Synoptic Activity in the Seas around Antarctica

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(Manuscript received 17 April 2001, in final form 22 April 2002)

ABSTRACT

The recent NCEP–Department of Energy (DOE) Reanalysis-2 update of the original NCEP–NCAR dataset provides what is arguably the highest quality analyses spanning two decades available for the high southern latitudes. It therefore offers an excellent starting point from which to assemble a modern, comprehensive, and reliable picture of synoptic activity in the subantarctic region. This set, covering the “modern satellite” era from January 1979 to February 2000, is used herein. In addition, the exploration in this study has been conducted with sophisticated feature-tracking and trajectory analysis software.

It is shown that the high southern latitude cyclone system density is greatest in the Indian Ocean and to the south of Australia near, or to the south of, 60°S. The numbers in winter exceed those in summer, except over a few, but important, regions such as the Bellingshausen Sea. The Antarctic coastal region is confirmed as one of high cyclonicity, as is that in the northern part of the Antarctic Peninsula and over and to the north of Drake Passage. Cyclolysis is much more confined to the near-coastal region. The mean intensity, radius, and depth of subantarctic cyclones assume their largest values near 60°S.

It is shown that the rate of change of cyclone central pressure is not a particularly useful gauge of intensification in the Southern Hemisphere, where large spatial variations of climatological pressure are found. When appropriate adjustments are made, it is found that the “corrected” central pressure of cyclones is seen to increase along the track for most systems found south of 45°S. The paper also documents the range of starting points of 4-day 500-hPa trajectories that reach points on the Antarctic coast. The broad frequency distribution reflects the very energetic nature of synoptic activity in the region. The counts of cyclones in the 21 yr of NCEP–DOE analyses show negative trends over most of the subantarctic region. At the same time, however, the annual mean cyclone intensity, radius, and depth all exhibit increases.

Finally, the frequency of occurrence of rapidly developing cyclones (or “bombs”) in the subantarctic environment is determined, and it is found that they are not uncommon features. Their number shows a maximum in winter but, unlike the Northern Hemisphere situation, many are also found in summer.

1. Introduction

The Antarctic and subantarctic regions can still be regarded as among the last frontiers in understanding global weather and climate. Hines et al. (2000) have reminded us that obtaining accurate representations of synoptic structure in the high southern latitudes is limited by a variety of obstacles, including scarcity of data and communications problems associated with long distances and aural effects. Extreme weather phenomena and sharp topographic and thermal contrasts also create unique difficulties for constructing reliable analyses in the Antarctica region. However, the identification of extratropical cyclones in these analyses is an important task as the systems found over the Southern Ocean and around the Antarctic continent play a major role both in the general circulation of the atmosphere and in the coupled atmosphere–ocean–ice system (King and Turner 1997). A recent review of some of the difficulties of performing analysis in this region may be found in Hutchinson et al. (1999).

One of the most significant recent advances for understanding atmospheric behavior in this part of the world has come from the use of “four-dimensional variational data assimilation” and “reanalysis.” In reanalysis, “optimum” use of observations is made within the physics-based framework of a numerical weather prediction model. Historical data may be inserted into the analysis cycle of the model, which in turn can produce an analysis, the quality of which is related to the density and quality of the observations that have been inserted. The generation of the reanalysis products has meant that atmospheric studies of the high southern latitudes may be undertaken with a level of confidence that has not been available heretofore.

One of the most comprehensive reanalysis sets to have been produced is the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) set, which comprises 6-hourly global atmospheric analyses since 1948 (Kalnay et
et al. 1996; Kistler et al. 2001; we refer below to this dataset as the NCEP dataset). This dataset has been used in a wide variety of meteorological and climatological studies, a range that is reflected by the fact that, as of November 2002, the Kalnay et al. paper had been cited 1590 times in the Institute for Scientific Information’s Web of Science database. We have used the set to study Southern Hemisphere (SH) cyclone behavior over the period 1958–97 (Simmonds and Keay 2000a,b, hereafter SKa and SKb).

After this set was produced it was realized that a number of errors were made during its production, and these errors raised questions as to its reliability. As a response to this realization a second reanalysis from January 1979 was performed by NCEP in collaboration with the Department of Energy (the so-called NCEP–DOE Reanalysis-2 dataset, which we shall refer to here as the NCEP-2 set). Given the errors in the NCEP reanalyses, the question naturally arises as to what effect they may have had on the diagnosis of SH cyclone behavior as documented in studies that had used them (e.g., SKa, SKb). In accord with this question, our overall aim in this paper is to document the synoptic activity in the subantarctic region as revealed in the recently released NCEP-2 dataset. By making use of a state-of-the-art cyclone tracking scheme in conjunction with the surface analyses obtained from this set covering the “modern satellite” era we are able to assemble what is arguably one of the best and most reliable compilations of subantarctic synoptic activity.

2. The NCEP-2 dataset and the cyclone tracking algorithm

A detailed description of the NCEP-2 reanalysis set and its production is provided by Kanamitsu et al. (2000, 2002) and Kistler et al. (2001). These papers itemize the many “fixes” that were made to the analysis system. One of the potentially most important of these for analyses over the subantarctic was the elimination of the Australian surface pressure bogus data (PAOBS) problem. (This error had arisen when estimates of sea level pressure produced by Australian analysts using satellite data were inserted into the analysis cycle but with a longitudinal shift of 180° from their correct position.) The period of the dataset we use here is 1 January 1979–29 February 2000, and the analyses are available every 6 h. The year 1979 is an excellent starting point for our investigation as it corresponds to a time of greatly increased data coverage. That was the year of the First Global Atmospheric Research Program (GARP) Global Experiment, and also is the start of the modern satellite era. Figure 1 of Kistler et al. (2001) documents the significant increase in the number of global observations at that time, an improvement that was particularly marked in the high southern latitudes (see also Kalnay et al. 2000).

When undertaking a study of this nature over the oceanic regions of the SH, one must recognize the analysis uncertainties that may be associated with the fact that many of the observational platforms that are used in reanalysis products are very sparse over the region. In that environment, satellite data forms very valuable input. Studies by Kanamitsu et al. (1997), Kistler et al. (2001), and others demonstrate the dramatic impact that satellite data makes on the quality of the reanalyses in the SH. The satisfactory SH forecast anomaly scores over the period considered here (Fig. 7 of Kistler et al. 2001) strongly suggest that a considerable degree of veracity can be associated with these analyses. The comments of Sinclair (1995) are representative of the view of many SH synopticians in that, “even over data-sparse regions of the world, the realism of these analyses now enables useful conclusions to be drawn from climatological and composite studies of weather systems.” Over and above these points we make the general observation that the reanalyses represent one of our best estimates of the three-dimensional structure of the SH atmosphere.

Part of the analysis presented here makes use of the sophisticated Melbourne University cyclone tracking scheme described in detail by Simmonds and Murray (1999) and Simmonds et al. (1999). A few brief words about the scheme are warranted here. The first step in it is to transform the latitude–longitude data by bicubic spline interpolation to a polar stereographic array centered on either the North or South Pole. This is done to eliminate anisotropy in the grid resolution, which would have had significant effects on our compilation at high latitudes (see also Sinclair 1997). The finding routine begins by searching for local maxima in the Laplacian of the pressure compared to that of the surrounding eight grid points. From these points the location of an associated pressure minimum is sought iteratively using ellipsoidal minimization techniques. The lows are then categorized as “open” or “closed.” In the case of a closed system the center of the cyclone is defined as the point of minimum pressure, while the point of inflection in the field is taken as a suitable equivalent in the case of an open system. The systems are then required to satisfy a minimum concavity criterion, to qualify as meteorologically significant phenomena. A reliable way that has been found to do this is to employ a threshold “area-averaged Laplacian” over a specified radial distance (in our case 2° latitude) from the cyclone center. The scheme performs well in the SH as can be appreciated from a case study comparison with manual identification presented by Simmonds et al. (1999).

In our compilation “cyclogenesis” is defined as the first appearance of a cyclone (which must last at least 24 h), and “cycloysis” is the last appearance of such a cyclone. Over regions of significant surface elevations the mean sea level pressure has little physical meaning, and for this reason we do not identify cyclones over areas where the topographic elevation exceeds 1 km. In
addition, in regions over which rapid changes in topographic slope occur, a situation found particularly on the Antarctic coast, the minimum curvature criterion for identifying systems is made more restrictive [Eq. (5) of Simmonds et al. (1999)]. The scheme calculates a number of statistics in connection with each cyclone it finds, including the central pressure and “intensity” (as measured by $\nabla^2 p$ in the vicinity of the center). [We comment that this term is used in many (and contradictory) senses in the literature. Our usage follows that precisely defined by Petterssen (1956, p. 52).] Other cyclone diagnostics used here are radius ($R$) and depth ($D$). Each of these parameters represent important and distinct aspects of a cyclonic activity, and can be shown to be related through

$$D = \frac{R^2}{4} \nabla^2 p.$$

The algorithm allows for cyclone tracks to be assembled from systems identified in successive 6-hourly analyses. In their assessment of three such schemes, Leonard et al. (1999) concluded that the Melbourne University algorithm shows a high degree of skill in identifying low pressure centers and tracking lows through a series of analyses. In this context see also the comments of Turner et al. (1998).

We mention that much work has been done with Eulerian measures of synoptic activity and “storm tracks.” These have been taken to be the geographical maxima of the temporal (auto)covariances of (filtered) atmospheric fields (e.g., Sawyer 1970; Blackmon 1976). This approach has the advantage of being simple and easily applied. It has the drawback of being somewhat removed from a synoptician’s understanding of storms, and does not easily allow for the determination of specific cyclone characteristics of interest to us here, such as intensity, radius, depth, or translation velocity. [Wallace et al. (1988), Sinclair and Watterson (1999), Sickmøller et al. (2000), SKa, and others have discussed these and other points of difference between the two approaches.] We see it as important that both perspectives of cyclone behavior be retained as these provide complementary information.

3. Mean cyclone characteristics

The character of surface cyclones is obviously intimately associated with that of the mean sea level pressure (MSLP). As such, an important starting point is an examination of the climatological MSLP as diagnosed in the NCEP-2 process. These are presented for winter (June–August) and summer (December–February) in Fig. 1. Immediately apparent is the strength of the westerlies to the north and the annual persistence of the circumpolar trough. In winter the deepest parts of the trough are found around most of East Antarctica and in the eastern part of the Ross Sea. In summer the deep parts of the trough form a wavenumber-3 pattern. For the most part the pressures around Antarctica are lower in winter, except in some regions such as the Bellingshausen, Amundsen, and Weddell Seas.

The cyclone system density for the two seasons is shown in Fig. 2. It will be seen that the highest densities are found near, or to the south of, 60oS and these reach peak values in the sectors in the Indian Ocean and to the south of Australia. Overall, the density of cyclones...
Fig. 2. System density (the mean number of cyclones found in a $10^3$ $^\circ$ lat$^2$ area per analysis) in (a) JJA and (b) DJF. The contour interval is $2 \times 10^{-3}$ ($^\circ$ lat)$^{-2}$. An additional isoline at $1 \times 10^{-3}$ ($^\circ$ lat)$^{-2}$ has been included in the plots.

is greater in winter, although the summer numbers exceed those of winter in a few locations, such as in the Bellingshausen Sea. There are isolated maxima, particularly in winter, off Riiser-Larsenhalvøya (near 34$^\circ$E) and in the southern parts of the Weddell and Ross Seas (note these are not as marked as those obtained by SKa with the NCEP data). With regard to the maxima in the south of the Weddell and Ross Seas, Figs. 1b and 1c in SKa suggested that these were quasi-stationary features. This was also found to be true in the present study, a finding consistent with the fact that cyclogenesis and cycloysis frequencies are very high in these locations (see below). Sinclair (1994) found features very similar to these in operational ECMWF analyses (his Fig. 6). The features may reflect a very localized interaction between the Antarctic topography, the presence of embayments, and other factors, or at least the way in which such interactions are represented in the assimilating model. We are exploring the origins of these systems and the extent to which they can be said to be “real” and of importance. In this context it should be noted that Keable et al. (2002) find high frequencies of 500-hPa cyclones over the Ross Ice Shelf and, in some seasons, over the Ronne Ice Shelf.

Significant winter Antarctic region cyclogenesis occurs in the Indian Ocean, both at about 45$^\circ$S and south of 60$^\circ$S (Fig. 3a). Other regions of enhanced genesis are found at the tip of the Antarctic Peninsula and in the southern parts of the Weddell and Ross Seas. In summer (Fig. 3b) the level of cyclogetic activity is considerably less, although, in particular, the Antarctic Peninsula is still a region of formation for a significant number of cyclones. The patterns of winter and summer cycloysis rates are somewhat similar (Figs. 3c and 3d) and show very high rates of decay in the Indian Ocean south of 60$^\circ$S and in the Bellingshausen Sea. The “budget” of cyclones can be conveniently understood from the difference between the density distributions of genesis and lysis. The geographical distribution of this statistic is remarkably similar in winter and summer (Figs. 3e and 3f). In both seasons genesis exceeds lysis almost everywhere north of 50$^\circ$S, with the opposite being true to the south of this latitude. Exceptions to this last statement are found in the area around Oates Land and to the east of the Antarctic Peninsula.

Figure 4a indicates that the mean intensity (as measured by the Laplacian of MSLP) of cyclones in winter shows a subantarctic maximum centered near 60$^\circ$S, with an extreme embedded in this in the west Pacific. Apart from smaller values of intensity in the Bellingshausen Sea and Drake Passage regions, the pattern displays considerable zonality. This symmetry is perhaps even more marked in summer (Fig. 4b), and the axis of maximum shifts somewhat to the north. Much more longitudinal structure is seen in the mean radius of cyclonic systems (Figs. 4c and 4d). The largest systems are found in the Indian Ocean in both seasons. In contrast to many of the statistics examined here, the mean radius in summer is more striking than its winter counterpart. Regions over which the mean radius of cyclones exceeds 6.5$^\circ$ latitude in summer include the area to the north of the Amundsen Sea and an arc extending from the Greenwich meridian to south of Australia. The distributions of the mean depth of cyclonic systems in the two seasons (Figs. 4e and 4f) are similar to those of radius, particularly in summer. On average, the deepest systems are
found in winter off Wilkes Land, where the mean depth exceeds 11 hPa.

Before leaving this section we comment that the typical distribution of cyclone attributes is consistent with those shown by Jones and Simmonds (1993) and SKa, and indeed with the very early work of Lamb and Britton (1955, see their Fig. 3). They differ somewhat from the results of Sinclair (1995, 1997), which showed that winter “track density maximizes between 50 and 60oS in the Atlantic and Indian Oceans sectors, and south of 60oS in the Pacific . . .” whereas our system densities show maxima farther south. Sinclair also diagnosed more modest levels of genesis in the immediate vicinity of Antarctica. Part of the reason for these differences is that Sinclair displays the track density of vorticity extrema from pressure fields that had been smoothed. He also chose to delete from the count any system that moves a total distance of 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.”

We also make mention of the fact that a number of studies (e.g., Trenberth 1991) show that many band-passed (Eulerian) covariance quantities exhibit maxima to the north of our regions of high cyclone density. As indicated earlier it is of great value to retain both Lagrangian and Eulerian perspectives of “storm activity.” In particular, it is of importance to bear in mind that frontal features associated with, but located to the north of, cyclones can be responsible for significant meridional transports.

Our results appear to be quite consistent with modern perspectives on cyclonic activity in this region. For example, the very careful and detailed observational study of Turner et al. (1998) revealed levels of cyclone density and genesis within the Antarctic Peninsula sector very similar to those displayed here. The structures are also consistent with many studies (e.g., Mechoso 1980; Kottmeier 1986; Berbery and Vera 1996), which show the regions around the periphery to be host to strong baroclinicity. King and Turner (1997) reflected this new appreciation of the level of cyclonic activity when they commented that recent studies have shown that the subantarctic trough region exhibits developments on meso- and synoptic scales more frequently than had been previously thought.

a. Lagrangian tendencies

One of the advantages of taking the Lagrangian approach to diagnosing synoptic behavior is that algorithms such as ours permit the compilation of statistics related to the behavior of individual synoptic systems. One of these important statistics is associated with the rate of change of central pressure of cyclones. Only a small number of studies have presented summaries of central pressure change of cyclones, among which we mention those of Colucci (1976) and Gyakum et al. (1989). Figure 5a indicates that, on average over the year, systems passing through regions to the north of 60oS experience central pressure reductions of up to 7 hPa day⁻¹. Systems found poleward of this latitude show increases in central pressure at most longitudes around the continent.

Before we can interpret this plot appropriately we must bear in mind the spatial variation of the climatological pressure in which these features are embedded (Fig. 1). The mean pressure over the subantarctic region has strong meridional gradients throughout the year. Hence the cyclones that develop in midlatitudes and migrate southward move into regions of lower climatological pressure. In such an environment the central pressure of a cyclone may decrease even if it is not intensifying. For this reason it is useful to define “relative” central pressure (e.g., Simmonds and Wu 1993) and to analyze the central pressure deepening rate with respect to this parameter, which represents a more useful statistic on central pressure change. Hence, mathematically, we define relative central pressure for a cyclone as

\[ p_r = p_r(\lambda, \theta) - P_{\text{me}}, \]

where \( p_r(\lambda, \theta) \) is the central pressure of the cyclone (located at longitude–latitude point \((\lambda, \theta)\)) and \( P_{\text{me}} \) is the climatological mean pressure at the location at the time of year when the cyclone is present. We accordingly present the mean Lagrangian time rate of change of relative central pressure in Fig. 5b. The distribution changes considerably when this more appropriate measure is used, and it can be seen that, on average, systems show a tendency to fill over most of the map, with the areas of deepening predominantly confined to lower latitudes. Regions over which systems deepen at the higher latitudes are restricted to an area south of Tasmania and to the east of the Drake Passage. Before closing we should mention that while tendencies of relative central pressure are more dynamically informative than those of central pressure, this diagnostic is not without shortcomings. If the intensity of the circumpolar trough is at least partly the result of so many intense cyclones located there, it is possible that the changes of relative central pressure overcorrect for the decrease in minimum pressure. That is, the correction could subtract not just the change in “background” pressure, but also some climatological measure of cy-
b. Origin of 500-hPa trajectories reaching the coast

An important component of forecasting in the Antarctic, particularly in coastal regions, is the production of reliable prognoses of precipitation likelihood and amount. For a wide range of reasons obtaining such prognoses is a challenging task (Turner et al. 1999). Recent research has started to quantify the synoptic origins of Antarctic precipitation (e.g., Turner et al. 1995, 1997) and the extent to which the nature of the vapor parcel trajectories from source regions to coastal Antarctica is closely tied to near-coastal precipitation characteristics (Marshall et al. 1998; Noone et al. 1999).

Given these considerations and the high level of synoptic activity around Antarctica, it is of value to compile information on the trajectories that (moist) air parcels take on their way to a particular point on the coast. There is obviously a wide variety of trajectories that particles take on a day-to-day basis and we have chosen, as a summary, to present all the origin points in the form of geographical frequency distributions. We confine ourselves to considering the origin points of all winter 4-day 500-hPa trajectories that terminate at two specific points on the coast. [Kottmeier and Fay (1998) have performed similar analyses for the Antarctic lower troposphere.] The trajectories are calculated for the parcels arriving at each 0000 UTC using the algorithm described by Perrin and Simmonds (1995). While three-dimensional trajectories (e.g., Noone and Simmonds 1999) would be more accurate, our present purpose is amply suited by diagnosing isobaric paths. Figure 6a shows the results of this compilation for the arrival point 67°S, 90°E (near Davis Sea), and the plot indicates the mean probability that a trajectory has commenced in the locality, where the values are normalized with respect to an area of 1000° latitude squared. It will be seen that the “center of gravity” of the origin points lies about 60° longitude to the west and 10° north of the terminus. It should be remarked that sizable frequencies are observed over a very broad region covering half the hemisphere. A small but significant number of these 500-hPa trajectories originate to the east of the reference point, while considerable numbers are seen as far away as to the north of the Weddell Sea, and into the midlatitudes of the Atlantic. A similar presentation for a coastal point on the opposite side of the continent (73°S, 90°W, near Ellsworth Land; Fig. 6b) shows, in relative terms (i.e., when the pattern is rotated 180°), overall similarities, but there are some interesting dif-
ferences. For this point on the edge of the Bellingshausen Sea far fewer trajectories are seen to start from the east, and the highest densities are found much farther west.

c. Surface wind structure and energy input to ocean waves

One of the consequences of the steep climatological pressure gradients and the presence of large numbers of cyclonic systems in the subantarctic region is a very active and variable wind regime. Prognosis of wind forms a very important part of the forecasting problem in the high southern latitudes, as this parameter affects shipping, aircraft movements, and activities at coastal bases, among other things. It also influences the rate at which mechanical energy is put into the ocean, which in turn manifests itself as waves and swell whose effect is found both locally and over a significant portion of the world’s oceans. Figure 7a presents the winter distribution of the mean “surface” (10 m) wind speed. Away from the Antarctic the greatest mean speeds are found in the Indian Ocean near 50°S, and an arc of speeds in excess of 12 m s\(^{-1}\) is spread across the Eastern Hemisphere, the axis of which is located farther south at its eastern end. This structure is broadly consistent with the mean geostrophic velocities implied by Fig. 1a and with the high density of cyclonic features in that hemisphere (Fig. 2a). The plot, while indicating the mean wind environment of the region, does not directly signify the rate at which energy is being put into the ocean to set up the wave spectrum. This rate is proportional to the cube of the wind speed, and it is the mean value of this parameter that is of interest here. The winter mean of this parameter is displayed in Fig. 7b. If the wind speeds were steady (i.e., had no temporal variations) this parameter could be obtained by taking the cube of the values displayed in Fig. 7a. However, given the presence of active cyclonic systems in the region, one would expect considerable nonlinearity. With this in mind it is perhaps a surprise that the structure of these two plots is very similar, and both exhibit a strong maximum in the Eastern Hemispheric arc. These displays serve to underline the central role that the mean winds and synoptic activity play in inserting massive amounts of energy into the Southern Ocean, particularly in the Indian and west Pacific sectors.

4. Variability and trends in Antarctic region synoptic behavior

There are many facets of variability and change that appear to be affecting the Antarctic region, and that have implications for the complex matrix of interactions between the sea ice, ocean, and atmosphere (e.g., Simmonds 1998; Thompson et al. 2000). Vacillations in synoptic activity appear to play a central role in these variations, and we explore some of these here. We first examine the interannual variability of winter cyclone density over our 21-yr period. Figure 8 indicates that the pattern of interannual variability resembles that of mean density (Fig. 2a), and assumes values between about one-quarter and one-third of the mean. A notable exception to this is found in the Bellingshausen Sea, along the western coast of the Antarctic Peninsula and
Fig. 7. (a) Mean 10-m wind speed and (b) mean cube of the 10-m wind speed from the NCEP-2 analyses for Jun–Aug 1979–99. The contour intervals are 1 m s\(^{-1}\) and 500 m\(^{3}\) s\(^{-3}\), respectively.

Fig. 8. Interannual variability (std dev) of mean winter cyclone density over 1979–99. The contour interval is 0.5 \(10^{-3}\) \(8 \text{ lat}^{-2}\).

into the western part of Drake Passage. High levels of interannual variability are identified here in regions of modest numbers of cyclones. It is becoming increasingly appreciated that this area is one exhibiting among the greatest MSLP and 500-hPa height variability over the Southern Hemisphere (e.g., King 1994; Connolley 1997; Simmonds and Murray 1999), and there is evidence to believe that at least a portion of this variability is linked to variations of the Southern Oscillation index (e.g., Karoly 1989; Sinclair et al. 1997; Marshall and King 1998; Kiladis and Mo 1998; Renwick and Revell 1999; Harangozo 2000; Kwok and Comiso 2002).

Earlier work has indicated that the Southern Hemisphere climate system has also been undergoing trends on top of various modes of variability [e.g., see the investigation of Sinclair et al. (1997) with the operational European Centre for Medium-Range Weather Forecasts (ECMWF) analyses]. SKb using 40 yr of the original NCEP reanalysis had identified trends in a number of synoptic quantities, and it is valuable to examine these using the improved NCEP-2 data considered over the period of improved data coverage. To set the scene against which the changes in synoptic behavior may be viewed, we first look at, in Fig. 9a, the linear trend that the annual average MSLP has displayed over the period. Most of the region south of 60\(^{\circ}\)S has displayed downward trends in mean pressure, and most of the trends around the coast and in the Drake Passage differ significantly (at the 95% confidence level) from zero. The trend pattern bears considerable resemblance to that obtained from the NCEP reanalyses for the 1979–93 period as displayed by Hines et al. (2000, their Fig. 5b). (It is also broadly similar to the ERA-15 trends shown by them for the same period, but there were a number of sizable differences.) It has been suggested by a number of authors (e.g., Hines et al. 2000) that the trends result in large part from a progressive weakening of the positive assimilation model pressure bias in the circumpolar trough as more data became available across the period. Hines et al. have shown that many coastal Antarctic stations have indeed exhibited pressure reductions over the last three decades, but these trends were much
Fig. 9. Slope of least squares best fit line to the annually average mean parameters over the period 1979–99. (a) MSLP (contour interval 0.5 hPa decade$^{-1}$), (b) system density [0.4 systems per 1000 (° lat)$^2$ decade$^{-1}$], (c) Laplacian of MSLP of the pressure field calculated around the center of the each cyclone [0.05 hPa (° lat)$^2$ decade$^{-1}$], (d) cyclone radius [0.1 (° lat) decade$^{-1}$], and (e) cyclone depth (0.5 ha decade$^{-1}$). Negative contours are dashed and the zero contour is highlighted. Regions over which the trends differ significantly (at the 95% confidence level) from zero are indicated by stippling.
smaller than those evident in the NCEP-2 reanalysis. Hence it may be concluded that a significant part of the trends displayed in Fig. 9a is an artifact of the reanalysis process. [See, also, Marshall and Harangozo (2000) for discussion on this issue.]

While fully cognizant of the problems that these artificial trends may cause for some climatological investigations, we believe they will not unduly influence the diagnosed trends and variability of cyclone behavior in the period since 1979. The trends in cyclone system density (Fig. 9b) are negative over most of the subantarctic region, and these trends can be seen to be significant over numerous areas including the region to the south of Australia and in a broad sweep from north of the Ross Sea around to the Bellingshausen Sea. By contrast, significant positive trends are observed in the Weddell Sea. This reversal of trend across the Antarctic Peninsula is reminiscent of the “Antarctic dipole” highlighted by Yuan and Martinson (2000, 2001). The trends in cyclone numbers in the arc centered on the Amundsen Sea are consistent with the changes in positioning of the Amundsen Sea low over much of this period (see, e.g., Cullather et al. 1996).

Figures 9c–e show the slope of the regression line fit to the annual averages of, respectively, mean cyclone intensity, radius, and depth. The mean intensity has increased significantly over many parts of the domain, particularly in the Atlantic, the east Pacific, and west Indian Oceans. The only notable exception to this is the significant reductions in the Bellingshausen–Amundsen Seas region. In many locations the mean radius of systems can be seen to have increased (Fig. 9d), and Fig. 9e indicates that a similar statement is true for the mean depth. Indeed, the spatial distribution of the trends in depth closely resembles that of intensity, except for a few regional features. These last include an absence of significant trend in depth over the Bellingshausen–Amundsen domain (one of the few regions over which cyclones have not become larger) and to the north of the arc from Oates Land to the Amery Ice Shelf.

We remark that the trends in these last three cyclone properties differ in many respects from those obtained over the 40-yr period with the NCEP reanalysis (Fig. 3 of SKb). To explore the reasons for the differences we have calculated the trends in these properties using the NCEP data only over the period 1979–97. The patterns obtained (not shown) are very similar to those exhibited above, indicating that the nature of the variability diagnosed since 1979 does not appear to depend greatly on which set of reanalyses have been used. This then leaves open the question as to whether the different trends identified over the four-decade period can be thought of as a true representation of change, or whether the mean intensity etc. of systems prior to 1979 is not accurately constrained. This complex question is being followed up independently, and we do not address it here. We remind the reader, however, that those involved in the generation of the reanalysis sets have recommended that trends for the period before and after 1979 be computed separately (e.g., Kistler et al. 2001).

We have seen that for the most part the cyclone density has decreased over the subantarctic region over the last two decades. A convenient summary of the variability and change can be obtained by compiling a time series of the mean annual cyclone counts per analysis in the latitude belt 50°–70°S. Figure 10 shows there was a maximum average of almost 16 cyclones per analysis in 1980, and the three lowest counts occurred in 1989, 1990, and 1991. Since that time the number of systems has increased modestly and shown little interannual variability through most of the 1990s. The variability shows great similarity (in the common period) with that derived from the NCEP analyses (Fig. 4c of SKb), except that there is a slightly smaller number of systems in the most recent reanalysis.

5. Meteorological “bombs” in the Antarctic region

The Antarctic region is one of very active, and not-infrequently intense, synoptic systems (e.g., Pendlebury and Reader 1993; Murphy and Simmonds 1993; Parish and Bromwich 1998; Dare and Budd 2001). It goes without saying that the skillful forecast of extreme weather conditions around the Antarctic coast are of vital importance for a wide range of reasons, not least of which is the safety and well-being of personnel at coastal bases.

A class of intense systems of particular concern is that of explosive cyclones. These system appear to develop from a combination of forcings associated with baroclinicity, surface fluxes, upper-level structure, etc. Their speed of development means that they are often poorly forecast and also poses considerable safety risks associated with sudden and perhaps unexpected deterioration of the weather. Over the last two decades explosive cyclones have received considerable attention from the research community. Tor Bergeron had initially defined a rapidly deepening extratropical cyclone as one
whose central pressure falls at least 24 hPa in 24 h. Modern research on this phenomenon can be thought of as starting with the work of Sanders and Gyakum (1980), who coined the term bomb for these features. They reasoned that the severity of a bomb may be related to the increase in its (geostrophic) wind speed. Accordingly, they modified Bergeron’s definition slightly by requiring that, what we shall call here the “normalized deepening rate” for central pressure ($NDR_c$),

$$NDR_c = \left( \left| \frac{\Delta p_c}{24 \ h} \right| \left( \frac{\sin 60}{\sin \theta} \right) \right)$$

exceeds unity. [Here, $\Delta p_c$ denotes the cyclone central pressure change (in hPa) over 24 h.] Hence at 60° latitude a system must deepen by at least 24 hPa in 24 h to be classed as a bomb (same definition as Bergeron), whereas at 50°, for example, the drop need only exceed 21.2 hPa.

Virtually all the research undertaken on bombs has been focused on the Northern Hemisphere (NH). There they have been found to be predominantly a maritime and cold-season phenomenon, and for the most part are associated with strong land–sea contrasts (e.g., Sanders and Gyakum 1980; Roebber 1984; Chen et al. 1992). The mid- and high latitudes in the SH do not experience these contrasts to the same extent, but are known to be regions of high baroclinicity (e.g., Berbery and Vera 1996; Walsh et al. 2000). Given the difficulty in predicting the development of these features, it is of importance to establish their frequency and behavior in the Antarctic region.

Sinclair (1995) and others have pointed out problems in using this criterion to identify explosive cyclone development in the SH. He referred to SH systems that exhibited deepening rates of greater than 1 bergeron but that showed little or no increase in cyclonic vorticity, and he commented that, “falling pressure is all too often an artifact of moving rapidly toward an area of climatologically lower pressure.” With this point in mind, as discussed in detail by Lim and Simmonds (2002), we can further refine the criterion for bombs by taking into account the spatial variation of the climatological pressure in which these features are embedded. For the reasons discussed above changes in the relative central pressure $\Delta p_r$, may be seen as a more useful indicator of rapid development than central pressure, as it removes the effect of central pressure falls due to the effect of migration across the climatological mean sea level pressure pattern. Hence we may also speak of a system as being a bomb if the normalized deepening rate based on the 24-h change in the relative central pressure ($NDR_r$) exceeds unity. Analogous to above, this measure is defined as

$$NDR_r = \left( \left| \frac{\Delta p_r}{24 \ h} \right| \left( \frac{\sin 60}{\sin \theta} \right) \right)$$

We have filtered our cyclone database to extract only those subantarctic cyclones for which the NDR exceeds unity. (The search is only conducted for all 24-h periods from 0000 UTC.) Figure 11a shows the tracks of all winter bombs identified over our record when the NDR, measure is used. It can be seen that there is a significant number of bombs over the region, particularly in the Atlantic and Indian Oceans. The overall structure of the tracks differs in many respects from that exhibited by...
all cyclones taken together (e.g., Jones and Simmonds 1993). The bomb track density is highest to the north of 60°S, while those of all cyclones are most dense well south of this latitude. In addition, most bomb tracks are directed toward the southeast, while all other systems show a much more modest southward motion.

When one uses the criterion based on the NDR, measure (to discount the effect of changes in climatological pressure along the track) a rather different picture emerges (Fig. 11b) and far fewer systems are diagnosed. (We remind the reader of the discussion on the Lagrangian rates of change of relative central pressure in section 3, and comment that with our new criterion the number of bombs could be underestimated.) There is also much less longitudinal asymmetry in track density, although there is a suggestion of more frequent bomb activity to the south of Australia. Another marked difference is that the bombs defined in terms of relative central pressure show a predominant eastward motion, rather than to the southeast mentioned above. In fact a number of systems in the eastern Indian Ocean, to the south of Australia, and to the south of the Tasman Sea, exhibit a marked northward component to their translation. These behaviors in this sector show strong similarities to the tracks of polar lows identified by Carleton and Song (1997).

As a summary of the bomb counts, we present in Table 1 the mean counts per season of bombs that halfway through their 24-h life found themselves in the 40°–70°S latitude belt. It will be seen that when the NDR criterion is used, winter is the most populous season, with the two intermediate seasons not falling far behind. In the summer the numbers are about 40% of those in the other three seasons, but still represent a bomb in the belt every 7 days. When change in relative pressure is used for identification, the numbers are considerably smaller. It will also be seen that a more well-defined maximum occurs in winter, but the ratio of winter to summer bomb numbers stays about the same. With this criterion on average a winter bomb is found over the domain every 4 days. Overall we can see that bombs are not an uncommon occurrence in the subantarctic region, and occur all year round, a finding consistent with the presence of strong westerlies over the Southern Ocean throughout the entire year. The modest bomb seasonality is in marked contrast with the NH case for which there is a very strong winter peak and virtually no bombs in summer.

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6. Concluding remarks

In this paper we have explored a number of aspects of synoptic behavior in the Antarctic region. This has been undertaken with the recently released NCEP–DOE Reanalysis-2 dataset covering the period of January 1979–February 2000. The results have been obtained by applying sophisticated feature tracking and trajectory analysis software to the 6-hourly analyses.

One of the ways in which we have characterized synoptic activity is in terms of the “system density” of cyclones. In comparing our results with those of studies undertaken with less reliable analyses and in interpreting our findings, it is important to bear in mind that various studies use different measures of this aspect. One common method of presenting information on cyclone activity is to express it in terms of how many cyclone tracks pass within a specified distance of a given point. Our method of compiling cyclone density [as in the original approach taken by Petterssen (1956), Klein (1957), and many modern studies] counts the presence of a cyclone at each analysis time and, hence, a given track may give rise to multiple counts. Track density and system density are both very useful parameters that provide different information, and in this paper we chose to display the system density, as we believe it conveys information that is of more use. This measure reflects the proportion of the time for which a given location is under the influence of cyclonic conditions [see also Reitan (1974) for a brief discussion on this point].

The climatological mean system density of mean sea level lows derived from this advanced analysis set shows its greatest values in the Indian Ocean and to the south of Australia near, or to the south of, 60°S. The density of cyclones in winter exceeds that in summer almost everywhere over the region, although a few parts, such as the Bellingshausen Sea, represent exceptions to this. These new results also confirm that the Antarctic coast region is one of significant cyclogenetic activity all year round, as is that in the northern part of the Antarctic Peninsula and over and to the north of Drake Passage. A winter genesis domain is also found in the Indian Ocean midlatitudes. Cyclolysis is overwhelmingly confined to the near-coastal region and shows only modest levels of zonal asymmetry. There is a net genesis of cyclones over most regions north of 50°S, and predominantly net lysis to the south of this latitude.

Our Lagrangian approach to studying synoptic behavior allows us to diagnose many cyclone parameters, including mean intensity, radius, and depth. In general these parameters assume their largest magnitudes near the 60°S latitude circle, with local minima near the Drake Passage. For two of these measures of system influence larger values are found in winter. By way of exception it is found that, on average, the summer cyclones are larger than those in winter over most of the subantarctic, particularly upstream of Drake Passage. Simmonds (2000) has shown (using NCEP data) that,
on average, SH cyclonic systems when first identified in the analyses have similar radii in summer and winter, but that the subsequent increase in scale is much more rapid for summer systems. The behavior is consistent with the data presented here.

In accord with the remarks of Sinclair (1995, 1997) our work has cautioned against interpreting Lagrangian time rates of change of cyclone central pressure as an index of intensification. Cyclones drifting south in the environment of the strong subantarctic meridional pressure gradients can show considerable central pressure decrease even in the absence of any actual development. We have seen that to the north of 60°S the average central pressure of systems decreases, while increasing to the south of this latitude. When allowance is made for the spatial variation of climatological MSLP, the mean "corrected" central pressure of cyclones is seen to increase along the cyclone track for most systems found south of 45°S.

The nature of "weather" experienced at coastal stations in the subantarctic region is significantly influenced by the synoptic situation and, specifically, the domains of origin of the air masses. We have determined the frequency distribution of the origin points of the 4-day 500-hPa winter trajectories that reach the Antarctic coast at 90°E and 90°W. The results reveal a very wide dispersion of source points, indicative of the high level of synoptic variability in the broad domain around these regions. Sizable numbers of starting points are found in a 180° longitudinal belt around the hemisphere and the center of gravity of these is located some 60° longitude to the west of the 90°E point, and about 120° west of the point on the southern side of the Bellingshausen Sea. A not inconsiderable number of trajectories for both cases commence their journey from points east of their terminus. The results obtained are consistent with the analysis of Turner et al. (1995) who found that about half of the cyclones that gave precipitation on the western side of the Antarctic Peninsula were found to have developed south of 60°S.

In our study of the synoptic characteristics of the Antarctic region and their consequences we have used the NCEP-2 10-m winds to diagnose the mean rate at which energy can be extracted from the atmosphere. This rate determines the character of the "fully developed sea," and the nature of waves and swell that originate from that area. We have shown that in winter the mechanical energy transfer into the ocean is maximum near 50°S in the Indian Ocean and extends in an arc across the Eastern Hemisphere and is the main source region for Southern Ocean swell.

One particular focus in our work was to determine the degree to which the synoptic parameters have exhibited trends and variability over the 21-yr period. The annually averaged cyclone density in this dataset has been found to exhibit downward trends over most of the subantarctic region. The annually averaged number of cyclones found in the 50°–70°S latitude band was found to decrease from about 16 in 1980, to less that 15 in the 1990s. In their annual mean, cyclone intensity, radius, and depth have all shown significant upward trends. Hence, while the number of cyclones has decreased, their mean activity has increased.

We finally briefly explored with this state-of-the-art dataset some of the characteristics of rapidly developing cyclones (or "bombs"). Very little research has been conducted on SH bombs, but there is much anecdotal evidence to indicate that these are not uncommon, and hence play an important part in Antarctic region synoptics. Using the conventional (i.e., NH) criterion for bomb identification we have found, on average, 93 bombs per year in the 40°–70°S latitude belt, or about one every 4 days. We have argued that applying this criterion in the SH leads to misleading conclusions because of the very strong climatological pressure gradients there. When allowance is made for these, the number of bombs decreases considerably, but our analysis still identifies a bomb every 12 days in winter. While we have found more bombs in winter than the other seasons, the seasonality of these features is nowhere near as marked as for their NH counterparts.

Acknowledgments. The authors are very grateful to NCEP for providing the Reanalysis-2 data in the public domain and, in particular, to Masao Kanamitsu for his help and cooperation in downloading the set. The paper benefited greatly from two anonymous reviews. Components of this work have been made possible by an Australian Antarctic Science grant and funding from the Australian Research Council.

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