A Qualitative Assessment of the Australian Tropical Region Analyses

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(Manuscript received 26 February 1987, in final form 22 April 1987)

ABSTRACT

The Bureau of Meteorology, Australia, routinely analyzes the tropospheric winds over the Australian Tropical Region (40°S–40°N, 70°–180°E). These wind data are assimilated without the use of a forecast model. While being free of any model bias, the optimum interpolation scheme imposes no dynamical constraints on the winds. To assess the realism of the Australian Tropical Region analyses, a qualitative comparison with gridded ECMWF wind data and OLR (as a proxy for tropical convection) is conducted.

In general, the depiction of the large-scale tropical circulation of the Australian Tropical Region analyses is quite reasonable. The gross features of the Australian and Asian Monsoons seem equally captured by both the ECMWF and Australian analyses. The seasonal development of the two monsoons and the relationship between the vertical structure of the divergence and zonal wind depicted in the Australian analyses agree well with previous theoretical and observational studies. Subtle differences (such as with the phase of the upper level anticyclones relative to the divergence) between the theory and the dynamics inferred from the Australian analyses are highlighted. However, we conclude that these objectively analyzed tropospheric winds are a valuable data resource for both the comparison with forecast model assimilated data and for deduction of physical processes.

1. Introduction

Since September 1983, the Bureau of Meteorology, Australia (BMA) has routinely analyzed the tropospheric winds over the Australian Tropical Region (40°S–40°N, 70°–180°E). These data, using many of the same observations available to the other major analysis centers (i.e., surface observations, radiosondes, aircraft reports, satellite cloud winds, etc.) are assimilated using a univariate optimum interpolation scheme (Davidson and McAvaney, 1981). The data are not assimilated with a forecast model and are not initialized.

The BMA data are of interest for a number of reasons. Because no forecast model or initialization is used during the assimilation, the analyzed wind fields are essentially the optimally interpolated observations. The BMA analysis scheme (Davidson and McAvaney, 1981) was designed solely to analyze tropical winds. The univariate interpolation scheme places no dynamical constraints on the winds. In particular geostrophy and mass balance are not enforced. Though the analysis extends 40° latitude from the equator, meaningful analyses probably only extend 30° from the equator. Nonetheless, the BMA data are unique in that gridded wind data, unbiased by a forecast model, are available on a continuing basis. Thus the BMA data offer an independent tropical analyses which can be compared with those generated at major forecast analysis centers. Another unique feature of the BMA data is that the operational scheme has remained unaltered since its implementation. The problem of assessing the impact of upgrading a forecast model assimilation scheme on the climatology is not present.

The BMA data is also of interest because the domain includes all of the Australian and most of the Asian summer monsoon regions. This domain is of particular importance to the time-mean Walker circulation and the global-scale circulation anomalies associated with El Niño/Southern Oscillation events.

The objectives of this paper are to assess how physically meaningful the BMA analyses are. The sparsity of observations in the tropics places a heavy burden on the analysis scheme. Because no dynamical constraints are placed on the analyzed winds, there is no guarantee that the analyzed winds will be physically meaningful. We will address this by examining seasonal means and the annual cycle of the analyzed tropospheric winds. By comparing to ECMWF gridded analyses, outgoing longwave radiation (OLR), and results from previous mesoscale and synoptic-scale programs such as GATE and MONEX, we will attempt to assess the benefits and the detriments of the BMA analysis scheme. The physical relationships between the analyzed winds and derived divergences (both in the vertical and horizontal), which we feel are well captured in the BMA analyses, will also be discussed.

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2. Datasets

A complete description of the BMA tropical analysis scheme is given by Davidson and McAvaney (1981). Its essential properties, as summarized by Davidson et al. (1983), are: 1) The scheme is univariate with zonal and meridional wind components objectively analyzed separately; 2) It is a three-dimensional optimum interpolation scheme; 3) The analyses from 12 h earlier are used as the first guess field; 4) Observations are taken from standard surface stations, ships, aircraft, satellite derived winds, etc; 5) The variables are analyzed on \( \sigma \) surfaces and interpolated to the constant pressure levels, 950, 850, 700, 500, 300, 200 and 100 mb. (The analysis scheme was designed to produce initial conditions for a sigma coordinate forecast model. Because no topography is included in the assimilation, sigma surfaces are approximately isobaric); 6) The analysis domain is 40°S to 40°N, 70°E to 180°. The grid resolution is 2.5°. Monthly means from 0000 UTC analyses of the horizontal winds, \( u \) and \( v \), the divergence, \( \nabla \cdot \mathbf{V} \), and the relative vorticity, \( \zeta \), are used for the period September 1983–May 1985.

The vertical velocity, \( \omega \), was kinematically produced from the BMA data. The continuity equation was integrated downwards from \( P = 100 \) mb where \( \omega \) was set to zero. Because no dynamical constraint is placed on the winds in the BMA analysis, it is not surprising that a net vertically integrated divergence exists. Kuo and Anthes (1984) have demonstrated the dynamical benefits of removing the mean divergence in each column prior to creating the vertical velocity. We have removed it in a manner similar to O'Brien (1970). The removal of the mean divergence was equally partitioned with pressure. Experimentation with other partitions, such as zero removal at the top increasing linearly towards the surface and vice versa, was carried out. Because the most reliable observations available for the BMA analysis scheme are in the upper troposphere and near the surface, we chose to distribute the removal of the mean divergence equally with pressure. The gross structure of the vertical velocity did not, however, seem to be sensitive to the various vertical partitions. The area averaged vertically integrated divergence was found to be an order of magnitude less than the local values, thus giving us confidence in the analyzed divergences.

To assess the realism of the BMA tropical analyses we want to compare them to a forecast model-assimilated dataset. The best available analyses to us are the gridded global set from the ECMWF. These data are available for the period January 1980–December 1984. Heckley (1985) and references therein describe the analysis scheme relevant to the tropics and the reliability of these initialized tropical analyses. Briefly, 1200 UTC data are available on a 2.5° grid. The previous 6-h forecast is used as the first guess and the winds are subjected to a nonlinear normal mode initialization. We will make use of monthly means of the initialized horizontal and vertical components of the wind. The data are available at 1000, 850, 700, 500, 300, 200 and 100 mb. We have calculated the vorticity, \( \zeta \), and divergence, \( \nabla \cdot \mathbf{V} \), on the same grid using a centered difference scheme.

As mentioned, the ECMWF data are available at 1200 UTC while the BMA data are available at 0000 UTC. This unfortunately prohibits a detailed comparison due to the large diurnal cycle in convective activity in the tropics. However, away from the surface, the large-scale circulation should not be drastically influenced by the diurnal cycle. We thus will use the ECMWF analyses for gross comparison and will only dwell on those differences we feel are attributable to the differing analysis schemes.

As a further independent comparison of the large-scale divergent motions, seasonal mean OLR maps are used. The OLR has been extensively used as a proxy for the horizontal distribution and intensity of deep tropical convection. We will not put too much emphasis on the detailed comparison of OLR; rather we will emphasize the similarities of the large-scale features. The OLR data were adapted from the Climate Diagnostics Bulletin of the NMC, which was kindly supplied by Dr. P. Arkin.

3. Seasonal-mean circulation

In the following section we describe the horizontal and vertical structure of the time–mean circulation for the two seasons, the 1983/84 Australian summer monsoon (December–February) and the 1984 Australian winter monsoon (June–August). Keeping in mind the 12 h difference in the two analyses, a direct comparison between the BMA and ECMWF analyses will be made.

The upper (200 mb) and lower (850 mb) vector winds are presented for the Australian summer monsoon (Fig. 1) and winter monsoon (Fig. 2). The agreement, for both seasons and at both levels, between the independent analysis schemes is quite good. The greatest discrepancies occur in the meridional winds at 850 mb off the west coast of Australia (30°–15°S, west of 110°E).

Both analyses depict the monsoonal characteristics of the 850-mb circulation in both hemispheres. These features in the Southern Hemisphere are the westerlies between 70° and 140°E extending to 15°S during the Australian summer monsoon (Fig. 1c and 1d) and the reversal to easterlies during the Australian winter monsoon. The Northern Hemisphere monsoonal westerlies only extend from 70°E to 120°E during the Asian summer monsoon (Fig. 2c and 2d) but extend poleward in excess of 20°. Note the eastern extent of the monsoonal winds (i.e., the seasonal reversal) is about 140°E which is captured equally well by both analyses. East of 140°E, year round low level easterlies prevail.

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FIG. 1. The time-mean winds during the 1983/84 Australian summer monsoon (December–February), from BMA data, (a) and (c) and ECMWF data, (b) and (d). The maximum vector for the 200 mb winds, (a) and (b) is 70 m s$^{-1}$ and for the 850 mb winds, (c) and (d) is 15 m s$^{-1}$.

FIG. 2. The time-mean winds during the 1984 Australian winter monsoon (June–August). The format is as in Fig. 1. The maximum vector for the 200 mb winds, (a) and (b), is 55 m s$^{-1}$ and for the 850 mb winds, (c) and (d), is 15 m s$^{-1}$. 
Fig. 3. The time-mean relative vorticity during the 1983/84 Australian summer monsoon. The format is as in Fig. 1. The contour interval is $7.5 \times 10^{-6} \text{ s}^{-1}$ and the zero contour has been omitted.

Fig. 4. As in Fig. 3 for the time-mean relative vorticity during the 1984 Australian winter monsoon.
At 850 mb, the two analyses agree quite well despite the smaller scale of the relative vorticity as compared to that at 200 mb. In particular, the elongated cyclonic circulation straddling the equator is captured equally well by both schemes during the Australian summer monsoon (Figs. 3c and 3d). Good agreement also is seen during the Asian summer monsoon when the cyclonic circulation in the Northern Hemisphere intensifies and moves poleward in the vicinity of 90°E (Figs. 4c and 4d). In general, less agreement is seen in the Southern Hemisphere between the two analysis schemes.

The divergence at 200 mb is presented for the Australian summer (Fig. 5) and winter monsoon (Fig. 6). The associated OLR is also presented. The OLR is a useful proxy for deep convection in the tropics from which the horizontal distribution of vertical motion and upper tropospheric divergence can be inferred. Low values of OLR are indicative of deep tropical convect-
tion. The distribution of the lower tropospheric convergence (not shown) appears quite similar to that of the upper tropospheric divergence. This is in accord with many previous studies which have shown upper level divergence to be associated with deep convection and latent heat release and hence low level convergence.

Despite the 12 hour difference in analysis time the agreement of the two different analyses of the divergence and the horizontal distribution and relative magnitude as inferred from the OLR is equally good. Slightly better agreement between the two analyses is seen during the winter monsoon (Fig. 6). Nonetheless we conclude, after examining all other available seasons, that the horizontal distribution and relative magnitude of divergence in the BMA data is physically meaningful. Another way of stating this is that no blatant differences exist between the OLR, ECMWF and BMA analyses.

The vertical structure of the divergence and vertical velocity is examined further by means of longitude-pressure sections along the equator. Substantial differences between the two analyses exist for both the Australian summer (Fig. 7) and winter monsoons (Fig. 8). In general the BMA analysis exhibits a single maximum in the vertical velocity between 500 mb and 300 mb, with an associated deep layer of convergence and shallow layer of upper level divergence. The ECMWF analysis exhibits a bimodal structure with distinct maximum vertical velocities at 200 and 850 mb and a very shallow layer of upper level divergence above 200 mb and lower level convergence below 850 mb. Compensating upper level convergence around 300 mb and lower level divergence around 700 mb appears to be taking place.

The vertical structure of the divergence in the BMA analysis agrees more favorably with the traditional view of the large-scale tropical circulation (e.g., Newell et al., 1974); however, important differences exist. The traditional view of the large-scale Hadley circulation is of a single maximum in the vertical velocity to exist around 500 mb with a roughly equal lower layer of convergence and upper layer of divergence. The maximum vertical velocity at 300 mb near 120°E (Fig. 7) is more typical of that produced in cloud clusters in the western Pacific (Ruprecht and Gray, 1976; Houze, 1982) rather than that produced by single cumulus towers. The high level maximum (300 mb) observed in the BMA data around 120°E during the Australian
Summer monsoon, with the level of maximum lowering to the east, supports the hypothesis of Hartmann et al. (1984) that the vertical distribution of the diabatic heating and vertical velocity in the west Pacific is a result of the mesoscale circulations produced in cloud clusters. In the far western Pacific cloud cluster account for much of the rainfall (Houze, 1982) and hence their dynamics may dominate the large-scale circulation. Near the dateline, higher mean OLR values are indicative of less deep convection and hence less diabatic heating resulting from latent heat release. The large-scale vertical velocity possesses a maximum at a lower level (500 mb) in this region, indicating that cloud cluster dynamics may not be as important. During the Australian winter monsoon, when most of the convection is north of the equator (Fig. 6), the maximum vertical velocity occurs around 500 mb along the equator near 120°E (Fig. 8). Further lowering to the east is again observed. Latitudinal sections (not shown) confirm that, through the regions of most intense divergence and low OLR, the level of maximum vertical velocity is around 300 mb. It is important to note that no variation in the spatial and temporal distribution of the ECMWF data.

It must be emphasized that the ECMWF analyses are 12 hours apart from the BMA analyses. Substantial diurnal variation can be expected in tropical convection and hence result in the differing structure between the two analyses. Indeed, Johnson and Young (1983) found a large diurnal differences in vertical velocities for mesoscale cloud clusters off the Borneo coast during winter MONEX. The morning soundings depicted a single vertical velocity maximum above 500 mb, while the late night soundings showed strong sinking motion around 700 mb with very weak vertical velocity above 400 mb. This diurnal variation of the mesoscale clusters appears not to account for the large-scale vertical motion field in the ECMWF. The strong rising motion both at 200 mb and below 800 mb in the ECMWF initialized analyses in no way resembles that found by Johnson and Young (1983).

A detailed comparison of the vertical structure of the divergent motions in the two analysis scheme is probably not warranted considering the 12 hour difference in analysis time. However, the basic differences observed in Figs. 7 and 8 clearly occur systematically over the entire equatorial domain. Presented in Fig. 9a are the longitudinally averaged (5°S–5°N, 70°E–180°E) divergence during DJF 1983/84 from both the BMA and ECMWF data. The 0000 UTC BMA data show a
deep layer of low level convergence and a shallower, more intense layer of upper tropospheric divergence. The 1200 UTC ECMWF initialized analyses capture the low level inflow and upper level outflow but mid-tropospheric convergence and divergence also appear. Again the possibility that the ECMWF analyses are accurately depicting a diurnal variation can be ruled out. The same vertical structure occurs in the zonal average (thus averaging all local times; Heckley, 1985). This was further confirmed by computing longitudinal averages with the ECMWF data over the other convectively active regions (Brazil and Africa). A very similar complicated structure was produced for all other available years (1980–84, not shown). Evidence exists for some of the bimodal structure to be real over Africa (Heckley, 1985); however not over Brazil (Silva Dias and Bonatti, 1985).

The ECMWF analysis scheme has undergone considerable refinement during the period 1980–84. In particular, diabatic processes were introduced into the initialization scheme in 1982 in order to alleviate the weak tropical divergence produced by the adiabatic initialization. That there are no major differences in the longitudinally averaged divergent circulation for years with (1983/84, 1982/83) and without (1980/81, 1981/88) diabatic processes in the initialization scheme (Fig. 9b) suggest that the ECMWF initialization (independent of the diabatic processes) is systematically introducing the complicated vertical structure over the entire equatorial domain.

Further support for the realism of the BMA derived divergences is gained by examining the derived divergences from the ECMWF FGGE 3b dataset. The analysis scheme (excluding the initialization) used by ECMWF during FGGE is essentially that used currently (Bengtsson et al., 1982). Shown in Fig. 9c are the longitudinal average (70°E–180°) of the uninitialized divergence (derived from the uninitialized horizontal winds) and initialized divergence (derived from initialized vertical velocity) from the ECMWF FGGE 3b 0000 UTC analyses for DJF 1978/79. The uninitialized divergence shows a layer of low level convergence and a more shallow and intense layer of upper level divergence. This structure agrees favorably with that found in the BMA data and the other cited studies relevant to the western Pacific. The initialized divergence, however, exhibits a similar complicated vertical structure as seen in the initialized ECMWF 1200 UTC analyses (1980/84). The reduction of magnitude between the initialized and uninitialized divergence (factor of 3) is consistent with that expected by an adiabatic initialization (K. Puri, personal communication, 1986). The vertical structure introduced by the adiabatic initialization is essentially a truncation problem whereby analyzed divergence gets projected onto the first uninitialized vertical mode (Hollingsworth and Cats, 1981). The similarity of this vertical structure with that seen in the ECMWF 1200 UTC analyses strongly suggests this problem is occurring even in the diabatic initialization.

Therefore, despite the 12 hour difference in analyses times, the differences in the vertical between the BMA and ECMWF vertical velocities and divergences do not seem to be due to diurnal variation. That the BMA analysis agrees more favorably with previous findings for the large-scale divergent circulation in the western Pacific gives us some confidence that their analysis scheme is doing a reasonable job of depicting the divergent circulation in this region.

4. Annual cycle

As a further step in investigating the realism of the BMA analysis, the annual variation of the horizontal
winds and divergence are examined. We will concentrate on the seasonal development of the low level monsoonal westerlies and their relation to the upper level easterlies and divergence. The similarities between the monsoons will be highlighted.

The low level monsoonal winds were seen to extend from 140°E to west of 70°E in the Southern Hemisphere and from 120°E to west of 70°E in the Northern Hemisphere (Figs. 1 and 2). Typical time–pressure sections of the zonal wind and divergence are shown for the Australian monsoon (Fig. 10) and Asian monsoon (Fig. 11). The temporal development and duration of both monsoons is similar.

In general, the development of low level westerlies in the summer hemisphere coincides with the development of upper level easterlies and divergence. The strongest zonal winds coincide with the strongest upper level divergence. Note that the Asian summer monsoon exhibits stronger low level westerlies, extending deeper into the troposphere. The baroclinic structure of the zonal winds during the summer monsoons, when

![Figure 10](image-url)

**Fig. 10.** Pressure–time section at 10°S, 120°E of (a) the zonal winds and (b) divergence from BMA data. The contour interval in (a) is 3 m s⁻¹ and in (b) is 1. × 10⁻⁶ s⁻¹.

![Figure 11](image-url)

**Fig. 11.** As in Fig. 10 but at 10°N, 90°E. The contour interval is 2 m s⁻¹ in (a) and 1. × 10⁻⁶ s⁻¹ in (b).

...strong upper level divergence (implying large diabatic heating) exists, and the more equivalent barotropic structure of the zonal winds during the winter monsoons, when upper level convergence (implying no diabatic heating) exists, agrees well with the simple scaling argument of Charney (1963).

Further evidence for the association of upper level divergence, low level westerlies and upper level easterlies is presented by means of time–latitude sections at representative longitudes of the Asian and Australian summer monsoon.

At 120°E, typical of the Australian monsoon (Fig. 12), the upper level divergence exhibits a pronounced seasonal cycle. The maximum divergence clearly develops in the summer hemisphere. Note that divergence exists year round north of the equator to about 15°N where as year round divergence is limited to about 5°S in the Southern Hemisphere. Low-level westerly winds clearly are at a maximum in the summer hemisphere when the upper level divergence is a maximum. The poleward extent of the westerlies closely coincides with that of the divergence.
vergence and lower level westerlies is also observed (Fig. 13). The divergence maxima and low level westerlies are confined to the Southern Hemisphere. At 150°E no land mass exists north of the equator and much less surface heating occurs during northern summer. Hence the Northern Hemisphere exhibits much less monsoonal characteristics at this longitude. As at 120°E, the upper level easterlies tend to develop symmetrically about the equator at the time of maximum divergence, regardless of its hemispheric displacement. A much weaker easterly maximum occurs during the northern summer as compared to 120°E, apparently due to a

While the divergence and low-level zonal winds clearly show a strong equatorially asymmetric signal (very reminiscent of the steady linear response to equatorially asymmetric diabatic heating; Gill, 1980), the upper level easterlies develop much more symmetrically about the equator. Three equatorially symmetric easterly maxima occur at the time of maximum divergence and low level westerlies. Note that an equatorially symmetric component of the divergence also does exist year round.

At the eastern extent of the Australian summer monsoon, 150°E, the concurrence of upper level di-
much less dramatic shift of the divergence into the Northern Hemisphere at this longitude.

At 90°E (Fig. 14), representative of the Asian monsoon, the same relationship between upper level divergence and lower level westerlies is seen. Strong divergence only extends to about 10°S during the southern summer, due to the lack of land mass at this longitude. Note, however, that divergence and low level westerlies exist year round in the Southern Hemisphere equatorward of 10°S. During the Asian summer monsoon, strong divergence and low level westerlies extend poleward in excess of 30°N. As with the Australian monsoon, maximum upper level easterlies tend to occur symmetrically about the equator while the divergence maximum tends to be asymmetric.

We have neglected a discussion of the temporal evolution of the meridional wind due to its dominance by the hemispheric shift of the Hadley circulation. A typical section for the monsoon regions is shown at 120°E for the upper level (Fig. 15). The center of the upper level branch of the Hadley cell clearly shifts into the summer hemisphere as does the upper level divergence (Fig. 10a). The low level meridional winds exhibit the same temporal evolution but blow in the opposite direction (not shown). At 90°E the meridional winds develop in much the same manner but with slightly less amplitude. At the eastern extent of the Australian monsoon (150°E), the meridional winds are much weaker and the seasonal cycle is less clearly defined. The prediction by Gill (1980) that meridional inflow at upper levels should develop in regions of upper level divergence (based on the balance of vorticity generation by convergence) is not evident (Fig. 15 and Fig. 10a). The large zonally symmetric component of the annual cycle of the meridional wind may be masking this tendency. A further investigation of the meridional winds with a longer, global dataset is required.

From this examination of the seasonal progression of the horizontal winds and divergence, we conclude that the BMA analyses hang together in a physically meaningful manner. We have not attempted more quantitative assessments (e.g., vorticity or kinetic energy budgets) but feel that much can be learned from the qualitative comparisons.

5. Discussion

In this paper we have qualitatively assessed the BMA Australian Tropical Region analyses. The univariate optimum interpolation scheme used by the BMA is free from forecast model bias and thus offers a comparison to data assimilated with a forecast model. Divergent tropical circulations are known to be drastically affected by initialization procedures required for forecast models. The divergent circulation depicted in the BMA data, if physically meaningful, thus present a useful standard. Through our comparison of the BMA data with ECMWF data (though at 12 hours difference analysis time), OLR and previous studies relevant to the Western Pacific, we concluded that indeed the time-mean tropical circulation depicted in the BMA data is reasonable. Insight into the dynamics of the tropical Western Pacific troposphere can be gained by a qualitative examination of the BMA data.

The two major differences between the BMA and ECMWF analyses were the low level meridional wind off the west coast of Australia and the detailed structure of derived divergence (both horizontally and vertically). Considering the lack of observations in the Indian Ocean, the degree of similarity between the analyses over the Indian Ocean is quite good. That the two

Fig. 14. As in Fig. 12 but at 90°E. The contour interval in (a) is $2 \times 10^{-6}$ s$^{-1}$, in (b) is 3 m s$^{-1}$, and in (c) is 10 m s$^{-1}$.
analyses differ slightly in such a data sparse region is not surprising. Acknowledging that the 12 hour difference in analysis time used in this study may drastically affect the derived divergent circulation, the similarity of the overall horizontal distribution of divergence is quite good (both spatially and in magnitude). Marked systematic differences in the vertical structure occur, however. All indications are that the ECMWF assimilation/initialization scheme is systematically introducing spurious vertical structure into the initialized analyses. The single maximum in vertical velocity above 500 mb in the BMA analyses appears to be more physically realistic.

The objectively analyzed data of the BMA were shown to produce time-mean divergences and vertical motions which agreed well with the horizontal distribution of diabatic heating inferred from OLR data and with the vertical structure observed over the far western Pacific in mature cloud clusters. The occurrence of the maximum large-scale vertical velocity in the BMA analysis at levels as high as 300 mb over Indonesia, however, differs markedly from the traditional view of the zonally symmetric tropical circulation (i.e., a maximum at 500 mb, Hantel and Baader, 1978). These findings tend to confirm the hypothesis of Hartmann et al. (1984) that the vertical structure of the time-mean vertical velocity over Indonesia is determined by the elevated diabatic heating associated with mature cloud clusters (Houze, 1982). Cloud clusters dominate the precipitation in the Indonesian (Williams and Houze, 1986) region and, hence, the large scale diabatic heating is determined by the cloud cluster dynamics. Further east, towards 180°E, higher OLR values are indicative of less clouds and hence smaller magnitude of \( \phi \). The resultant vertical velocity profile, thus, relaxes back to the traditional midtropospheric maximum.

Useful insight into the structure and dynamics of both the seasonal mean and annual variation of the tropical circulation that we observed in the Australian Tropical Region can be gained by comparing to the linear atmospheric response to steady tropical diabatic heating (Gill, 1980). The Australian summer monsoon exhibits many of the linear features, if one assumes that the nearly equatorially symmetric divergence is produced by steady diabatic heating. These features are the upper level anticyclones and lower level cyclones (Fig. 3) which straddle the equator at roughly the same longitude as the divergence (Fig. 5) and the greater intensity of the zonal winds to the west of the divergence as compared to the east (Fig. 1). Similar comparison can be made during the Asian winter monsoon, taking into account the northward and westward shift of the diabatic heating. Important discrepancies exist, however, with the linear theory.

During the Australian summer monsoon no westward displacement of the upper level anticyclones with respect to the divergence, as predicted by linear theory, is observed. Sardeshmukh and Hoskins (1985) and Hendon (1986) have postulated that nonlinearity, which is of first-order importance in the tropical upper troposphere, is responsible for this lack of displacement. Also evident during the Australian summer monsoon (Fig. 3) is the equatorial trapping of the low level cyclones within 15° of the equator while the upper level cyclones extend poleward in excess of 30°. Linear theory predicts the low level trapping but does not account for the large latitudinal extent at upper levels.

During both the Asian and Australian summer monsoons the upper level divergence (Figs. 5 and 6) exhibits a large equatorially asymmetric component, tending to maximize in the summer hemisphere. The low level zonal winds also exhibit this asymmetry (Figs. 1b and 2b). The low level circulation seems to be well explained by the linear response to this equatorially asymmetric heating (see Gill, 1980 for the steady linear response to equatorially asymmetric heating). The major features of this response near the equator are the low level westerlies in the hemisphere of the heating and easterlies in the other hemisphere. The seasonal development of the upper level divergence and low-level zonal winds (Figs. 12–14) clearly show this asymmetric structure. The upper-level zonal winds, however, develop much more symmetrically with respect to the equator, as if the diabatic heating were purely symmetric. This asymmetry of the divergence and low level circulation and symmetry of the upper level circulation was produced in the GCM experiments by Keshavamurty (1982) and observed in the 1982–83 El Niño (Rasmussen and Wallace, 1983). Furthermore, while the low level winds exhibit much structure at small scales (also seen in the upper level divergence), the upper level winds are much smoother with less small scale structure. Linear theory does not explain either of these differences between the two levels.

Nonlinearity is a possible explanation for why the equatorially asymmetric upper level divergence (and equatorially asymmetric low level convergence of roughly equal magnitude) produces low-level equatorially asymmetric circulation with small scale while the
upper level circulation produced is much more equatorially symmetric and at a larger scale. The vorticity balance at each level is proposed to be markedly different (Sardeshmukh and Hoskins, 1985; Hendon, 1985). In the upper troposphere nonlinear zonal advection of relative vorticity plays a dominant role. Much of the small scale structure of the rotational component of the flow produced by the divergence could be washed out by the large zonal advection. At the lower level friction and planetary vorticity advection dominate. The low level rotational component tends to be dominated by the “local” forcing due to convergence and thus exhibits the small scale features of the convergence forcing. The tendency of the upper level to respond more efficiently to the symmetric component of the heating (divergence) while the lower level is dominated by the asymmetric component also may be a result of the dominance of nonlinear zonal advection at upper levels. Recent theoretical work by Van Tuyll (1986) suggests that indeed nonlinearity tends to produce easterly anomalous winds along the equator in a simple shallow water model forced by idealized low latitude heating. More simple nonlinear modeling with basic state winds with realistic horizontal and vertical shear are needed to understand these details.

At least on monthly time scales, upper level easterlies, lower level westerlies and upper level divergence appear to occur simultaneously in the summer hemisphere of the Australian Tropical Region. The use of monthly averaged data precludes the examination of the phase relationship between the winds and divergence at shorter periods. Also large temporal fluctuations, both synoptic and low frequency (e.g., the 40–50 day oscillation and Southern Oscillation), occur in the divergence, OLR, rainfall, etc., over the Indonesian region (see McBride, 1985, for an excellent review). The short period of monthly-months used in the present study clearly prevent examination of these fluctuations. The realism of the BMA data seems to be such that examination of these fluctuations would be most revealing. As the duration of the BMA tropical dataset increases, the interactions between these various time scales can be examined more fully.

Acknowledgments. Noel Davidson kindly supplied the BMA dataset. The ECMWF data were made available to CSIRO by the ECMWF. I wish to thank Phillip Arkin, who supplied the OLR data. The comments of Geoff Love, Alan Plumb, Werner Wergen, Mark Williams, the referees and editor greatly improved the manuscript. Fruitful discussions on the climatology of the Australian–Indonesian region with G. Holland, T. Keenan and J. McBride are acknowledged. Sue Webdale graciously typed the manuscript.

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