Characteristics of Tropical Cyclones in the Australian Region

RICHARD A. DARE AND NOEL E. DAVIDSON

Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia

(Manuscript received 8 October 2003, in final form 7 June 2004)

ABSTRACT

Characteristics of 500 tropical cyclones (TCs) in the Australian region and its three individual basins are examined based on 40 yr of satellite-supported observations. While tropical cyclones exhibit highly individual behaviors resulting in significant standard deviations, there are some systematic behaviors, which are documented. Most TCs in the Australian region originate from December to April. About 13 are observed each season, with half occurring in the western basin. Generally, the lifetime of a TC is about 7½ days, during which time it covers over 2500 km at a mean speed of 15 km h^{-1}. Around half of the storms reach a maximum intensity corresponding to category 3 or higher (<970 hPa), as classified using a modified Saffir–Simpson scale. Tropical cyclones in the western and eastern basins have around 25% chance of making landfall, while those in the northern basin have an 80% chance.

There appear to be preferred locations for TC genesis, close to the Australian coastline at around 120°, 135°, and 150°E. Genesis occurs near the mean position of the maximum low-level cyclonic vorticity and coincides with the monsoon trough from December to February, but occurs poleward of the trough in other months. The maximum intensity eventually achieved by TCs varies with genesis locations. For storms that reach category 3 or above, there are more corresponding origin points in the west than in both the gulf and the eastern basin.

Recurvature generally follows attainment of maximum intensity, suggesting the importance of trough interactions on this behavior. The likelihood of extratropical transition of TCs, in the mean, increases to a peak in March, although there is variability across the three basins of the Australian region. Final dissipation has no preferred latitude, with many storms dissipating over the warm tropical oceans equatorward of 20°S.

1. Introduction

A large part of northern continental Australia and many thousands of kilometers of Australian coastline lie in the Tropics and are subject to development of the austral summer monsoon. As a result, the region is subject to strong winds and heavy rainfalls associated with monsoon depressions, tropical storms, and tropical cyclones (TCs) that evolve within the monsoon trough over the warm tropical waters. The development and behavior of TCs are critically important because these warm-cored low pressure systems contain the most destructive near-surface winds observed virtually anywhere in Australia. In addition to the strong winds, human lives and property are threatened by the associated sea swells, coastal storm surges, and floods. In terms of responsibility for forecasting of TCs, the Australian region reaches from 90° to 160°E in the Southern Hemisphere, encompassing the northern coastlines of Western Australia, Northern Territory, and Queensland and extending toward neighboring lands including Indonesia, Papua New Guinea, and Fiji. The Australian region is, of course, just one of several basins in the world's tropical oceans that support the existence of TCs (Palmen 1948; Pielke 1990), with around 15%–20% of the world's total occurring in this basin (Gray 1975).

Several factors are thought to be responsible for the genesis and continued support of TCs. These include a warm mixed layer in the upper ocean (with SST at least 26°C), moderately small wind shear between the lower and upper troposphere, low-level convergence, a conditionally unstable atmosphere, and a location poleward of about 5° of latitude (Gray 1979; Pielke 1990). Upper-tropospheric divergence is also believed to bolster genesis. While tropical regions provide the required warm oceans, those areas very near the equator are not usually supportive of TC genesis because of the small Coriolis effect at very low latitudes. Once a TC has developed, a primary factor that influences its continued existence is the heat and moisture supply from the surface. Therefore, movement of a TC from over an ocean surface to over land generally means that the system decays within a few hours or days. Of course, this time period varies depending on the underlying surface and the synoptic environment in which the TC is embedded. It is even possible that the circulation may reintensify if it were to move offshore into a favorable environment.

Over recent decades, several climatologies of TC gen-

Corresponding author address: Dr. R. A. Dare, BMRC, P.O. Box 1289K, Melbourne, Victoria 3001, Australia.
E-mail: rad@bom.gov.au

TABLE 1. Boundaries of the three sub-Australian regions in the Southern Hemisphere.

Australian region (basin)	Lon range
1) Western	90° to 125°E
2) Northern	125° to 142°30′E
3) Eastern	142°30′ to 160°E

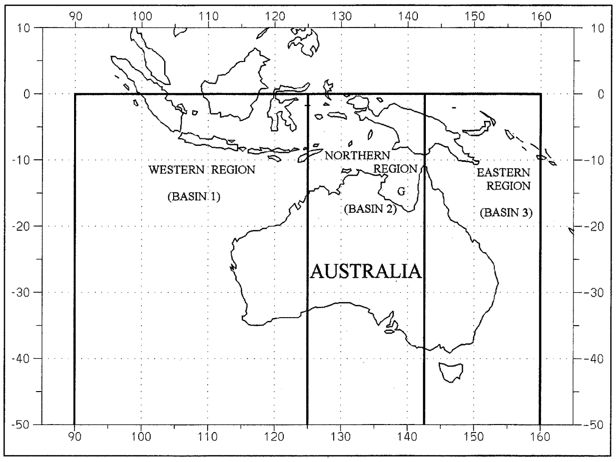

FIG. 1. The Australian region and its three basins between 90° and 160°E (refer to Table 1). In the present work, for purposes of climatological analysis, the regions are simplified relative to those defined for operational and political purposes. Also noted is the Gulf of Carpentaria (G).

esis and motions have been constructed for the Australian region (Lourensz 1977, 1981; McBride and Keenan 1982; Holland 1984). While each of these reports made use of high quality datasets, relatively few observations were available from the period following the introduction of satellite observations in 1964. The present work differs in that it uses the entire record of TC tracks and central pressures observed during the satellite era, with more than half of the entries further enhanced by the presence of Japan's Geostationary Meteorological Satellite (GMS) over the Australian region since about 1978. Currently, this dataset covers over 40 yr of satellite-era observations. While one may wish to establish a climatology based on records covering an even greater period of time, the high quality of the data, due to the satellite support, means that the present set of data may have greater reliability than a more extensive dataset covering the nonsatellite era.

In the following section, some issues regarding data processing and definitions are discussed. Section 3 contains a discussion on the mean large-scale environment of the Australian region monsoon, in which TCs develop. Climatological and seasonal mean characteristics of TCs are considered in section 4. Geographic distributions of TCs during various phases of their lifetimes are discussed in section 5, followed in section 6 by an analysis of characteristics associated with TC origins. The poleward movements of TCs, which provides the possibility of extratropical transition, are discussed in section 7. A summary and conclusions are given in section 8.

2. Definitions and data processing

In this section, some relevant terms are defined and some issues regarding the processing and the use and discarding of observations are discussed.

In the Australian region, a TC is defined to be a nonfrontal, synoptic-scale cyclone that has developed over tropical waters, with a 10-min average wind speed, $V \geq 63$ km h^{-1} near the center of the organized wind circulation.

The definition of the Australian region of responsibility for TC warnings is somewhat dependent on both international and domestic political boundaries (see, e.g., Kingston 1986). However, as the region is quite extensive, reaching from 90° to 160°E, with northern boundaries varying between 12°S and the equator, it is likely to contain TCs relevant to Australia. For simplicity and because political boundaries are not relevant to the study of TC behavior, some adjustments are made to the boundaries. As the TCs considered in the present work are only those that have been previously observed within the Australian region, the northern and southern boundaries are no longer relevant and may be discarded. More significantly, boundaries between domestic TC regions of responsibility are slightly altered (Table 1 and Fig. 1). While it may be feasible to divide the Gulf of Carpentaria based on domestic political boundaries for purposes of assigning regions of responsibility for issuing TC warnings, it is not useful from a geographically based climatological point of view. Instead, the eastern boundary of the northern region is redefined to be the longitude 142°30′E, which passes close to the northern tip of the Cape York Peninsula (Fig. 1). The western boundary of the northern region is also altered, with the boundary remaining set at 125°E regardless of latitude and the continental domestic border.

A TC season is defined to be the period from the appearance of the first TC from 1 July of one year to the last day of the last TC up to 30 June the following year. For convenience, each season is labeled using the first of the two relevant calendar years; for example, the season covering the period July 1963 to June 1964 is referred to as season 1963.

In order to maximize accuracy, the ''best track'' data used in the present work have been refined after the event to allow incorporation of all relevant observations without the imposition of time constraints often present in an operational forecasting environment. This means that the dataset solely contains observations of storms categorized as TCs. However, additional filtering of the data is required to ensure that only reliable data are used in the analysis. The majority of the dataset contained points separated by intervals of 6 h, with TC location and central pressure defined at 0000, 0600, 1200, and

TABLE 2. Tropical cyclone categories and corresponding values of approximate average maximum wind speeds and central pressures, modified for the Australian region from the Saffir–Simpson scale (Simpson 1974).

Category	Avg max wind (km h^{-1})	Central pressure (hPa)
1	63–90	>985
2	90–125	985–970
3	125–165	970–955
4	165–225	955–930
5	>225	<930

1800 UTC. To ensure temporal consistency throughout the dataset, some points required interpolation to these key times.

One must be aware that some points in the dataset do not define a TC's central pressure. While these points cannot be used in any analysis that depends on central pressure, the corresponding information defining the location of the storm can be used in other calculations. Care must also be taken in examining the origin of each TC. An origin point is defined to be the earliest location along a TC's path where the storm is located over a water surface. This is a necessary condition to apply because the dataset contains storm paths prior to their intensification to the level of a tropical cyclone, with some of these points present over land surfaces. Some TCs in the dataset originated within the Australian region but then moved, and spent the majority of their lives, out of the domain. There were also TCs that originated outside of the Australian region but later relocated to this region. These data are included in the analysis where applicable, although the majority of TCs considered did originate and remain within the Australian region. Despite these minor shortcomings, there is still valuable information to be gained from careful analysis of the data.

Estimation of TC intensity in the Australian region is based almost exclusively on the method of Dvorak (1984). From this method's determination of the current intensity number, the maximum wind and central pressure are estimated using the method of Atkinson and Holliday (1977), but with modifications to account for operational experience and available observations. Errors in intensity estimates might be large, but the analysis performed here may be valuable for operations and in documenting systematic characteristics of this parameter. Tropical cyclone categories similar to the Saffir–Simpson hurricane scale (Simpson 1974) are used. The scale has been modified for local use in the Australian region, with ranges of central pressures for the five categories that differ from those in other basins (Table 2).

3. The large-scale environment of the Australian region monsoon

Before discussing parameters associated with TC behavior, it is useful to briefly examine the mean large-scale environment of northern Australia and adjacent tropical regions. It has been recognized (McBride and Keenan 1982) that Australian-region TCs appear to develop in the Southern Hemisphere monsoon trough (MT). Discussions here and in later sections support this observation. Midlatitude troughs and ridges that develop and propagate in regions south of the MT also influence the subsequent evolution of TCs. To illustrate, Fig. 2 shows, from a December-to-April mean based on National Centers for Environmental Prediction (NCEP) reanalyses (Kalnay et al. 1996), the 850-hPa wind and relative vorticity, the 200-hPa mean flow, and a north–south cross section of zonal wind and relative vorticity averaged over monsoon longitudes.

In the mean, the 850-hPa monsoon trough, which we define to be the line of separation between the tropical westerlies and subtropical easterlies, covers the entire Australian-region TC basin.

The line of maximum cyclonic vorticity often coincides with the MT, but depending on the strength of the wind maxima to the north and south, it can be displaced from the trough. Later (section 6), it will be shown that regions of genesis generally correspond with the line of maximum cyclonic vorticity. Local maxima in cyclonic vorticity at 850 hPa, evident in Fig. 2a, correspond well with regions of preferred genesis near 135° and 150°E (section 5). Interestingly, a local minima in cyclonic vorticity near 120°E also corresponds with a region of preferred genesis. Perhaps understandably, there are other factors apart from low-level cyclonic vorticity influencing TC formation. It is important to note that the mean field contains representations of TCs and their associated large cyclonic vorticity. It is not clear to what degree the mean flow and the vorticity distribution are defined by the very presence of TCs.

At upper levels (Fig. 2b) the subtropical ridge is located around 12°S, with tropical easterlies to its north extending well into the Northern Hemisphere. The weak wind shear regime of an upper-level ridge overlaying the monsoon trough provides seemingly favorable conditions for TC formation. Midlatitude westerlies are evident just to the south of the ridge. The close approach by this major wind system, with embedded troughs and ridges, appears to have a large influence on the often erratic behavior of TCs, the nature of which is noted throughout later sections.

The zonal wind cross section illustrates the vertical structure of the large-scale monsoon environment (Fig. 2c). The slight poleward displacement of the line of maximum cyclonic vorticity from the MT is evident at low levels. The MT extends to about 600 hPa and, coupled with the weak wind shear, further illustrates the favorable conditions for TC formation. Westerly winds associated with the fringe of the Southern Hemisphere subtropical jet (located in the mean near 200 hPa between 25° and 30°S) extend northward to within a few hundred kilometers of the MT.

The geography shown in Fig. 1 and the large-scale

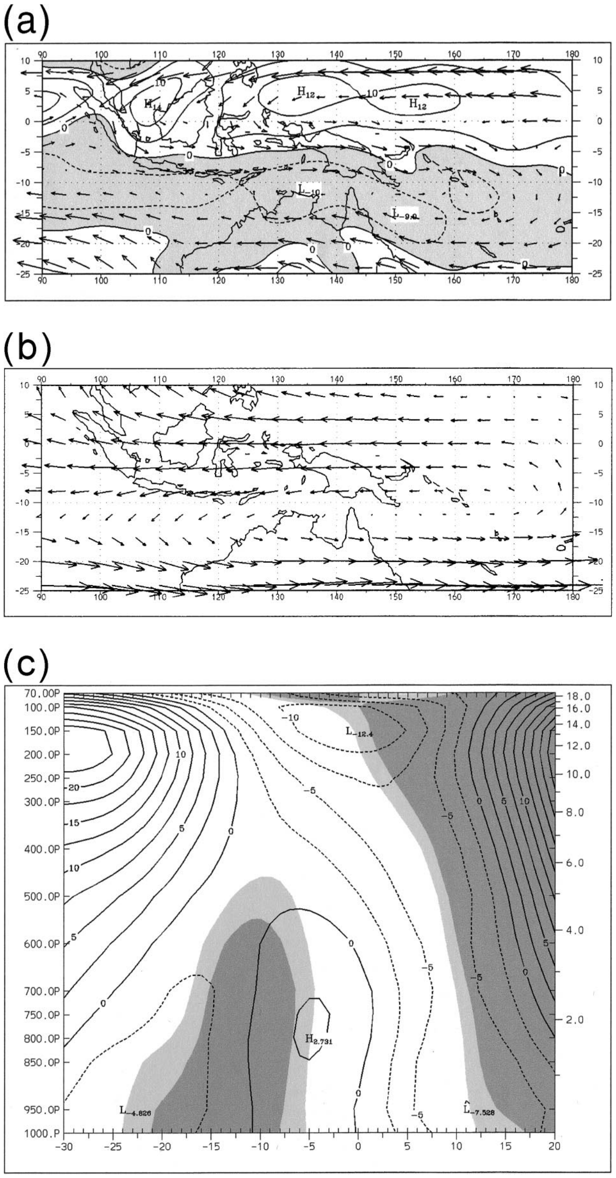

FIG. 2. (a) Mean Dec–Apr 850-hPa-level wind vectors and relative vorticity contours over northern Australia and tropical regions 90°E to 180°, based on NCEP reanalyses (Kalnay et al. 1996). Negative contours are dashed and shaded and indicate cyclonic vorticity in the Southern Hemisphere. The contour interval is 5×10^{-6} s^{-1}. (b) Mean Dec–Apr 200-hPa-level wind vectors over northern Australia and tropical regions 90°E to 180°, based on NCEP reanalyses (Kalnay et al. 1996). (c) Mean Dec–Apr vertical north–south cross section of zonal wind speed contours and relative vorticity (shaded) over monsoon longitudes 90°E to 180°, based on NCEP reanalyses (Kalnay et al. 1996). The contour interval is 2.5 m s^{-1} for wind and 10^{-6} s^{-1} for relative vorticity. Cyclonic vorticity is negative in the Southern Hemisphere. The latitudes are labeled in the conventional manner, with the Southern Hemisphere indicated using negative values.

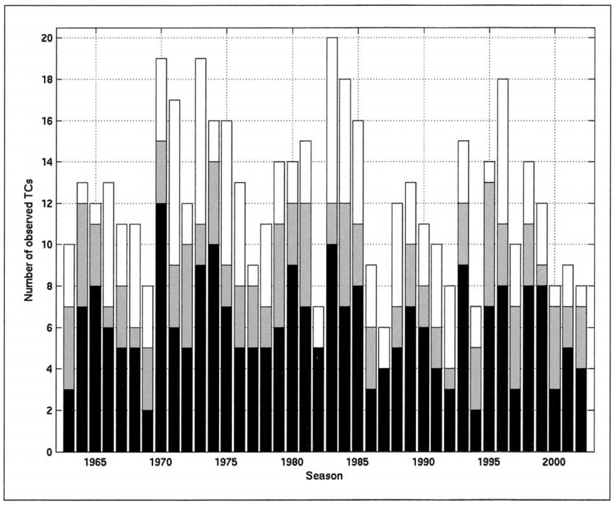

FIG. 3. Number of observed TCs each season for basin 1 (west, black), basin 2 (north, gray), and basin 3 (east, white).

mean structures illustrated in Fig. 2 suggest that unique features of the Australian basin are 1) the monsoon environment, 2) the close approach of the midlatitude westerlies, and 3) the existence of a major landmass: the Australian continent. These features appear to strongly influence the mean behavior of TCs in the Australian region (see also Holland 1984) and may lead to much greater variability in behavior of TCs relative to other basins. In a comparison of motion for seven TC basins, Bessafi et al. (2002) document the much greater variability in speed and direction of motion for Australian-region TCs. As noted throughout the sections that follow, characteristics of TCs in the Australian region are found to be quite variable.

4. Climatology of TC characteristics

a. TC number, lifetime, and days

The total number of TCs observed in the Australian region from season 1963 (–1964) to 2002 (–2003) was 500. The numbers of TCs observed each season during this period are shown in Fig. 3. There was generally TC activity in all three basins each season. Large interannual variations are evident throughout the 40-yr period covered by the dataset, with the total number per season ranging from 6 up to 20. The climatological mean number of TCs per season for the period in question is 12.5. Around half of these appear in the west basin (Table 3, row 1), which is probably due in part to the very large area covered by this basin compared with the other two basins of the Australian region.

The mean first day of appearance of a TC in the Australian region each season is 19 December. There is a 64% chance that the first TC will appear in the western basin. Neglecting the appearance of TC Lindsay during winter (July 1996), the earliest first day of appearance of a TC was 7 October 1998 (TC Zelia), while the latest first day of the appearance of a TC was 17 January 1987 (TC Connie). The mean last day of TC activity in the Australian region is 14 May. The last day has varied from 26 March, with TC Nathan in 1998, to as late as

TABLE 3. Climatological mean characteristics of tropical cyclones in the Australian region and its three basins. Standard deviations corresponding to mean values are given in square brackets; d is days.

	Climatological mean field	All Australian basins		Basin 1 (west)		Basin 2 (north)		Basin 3 (east)	
1	Number of TCs per season	12.5	[3.6]	6.0	[2.3]	2.9	[1.4]	3.6	[2.0]
2	TC lifetime	7d 11h	[4d 3h]	7d 16h	[4d 0h]	6d 11h	[3d 10h]	7d 22h	[4d 17h]
3	TC days per season	75.4	[24.7]	44.2	[21.0]	19.4	[10.6]	27.1	[17.1]
4	Landfall TCs per season (% total)	4.9 (40%)	[2.3]	1.5 (28%)	[1.1]	2.3 (73%)	[1.4]	1.2 (31%)	[1.1]
5	No. of landfalls per season	6.6	[3.3]	1.6	[1.2]	3.5	[2.7]	1.5	[1.6]
6	Total distance traveled (km)	2868	[1835]	2842	[1726]	2475	[1677]	3236	[2059]
7	Total displacement (km)	2042	[1391]	2007	[1210]	1838	[1380]	2270	[1640]
8	Displacement/distance (totals)	71%	[22]	71%	[21]	74%	[21]	70%	[24]
9	LCP (hPa)	969	[23]	967	[24]	972	[23]	971	[21]
10	Time to reach LCP (% life)	3d 12h (47%)	[2d 13h]	3d 15h (47%)	[2d 9h]	3d 11h (52%)	[2d 9h]	3d 10h (44%)	[3d 0h]
11	Time within 10-hPa LCP (% life)	1d 14h (23%)	[1d 7h]	1d 13h (22%)	[1d 6h]	1d 14h (26%)	[1d 7h]	1d 16h (21%)	[1d 11h]
12	Distance to LCP (km)	1205	[981]	1150	[905]	1220	[1042]	1287	[1047]
13	Displacement to LCP (km)	986	[806]	945	[721]	1065	[927]	990	[834]
14	Displacement/distance (LCP)	82%	[44]	82%	[46]	87%	[30]	77%	[49]
15	%total distance to LCP	42%	[22]	40%	[21]	49%	[18]	40%	[25]
16	%total displacement to LCP	48%	[23]	47%	[21]	58%	[22]	44%	[27]
17	Speed (km h^{-1})	16	[6]	15	[6]	15	[6]	17	[7]
18	Speed to LCP (km h^{-1})	14	[6]	13	[6]	14	[6]	15	[7]
19	Speed after LCP (km h^{-1})	17	[10]	17	[9]	17	[9]	18	[11]

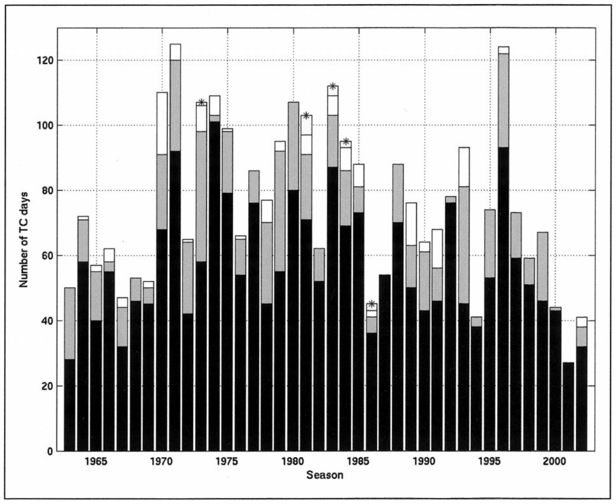

FIG. 4. Number of TC days in the Australian region each season. The columns of the histogram are separated into 1-TC days (black), 2-TC days (gray), 3-TC days (white), and 4-TC days (gray with asterisk).

6 June 1972 (TC Ida). Therefore, there is the potential for the Australian TC season to vary in duration from about 2 to 8 months.

Mean lifetimes of TCs have been computed over the Australian region and its individual basins. Generally, a TC will exist for a period of about 5 to 10 days, with a mean of about 7½ days. Climatological mean lifetimes (Table 3, row 2) of TCs present in basin 2 (north) are more than a day shorter than the other two basins. This is probably due to the somewhat landlocked nature of the northern environment, where the movement of a TC is likely to result in its eventual relocation over a land surface, leading to dissipation of the storm and the consequential shortening of the mean lifetime. This is particularly so when one considers the general poleward movement of TCs, with the northern basin bordered to its south by land. Despite the relatively short climatological mean lifetime of TCs in the northern basin, the mean seasonal lifetime of TCs originating in this basin exceeded those in the western and eastern basins during 30% to 40% of the seasons analyzed. The regions that show the most interseasonal variability are the northern and eastern. This may be due, at least partly, to the relatively small numbers of TCs observed in these two basins; the calculation of seasonal means based on a smaller number of TCs means, of course, that the result is influenced to a greater degree by the behavior of individual TCs. Relevant to this discussion is the well-known observation that TC motions can be quite erratic in the Australian region.

Considering the Australian region as a whole, there are about 75 days per season during which at least one TC is present (Table 3, row 3). As can be seen in Fig. 4, most TCs are present in the Australian region unaccompanied by other TCs. However, it is not rare to

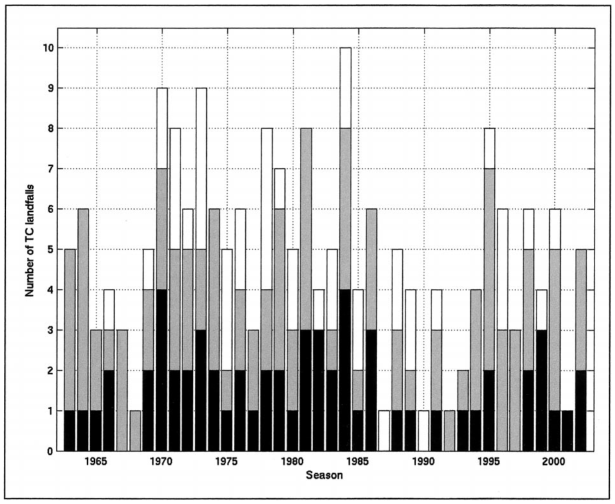

FIG. 5. Number of TCs that landfall each season in basin 1 (west, black), basin 2 (north, gray), and basin 3 (east, white).

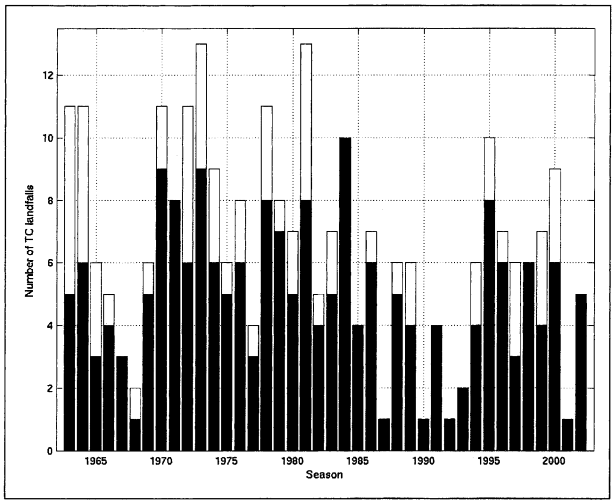

FIG. 6. Number of TCs that landfall in the Australian region per season (black) and the number of landfalls in the Australian region per season due to multiple coastal crossings by some TCs (black + white).

find two Australian-region TCs present on the same day, with this event occurring during all but two seasons from 1963 to 2002. Note that this analysis does not demand that the TCs are present between 90° and 160°E at the same time, but only that the TCs are active at the same moment and at some time during their lives were present between these longitudes. There are also many occasions when three Australian-region TCs are present at the same time, although the presence of four TCs at the same time is a relatively rare event.

b. *Landfalling TCs*

The mean number of TCs that landfall over the Australian continent (neglecting contact with small islands) each season is 4.9 (Table 3, row 4). The percentages shown here are intrabasin values indicating the fraction of TC numbers that landfall out of the total in each basin. Figure 5 shows that the number of landfalls per season has varied from a minimum of 1 up to a maximum of 10 over the 40 seasons analyzed. A seasonal mean of 2.3 TCs originating in the northern basin make landfall. That this value is larger than those found for the other two basins, with means of 1.5 and 1.2, respectively, is not unexpected, based on reasons associated with the relatively landlocked environment of the northern region. Differences between the basins, in terms of landfalls per season, are further pronounced by considering the percentage of TCs that make landfall. As shown in Table 3, 73% of TCs from basin 2 pass from the ocean to over land, while the other two basins present values of 28% (basin 1) and 31% (basin 3). Again, the relatively landlocked environment of the northern region can explain these differences. While there were some years in which every TC in either the west or east basins made landfall, observations of the north basin reveal that every TC present made landfall during as many as half of the seasons considered.

Although about five TCs move from over a water surface to over land per season (Table 3), the paths of some TCs is such that they make multiple landfalls. Figure 6 shows that at least one TC performed multiple landfalls somewhere within the Australian region during about 75% of the seasons examined. The climatological mean was found to be 6.6 landfalls per season in the Australian region (Table 3, row 5).

c. *Distances and displacements*

With an individual TC expected to exist for about one week, the mean distances covered by a TC throughout the Australian region generally varies between about 2000 and 4000 km (Table 3, row 6). In terms of distance covered, there is some general agreement between the mean behavior of TCs in the western basin and the Australian region. However, distances covered by TCs that originate in the northern basin are less than the all-basin mean, while those in the eastern basin are greater than the mean. Note the large standard deviations of these mean distances. In basins 2 and 3, mean distances covered by TCs are quite variable compared with the western and Australian regions. Although displacements are, of course, less than distances, the same general statements could be made in regard to displacement in comparing the mean behavior of TCs between basins (Table 3, row 7).

Tropical cyclones originating in the northern basin exhibit mean distances and displacements that are small compared with the other basins. Once again, the fact that the environment of the northern region is relatively landlocked explains this behavior. The significant differences in mean distance and displacement between the western and eastern regions are not so easily explained. As a slightly larger percentage of TCs make landfall in the eastern than in the western region, it might be expected that the mean distances and displacements found in the eastern region would be less than those in the western region. However, mean lifetime, distance, and displacement of TCs in the east are greater than those in the west. There are two points to make regarding these observations. First, one may conclude that TCs in the eastern region meander to a greater extent than those in the west. Second, a major difference between these two basins is that after recurvature, TCs in the west often make landfall over continental Australia while those in the east continue to exist over the ocean (moving eastward away from the continent located to the west), thus extending their lifetimes.

Calculating the ratio of displacement to distance is a simple method to assess the tendency of a TC to meander, or to at least move along a curved path, with a lower value suggesting greater meandering (Table 3, row 8). While the results do not reveal large differences between the various basins, the mean values suggest that TCs are least likely to meander in the northern basin and most likely to meander in the eastern basin.

d. Lowest central pressures

1) DISTRIBUTION AND LIFETIME

Sometime during the life of a TC, it achieves a maximum intensity, or lowest central pressure (LCP). Although there are large variations across the TC population, the mean values (Table 3, row 9) show that Australian TCs generally intensify to around category 2 or 3 (categorization based on Table 2), with the most intense storms likely to be found in the western basin. To further assess the intensity of TCs in the Australian region and its individual basins, each TC is counted, and then expressed as a percentage, based on the lowest central pressure achieved within 10-hPa intervals (Fig. 7). The general pattern is one of well-defined peaks corresponding to intensities of around 980–990 hPa, with a decline in occurrences toward higher intensities. Distributions for individual basins (not shown) are generally similar to that shown for the entire Australian region in Fig. 7.

Table 3 (row 10) shows climatological mean values of the period of time from the origin to achievement of LCP for each basin. The overall time period is about 3½ days, although this generally varies between about 2–4 days. The mean values are remarkably similar between basins, differing by no more than 5 h, a time period that is virtually insubstantial given the difficulties inherent in the observation of TC characteristics, such as intensity and position, upon which the lifetime of each TC is based. Also showing remarkable agreement between basins are the mean periods of time that the central pressure of a TC is within 10 hPa of the LCP (Table 3, row 11); as long as around 1½ days, or about 23% of the total lifetime, is spent within this zone.

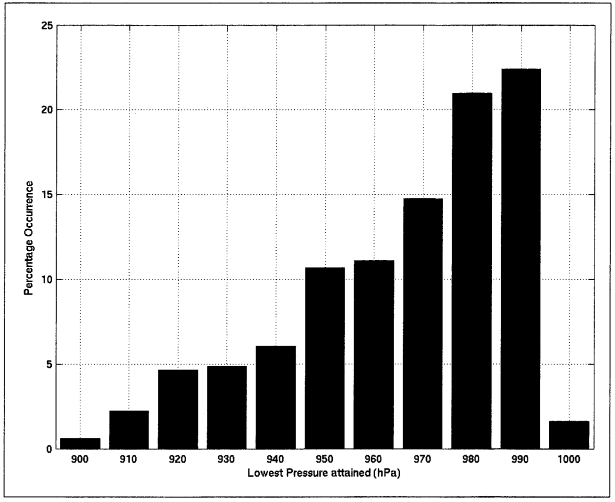

FIG. 7. Percentage occurrence of lowest central pressure attained by TCs in the Australian region (all basins) when classified into 10-hPa classes.

To place these periods in perspective, the percentage of a TC's lifetime from point of origin to maximum intensification has also been calculated (Table 3, row 10). One might expect that in an environment where TCs are located over waters surrounded by land, in the few days that a TC is occupied with intensification, there is some chance that its movement would result in its relocation over land, with the possibility of the circulation's demise. In such a situation, one would expect that the attainment of the LCP would occur toward the end of a TC's life, with a consequential increase in the percentage of a TC's lifetime occupied with intensification. Although there are only insignificant differences between the actual mean time periods taken for TCs to reach LCP in the respective basins, the climatological mean values show that TCs in the northern basin do spend a greater percentage of their (shorter) lifetimes attaining LCP than do TCs in the other two basins.

2) DISTANCES AND DISPLACEMENTS

Climatological mean distances and displacements covered by TCs from their point of origin to the point of LCP are shown in Table 3 (rows 12 and 13). As discussed above, a lower value of the ratio of displacement to distance may be used as a simple indicator of the tendency of a TC to meander. For the TC paths from origin to LCP, these ratios have been computed and expressed as percentages (Table 3, row 14). These values are larger than those based on total distance and displacement in row 8, which implies that while a TC is intensifying it follows a straighter path than during the remainder of its life, or in other words, a TC's path is likely to be more curved following intensification. These ratios also suggest that prior to reaching LCP, TCs in the eastern region are more likely to meander than those in other basins.

Climatological ratios of distance covered on reaching LCP over total distance traveled by TCs (Table 3, row 15) show that a TC will cover approximately 40% of the total distance by the time it reaches its LCP. This means that a TC covers more distance after reaching its LCP than during the earlier stage of its life, except in the northern region where the ratio is close to 50%. As these values are less than the percentage of TC lifetime taken to reach LCP (row 10), there is an implication that TCs move faster following intensification. Mean climatological ratios of a TC's displacement from its origin on achieving LCP over final displacement are shown in row 16. Again, the TCs in the northern region provide the largest mean ratio. This means that TCs in the northern region have already covered almost 60% of the total displacement at the point of LCP, while TCs in the other basins have covered only about 40% to 50% of their total displacements.

e. *TC movement and lowest central pressure*

Climatological mean values of speeds of TC movements (Table 3, row 17) show that TCs are fastest moving in the eastern basin. Examination of speeds before and after the point of LCP (rows 18 and 19) shows that TCs generally move faster following intensification. The mean speed of TCs is greatest in the eastern region regardless of the phase of the TC's lifetime.

Climatological changes in longitude between the point of origin and the end point are given in Table 4 for each basin. Apart from the eastern region, where there is a climatological mean increase in longitude (movement to the east), TCs generally move to the west in the Australian region. Changes in latitude show clear poleward movements. For the period of a TC's life following genesis, when it approaches its maximum intensity, the changes in longitude are more consistent between basins, with values indicating that TCs generally move to the west. In agreement with overall-lifetime trends, there are general poleward movements during this period. Following achievement of LCP, TCs continue to move poleward, while movements to the east or west are not well defined, except for perhaps in the eastern region where climatological means suggest movements to the east. It is important to note here that the standard deviations associated with each of these means are quite large. While there is evidence for movement of TCs away from the equator, mean values of changes in longitude are difficult to state with certainty. The large standard deviations demonstrate that TC movements are quite erratic in the Australian region. This means that these values cannot be easily applied to the prediction of individual storms. Although large variability exists, TCs in the mean approach their max-

TABLE 4. Climatological mean changes in longitudes (lon) and latitudes (lat) of TC positions between the origin point (O), the end point (End), and the point of LCP for the Australian region and its individual basins. Standard deviations are given in parentheses following each mean value.

Climatological mean field		All Australian basins		Basin 1 (west)		Basin 2 (north)		Basin 3 (east)	
Δ lon	O → End	−2°40′	(18°25′)	−5°57′	(16°01′)	−5°05′	(17°52′)	+5°03′	(20°24′)
Δ lat	O → End	−10°45′	(8°29′)	−11°07′	(7°35′)	−8°16′	(6°52′)	−12°10′	(10°29′)
Δ lon	O → LCP	−3°39′	(9°43′)	−4°12′	(8°26′)	−4°53′	(11°00′)	−1°39′	(10°22′)
Δ lat	O → LCP	−3°57′	(3°54′)	−4°11′	(3°44′)	−3°21′	(3°52′)	−4°01′	(4°10′)
Δ lon	LCP → End	+0°59′	(13°30′)	−1°45′	(12°48′)	−0°12′	(10°28′)	+6°42′	(15°05′)
Δ lat	LCP → End	−6°48′	(6°54′)	−6°56′	(6°25′)	−4°55′	(4°32′)	−8°09′	(8°45′)

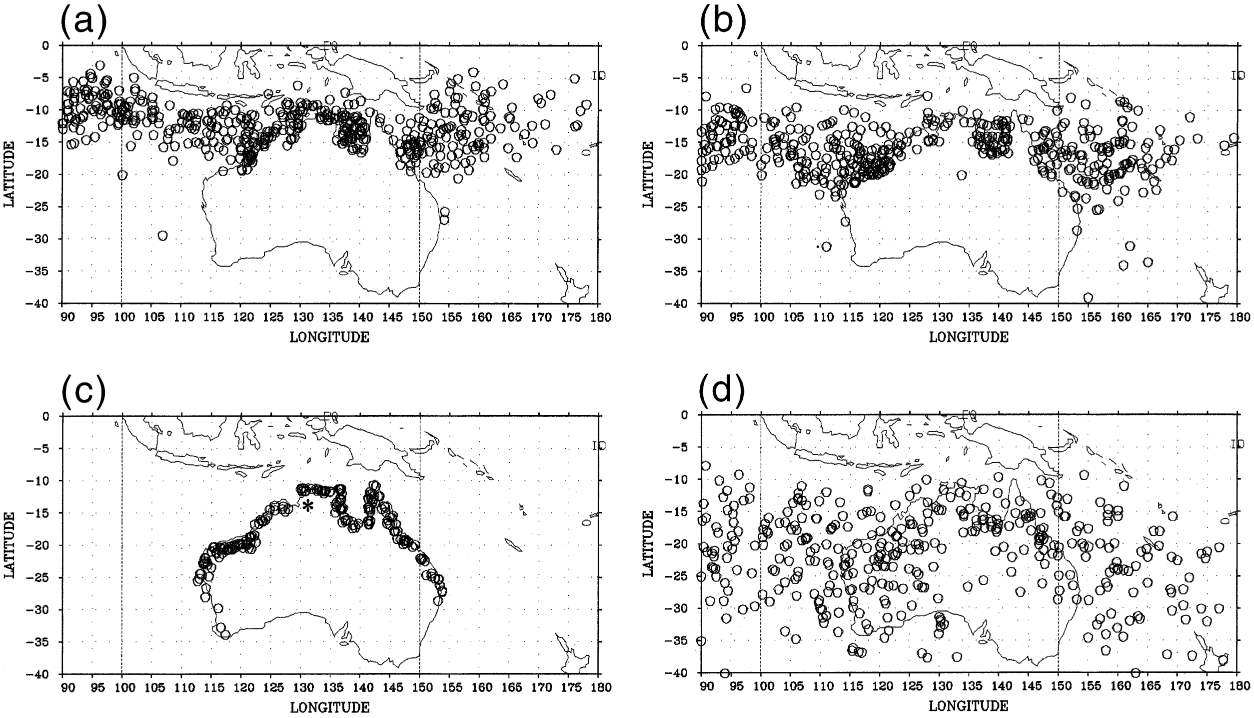

FIG. 8. (a) Locations of TC origins in the Australian region for all months. (b) Locations of achievement of LCP for individual TCs in the Australian region for all months. (c) Landfall locations for individual TCs in the Australian region for all months. The asterisk indicates a stretch of coastline free of landfalling TCs. (d) Final (termination) points of individual TCs in the Australian region for all months.

imum intensities as they move westward and just prior to poleward recurvature. We speculate that trough interactions (Molinari et al. 1998; Davidson and Kar 2002), which can influence both the intensity and motion of storms, are important during this phase of TC life cycle.

5. Geographical distributions of TCs and corresponding properties

Up to this point, seasonal and climatological mean values of parameters associated with TCs in the Australian region and its three basins have been considered. In this section, properties of TCs are examined with regard to their geographical distributions. In particular, locations of origin, LCP, landfall, and termination for individual TCs are illustrated. Following this, the analysis is extended by the separating the TC population into classes based on the highest intensity category achieved.

a. Origin, LCP, landfall, and termination: All category TCs

Origin points are generally observed between 5° and 15°S, although over the longitudes corresponding to the Australian continent there is a southward shift with some points close to 20°S (Fig. 8a). The use of satellite-supported observations reduces the possibility that this feature is due to observational bias, as may have been assumed prior to the satellite era. The overall mean latitude of these origins is 12°18′S. Locations of TCs at their most intense are shown in Fig. 8b. As might be expected, there has been a general poleward movement away from the origin points, with the mean latitude now at 16°11′S. Following the large number of origin points near to the coast, it is not surprising to find that there are many TCs adjacent to the continent at the time of achieving lowest central pressure. Of course, if the environment is such that TCs were in the process of intensifying prior to making landfall, the LCPs will be found very near to the coast, with any movement over land likely to result in dissipation of the circulation.

Given the variable paths taken by TCs, it is not surprising to find that most sections of the coastline of the northern half of the continent have been subjected to TCs making landfall (Fig. 8c). As was also present in Fig. 8b, there is a higher concentration of TC location points along the western coast between about 115° to 122°E than along the neighboring stretch of coast between about 122° to 128°E. Farther northeastward along this region of coast, it is interesting to find that there is a substantial gap (about 200 km in length) in the occurrence of landfalling TCs near 130°E (to the left of the asterisk in Fig. 8c). This gap was not found by Lourensz (1977), although he did find a different gap not far to the southwest based on observations from the period 1909–75. Although one might hypothesize that

TCs rarely make landfall over certain regions because of a combination of the orientation of the coastline and the general poleward movements of TCs, such an argument is not acceptable for the following reasons. First, Figs. 8a and 8b both show TCs positioned very close to this section of coast. Even if actual storm centers do not make landfall along a particular stretch of coast, the horizontal extent of TC circulations means that nearby coastal regions experience conditions driven by these storms. Second, as TC movements are quite erratic, it is inevitable that TCs will make landfall at this location, as shown by Lourensz (1977). The minor disagreements between the present analysis and that of Lourensz (1977) suggest that even a 40-season record compiled from observations of about 500 TCs is not necessarily adequate to capture all the basic characteristics of TC behavior. In other words, the highly erratic nature of TC movements does not guarantee an extremely well distributed set of data even for a large number of observations. From this, one might conclude that there must be some difficulty in using statistical methods to predict TC behavior.

The final locations of TCs, based on the best-track dataset, are shown in Fig. 8d. Ideally, these points would correspond to where circulations cease to be classified as TCs, due to dissipation, extratropical transition (ETT), or merging with other synoptic-scale features. However, as it was possible to trace some circulations substantial distances over continents or toward the pole, even after they may cease to exist as valid TCs, and such tracks are present within the dataset employed here, this figure may be somewhat misleading. Without further analysis of individual storms, one might otherwise assume that TCs that moved south of, say 30°S, must have undergone ETT and should therefore no longer be classified as valid tropical storms. Also note that some TCs have moved out of the domain shown in this figure. The points shown in Fig. 8d are mostly south of 10°S and cover a wide range of latitudes. Compared with some variable spatial concentrations present in Figs. 8a–c, the distribution here is virtually random. This shows that there are no typical motions associated with TCs in the Australian region, which naturally makes forecasting difficult. Interestingly, there are many storms that dissipate at relatively low latitudes over warm tropical oceans. Work is underway to study the impact of vertical shear during such events. An extension of this work will be to extract possible ETT events from the dataset for further investigation.

b. *Origin, LCP, landfall, and termination: TC categories 1–2 versus 3–5*

The largest differences in concentrations of TC origin points when comparing categories 1–2 and 3–5 (Table 2) occur near the Australian coastline (Figs. 9a and 10a). There are higher concentrations of TC origins along the northwest coastline (120° to 130°E) for category 3–5 storms than for the lower categories. The situation is reversed for the Gulf of Carpentaria (135° to 140°E) and the northeastern coastline (145° to 150°E), with higher concentrations of origin points for storms that evolve to category 1–2. There are also marked differences in locations of LCPs (Figs. 9b and 10b). For the higher-category TCs, the greatest concentration in locations of LCPs was observed near the northwest coastline (115° to 123°E), while there were relatively few in the gulf and there was good dispersal eastward away from the northeast coastline. In contrast, the locations of LCPs for category 1–2 TCs were concentrated in the Gulf of Carpentaria and relatively close to the northeast coast. There were also significant concentrations of category 1–2 TCs near the northwest coastline, although not as concentrated as for the higher-category storms. For TCs that make landfall (Figs. 9c and 10c), most category 3–5 storms appear to hit the northwest coast near 20°S or the northeast coast south of about 15°S. Relatively high concentrations of landfalls have been observed along the northern and gulf coastlines for category 1–2 storms, with relatively few in agreement with the landfall locations found for higher-category storms. However, while these are interesting differences, there are observations of landfalls by both classes of storm virtually everywhere along Australian coastlines north of about 25°S. The locations of TC termination points (Figs. 9d and 10d) show that most category 1–2 storms were found poleward of 10°S, while most storms in the more intense class were found south of 15°S. Again, the spatial distributions of the termination points indicate that TCs in the Australian region do not follow any general track, other than a dispersal away from the equator.

It is now interesting to investigate the mean latitudes of locations of TCs throughout their lifetimes with separation of the storms into classes depending on the highest category attained. One must remember, of course, that latitude is just one factor to consider, as demonstrated by the differences in spatial distributions between Figs. 9 and 10. Also note that these figures have illustrated the large dispersal of points, indicating that mean values do not always provide useful information, particularly when considering the termination points. Table 5 shows that there are negligible variations in the mean latitudes of origin points regardless of the intensity that the TC later reaches. The differences are better defined when considering the mean latitude of LCPs; the mean latitude for TCs of category 3–5 is further poleward than for the weaker storms. This is not surprising as it takes time to intensify, with TCs drifting poleward over this period. Even so, the differences in mean latitude of LCP between the different category classes amount to a distance of only about 150 km. This is an almost negligible distance when considering the diameter of a TC, the substantial percentage of lifetime spent within 10 hPa of the LCP (Table 3), and the mean speed of a TC.

The mean latitude of landfall for TCs that belong to

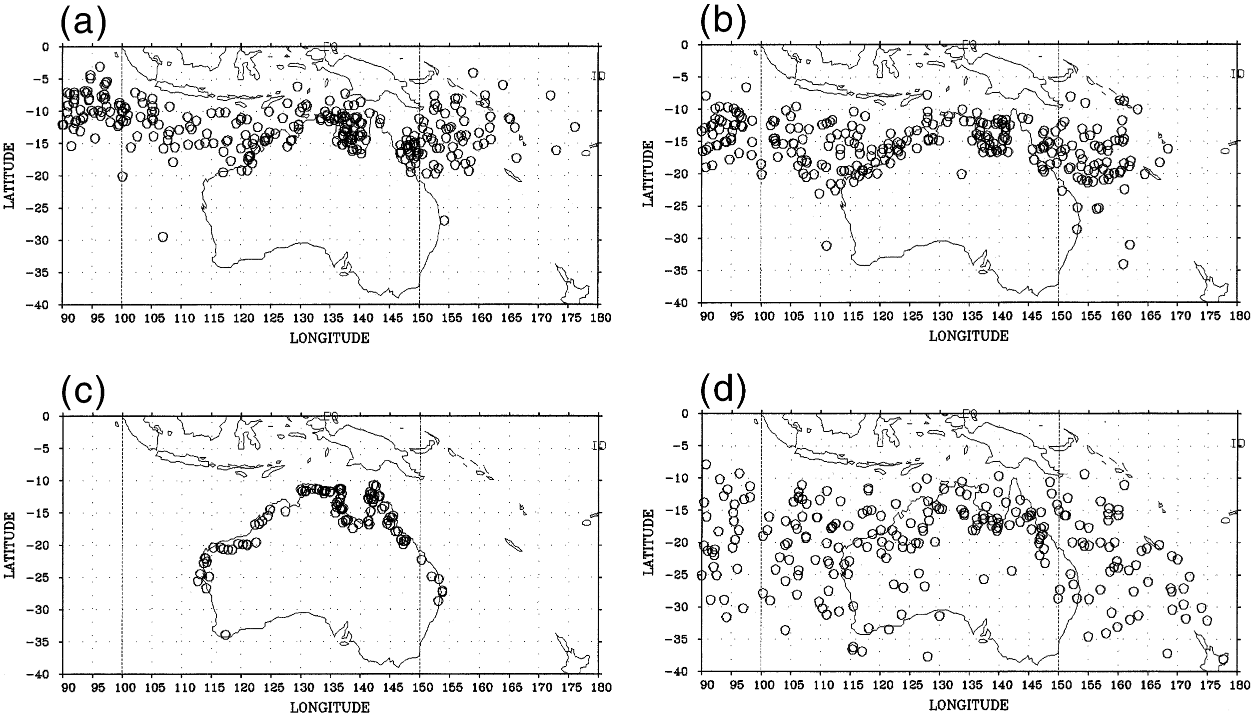

FIG. 9. (a) Locations of TC origins in the Australian region for all months, for TCs that achieved LCP ≥ 970 hPa (category 1–2). (b) Locations of achievement of LCP for individual TCs in the Australian region for all months, for TCs that achieved LCP ≥ 970 hPa (category 1–2). (c) Landfall locations for individual TCs in the Australian region for all months, for TCs that achieved LCP ≥ 970 hPa (category 1–2). (d) Final (termination) points of individual TCs in the Australian region for all months, for TCs that achieved LCP ≥ 970 hPa (category 1–2).

the higher categories is poleward of that corresponding to less intense storms. While environmental conditions must be favorable for the occurrence of significant intensification, interpretation of these mean figures suggests that higher-category TCs result from the circulation existing for an adequate period of time to allow intensification while avoiding land. The mean latitude of termination is also further removed from the equator for higher-category TCs. If the storm is steered such that it avoids landfall, there is some chance that it will further intensify and move farther poleward. There may also be an element of observer bias in the observation of the final point: a TC that has reached a high category may continue to attract one's interest as it moves poleward, while one might assume that a TC that reached a lower category had sooner dissipated or merged with the midlatitude synoptic pattern.

6. Characteristics of TC formation

It was shown in section 5 that a significant number of TCs in the Australian region originate quite close to the Australian coastline. This causes a significant problem for forecasters because these dangerous tropical storms can develop over a short period of time and there is little information available on which to base a forecast of future movement. In addition to the well-recognized difficulties in predicting movements of TCs, some skill is also demanded in terms of the prediction of TC genesis, which itself is not yet fully understood. In this section, some characteristics of TC origins are investigated.

As noted in section 4, the Australian TC season has a mean beginning during December and a mean ending during May. This agrees well with Fig. 11, which shows the percentage of TC origins per month. The majority of TC origins occur from December to April.

The data shown in Fig. 8a are used to compute mean latitudes of origins over longitude intervals of 5° (Fig. 12a). The resultant mean line (Fig. 12a) is worthy of comment for two reasons. First, a feature of this mean line is its poleward slant as the Australian continent is approached from both the Indian and Pacific Oceans. Second, the line tends to follow the coastline between about 120° and 150°E. Calculating the percentage occurrence of TC origins within each 5° longitude interval (Fig. 12b) allows some assessment of the clustering of points seen previously in Fig. 8a. As the percentage values plotted in Fig. 12b are positioned to approximately indicate the mean latitude of origins within each longitude band, there is agreement with the mean line shown in Fig. 12a. The local maxima highlighted using asterisks indicate locations where TC genesis has been observed to be most active. There are four maxima in

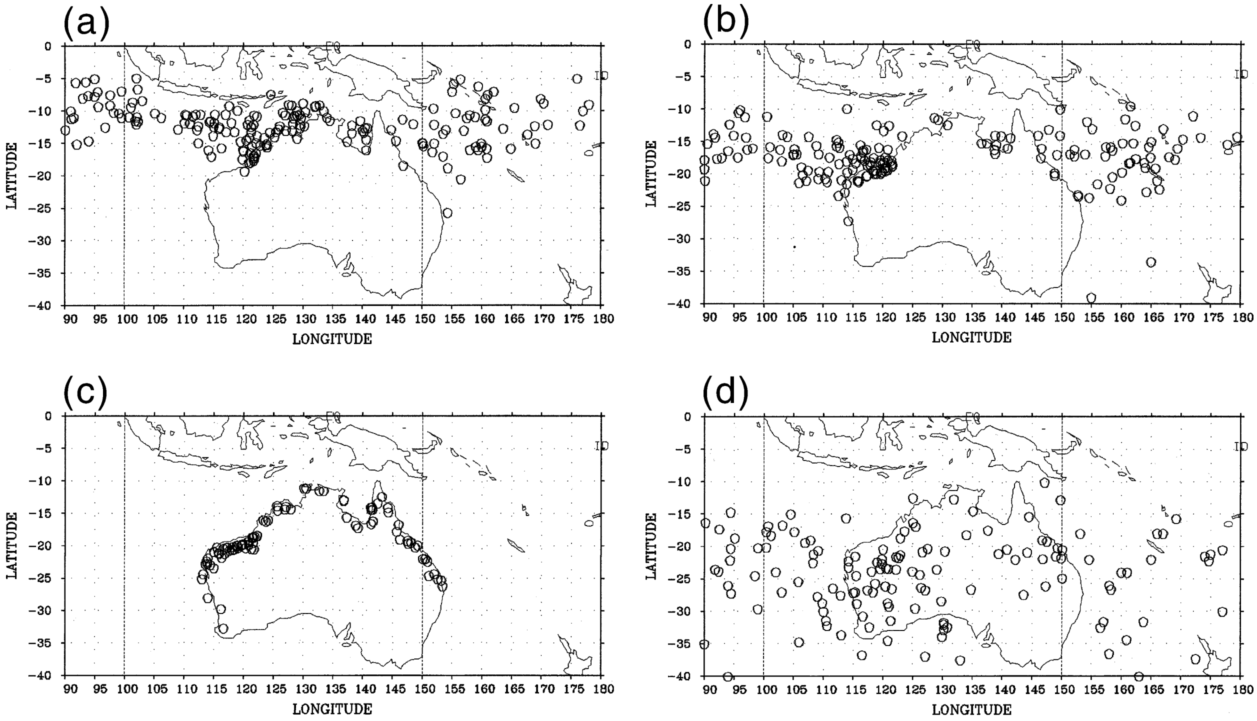

FIG. 10. (a) Locations of TC origins in the Australian region for all months, for TCs that achieved LCP < 970 hPa (category 3–5). (b) Locations of achievement of LCP for individual TCs in the Australian region for all months, for TCs that achieved LCP < 970 hPa (category 3–5). (c) Landfall locations for individual TCs in the Australian region for all months, for TCs that achieved LCP < 970 hPa (category 3–5). (d) Final (termination) points of individual TCs in the Australian region for all months, for TCs that achieved LCP < 970 hPa (category 3–5).

the Australian region of responsibility (90° to 160°E) and three in the zone corresponding to Australian continental longitudes (110° to 155°E). It is interesting that these three maxima are spaced about 15° longitude apart, with one in each of the basins (as defined in Table 1), while the maximum in the Indian Ocean is well removed to the west. The even separation of preferred genesis areas may be related to the land–sea distribution and to the downstream development process described by Davidson and Hendon (1989). This energy dispersion process is seen as the successive eastward development of troughs and ridges, following some initial TC formation. Further formations have been observed to occur in the downstream troughs.

Percentage occurrences of TC origins within each 5° longitude interval are plotted for five individual months (December to April) to further examine the clustering and spatial distributions of origin locations (Fig. 13). In agreement with the all-month mean (Fig. 12b), the five months show an average of four maxima from 90° to 160°E. All months show a maximum in the Gulf of Carpentaria (135° to 140°E), although this is not surprising because there is much land immediately east and west of this location. Four of the five months show maxima in the Indian Ocean (90° to 105°E) and in the

TABLE 5. Mean latitudes of TC locations during occurrence of specific characteristics, for all TCs and for separation based on highest category achieved (see Table 2).

Characteristic	All categories	Category 1–2	Category 3–5
Origin	12°18′S	12°23′S	12°09′S
LCP	16°11′S	15°36′S	17°01′S
Landfall	17°33′S	16°14′S	19°08′S
Termination	23°08′S	21°05′S	26°07′S

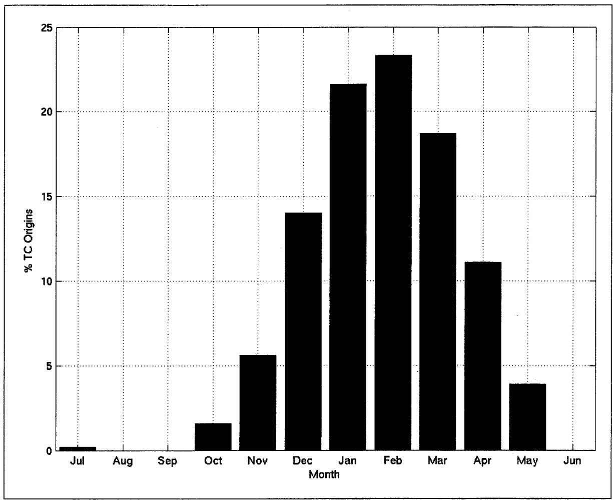

FIG. 11. Monthly mean percentage occurrences of TC origins in the Australian region.

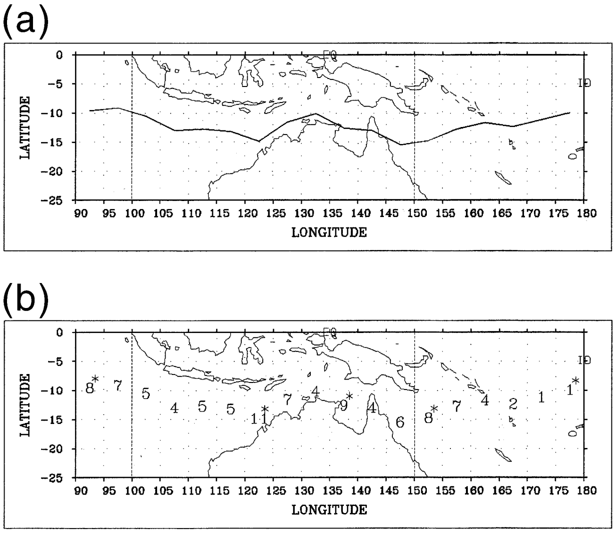

FIG. 12. (a) All-month mean latitudes of TC origins for longitudes spanning the Australian region. (b) Percentage occurrence of TC origins for all months separated into regions spanning 5° lon, with position of values indicating mean lat. Asterisks indicate local maxima.

Pacific Ocean, somewhere between 145° to 160°E. Significantly, there is a maximum off the northwest coastline (115° to 130°E) during all five months. Furthermore, the largest maximum during each of the five months occurs here off the northwest coastline. For maxima corresponding to Australian continental longitudes (110° to 155°E), changes in longitude between successive maxima varied from 10° to 20° with a mean of 13° longitude, comparing well with the 15° observed for the all-month mean. Of course, such values may be influenced by the use of longitude bands of 5° width in these calculations, although a subjective assessment of separation of clustering maxima based on Fig. 8a suggests that these conclusions are reasonable.

Although this analysis has revealed some interesting points regarding spatial concentrations of TC origins, results based on the five months (Fig. 13) are largely in agreement with the all-month mean (Fig. 12b). However, not revealed by the all-month mean are variations in the latitudes of the mean locations of TC origins. Perusal of the mean latitudes from December to April (Fig. 13) shows that TC origins tend to occur farther south and closer to the Australian coastline from January to March than they do during December and April. These variations are considered further in the following discussion.

Mean latitudes of TC origins for each of the Australian basins throughout the TC season are shown in Fig. 14a. All basins show a general poleward movement in the location of TC origins near the height of the season: the northern basin during January, the western during February, and the eastern during March. The northern

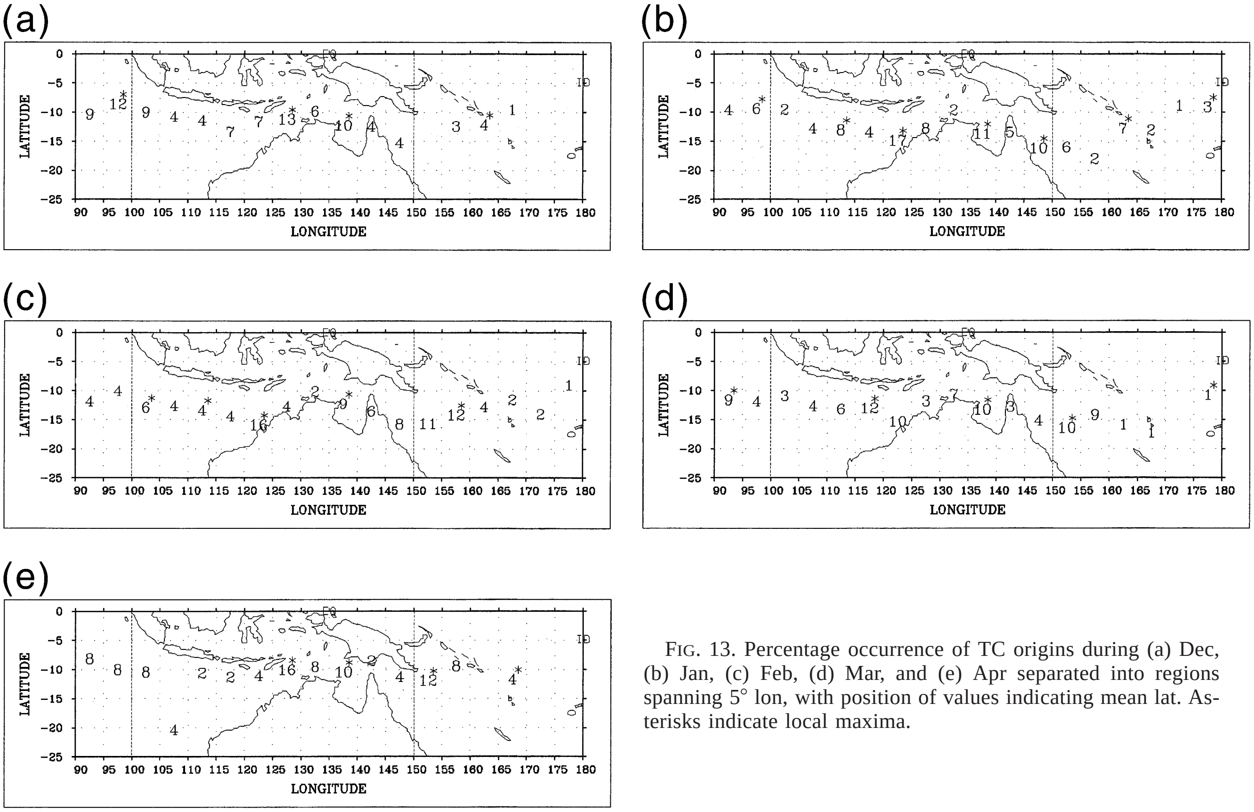

FIG. 13. Percentage occurrence of TC origins during (a) Dec, (b) Jan, (c) Feb, (d) Mar, and (e) Apr separated into regions spanning 5° lon, with position of values indicating mean lat. Asterisks indicate local maxima.

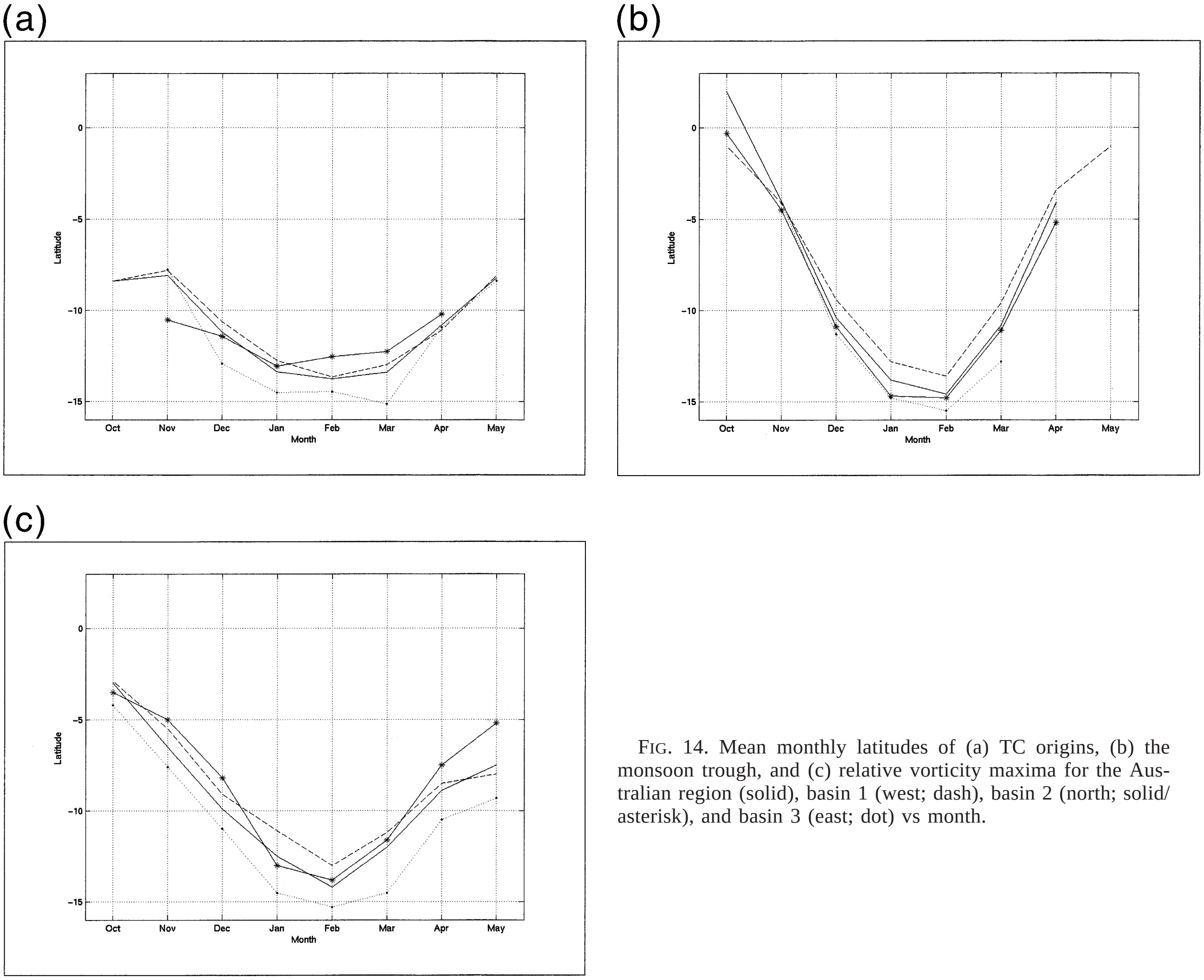

FIG. 14. Mean monthly latitudes of (a) TC origins, (b) the monsoon trough, and (c) relative vorticity maxima for the Australian region (solid), basin 1 (west; dash), basin 2 (north; solid/asterisk), and basin 3 (east; dot) vs month.

basin is restricted in its poleward extent due to bordering by the Australian continent, while the mean values computed based on observations from the eastern basin show the greatest extent southward of any basin. These values are now compared with parameters representing the large-scale environment based on NCEP reanalyses (Kalnay et al. 1996). Approximate mean locations of the monsoon trough and the relative vorticity maxima in each basin (estimated from NCEP reanalyses) are shown in Figs. 14b and 14c, respectively. Unlike the positions of TC origins, there are agreements between these data in terms of the timing of maximum poleward extent, with every basin showing maxima during February. There is some separation in poleward extent of these fields between the basins, at least from January to March. It is interesting that this separation can be seen as based on the longitude of each basin, with the western basin equatorward of the other two basins, and the eastern basin most poleward. The main difference between these fields based on the large-scale environment and observations of TC origins is the range of latitudes covered throughout the season. One may immediately conclude that these large-scale fields are not the sole controllers of TC genesis. It is also important to realize that there is not a clear separation between the influence of these fields on TC genesis and the influence of a TC on the definition of these fields. For example, the large vorticity present within a TC's circulation results in some increase in the mean vorticity of the large-scale environment, which is now being compared with the TC positions.

The large-scale fields and various TC characteristics are compared for each basin in Fig. 15. There appears to be better agreement between the mean latitudes of TC origins and the location of the relative vorticity maxima than with the monsoon trough. However, there is quite good agreement between TC origin locations and the monsoon trough locations during the height of the TC season, particularly January and February. It is during these months that the mean latitude of the trough closely matches or is positioned just poleward of the mean latitude of TC origins. The least agreement occurs

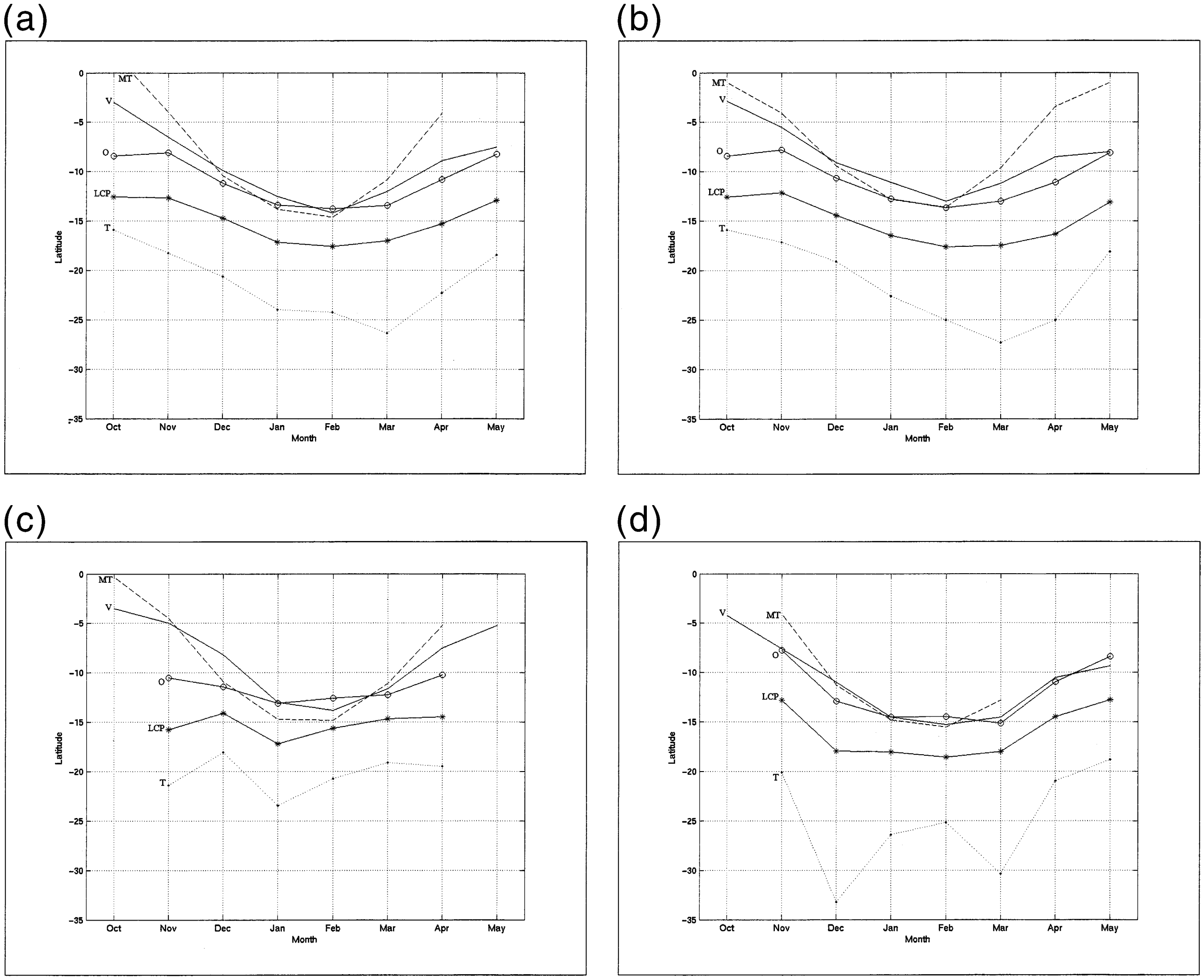

FIG. 15. Mean monthly latitudes of the monsoon trough (MT, dash), relative vorticity maxima (V, solid), TC origins (O, solid/circle), lowest central pressures (LCP, solid/asterisk), and TC terminations (T, dot) vs month for (a) all basins in the Australian region, (b) basin 1, (c) basin 2, and (d) basin 3.

in the northern basin, possibly due to the movement of the large-scale features southward while TC genesis is restricted to the more northern maritime areas. Note the small latitudinal variation in TC origins throughout the season in the northern basin (Fig. 15c) relative to those in the western and eastern basins (Figs. 15b and 15d, respectively).

7. Poleward movement and extratropical transition

While it is beyond the scope of the present work to examine the topic of extratropical transitioning of TCs in detail, analysis of the best-track dataset does allow some assessment of the numbers of TCs that move poleward beyond specific latitudes. Figure 15a provides some representation of the mean behavior of TC movements from point of origin to achievement of LCP, and finally to termination point throughout the season. It is interesting that the mean latitudes of LCPs closely parallel the mean locations of origin points from month to month, with a separation of about 4° to 5°. This characteristic is also mostly observed in the individual basins (Figs. 15b–d). In contrast, the mean latitudes of the final points do not generally parallel the mean latitudes of the origin or LCP locations. The exception is the northern basin (Fig. 15c), where the somewhat limited extent of sea surface leads to the final point in a TC's life not being far from its achievement of LCP, as discussed previously.

The all-basin mean (Fig. 15a) shows that the greatest mean poleward displacement of TCs occurs during March. This is supported by data from the western basin (Fig. 15b) and to some extent by data from the eastern basin (Fig. 15d). Observations show that TCs in the eastern basin move much farther south than those in the other two basins, with greatest poleward movements during December and March. Table 6 shows that the

TABLE 6. Mean numbers of TCs that move at least as far south as various latitudes (20° to 40°S) each season in the Australian region and its individual basins. Standard deviations are given in square brackets following each mean value.

Climatological mean field	All Australian basins		Basin 1 (west)		Basin 2 (north)		Basin 3 (east)	
TCs to 20°S per season (% total)	5.9 (48%)	[7.5]	3.0 (50%)	[3.8]	1.0 (34%)	[2.3]	1.9 (54%)	[2.6]
TCs to 25°S per season (% total)	3.5 (28%)	[9.7]	1.7 (29%)	[4.9]	0.5 (18%)	[2.7]	1.2 (35%)	[3.1]
TCs to 30°S per season (% total)	2.2 (18%)	[10.9]	1.0 (17%)	[5.5]	0.3 (10%)	[2.9]	0.9 (25%)	[3.4]
TCs to 35°S per season (% total)	1.1 (9%)	[11.9]	0.5 (8%)	[6.0]	0.1 (2%)	[3.1]	0.6 (16%)	[3.6]
TCs to 40°S per season (% total)	0.4 (4%)	[12.5]	0.1 (2%)	[6.4]	0.1 (2%)	[3.1]	0.3 (9%)	[3.8]

percentage of TCs that move south of 20°S each season is greatest in the eastern basin (54%), although this does not differ greatly from the western basin (50%). As the poleward extent of movements is increased, the separation between these two basins increases, until almost 10% of TCs in the eastern basin may move as far south as 40°S while the corresponding value for the western basin is just 2%. Despite these values, it is important to note that the standard deviations are quite large (Table 6). It should also be noted that after recurvature, many TCs in the western basin make landfall over the Australian coastline west of 125°E. The different meridionally based land–sea distributions in the west and east basins contribute to the different TC behaviors in these two basins. Although further detailed diagnostics are needed, the preliminary evidence discussed here suggests a trend for storms to move farther poleward and transition during the early and late parts of the season. This is likely consistent with the close approach of active midlatitude troughs during these times. NCEP reanalysis data indicate that the upper-level subtropical westerlies over monsoon longitudes extend to near 10°S in November, withdraw to near 18°S in February, and then return to near 10°S by April.

8. Conclusions

Characteristics of tropical cyclones in the Australian region have been examined based on 40 seasons of satellite-supported observations. Many parameters of TC behavior have been considered for the Australian region as a whole and for its individual basins (Table 3). The erratic nature of TCs in the Australian region has been well illustrated by the inclusion of standard deviations. These have sometimes been neglected in previous compilations of TC characteristics. This has resulted in a somewhat misleading interpretation of TC behaviors. For example, statements regarding the mean paths followed by TCs within the Australian region must be viewed with caution.

Very generally, about 13 TCs are observed in the Australian region each season, with half of these occurring in the western basin, mainly from December to April. A TC exists for about 7½ days, and there is a 25% to 30% chance that it will make landfall if present in the western or eastern basins but an 80% chance for storms in the northern region. Distances traveled by TCs are quite variable but they may cover around 2000–4000 km, with speeds of approximately 15 km h^{-1}. Around half of the storms reach a maximum intensity corresponding to category 3 or higher (lowest central pressure < 970 hPa).

There appear to be favored locations for TC genesis, near the Australian coastline 120° to 125°E, in the Gulf of Carpentaria, and 145° to 155°E. It is interesting that there are separations of about 15° longitude between each of these regions. This may be a consequence of the geography of the Australian continent and of a downstream development process described by Davidson and Hendon (1989). There is some evidence that these locations vary with the maximum intensity that is eventually achieved, with fewer origin points in the Gulf of Carpentaria and the eastern basin, and more near the northwest coast, for storms that reach category 3 or above. During the height of the season, there is some correspondence between the mean latitudes of TC origins, monsoon trough, and relative vorticity maxima. Recurvature generally follows achievement of maximum intensification, suggesting the importance of trough interactions on this behavior. Displays of TC termination points reveal a virtually random pattern, suggesting that there are no general paths followed by TCs in the Australian region and that the environment has a large influence on behavior. Interestingly, many storms dissipate over the warm tropical oceans equatorward of 20°S.

While some conclusions regarding mean movements of TCs could be made based on the data presented in Table 4, the consideration of standard deviations shows that the variations between TCs are significant during all phases of a storm's lifetime in all basins of the Australian region. General poleward movements are supported, while movements to the east and west are quite unclear. It seems likely that the best prediction of TC movement could be achieved by considering the individual circulation and its interaction with the environment in which it is embedded, rather than relying on statistical methods.

Although specific details of extratropical transitions have not been considered in the present work, poleward movements of TCs have been examined. It is no surprise that TCs originating in the northern basin have the smallest chance of moving a significant distance toward the pole. In the other basins, about half of the observed TCs may move as far south as 20°S, but the numbers decrease with distance poleward while standard deviations increase. It appears that TCs in the eastern basin have twice the chance of those in the west of moving as far south as 35° to 40°S. The trend for storms to move farther poleward and possibly transition peaks in December and March. However, as for all parameters associated with Australian-region TCs, one must remember that standard deviations are quite large due to significant variations between individual storms.

Finally, it is hoped that the analysis presented here will provide a framework for detailed investigations of the systematic and nonsystematic behavior of various phases of TC life cycles, in particular, formation, intensification, recurvature, landfall, and extratropical transition.

Acknowledgments. We thank Mr. Jon Gill and Mr. Alan Sharp for supplying the data. We appreciate the expertise offered by Mr. Ian Shepherd and Mr. Jeff Callaghan. We thank Drs. Kevin Tory, John McBride, Kamal Puri, and Michael Manton for reading the manuscript and making constructive comments. This work was supported by NICOP, ONR Grant N 00014-02-1-0431, as part of a collaborative project with NRL.

REFERENCES

Atkinson, G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationships for the western North Pacific. *Mon. Wea. Rev.,* **105,** 421–427.

Bessafi, M., A. Lasserre-Bigorry, C. J. Neumann, F. Pignolet-Tardan, D. Payet, and M. Lee-Ching-Ken, 2002: Statistical prediction of tropical cyclone motion: An analog-CLIPER approach. *Wea. Forecasting,* **17,** 821–831.

Davidson, N. E., and H. H. Hendon, 1989: Downstream development in the Southern Hemisphere monsoon during FGGE/WMONEX. *Mon. Wea. Rev.,* **117,** 1458–1470.

——, and S. K. Kar, 2002: Upper tropospheric flow transitions during rapid tropical cyclone intensification. *Quart. J. Roy. Meteor., Soc.,* **128,** 861–891.

Dvorak, V. F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 47 pp.

Gray, W. M., 1975: Tropical cyclone genesis. Dept. of Atmospheric Science Paper 232, Colorado State University, Fort Collins, CO, 121 pp.

——, 1979: Tropical cyclone origin, movement and intensity characteristics based on data compositing techniques. NAVENVPREDRSCHFAC Contract Rep. CR 79-06, Naval Environmental Prediction Research Facility, Monterey, CA, 124 pp.

Holland, G. J., 1984: On the climatology and structure of tropical cyclones in the Australian/southwest Pacific region: I. Data and tropical storms. *Aust. Meteor. Mag.,* **32,** 1–15.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kingston, G., 1986: The Australian tropical cyclone season 1985–86. *Aust. Meteor. Mag.,* **34,** 103–115.

Lourensz, R. S., 1977: Tropical cyclones in the Australian region, July 1909 to June 1975. Meteorological Summary, Dept. of Science, Bureau of Meteorology, Canberra, 111 pp.

——, 1981: Tropical cyclones in the Australian region, July 1909 to June 1980. rev. ed. Meteorological Summary, Dept. of Science, Bureau of Meteorology, Canberra, 94 pp.

McBride, J. L., and T. D. Keenan, 1982: Climatology of tropical cyclone genesis in the Australian region. *J. Climatol.,* **2,** 13–33.

Molinari, J., S. Skubis, D. Vollaro, F. Alsheimer, and H. E. Willoughby, 1998: Potential vorticity analysis of tropical cyclone intensification. *J. Atmos. Sci.,* **55,** 2632–2644.

Palmen, E., 1948: On the formation and structure of tropical hurricanes. *Geophysica,* **3,** 26–38.

Pielke, R. A., 1990: *The Hurricane.* Routledge, 225 pp.

Simpson, R. H., 1974: The hurricane diaster potential scale. *Weatherwise,* **27,** 169, 186.