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THE WALKER CIRCULATION AND ATMOSPHERIC WATER VAPOUR CHARACTERISTICS OVER THE PACIFIC FOR TWO CONTRASTING YEARS

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ABSTRACT

The Walker circulation for two contrasting years 1983 (ENSO year) and 1984 (non-ENSO year) is determined. Principal changes in the upper level divergence are noted in the western and central Pacific regions. Thus, this part seems to form the principal branch of the Walker circulation, where a reversal takes place during the two contrasting years. Water vapour characteristics of the atmosphere over the western and central Pacific regions are determined using radiosonde data. During the ENSO event of 1983 an unusual accumulation of water vapour over the central Pacific and a depletion of it over the Indonesian region is noted. Further, the correlation coefficient between the SO index and water vapour variation showed significant values. Another aspect of the tropical atmosphere discussed here is the thermodynamic structure and its implications for the development of convection. Our study revealed a spectacular reversal of atmospheric properties such as the upper level divergence, water vapour, and thermodynamic structure during the two contrasting years.

KEY WORDS Water vapour content Tropical circulations Thermodynamic structure ENSO

1. INTRODUCTION

Due to their influence on global climate, the El Niño–Southern Oscillation (ENSO) events have received much attention in recent years. The most recent ENSO event of 1983 is considered to be the strongest of this century (Rasmusson and Wallace, 1983) and has provided a new impetus to studies of ENSO. Several recent articles have described the development and the associated climatic anomalies of this extraordinary event (Chen, 1983; Krueger, 1983; Quiroz, 1983; Kousky *et al.*, 1984). The development and decay of ENSO events have several interesting and yet unexplored facets. One such feature is the water vapour content and thermodynamic structure of the tropical atmosphere. In this paper we study the Walker circulation, atmospheric water vapour and thermodynamic structure for two contrasting years 1983 and 1984. Rainfall characteristics approximately reversed between these two years. Although parts of these characteristics have been discussed earlier in other papers, the present study brings together many of the features of the tropical atmosphere, a novelty being the discussion on thermodynamic structure during the contrasting years. Our results show a close interconnection between such atmospheric properties as upper level divergence, water vapour, rainfall and thermodynamic structure and the phase of ENSO.

2. DATA AND METHODOLOGY

Wind data (monthly means) were obtained from the National Meteorological Center (NMC) tropical grid point data. Wind data are available at 1000, 850, 700, 500, 300, and 200 mb levels. The temperature and rainfall data are obtained from Monthly Climatic Data for the World, US Department of Commerce (1976–1986). Velocity potential (χ) is computed by relaxation of the 200 mb divergence, which is calculated using the NMC data. The boundary conditions used are the same as those of Murakami and Unninayar

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(1977), except that the southern boundary is extended to 48·1 °S. Precipitable water is calculated using the formula:

$$P_w = \frac{1}{g}\int_{p_T}^{p_0} q\,\mathrm{d}p \tag{1}$$

where q is the specific humidity, $p_T = 300$ mb, $p_0 = 1000$ mb and g is the acceleration of gravity. In this study we propose to calculate the so-called 'precipitation efficiency' (*PE*). This might show interesting differences between the contrasting years. Sellers (1965) defined *PE* as the ratio between mean daily precipitation and the average precipitable water. He suggested that this ratio can be thought of as the fraction of the average moisture overhead which falls as precipitation on an average day. Following Sellers (1965) we write *PE* as

$$PE = \frac{P}{n P_w} 100 \text{ per cent} \tag{2}$$

where P is the monthly mean precipitation, P_w is monthly mean precipitable water and n is the number of days in a month.

To study the thermodynamic structure, we calculated equivalent potential temperature (θ_e), in addition to potential temperature (θ) and saturated equivalent potential temperature (θ_e^*) using the method given in Simpson (1978).

3. RESULTS AND DISCUSSION

3.1. Walker circulation

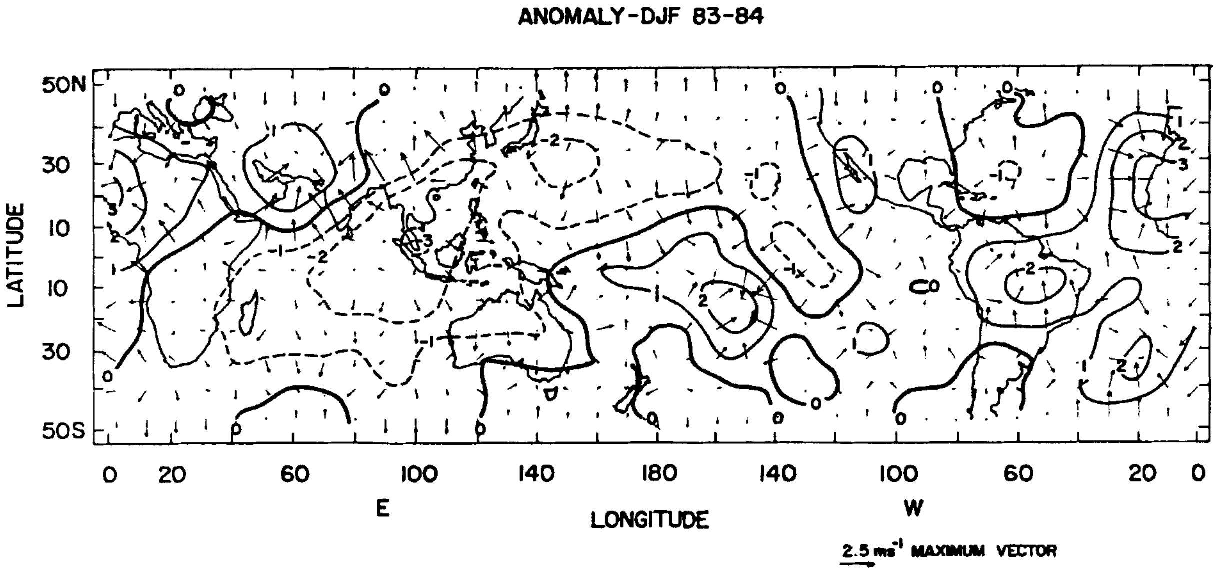
The interannual variation of the east–west circulation is examined through the 200 mb divergent flow. This circulation in the equatorial vertical zonal plane is called the Walker circulation. Velocity potential (χ) shows the upper branches of thermal circulations such as the Walker circulation (Krishnamurti, 1971). Figures 1 and 2 show the 3-month mean and anomaly fields of χ for the two periods DJF (December, January, February) 1982–1983 and DJF 1983–1984, respectively. Anomalies are calculated by subtracting the mean of 6 years (1980–1985) from the individual fields. Figures 1a and 2a show the main differences of the atmospheric circulations over the equatorial Pacific. During DJF 1982–1983 divergent flow over the central equatorial Pacific and convergent flow over the Indonesia/Borneo region prevailed, while during DJF 1983–1984 the divergent flow extended through the Indonesia/Borneo region and adjacent oceanic areas.

The contrast in the circulation patterns over the equatorial Pacific between 1983 and 1984 is more evident in the anomalous fields of χ. Figure 1b can be compared with the (lower) figure 10 of Rasmusson and Arkin (1985). Both figures show essentially the same features. The convergent flow over the Indonesian region and the divergent flow to the east can be seen. During DJF 1983–1984 the anomaly field of χ (Figure 2b) was close to the mean (see figure 3 of Rasmusson and Arkin, 1985).

These features are in general agreement with the tropical circulation characteristics discussed by Kayano *et al.* (1988) with an anomalous Walker circulation during DJF 1982–1983 and the return to normal conditions during DJF 1983–1984. During DJF 1982–1983, rising motion prevailed over the central equatorial Pacific with sinking to the east and west, while at low levels, westerlies occurred in the western Pacific and easterlies in the eastern Pacific. The circulation reversed over the equatorial Pacific and Indonesia/Borneo region during DJF 1983–1984 (Kayano *et al.*, 1988).

The rainfall pattern during DJF 1982–1983 associated with the anomalous atmospheric circulation was such that heavy rainfall occurred over the central Pacific region and relatively dry conditions prevailed over the Indonesia/Borneo region (see Figure 3 for the rainfall at two key stations, Atuona and Singapore). Even in the other regions there is a good agreement between the rising and sinking motion and the rainfall characteristics, as inferred from the outgoing longwave radiation pattern given in Rasmusson and Wallace (1983) and those given in Kayano (1986) for the continental tropics.

The observed upper level divergence pattern is consistent with the contemporary theoretical notions on heat-induced equatorial circulations. Gill (1980) in an elegant analytical study dealing with these type of



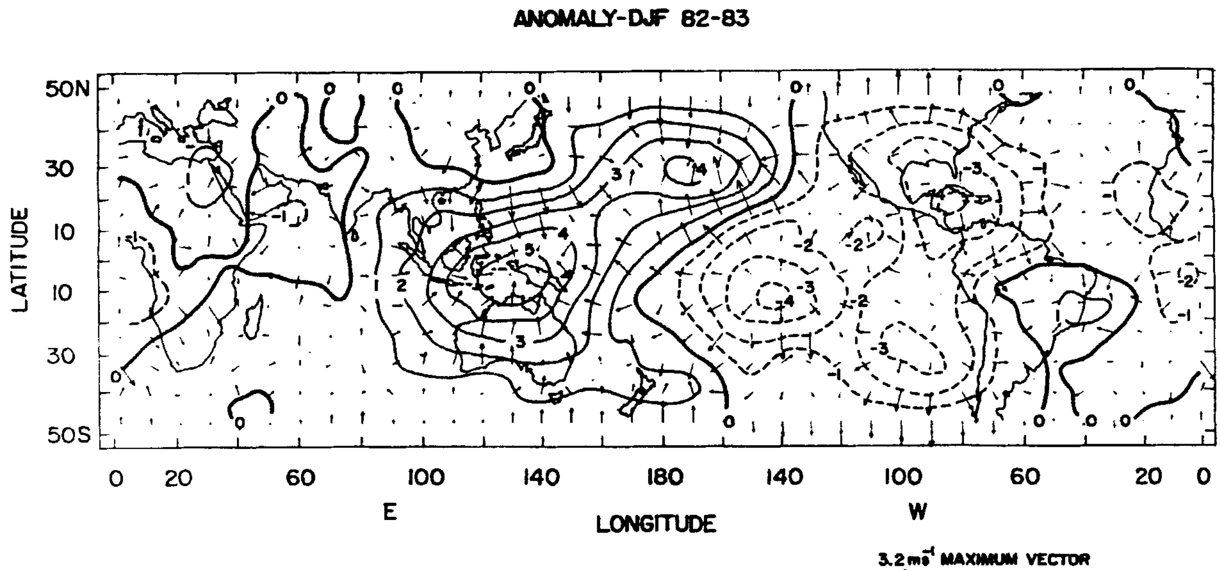


Figure 1. Mean and anomaly fields of velocity potential (10^6 $m^2 s^{-1}$) at 200 mb for the 3-month period December 1982, January and February 1983. Anomalies are calculated by subtracting the mean of 6 years (1980–1985) from the individual fields (contour intervals are 10^6 $m^2 s^{-1}$)

circulations, showed that rising motion occurs directly above the heat source with easterlies to the east of it and a smaller region of westerlies to the west. He interpreted this pattern in terms of equatorially trapped Kelvin and Rossby waves. When the heating is switched on at an initial time, Kelvin waves travel eastward creating easterlies to the east of the heating. Rossby waves that have a phase speed approximately one-third to that of Kelvin wave speed travel westward. Because of the slower Rossby wave speed the region of westerlies to the west is more limited. Thus, easterlies to the east and westerlies to the west in the lower levels induce convergence and rising motion over the heat source. In the steady state the heating rate is balanced by the adiabatic cooling of the ascent.

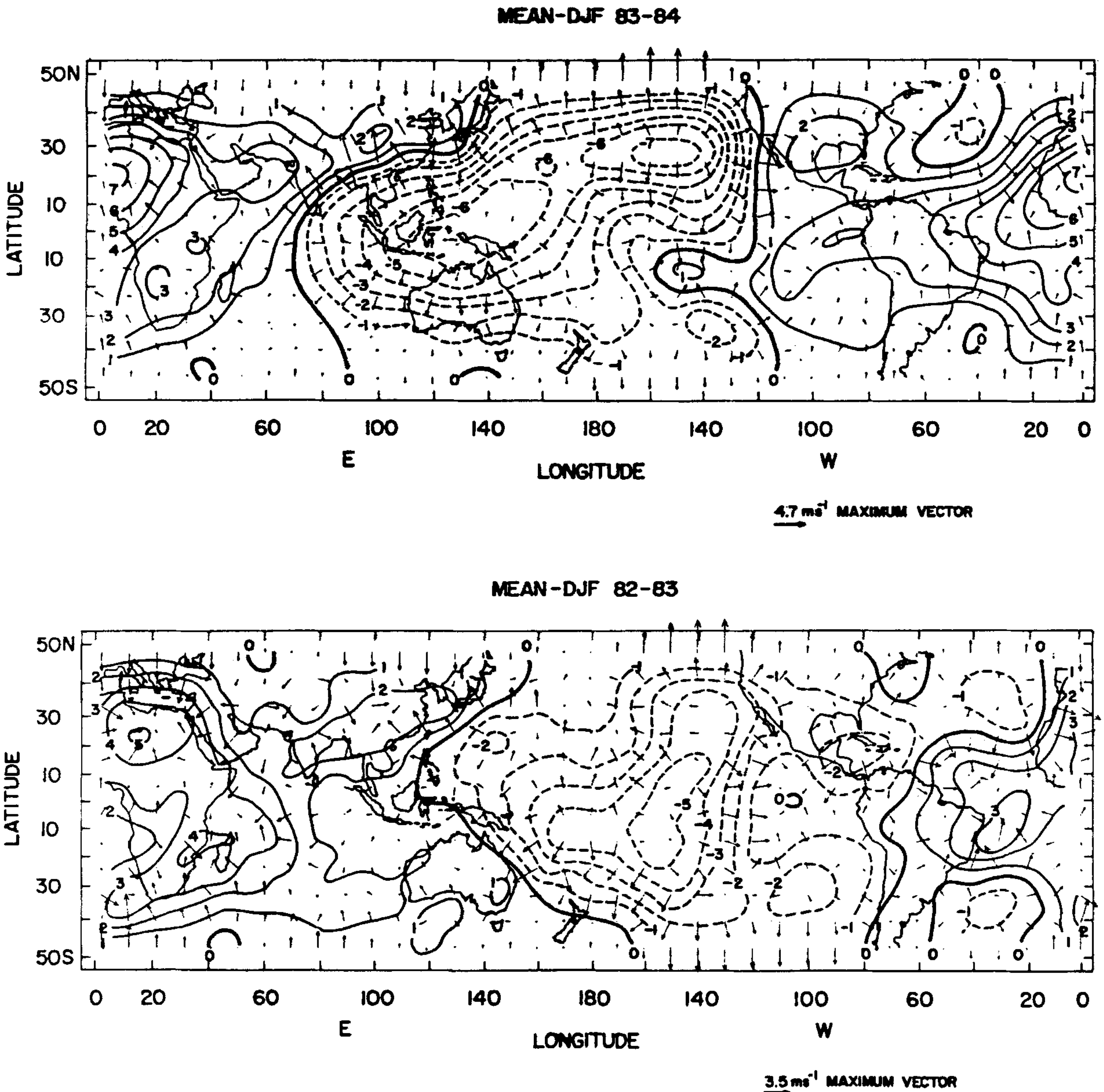


Figure 2. Same as Figure 1 for the 3-month period December 1983, January and February 1984

3.2. Water vapour and thermodynamic characteristics

From the earlier discussion it appears that principal changes during the contrasting years (in terms of ENSO) seem to happen in the equatorial Pacific region. So far, the water vapour characteristics and interannual variations in this region have not been examined adequately. Since the variations of water vapour content are essentially controlled by the variations of the low-level convergence or divergence, the variations noted earlier during two contrasting years will have strong implications for the water vapour content. Figure 3 shows the precipitable water (P_w) and rainfall variations for two key stations, Singapore and Atuona. The middle part of the figure shows the monthly mean values of P_w, while the corresponding monthly rainfall totals are shown in

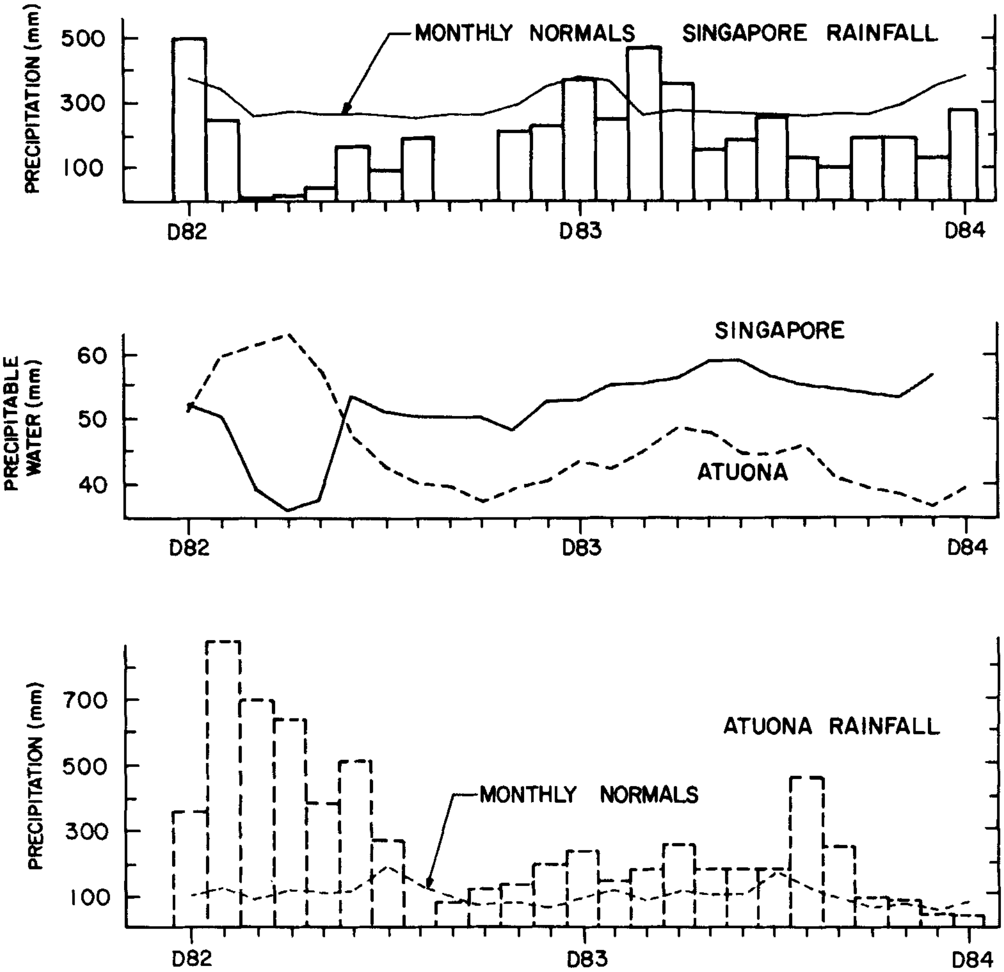


Figure 3. Monthly means of precipitable water (mm) and the corresponding monthly rainfall (mm) totals for Atuona and Singapore. December 1982 (D82) to December 1984 (D84). In the top and bottom figures the monthly normals (long-term means) are shown as continuous and broken lines, respectively. Data for August and September 1983 at Singapore and for July 1983 at Atuona were missing. Continuous lines = Singapore; broken lines = Atuona

upper and lower diagrams as bar graphs for the period December 1982 to December 1984. These two stations are selected such that they represent the rising and sinking limbs of the principal cell of the Walker circulation.

The most important aspect shown in Figure 3 is the marked precipitable water and rainfall changes varying inversely at the two stations during the first half of 1983. Note in the upper and lower parts of Figure 3, the unusually very high rainfall over Atuona and lack of it over Singapore. During the month of February, Atuona recorded 883 mm compared to the normal of 87 mm and Singapore recorded a meagre 6 mm compared to the normal of 164 mm! These features are certainly related to the rising and sinking motions associated with the Walker circulation discussed earlier. Most of the time the water vapour content in the atmosphere over Singapore was more than that over Atuona, but during the first half of 1983 the situation reversed. During March 1983, the difference in precipitable water of the two stations (Singapore minus Atuona) was $-26{\cdot}85$ mm, compared to a mean difference of 5·98 mm! The linear correlation coefficient between the two time series is $-0{\cdot}62$, which is significant at the 99 per cent level.

The decrease of rainfall at Singapore from December 1982 up to April 1983 was associated with a decrease of water vapour content and the higher rainfall during this time at Atuona was associated with a rise of water vapour content. Cornejo-Garrido and Stone (1977) suggested that enhanced condensation in the rising branch of normal Walker circulation (during a non-ENSO period) is a consequence of water vapour convergence, not enhanced evaporation. Even during an ENSO event this seems to be true. The higher water vapour content over Atuona during the beginning of 1983 was probably due to water vapour convergence in the lower atmosphere, associated with easterlies to the east and westerlies to the west. The theoretical implications for the creation of these easterlies and westerlies have already been interpreted earlier in terms of equatorially trapped Kelvin and Rossby waves. Somewhat similar conclusions have been reached in a recent study (Prabhakara *et al.*, 1985) using satellite inferred water vapour content. However, our results give additional information of the extraordinary ENSO event of 1983, particularly the thermodynamic structure over the tropical Pacific, which will be discussed later in this paper. Further, it is necessary to supplement studies with remotely sensed data wherever possible with data measured 'in situ', such as the radiosonde data.

In order to clarify how the water vapour variations are linked to the Southern Oscillation (SO), we computed for eight key radiosonde stations, the linear correlation coefficient between their P_w time-series and the SO index for two periods (January 1983 to December 1984 and January 1976 to February 1986) (Table I). In the latter series, deviations from the monthly means are used to calculate the correlations. The first four stations in Table I, in the equatorial Pacific, are negatively correlated with the SO index, while the last four stations, in the Indonesia/Borneo region, are positively correlated with the SO index. For the 2-year period (1983–1984) all the values except the one for Tahiti are significant at the 99·9 per cent level, and for the longer period (1976–1986) the significance of the correlation coefficient continued to be at the 99·9 per cent level for many stations. This shows a spatial and temporal consistency in the behaviour of the atmospheric water vapour as a response to the SO.

Table II shows the rainfall, P_w and PE for the two key stations, Singapore and Atuona. Parameter PE is calculated using equation (2). Note that in Table II, PE was 47·6 per cent in January 1983 at Atuona and

Table I. Correlation coefficient between precipitable water and SO index. Correlation coefficients are calculated with 5-month running means. The SO index (normalized sea-level pressure (NSPL) at Tahiti minus NSPL at Darwin) series are taken from Climate Diagnostics Bulletin, March 1986, Climatic Analysis Center, National Meteorological Center, Washington

Station/location	1983–1984	1976–1986
Tarawa (01°21′N, 172°55′E)	−0·81**	−0·57**
Funafuti (08°31′S, 179°13′E)	−0·73**	−0·59**
Atuona (09°48′S, 139°02′W)	−0·86**	−0·58**
Tahiti (17°33′S, 149°34′W)	−0·09	−0·12
Singapore (01°22′N, 103°55′E)	0·90**	0·46**
Kota Bharu (06°10′N, 102°17′E)	0·64**	0·46**
Kuala Lumpur (03°07′N, 101°33′E)	0·75**	0·19
Kuantan (03°47′N, 103°13′E)	0·67**	0·27*

** Significant at 99·9 per cent level.
* Significant at 99·0 per cent level.

Table II. Precipitation, precipitable water, and precipitation efficiencies for Singapore and Atuona

		Precipitation (mm)		Precipitable water (mm)		Efficiency (%)	
		Singapore	Atuona	Singapore	Atuona	Singapore	Atuona
1983	Jan.	246	883	50·9	59·8	15·6	47·6
	Feb.	6	702	39·5	61·4	0·5	40·8
	Mar.	19	644	36·4	63·2	1·7	32·9
1984	Jan.	251	152	55·5	44·8	14·6	11·5
	Feb.	470	188	55·7	45·6	30·1	14·7
	Mar.	361	264	56·7	49·2	20·5	17·3

reduced to 11·5 per cent in January 1984. However, at Singapore it was a mere 0·5 per cent in February 1983 and increased to 30·1 per cent in February 1984. Thus, precipitation-producing processes were efficient at Atuona and very inefficient at Singapore in the beginning of 1983 and the reverse happened during 1984 at these two stations. In general, precipitable water variations are small compared to the rainfall variations. However, during the ENSO event of 1983, precipitable water showed large changes, as noted earlier.

Furthermore, we have analysed the precipitable water variations during 1983–1984 for other radiosonde stations of near-equatorial South America and Africa. However, none showed such contrasting and consistent changes as those seen earlier over the western and central equatorial Pacific areas. So we conclude that the principal limbs of the Walker circulation are those over the central equatorial Pacific and Indonesia/Borneo region.

Another interesting aspect of the equatorial atmosphere related to the ascending and descending branches of the Walker circulation is the thermodynamic vertical structure during 1983–1984. Figure 4 shows the vertical profile of potential temperature (θ), equivalent potential temperature (θ_e) and the saturated equivalent potential temperature (θ_e^*) the environment would have if it is isothermally brought to saturation. These profiles for Atuona and Singapore are shown for March 1983 and March 1984. The importance of the thermodynamic properties of the tropical atmosphere lies in the fact that tropical precipitation is essentially of convective origin. Typical tropical profiles and the methodology for inferring convection are given in Holton (1979). The differences between the profiles of March 1983 and 1984 over Singapore are striking. The proximity of θ_e and θ_e^* during March 1984 shows that the atmosphere was very humid. The more uniform profile of θ_e is due to strong convection and vertical mixing favoured by the large-scale ascending motion (Aspliden, 1976). The layer of conditional instability was deep and favourable for deep convection during March 1984. During March 1983, however, the atmosphere over Singapore was very dry and the layer of conditional instability was also shallow. A careful comparison between θ profiles of 1983 and 1984 shows that the θ values are, in general, higher during March 1983, as expected because of the large-scale sinking motion. Almost reverse conditions prevailed over Atuona, with profiles of θ_e and θ_e^* over Atuona (Singapore) during March 1983 looking like those of Singapore (Atuona) during March 1984.

The profiles of θ, θ_e and θ_e^* show some interesting differences in the planetary boundary layer (PBL), but detailed analysis is not possible because of the low resolution of these profiles in the PBL. Nevertheless, some general features can be inferred. It can be seen that over Atuona, the θ profile is somewhat uniform between 1000 mb and 850 mb, while over Singapore it increased with height. These and other differences noted below are probably due to the hour of observation.The hour of observation at both the stations was 00 GMT, which means approximately 15:00 h local time at Atuona and 07:00 h local time at Singapore. Thus, the mixed layer was well established at 15:00 h over Atuona and over Singapore it was probably destroyed at 07:00 h. Further, note that the atmosphere at 1000 mb over Atuona was dry as inferred by the large difference between θ_e and θ_e^*, while at Singapore the difference was much less. We noted these differences in almost all the months we analysed. Further, temperature observations show that the 1000 mb temperatures at Atuona were always higher than at Singapore with the reverse being true at 700 mb. These observations suggest that the PBL of Atuona was always characterized by a mechanism which causes a rise of temperature and a decrease of humidity. Such a mechanism is possibly downdraughts in the near-surface layers. Fitzjarrald and Garstang (1981) discussed the vertical structure of the tropical boundary layer and noted the importance of the downdraughts. Further studies, using data with better resolution, are necessary to make detailed analysis of the PBL during the contrasting years.

4. SUMMARY AND CONCLUDING REMARKS

The Walker circulation is determined for two contrasting years, 1983 and 1984. The year 1983 was characterized by a strong ENSO event and 1984 was a non-ENSO year. The general features of the Walker circulation for the two contrasting years, as inferred by the characteristics of mean and anomaly fields of the velocity potential (χ) at the 200 mb level, are consistent with the vertical velocity field shown by Kayano *et al.* (1988). The principal changes in upper level convergence and divergence during the two contrasting years

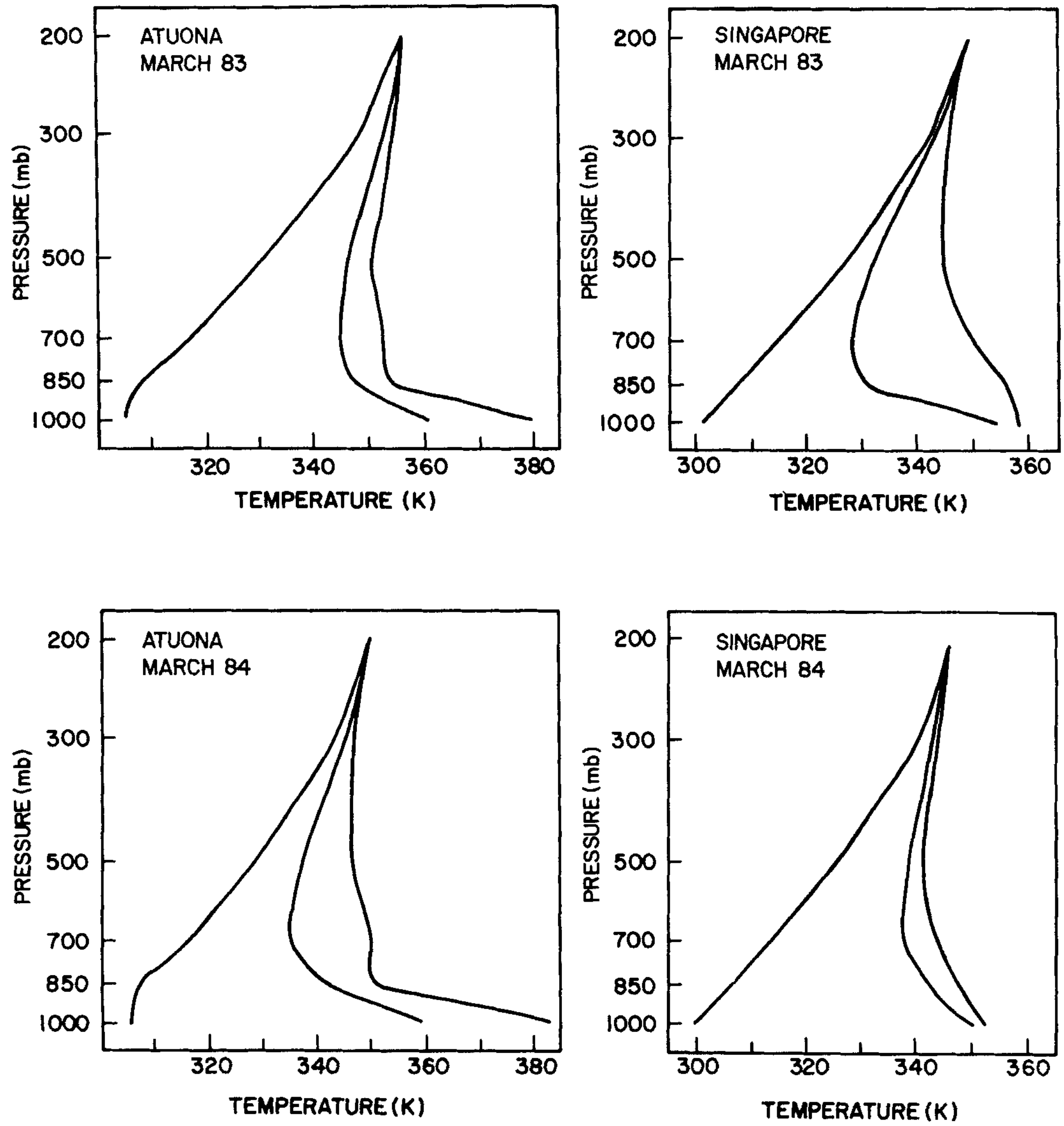


Figure 4. Vertical profiles of potential temperature (θ), equivalent potential temperature (θ_e), and saturated equivalent potential temperature (θ_e^*) for March 1983 and March 1984 at Atuona and Singapore. In these figures all curves at extreme left are θ, then followed by θ_e, and θ_e^*

happened in the western and central Pacific. Thus, this part of the Walker circulation forms the principal cell where major changes take place.

We calculated water vapour characteristics for two groups of four radiosonde stations, each representing the two limbs of the main cell of the Walker circulation in the Pacific. The variations during the two contrasting years showed accumulation of water vapour in the central Pacific and depletion of it in the Indonesian region. Further, the calculation of correlation coefficients between water vapour and the SO index showed highly significant (at 99·9 per cent level) values.

A novel feature of the present study is the discussion of the thermodynamic structure of the principal Walker circulation branch in the Pacific during the two contrasting years. The vertical profiles of θ, θ_e, and θ_e^* showed striking differences over the rising and sinking limbs of the Pacific Walker circulation between 1983 and 1984. The vertical structure of these profiles is interpreted in terms of conditions favourable or unfavourable for the development of tropical convection and precipitation. Further, although the vertical resolution of the profiles is low, some inferences could be drawn regarding the PBL. Thus, in summary, our results show a spectacular reversal of atmospheric properties, such as upper level divergence, water vapour, and thermodynamic structure, between the two contrasting years.

An interesting aspect of the Walker circulation is the mechanism which maintains it. In addition, the heat balance of the Walker circulation forms a curious problem. These aspects are currently being investigated.

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