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A climatology of Southern Hemisphere extratropical cyclones

David A Jones, Ian Simmonds

School of Earth Sciences, University of Melbourne, Parkville, Victoria, 3052, Australia

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Abstract. A climatology of extratropical cyclones determined by an objective automatic scheme applied to 15 years (1975–89) of once-daily Australian Bureau of Meteorology hemispheric analyses is presented. Contour maps of the positions of formation (cyclogenesis), dissipation (cyclolysis) together with other cyclone statistics are presented. The distribution of cyclones through the hemisphere was found to be dominated by a permanent high latitude core coincident with the circumpolar trough. During the winter and intermediate seasons, two mid latitude branches are evident in the cyclone density originating in the Tasman Sea and South American sectors, both spiraling poleward and merging with the circumpolar core in the Southern Oceans. Systems were observed to move in an east-south-east direction, away from their location of formation, exhibiting peak speeds of migration in the mid latitudes. Little seasonality was evident in the densitiy distribution of cyclones through the Southern Oceans, but a considerable amount was found in their central pressure.

Introduction

The extratropical regions of both hemispheres are characterized by a continual procession of migratory synoptic features, resulting in much of the short-term atmospheric variability known as weather. These systems, in particular anticyclones, lows and associated fronts have a considerable impact on the local atmospheric conditions in addition to providing a significant mechanism for the transport of energy and momentum, important for the maintenance of the global atmospheric budgets. As a consequence of the primary part played by these features, studies pertaining to their distribution and behavior, both in observational and model derived data sets, are important. This is especially the case in the Southern Hemisphere (SH) where the coincident placement of the temperature and height standing waves means the dominant transfer mechanism for energy is through transient eddy transport (compare Oort and Peixóto 1983; Trenberth 1991).

Correspondence to: I Simmonds

Given the important role of transient disturbances, particularly in the SH, it makes sense to examine their climatology with all available techniques. Jones and Simmonds (1993) have referred to a number of definitions of "storm tracks" which have been used in the literature and the differences between them. Given the plethora of definitions, it is important that a climatology of low pressure centers be established.

Studies of the distribution and behavior of extratropical cyclones are not new. With reliable Northern Hemispheric analyses dating back to the nineteenth century, studies of extratropical lows in the Northern Hemisphere (NH) based on analyses over extended time periods have been possible. Petterssen (1956) presents the geographical distribution of the frequency of cyclones and cyclogenesis events for the period, 1899–1939. Klein (1957), using the same 40 year period, determined the distribution of the temporal frequency of cyclones in all 12 calendar months in $5° \times 5°$ quadrangles throughout the NH. Using 20 selected years, with superior data coverage, Klein investigated the geographical distribution of cyclogenesis events.

In the SH such studies have been more restricted as a consequence of the lack of long-term and consistent analyses, and general deficiencies in the observational network. In particular, the large oceanic regions, which comprise the major part of the hemisphere, are grossly under-observed, with only scattered ship, buoy and island observations being available prior to the advent of sophisticated satellite technologies.

Although large-scale studies pertaining to extratropical cyclones in the SH can be traced back to the early part of the current century (see Palmer 1942; Gibbs 1953), it was not until the International Geophysical Year (IGY) (July 1957–December 1958) that the observational network reached a level adequate to provide a reasonable picture of the behavior of systems on a hemispheric scale. The resultant availability of comprehensive analyses arising from this research effort resulted in the publication of numerous articles and precipitated the synoptic appraisals of Van Loon (1965) and Taljaard (1967). Taljaard's study documented the existence of a core of increased cyclone density through the high southern latitudes, coincident with the circumpolar trough (CPT). During the summer and intermediate seasons, well defined regions of enhanced density of lows were evident over the subtropical continents, primarily associated with persistent thermal lows. Of note, during the winter and to a lesser extent the transitional months, two primary spiral arms were evident in the cyclone density, the first extending from the Gran Chaco region of South America through the South Atlantic and the second, stretching from the Tasman Sea through the South Pacific spiraling southeast and merging with the CPT core near Drake Passage.

More recently, with the advent of satellite technologies, SH studies of cyclones have made use of visible and infrared imagery (Streten and Troup 1973; Carleton 1979, 1981) to study the development, movement and dissipation of cyclonic vortices. Based on the characteristic cloud signatures in the imagery, these authors bypassed the conventional analyses with their associated shortcomings due to the paucity of observational data, but faced the limitations associated with manual techniques.

Kep (1984) used 10 years (1972–1981) of manual analyses, to develop a climatology of cyclogenesis, cyclolysis and track density throughout the hemisphere. This study confirmed many of the findings of early authors with a core of high track density throughout the high latitudes of the hemisphere. Kep noted a general tendency for systems to form preferentially between 40–50°S during July and 50–60°S during the month of January. The banding structure in the cyclone tracks, alluded to in the aforementioned studies, was not in evidence in Kep's climatology, possibly as a result of the coarse grid resolution used (10°×10°) and temporal averaging.

It has only been in recent times, with the massive advances in computer resources, that numerical schemes have become feasible and available for the objective extraction of cyclone based statistics. Earlier studies based on the manual interpretation of analyses or satellite imagery had the disadvantage of being labour intensive, while the requirement for human intervention makes possible the introduction of considerable subjectivity. Numerical schemes based on the mathematical determination of cyclone positions and tracks from digital analyses have been initiated in light of the methods developed for manual studies. This formulation ensures consistency throughout the duration of the study and makes possible the objective production of statistics.

To date, only a handful of studies have made use of numerical algorithms to investigate extratropical lows. Le Marshall and Kelly (1981) in a review of the climatology of the Australian analyses for the five year period 1973–1977, used an automatic vortex finding routine based on a continuous space, gradient technique, to investigate the zonal and geographic distribution of cyclones and anticyclones. Their distributions had much in common with those of earlier researchers, with a core of high cyclone densitiy throughout the high latitudes. The spiral bands evident during winter in the IGY-based studies were also in evidence but somewhat less clearly defined. They concluded that these bands were partially truncated as a result of the temporal averaging procedure which results in a zonal smoothing.

More recently, Lambert (1988) used an automatic cyclone finding routine to form winter climatologies, for both hemispheres, of the cyclonic features in ECMWF/WMO analyses for the years 1980–1984 and in a 5 year simulation of the Canadian Climate Centre general circulation model. Le Treut and Kalnay (1990) made use of a numerical scheme to find and track cyclones for two special 50-day observing periods of the First GARP Global Experiment (FGGE) and a series of general circulation model (GCM) simulations.

Until now, no objective study of extratropical cyclones has been presented for the SH, based on an extended period of numerical analyses. It is this task that the current study aims to address. A full 15 years of numerical analyses have been processed using a version of the low "finding" and "tracking" scheme of Murray and Simmonds (1991a). The results of this have been used to generate a climatology of the distribution and behavior of extratropical cyclones throughout the hemisphere. As a consequence of the techniques employed, the current study is purely objective, with no manual interference following the initial specification of the search and tracking parameters.

The data and summary of techniques

The data analyses on which the current study is based are the 2300 GMT numerical analyses from the Australian Bureau of Meteorology, Melbourne, Australia. These numerical analyses (here referred to as the ASH analyses), are presented on a 47×47 polar stereographic (PS) grid centered on the south pole, giving an effective resolution of approximately 500 km at 45°S (Guymer 1986). The earlier years of this set have been used in a wide range of studies (e.g., Le Marshall and Kelly 1981; Trenberth 1981). The quality and veracity of these data has been extensively discussed by Trenberth (1979), Swanson and Trenberth (1981) and Nydam (1989). For an overview of the methods used in the generation of this data set together with the data used as input, the reader is referred to Le Marshall et al. (1985).

Of particular relevance to the current study are discrepancies which have been noted between the 1100 GMT and 2300 GMT analysis time, the latter generally considered to be the superior subset. While the "tracking" scheme used in this study may be applied to analyses provided at any temporal frequency, the inconsistencies between the two sampling times lead to the confinement of the current study to the superior 2300 GMT time. The current work is based on analyses for the 15-year period, February 1975 to March 1990. The earlier analyses in the ASH archives (July 1972 to January 1975) were excluded owing to the high frequency of missing analyses which complicates and prejudices the tracking of systems.

We have used a version of the objective low finding and tracking scheme described in Murray (1988), Murray and Simmonds (1991a) (MSa) and used in the atmospheric model based study of Murray and Simmonds (1991b) (MSb). This scheme is fully objective, with no manual intervention after the initial prescription of a series of search and tracking parameters. To find the lows, the digital pressure fields, on a conformal polar stereographic grid, are represented in terms of continuous functions using cubic splines computed along the grid axes. An iterative differential routine based on the ellipsoidal minimization techniques, is used to define the location of lows in continuous space. Both closed (those systems possessing a closed isobar at a given interval) and open depressions (those not containing a closed isobar) are included in the present study. The position of the closed depressions were defined by the minimization of the pressure functions, while open depressions, indicating inflexions in the pressure field, were found by a search for minima in the absolute value of the local pressure gradient.

To avoid the inclusion of small-scale or broad shallow systems being prone to be associated with topographical or analytical effects rather than being significant migratory features, a minimum curvature test was applied to the data. This "curvature test" requires that the value of the Laplacian of pressure must exceed some specified minimum value for the system to be included as significant, and be used in the subsequent analysis. In the present study this test has been:

$$\overline{\nabla^2 P} + 0.1\nabla^2 P \geq 0.08\,\text{hPa}(\text{deg.lat.})^{-2}$$

where

$$\nabla^2 P = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}$$

The overbar represents the areal average of the pressure curvature over a pass radius of 5° of latitude. This has been calculated by a numerical integration of the continuous Laplacian of pressure over a radius of 5° latitude about each cyclone's center. (In this work we have chosen 1° of latitude as a basic unit of length, and the square of this as the unit of area.)

Cyclone paths were computed according to the probability of the association of "predicted" and subsequent observed cyclone positions and pressures. Where no match occurred above a predefined probability level, cyclogenesis or cyclolysis was deemed to have occurred. The probability of matching was computed by a weighted average of the difference in the location and central pressure of predicted and subsequently observed cyclones. The prediction of the system position involved the use of the past movement of the system in addition to a zonally averaged velocity (in the north-south, east-west directions) of the expected climatic movement. The central pressure predicted for the subsequent time was based on the systems pressure and its past tendency.

The present statistics are based on all systems which existed at two sequential analyses times (i.e., a minimum track life-time of 24 h). The derivation of statistics involved the interpolation (using cubic splines) of cyclone positions to four intervening positions between the analyses times with all positions, both interpolated and observed being used in the generation of the cyclone statistics. A Cressman weighting scheme was then applied to each cyclone position to distribute the data about a small group of surrounding grid points. The cyclone statistics were derived on a 47 × 47 PS grid compatible with the original ASH grid.

Cyclone track histories were generated for each calendar season with a 10 day extension used at the start and finish of every individual season to facilitate tracking over the seasonal "boundaries". In the case of missing analyses, the tracking was performed over the break provided the discontinuity was less than three consecutive analyses. In the case of three or more missing consecutive analyses, the tracking was terminated, and it was started again after the time discontinuity (in the 60 seasons only six such cases were encountered). The various seasonal statistics presented are the average of those over each individual season with the weighting based on the number of analysis times contained in each season. Cyclogenesis was defined to have occurred at the initial position of each cyclone track while the final tracked position was defined to be the location of cyclolysis.

Sea level pressure

As a background against which we consider the SH cyclones, we present the time-mean mean sea level pressure (MSLP) from the ASH set. In Fig. 1 is displayed this variable for summer (December, January and February) and winter (June, July, August). While the limitations associated with the paucity of data means no analyses set may be considered as truly representing the atmospheric state, the ASH set has proven to be of a sufficient quality to allow meaningful studies of the current type.

Cyclone tracks

In Fig. 2 are shown the cyclone tracks and daily positions of cyclones covering the 5-year period, 1985–89, for the summer, autumn (March, April and May), winter and spring (September, October and November) seasons. (To reduce the degree of clutter, only the last five years of the 15 year set have been plotted.) Comparison with the tracks for the remaining 10 years indicate no substantial differences, suggesting that a 5-year period is sufficient for qualitatively stable statistics.

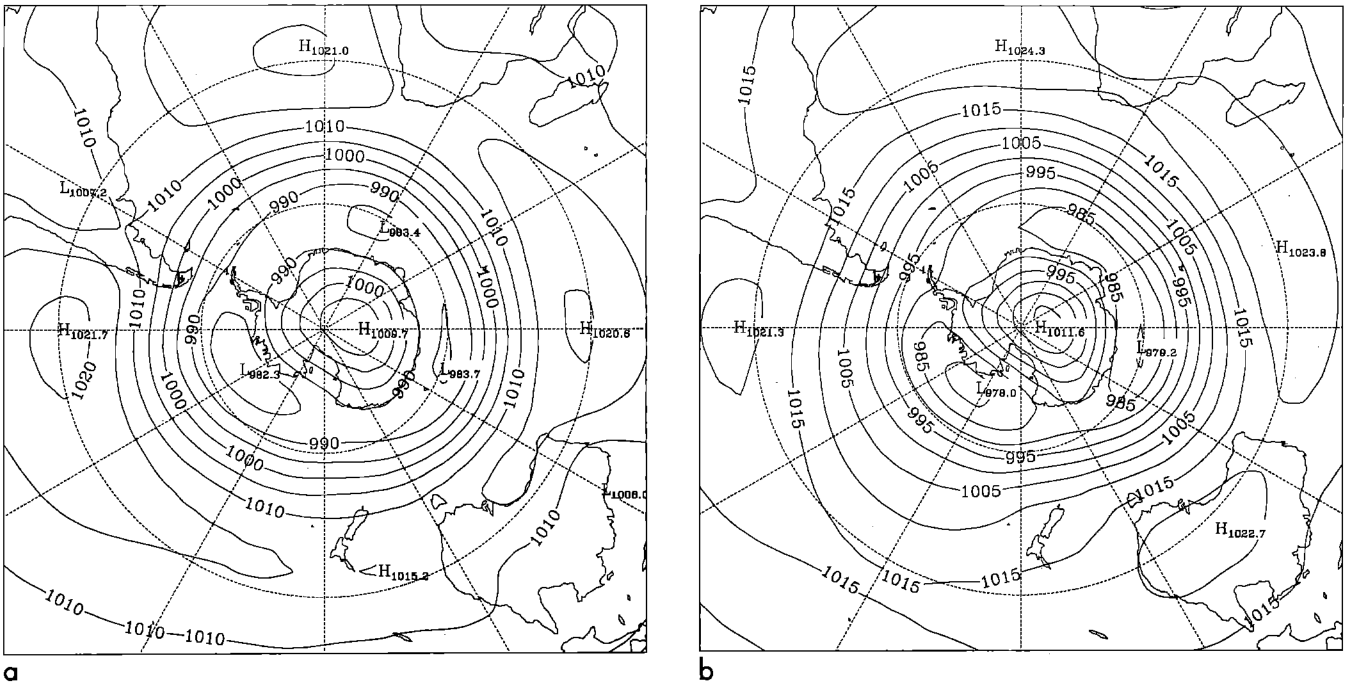


Fig. 1a. The mean sea level pressure as inferred from the ASH set for summer and **b** winter. The *contour interval* is 5.0 hPa

In all seasons one observes peak cyclone track density around the Antarctic coast, in the latitude band 55–70° S, coincident with the CPT. These plots indicate a tendency for systems to develop at lower latitudes before migrating typically in an east-south-east (ESE) direction towards higher latitudes where they merge with the circumpolar core and eventually decay.

During the summer and transition seasons, there are locally increased track concentrations over the subtropical continents, while tropical lows are responsible for the local maxima in cyclone numbers to the northwest of Australia, in the Coral Sea and near Madagascar. In winter the subtropical maxima over Africa and Australia disappear, while the core of high track density about the Antarctic coast takes on a more extensive and diffuse form. One observes enhanced track densities throughout the mid latitudes while the CPT region displays generally reduced system numbers.

Examination of the cyclone tracks through the mid latitudes indicates the existence of two branches of enhanced cyclone density. The principal of these occurs in the Pacific, stretching from Eastern Australia in an ESE direction across the Pacific, merging with the CPT core near Drake Passage. The second, less developed branch, extends from the Gran Chaco region of South America, southeast (SE) across the South Atlantic, merging with the CPT core to the southwest of Africa. Both cores are best developed during winter and spring and only weakly evident during summer.

Seasonal mean fields

System density

The geographical distribution of the area normalized system density (the number of systems per degree latitude square), for the summer and winter seasons is displayed in Fig. 3. Peak cyclone densities are observed in a ring coincident with the CPT, with a number of embedded maxima evident within this core. These maxima, located to the south of Africa, in the Southern Indian Ocean and in the East Ross Sea are in evidence during both seasons while a less pronounced maximum occurs in the Weddell Sea during winter. The high levels of system density about the East Antarctic coast would appear to be a consequence of enhanced baroclinicity (van Loon and Kidson 1993) and a more constricted storm track through this region (Fig. 2). The maximum in the East Ross Sea lies in a region of frequent system stagnation and decay which, combined with the confluence of systems from the Tasman Sea-South Pacific, results in a local enhancement of the cyclone density.

Through the mid and low latitudes, the distribution of cyclones shows an increased structure with clearly delineated regions of enhanced cyclone density. The summer continental maxima at low latitudes are primarily a product of persistent thermal lows formed chiefly as a consequence of the temperature excess in the lower troposphere.

A secondary branch of increased cyclone density is evident in the South Pacific, stretching from southern Australia, through the Tasman Sea and merging with the circumpolar core near Drake Passage. This branch,

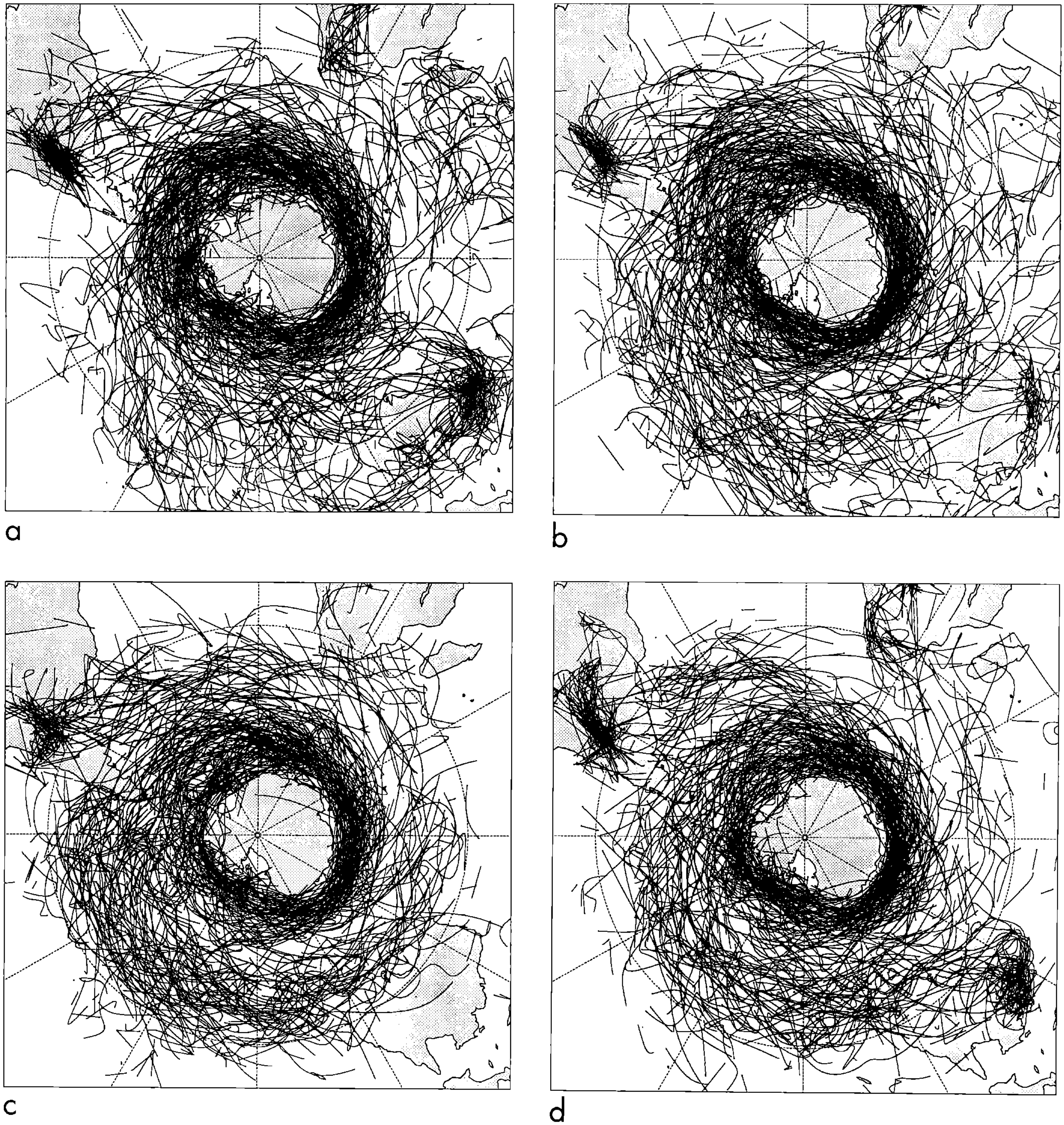


Fig. 2a–d. Tracks and daily positions of all cyclones for **a** summer; **b** atumn, **c** winter and **d** spring (for the years 1985–89 inclusive)

evident in both seasons, is most clearly defined in winter. While the initiation point of this band is somewhat uncertain, the region of enhanced cyclone density appears to commence over the Tasman Sea. Although the Australian Bight shows enhanced cyclone density, this appears disjointed from the band in the Tasman Sea particularly near southeast Australia. This interpretation is supported by the regional study of Leighton and Deslandes (1991), which indicates a relative minimum in the cyclonicity near Tasmania. The increased values of the system density in the Tasman Sea, coincide with a maximum in the incidence of cyclogenesis (Fig. 4) (see Taljaard 1967; Le Treut and Kalnay 1990). The weaker nature of the band during summer would appear to be a consequence of the reduced incidence of genesis during this season.

Through the South Pacific, this branch of enhanced cyclone density coincides with increased cyclogenetic activity. The increased cyclone density and enhanced levels of genesis coincides with enhanced cloudiness

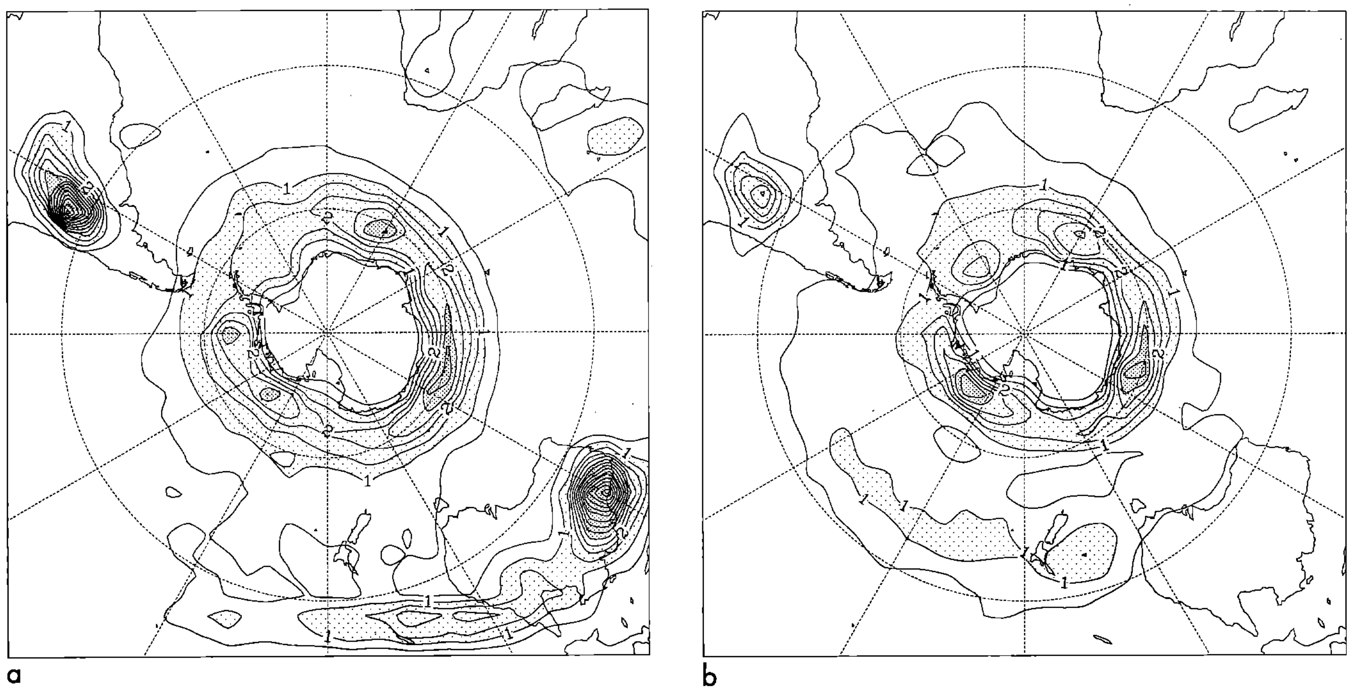


Fig. 3. a The cyclone system density for summer and **b** winter. The *contour interval* is 0.5×10^{-3} cyclones(deg.lat.)$^{-2}$. *Light* and *heavy stippling* denotes area above 1.0 and 3.0 respectively

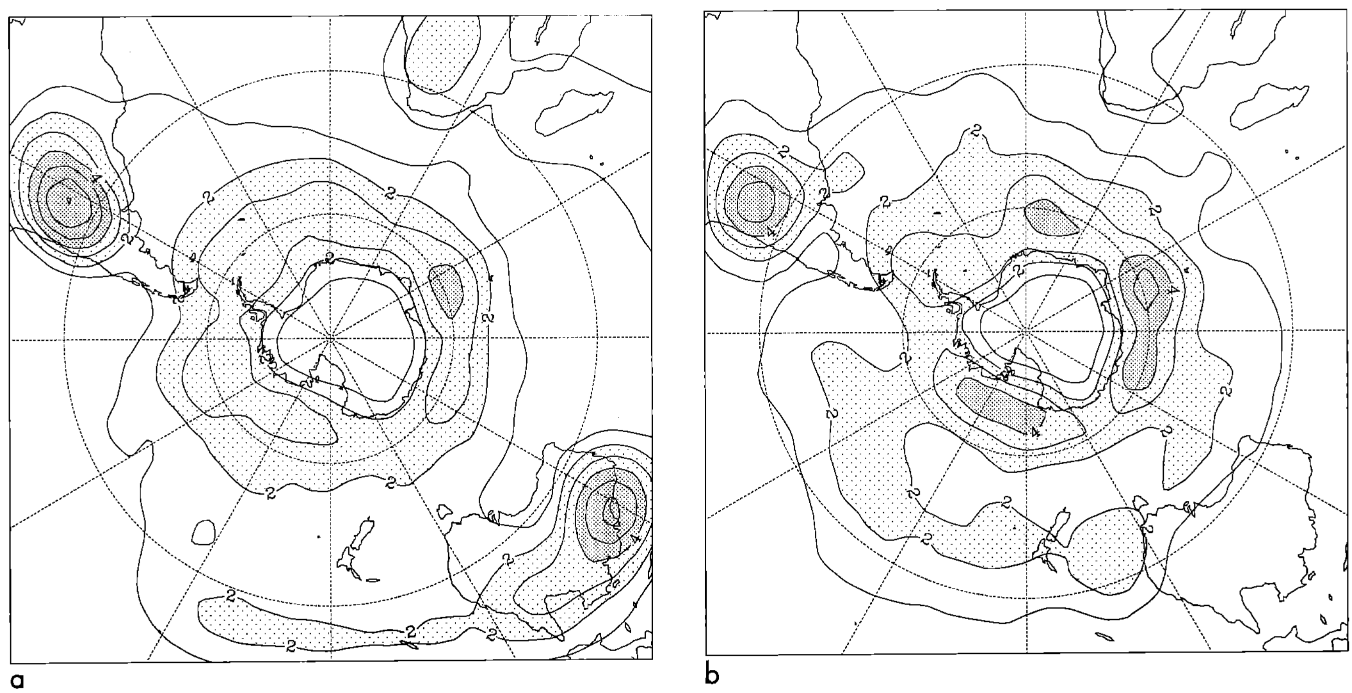


Fig. 4. a The density of cyclogenesis for summer and **b** winter. The *contour interval* is 1.0×10^{-4} cyclones.day^{-1}(deg.lat.)$^{-2}$. *Light* and *heavy stippling* denotes area above 2.0 and 4.0 respectively

associated with the semi-permanent South Pacific Convergence Zone. Streten and Troup (1973) have confirmed this zone of considerable cloudinesss to be an area of substantial weather activity with wave disturbances and cyclogenesis activity occurring along its length, the so-formed depressions moving in a general southeasterly direction towards Cape Horn.

Through the Atlantic, there is evidence of a second mid latitude band of enhanced cyclone density to the lee of the Andes, merging with the CPT maximum near the Greenwich meridian. This is most strongly in evidence during winter, and only weakly apparent during summer. Examination of the cyclone tracks in this region indicates two chief genesis regions contributing to the increased cyclone density. The first, centered in the Gran Chaco region of South America is the more active of the two. Topographical and thermal effects are thought to be the chief mechanism contributing to the existence of this maximum of the system density and genesis, the damming effect of the Andes mountain chain, and low-level warm air advection from the northwest playing the major role. Most of these systems remain semi-stationary as a consequence of their relationship to local influences, relatively few of these becoming transient and contributing to the system density downstream. The second less active, but paradoxically more important source of transient systems lies near 40° W. This coincides with the region of enhanced baroclinicity associated with the frontal zone over the Brazil current (Hoflich 1984).

Cyclogenesis

Figure 4 shows the areal frequency of cyclogenesis for the summer and winter seasons. Although the contouring of any feature characterized by discrete episodes must be treated with caution, the large data sample used ensures continuity of statistics in the current results.

Significant numbers of cyclone formations are observed to occur throughout the hemisphere with the exception of the eastern ocean basins year round, and subtropical East Africa and Australia during winter. The Antarctic interior is devoid of genesis events, through the high relief and the associated integration of surface pressure to sea level complicates interpretation.

Substantial cyclone formation is observed to occur throughout the high southern latitudes within, and to the south of, the CPT in agreement with Kep (1984) and Le Treut and Kalnay (1990). The region centered on the CPT is one the most active genesis regions in the hemisphere, with only the subtropical continents displaying a greater incidence of cyclogenesis.

A number of preferred regions of enhanced genesis are observed through the mid and low latitudes of the hemisphere. Among the most prominent of these are the Gran Chaco region of South America all year round, and Africa and Northern Australia which show geographical maxima in the density of genesis during the summer and intermediate seasons (see Fig. 2). Additional to the continental peaks, the Central Pacific and New Zealand regions show maxima, especially during the winter season.

Cyclolysis

A similar presentation for cyclolysis (Fig. 5) serves to illuminate the typical life sequence of cyclonic vortices in the SH. Much similarity is evident between the distribution of the frequency density of cyclolysis and cyclogenesis suggesting considerable in situ development and decay. In particular, the continental cyclogenesis maxima in the subtropics all exhibit equivalent regions of enhanced cyclolysis, the latter being typically 5° poleward and downstream of the formative centers.

Through the mid latitudes, there is a general excess of formation over decay, indicating these regions serve as a net source of cyclonic vortices. The converse is the case at higher latitudes, particularly south of 65° S. The

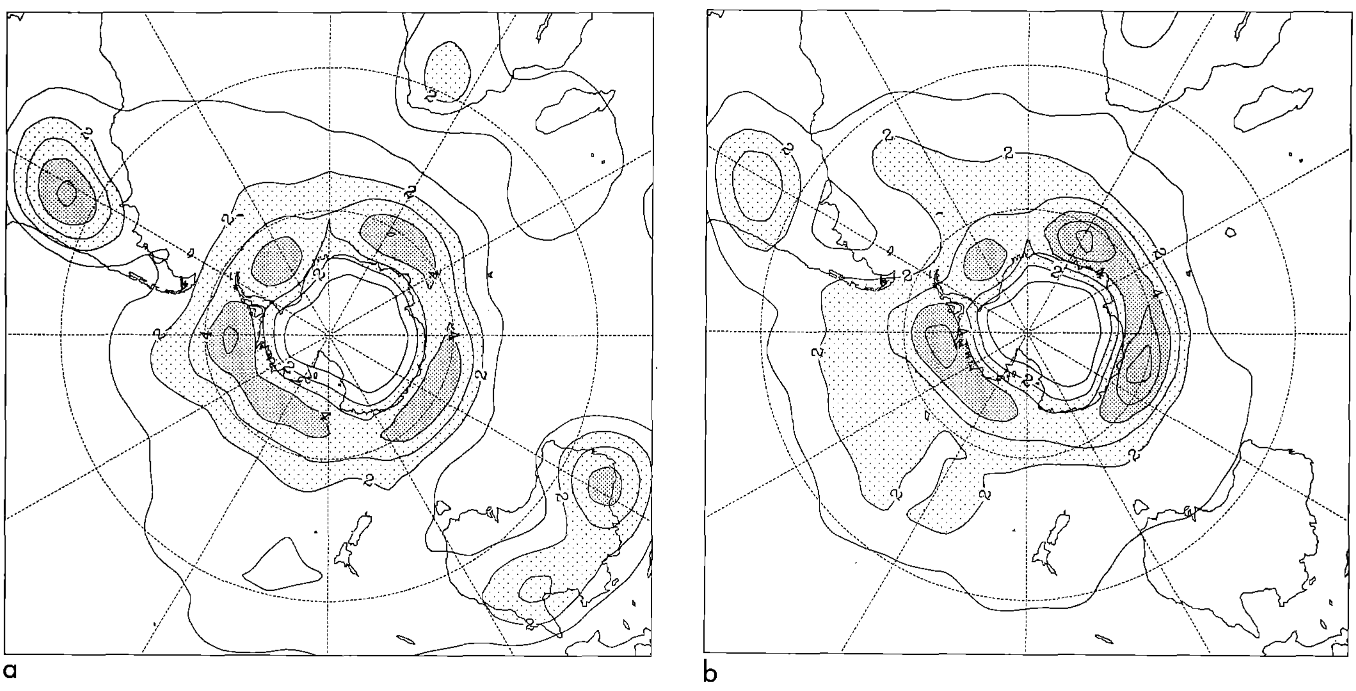


Fig. 5. a The density of cyclolysis for summer and **b** winter. The *contour interval* is 1.0×10^{-4} cyclones.day^{-1}(deg.lat.)$^{-2}$. *Light* and *heavy stippling* denotes area above 2.0 and 4.0 respectively

extratropical maximum of the cyclolysis is found to lie typically 5° south of the location of the time-mean CPT, supporting the interpretation of Taljaard and others, that this region acts as a net sink of decaying systems.

Apparent in the distribution of cyclolysis is a tendency for increased levels to coincide with the embayments of the Antarctic coast, most notably the Weddell and Bellingshausen Sea. This structure has been commented on by a number of authors (e.g., Streten and Troup 1973; Carleton 1979; Budd 1986) who have ascribed enhanced cyclolysis to major embayments of the Antarctic coast. Although the plots shown here generally suggest a link, the placement of the hemispheric peak in cyclolysis off the East Antarctic coast, a region devoid of such embayments, suggests such regions are not unique in their high levels of cyclolysis. Examination of the cyclone tracks (Fig. 2) indicates that the enhanced levels of cyclolysis in the Bellingshausen and Weddell Seas may be as much tied to their position downstream of regions of increased cyclogenesis, both at mid and high latitudes as to local effects. This is suggestive that the correspondence between the Antarctic embayments and regions of enhanced cyclolytic activity may be partly an artifact of effects upstream rather than being tied wholly to regional features.

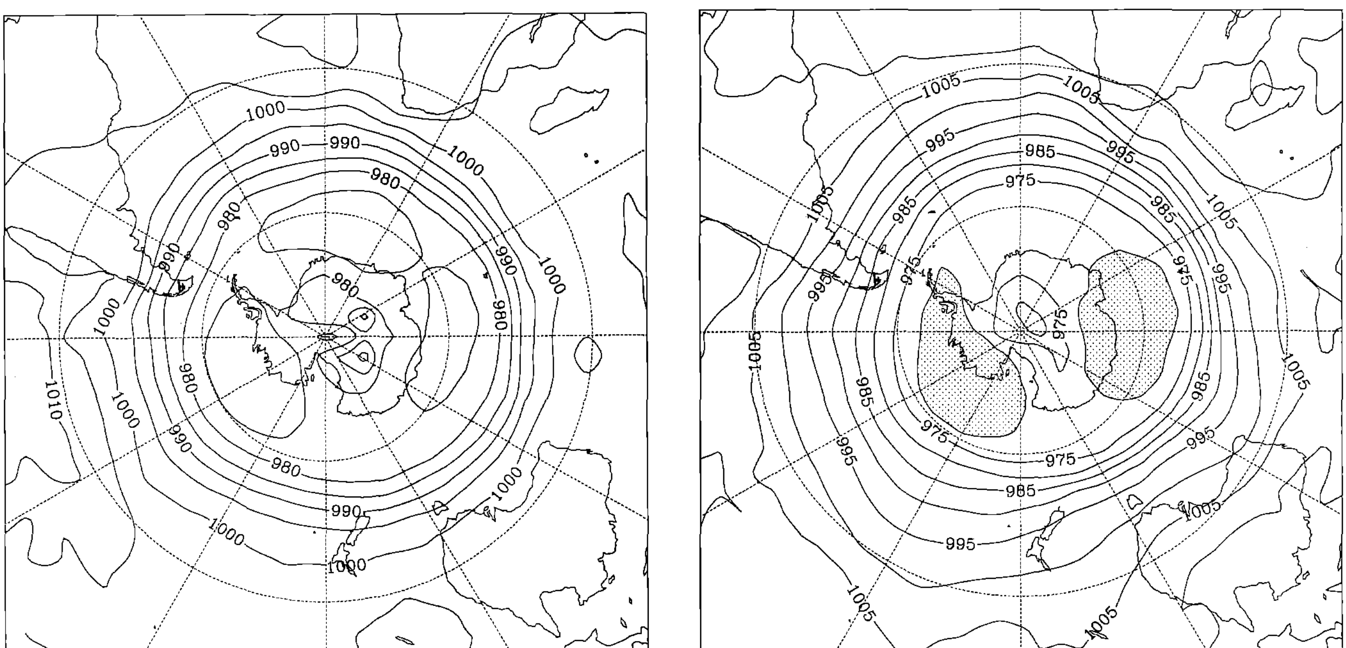
Mean central pressure

Maps of the geographical distribution of the mean central pressure (MCP) (the mean of the central pressure of systems) of cyclones for the summer and winter seasons are displayed in Fig. 6. These show a considerable degree of zonal symmetry with minima in the field coincident with the CPT. Peak values are found in the subtropics, near the subtropical ridge (STR).

The MCP shows considerable seasonality particularly at high latitudes. In the CPT, the winter MCP is typically 5 hPa less than that during summer, with extensive regions displaying values less than 970 hPa. At lower latitudes, where warm core systems dominate, the seasonality is reversed with the deepest depressions occurring during the summer period.

Although the absence of observational studies relating to the central pressure of systems excludes the possibility of hemispheric comparisons with previously derived fields, a limited comparison can be made with the profiles of Karelsky (1963). Even though the averaging periods are different, his figures provide a useful set for comparative purposes. Comparison of the current summer profile with Karelsky (his Fig. 3) shows that, although some of the finer structure is not apparent in our figures, possibly due to the effect of averaging over a greater time period, there is a broad agreement. The placement of the 990 and 996 hPa contours is similar while the 1000 hPa contour shows a slight equatorward shift in the current work. The similarity continues in winter (Karelsky Fig. 7); in particular, the trough in the New Zealand sector is duplicated as is the ridge through southeast Australia.

The interpreation of the mean intensity of cyclones and the seasonality of this is complicated by geographical and temporal variations of the background MSLP field against which cyclones are defined. Hence the deviation of the MCP from the time-averaged MSLP, rather than the MCP itself may be a more appropriate measure of the intensity of individual cyclones. Simmonds and Wu (1993) have defined this quantity as the



a b

Fig. 6. a The mean central pressure of cyclones for summer and **b** winter. The *contour interval* is 5.0 hPa. Areas below 970 hPa are *stippled*

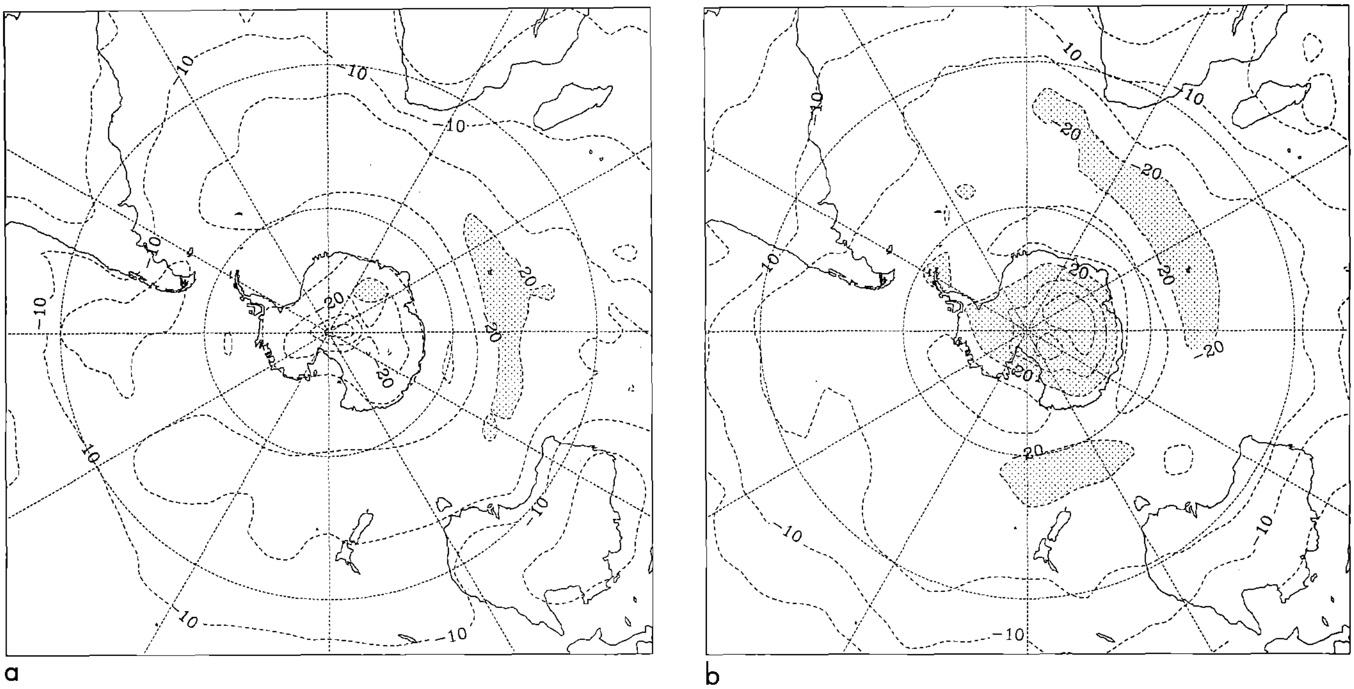


Fig. 7. a The relative mean central pressure of cyclones for summer and **b** winter. The *contour interval* is 5.0 hPa. Areas below −20.0 hPa are *stippled*

"relative central pressure" and this nomenclature will be continued in the current discussion.

In Fig. 7 the geographical distribution of the relative central pressure for the summer and winter seasons is shown. These figures indicate a tendency for the systems with the greatest departure from the time averaged pressure to occur in an arc centered on 50° S, with reduced values both to the north and south. Minimum deviations occur over the subtropical continents during the summer period where generally weak quasi-stationary thermal lows occupy the same regions for extended periods of time.

In general, the degree of seasonality in this relative field is substantially less than that of the MCP, suggesting the major contributing factor to the seasonality of the central pressure is that in the background pressure field. Throughout the Southern Ocean the relative central pressure displays a relatively weak seasonal signal (2–3 hPa) with the exception of the Antarctic Peninsula, where the amplitude approaches 7 hPa.

Of particular interest is the ring of reduced values of the relative central pressure about the Antarctic coast, centered on or slightly poleward of the CPT. Despite the fact that this region contains the deepest extratropical cyclones in the hemisphere, their high frequency of occurrence combined with the relative absence of anticyclones serves to lower the MSLP to such an extent that the relative central pressure is reduced.

Cyclone movement

Figure 8 shows the velocity vectors and speed isotachs for all systems existing for two or more days. These indicate a tendency for systems to move in an ESE direction towards higher latitudes. During both seasons peak speeds are found in the mid latitudes, with the hemispheric maxima located in the South Atlantic and southwest Indian Oceans.

These figures indicate a preference for systems to show the greatest contribution by the meridional velocity to the systems speeds in the low latitudes, vectors aligned in a SE to ESE direction. At higher latitudes, increases in the eastward component, coupled with decreased meridional speeds leads to vectors in the high latitudes which are orientated typically in an ESE and in places approaching due east direction.

While the average behavior at high latitudes is for predominately eastward migration, a number of systems show a tendency for abrupt poleward movement while others, particularly on the poleward side of the CPT, show an abrupt recurving with westward motion being common. Such atypical behavior warrants that a degree of caution be taken when investigating the mean behavior of these systems.

Little seasonality is evident through the Southern Oceans for either the speed or direction of movement. At lower latitudes, the seasonality is greater with system speeds throughout much of the Indian and Pacific Oceans, typically 3 ms^{-1} greater during winter. The meridional component of the velocity throughout the extratropics shows a general increase of about 1 ms^{-1} during winter. The converse is observed at low latitudes, where systems show increased rates of poleward migration during summer.

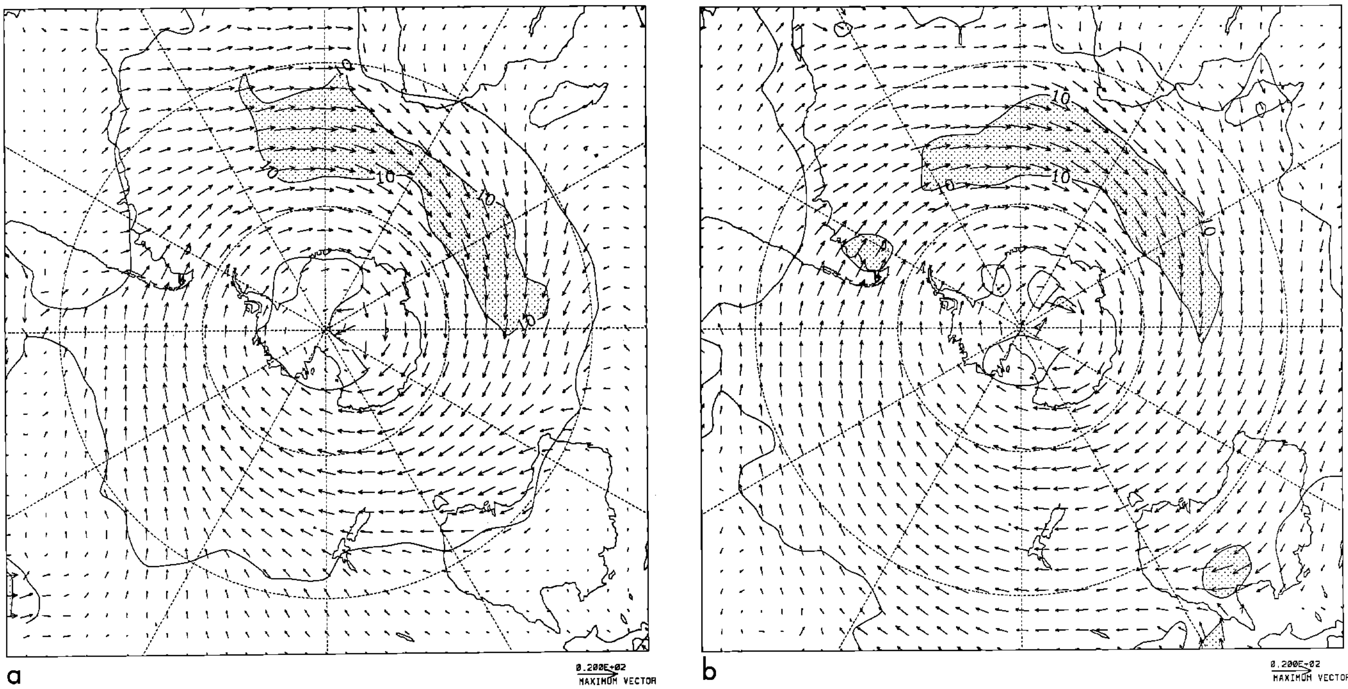


Fig. 8. a Velocities and overlaid speed isotachs of cyclones for summer and **b** winter. 1 *grid space* = 20.0 ms^{-1}, the *contour interval* is 5.0 ms^{-1}. Areas above 10.0 ms^{-1} are *stippled*

Meridional profiles

Next we explore the zonal averages of a variety of cyclone based statistics. The SH atmosphere lends itself, to some extent, to a description in terms of zonal averages due to the high degree of zonal symmetry and because the circulation is not dominated by jet stream entrance and exit regions (Trenberth 1991).

System density

The zonally averaged system density for the four calendar seasons is shown in Fig. 9. The most conspicuous facet of the distribution of the system density is the dominant peak near 60°S in all seasons. Poleward of this band a sharp decline is evident, while to the north the decrease in the system density is generally less rapid. While the position of this maximum of the normalized system density is similar in all seasons, the amplitude and shape show a degree of seasonality. The summer period is characterized by an increased amplitude, and a broadening of the band about its peak while during winter, the high latitude maxima shows a decrease.

Additional to the high latitude maximum are two subsidiary maxima, one centered near 40°S in the winter and intermediate seasons, while a second is apparent near 20°S during summer. The maximum evident in the mid latitudes is attributable to bands of enhanced cyclone density in the South Pacific and Atlantic Oceans which are more evident in winter, autumn and spring. The subtropical maximum is a consequence of persistent thermal depressions and occasional tropical lows which are most prevalent during the warmer period of the year.

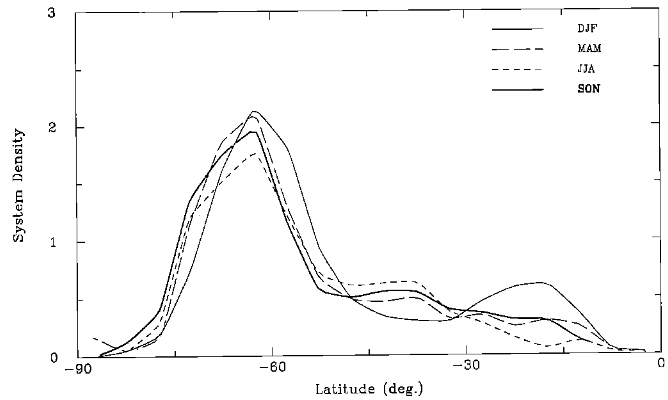


Fig. 9. Zonal average of the cyclone system density for summer, autumn, winter and spring. The units are 10^{-3}cyclones (deg.lat.)$^{-2}$

Cyclogenesis and cyclolysis

The distribution of cyclogenesis (Fig. 10) shows a tendency for genesis to occur at all latitudes with the possible exception of the Antarctic continent south of 80°S. The peak in the genesis throughout the year is found between 55–65°S; this peak is primarily attributable to the large number of formations evident in the South Indian Ocean. The peak in the cyclogenesis is

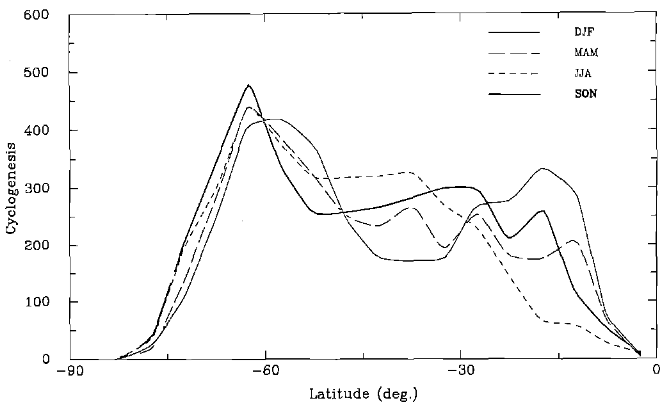


Fig. 10. The total count of cyclogenesis in 5° latitude bands for summer, autumn, winter and spring, for the period, 1975–89. The units are cyclones

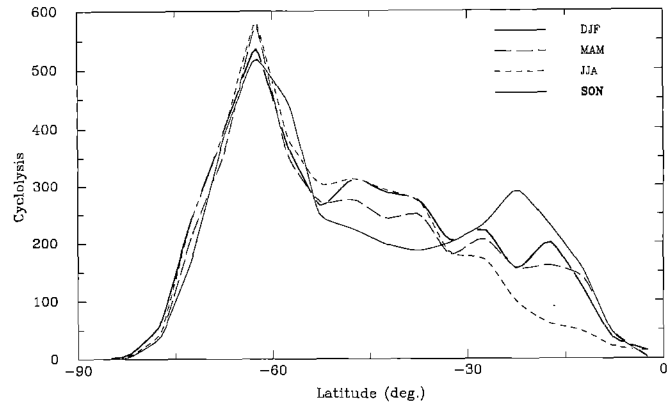


Fig. 11. The total count of cyclolysis in 5° latitude bands for summer, autumn, winter and spring, for the period, 1975–89. The units are cyclones

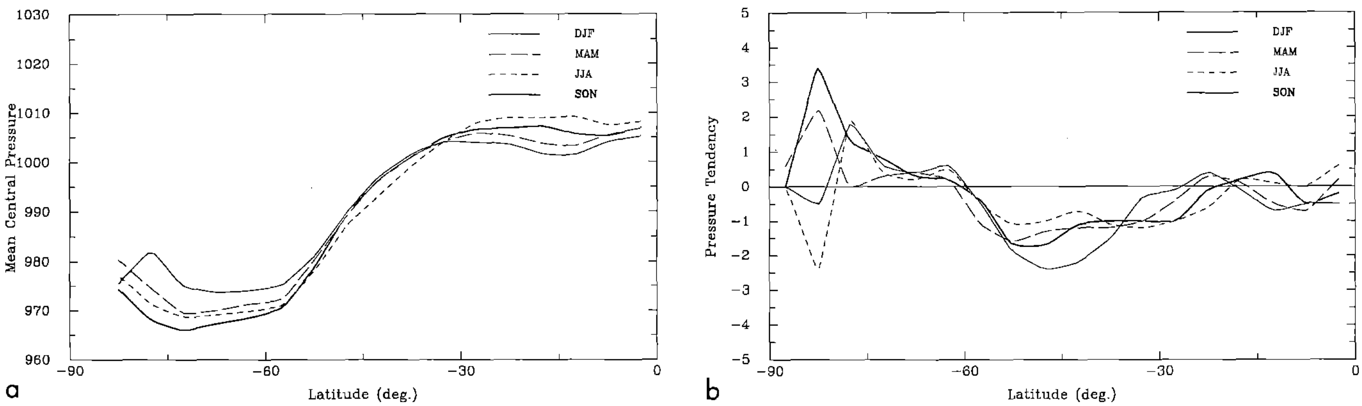


Fig. 12. a Zonal average of the mean central pressure and **b** pressure tendency, of cyclones for summer, autumn, winter and spring. The units are hPa and hPa.day^{-1}

somewhat poleward of that in many previous studies, e.g., Taljaard (1967), Kep (1984). As to whether this is a manifestation of the differences in the definition of cyclogenesis and cyclolysis (in particular differing minimum life times) or the different mean properties of the analysis used is difficult to determine. We note that our profiles more closely resemble the recent results of Le Treut and Kalnay (1990). The substantial impact of satellite data, together with the complexity of tracking systems in the high cyclone density CPT region may go a long way towards explaining the apparent disparity between the more recent, and earlier work. The observed peaks in the number of genesis events at lower latitudes are associated with specific regions of cyclogenesis, such as the Tasman Sea and the subtropical continents.

The distribution of the cyclolysis (Fig. 11) shows a sharp maximum in all seasons near 65°S. Poleward of this maximum, substantial numbers of dissipating cyclones are evident, with typically twice as many systems decaying as forming (Fig. 10).

Central pressure and its tendency

The zonally averaged central pressure and its mean tendency are displayed in Fig. 12. The former (part a) peaks in the subtropics, in the region of the STR. With increasing southerly latitude there is a steady decrease, with the minimum values of the MCP located in the latitude band 65–75°S. The central pressure throughout the mid latitudes varies little through the year but the high latitudes display a strong seasonal dependence. The minimum pressure is observed to occur in the spring period, during the period of most northerly expansion of the Antarctic sea-ice boundary and greatest high latitude baroclinicity (Taljaard et al. 1969; Budd 1982).

The central pressure tendency for systems (Fig. 12b) shows a noisy structure, but in general, systems show intensification between 30 and 65°S, with the peak rates of deepening located in the mid latitudes. Polewards of 65°S, the observed cyclones show an average weakening as indicated by the positive values of the pressure tendency. This serves to confirm the previous notion of the CPT region being a net sink of cyclonic systems.

The peak zonally averaged rates of cyclone intensification are evident in the mid latitudes, with a peak of 2.5 hPa day^{-1} near 50° S. The tendency for the greatest rates of deepening to occur during summer, is somewhat surprising in light of the seasonality in the MCP. This appears to be a consequence of the seasonality of the background MSLP field and the limiting of system intensification to a more restricted latitude band during summer.

Interannual and decadal variability

As fundamentally important as the time averaged aspects of the atmospheric system and its subcomponents, is its variability over the range of contributing time frames. There is clear evidence for the existence of long term and systematic variations of the southern extratropical atmosphere which, combined with possible anthropogenic factors, raises the question of the variation and/or trend of SH cyclonic activity. Although some of the observed changes in the analyzed mean climatic state may be due to changes in the coverage and quality of the contributing data (Guymer and Le Marshall 1980; Le Marshall et al. 1985), the investigation of temporal variations of the analyzed state is constructive. In this regard, the relatively unchanged nature of the analysis scheme used in the development of the ASH set simplifies interpretation. Le Marshall et al. (1985) have demonstrated significant differences in the level of daily variability of the geopotential height field for the first and second 5 year periods of the ASH set. This raises the question of the stability and variability of the current cyclone data set. Carleton (1989) and Enomoto (1991) have demonstrated fluctuations of the broad scale SH circulation over periods of decades. Carleton (1992) has suggested that periods greater than 10 years are needed for the description of the variability of the synoptic circulation of the southern extratropics. Although the duration of the current set precludes the possibility of establishing the level of significance, the patterns of observed variation are informative. For the purpose of brevity, the current discussion is limited to the MCP (both absolute and relative) for the summer and winter seasons.

In Fig. 13 the latitude-time structure of the zonally averaged MCP for the summer and winter seasons are shown. These serve to highlight the interannual variability of the MCP a measure of the absolute intensity of cyclonic vortices. These figures indicate substantial interannual variability more particularly in the high latitudes.

The winter profile displays a trend for decreased values of the analyzed MCP through the high latitudes during the period of study. The interpretation is, however, complicated by changes in the observing network which may have resulted in systematic changes in the derived numerical analyses on which these figures are based. Although there is evidence for decreasing values of the MCP through the late 1980s, much of the shift towards more intense systems appears centered on the late 1970s. This coincides with the deployment of the extensive FGGE buoy network, and the inclusion of improved and increased satellite data during 1978–1979 (Le Marshall et al. 1985; Nydam 1989).

Guymer and Le Marshall (1980) suggest the anomalous structure of the SH analyses during the FGGE period was primary a consequence of the improved data

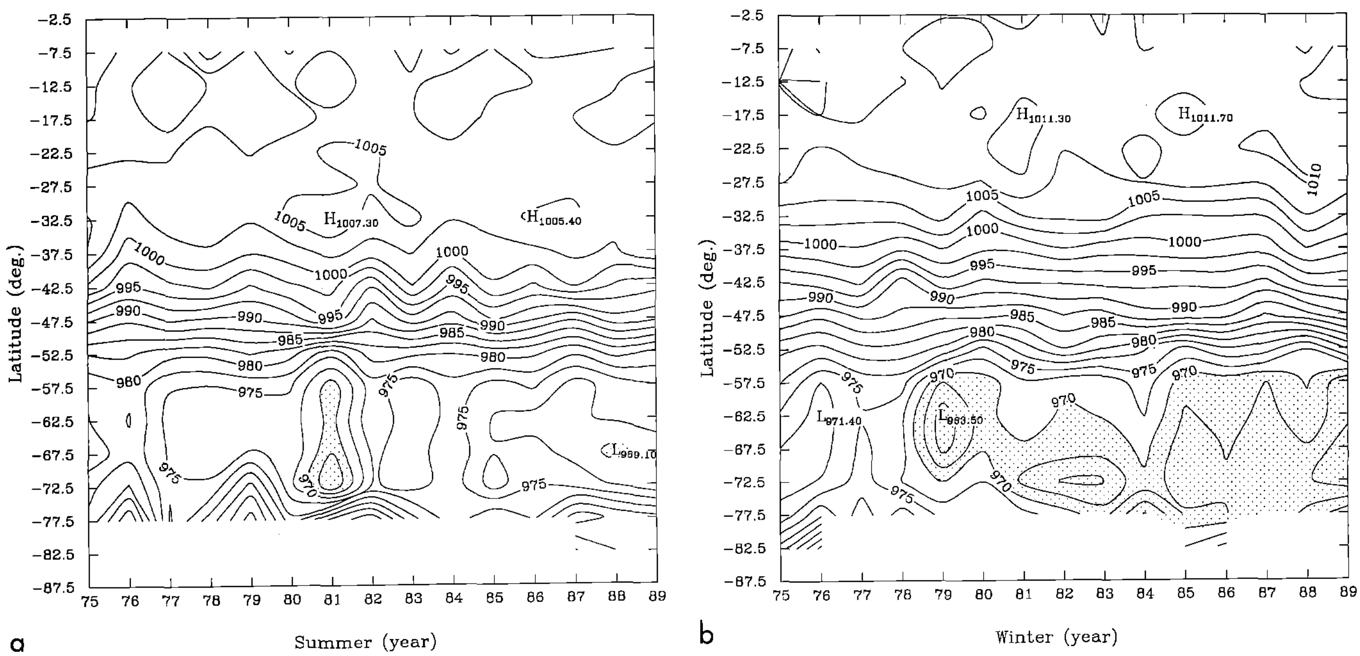


Fig. 13a, b. Zonally averaged time series of the mean central pressure of cyclones for **a** summer and **b** winter. The *contour interval* is 2.5 hPa. Areas below 970.0 hPa are *stippled* coverage. While the post-FGGE period saw a decline in the density of observing, the sampling has remained superior to that prior to this research experiment, this improvement remaining a possible factor contributing to the apparent trends. Although the impact of a vastly improved observational network cannot be disputed, Trenberth (1984) has demonstrated the consistent nature of the observed anomalies in the analyzed atmospheric state during the FGGE period supporting the interpretation that the anomalous characteristics of analyses were not mere artifacts of an improved data base. This is further supported by station data (e.g., Schwerdtfeger 1984), which indicate the anomalous state of the SH circulation during much of the FGGE period. The anomalous characteristics of the circulation during this period when much increase took place in the level of observing serves to inhibit the precise determination of the impact of these changes on the derived analyses. Of relevance to the current discussion, van Loon and Kidson (1993), using 9 years of analyses from the European Centre for Medium Range Weather Forecasts, have demonstrated a trend for increased transient eddy flux throughout the winter extratropics for the period 1980–88. Although this does not include the FGGE period, it is suggestive of a real increase in the level of transient eddy activity through the 1980s, consistent with our results.

Examination of the equivalent summer profile indicates little trend in the MCP. Although periods of enhanced intensity are evident (e.g., 1977–1981 and 1985–1989), the MCP is relatively constant through the period.

Similar time series for the relative central pressure, a field inherently detrended from the background pressure field are shown in Fig. 14. The relative central pressure shows considerable interannual variability during both seasons. The previously mentioned discontinuity in the strength of cyclones around the FGGE period is less obvious, the post-FGGE relative central pressure being only marginally smaller than that in the earlier seasons. During the later half of the time series there is a suggestion of decreased values of the relative central pressure, particularly during winter, suggesting increased system intensities during the later part of the 1980s.

The presence of trends, particularly in the later half of the analysis period, raises the question of stability of statistics and the minimum period upon which a climatology should be based. Such considerations highlight the dangers of determining climatologies on relatively brief data periods.

Conclusions

We have used an objective low "finding" and "tracking" scheme to produce a climatology of the distribution and behavior of SH cyclones from a data base of 15 years of daily numerical analyses. The application of the scheme in the current investigation has enabled a comprehensive study of extratropical low pressure systems in the SH, and has made available cyclone statistics which up to now have not been computed.

In agreement with many prior studies, the current investigation has revealed a single high latitude core of cyclone density, coincident with the CPT. During the winter and intermediate seasons, dual branching has been observed with two mid latitude bands evident in

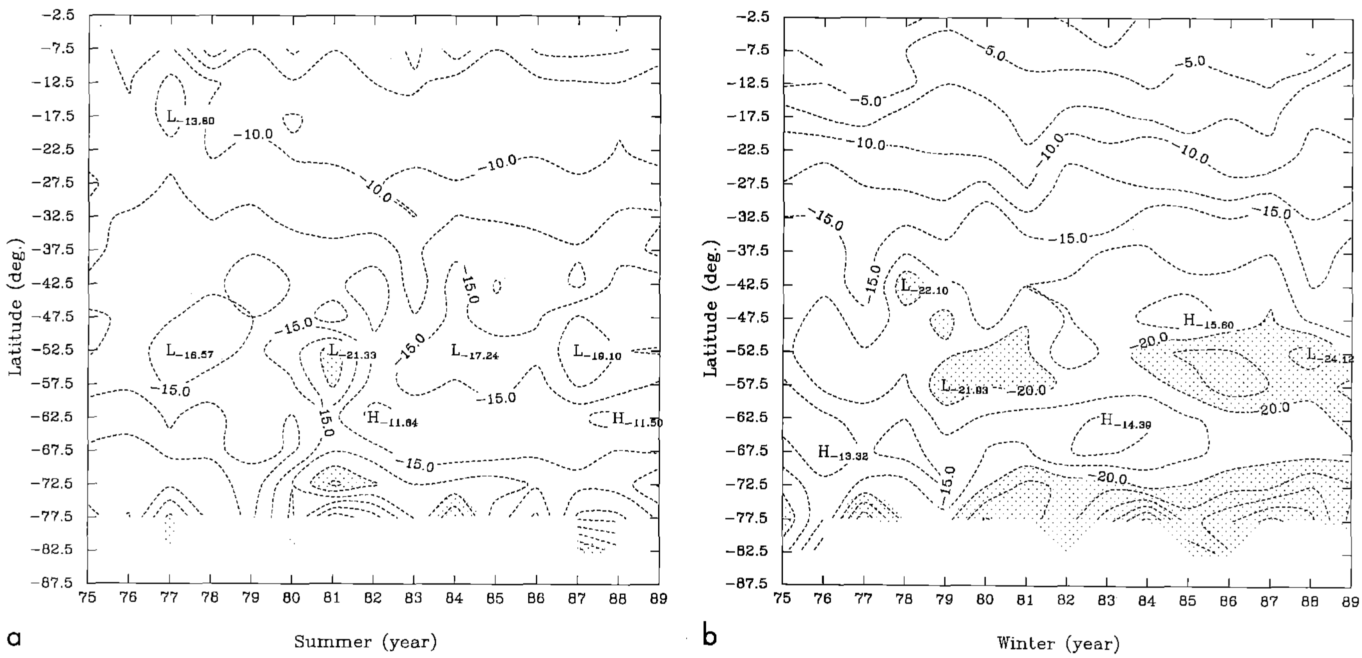


Fig. 14a,b. Zonally averaged time series of the relative mean central pressure of cyclones for **a** summer and **b** winter. The *contour interval* is 2.5 hPa. Areas below −20.0 hPa are *stippled* the cyclone densities. The most prominent of the two bands of enhanced cyclone density is found to originate in the Tasman Sea – southeast Australia region, spiraling polewards and merging with the high latitude core in the vicinity of the Drake Passage. A second, less well-defined, band originates in the region of South America, stretching SE through the South Atlantic, and merging with the circumpolar core to the south of Africa. Both bands originate in regions of enhanced mid latitude cyclogenesis, and merge with the CPT core in the high southern latitudes.

Examination of the properties of the observed systems indicated that the most intense systems occur in a ring coincident with the CPT. Values of the averaged MCP were at a minimum during the spring and winter periods, while the summer was characterized by an increase in the MCP of typically 5–8 hPa. Cyclonic systems were found to generally move in an ESE to SE direction in the low and mid latitudes while at higher latitudes systems showed general ESE and in places easterly movement.

For the most part the results obtained are similar to those found in earlier studies. There are differences in some quantities, which may be a comment on the paucity of data used in earlier analyses. The use of an objective scheme allows us, with ease, to produce many statistics of cyclone behaviour which have not been previously presented. Given the length of the data period used and the objective and reliable nature of the scheme, it can be argued that the present results represent the best statistics of SH extratropical cyclones available.

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