Southern Hemisphere Summer Monsoon Circulation during the 1978-79 WMONEX Part I: Monthly Mean Wind Fields¹

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Abstract

Some of the characteristic features of the Southern Hemisphere summer monsoon were investigated by using twice-daily, objectively analyzed wind data at 850 and 200 mb for December 1978 to February 1979, over an expanded WMONEX region (90°E-140°W, 30°N-30°S).

In January, the extent of the Southern Hemisphere monsoon is probably denoted by a zone of strong 850 mb equatorial westerlies that extends along about 10°S from the northeastern Indian Ocean (100°E), across the Indonesian Seas and New Guinea, to the western South Pacific (180°). The eastern end of the Southern Hemisphere monsoon trough is characterized by a major low-level (850 mb) convergent center and an upper-level (200 mb) anticyclonic system associated with pronounced divergence.

In the immediate vicinity of the Southern Hemisphere monsoon trough (15°S), the divergence effect was the main factor in low-level disturbance development. Conversely, between the equator and 10°S, disturbances developed by receiving vorticity from the zonal mean flow via barotropic nonlinear interactions.

1. Introduction

Ramage (1971) made an exhaustive survey of Southern Hemisphere monsoon related studies before the late sixties. Most of these synoptic studies focused on local circulation features over areas such as Indonesia and/or northern Australia. In addition, some case studies pertaining to specific aspects of the summer monsoon in the immediate vicinity of Australia were also made without reference to prominent circulation features of a much larger scale. This is primarily due to a lack of data over the Southern Hemisphere summer monsoon domain at that time.

During the 1970s, an increase in the data

coverage over this region produced some significant results. Based primarily on commercial aircraft data, Sadler (1975) compiled monthly mean, upper-air wind charts over the global tropics, and demonstrated that upper-level anticyclonic cells exist over Australia and the western South Pacific from December to February. Krishnamurti *et al.* (1973) showed that a distinct region of strong upper-level divergence is located over the Indonesian region near 5°S, 120°E. As confirmed by Murakami and Unninayar (1977), the outflow from this Indonesian area is directed northward (southward) and converges into a continental heat sink region over northern China (southern Australia). Thus, a planetary-scale, meridionally oriented circulation is implied in this region.

Although most of the studies cited above are

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interesting and informative, they are based primarily on pre-FGGE (First Global GARP Experiment) data which are of relatively poor coverage and questionable accuracy over certain tropical regions (*e.g.*, the Indian and South Pacific Oceans). Thus, many unanswered questions remain. For example, the simple problem of determining the exact geographical extent of the Southern Hemisphere summer monsoon is still unresolved, *i.e.*, is it limited to the immediate vicinity of the Australian continent? To what extent (longitudinally and latitudinally), if any, does the Australian continent exert some measure of control in establishing the Southern Hemisphere monsoon?

In the present study, these problems are examined by using objectively analyzed, 850 and 200 mb wind data collected during the Winter Monsoon Experiment (WMONEX) of December 1978 to February 1979. These WMONEX data provided the best data coverage ever obtained over the Southern Hemisphere summer monsoon region. This is primarily due to the availability of FGGE Level IIb satellite wind data from the University of Wisconsin. The results of this investigation are also compared with previous studies of the Northern Hemisphere summer monsoon circulation. Here, the sharp geographical contrasts (east-west and north-south extents, topography, etc.) between the Australian and

Fig. 1 December mean wind and velocity potential fields at 850 mb. Top: Wind vectors; bar $\sim 1.0 \text{ ms}^{-1}$; half bar $\sim 2.5 \text{ ms}^{-1}$; and full bar $\sim 5 \text{ ms}^{-1}$. Also shown are the major trough (heavy full line) and ridge (heavy dashed line) axes, and the major anticyclonic (A) and cyclonic (C) centers. Bottom: Divergent wind (arrows; 3 ms^{-1} unit vector) and velocity potential (full lines; $10^6 \text{ m}^2 \text{ s}^{-1}$ unit) fields. Velocity potential intervals are 1 unit. Also shown are the major divergent (D) and convergent (C) centers.

Asian continents may result in substantial differences in the natures of these Southern and Northern Hemisphere summer monsoon circulations.

2. Data

The data used in this study were extracted from the objectively analyzed, FGGE/WMONEX data set prepared by Sumi and Murakami (1981), i.e., twice-daily, objectively analyzed 2.5° latitude-longitude resolution u , v , ζ , D , ϕ , and χ data at 200 and 850 mb over an expanded WMONEX region (40°E - 100°W , 45°N - 30°S) for December 1978 to February 1979. (A list of symbol is given in Appendix I.) For a more detailed description of these data and the objective analysis scheme, refer to the paper by Sumi and Murakami (1981).

During the FGGE/WMONEX period of December 1978 to February 1979, low-level northerly surges, equatorial disturbances and the associated convective activity over the South China Sea (regional WMONEX domain) were weaker

than normal. However, Japanese satellite cloud pictures indicated that pronounced convective activity occurred over the central South Pacific near the dateline. To determine the relationship between this region of convective activity and the Southern Hemisphere summer monsoon system, the area of investigation in this study was defined to extend from 90°E to 140°W and 30°N to 30°S .

Daily wind and velocity potential fields over this region at 200 and 850 mb for December 1978 to February 1979 were recently compiled by Murakami *et al.* (1981). The reader is directed to these maps for a detailed exhibition of the day-to-day changes in the Southern Hemisphere summer monsoon circulation.

3. Monthly mean wind fields

The characteristic features of the monthly mean wind and velocity potential fields were described by Sumi and Murakami (1981) and

Fig. 2 As in Fig. 1, except for January.

briefly restated here to facilitate the present discussion. In Fig. 1 for December, the Northern Hemisphere near-equatorial trough at 850 mb extends along about 2° - 3° N from the Bay of Bengal, across the South China Sea and Borneo, to the central Pacific ($\sim 175^{\circ}$ E). North of this trough, northeast trades dominate with maximum wind speeds ($\sim 13 \text{ ms}^{-1}$) in the area of 10° - 15° N, 135° - 145° E. Along the equator, cross-equatorial northerlies are predominant between the Malaysian Peninsula and Borneo. Over the western Pacific from about 120° to 175° E, weak cross-equatorial northwesterly flows carry westerly momentum into the Southern Hemisphere. In contrast, equatorial winds east of the dateline are predominantly easterly with the strongest winds ($\sim 12 \text{ ms}^{-1}$) occurring near 140° W. In the Southern Hemisphere, an ill-organized, near-equatorial trough lies along the northern coast of Australia and extends into the equatorial South Pacific to 7° S, 180° . Weak low-level west-

erlies (easterlies) are found to the north (south) of this trough.

In January (Fig. 2), the Southern Hemisphere summer monsoon appears to be fully established, with well-defined, Northern and Southern Hemisphere near-equatorial troughs along about 2° - 5° N and 10° - 20° S, respectively. Strong equatorial westerlies prevail in the equatorial region between these two troughs, with maximum winds (12 ms^{-1}) occurring over the Arafura Sea (10° S, 140° E). Figure 2 (bottom) reveals that this region of strong westerlies is characterized by substantial low-level convergence. Similarly, another convergent center over the South Pacific near 10° S, 170° E is also embedded in an area of equatorial westerlies. In general, low-level convergence (rainfall) seems to be most pronounced about 5 degrees of latitude equatorward of the Southern Hemisphere monsoon trough.

During February (Fig. 3), the low-level, near-equatorial westerlies weaken considerably in as-

Fig. 3. As in Fig. 1, except for February.

sociation with a westward retreat of the monsoon trough from the dateline in January to near 165°E in February. Figure 3 (bottom) indicates that the low-level convergence center over the South Pacific also shifts about ten degrees westward from its position in January.

The 200 mb monthly mean wind fields for January are shown in Fig. 4. For brevity, discussions of the December and February mean 200 mb circulations will be made without reference to figures. In Fig. 4 (top), the equatorial winds east of about 170°W are predominantly westerly. These equatorial westerlies are related to an upper-level trough over the North Pacific which extends southwestward from around 30°N , 145°W to 10°N , 155°W . Conversely, west of the dateline, fairly strong equatorial easterlies

are associated with the Northern and Southern Hemisphere ridge systems along about 10°N and 15°S , respectively. These easterlies are strongest ($\sim 10\text{ ms}^{-1}$) in the vicinity of Borneo.

In the Southern Hemisphere, note that the 200 mb ridge axis nearly coincides with the low-level monsoon trough position in Fig. 2. Thus, the Southern Hemisphere monsoon circulation is characterized by a low- (upper-) level trough (ridge) system. Interestingly, these features are similar to the Northern Hemisphere summer monsoon which is associated with a deep low-level monsoon trough over southern Asia and a pronounced Tibetan high aloft.

A comparison of Figs. 2 (bottom) and 4 (bottom) reveals an approximately inverse relationship between the 850 and 200 mb, January mean

Fig. 4 January mean wind and velocity potential fields at 200 mb. Top: Wind vectors; bar $\sim 2\text{ ms}^{-1}$, half bar $\sim 5\text{ ms}^{-1}$, full bar $\sim 10\text{ ms}^{-1}$, and flag $\sim 50\text{ ms}^{-1}$. Bottom: Divergent wind (arrows; 5 ms^{-1} unit vector) and velocity potential (full lines; $10^6\text{ m}^2\text{s}^{-1}$ unit) fields. Velocity potential intervals are 2.5 units. Refer to Fig. 1 for further information.

velocity potential patterns. Here, pronounced 200 (850) mb divergent outflow (convergent inflow) is centered over the equatorial South Pacific at about 10°S , 170°E and dominates the entire Pacific region. Outflow from the divergent center at 200 mb is directed northward (southward) over the tropical North (South) Pacific, with strong northerly (southerly) return flows at 850 mb. These local Hadley circulations appear to be strongest along about 170°E , with the associated updraft area near 10°S , 170°E being a major heat source (condensation) region for the Southern Hemisphere summer monsoon circulation.

4. Transient disturbance activity

Figure 5 depicts the longitudinal profiles of monthly mean $\langle v \rangle$ and $\langle v^2 \rangle$ along the equator for December (top), January (middle), and February (bottom), respectively. Here, the strongest cross-equatorial $\langle v \rangle$ northerlies of -6 ms^{-1} occur between 100° and 105°E (near Singapore)

during December. [In comparison, the cross-equatorial, low-level jet off the east coast of Africa during the Northern Hemisphere summer monsoon exceeds 12 ms^{-1} (see the 850 mb maps compiled by Ramage and Raman, 1972).] Interestingly, the longitudinal profile for January indicates that $\langle v \rangle$ exceeds -2 ms^{-1} at around 105°E , 125°E , 150°E , 175°E , and 170°W , respectively. Thus, the Southern Hemisphere summer monsoon is characterized by widespread cross-equatorial flows from the Northern Hemisphere. This is in sharp contrast to the Indian monsoon which only exhibits strong cross-equatorial flows in the vicinity of the east coast of Africa.

In Fig. 5, the strongest $\langle v \rangle$ northerlies of the season occur near Singapore (100° - 105°E) and are associated with very small $\langle v^2 \rangle$ values. Consequently, these cross-equatorial northerlies are quasi-stationary in this region. Conversely, $\langle v^2 \rangle$ is quite large over the equatorial Pacific.

Fig. 5 Longitudinal profiles of monthly mean $\langle v \rangle$ (full lines; ms^{-1} unit) and $\langle v^2 \rangle$ (dashed lines; $\text{m}^2 \text{s}^{-2}$ unit) at 850 mb along the equator. Hatching (shading) denotes $\langle v \rangle$ ($\langle v^2 \rangle$) regions of less (greater) than -2 (10) units.

For example, between 160°E and the dateline, $\langle v^{*2} \rangle$ exceeds $10 \text{ m}^2 \text{ s}^{-2}$ in January. Thus, this region appears to be a key area for interhemi-

spheric interactions associated with intraseasonal changes ("onset", "active" and "break" spells) in the Southern Hemisphere summer monsoon. This aspect of the monsoon will be discussed in Part II.

Monthly mean $\langle \zeta^{*2} \rangle$ distributions at 850 mb for December, January, and February are shown in Fig. 6. Weak low-level disturbance activity over the WMONEX region during the 1978-79 winter is reflected by the very small $\langle \zeta^{*2} \rangle$ values over the South China Sea. In comparison, disturbance activity is much more pronounced over the equatorial North Pacific. In January, $\langle \zeta^{*2} \rangle$ exceeds 2 units at around $(18^{\circ}\text{N}, 135^{\circ}\text{E})$, $(0^{\circ}, 145^{\circ}\text{E})$, and $(3^{\circ}\text{N}, 165^{\circ}\text{E})$. These maxima are associated with the frequent southward penetration of northerly surges, which cause anomalous shear vorticity variations within the Northern Hemisphere tradewind regime. Furthermore, these northerly surges occasionally reach as far south as 10°S , and may facilitate the development of low-level disturbances over the equatorial South Pacific. This is confirmed in Fig. 7 as strong northerly $(\langle u^{*}\zeta^{*} \rangle, \langle v^{*}\zeta^{*} \rangle)$ -flux vectors between the equator and 10°S at about 170°E closely correspond to a distinct zone of large $\langle \zeta^{*2} \rangle$ in Fig. 6 (middle). Note that these flux vectors are directed down the gradient of January mean absolute vorticity at 850 mb. Consequently, transient vorticity perturbations in the equatorial South Pacific region probably develop by receiving vorticity from the time mean (standing) fields. The major contributor in these non-linear barotropic interactions is the northerly

Fig. 6 Monthly mean $\langle \zeta^{*2} \rangle$ (10^{-10} s^{-2} unit) at 850 mb. Intervals are 1 unit with hatching denoting regions of greater than 1 unit.

Fig. 7 January mean $(\langle u^{*}\zeta^{*} \rangle, \langle v^{*}\zeta^{*} \rangle)$ -flux vectors (arrows; $4 \times 10^{-5} \text{ m s}^{-2}$ unit vector) and vorticity (full lines; 10^{-5} s^{-1} unit) field at 850 mb. Hatching denotes regions of positive vorticity.

$\langle v^* \zeta^* \rangle$ -flux due to transient flows (surges) along about 170°E.

Interestingly, the large $\langle \zeta^{*2} \rangle$ values around the Cape York Peninsula (10°-20°S, 140°-145°E) in January do not appear to be directly related to the northerly $\langle v^* \zeta^* \rangle$ -flux vectors from the Northern Hemisphere, i.e., northerly surges may not be the major controlling factor for inducing low-level disturbances in and around the monsoon trough near the Cape York Peninsula. In February, small $\langle \zeta^{*2} \rangle$ terms over the equatorial North Pacific (Fig. 6, bottom) and reduced $\langle v^{*2} \rangle$ values along the equator (Fig. 5, bottom) indicate that northerly surge activity is substantially depressed during this period. However, it should be noted that $\langle \zeta^{*2} \rangle$ between 10° and 20°S (Fig. 6, bottom) still exceeds 3 units near (20°S, 143°E), (17°S, 153°E), and (18°S, 170°), respectively. As will be shown in Section 5, the divergence effect is primarily responsible for the

development of low-level disturbances in the immediate vicinity of the Southern Hemisphere monsoon trough. Therefore, the mechanisms that are responsible for low-level disturbances differ considerably within the Southern Hemisphere monsoon region.

5. Maintenance of vorticity perturbations

To identify the major processes that are responsible for the maintenance of eddy vorticity perturbations during the Southern Hemisphere monsoon, both sides of the vorticity equation were multiplied by ζ' and each term in the resulting equation was zonally averaged between 100°E and the dateline. By defining $Z = \zeta'^2/2$, the following equation was then obtained:

$$\frac{\partial \bar{Z}}{\partial t} = -\frac{\partial \bar{u} \bar{Z}}{\partial x} - \frac{\partial \bar{v} \bar{Z} \cos \phi}{\cos \phi \partial y} - \overline{v' \zeta' \frac{\partial \bar{\eta}}{\partial y}} - \bar{\zeta' D' \bar{\eta}} - 2 \bar{DZ} + \bar{R(Z)}. \tag{1}$$

Fig. 8 Zonal mean-time (twice-daily; $i=1$ to 180) sections of $\bar{Z}$ ($10^{-11} s^{-2}$ unit) and the computed results of terms in eq (1) ($10^{-15} s^{-3}$ unit). For $\bar{Z}$, $(-\overline{v' \zeta' \partial \bar{\eta} / \partial y})$, $(-\overline{\zeta' D' \bar{\eta}})$, and $\bar{R(Z)}$ with intervals of (5, 5, 5, and 10) units. Full (dashed) lines represent positive (negative) intervals (no zero line). Hatching denotes regions of greater than (10, 5, 5, and 10) units, respectively.

The computed results of 850 mb $\bar{Z}$ square-vorticity and the three major terms in eq.(1), i.e., $(-\overline{v'\zeta'\partial\eta/\partial y})$, $(-\zeta'D'\bar{\eta})$ and $\bar{R}(Z)$, are presented in the time-series of Fig. 8.

In Fig. 8 (left), note that $\bar{Z}$ square-vorticity along about 10°-20°S increases abruptly during the onset period (23-25 December). This is probably a reflection of the sudden intensification of low-level disturbance activity in and around the Southern Hemisphere near-equatorial trough. These disturbances are primarily induced by the $(-\zeta'D'\bar{\eta})$ divergence term, which is positive and substantial during the post-onset phase.

As shown in Fig. 9 (right), ζ' and D' perturbations are generally positively correlated in the vicinity of the Southern Hemisphere trough (15°S). Conversely, $\zeta'D'$ at the equator is small and frequently changes sign. Thus, the associated $(-\zeta'D'\bar{\eta})$ divergence effect is not a major factor in the development of equatorial disturbances (Fig. 8, middle-right). Here, barotropic interaction

processes, i.e., $(-\overline{v'\zeta'\partial\eta/\partial y})$, appear to be the main contributor to disturbance development. Similarly, low-level disturbances over the region between 5° and 10°S also intensify via barotropic processes. This can be reconfirmed in Fig. 9 (middle), which reveals that the zonal mean $\overline{v'\zeta'}$ -flux vectors at 850 mb are directed southward and down the gradient of zonal mean absolute vorticity between the equator and 10°S. Therefore, low-level vorticity perturbation equatorward of the Southern Hemisphere near-equatorial trough tend to intensify by receiving vorticity from the zonal mean circulation via nonlinear barotropic processes.

Another feature of interest in Fig. 8 is the approximately inverse relationship between $\bar{Z}$ and $\bar{R}(Z)$ at nearly every latitude. This relationship is most clearly defined in the region of 5°N to 15°S. Presumably, this is indicative of the planetary boundary layer frictional effect.

Table 1 is a summary of the major terms in eq. (1), averaged for the WMONEX period of December 1978 to February 1979, at 850 and 200 mb, respectively. For brevity, the following discussion will only focus on the computed results at 850 mb. We note the following features:

Table 1. Zonally-averaged (100°E-180°), season mean (December 1978-February 1979) values of $\bar{Z}$ and the major terms in eq. (1). Top: At 850 mb. Units are 10^{-11}s^{-2} and 10^{-16}s^{-3} , respectively. Bottom: At 200 mb. Units are 10^{-10}s^{-2} and 10^{-15}s^{-3} , respectively.

	Lat.	$\bar{Z}$	$-\frac{\partial\bar{v}\bar{Z}\cos\phi}{\partial y}$	$-\frac{\bar{v}\bar{\zeta}'\partial\bar{\eta}}{\partial y}$	$-\bar{\zeta}'D'\bar{\eta}$	$-\bar{D}\bar{Z}$	$\bar{R}(Z)$
850 MB	30	7.0	-0.0	0.2	5.5	0.7	-6.2
	25	4.7	-0.7	-0.5	2.3	0.1	-1.0
	20	3.0	-0.9	0.1	0.4	-0.1	0.7
	15	3.1	-0.5	0.3	-0.2	-0.1	0.5
	10	3.7	-0.2	0.0	0.8	0.1	-0.7
	5	3.6	-0.2	0.1	0.6	0.6	-1.1
	0	5.4	0.1	0.6	-0.0	1.5	-2.4
	-5	4.8	0.0	1.3	0.2	1.3	-2.6
	-10	6.1	-0.5	1.4	1.1	2.1	-4.0
	-15	8.2	0.8	-0.7	3.0	2.8	-6.0
	-20	7.0	1.6	0.4	0.9	1.3	-4.0
	-25	5.9	0.1	0.2	1.8	-0.3	-1.7
	-30	8.0	-0.6	-0.5	2.7	-0.5	-1.3
	30	4.7	1.0	-1.2	3.4	1.2	-4.7
	25	2.9	-2.6	0.2	0.5	0.3	1.4
200 MB	20	1.7	0.3	0.2	0.6	1.6	-2.1
	15	1.3	0.6	0.1	0.1	0.7	-1.2
	10	0.9	0.3	0.0	0.1	0.2	-0.3
	5	0.7	0.1	0.0	0.1	-0.1	0.1
	0	0.7	-0.1	0.0	0.0	-0.3	0.4
	-5	0.8	-0.2	0.1	0.1	-0.6	0.7
	-10	0.9	-0.2	-0.0	0.2	-0.5	0.7
	-15	1.2	-0.2	-0.0	0.3	-0.2	-0.0
	-20	2.4	-0.0	0.1	0.8	0.6	-1.4
	-25	4.1	-0.6	0.9	2.3	0.9	-3.6
	-30	5.5	-0.4	0.2	4.5	2.1	-5.8

Fig. 9 As in Fig. 8, except for $\overline{u'v'}$ ($1\text{ m}^2\text{s}^{-2}$ unit), $\overline{v'\zeta'}$ (10^{-6}ms^{-2} unit), and $\overline{\zeta'D'}$ (10^{-11}s^{-2} unit) with intervals of (5, 5, and 1) units. Full (dashed) lines represent positive (negative) intervals (no zero line). Hatching denotes regions of greater than (5, 5, and 1) units, respectively.

(1) Maximum $\bar{Z}$ square-vorticity (8.2 units) occurs at 15°S; (2) The $(-\partial \bar{v} \bar{Z} \cos \phi / \cos \phi \partial y)$ meridional advection effect is maximum (1.6 units) at 20°S; (3) The $(-\bar{v}' \zeta' \partial \bar{\eta} / \partial y)$ barotropic interaction processes are most pronounced (1.4 units) at 10°S; (4) The $(-\zeta' \bar{D}' \bar{\eta})$ divergence effect at 15°S (3.0 units) is the largest contributor to the maintenance of $\bar{Z}$ in the vicinity of the Southern Hemisphere near-equatorial trough; (5) The $(-2 \bar{D} \bar{Z})$ term at 15°S is also substantial (2.8 units), with the $(-2 \bar{D} \bar{Z})$ component being the main contributor; and (6) The negative $\bar{R}(\zeta)$ effect is most pronounced (-6.0 units) at 15°S.

6. Concluding remarks

This study utilized twice-daily, objectively analyzed, 2.5° latitude-longitude resolution, 850 and 200 mb u , v , ζ , D , ϕ , χ data for December 1978 to February 1979 over an expanded WMONEX region (90°E-140°W, 30°N-30°S). These data appear to be adequate to describe at least some of the characteristic features of the Southern Hemisphere summer monsoon circulation.

In January (mid-season), the domain of the Southern Hemisphere monsoon probably coincides with a region of strong equatorial westerlies extending from the northeastern Indian Ocean (100°E), across the Indonesian Seas and New Guinea, to the western South Pacific (180°) at 850 mb. East of the Indonesian Seas ($\sim 140^\circ$ E), these equatorial westerlies are related to pronounced low-level convergence (convection). The eastern end (around 10°S, 170°E) of the Southern Hemisphere monsoon trough is characterized by a major convergent center at 850 mb and a 200 mb anticyclonic system associated with dominant upper-level divergence.

A comparison of the Southern and Northern Hemisphere summer monsoons reveals some similarities between these circulations. For example, the Northern Hemisphere monsoon is also associated with low-level westerlies, heavy rainfall in the east (western North Pacific, Indochina, Bay of Bengal and India), and dry weather (downdrafts) in the west (Arabian Sea and Saudi Arabian Desert). Furthermore, 200 mb divergence in the major updraft region (western South Pacific) of the 1978-1979 Southern Hemisphere summer monsoon is comparable to, or even larger than, that of the Northern Hemisphere monsoon. However, the corresponding 200 mb anticyclonic cells in the Southern Hemisphere during January are much weaker than the Tibetan

high in July. Similarly, although both monsoon circulations exhibit easterly equatorial flows at 200 mb, weak easterlies ($\sim 10 \text{ ms}^{-1}$) over Borneo in January are contrasted with extremely strong easterlies ($\sim 25 \text{ ms}^{-1}$) over the equatorial Arabian Sea during July. These discrepancies are due, at least partially, to the different locations (with respect to the equator) of the major 200 mb divergent centers (10°S vs. 20°N) during the Southern and Northern Hemisphere summer monsoons. Substantial differences in these monsoon circulations may also be the result of the marked geographic contrasts between the two regions; namely, the Australian continent is basically mountain-free with a much smaller latitudinal and longitudinal extent than Asia.

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Appendix I: List of Symbols

- λ, ϕ : longitude and latitude
- dx, dy : $a \cos \theta d\lambda$ and $ad\theta$; a , radius of earth
- t : time
- u, v : zonal and meridional winds
- ζ, D : vorticity and divergence
- ϕ, χ : streamfunction and velocity potential
- f : Coriolis parameter
- β : df/dy
- η : $f + \zeta$
- $(\bar{\quad})$: zonal average between 100°E and 180°
- $(\quad)'$: departure from zonal average
- $\langle \quad \rangle$: time average
- $(\quad)^*$: departure from time average
- Z : $\zeta^2/2$

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WMONEX (1978-79) 期間中における 南半球の夏期モンスーン循環

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客観解析による 850 と 200 mb の風のデータを用いた。期間は1978年12月1日から1979年2月28日まで、範囲は 90°E — 140°W , 30°N — 30°S である。

モンスーン循環は1月中旬にもっとも顕著になり、強い西風帯 (850 mb) が 10°S にそって印度洋 (100°E) から、アラフラ海 (130°E) をへて、南太平洋 (180°) にまでのびる。モンスーン域の東端近く (南太平洋) では強い下 (上) 層収斂 (発散) があり、モンスーン循環の熱源の中心域と思われる。

モンスーン・トラフ附近 (15°S) では、下層擾乱は主として発散効果により発達する。一方赤道から 10°S までのモンスーン偏東風帯では下層擾乱は带状流とのパロトロピック交換により発達する。