Size Changes over the Life of Sea Level Cyclones in the NCEP Reanalysis

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ABSTRACT

This paper addresses the extent to which sea level pressure cyclones change size as they develop. A state-of-the-art cyclone tracking scheme has been applied to the global ''reanalyses'' produced by the National Centers for Environmental Prediction for the four-decade period 1958–97. The analysis is based on all the cyclones found in the analyses, and on those which halfway through their lifetimes are located in the 30°–50° and 50°–70° latitude bands. Systems in both the Northern Hemisphere (NH) and Southern Hemisphere are considered, as are those in the December–February and June–August periods.

The results show that the radius of surface cyclonic systems increases as they evolve to maturity. This finding holds for the two baroclinic domains considered in both hemispheres and in both winter and summer. In the NH winter in the 30°–50°N and 50°–70°N belts the average increase in size of systems that last longer than 3 days is about 33% over 4 days. In the northern summer the rate of increase in radius is less marked, particularly in the midlatitude belt. In the Southern Hemisphere winter the mean rate of size increase is somewhat more modest than in the northern winter. The increase in size in the southern summer is greater than in the north, particularly in the 50°–70° band.

The small number of studies on this topic have indicated that over specific domains and limited samples the size of cyclones increase as they evolve from their point of first identification. The present results show that these increases occur in the extratropics of both hemispheres and in both winter and summer.

1. Introduction

In recent times there has been an increase in the number of studies directed at documenting and understanding the genesis and structure of sea level cyclones. Such activity is enhancing our appreciation of these features over many and diverse geographical regions (e.g., Mass 1991; Joly et al. 1997; Turner et al. 1998), and is made possible by better observing systems and more reliable regional and global analyses.

As part of this development increasing attention is being paid to relationships between various cyclone characteristics, and in this paper attention is focused on the extent to which the size of cyclonic systems change as they evolve. Recently, Grotjahn et al. (1999, hereafter referred to as GHC) stated that many linear theoretical studies assume that cyclones do not change size as they evolve, yet most people who look at weather maps have the subjective impression that the lows become larger over time. Such changes modify our thinking on cyclone development and, in particular, the scale of the ''most unstable'' mode. Nielsen and Dole (1992) were probably the first to undertake a systematic investigation of the size distribution of analyzed cyclones, using [National Meteorlogical Center, now known as the National Centers for Environmental Prediction (NCEP)] analyses produced during the Genesis of Atlantic Lows Experiment. They defined the radius of a cyclone to be ''the distance from the cyclone center to the nearest col (saddle point) of sea level pressure.'' They found the radius of a typical cyclone to change considerably during its lifetime. GHC made a significant contribution to this topic by studying the evolution of 12 Pacific lows in the Northern Hemisphere (NH) winter (December–February). They undertook wavelet analysis and used the results to calculate the ''width'' of a cyclone. It was revealed that, on average, the radius of their dozen systems doubled over a 4-day period.

Grotjahn and Castello (2000, hereafter GC) proposed another method for determining the radius of a system, which made use of the geostrophic kinetic energy calculated from the perturbation geopotential field. From this field a cylindrical average was calculated as a function of radial distance from the perturbation low center. In their method the scale of the system is defined in terms of the radial distribution of the kinetic energy. They found increases in this measure of scale consistent with those that had been derived with the wavelet approach. They raised the question as to the generality of

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their findings and whether the scale changes for systems that develop elsewhere.

In this paper the aim is to explore this issue further in a number of respects. The work of both Nielsen and Dole (1992) and GHC focused on limited time and/or space domains. While devoting most attention to the documentation of the evolution of the radius of cyclones in the NH winter, consideration is here also given to the baroclinic domains in both hemispheres and seasons. The analysis will be conducted by making use of the ''reanalyses'' produced by NCEP and the National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996) for the four-decade period 1958–97. These are among the best global analyses ever compiled. The research also makes use of a state-of-the-art cyclone tracking scheme (from which a variety of cyclone characteristics, including radius, can be derived).

2. Research design

As outlined above, in this work sea level pressure cyclonic systems are identified using the NCEP 6-hourly reanalysis set covering the 40-yr period 1958–97. These analyses were obtained by assimilating past data into a frozen state-of-the-art analysis–forecast model system. The system used is the same as the version of the NCEP analysis system implemented operationally on 10 January 1995, with the exception that the horizontal resolution is set at T62 instead of T126, and the data are provided by NCEP on a 2½° × 2½° latitude–longitude grid. In the vertical, 28 sigma levels are used. As explained by Kalnay et al. (1996) many special datasets from international sources were obtained that were not available operationally through the Global Telecommunications System. The reanalysis made use of modern sea ice and sea surface temperature analyses, cloud-drift winds, aircraft data, and Special Sensor Microwave/Imager surface wind speeds. The reanalysis product can be regarded as one of the most complete, physically consistent meteorological datasets. Having said this, the reader should be aware of the reduced amount of data which went into the reanalyses over the southern oceans, particularly prior to the satellite era. It is difficult to assess the extent to which this would have compromised the analyses, but a number of recent studies (e.g., Hines et al. 2000; Connolley and Harangozo 2000) have cast considerable light on the matter. While the present reanalysis sets may be seen as less than optimal in the southern oceans, the conduct of reanalyses is seen as an ongoing process. Data that had not been incorporated into previous reanalyses (e.g., a significant amount of coastal Antarctic observations) will be incorporated into new state-of-the-art forecast–analysis schemes. Kanamitsu et al. (1999) and others have already reported on the next generation of reanalysis products.

To identify and track surface cyclonic systems from these digital analyses use is made of the Melbourne University automatic cyclone detection algorithm, as de-

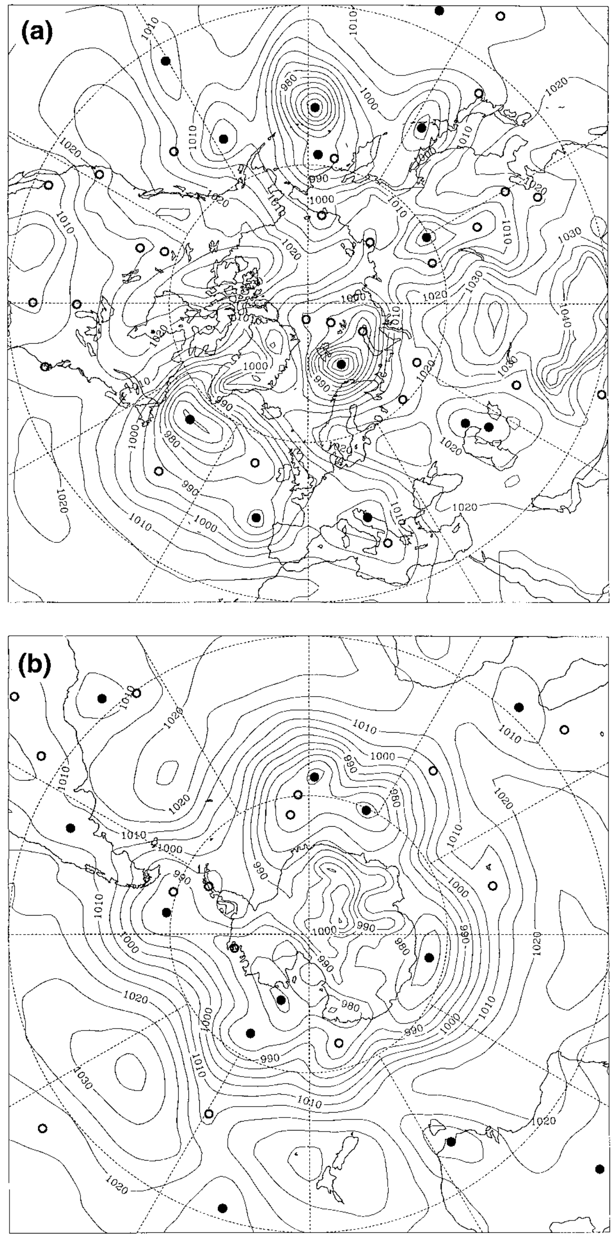

FIG. 1. ''Closed'' (filled circles) and ''open'' (open circles) depressions identified by the cyclone finding scheme at 0000 UTC 1 Jan 1996. The contour interval is 5 hPa: (a) NH, (b) SH.

scribed by Simmonds and Murray (1999) and Simmonds et al. (1999). Leonard et al. (1999) concluded that the scheme shows a high degree of skill in identifying low pressure centers and tracking the lows through a series of analyses. To exemplify the characteristics of the ''detection'' part of the algorithm, Fig. 1 shows all the ''open'' and ''closed'' depressions found in the two hemispheres at 0000 UTC 1 January 1996. (The reader is reminded that we ignore any system identified at a location where the height of the topography exceeds 1 km. This is done because the concept of sea level pressure has limited meaning at such locations.) It will be seen that in both hemispheres the algorithm can faithfully identify multiple centers within a low complex. Some of these are quite close, but would be identified as separate systems by a synoptician. Another thing of note in the figure is the absence of structures that could be regarded as polar lows. Given the small scales of these features (e.g., Turner et al. 1996) it is not surprising that the relatively coarse resolution of the analysis fails to capture them. It is pointed out that this study is focused on the behavior of ''synoptic'' systems and hence it is not of great concern that most polar lows are not able to be resolved.

The present study restricts attention to systems that last at least 24 h. In addition, because in this work the focus is on ''mobile'' midlatitude systems, consideration is given only to cyclones whose initial and final positions were separated by at least 1000 km. This restriction is similar to that of Sinclair (1994, 1995) who eliminated cyclones that moved less than a distance equivalent to 10° of latitude. It effectively precludes heat lows, leeside troughs, and other features tied to topography from consideration. Among the important statistics that the cyclone tracking scheme can produce are measures of strength and influence of the features. The latter, as discussed by Simmonds and Keay (2000a), may be related to the meridional transport for which a cyclone is responsible, and is not connected in a one-to-one sense to the strength of the eddy. A measure of cyclone intensity may be provided by the Laplacian of the pressure field calculated at the center of the system ($\nabla^2 p$) [which must exceed 0.2 hPa (° lat)$^{-2}$ to be regarded as a cyclone (Simmonds and Murray 1999)]. Other measures, including the ''depth'' (D) and ''radius'' (R) can be assembled to compile a complete picture of cyclone characteristics. All these concepts are related. This can be most easily be seen for the idealized case of an axially symmetric paraboloidal depression of radius R on a flat field. Simmonds and Keay (2000a) have shown that in this case these terms are related by

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

and they make the argument that the depth reflects the importance of a cyclone in the circulation. [Note that depth defined in this way is similar to the ''pressure deficit'' introduced by Nielsen and Dole (1992)]. They explain how the radius is calculated in the more common case of a nonaxially symmetric system. Briefly stated they find first a number of points that together bound the cyclonic region, which in the first instance can conveniently be defined as the region surrounding the $\nabla^2 p$ maximum in which $\nabla^2 p$ is positive. For a depression with contours of monotonic curvature, the perimeter points may easily be found by searching outward along radial lines. As indicated above, it frequently happens that two centers will exist within a single region of positive $\nabla^2 p$; in this case it is sensible to take the cyclonic domain of a particular center as being limited to the area over which the $\nabla^2 p$ decreases away from the center [see Fig. 5 of Murray and Simmonds (1991) for a graphical explanation of this]. As before, the algorithm performs searches along a suitable number of paths radiating from each cyclonic center.

3. Results

Part of the interest in this research centers on the difference between the evolution of the cyclone radius in the middle and higher latitudes. On a range of timescales the atmosphere exhibits modes whereby weather and climate anomalies in the midlatitudes are out of phase with those at higher latitudes. For the NH the work of, for example, Rajagopalan et al. (1998), Watanabe and Nitta (1999), and Walsh and Portis (1999) highlights aspects of this. In the Southern Hemisphere (SH) Mo and White (1985) found the monthly anomalies of mean sea level pressure between 50° and 70°S to be significantly negatively correlated with those in the 30°–50°S belt over nine winters. Kidson (1999) and Kidson and Watterson (1999) have found similar characteristics in the NCEP–NCAR reanalyses and model simulations, respectively. Simmonds and Keay (2000b) discovered that the year-to-year changes of cyclone numbers in these two latitude were (significantly) negatively correlated. The phase of the important semiannual oscillation changes at about 55°S (Simmonds and Jones 1988) and in that sense represents an important crossover point in the SH. In accord with these considerations, the analysis of cyclone size is undertaken for the two hemispheric latitude bands 30°–50° and 50°–70°.

a. Scale changes in Northern Hemisphere winter

Attention is first confined to winter cyclones (the season that was the subject of the work of Grotjahn and his colleagues) that are in the 30°–50°N belt at the halfway point of their lifetimes. All cyclones that are still in existence after a specified period from their first identification are compiled. The mean radius of all such cyclones is then calculated. Figure 2a shows the plot of this mean radius as a function of time since cyclone inception. (It will be noticed in this and similar plots that the curve becomes more noisy with lifetime, because only a small fraction of cases survive to the longer times. The spike at day 13 is due to this sampling problem, and only 11 cases over the entire period contribute to this average.) At the initial time the mean radius of these cyclones is 4.8° of latitude. It will be seen that the radius increases to a flat maximum at about day 5, at which time the mean radius is 6.1° lat. Subsequent to this, the cyclones show a slow trend toward becoming smaller. The increase in radius is in qualitative agreement with the findings of GHC and GC. The growth rate, however, is smaller, representing an increase of

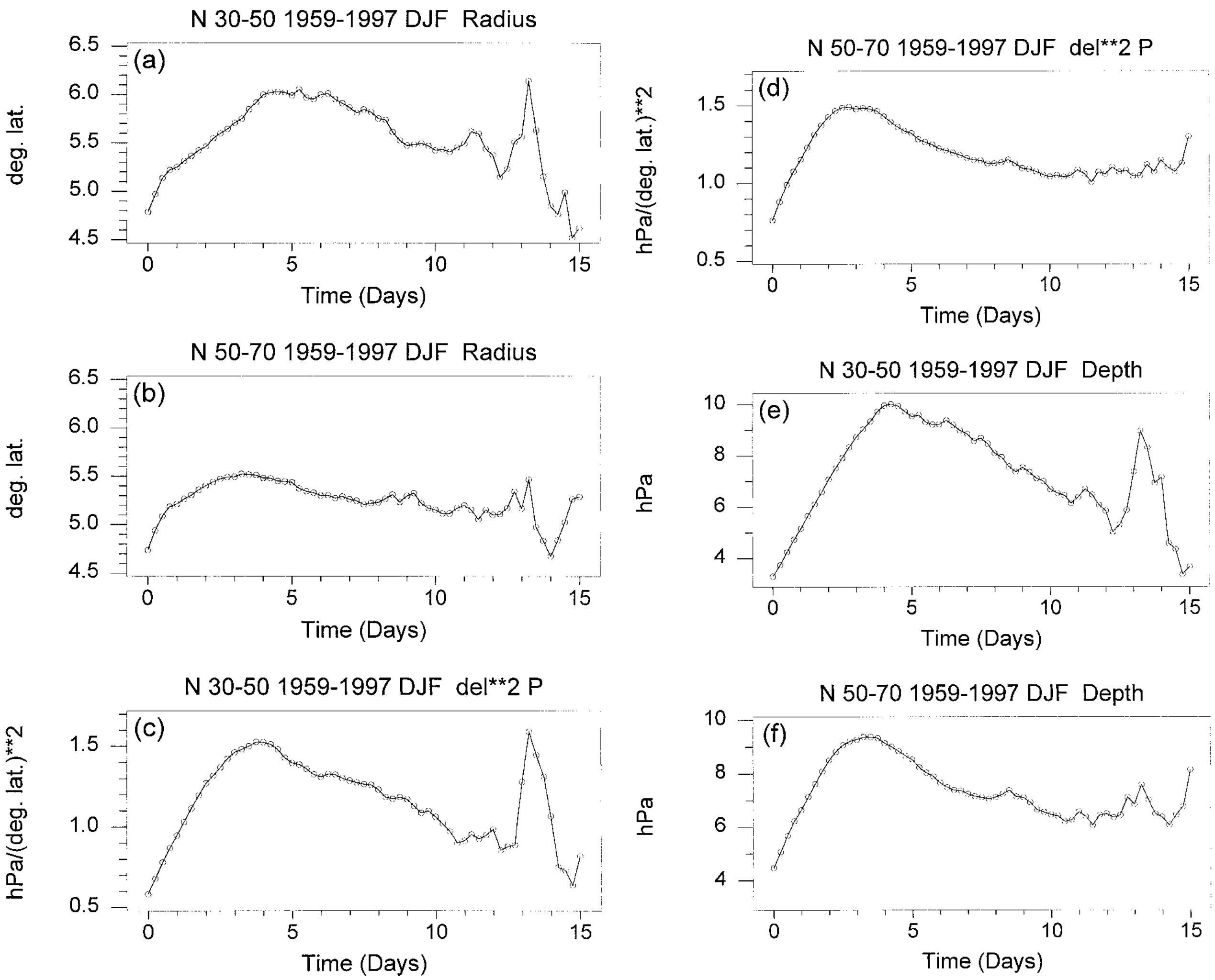

FIG. 2. Mean radius of cyclones as a function of time after formation in (a) 30°–50°N and (b) 50°–70°N. Mean $\nabla^2 p$ of cyclones as a function of time after formation in (c) 30°–50°N and (d) 50°–70°N. Mean depth of cyclones as a function of time after formation in (e) 30°–50°N and (f) 50°–70°N. The data are compiled for all Dec–Feb periods from 1959 to 1997. (Cyclones are placed in the band in which they were located halfway through their lifetimes.) The units are ° lat, hPa (° lat)$^{-2}$, and hPa.

about 27% over 5 days. A somewhat similar picture is revealed when the winter cyclones in the 50°–70°N latitude belt is considered (Fig. 2b). In this case the mean maximum is reached just after 3 days (4.7°–5.5° lat), a growth of about 17%.

In assessing the role cyclones play in weather and climate it is important to obtain measures to quantify their significance. The earlier discussion pointed to the importance of the intensity (as measured by the Laplacian of pressure, $\nabla^2 p$, in the vicinity of the center) and the depth D of the system. Figures 2c and 2d show the evolution of the mean intensity of systems in the two belts. In the midlatitudes, this parameter reaches a maximum in less than 4 days, and undergoes an increase of about 180% in that time. The rate of intensification in the 50°–70°N latitude belt is slightly more modest, but a flat maximum is reached at about day 3. The mean depth of the systems undergoes an even greater percentage change. The structure of the plots of depth (Figs. 2e and 2f) are very similar to those of intensity except, as one would expect, the maxima occur slightly later.

In interpreting the above figures it is important to bear in mind that as longer periods after initiation are considered fewer cyclones participate in the averaging process. So, for example, the decrease in radius after 5 days may not be a comment on a mean weakening of systems but could conceivably be due to the longer-lived systems being inherently weaker. To obtain an appreciation of the distribution of cyclone lifetimes presented in columns 2 and 3 of Table 1 are the percentage of tracks in the two latitude bands, which last precisely 1 day, greater than 1 and up to 2 days, . . . , greater than 9 and up to 10 days, and greater than 10 days. It will be seen that in the 50°–70°N band, for example, that about half the tracks last longer than 3 days, about 24% exceed 5 days, and approximately 9% have a lifetime

TABLE 1. The percentage (and totals in parentheses) breakdown of tracks in the latitude bands 30°–50° and 50°–70° (in both the NH and SH) in Dec–Feb (DJF) and JJA by lifetime. A cyclone track is allocated to the latitude band in which it was located halfway through its life.

Duration (days)	DJF		JJA		DJF		JJA	
	30°–50°N	50°–70°N	30°–50°N	50°–70°N	30°–50°S	50°–70°S	30°–50°S	50°–70°S
1	9.6 (652)	6.5 (464)	5.1 (202)	3.9 (244)	10.6 (510)	6.1 (482)	10.2 (788)	6.8 (656)
1.25–2	31.7 (2148)	26.0 (1849)	25.7 (1010)	22.6 (1428)	36.0 (1736)	22.6 (1783)	33.1 (2551)	23.6 (2283)
2.25–3	19.6 (1327)	18.7 (1335)	21.0 (826)	20.1 (1270)	19.3 (929)	15.7 (1236)	19.4 (1494)	16.1 (1560)
3.25–4	13.0 (879)	14.1 (1003)	13.5 (530)	15.5 (976)	11.4 (551)	12.3 (973)	11.3 (873)	12.5 (1210)
4.25–5	8.6 (582)	11.1 (787)	10.9 (426)	12.2 (771)	7.7 (371)	10.6 (835)	7.9 (612)	10.6 (1025)
5.25–6	6.5 (439)	8.6 (612)	6.8 (266)	8.8 (556)	4.7 (225)	8.4 (663)	5.6 (431)	8.1 (782)
6.25–7	4.5 (303)	5.7 (405)	5.2 (204)	5.3 (334)	3.1 (149)	7.1 (559)	3.9 (298)	6.4 (618)
7.25–8	2.5 (168)	3.8 (272)	4.2 (164)	4.4 (274)	2.4 (116)	5.2 (409)	2.8 (216)	4.7 (456)
8.25–9	1.8 (121)	2.1 (146)	2.6 (101)	2.3 (145)	1.4 (65)	4.3 (336)	1.9 (143)	3.3 (319)
9.25–10	1.0 (70)	1.4 (96)	1.6 (63)	1.6 (102)	1.0 (47)	2.5 (194)	1.2 (96)	2.5 (244)
> 10	1.3 (86)	2.1 (154)	3.5 (139)	3.3 (206)	2.5 (118)	5.2 (412)	2.8 (212)	5.3 (510)
Total	100 (6775)	100 (7123)	100 (3931)	100 (6306)	100 (4817)	100 (7882)	100 (7714)	100 (9663)

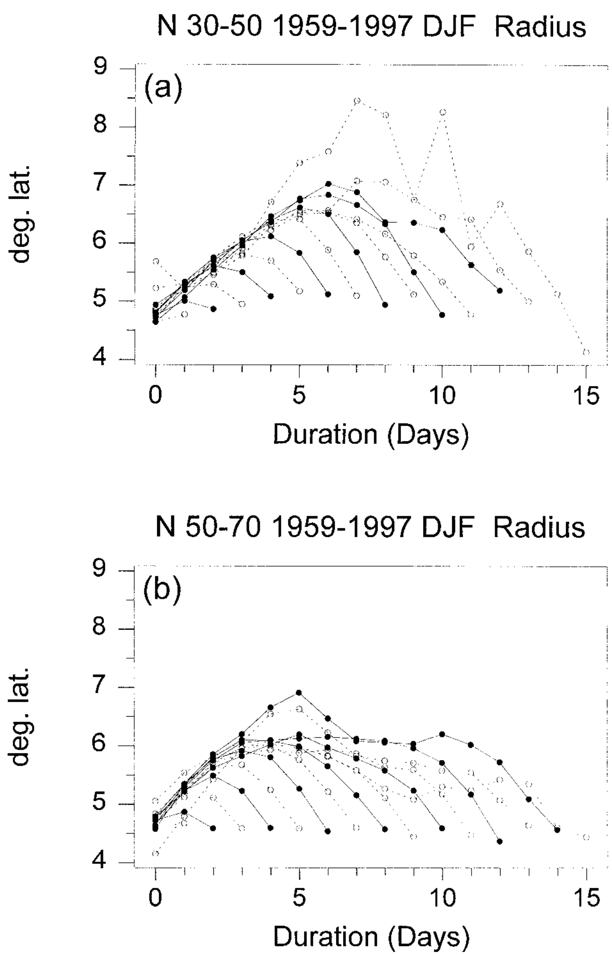

FIG. 3. (a) Mean evolution of the radius of cyclones that last for precisely 1 day, greater than 1 and up to 2 days, . . . , and greater than 14 and up to 15 days. These data are for the 30°–50°N belt for all Dec–Feb periods from 1959 to 1997. (b) As in (a) but for the 50°–70°N belt. (Cyclones are placed in the band in which they were located halfway through their lifetimes.) The units are ° lat.

in excess of 1 week. Hence there is a sizeable proportion of systems that are long lived. To expose the potential bias mentioned above all the cyclones are stratified by the length of their lifetimes, and the evolution of their mean radius up to their termination is considered. In Fig. 3 is plotted the evolution of the radius of systems that last for precisely 1 day, greater than 1 and up to 2 days, . . . , and greater than 14 and up to 15 days. The plot reveals a number of interesting features. First the initial growth rate of systems that have lifetimes of less than 3 days is considerably less than that of the longer-lived cyclones. The growth rates of systems that last longer than this are all rather similar at about 33% over 4 days. Hence, by confining attention to the part of the sample that lasts in excess of 3 days the rate of increase in radius is considerably in excess of that derived above.

Another feature worthy of comment in Fig. 3 is that while most of the curves display a close to symmetric structure, they do exhibit small negative skewness; that is, the rate at which the radius decreases after its maximum exceeds the rate of increase during the growth phase. In general, one can say that the longer-lived cyclones assume greater maximum radius, a finding in agreement for the results of Nielsen and Dole (1992).

Figure 3b presents similar information but for the 50°–70°N latitude band. In this case also the longer-lived systems are seen to increase their radius by about one-third over the first 4 days, but it will be noted that the initial rate of increase in size of these systems (which, recall, find themselves in the 50°–70°N latitude belt halfway through their lives) is much larger that those found on the latitude belt to the south. Another point of difference is that the individual curves show very little, or even positive, skewness.

b. Northern Hemisphere summer

Although, following the work of Grotjahn and his coworkers, the primary focus here is on scale changes in winter cyclones, it is informative to also consider the

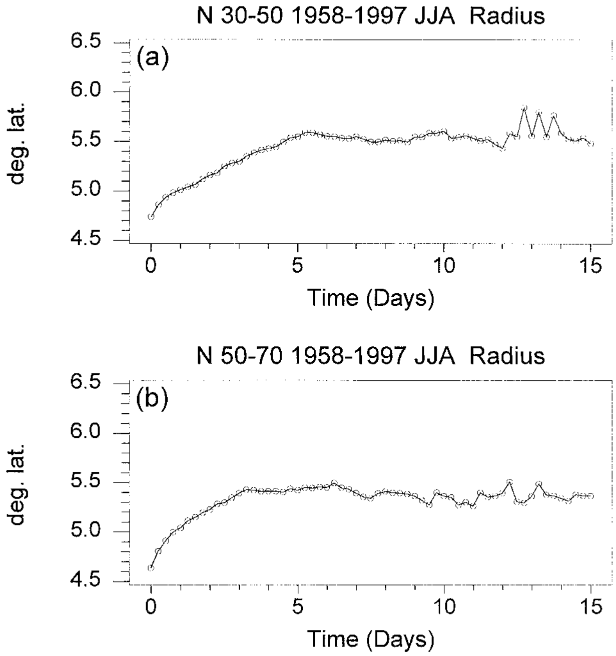

FIG. 4. Mean radius of cyclones as a function of time after formation in (a) 30°–50°N and (b) 50°–70°N. The data are compiled for all Jun–Aug periods from 1958 to 1997. (Cyclones are placed in the band in which they were located halfway through their lifetimes.) The units are ° lat, hPa (° lat)$^{-2}$, and hPa.

mean behavior in summer [June–August (JJA)]. The evolution of the mean radius in the 30°–50°N and 50°–70°N latitude belts in this season are presented in Fig. 4. The behavior of the graphs for the two seasons have a number of features in common, but the summer plots rise to their maxima somewhat later than their winter counterparts. In addition, the information in Table 1 shows that the percentage breakdown of systems by lifetime range is similar in summer and winter. However, the rate of increase in radius is less marked in summer, particularly in the midlatitude belt, and the systems at maximum radius tend to be somewhat smaller. Another interesting point of difference is that in summer the mean radius in the two belts does not show a reduction in scale after day 5.

c. Southern Hemisphere scale changes

Bearing in mind the aim of assessing the generality of the results obtained by GHC these considerations of radius change are extended to SH cyclones. It is known that the behavior of cyclonic systems in that hemisphere tend to differ in many respects from that in the north. For example, Hoskins and Valdes (1990) concluded that diabatic heating maintains the baroclinicity of the NH storm track regions. They cautioned that the storm track maintenance mechanisms in the SH may be different because of the weakness of the midlatitude land–ocean contrasts. Part of the reason for this hemispheric asymmetry is the very different continentality and topography in the two hemispheres, which result in dissimilar thermal and dynamical influences on cyclonic initiation and evolution (see, e.g., Trenberth 1987, 1991; Jones and Simmonds 1993; Sinclair 1994, 1997). Sinclair (1997) undertook some case studies of the allocation of a domain to a cyclone in the SH, but did not present climatologies of the size of these domains.

In winter, the mean radius of cyclones in the belts 30°–50°S and 50°–70°S (Figs. 5a and 5b) are seen also to exhibit an increase in scale after first identification. The peaks are reached somewhat later than in the NH (at about day 6), while the scale increases are similar over the period. It will be noticed that the SH systems are larger, this being particularly marked at the high latitudes. This may be a reflection of the poorer data coverage in the SH, or it may have a physical basis in that as the cyclone distribution in the SH is more zonally symmetric they have more freedom to grow to larger size than in the NH where stationary long waves cause lows to bunch up. Figures 5c and 5d show that in the southern summer surface cyclonic systems also manifest an increase in scale in the early days of their development. In the 30°–50°S belt the evolution of the radius differs from that in winter and resembles that of the northern summer. It will be noted that the maximum scale is reached later in the SH (about day 8). In the interest of brevity the evolution of the radius of systems stratified by lifetime is not shown here, but is similar to that revealed for the NH. Of note is the deduction which can be drawn from Table 1 that the percentage of systems lasting in excess of 4 days is about 43% in the 50°–70°S belt, while only about 25% in the 30°–50°S belt, a statement that holds for both seasons. On average, the winter systems are larger than those in summer in the 30°–50°S belt, while the opposite is true in the 50°–70°S domain. This difference in seasonality is also apparent from the geographical distribution of mean cyclone radius presented by Simmonds and Keay (2000a).

4. Discussion and concluding remarks

The results obtained here are in agreement with those in the limited literature on this topic. This comprehensive study has shown that the radius of surface cyclonic systems increases as they evolve to maturity. This general result appears to hold for the two baroclinic domains considered in both hemispheres. In addition, cyclonic systems exhibit this behavior in both winter and summer, although there are some interesting seasonal differences in detail. The scale changes assumed a structure that was quasi-linear in time, a result consistent with the findings of GHC.

It is worth making the point explicitly that there is no single, ''best'' definition of radius or size of a system and different measures have been used in past studies. It had been commented earlier that the cyclone scheme

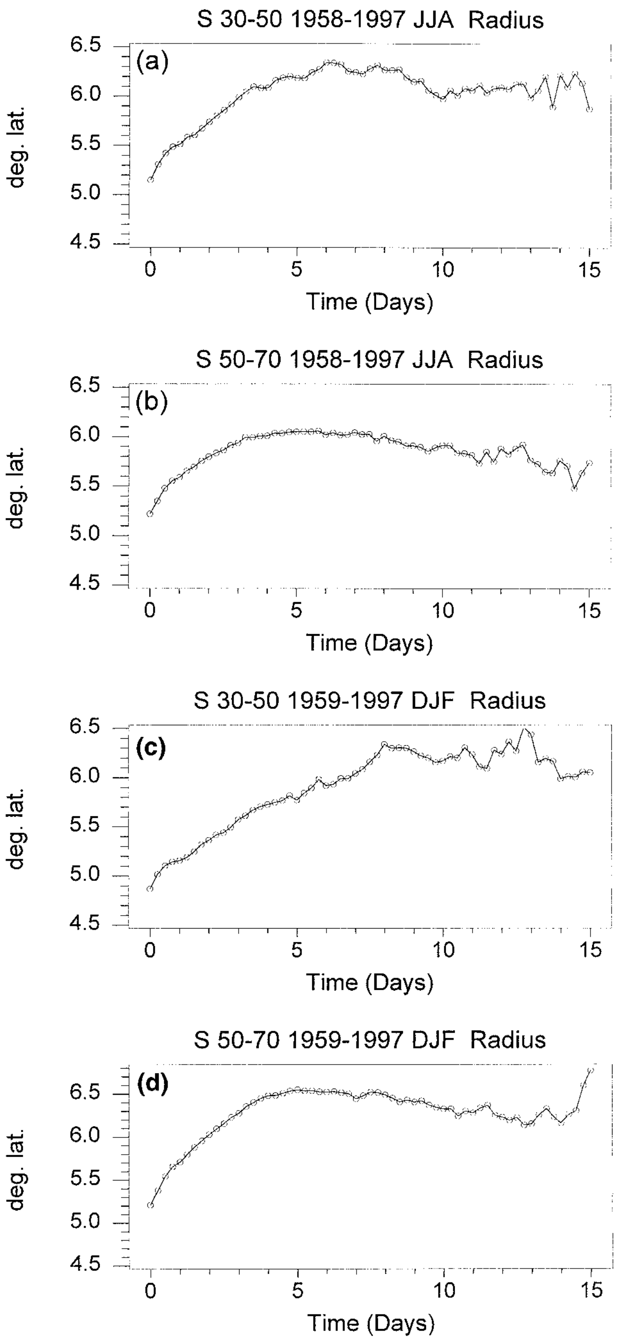

FIG. 5. Mean radius of cyclones as a function of time after formation in (a) 30°–50°S and (b) 50°–70°S for all Jun–Aug periods from 1958 to 1997. Mean radius of cyclones as a function of time after formation in (c) 30°–50°S and (d) 50°–70°S for all Dec–Feb periods from 1959 to 1997. (Cyclones are placed in the band in which they were located halfway through their lifetimes.) The units are ° lat, hPa (° lat)$^{-2}$, and hPa.

is sufficiently sophisticated to identify multiple centers as would a synoptician. Because of this, the mean radius in the region would be somewhat smaller than if one considered the whole complex as a single low. Hence while it is not possible to compare the present results directly with those previously obtained in regional studies, one would agree with the tenor of the comment of GHC that the ‘‘widths’’ (in their case calculated from a wavelet analysis) ‘‘are not intended to represent exactly one half-wavelength but merely a consistent, objective measure of a specific property of that cyclone.’’ Hence the precise definition of the size of a system may not be all that important, particularly in studies where it is the geographical distribution and *change* in this parameter that is of interest.

The fact that the increase in cyclone radius is a global phenomenon reinforces the idea that linear theoretical models of cyclone development (e.g., Holton 1992) may have only limited applicability to understanding the evolution of real cyclonic systems. Of course, there is a large body of work that has been devoted to distinguishing between types of cyclone development, and the behavior of modal and nonmodal baroclinic waves. Theoretical (e.g., Farrell 1984, 1985, 1988, 1989; Farrell and Ioannou 1996; Tippett 1999) and observational (e.g., Frederiksen 1985, 1997) investigations have shown that the structure of nonnormal modes produced by the ‘‘initial value’’ approach can be quite different to those to be expected from normal mode analysis.

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