from that of the center of the storm track. In agreement with the comments of Trenberth (1991), we see it as important that both perspectives of storm tracks be retained. It is crucial to bear in mind, however, that the two approaches are telling us different things (see, e.g., Jones and Simmonds 1993b) and that direct comparison of results should be undertaken cautiously.

The focus in this paper has been the documentation of the *mean* behavior of various characteristics of SH cyclones over a four decade period. The dataset derived, however, allows us to consider also many aspects of the *variability* of these features have shown over the four decades. The results of such an investigation are presented Simmonds and Keay (2000).

Acknowledgments. Parts of this research were made possible by funding from the Australian Research Council and the Australian Antarctic Science Advisory Committee.

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