Explosive Cyclone Development in the Southern Hemisphere and a Comparison with Northern Hemisphere Events

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ABSTRACT

A compilation of Southern Hemisphere (SH) explosively developing cyclones (or ''bombs'') has been assembled based on the National Centers for Environmental Prediction–Department of Energy reanalysis-2 data over the 21-yr period from 1979 to 1999. The identification of these features was undertaken with an objective automated cyclone finding and tracking scheme. The procedure allows for the confounding influence of spatial variations of climatological mean pressure on the pressure deepening of explosive cyclones, a perspective of particular importance in the SH.

On average, 26 explosive cyclones occur per year in the SH. They are more prevalent in winter although their seasonality is more modest than that seen in the Northern Hemisphere (NH). The distribution of SH explosive cyclones has a close association with that of strong baroclinicity, although the relationship is not one to one. It is found that many of these cyclones occurring south of 50°S show equatorward movement, in contrast with the poleward motion of most NH bombs. The explosive cyclones exhibit greater mean intensity and depth than does the entire population of cyclonic systems.

Aspects of NH explosive cyclones revealed in the reanalysis-2 set are briefly examined, with a view to comparing them with the details revealed about SH events. The authors' analysis detects, on average, 45 explosive cyclones per year in that hemisphere. It is found that over the last 21 yr the number of these systems has increased globally and in both hemispheres, and that positive trends of global and SH systems are statistically significant.

1. Introduction

Over the last two decades explosive cyclones have received considerable attention from the research community. The characteristic features of these systems, also known as meteorological ''bombs,'' are rapid central pressure reduction and an attendant increase in intensity. Such characteristics are associated with difficulty of prediction and also with serious threats to human life and property when these cyclones occur off coastal regions, or in shipping lanes. According to the landmark study of Sanders and Gyakum (1980), bomb events are predominantly maritime and cold-season phenomena. Moreover, in the Northern Hemisphere (NH) it has been observed that the maximum frequency of bombs occurs in the westernmost portions of both the Atlantic and Pacific Oceans within, or just north of, the warm currents of the Gulf Stream and the Kuroshio, respectively (Sanders and Gyakum 1980; Roebber 1984; Chen et al. 1992). This geographical distribution suggests that baroclinicity and (weak) static stability are important factors in initiating explosive development.

Having said this, a broad range of other factors are frequently and interactively associated with these developments. In particular, the relative placement of a 500-hPa trough and thickness patterns has been seen to be implicated with development (Sanders and Gyakum 1980; Sanders 1986; Sanders and Davis 1988; Gyakum and Danielson 2000), as have deep tropospheric frontogenetic processes occurring both upstream and downstream of the surface low (e.g., Bullock and Gyakum 1993). As well, many studies have identified the influence of air–sea interaction (Emanuel and Rotunno 1989), and latent heat release (Kuo et al. 1995; Revell and Ridley 1995). It is apparent, then, that subsets of these thermodynamic and dynamic mechanisms are woven together in complicated and nonlinear ways to induce explosive cyclones (e.g., Kuo and Low-Nam 1990; Bluestein 1993). An excellent recent summary of our current understanding of these matters is presented by Bosart (1999).

The preceding two-decade period has seen much research directed to exploring the mechanisms that trigger rapid pressure reduction and to documenting some of the mean characteristics of NH explosive cyclones. By

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contrast, there have been only a few studies of Southern Hemisphere (SH) bombs. Of these, the works of Sinclair (1995, 1997) are of especial note. In the first of these papers he presented a compilation of rapidly developing cyclones using 7 yr (1980–86) of operational European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. He also discussed the appropriate definition of these features, and the particular challenges that the SH presents in determining appropriate criteria. While ''climatological'' studies of SH explosive systems have been very few, there are a number of well-documented specific episodes, the severity of many of which impacted on human life and welfare. For instance, the New South Wales region in Australia has over the years suffered serious damage from these kinds of cyclones, known as Australian east coast type-2 cyclones (Holland et al. 1987; Leslie and Speer 1998). A notorious case of explosive development in eastern Australia, the Sydney–Hobart yacht race cyclone (26–27 December, 1998) (Buckley and Leslie 2000), resulted in the death of six race participants. Seluchi and Saulo (1998) pointed out that explosive cyclones accompanied by significant rainfall often cause floods in heavily populated areas in Argentina.

The major aim of this study is to reveal the overall features of SH bombs such as frequency, scale, and intensity. We also wish to contribute to the goal to determine indices of explosive development that make no assumptions about the climatological structure or hemisphere in which they are found. In this sense we follow on from Sinclair (1995, 1997) who raised concerns about deducing cyclogenesis from pressure deepening rates. Furthermore, it will be useful to compare SH bomb behavior with the more familiar NH counterpart, and in the process we will briefly present a new climatology of NH bombs. Another aim of the present work is to explore the extent to which the number of global and hemispheric explosive cyclones identified in the analyses have changed over the period under examination.

2. Dataset and cyclone identification system

The set of mean sea level pressure analyses we use in this work is the National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) reanalysis-2 set. Full details of the set and its production are provided by Kanamitsu et al. (2000, 2002) and Kistler et al. (2001). A wide variety of data were used in the reanalysis including that from the global rawinsonde network, Comprehensive Ocean–Atmosphere Data Set (COADS) surface marine record, aircraft, surface land synoptic observations, satellite sounders, Special Sensor Microwave Imager (SSM/I) winds, and satellite cloud drift winds. The system also uses complex quality control mechanisms and automatic monitoring of reanalysis output. This analysis set is an update of the original NCEP reanalysis (Kalnay et al. 1996), which is now known to be subject to a number of errors. The papers cited itemize the many ''fixes'' that were made to the analysis system. One of the potentially most important of these for analyses over the SH was the elimination of the Australian PAOBS problem. (This error had arisen when estimates of sea level pressure produced by Australian analysts using satellite data were inserted into the analysis cycles but with a longitudinal shift of 180° from their correct position.) The period of the dataset we use here is 1 January 1979 to 31 December 1999, and the analyses are available every 6 h on a $2\frac{1}{2}° \times 2\frac{1}{2}°$ latitude–longitude grid. The year 1979 corresponded 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.

Before we proceed a few words are warranted as to the reliability of the reanalysis-2 dataset over the SH oceans of principal concern here. Many of the observational platforms itemized above are very sparse over the SH, and satellite data form a very valuable input to the system there. Kanamitsu et al. (1997) and Kistler et al. (2001) demonstrate the dramatic impact that satellite data make on the quality of the reanalyses in that hemisphere. While it is very difficult to specify with confidence what the relative contributions to the reanalysis of observations are versus model-derived information, the reasonable SH forecast anomaly scores over the period considered here (Fig. 7 of Kistler et al. 2001) are a source of comfort. The reanalyses represent one of our best estimates of the three-dimensional structure of the SH atmosphere and we believe our compilation to represent faithfully the major characteristics of explosive cyclones over that hemisphere. We agree with the spirit of comments of Sinclair (1995) (and many others) 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.'' Having said this, the reanalysis concept is an ongoing process, which at appropriate intervals will make use of major improvements in the modeling of the global operational system and of the contents of quality controlled, comprehensive observational databases (Kistler et al. 2001).

The identification and tracking of cyclones from these reanalyses was undertaken with the Melbourne University scheme, described in detail by Simmonds et al. (1999) and Simmonds and Murray (1999). Briefly stated, the first step is to transform the latitude–longitude data by bicubic spline interpolation to a polar stereographic array (whose resolution is 0.955° and 1.91° of latitude at the equator and pole, respectively) 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. The finding routine begins by searching for local maxima in the Laplacian of the pressure compared to those 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, the point of inflection in the field being 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 numerical algorithm also determines the ''effective radius'' and ''depth'' of systems, as discussed below. 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).

3. ''Explosive development'' criteria

The magnitude of explosive cyclone development can be expressed, following the criterion of Sanders and Gyakum (1980), in terms of what we refer to here as the normalized central pressure deepening rate (NDR_c). This is defined as

$$\mathrm{NDR}_c = \frac{\Delta p_c}{24\ \mathrm{hPa}} \frac{\sin 60}{|\sin\phi|}, \qquad (1)$$

where Δp_c is the central pressure change of a system over 24 h and ϕ is latitude. When this measure exceeds unity the system is deemed to be an explosive developer or ''bomb'' in the sense of Sanders and Gyakum (1980) (and $\mathrm{NDR}_c = 1$ is equivalent to 1 ''bergeron'' in their terminology).

Much of the research on explosive cyclones has been undertaken with threshold criteria based on the value of NDR_c. This approach has drawbacks in that, of itself, cyclone central pressure (and its rate of change) may have limited physical meaning and may not diagnose a great deal about a cyclone. For example, a low of central pressure 980 hPa would be regarded as quite an intense system in the subtropics, whereas a low in the subantarctic region with this central pressure would be regarded as very weak. Simmonds and Wu (1993) and Sinclair (1995, 1997) have discussed how the dynamic meaning of the central pressure of systems can be more fruitfully seen relative to the background of climatological mean sea level pressure. Sinclair (1995) cites examples of SH systems that exhibited deepening rates of greater than 1 bergeron, but little or no increase in cyclonic vorticity. Sinclair commented that, ''falling pressure is all too often an artifact of moving rapidly toward an area of climatologically lower pressure.'' In accord with these considerations, we introduce another, but related, definition of explosive cyclones that takes into account spatial changes of background (or climatological) pressure along the cyclone path. The Southern Ocean is host to strong meridional climatological pressure gradients throughout the year. Many SH cyclones develop in the midlatitudes and migrate to the southeast (Jones and Simmonds 1993; Simmonds and Keay 2000a) and hence move into regions of lower climatological pressure. In such an environment, even if the vorticity was undergoing no change (i.e., the system was undergoing no intensification), the central pressure of the cyclone would decrease. Hence using a criterion based purely on central pressure to identify explosive development can erroneously identify such systems. This source of error is particularly significant in the SH for the reasons cited above, and it is important that it be allowed for. In this context it is useful to define ''relative'' central pressure (see, e.g., Simmonds and Wu (1993) as the difference between the central pressure of a cyclone and the climatological pressure at the cyclone location at that time of year. Changes in this *relative* central pressure (Δp_r) can then be seen to be a more useful indicator of rapid development than central pressure. [Carnell et al. (1996) have also commented on the dangers of diagnosing the behavior of cyclones (particularly strong ones) in terms of central pressure (and its changes) and have found the use of ''central pressure minus the average pressure over the region'' to be more reliable and physically consistent.] It allows one to take out the effect of central pressure falls due to the effect of migration across the climatological mean sea level pressure pattern. To exemplify the concept, we can take the case of a system of 1000-hPa central pressure located in a region of the South Pacific where the climatological mean pressure is 1015 hPa. The relative central pressure of this feature is hence −15 hPa. Suppose the central pressure of the system decreases to 990 hPa as it moves to a location where the climatological pressure is 1005 hPa. In this simple example, even though the central pressure has decreased by 10 hPa the relative central pressure has remained unaltered. That is, the central pressure of the system has decreased because it has moved into an environment of lower background pressure, rather than being the result of intensification.

From these considerations, we can also categorize a system to be an explosive developer if its *relative* central pressure normalized deepening rate (NDR_r) exceeds unity. By analogy with NDR_c, NDR_r is defined as

$$\mathrm{NDR}_r = \frac{\Delta p_r}{24\ \mathrm{hPa}} \frac{\sin 60}{|\sin\phi|}, \qquad (2)$$

where Δp_r is the relative central pressure change of a system over 24 h.

In this paper we consider the 24-h periods of pressure deepening to all start at 0000 UTC. (This constraint avoids the possibility of double counting. For suppose

TABLE 1. Mean number of explosive cyclones per year by season and hemisphere.

	DJF	MAM	JJA	SON	Annual
SH	3.0	6.5	10.7	6.2	26.4
NH	26.4	9.2	0.5	9.7	45.9
Global	29.5	15.7	11.2	15.9	72.3

a system deepened dramatically between 0600 and 1800 UTC on a given day. Then the 24-h sectors of the cyclone starting at 0000 and 0600 UTC could both be classified as bombs.) We select bombs that start their rapid pressure reduction poleward of 25° latitude. Lim and Simmonds (2001) show that one diagnoses many more explosive cyclones in the SH when the NDR_c criterion is used. This is not surprising in view of the discussion presented above, and one is left to conclude from their results that many systems that achieve $\mathrm{NDR}_c \geq 1.0$ cannot be said to be genuine ''explosive developers.'' Unless otherwise stated, our explosive cyclones are identified with the NDR_r criterion.

4. Mean number of explosive cyclones per year

Table 1 shows that about 72 explosive deepeners occur over the globe every year, and about twice as many bombs appear in the NH as in the SH. Bombs are obviously predominant in winter in both hemispheres. However, the degree of seasonality is much less in the SH. We can see that the NH winter has over twice as many explosive systems as the SH winter. The smaller number of bombs in the SH is likely to be associated with the proportion and distribution of landmass and ocean in the SH. Revell and Ridley (1995) pointed out that because much of the SH landmass (except for Antarctica) is located in the subtropical region, it is not as capable of producing remarkable land–sea temperature contrasts as occur off the east coasts of the more polar continents of the NH during winter. Conversely, summer explosive cyclones in the SH are six times more numerous than those in the NH. In the intermediate seasons the count is somewhat higher in the NH. The more modest difference of SH bomb numbers in winter and intermediate seasons is probably influenced by the semiannual oscillation, which is a ubiquitous feature of the atmosphere over the Southern Ocean characterized by strong meridional temperature gradients in the midtroposphere and the development of deep climatological pressure and vigorous cyclonic activity in March and October (van Loon 1967; Carleton and Song 1997; Simmonds and Jones 1998). In the NH case most investigations have been restricted to the warm season [May–August (or September)] and cold season [September (or October)–April]. Along with Gulev et al. (2001) and others we believe it is important to avoid mixing cyclonic features of the autumn and winter seasons, and hence we retain a perspective of the four ''3-month'' seasons.

5. SH bomb characteristics

a. Bomb system density

Figure 1 shows the seasonal distributions of bomb tracks (plotted with 6-h segments over the 24 h of explosive development) compiled for the 21 yr of record. [The dashed lines in the plots indicate the seasonal mean sea ice edge taken from the Jacka dataset (see Simmonds and Jacka 1995) for the period 1973–96.] One sees a significant number of explosive developments to the east of Uruguay at all times of the year. In winter particularly, many explosive cyclones are found in a band extending from this region across the Atlantic and Indian Oceans, and particularly to the south of Australia and the Tasman Sea. This belt may be traced, though with somewhat fewer systems, across the Pacific as far as the Drake Passage. A high frequency of tracks is also seen in a broad band centered on 30°S in the Pacific Ocean. The distribution of bomb tracks has some similarity to that of the entire cyclone population in that both show spiral bands stretching from South America and Australia (Jones and Simmonds 1993). However, explosive cyclone tracks are observed across mid- and high latitudes, whereas the tracks of the entire cyclone population are very dense near the circumpolar trough (Jones and Simmonds 1993; Simmonds and Keay 2000a).

A striking feature in Fig. 1 is that a number of bomb tracks demonstrate a northward component to their motion. A northeast movement of bombs is observed clearly in the main spiral band, and the behavior is in stark contrast to the motion of all other cyclonic systems that, for the most part, have a strong southeastward component (Jones and Simmonds 1993). In general, bombs in lower latitudes move east-southeast, while those moving northeast are mostly found to the south of 50°S. Consequently, the 40°–50°S latitude band is a confluent region for bombs and a favored place for the deepest stage of rapid pressure reduction in all seasons. Equatorward movement has been found among mesoscale cyclones. Carleton and Fitch (1993) observed a number of mesocyclones moving northward in Antarctic and subantarctic latitudes in winter and associated it with the Antarctic sea ice expansion and katabatic outflow. It will be noticed that most of these bombs tend to avoid the sea ice covered regions, and we remark that the sea ice edge shows considerable interannual variability (e.g., Simmonds and Jacka 1995). Carleton and Fitch remark that the v component of the geostrophic wind is dominantly northward in the longitudes of high mesocyclone frequencies. These rapid developments in the cold air sector are frequently able to be resolved in synoptic analyses. For example, Turner and Thomas (1994) found that a proportion of these vortices were correctly represented on the Met Office analyses of the time. (These authors also explored the relationship between Antarctic regional mesoscale vortex activity and the broad-scale synoptic flow, sea ice, and geographical location.) Hence, the findings cited here bear on the

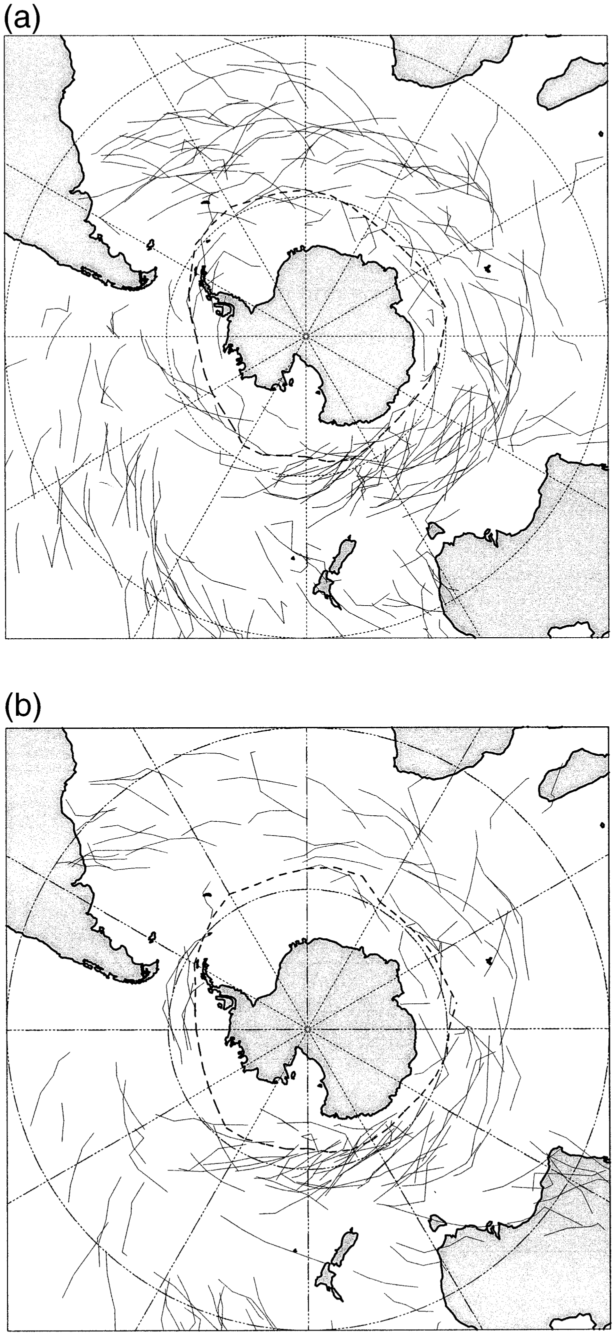

FIG. 1. Tracks of SH explosive cyclones (plotted with 6-h segments over the 24 h of explosive development) in (a) Dec–Feb (DJF), (b) Mar–May (MAM), (c) Jun–Aug (JJA), and (d) Sep–Nov (SON) over 1979–99. (The direction of motion, for all but an insignificant number of systems, is to the east.) The dashed lines in the plots indicate the seasonal mean sea ice edge.

sense of meridional motion of high-latitude explosive cyclones we have identified.

To obtain a more comprehensive understanding of these northward moving systems we have conducted an analysis of many of those appearing in winter. By way of illustration we shall present one of these here. The mean sea level pattern at 0000 UTC on 14 June 1999 is presented in Fig. 2a. Our cyclone algorithm identifies the (open) depression near 55°S, 10°E (indicated in the plot) with a central pressure of 993 hPa as the genesis of a bomb. Twelve hours later it has moved north and its pressure has decreased (Fig. 2b). The map at 0000 UTC on 15 June shown in Fig. 2c indicates the system moved farther north and attained a central pressure of 975 hPa, a 24-h decrease of about 18 hPa (giving a value for NDR_r of 1.08). In light of the discussion above

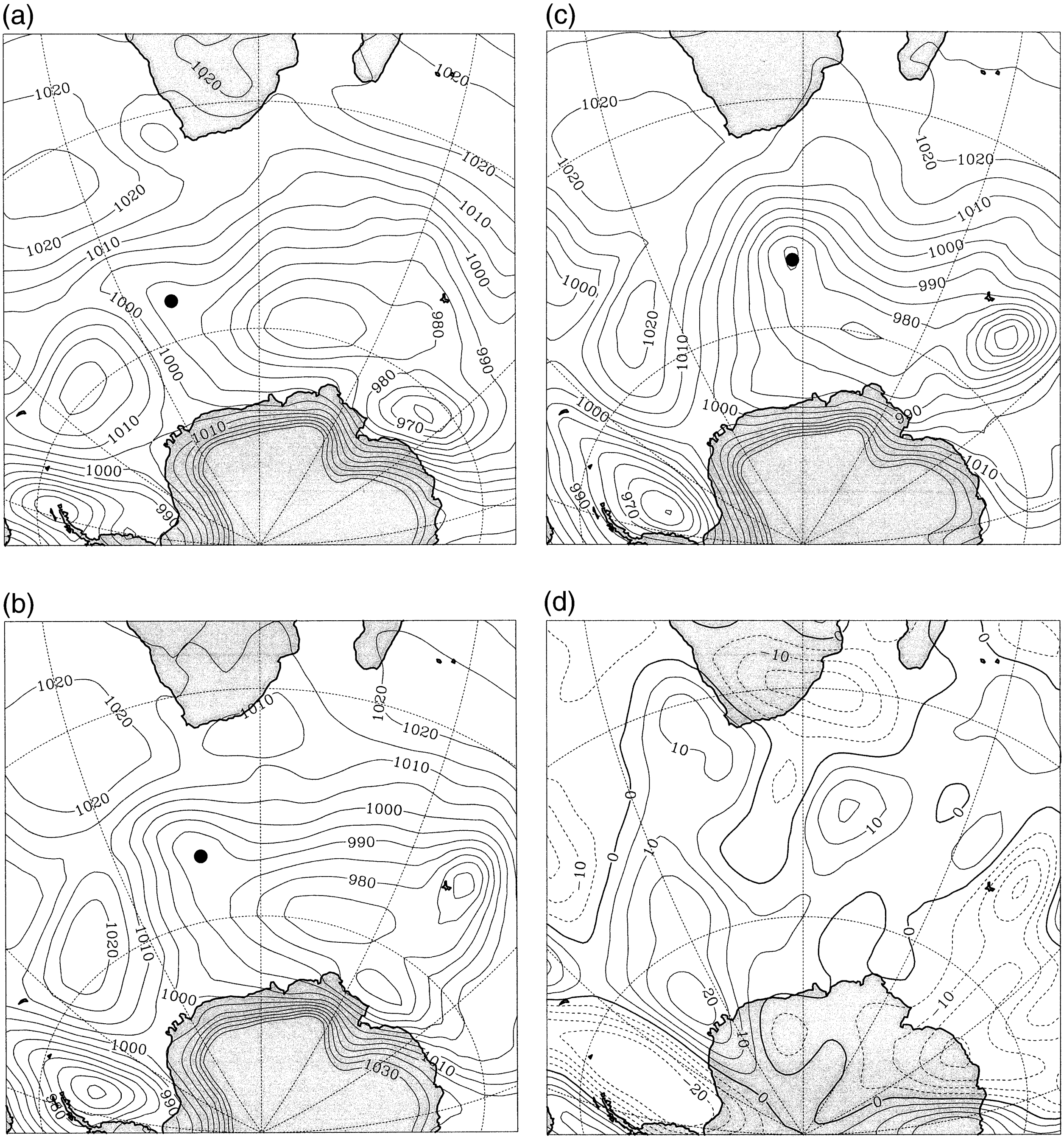

FIG. 2. Surface synoptic maps showing the evolution of a rapid developer from the time of its first identification at (a) 0000 UTC 14 Jun 1999 (near 55°S, 10°E, indicated in plot) (b) 1200 UTC 14 Jun, and (c) 0000 UTC 15 Jun. (d) The 500-hPa meridional wind component is displayed at 1200 UTC 14 Jun (halfway thorough the life of the bomb). The contour interval is 5 hPa in (a)–(c) (values greater than 1030 hPa are not contoured) and 5 m s^{-1} in (d).

it is clear that this rapid development has taken place in the cold air sector to the west of the main cyclonic center. It will be noted that throughout the process the main center experiences little change in central pressure. The upper-level flow associated with this development can be most conveniently represented by the 500-hPa meridional wind component, and we restrict ourselves to displaying this at halfway thorough the life of the bomb (i.e., at 1200 UTC on 14 June) in Fig. 2d. Strong southerlies are apparent over the region over which the development took place, and there is clearly a strong Antarctic connection. The evolution presented here is typical of many of the explosive developments at these high southern latitudes.

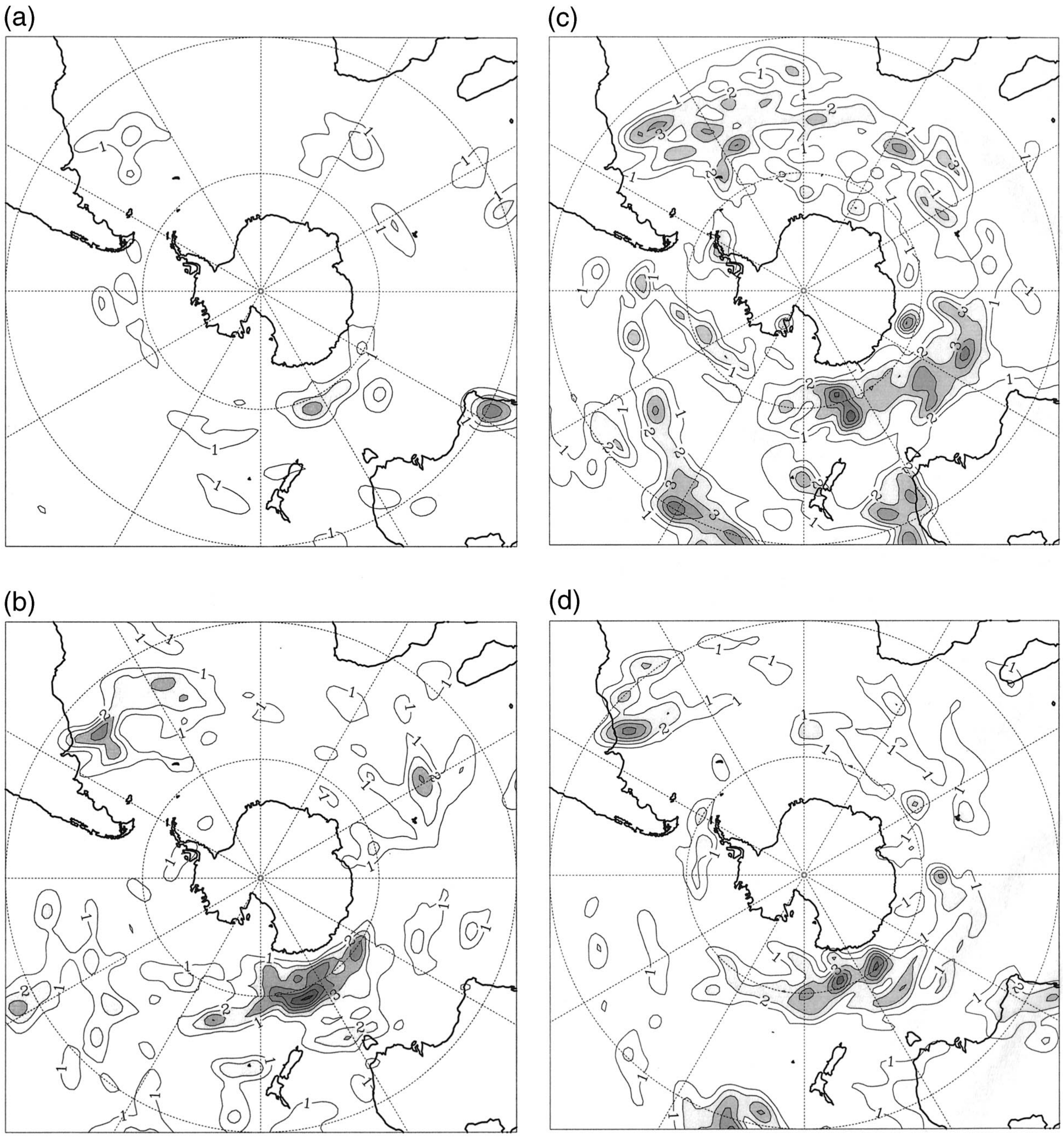

FIG. 3. Mean SH explosive cyclone system density in (a) DJF, (b) MAM, (c) JJA, and (d) SON. The contour interval is 1×10^{-5} explosive cyclones (° lat)$^{-2}$.

As both Table 1 and Fig. 1a show, the number of summer bombs is modest, but they are far from rare. The maximum density of summer bombs is found in western Australia (Fig. 3a). Northwest Australia is a region of high tropical cyclone frequency (e.g., Holland 1984). The continental bombs identified here might be interpreted as the extratropical transition of tropical cyclones in that region. Foley and Hanstrum (1994) found that tropical cyclones in this vicinity can get ''captured'' by prefrontal westerlies as they move southward and these systems experience considerable acceleration. They also experience significant central pressure decreases as they rapidly get caught up in vigorous midlatitude troughs. The general structure of the tracks of such captured systems (Fig. 6b of Foley and Hanstrum 1994) bear considerable resemblance to those displayed in Fig. 1a. Harr and Elsberry (2000) have shown that a number of (North Pacific) recurving tropical cyclones evolve into a fast moving and rapidly developing extratropical cyclones accompanied by gale, or even tropical cyclone force, winds. In autumn, the number of bombs starts to increase considerably. Most explosive cyclones are located broadly in the midlatitudes, but the maximum density is found in the Southern Ocean between 120° and 150°E around 60°S and to the east of Uruguay (Fig. 3b). In winter, the bomb distribution bands aforementioned fully develop (Fig. 3c). The maximum densities in excess of 3.0×10^{-5} bombs $(°\mathrm{lat})^{-2}$ are found in the sector of 45°–60°S, 90°E–180° to the south of Australia and in the western Pacific Ocean near 30°S. Coastal southeastern Australia and the Tasman Sea also host many explosive developments, among which are the east coast low type-2 features. As the seasonal cycle moves to spring, the number of explosive cyclones decreases sharply (Fig. 3d) and the number of the western Australian bombs starts to increase again. The bombs occurring to the east of Uruguay are more dominant in the intermediate seasons than winter.

To obtain an estimate of the role that mean baroclinicity may be playing in determining the mean structure of explosive cyclone frequency in the SH circulation, we can compare their distribution to that of the mean Eady growth rate defined as

$$\sigma = \frac{0.31f}{N}\left|\frac{\partial V}{\partial z}\right|,$$

where f is the Coriolis parameter, $\partial V/\partial z$ the vertical shear of the zonal wind, and N the Brunt–Väisälä frequency. Berbery and Vera (1996) showed a winter distribution of Eady growth rates (for the 850–700-hPa layer) (their Fig. 1b) very similar to that of our bomb system density in that season. Hence baroclinicity plays an important role in SH explosive cyclone occurrence as in the NH, even though there is less land–sea contrast in the SH. Moreover, SH baroclinicity seems to be less affected by the seasonal cycle in that summer bombs also develop along the spiral band of high baroclinicity.

In addition to baroclinicity, the model experiments of Revell and Ridley (1995) and Seluchi and Saulo (1998) suggest that latent heat flux also plays an important role in generating bombs in the Tasman Sea and off the east coast of Uruguay, respectively. Moreover, Coughlan (1983) and Holland et al. (1987) found that the eastern sides of SH continents are host to troughs or waves in the subtropical easterly flow (known to Australian synopticians as ''easterly dips'') that affect the development of intense cyclones, particularly in late winter and early spring. Therefore, explosive systems found to the east of Uruguay and southeast Australia and in the Tasman Sea are likely to develop in such an easterly dip environment.

Strong katabatic outflow from East Antarctica (Bromwich 1991; Carleton 1992; Bromwich and Parish 1998) and great baroclinicity on the periphery of Antarctica (Berbery and Vera 1996) have been regarded as causative mechanisms for mesocyclones occurring in the Australasian sector (70°–210°E, Carleton and Song 1997). Our results show that the Australasian sector centered on 60°S is also a region of frequent explosive development. Hence, the causative mechanisms of bombs and mesocyclones found in this region may have common features.

Before we go on to discuss other important mean features of explosive cyclones that have not been considered elsewhere, we compare our frequency distributions with those obtained by Sinclair. He assessed the distributions of explosive development under a number of different criteria. When he used the (traditional) NDR_c criterion he obtained a distribution (Fig. 12a in Sinclair 1995) that bears little relationship to our Fig. 3c. Sinclair commented that his distribution showed ''little tendency to cluster near eastern seaboards or near climatological positions of jet streams and SST gradients.'' Conversely, when he considered explosive development to have occurred when system geostrophic cyclonic vorticity increased in 24 h by more than $4 \times 10^{-5}\ \mathrm{s}^{-1}$ (Fig. 11e of Sinclair 1997) or $7.8 \times 10^{-5}\ \mathrm{s}^{-1}$ (Fig. 12b of Sinclair 1995), he obtained very different distributions, and these much more closely resembled those displayed in Fig. 3. The rather small differences between his and our mean structures can be understood in light of the fact that different approaches have been taken, and that the distributions he obtains show a degree of sensitivity to the vorticity change criterion used. (For example, the difference between the two of his plots referred to above is similar, or greater than, either of them compared to the structures in Fig. 3.) We also mention that his investigation was based on ECMWF operational analyses and he compiled his statistics over the ''winter half of the year'' (defined as May to October in the former paper, and April to September in the latter). Taken overall, these findings strongly support our conjecture that the explosive development criterion based on NDR_c is inappropriate in the SH and leads to climatological distributions that make little dynamic sense, whereas those obtained with the NDR_r threshold fit in clearly with basic physical reasoning. We mention in passing that while the NDR_c and vorticity change criteria give very different distributions in the SH (Figs. 11e and 11f of Sinclair (1997), those obtained in the NH are very similar (Figs. 9e and 9f in that same paper). It follows that central pressure deepening rates present a reliable index of explosive development in the NH but not in the SH. We shall return to this important point below.

b. Mean intensity, radius, and depth of bombs

To date we have shown the tracks and density of all SH explosive cyclones identified over our 21-yr record. These do not represent a comprehensive picture of these features as they give no indication of their mean intensity, size, or depth (which we here denote by $\nabla^2 p$, R, and D, respectively). [The term intensity has been used in a number of inconsistent senses in the literature. Our usage follows the precisely defined terminology of Petterssen (1956, p. 52).] It is possible, for example, for a region to be host to a large number of such systems but they may all be rather small or weak. Hence, even though the density is high the net impact of these may be diminished. To explore this we present the summer and winter means of these important and distinct aspects of cyclone morphology. Simmonds et al. (1999) and Simmonds and Keay (2000a) have discussed these and show that they are related by

$$D = \frac{R^2\nabla^2 p}{4}. \qquad (3)$$

Simmonds and Keay (2000a) have shown that D can be interpreted as reflecting the importance or strength of a cyclone. Although the terminology is different, Sinclair (1997) takes "circulation" (equivalent to the area enclosed by a curve times the mean vorticity over the area) as a measure of cyclone strength. It may be seen that these measures differ only by a factor proportional to f.

The mean summer and winter distributions of $\nabla^2 p$ are shown in Fig. 4. (Note that in this and other figures we do not attempt to contour the mean of the variable over regions for which a very low frequency of systems would make such an average meaningless.) Values exceed 1 hPa (° lat)$^{-2}$ in most areas over which explosive cyclone numbers are sufficient to warrant calculation of this mean quantity. [Simmonds et al. (1999) classified cyclones having $\nabla^2 p$ values greater than 0.7 hPa (° lat)$^{-2}$ as "strong systems." By this criterion, bombs are indeed very intense cyclones.] Maxima in excess of 1.5 hPa (° lat)$^{-2}$ are found in the midlatitudes in both seasons. In winter, the Pacific Ocean is host to intense bombs in a broad area from the eastern coast of Australia to the southern tip of South America (Fig. 4b). Moreover, a number of intense explosive developers occur off Dronning Maud Land in Antarctica. Overall, the mean intensity of summer bombs is similar to those in winter, although they are less frequent. In particular, in summer, explosive cyclones off the coast of Antarctica in Australasian longitudes are more intense (Fig. 4a) than their winter counterparts, as are those in the midlatitudes of the western Atlantic. By contrast, the continental bombs occurring over western Australia discussed earlier are shown to have relatively modest intensity.

The size (or radius) of the explosive cyclones is also an important diagnostic parameter pertaining to these features. Figure 5 shows that a significant portion of the midlatitudes is host to explosive systems whose mean radius exceeds 6.0° latitude. It can be seen that, in general, explosive systems are larger in summer than in winter, meaning that their influence is felt over a larger region in the warm season. This is particularly marked in the Southern Ocean from south of Africa to the date line.

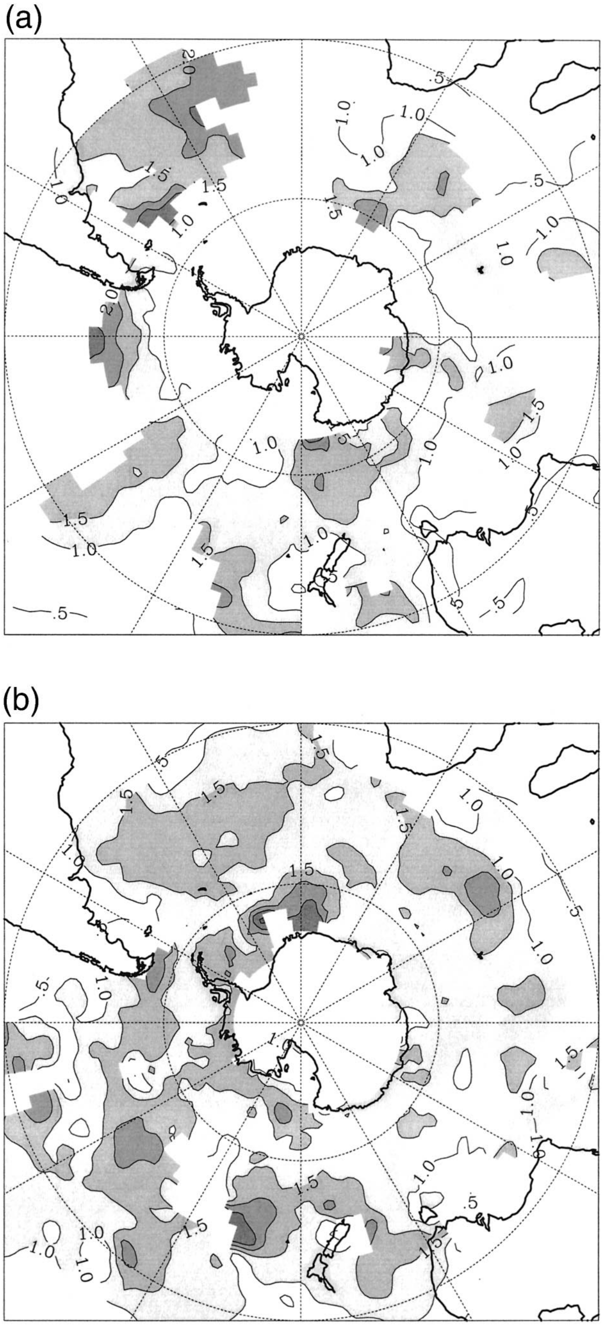

FIG. 4. Mean SH explosive cyclone $\nabla^2 p$ in (a) DJF and (b) JJA. The contour interval is 0.5 hPa (° lat)$^{-2}$.

The average depth of bombs exceeds 9 hPa over a considerable fraction of the SH (Fig. 6). We had remarked earlier that confining ourselves to considering solely explosive cyclone counts or frequencies (as do many studies) has the potential to misrepresent the overall impact of explosive systems. Figure 3 shows a high density of these systems near 60°S south of Australia and the Tasman Sea in both summer and winter. How-

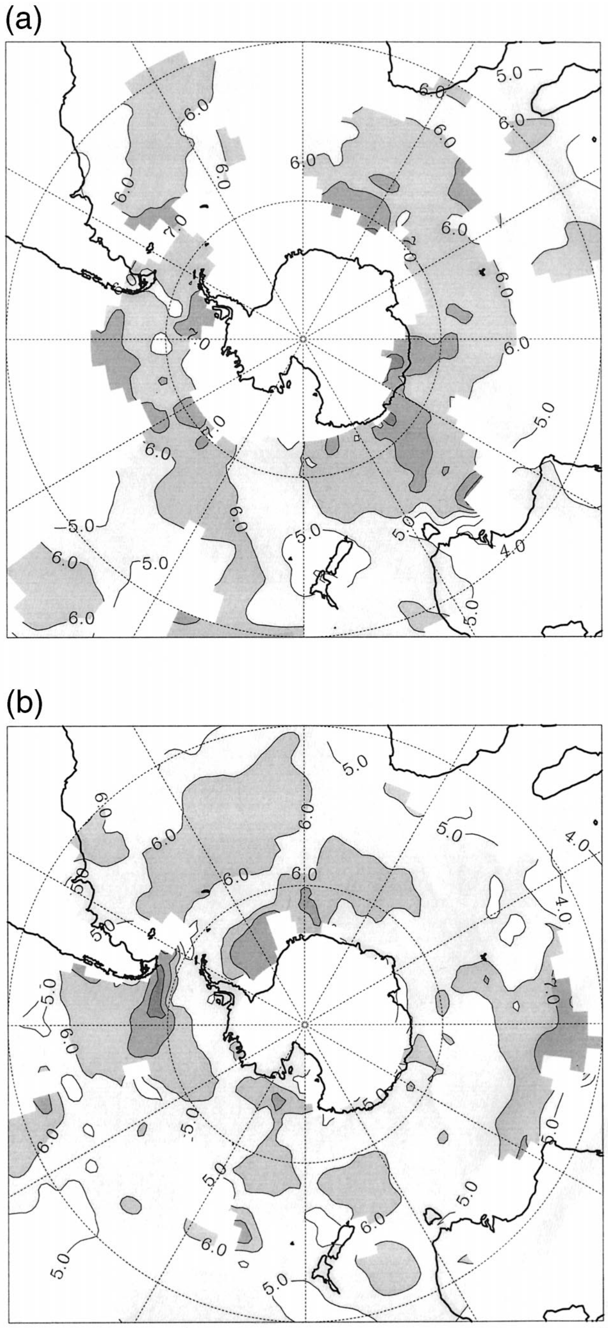

FIG. 5. Mean SH explosive cyclone radius in (a) DJF and (b) JJA. The contour interval is 1 (°lat).

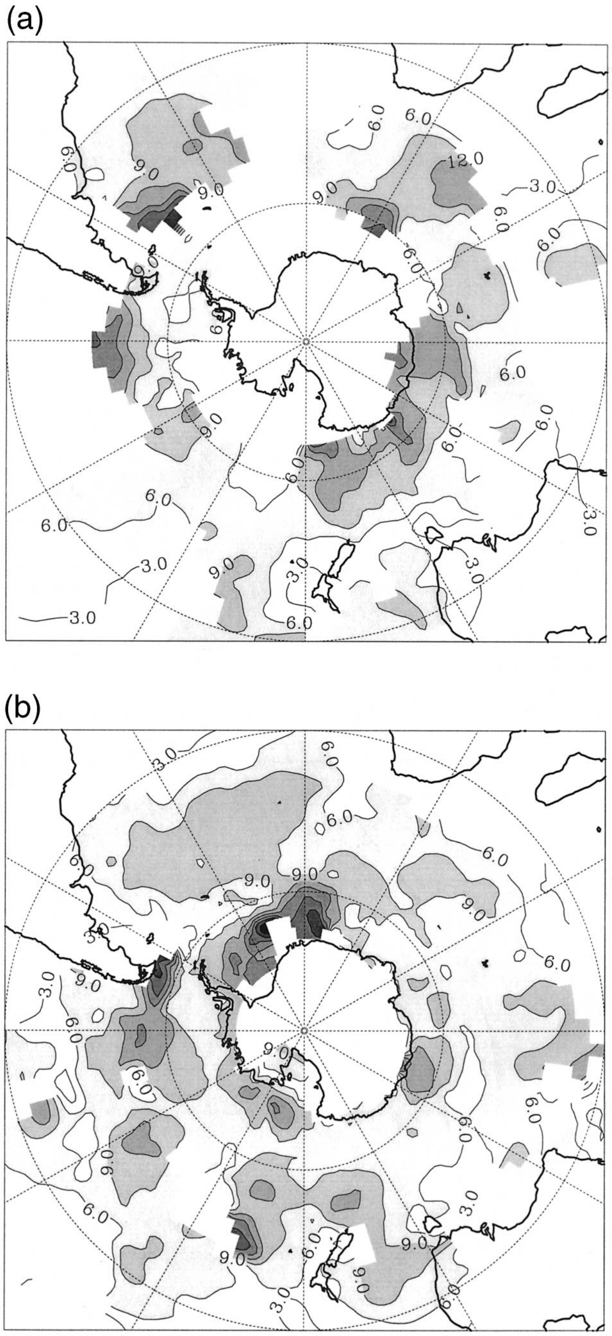

FIG. 6. Mean SH explosive cyclone depth in (a) DJF and (b) JJA. The contour interval is 3 hPa.

ever, one can see that the mean winter depth of these systems is quite modest (Fig. 6b). For individual systems, the depth is related to the product of the intensity and area [Eq. (3)], and our past studies suggest that this relationship also holds reasonably well for the *mean* of these characteristics (Simmonds and Keay 2000a). We also find that winter explosive cyclones exhibit low values of intensity (Fig. 4b) and radius (Fig. 5b) in this region. Hence, again, statistics based purely on frequencies can give a distorted perspective of these features. As another aspect of this complexity we mention that *summer* explosive cyclones in this region under discussion are indeed deep (Fig. 6a). Reference to the previous two figures shows that this extreme depth is associated with maxima of intensity between 150°E and 180° (Fig. 4a) and of radius between 90° and 150°E (Fig. 5a). Overall, the deepest explosive cyclones are found in winter in, and to the east of, the Weddell Sea and to the west of the southern tip of South America. The former of these, however, is a region of relatively few systems.

c. Comparison of the characteristics of bombs with those of the entire cyclone population

In this section we address how some of the mean characteristics of the explosive cyclones we have identified compare with those of the entire population of extratropical cyclones. A simple way of effecting this is to contrast the mean of a given characteristic of bombs, α, to its average over all cyclones at a given location. This can be conveniently represented as a geographical plot of their ratio, $\alpha_{\mathrm{bombs}}/\alpha_{\mathrm{all\ cyclones}}$. Figure 7 shows such a ratio for system density. Explosive cyclones represent less than 0.5% in summer and 1% in winter of the total cyclone population over most regions of the SH. An interesting feature of these plots is that, in both seasons, the regions that have a high proportion of cyclones that are explosive are, in general, coincident with, or somewhat equatorward of, those exhibiting high explosive system density (Figs. 3a and 3c). The ratio of these densities allows one to obtain an appreciation of the hemispheric distribution of explosive cyclones after the *mean* effects of baroclinicity, upper-level circulation, surface fluxes, etc. (as reflected in the system density of the entire cyclone population) have been accounted for. If these processes acted, in the mean, equally on explosive and regular extratropical cyclones, the distribution of the density ratio would be spatially uniform. The regions of high ratio are essentially those regions over which, from time to time, many of these formation processes (and those discussed earlier) are likely to act in concert, and produce development much more dramatic than the sum of each acting in isolation. The message from the fact that regions that exhibit large density ratios are close to coincident with those showing high bomb densities is that, while baroclinicity is an important driver of bomb occurrence, the contributions from other aspects of atmospheric structure (which may be indirectly associated with baroclinicity) contribute in constructive and nonlinear ways to explosive cyclogenesis.

These considerations also have relevance to the distributions of the ratios of intensity, radius, and depth. For the most part, in midlatitudes the mean intensity of explosive cyclones is greater than that of all cyclones (Fig. 8). An enhancement is particularly apparent over the Tasman Sea and across to the south of New Zealand. At higher latitudes the mean $\nabla^2 p$ values are more similar. In particular, the mean intensity of winter explosive cyclones in the (high density) 90°E–180° sector discussed earlier is similar to, and perhaps even less than, the average over all cyclones in this active region. It is over this region that the mean intensity of all cyclones assumes its largest values in both summer and winter (Fig. 6 of Simmonds and Keay 2000a).

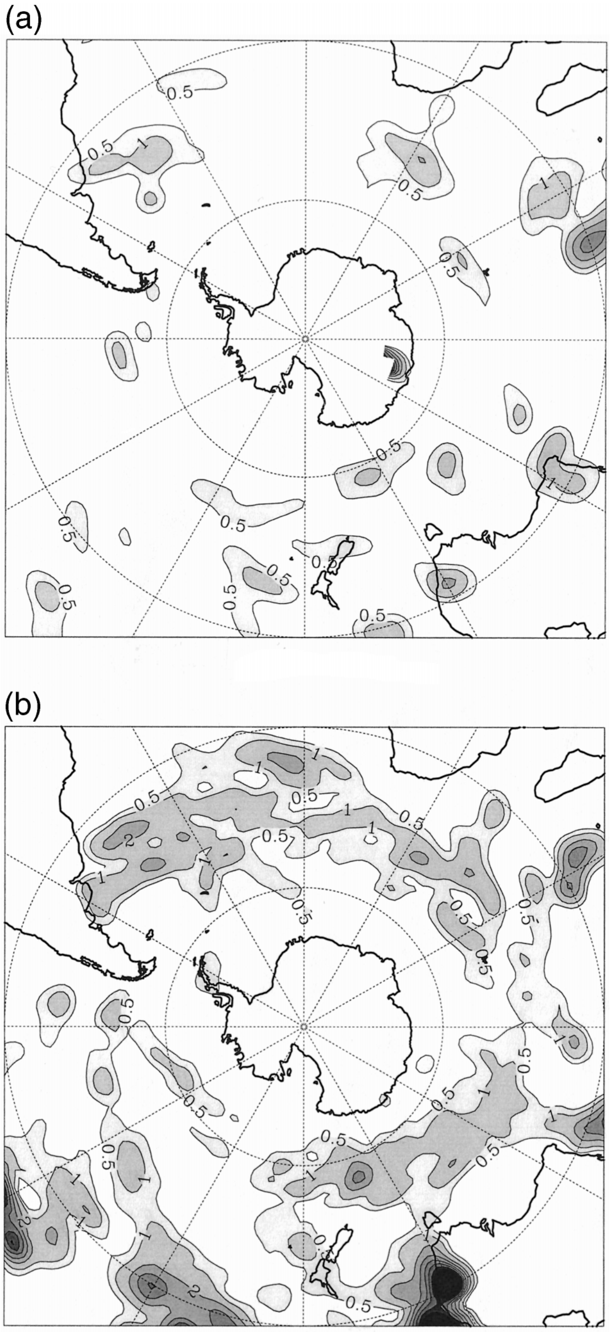

FIG. 7. Ratio of mean SH explosive cyclone system density to that of all cyclones in (a) DJF and (b) JJA, expressed as a percentage. The contour interval is 1% and an additional isoline has been included at 0.5%.

Figure 9 indicates that the mean radius of explosive cyclones is, predominantly, similar or slightly greater than the mean radius of the entire cyclone population. Having said this, the radius in winter is somewhat smaller over the high latitudes of the Indian Ocean and a considerable portion of the Pacific. The ratio of the depths of explosive developers compared to that of the

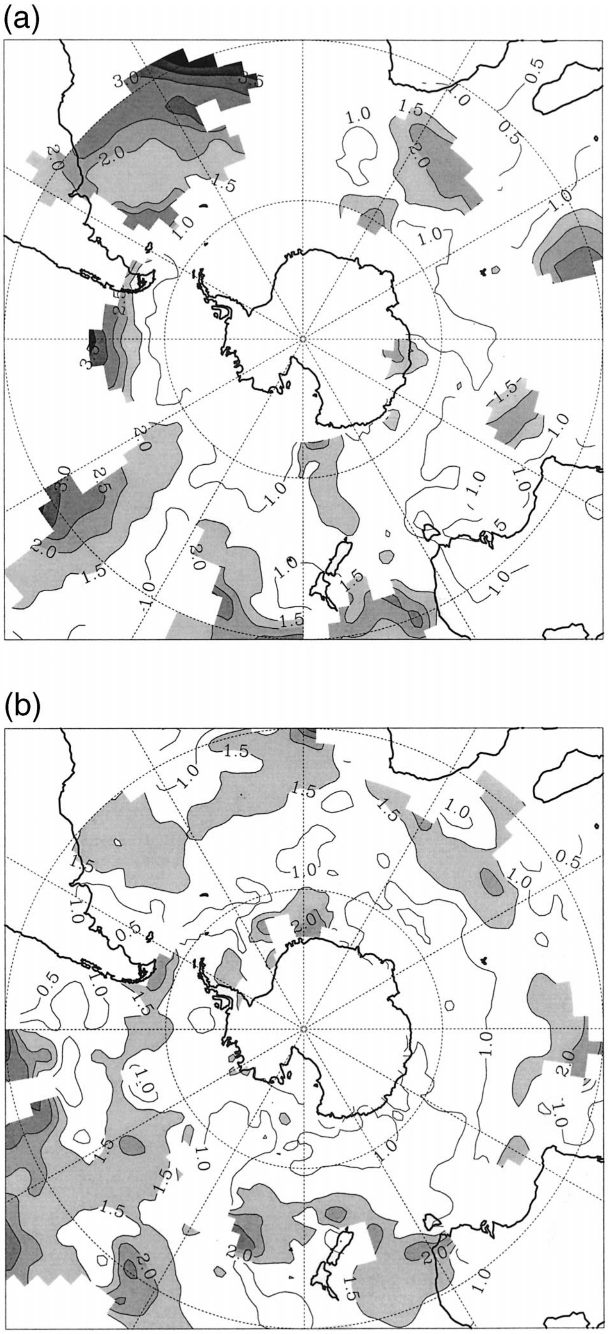

FIG. 8. Ratio of mean SH explosive cyclone $\nabla^2 p$ to that of all cyclones in (a) DJF and (b) JJA. The contour interval is 0.5.

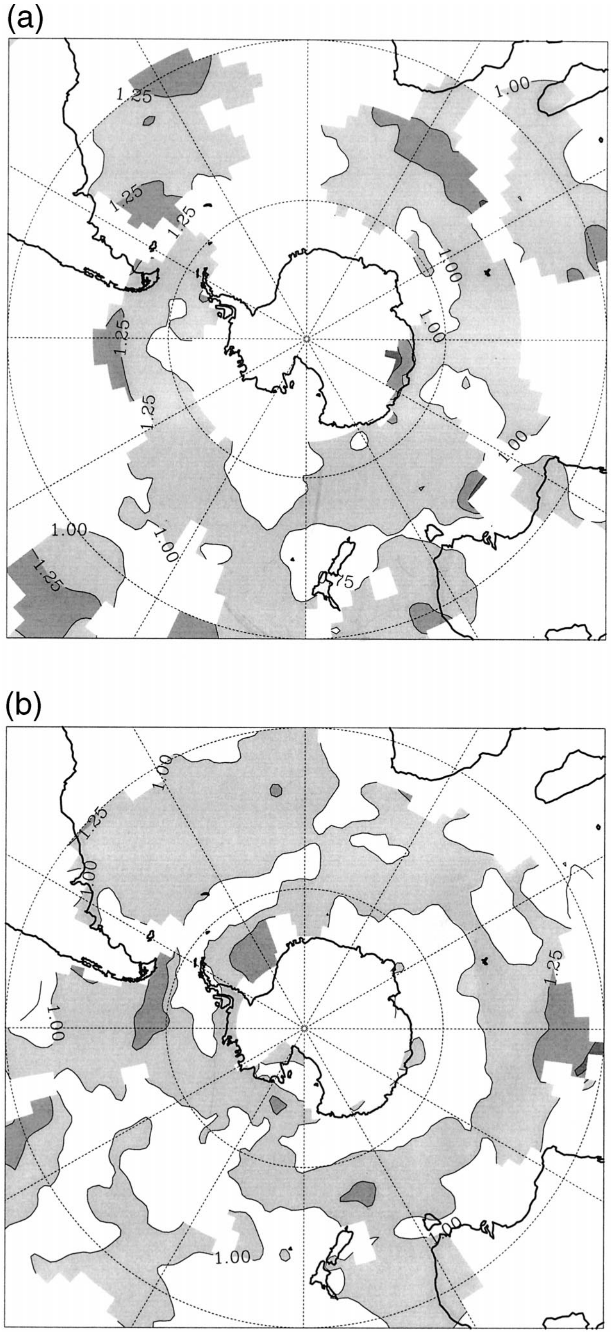

FIG. 9. Ratio of mean SH explosive cyclone radius to that of all cyclones in (a) DJF and (b) JJA. The contour interval is 0.25.

complete cyclone population (Fig. 10) shows patterns very similar to those of the ratio of $\nabla^2 p$. In particular, the difference of depths between explosive cyclones and all cyclones tends to be more conspicuous in summer than in winter. Regions over which the ratio exceeds 2 include parts of the subtropical regions in the Pacific and Atlantic Oceans, to the west of the southern tip of South America.

6. NH bomb characteristics

A primary purpose of this paper is to present for the first time a comprehensive climatology of explosive cyclones in the SH. However, as we mentioned earlier, part of this exposition is to document the manner in which these differ from their NH counterparts. We hence take the opportunity of applying the same cyclone tracking scheme to the same long reanalysis set, so the com-

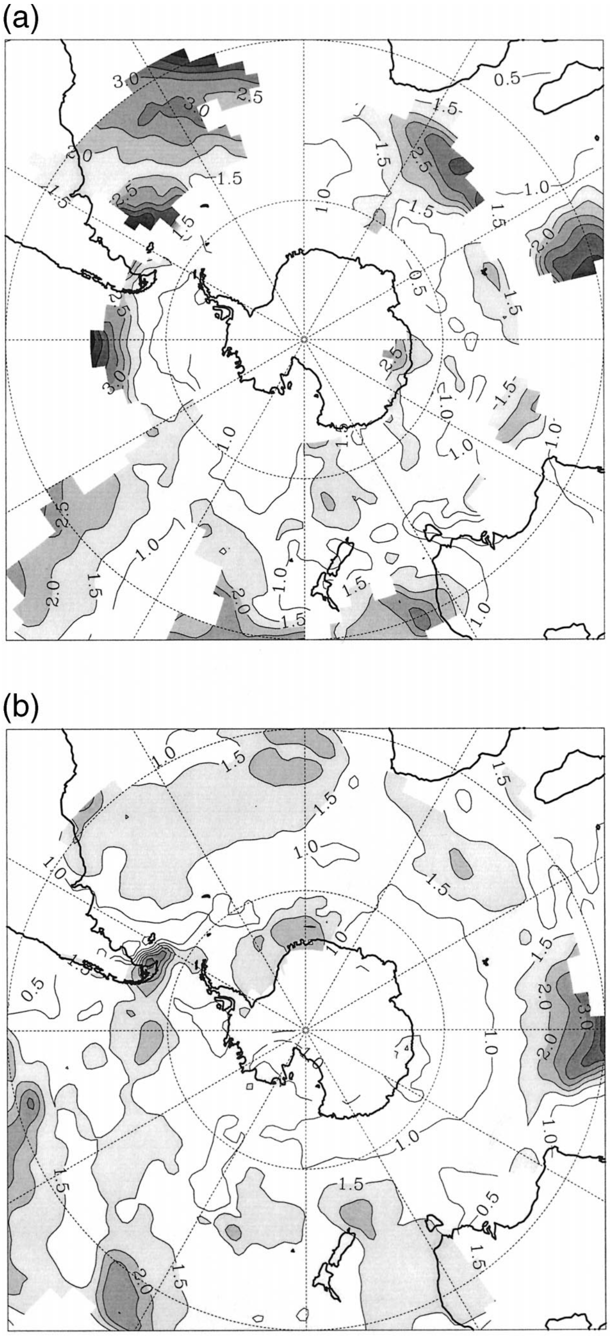

FIG. 10. Ratio of mean SH explosive cyclone depth to that of all cyclones in (a) DJF and (b) JJA. The contour interval is 0.5.

parison can be as rigorous as possible. As shown in Table 1, bomb events are concentrated in winter. For brevity, we confine ourselves to showing some NH statistics for winter only.

a. Explosive cyclone density and other characteristics

The overall structure of tracks of NH bombs presented in earlier studies (e.g., Sanders and Gyakum 1980; Roebber 1984; Chen et al. 1992) is confirmed in our results with the reanalysis data. In particular, we find a high frequency of bombs in the vicinity of the Kuroshio current and the Gulf Stream (Fig. 11a). Pacific explosive cyclone frequency is aligned quasi-zonally, whereas that in the Atlantic shows more of a NE–SW orientation. Inspection of Fig. 11a (and Fig. 1) suggests that explosive cyclones travel farther in 24 h than do typical cyclones. This aspect is frequently referred to, and indeed is confirmed when the mean speeds of bombs and of all cyclones over the seasons are compared for both hemispheres in Table 2. We find the explosive cyclones to travel some 45%–50% faster. This is consistent with our understanding of the environment in which these systems occur, including strong baroclinicity and strong westerly flow. Consequently, in one day bombs move, on average, about 570 and 487 km farther in the NH and the SH, respectively, than general cyclones.

Winter system density (Fig. 11b) has a maximum off the coast of the United States. Secondary maxima are located to the south of Iceland and to the east of Japan. The west Atlantic belt of high frequency extends somewhat farther north than that shown in earlier compilations. Sanders and Gyakum (1980) found the density maximum to lie to the south of Newfoundland, with relatively few systems diagnosed in the region to the south of Greenland and Iceland (their Fig. 3). The analysis of Roebber (1984) indicated a similar overall distribution. These analyses were performed on short records of three and one ‘‘cold season(s),’’ respectively. The later compilation of Sinclair (1997) undertaken with 7 yr of data locates the maximum Atlantic bomb frequency considerably farther northeast (and at a longitude east of the southern tip of Greenland (his Fig. 9f), and with significant bomb numbers being found in the vicinity of Iceland and just to the west of the British Isles, in much closer agreement with our distribution. Wang and Rogers (2001) found the frequency of rapid cyclogenesis in the Greenland–Iceland region to be higher than previously thought. They remarked that some of these events were extremely violent. We also comment that the climatological winter low in this region is centered between Iceland and the southern tip of Greenland. Hence explosive cyclones found at longitudes east of this will find themselves in an environment in which this background pressure is increasing. For the reasons discussed above, traditional methods based on 1-bergeron deepening rates will be less likely to identify explosive cyclones in that region than will the method used here.

At this point it is worth emphasizing that apart from some specific details (which as we have seen may be associated with the shorter periods of record used in earlier studies) the frequency distribution of winter explosive cyclone development identified here is in close agreement with those diagnosed by other workers using the central pressure method. This is in marked contrast to the situation in the SH. There are several reasons why

TABLE 2. Mean speed (m s^{-1}) of explosive cyclones (over 24-h rapid development periods) and all cyclones by hemisphere.

	SH	NH
Explosive cyclones	18.40	17.30
All cyclones	12.76	10.70

the central pressure method appears to produce reasonable results in the NH when compared with the more physically based method used here. First, the horizontal gradients of winter mean sea level pressure are much more modest in the NH. [We remind the reader that Sinclair (1995) had commented, that ''the widespread practice of relating cyclogenesis to a central pressure change can be misleading, especially where cyclones migrate rapidly toward an area of climatologically lower pressure.''] Hence, due to that effect alone, one would expect much less sensitivity in the NH to whether NDR$_c$ or NDR$_r$ is used to identify explosive cyclones. Further, Table 2 shows that, on average, NH bombs move 6% more slowly (across a climatological field) than their SH counterparts. Finally, we comment on the tracks and frequency of NH explosive cyclones (Figs. 11a and 11b) and their relationships with the average winter mean sea level distribution of the NH (e.g., Fig. 2b of Murray and Simmonds 1995). One can see that the majority of these systems track through regions of weak mean gradient, or have a broad tendency to follow the contours of mean pressure. Hence they are not migrating rapidly toward an area of climatologically lower pressure, and in the NH the along-track correction for spatial variations in mean pressure has much less impact than in the SH.

By contrast with the distribution of mean $\nabla^2 p$ of SH explosive cyclones, which shows its highest values mainly in midlatitudes, the most intense NH systems are found in the higher latitudes (Fig. 11c). The difference of these patterns is related to the difference in the preferred paths in the two hemispheres in that explosive cyclones would be expected to have the maximum $\nabla^2 p$ values at the last stage of rapid pressure deepening. Most regions influenced by explosive cyclones show values of $\nabla^2 p$ of more than 1.5 hPa (° lat)$^{-2}$, and broad areas in the Atlantic Ocean to the north of 40°N and the middle of Pacific Ocean show mean intensities in excess of 2.0 hPa (° lat)$^{-2}$. Overall, NH winter bombs appear to have greater intensity than their SH counterparts. The most intense explosive cyclones, having mean $\nabla^2 p$ values of more than 2.5 hPa (° lat)$^{-2}$, are observed in the middle of the Aleutian Islands and the Kamchatka Peninsula, Hudson Strait, and the North Sea.

Figure 11d shows that typical mean radii are about 5°–6° lat, and that the larger systems are found mainly at high latitudes. In general, NH bombs are somewhat smaller than those in the SH. This is consistent with the results of Carleton and Song (1997) and Simmonds (2000) who found that NH synoptic cyclones are, on average, smaller than those in the SH. In a similar vein, we can see that the deepest explosive cyclones occur in high latitudes (Fig. 11e), with particularly deep ones being found in Hudson Strait and the Labrador Sea. Furthermore, our results show that the distribution of the mean depth of explosive cyclones is more closely associated with that of $\nabla^2 p$ rather than radius. A similar comment is true for the SH.

A very useful summary of these statistics is presented in Table 3, which shows the mean intensity, radius, and depth of bombs for the four seasons, at the start of the 24-h bomb period (''explosive cyclone genesis''). We present these for the two hemispheres separately. The statistics are also shown at the end of the 24 h (''explosive cyclone lysis''), and the final column indicates how the means of these parameters have changed between these two times. (Note that when we speak of explosive cyclone genesis and explosive cyclone lysis we are referring to the beginning and end of the 24-h period over which the normalized deepening rate exceeds unity.) The table indicates that NH bombs have greater intensity and depth but smaller radius than their counterparts in the SH. Moreover, the mean increments in intensity and depth are greater in the NH. However, the mean increment of radius is smaller in the NH. These characteristics are similar to those found nonexplosive systems by Simmonds (2000).

b. Comparison of the characteristics of bombs with those of the entire cyclone population

Finally in this section are presented some statistics on the ratio of the mean of explosive cyclone properties to that of the mean of the entire cyclone population. We first present this ratio for system density. The proportion of all winter cyclones that are made up by explosive systems is more than 2% over much of the extratropical NH (Fig. 12a). In the NH the regions that have relatively more explosive cyclones are coincident with the places

TABLE 3. Mean of intensity, radius, and depth of SH and NH explosive cyclones at their genesis and lysis, and the mean changes in these over the 24 h.

	At bomb genesis		At bomb lysis		Mean change	
Property	SH	NH	SH	NH	SH	NH
$\nabla^2 p$ [hPa (° lat)$^{-2}$]	0.90	1.07	1.94	2.80	1.05	1.73
Radius (° lat)	5.46	5.20	6.55	6.09	1.09	0.89
Depth (hPa)	4.98	5.51	12.92	16.19	7.94	10.68

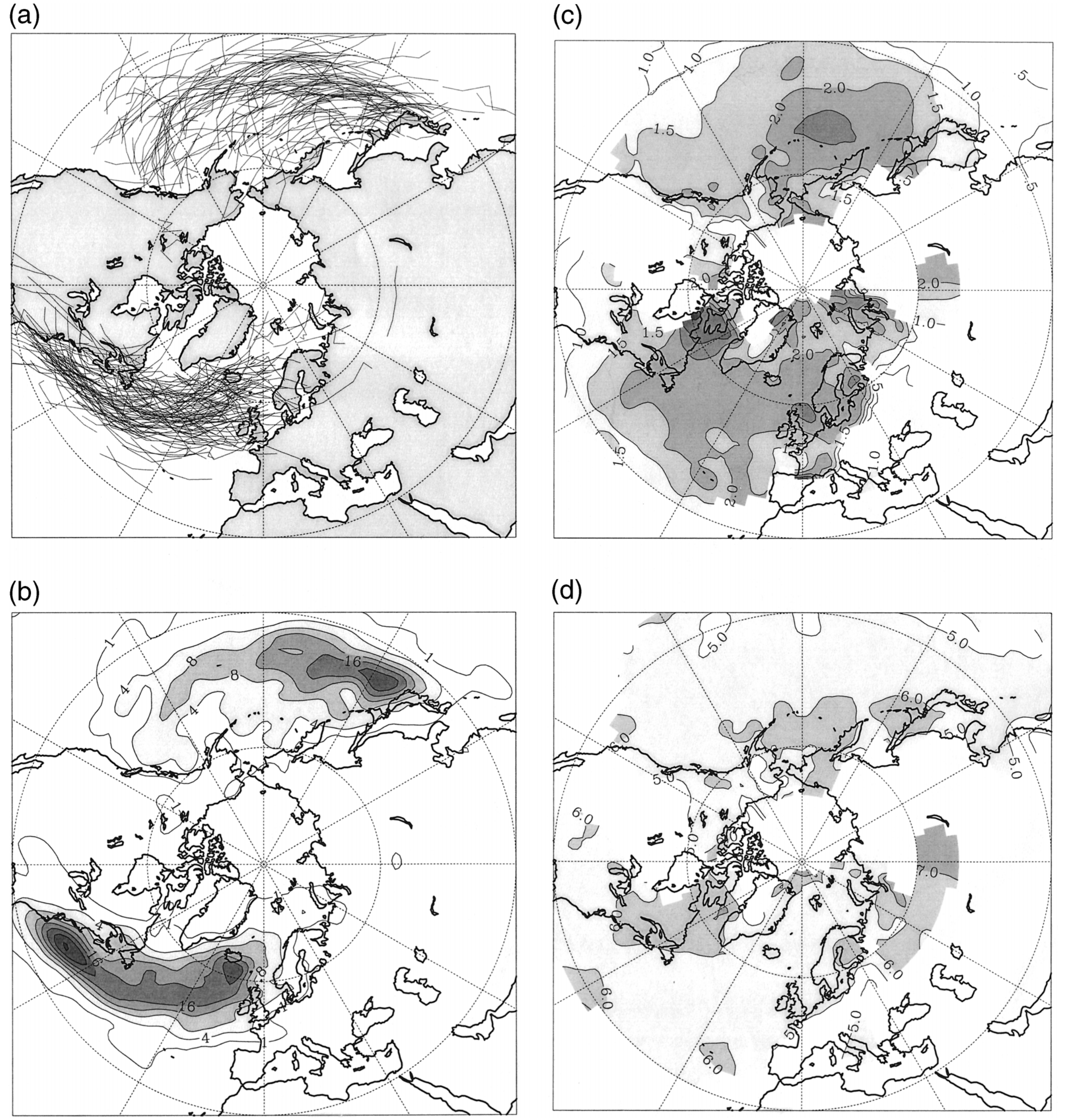

FIG. 11. Winter NH explosive cyclone (a) tracks (plotted with 6-h segments over the 24 h of explosive development), (b) mean system density [contour interval is 4×10^{-5} explosive cyclones (° lat)$^{-2}$, with an additional contour at 1×10^{-5}], (c) mean $\nabla^2 p$ [contour interval is 0.5 hPa (° lat)$^{-2}$], (d) mean radius (contour interval is 1 °lat), and (e) mean depth (contour interval is 3 hPa).

showing high densities in Fig. 11b, a finding consistent with the case in the SH. Indeed, at many locations along the alley between the east coast of the United States and to just west of the British Isles explosive cyclones make up more than 6% of the cyclone population. Figure 12b indicates that the mean intensity of explosive cyclones is almost everywhere at least 50% greater than that of all cyclones considered together.

Overall, explosive cyclones exhibit a tendency to be slightly larger (see Fig. 12c), although in certain key regions (e.g., in the east Pacific and around 50°N in the central Atlantic) the systems are smaller than those of the entire cyclone population in that region. The distribution of the ratio of mean depths (Fig. 12d) is quite similar to that of the intensity ratio. Particular enhancement of explosive cyclone depths is apparent near 30°N over Hudson Strait, the Kamchatka Peninsula, and northern Japan.

(e)

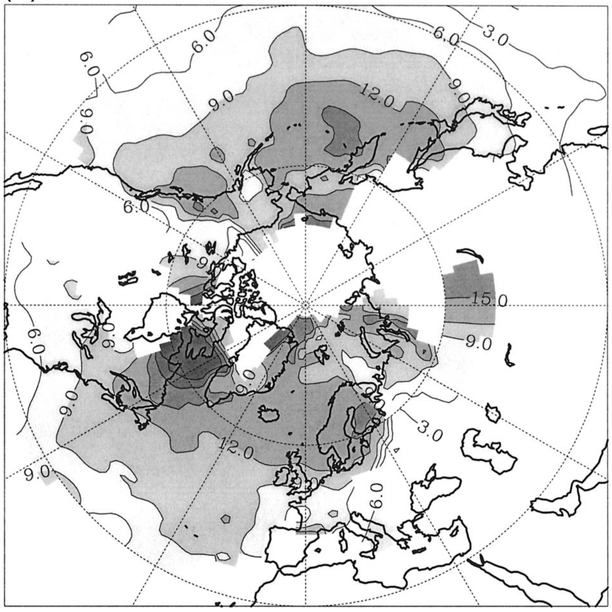

FIG. 11. (*Continued*)

7. Zonal mean distributions

Fig. 13 summarizes interesting features of the mean distributions of explosive cyclone genesis and lysis revealed in the foregoing sections. The number of genesis and lysis events is counted in each 10° latitude belt from 25° to 90° in the two hemispheres (the bin between 20° and 30° latitude actually represents the number of explosive cyclones occurring between 25° and 30° latitude). Southern Hemisphere bomb genesis occurs in the broad region from 30° to 70°S in all seasons. The peak values are found in the band from 50° to 60°S in all seasons except for March–May (MAM), which has its maximum between 60° and 70°S. There is a second maximum whose location varies according to season. In summer, its peak is found between 25° and 30°S, which may reflect the subtropical penetration of tropical cyclones. In the other seasons, the band between 30° and 40°S or the band between 60° and 70°S has the secondary maximum of explosive cyclone genesis.

Southern Hemisphere bomb lysis shows the largest counts between 40° and 50°S in autumn and winter, and between 50° and 60°S in spring and summer. This high concentration between 40° and 60°S is consistent with Fig. 1, which indicates the confluence of high-latitude bombs and their lower-latitude counterparts in that domain.

Northern Hemisphere explosive cyclone genesis is highly concentrated between 30° and 50°N, while lysis predominantly occurs between 40° and 50°N in all seasons. In the NH the peak of lysis occurs poleward of that of genesis, meaning that, on average, bombs move poleward. These zonally averaged plots make it very clear that explosive cyclones are predominantly midlatitude events in the NH, whereas they are found over a broader latitude range in the SH.

8. Interannual variability of explosive cyclone occurrence

As in all aspects of climate, the systems of interest to us here exhibit interannual variability. Concern has been expressed by the climate community that the frequency of extreme events may increase under global climate conditions in the twenty-first century. Our dataset presents us with the opportunity to examine whether the frequency of explosive cyclones, or at least those revealed in reanalysis-2, has changed in the recent past. Figure 14 presents time series of the total number of explosive cyclones for the two hemispheres in each year for the period 1979–99. Both series display considerable interannual variability, and the superimposed lines of least squares best fit show positive slopes. These slopes are 0.56 systems per year [significantly different from zero at the nominal 95% confidence level (and indeed at 99%)] and 0.21 systems per year in the SH and the NH, respectively. In the NH case, the positive slope cannot be said to differ significantly from zero. The number of explosive systems over the entire globe has exhibited a significant increase of 0.78 systems per year.

Before accepting the behavior of these time series as a genuine reflection of real variability in the atmosphere we need to consider the extent to which changes in the observational data platforms over the 21 yr could impact on the reanalysis quality and hence the determination and counting of explosive cyclones. While obtaining a definitive answer to this question is very difficult, a few relevant points may be made. First, as mentioned above, the First GARP Global Experiment, a campaign during which special efforts were made in data collection, was conducted in 1979. There is no suggestion in Fig. 14a that an unusually large number of explosive cyclones were identified in that year. Figure 1 of Kistler et al. (2001) indicates that a significant increase in the number of SH observations of all types was available since 1979. We have calculated a similar time series to that above, but for the count of all cyclones over the SH extratropics [we do not show the results here but they are very similar to those presented by Simmonds and Keay (2000b) for the original NCEP reanalysis set], and these show a significant downward trend. As Simmonds and Keay commented, had the numbers of cyclones identified exhibited *increases* during the period, one might have been led to suspect that the increased data were producing more structure in the analyses and hence allowing more cyclones to be found. The fact that the opposite occurs is strong circumstantial evidence that the changes in the entire cyclone population size are ‘‘real’’ and, given that, that the variability in bomb numbers is not unduly influenced by changes in the observational database.

To further clarify the extent to which the changes we have demonstrated may be contaminated by trends in

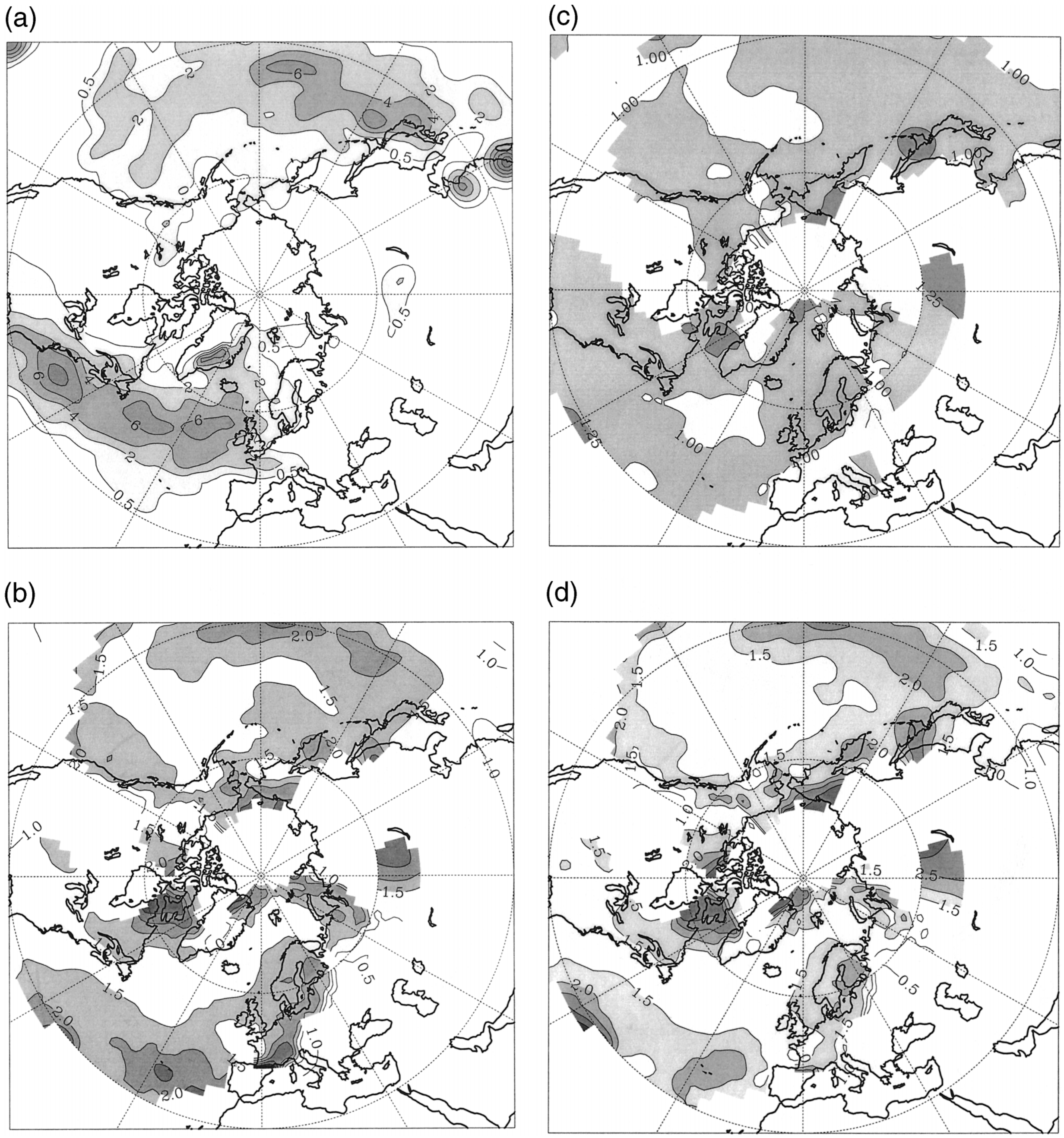

FIG. 12. Ratio of mean winter NH explosive cyclone properties to those of all cyclones: (a) system density, (b) $\nabla^2 p$, (c) radius, and (d) depth. The contour intervals are 2% (with an additional contour at 0.5%), 0.5, 0.25, and 0.5, respectively.

data coverage that might impact on the detectability of rapid developers we have broken our period up into two decades (1980–89 and 1990–99). We present in Fig. 14c the difference in mean SH winter explosive cyclone system density between these two epochs. In general, the changes between the two periods are quite small and are perhaps what could be expected from natural variability. If the largest changes had occurred over data-poor areas of the SH one might have had concern as to the reality of the overall trends. There is no suggestion that this is happening. Indeed, some of the largest changes (increases) are found in the well-observed regions of the Tasman Sea and immediately to the south of Australia. For completeness we show a similar difference plot for the NH winter (Fig. 14d). Here the magnitude of local changes tends to be somewhat greater than in the south. The greatest increases in bomb frequency are found over the regions that already host large numbers

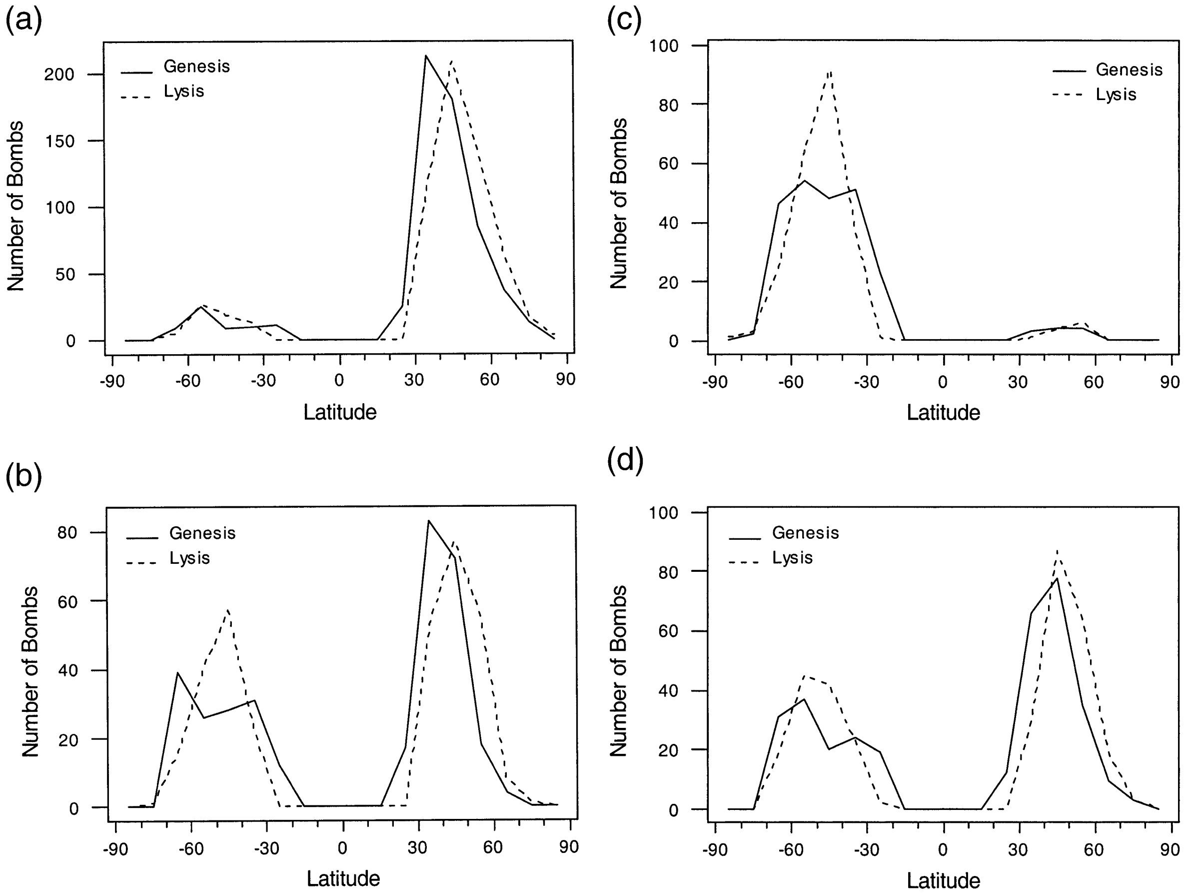

FIG. 13. Total number of explosive cyclone genesis and lysis events in 10° lat wide bins in (a) DJF, (b) MAM, (c) JJA, and (d) SON for the period 1979–99.

(Fig. 11b), with the exception of the region just off the eastern U.S. seaboard. Most other regions of the NH have exhibited fewer explosive systems in the second decade.

These overall increases bear general agreement with those obtained in a range of observational studies. Many of these have documented recent significant increases in the numbers of intense systems (or in the activity of systems) (e.g., Lambert 1996; Gustafsson 1997; McCabe et al. 2001; Graham and Diaz 2001). Some investigations (e.g., Gulev et al. 2001) have specifically reported on increases in the numbers of rapidly developing systems. Chen and Kuo (1994) found a significant positive relationship between NH mean temperature and the number of explosive cyclones in the northwest Pacific over the period 1951–70. These changes have been occurring while the entire population of cyclone numbers (in both hemispheres) over the last few decades has been decreasing (e.g., Key and Chan 1999; Simmonds and Keay 2000b; Gulev et al. 2001; McCabe et al. 2001).

We remark that the overall nature of the changes in the numbers of intense cyclones and in the entire population of cyclones is in accord with responses obtained in CO_2-enhanced climate model simulations [see, e.g., the work of Lambert (1995), Zhang and Wang (1997), and Knippertz et al. (2000)]. The opposing nature of the trends of the two types of systems have been addressed in many studies. For example, Carnell and Senior (1998) argue that the reduced baroclinicity in a CO_2-enhanced climate will result in fewer systems. However, in a warmer environment there is more moisture available to the storms that do form, which in turn may lead to deeper storms. These findings, taken collectively, could lead one to suggest that the warming of the hemispheres may lead to a larger population of intensely developing cyclones.

9. Distribution of explosive cyclone deepening rates and timing

So far we have considered all explosive systems (for which $NDR_r \geq 1$) together. It is also useful to document the different characteristics of these features according to their deepening rate. Sanders (1986) classified bombs as "weak" ($1.0 \leq NDR_c \leq 1.2$), "moderate" ($1.3 \leq$

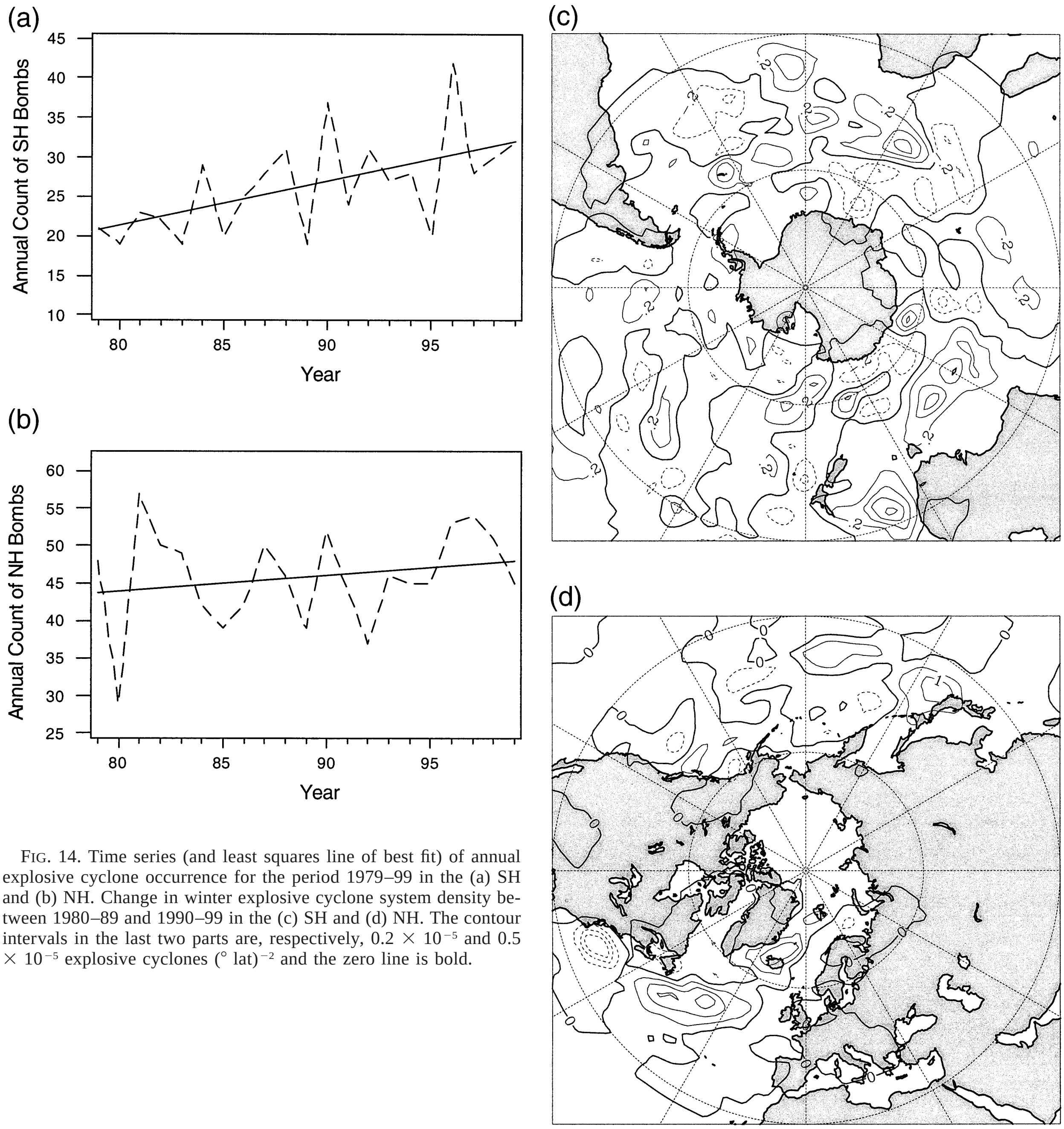

FIG. 14. Time series (and least squares line of best fit) of annual explosive cyclone occurrence for the period 1979–99 in the (a) SH and (b) NH. Change in winter explosive cyclone system density between 1980–89 and 1990–99 in the (c) SH and (d) NH. The contour intervals in the last two parts are, respectively, 0.2×10^{-5} and 0.5×10^{-5} explosive cyclones (° lat)$^{-2}$ and the zero line is bold.

$NDR_c \leq 1.8$), and ''strong'' ($NDR_c > 1.8$). He found that about 22% of the explosive cyclones that were investigated in the western North Atlantic Ocean for 1981–84 were strong bombs, whereas Chen et al. (1992) found, with data from the same period used by Sanders, that 8% of all bombs appearing off the east Asian coast were strong bombs.

Figure 15a shows the total population of explosive cyclones binned according to NDR_r (with a bin width of 0.1). One can see that the number decreases almost monotonically with NDR_r in both hemispheres. Most strong systems are found in the NH winter (about 3% of all bombs). One ''superbomb,'' which occurred to the east of Japan (on 25 February 1992), achieved as NDR_r of 2.32. However, strong bombs represent only about 1% of all bombs in the other seasons. Strong bombs are even rarer events in the SH. In our entire compilation, only two explosive cyclones in the SH winter and one in each of intermediate seasons can be classified as strong. In the NH moderate bombs compose 25% of the entire explosive cyclone population, whereas this figure is only 12% in the SH. Consequently, most of the explosive cyclones showing extreme values of NDR_r appear in the NH. As mentioned earlier, SH bombs develop in a more moderate environment.

Finally in this section we wish to determine at which stage of a cyclone track do these explosive (24 h) episodes take place. To do this, we determine the day in the lifetime of the ‘‘host’’ cyclone on which the explosive development occurred. Accordingly, Fig. 15b shows the percentage of bombs that occur on a given day of the life of the cyclone in which they form a segment. In both hemispheres a very high proportion of bombs occur on day 1. That is, in these cases, rapid deepening occurs almost as soon as cyclonic systems are identified in the reanalysis-2 surface pressure field, and this preference is most clearly marked in the SH (51.7% of all bomb occurrences). It will be seen that the proportion of bombs that occur on a given day of the extratropical cyclone lifetime drops almost monotonically with day number and the timing of bombs is heavily skewed toward the ‘‘young’’ end of the host extratropical cyclones existence, particularly in the SH.

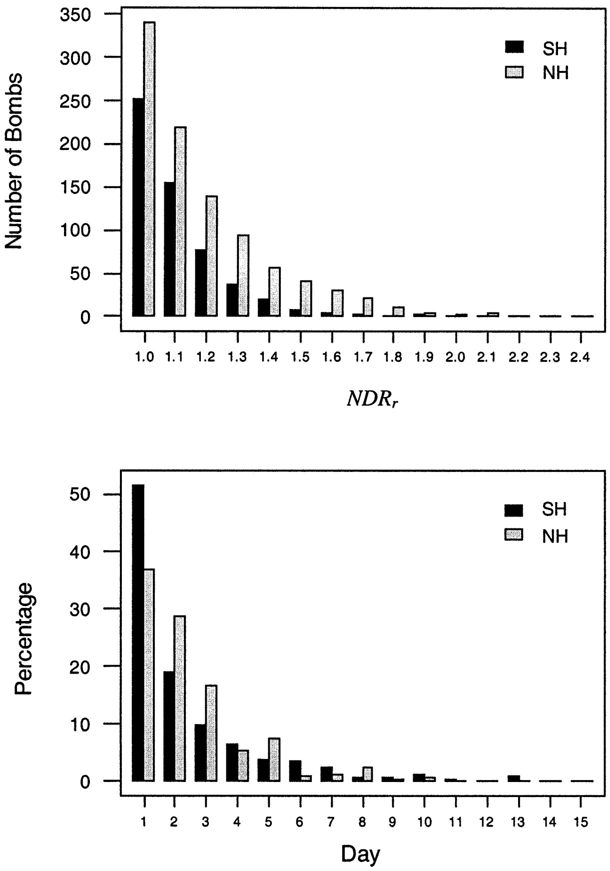

FIG. 15. Stratification of all explosive cyclones by (a) NDR_r and (b) day number in life of the host cyclone. The results are presented for the two hemispheres separately.

10. Concluding remarks

This comprehensive climatology of the features and behavior of SH bombs has been assembled using the NCEP–DOE reanalysis-2 data from 1979 to 1999 in conjunction with the Melbourne University automated cyclone finding and tracking scheme. Our research has investigated bombs taking into account the influence of the spatial distribution of climatological mean pressure, and this use of ‘‘relative central pressure’’ is particularly important when SH bombs are considered. This has served to show that specific cases of dramatic decreases in cyclonic central pressure need not be associated with bombs. Globally, about 72 bombs occur per year with almost two-thirds of these being found in the NH. In the NH, bombs are predominantly winter events, whereas the number of SH explosive cyclones show much less seasonality.

A band of significant winter SH explosive cyclone activity is seen to originate in the west Atlantic off the coast of Uruguay, extend eastward across the Atlantic and Indian Oceans, and reach a maximum at much higher latitudes to the south of Australia and New Zealand. In more modest form this band can be discerned across the Pacific as far as the environs of Drake Passage. Other regions of significant winter explosive cyclone occurrence are off the southeast coast of Australia, and in the South Pacific at subtropical latitudes. We have found these regions to be similar to those of strong baroclinicity. However, we have also emphasized there are a number of other important processes that contribute to the incidence of explosive cyclones. A most interesting feature of SH bombs in marked contrast to NH bombs was the equatorward component of motion in mid- and high latitudes. We have briefly explored some characteristics of NH bombs as revealed in the reanalysis dataset. In general, the results confirm those obtained in earlier studies (e.g., Sanders and Gyakum 1980; Roebber 1984, 1989; Gyakum et al. 1989; Chen et al. 1992), which, for the most part, had used shorter records and manual analyses.

Zonal average plots of bomb genesis and lysis confirmed the fact that SH bomb genesis has been shown to be broadly spread across 30°–70°S, whereas SH bomb lysis has been highly concentrated on 40°–50°S latitude bands. By contrast, NH bombs start their pressure deepening at 30°–40°N, and their maximum lysis is found at 40°–50°N.

In the mean the intensity exceeds 1 hPa $(° \text{lat})^{-2}$, and radii are more than 5° lat and depths in excess of 6 hPa in all the regions in the two hemispheres where explosive cyclones are reasonably numerous. We have made the case that depth [in accord with the arguments made for circulation by Sinclair (1997)] is an important measure of the strength of a cyclone. We have seen that, for the most part, the depths of explosive cyclones are determined more by their $\nabla^2 p$ values than their area. Northern Hemisphere bombs have had greater mean intensity and depth than SH bombs, but the mean radius of SH bombs is somewhat greater than that of NH bombs.

The number of explosive cyclones in the two hemispheres shows considerable interannual variability over the 21-yr period, and exhibits trend line increases of 0.56 and 0.21 bombs per year in the SH and NH, respectively, and the trend in global and SH counts differs significantly from zero. The increase in frequency of this class of intense cyclone bears similarities with a number of observational studies and with results of climate model studies undertaken with increased radiatively active gas concentrations. Most of the identified explosive cyclones are ''weak'' (about 73% in the NH, 87% in the SH). Strong bombs were not common events in either hemisphere, and most of them were found in the NH winter. In addition, this research has shown that a very high proportion of bombs occur very early in the life of the cyclone track of which they form a 24-h part. Our findings that winter bombs have rather small radius, and that bombs tend to appear in the early stage of entire system lifetime, are consistent with the results of Nielsen and Dole (1992) and Simmonds (2000), who found that cyclonic systems are smallest in their early life.

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