On meridional circulation and heat budget of the troposphere over the Equatorial Central Pacific

By STEFAN L. HASTENRATH, *The University of Wisconsin*

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ABSTRACT

The existence of an equatorial dry zone in the Central Pacific enclosed between moister belts in both hemispheres is borne out by rainfall measurements and daily ESSA III and ESSA V cloud mosaics. The tropospheric wind regime is studied mainly on the basis of aerological soundings during the Line Islands Experiment (LIE) in spring 1967 and observations of earlier periods. During LIE, upper-tropospheric Westerlies extend continuously across the equator. In the lower layers, Easterlies dominate in the equatorial belt. The meridional wind component in the region of the Line Islands is from the South in the lower layers, and from the North in the upper troposphere.

From the vertical profiles of heat content and the distribution of diabatic heat sources and sinks during LIE, vertical profiles of divergence are derived, with the constraint that both the atmospheric heat and moisture budgets are satisfied. Lower-layer convergence and upper-tropospheric divergence result for the rain belt (Palmyra), with the opposite pattern prevailing in the equatorial dry zone (Christmas). Circulation in a mean meridional-vertical plane, derived from these profiles under certain assumptions is characterized by poleward flow in the lower layers, ascending motion in the rain belt, equatorward flow in the upper troposphere, and subsidence in the equatorial dry zone.

The ocean-troposphere system gains heat by radiation in both the rain belt and the equatorial dry zone. In the rain belt, export of potential energy and sensible heat exceeds the lower-layer import of latent heat; both troposphere and ocean in this region act as exporters of heat to other parts of the globe. In the equatorial dry zone, import of potential energy and sensible heat exceeds the export of latent heat, resulting in a net import of heat for the tropospheric column as a whole. Heat surplus from this region is disposed of only by the ocean.

1. Introduction

The existence of an equatorial dry zone across great part of the Pacific Ocean has long been recognized as one of the astounding phenomena in tropical climatology (e.g. Woeikoff, 1880; Hann, 1880; Koeppen, 1895; Deutsche Seewarte, 1896–1897). Meteorological experience during World War II has led to a model of the mean meridional circulation, in which two wheels turning in the opposite sense are enclosed between the two conventional Hadley cells, in such a way that subsidence prevails over the equator (e.g. Fletcher, 1945; Bryson, 1948; Rossby, 1949).

A meridional circulation with subsidence and owerlayer divergence over the equator raises an interesting problem regarding the characteristics of the tropospheric heat budget and the role of the equatorial region as an exporter of heat to higher latitudes. This is the subject of the present paper. Surface, radiosonde, aircraft, and satellite observations collected during the Line Islands Experiment (LIE) in spring 1967 (Ziper & Taylor, 1968), provide the main basis for the study. Available surface and upper-air data of earlier years over the Equatorial Pacific supplement this unique complex of simultaneous observations.

2. Pattern of cloudiness and rainfall

Early climatological descriptions of the Tropical Pacific (e.g. Koeppen, 1895; Schott, 1933*a*) have pointed at the existence of a dry zone along the equator, enclosed between elongated belts of abundant rainfall in both hemispheres. A meridional precipitation profile along approximately 160° W, constructed from Seelye's (1950) annual map, and other sources (Sekiguchi, 1952; Sadler, 1957; British Meteor.

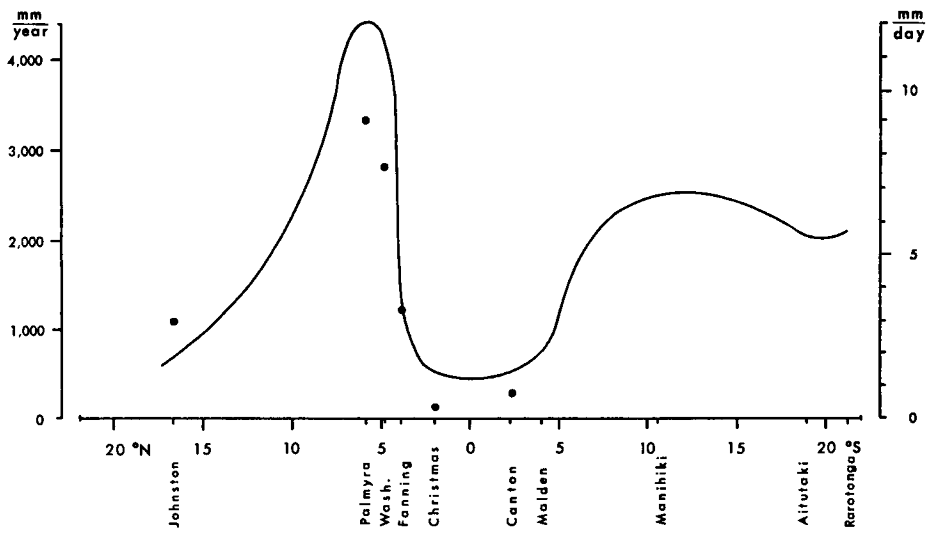

Fig. 1. Annual rainfall totals in a transect along approximately 160° W (solid line) (source: Seelye, 1950; Sekiguchi, 1952; Sadler, 1957; British Meteor. Office, 1958; Ichiye & Petersen, 1963;ESSA, 1968) and average daily rainfall during the Line Islands Experiment, Spring 1967 (dots) (source: ESSA, 1967*a* and unpublished LIE data).

Office, 1958; Ichiye & Petersen, 1963; ESSA 1967*a*, 1968; and unpublished LIE data), is presented in Fig. 1. Annual rainfall totals drop from a maximum of more than 4 000 mm/year at about 6° N to less than 500 mm/year in the vicinity of the equator, increasing again to about 2 500 mm/year around 10° S. Rainfall, P, measured during the Line Islands Experiment (March 16 to April 15, 1967) is also entered in Fig. 1, showing a decrease from 9.1 mm/day at Palmyra, to 3.3 mm/day at Fanning, and 0.35 mm/day at Christmas. For further details on rainfall distribution and regime, reference can be made to the pertinent literature (Schott, 1933*a*, 1938; Seelye, 1950; Sekiguchi, 1952).

In fair agreement with this, early annual and seasonal charts of the cloud distribution (Schott, 1933*b*; U.S. Weather Bureau, 1938) based mainly on ship observations, already indicated the existence of a relatively clear zone in the vicinity of the equator, over much of the Eastern and Central Pacific Ocean. Satellite observations in recent years have provided a more adequate survey of cloud distributions, the ESSA III and ESSA V daily mosaics being a particularly useful data source. On this basis, Kornfield et al. (1967) have constructed monthly average composite photographs, which show most impressively the tendency to a double structure, with belts of extended cloudiness enclosing a relatively clear zone along the equator (cf. Lettau, 1967). Kornfield et al. (1967) also discuss the seasonal variation of the cloud pattern.

Although the monthly composite photographs illustrate nicely the average pattern, some information is lost, since for example one day with extended cloud cover could give the same signal as many days with scattered cloudiness. Therefore, it was decided to evaluate the individual daily mosaics of ESSA III and V of a limited period, March and April 1967, in more detail. The belt between 10° N and 10° S was divided into 2.5° squares, and for each individual square and each day cloudiness was ascribed to one of the following four classes: (1) cloudiness more than half; (2) cloudiness less than half; (3) only traces of clouds; (4) entire area clear. Decision in favor of one of two adjacent classes is slightly subjective in marginal cases, but reasonable consistency can be achieved after some practice, and 15 day collectives can be considered meaningful. From the fortnightly compilatons of the relative frequency of the four classes, maps were constructed for the entire period 1 March through 30 April 1967. In drawing isopleths, values were always ascribed to the center of the respective individual square. Only

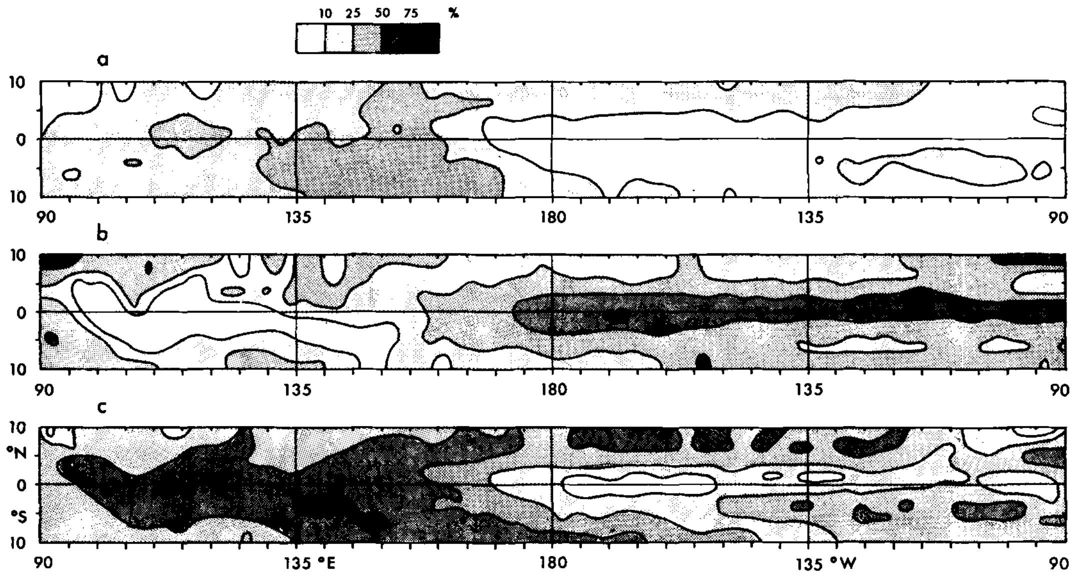

Fig. 2. Cloud pattern over the Equatorial Pacificin March–April 1967, from 2.5° squares evaluation of daily ESSA III and ESSA V Satellite mosaic photographs. (*a*) Percentage frequency of cloudiness "more than half"; (*b*) percentage frequency of "entire area clear"; (*c*) ratio of frequencies $(F_1+F_2)/(F_3+F_4)$.

the charts for classes 1 and 4, for the Pacific Ocean half of the earth, are reproduced in Figs. 2*a* and *b*. Furthermore, the frequencies of the upper two classes, F_1 and F_2, and of the lower two classes, F_3 and F_4, respectively, were added, and the ratio of these sums $(F_1+F_2)/(F_3+F_4)$, was computed. This ratio is mapped in Fig. 2*c*, and can be considered as representative of the ratio of the frequency of cloudy to that of clear days.

Figs. 2*a* through *c* consistently describe belts of increased cloudiness at 5° or poleward of it, in both hemispheres, and a relatively clear zone in the vicinity of the equator. Westward of about 170° E, this belt-like arrangement gradually vanishes. Inspection of monthly composite photographs of later periods reveals a similar pattern. While agreeing with the monthly composite photographs of Kornfield et al. (1967) in the basic features, Figs. 2*a* through *c* would seem to provide a more detailed description of the pattern of cloudiness.

3. Tropospheric circulation

(*a*) *Upper-air winds*

The evidence on rainfall and cloud distribution discussed in the preceding section 2 is indeed very suggestive of a mean meridional circulation similar to that proposed two decades ago by Fletcher (1945), Bryson (1948), and Rossby (1949). However, an attempt should be made to substantiate this model in terms of the scarce direct measurements of upper-air winds over the Equatorial Central Pacific.

Long-term ship observations compiled for 5° squares (U.S. Weather Bureau, 1938; Riehl, 1950; Mintz & Dean, 1952) indeed indicate, over the Central and Eastern Pacific, a zone of divergence in the surface winds along the equator, with belts of convergence in both hemispheres. From the available long-term ship observations (U.S. Weather Bureau, 1938) divergence of surface winds during March and April was computed, and is mapped in Figs. 3*a* to *c*. Figs. 3*a* through *c* show that the pattern of total divergence is essentially determined by the distribution of $\partial v/\partial y$. A fair agreement is indicated between Figs. 3*b* and 3*c* and the pattern of cloudiness illustrated in Figs. 2*a* through *c*. Location of upper-air stations to be mentioned later is also entered in Fig. 3*a*.

Published upper-air soundings for March and April 1967 (ESSA, 1967*b*), and observations taken during LIE were combined into a schematic meridional-vertical cross-section of zonal winds along approximately 160° W (cf. Fig. 4).

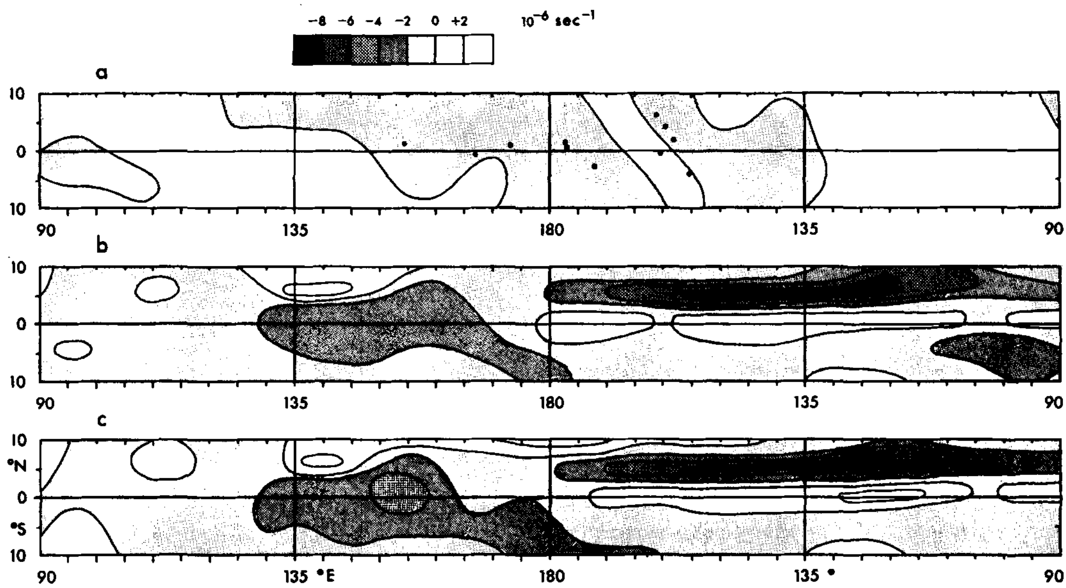

Fig. 3. Divergence of surface wind in 10^{-6} sec^{-1} in March and April (source: U.S. Weather Bureau, 1938). (*a*) zonal component; (*b*) meridional component; (*c*) total divergence.

The boundary between the temperate latitude westerlies and the tropical easterlies rises from about the 800 mb level at 25° N to about 550 mb over the equator, and to above 300 mb at 15° S, descending again towards the higher latitudes of the southern hemisphere. The regime of upper-tropospheric westerlies thus extends without interruption across the entire tropical belt. Above 150 mb, easterlies appear around latitude 15° S. A speed maximum in the westerlies of more than 30 m/sec is located at 200 mb and near 20° N, but upper-tropospheric westerlies are still in excess of 10 m/sec in the vicinity of the equator. The lower-tropospheric easterlies

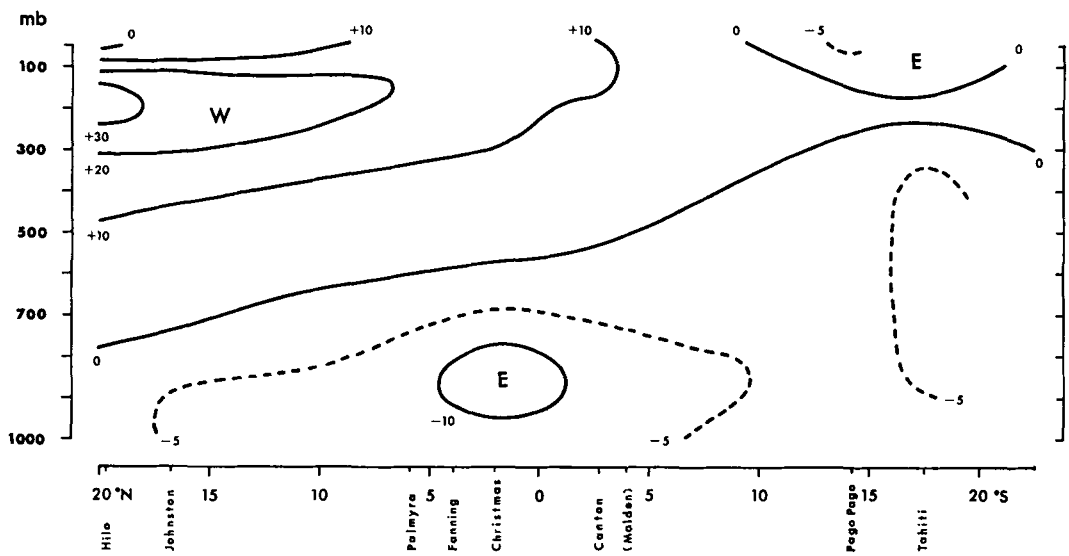

Fig. 4. Zonal wind component (m/sec) during March and April 1967, in a meridional transect along approximately 160° W (source: ESSA, 1967; and unpublished LIE data).

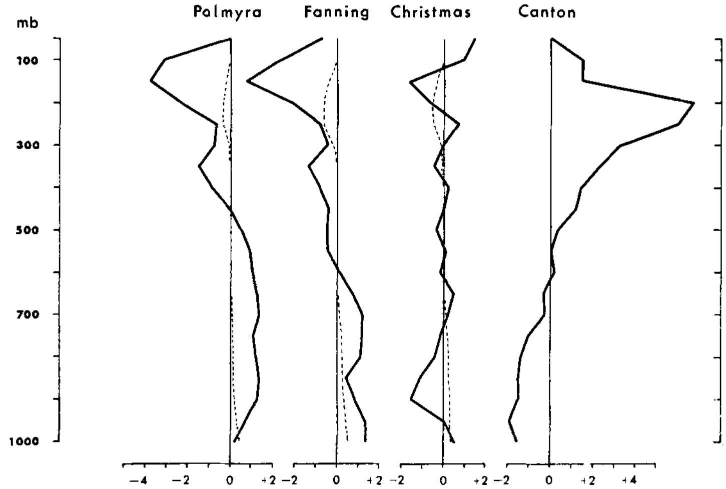

Fig. 5. Meridional wind component over Palmyra, Fanning, Christmas and Canton, during March and April 1967; m/sec, southerlies positive (source: ESSA, 1967*b*; and unpublished LIE data).

show a maximum of more than 10 m/sec between 800 and 950 mb, in the northern hemisphere.

Available observations do not warrant the construction of a similar transect for the meridional wind component. Interest focuses on the vertical profile of meridional winds in the equatorial belt. This is plotted in Fig. 5, for the stations Palmyra, Fanning, Christmas, and Canton, during the LIE period. Vertical time sections based on the same data for Palmyra and Christmas have been presented by Madden & Zipser (1970).

Palmyra shows a southerly flow of the order of one m/sec in the lower layers, which seems nearly completely compensated, still below the level of the tropical tropopause, by a northerly flow concentrated in the upper troposphere. The profile for Fanning is similar, but at Christmas Island, the station closest to the equator, the profile becomes irregular and meridional wind components are small. At Canton Island, south of the equator, the pattern of the vertical profile appears reversed. Fig. 5 may seem to indicate at meridional circulation pattern in the equatorial belt of the kind proposed by Fletcher (1945), Bryson (1948), and Rossby (1949). It must be remembered, however, that the LIE soundings provide only a small sample, regarding both time and longitudinal distance. In this connection, the scarce upper-air soundings taken over the Equatorial Pacific during earlier years are of interest.

Wiederanders' (1961) four-year monthly streamline charts at selected pressure levels are severely affected by the chronical paucity of upper-air stations in the equatorial belt proper.

Monthly summaries of upper-air resultant winds are available in published form (Joint Task Force Seven Meteorological Center, 1960–61) for the following five stations near the equator: Tarawa and Kapingamarangi (March–July 1956 and 1958), Nauru (April–July 1958), Christmas (October 1956–October 1959), and Canton, which has been operative since 1949. The first three of these islands are situated west of 175° E and are less useful for the present problem, since the rainfall and cloudiness pattern as reviewed in section 2 does not display a double structure in this area. Upper-air stations were operated at Palmyra, Christmas, and Malden, during Operation Dominic, March–July 1962. At Palmyra, upper-air soundings were also taken during September–October 1962 and May–June 1957. Data were obtained on punch cards from the National Weather Records Center, Asheville N.C. Pibal observations of different periods, combined into three-monthly resultant winds, have been published (U.S. Hydrographic Office, 1944) for Howland, Jarvis, and Canton.

The meridional wind profiles of Canton (U.S. Weather Bureau, 1962) and Palmyra, Christmas, and Malden in March–July 1962 (Operation Dominic) are particularly interesting in comparison to the profiles of the LIE period

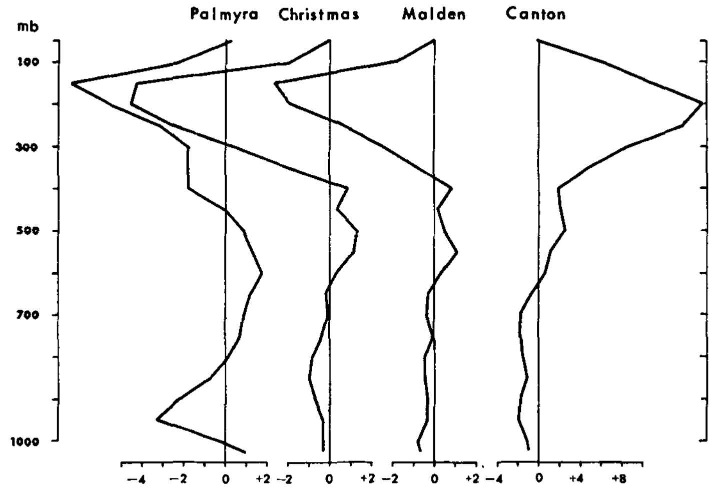

Fig. 6. Meridional wind component over Palmyra, Christmas, Malden and Canton during March and April 1965; m/sec, southerlies positive (source: ESSA, 1962; and unpublished data of Operation Dominic). Note that scale is halved for Canton.

(Fig. 5). Plots for March–April 1962 are therefore presented in Fig. 6. The general shape of the profiles bears some resemblance, but the upper-tropospheric northerlies are much stronger in 1962, appearing also at Malden, south of the equator, while increased southerlies are found over Canton. In contrast to the LIE period, the northerly flow in the area of the Line Islands far exceeds the southerly flow within the troposphere as a whole. The northerly component in the upper troposphere increases from Palmyra to Christmas, and then decreases further southward to Malden Island. From a streamline analysis for selected pressure levels it can be inferred that 200 mb winds over Canton should have a more southerly, and those over Malden a more northerly component. Maps analyzed for individual months indicate that large-scale flow conditions differed appreciably in spring 1962 and 1967, respectively.

From the data sources described above, monthly profiles of the meridional wind component, similar to Figs. 5 and 6, were constructed, but the numerous graphs are not reproduced here. As the season progresses towards the peak of the northern hemisphere summer, the profiles for the various stations in the equatorial belt show an increased southerly flow in the lower, with an increased northerly flow in the upper layers. Such a seasonal reversal of cross-equatorial flow prevails also east of 170° E, where an equatorial dry belt is most conspicuous. This suggests that the "equatorial cells" proposed by Fletcher (1945), Bryson (1948), and Rossby (1949), should not be considered as completely closed meridional circulations, and that the "equatorial cell" of only one hemisphere may be well-developed, depending on the season. Mean meridional circulations should at any rate be thought of as the resultant of individual daily flow patterns.

Since the "equatorial cell" may not be a closed meridional circulation, it seems difficult to estimate its intensity from stations arranged in a meridional cross-section, such as in Figs. 5 and 6. The situation is aggravated by the fact that soundings taken during LIE and Operation Dominic provide only a small sample, regarding both time and longitudinal distance.

Riehl & Malkus (1958) were faced with a similar problem in their attempt at assessing the lateral transport of heat into and out of the equatorial trough zone. Existing wind data from stations around the globe were insufficient for computing a representative vertical profile of the mean wind component normal to the winter side of the equatorial trough, although the same stations were entirely adequate for estimating the vertical distribution of heat content. Therefore, Riehl & Malkus (1958) altogether ignored the wind information from the various stations, and instead fitted a mean wind profile meeting certain constraints of the heat budget. A similar indirect reasoning will have

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to be applied here, in order to arrive an an estimate of meridional circulation and vertical motion within the "equatorial cell".

(b) Vertical motion and circulation in a mean meridional-vertical plane

The distribution of divergence and hence vertical motion could be derived from measured profiles of the meridional wind component such as in Fig. 5, if these could be considered representative for a mean meridional-vertical transect across the rain belt and the equatorial dry zone. However, divergence profiles computed from the measured meridional winds in Fig. 5 were found to be in striking disagreement with constraints of the atmospheric heat and moisture budget. Therefore, a procedure similar to that introduced by Riehl & Malkus (1958) was followed. Vertical profiles of divergence for Palmyra and Christmas were fitted (cf. section 4) so as to satisfy both the budget of potential energy and sensible heat and the budget of atmospheric moisture, for the tropospheric column as a whole (e.g. Eqs. (1) and (2)). As further constraints, divergence values read from the mean surface map, Fig. 3, were ascribed to 1 000 mb, and divergence was assumed to become zero at 100 mb. Vertical profiles of divergence thus derived for Palmyra and Christmas are illustrated in Fig. 7, while details of the construction of these profiles will be discussed in connection with the atmospheric heat and moisture budget in section 4.

Palmyra, which can be regarded as characteristic of the rain belt, shows lower-layer convergence of the order of $40-10 \times 10^{-7}\text{sec}^{-1}$, a nearly non-divergent layer between 700 and 300 mb, and outflow concentrated in the upper troposphere. The profile for Christmas in the equatorial dry zone displays convergence of the order of 30×10^{-7} sec^{-1} between the tropopause and 300 mb, an essentially non-divergent layer in the middle troposphere, and divergence of the order of 10×10^{-7} sec^{-1} in the surface layer.

Vertical motion was computed from the divergence profiles with the use of the continuity equation, and was also plotted in Fig. 7. Over Palmyra in the rain belt ascending motion is found, with a maximum of about 9 mm/sec at 300 mb. Contrarywise, subsidence prevails over Christmas in the equatorial dry zone, with a maximum of about 7 mm/sec at 300 mb.

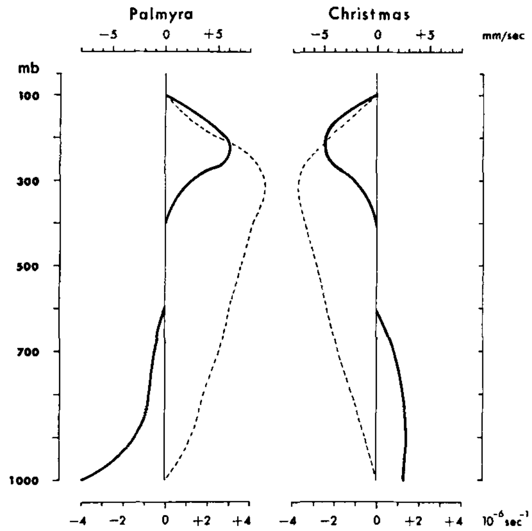

Fig. 7. Vertical profiles of divergence in 10^{-6}sec^{-1} (solid lines) for Palmyra and Christmas during March–April 1967, derived from the vertical distribution of energy content and the atmospheric heat and moisture budgets; and vertical motion in mm/sec (broken lines).

The circulation in a mean meridional-vertical plane across the rain belt and the equatorial dry zone, in terms of the divergent component of the wind, can be derived from the divergence profiles in Fig. 7 only under certain assumptions. Such model calculations were carried out, but details are not presented here. The circulation pattern obtained is characterized by poleward flow in the lower layers, ascending motion in the rain belt, equatorward flow in the upper troposphere and subsidence in the vicinity of the equator.

4. Atmospheric energy budget

(a) Basic data

From the radiosondes during the LIE period (March 16 through April 15, 1967) the content of potential energy and sensible heat $(gz + c_pT)$, and latent heat, Lq, at constant pressure levels over Palmyra, Fanning, and Christmas was computed, as summarized in Table 1. Following conventional notation, g means acceleration of gravity, z height, T absolute temperature, q specific humidity, L latent heat of evaporation, and c_p specific heat at constant pressure. Table 1

Table 1. *Sensible heat and potential energy* $(gz + c_p T)$, *and latent heat* (Lq) *content of the troposphere over Palmyra and Christmas, during March–April 1967, in cal/g*

	Palmyra		Christmas	
	$(gz + c_p T)$	Lq	$(gz + c_p T)$	Lq
100	86.3		86.0	
200	82.3		82.0	
300	81.0	0.1	80.8	0.1
400	79.8	0.5	79.5	0.3
500	78.2	1.1	78.0	0.6
600	76.7	2.2	76.5	1.3
700	75.4	3.2	75.4	2.1
800	74.4	5.3	74.3	3.5
900	72.7	7.8	72.3	6.8
1 000	72.0	10.1	71.7	9.7

illustrates the striking moisture contrast between the rain belt and the equatorial dry zone, and reveals also the mid-tropospheric minimum of the total energy content characteristic of lower latitudes (e.g. Riehl & Malkus, 1958; Colón, 1960; Hastenrath, 1966). This data will be used further below in the computation of energy import and export by atmospheric motions.

Absorption of solar radiation was computed from conventional radiosondes and surface observations of cloudiness during LIE, following the procedure of Mügge & Möller (1932) for clear sky, and using the values of reflectivity, absorptivity, and transmissivity presented by Korb et al. (1956) for different cloud types. Computations were performed for 100 mb thick layers between 1 000 and 300 mb, separately for clear sky, an overcast of low clouds (900–800 mb), and an overcast of middle clouds (650–600 mb). Results were then weighted for every 100 mb thick layer, according to the three-hourly surface observations of cloudiness at Palmyra, Fanning, and Christmas, assuming no overlap of areas with low clouds and middle clouds, respectively. For the layer 300 to 100 mb, Yamamoto's (1962) values for April and the latitude belt 0–10° N were adopted.

Infrared cooling of the troposphere over Palmyra and Christmas during the LIE period was measured directly by radiation-sondes released daily at 0600 GCT. Combining the direct measurements of longwave radiation and the computations of absorbed solar radiation, the net radiative flux divergence of finite layers was obtained, as listed in Tables 2 and 3.

An estimate of the precipitational heating of the entire tropospheric column, LP, is given by the rainfall totals during LIE, plotted in Fig. 1. The magnitude of the sensible heat flux, Q_s, and the latent heat flux, Q_e, at the sea-air interface for long-term mean conditions can be taken from Budyko's (1963) atlas or the more detailed study of Wyrtki (1965, 1966). Estimates of LP, Q_s, and Q_e are summarized in Table 4. Budyko's (1963) and Wyrtki's (1965, 1966) publications also contain estimates of the net radiation at the ocean surface. Direct measurements of the surface radiation budget were performed during LIE at Palmyra (Cox & Hastenrath, 1970).

(b) *Tentative model of the tropospheric heat budget*

The budget equation of potential energy and sensible heat can for the tropospheric column as a whole, and for climatic mean conditions, be written

$$\int_{1000\,\mathrm{mb}}^{100\,\mathrm{mb}} \nabla_p \cdot \mathbf{V}\varrho(gz + c_p T)\frac{dp}{g\varrho} = -[Rad]_{1000}^{100} + LP + Q_s \quad (1)$$

Following conventional notation, ϱ means air density, p pressure, $\mathbf{V}$ horizontal wind vector, and $\nabla_p \cdot$ the two-dimensional $\nabla \cdot$ operator on a constant pressure surface. The right-hand terms represent the diabatic heat sources and sinks for the entire column, namely net radiative cooling, precipitational heating, and sensible heat flux across the sea-air interface. Local time derivatives are disregarded, since a sufficiently long period of time is considered here; and no vertical transport across the tropopause (approximately 100 mb) is assumed.

The right-hand terms are available in Tables 2, 3, and 4 for Palmyra and Christmas. The sensible heat flux across the sea-air interface, Q_s, can be safely disregarded in comparison to the first two right-hand terms. With a Bowen Ratio larger than estimated by Wyrtki (1966), the picture would be altered somewhat. The right-hand side of Eq. (1) results in a net heating of the tropospheric column, and thus a net export of $(gz + c_p T)$ by atmospheric motions from the tropospheric column over Palmyra, while import is called for at Christmas. Expanding, $\nabla \cdot \mathbf{V}\varrho(gz + c_p T) = \varrho(gz + c_p T)\nabla \cdot \mathbf{V} + \mathbf{V} \cdot \nabla\varrho(gz + c_p T)$.

Table 2. *Heat budget of the troposphere over Palmyra during March–April 1967*

[Rad] = net radiative flux divergence in finite atmospheric layers; $\int \varrho (gz + C_p T) \nabla \cdot \mathbf{V} (dp/gp)$ = lateral export of $(gz + c_p T)$; $\varrho (gz + c_p T) w$ = vertical transport of $(gz + c_p T)$; $\int \varrho Lq \nabla \cdot \mathbf{V} (dp/g\varrho)$ = lateral export of Lq; and ϱLqw = vertical transport of Lq, all as performed by the mean mass circulation. Units 10^{-5} cal cm^{-2} sec^{-1}

mb	[Rad]	$\int \varrho (gz + c_p T) \nabla \cdot \mathbf{V}$ $(dp/g\varrho)$	$\varrho (gz + c_p T) w$	$\int \varrho Lq \nabla \cdot \mathbf{V} (dp/g\varrho)$	ϱLqw
100			0		
	− 16	+ 1 283			
200			+ 1 276		
	+ 38	+ 2 066			
300			+ 3 301		+ 4
	+ 46	+ 424			
400			+ 3 671		+ 23
	+ 44	0			
500			+ 3 597		+ 51
	+ 26	0		0	
600			+ 3 528		+ 101
	+ 19	− 208		− 8	
700			+ 3 261		+ 138
	+ 30	− 524		− 31	
800			+ 2 697		+ 192
	− 14	− 770		− 71	
900			+ 1 872		+ 201
	+ 49	− 1 860		− 239	
1 000			0		0
1 000–100	+ 222	+ 411		− 349	

Table 3. *Heat budget of the troposphere over Christmas during March–April 1967*

[Rad] = net radiative flux divergence in finite atmospheric layer; $\int \varrho (gz + CpT) \nabla \cdot \mathbf{V} (dp/g\varrho)$ = lateral export of $(gz + c_p T)$; $\varrho (gz + c_p T) w$ = vertical transport of $(gz + c_p T)$; $\int \varrho Lq \nabla \cdot \mathbf{V} (dp/g\varrho)$ = lateral export of Lq; and ϱLqw = vertical transport of Lq, all as performed by the mean mass circulation. Units 10^{-5} cal cm^{-2} sec^{-1}

mb	[Rad]	$\int \varrho (gz + c_p T) \nabla \cdot \mathbf{V}$ $(dp/g\varrho)$	$\varrho (gz + c_p T) w$	$\int \varrho Lg \nabla \cdot \mathbf{V} (dp/g\varrho)$	ϱLqw
100					
	+ 3	− 1 136			
200			− 1 128		
	+ 25	− 1 548			
300			− 2 646		− 3
	+ 39	− 262			
400			− 2 862		− 11
	+ 47	0			
500			− 2 808		− 22
	+ 45	0		0	
600			− 2 754		− 47
	+ 34	+ 246		+ 6	
700			− 2 469		− 69
	+ 42	+ 710		+ 25	
800			− 1 728		− 81
	+ 30	+ 823		+ 55	
900			− 868		− 82
	+ 63	+ 862		+ 84	
1 000			0		0
1 000–100	+ 328	− 305		+ 170	

Table 4. *Heat and moisture budget data for Palmyra and Christmas in March–April*

Sensible, Q_s, and latent heat flux, Q_e, at the sea-air interface (after Wyrtki, 1966), and precipitational heating, LP, in March–April 1967 (unpublished LIE data), in 10^{-5} cal cm^{-2}sec^{-1}; and evaporation, Q_e/L, and rainfall, P, in mm H_2O/day

	Q_s	Q_e	LP	Q_e/L	P
Palmyra	+1	295	632	4.25	9.10
Christmas	−1	171	23	2.46	0.35

Inspection of the LIE upper-air data indicates that the second term in the expansion is very small compared to the first one. Therefore, the product of energy content and horizontal wind divergence can be used in the left-hand term of Eq. (1). It is also recognized that the contribution by transient eddy fluxes of $(gz + c_pT)$ is insignificant. Given the vertical distribution of $(gz + c_pT)$ listed in Table 1, a vertical profile of $\nabla \cdot \mathbf{V}$ was fitted under the constraints described in section 3*b*, in such a way that Eq. (1) was satisfied. Divergence profiles thus obtained are reproduced in Fig. 7, and have been discussed in section 3*b*. The vertical distribution of lateral export and vertical transport of $(gz + c_pT)$ associated with the mean mass circulation thus derived is presented in Tables 2 and 3.

Over Palmyra (Table 2), export of $(gz + c_pT)$ is concentrated in the upper troposphere, and exceeds the import in the lower layers. Vertical energy transports associated with the mean mass circulation are found insufficient to meet the energy balance requirements of finite atmospheric layers. Instead, upward transports by other than the time-area mean vertical motion are called for, in agreement with previous regional studies (Riehl & Malkus, 1958; Colón, 1960; Hastenrath, 1966).

Over Christmas (Table 3), diabatic heat losses within the tropospheric column as a whole are made up by upper-tropospheric import of $(gz + c_pT)$ exceeding the export in the lower layers. There are indications for a substantial downward directed heat transport by other than the mean mass circulation.

In fitting the divergence profiles it is found that constraints of the heat budget Eq. (1) leave little room for arbitrary choice, apart from minor details in the shape of the profile. This is further restrained by the condition that the vertical distribution of divergence must also be compatible with the atmospheric moisture budget, as will become apparent in the following.

(*c*) *Moisture budget*

The budget of atmospheric water vapor can for steady-state conditions in good approximation be stated as

$$\int_{1000\,\text{mb}}^{300\,\text{mb}} \nabla_p \cdot \mathbf{V}\varrho q \frac{dp}{g\varrho} = Q_e/L - P \qquad (2)$$

Storage of water vapor inside the column and vertical transport across the top of the water vapor atmosphere are disregarded. With these reservations, Eq. (2) states that the difference between large-scale evaporation ($E = Q_e/L$) and precipitation equals the vertically integrated divergence of the atmospheric water vapor flux.

Contrary to the horizontal uniformity of $(gz + c_pT)$, the meridional gradient of specific humidity is conspicuous. However, for a location well within the rain belt, as Palmyra, and a station near the axis of the equatorial dry zone, as Christmas, it seems permissible to approximate $\nabla \cdot \mathbf{V}\varrho q$ by $\varrho q \nabla \cdot \mathbf{V}$. This could not be justified for the transitional strip in which Fanning is situated.

From the upper-air soundings taken several times daily during LIE and Operation Dominic, transient eddy flux (Starr & White, 1952) and total flux of $(gz + c_pT)$ and Lq were computed. The transient eddy flux of potential energy and sensible heat was always insignificant, but the meridional component of the transient eddy flux of water vapor was found to reach sizeable proportions as related to the total meridional flux, within the equatorial dry zone. As can be expected, the transient eddy flux is in general directed from the rain belt towards the interior of the equatorial dry zone.

Table 2 shows for Palmyra the evaluation of the left-hand term of Eq. (2), as resulting from the vertical distribution of moisture (cf. Table 1) and the divergence profile in Fig. 6, which was fitted to satisfy Eqs. (1) and (2). Estimates of the right-hand terms of Eq. (2) are listed in Table 4. Agreement is complete, for all practical purposes. The slight imbalance of 0.25 mm H_2O/day can easily be accounted for by the above-mentioned transient eddy export of moisture.

The corresponding evaluation of the left-hand term of Eq. (2) for Christmas is presented in Table 3. Estimates of the right-hand terms are contained in Table 4. According to Table 3, the mean mass circulation would export an equivalent of 2.6 mm H_2O/day, while local evaporation exceeds precipitation only by about 2.1 mm H_2O/day. The possibility of a 20% error in Wyrtki's (1966) evaporation estimate cannot be discarded. On the other hand, it was found impossible to adjust the divergence profile (Fig. 7) any further, so as to yield a moisture export by the mean mass circulation equivalent to about 2.1 mm H_2O/day, and still satisfy Eq. (1). It is concluded that convergence of the conspicuous meridional component of the transient eddy flux of moisture, as borne out by the data of LIE and Operation Dominic, may play an important role for the atmospheric water vapor budget in the equatorial dry zone.

5. Heat budget of the ocean-atmosphere system

The columnar heat budget of the ocean-troposphere system can be expressed as

$$-R_{oa} = Q_{va} + Q_{vo} + S_a + S_o \tag{3}$$

Here R_{oa} denotes the net radiative flux at the tropopause, S the seasonal heat storage, Q_v the divergence of the heat transport by horizontal motions, and the subscripts a and o refer to the troposphere and the oceanic water body, respectively.

The oceanic heat budget equation reads

$$-R_o = Q_e + Q_s + Q_{vo} + S_o \tag{4}$$

where $-R_o$ is the net radiation at the ocean surface. Wyrtki (1965, 1966) has studied the heat budget of the Equatorial Pacific Ocean. Values of Q_e and Q_s read from his maps are contained in Table 4, and his computations of residual $(Q_{vo} + S_o)$ are listed in Table 5.

In connection with a study of the radiation budget in the Line Islands region (Cox & Hastenrath, 1970), R_o at Palmyra was measured directly, and an attempt was made to estimate the net radiative flux at the tropopause, R_{oa}. The net upward directed infrared radiation is available from daily radiation-sonde flights at Palmyra and Christmas. Net short-wave radiation at the surface during the LIE period was measured at Palmyra. Accepting the computations of solar radiation absorbed within the troposphere, as discussed in section 4a, the net short-wave radiation at the tropopause can be inferred. Values of R_o and R_{oa} thus obtained for Palmyra are listed in Table 5.

Regarding an assessment of R_o and R_{oa} for Christmas, only long-wave radiation has been measured by radiation-sondes; however, in contrast to Palmyra, no direct surface measurements of short-wave radiation are available. Therefore, an attempt was made to infer the net short-wave radiation at the surface and at the tropopause over Christmas, using the direct surface measurements at Palmyra.

Solar radiation at the top of the atmosphere according to latitude and season can be taken from the Smithsonian Meteorological Tables (List, 1968). Subtracting Rodgers' (1967) value for the solar radiation absorbed in the layer 7 to 100 mb yields an estimate of the downward directed short-wave radiation at the tropopause over Palmyra and Christmas, respectively. For Palmyra, the net short-wave radiation at the tropopause has been determined additionally, as described above. From this an estimate of the planetary (short-wave) albedo at Palmyra during LIE is readily obtained. The estimated value of 32% is larger than values read from Raschke's (1968) albedo maps for various fortnightly periods in May–July 1966. This may seem compatible with the characteristic seasonal variation of cloudiness in the Line Islands region. However, unpublished precipitation records (courtesy of British Meteor. Office) for Christmas and Fanning Islands indicate larger rainfall in May–July 1966 than in March–April 1967. The consistency of planetary albedo estimates for LIE with Raschke's 1966 maps can thus not be clearly assessed. Apart from the different space scale it should also be recalled that Raschke's maps are based on noontime observations. Sea surface albedo at Palmyra was found to be about 6.5% (Cox & Hastenrath, 1970). Total cloudiness is available from surface observations during LIE ($C_T = 0.49$ for Palmyra). From this information, and weighting albedo according to the proportion of clear and cloudy areas, a representative average cloud albedo over Palmyra can be derived (55%).

Now assume that the Palmyra estimates of surface and cloud albedo are approximately

Table 5. *Heat budget of the ocean-troposphere column at Palmyra and Christmas in March–April*

Net downward directed radiative flux at the tropopause, $-R_{oa}$, net radiation at the ocean surface, $-R_o$ (source: unpublished LIE data; Rodgers, 1967; List, 1968); divergence of the total heat transport within the troposphere, Q_{va}, from Tables 2, 3, and 4; sum of storage and divergence of heat transport within the ocean $(Q_{vo}+S_o)$, after Wyrtki (1966), W, and as obtained in the present study, H. Units 10^{-5} cal cm^{-2} sec^{-1}

	$-R_{oa}$	$-R_o$	Q_{va}	$(Q_{vo}+S_o)_W$	$(Q_{vo}+S_o)_H$
Palmyra	255	477	+ 73	+ 28	+181
Christmas	241	569	−158	+260	+399

valid for Christmas, and use the surface observations of total cloudiness over Christmas during LIE ($C_T = 0.32$). Then a value of the planetary albedo representative of the Christmas region can be derived (22%). From the planetary albedo and the downward directed short-wave radiation at the tropopause, as assessed further above, an estimate of the net short-wave radiation at the tropopause is obtained. Subtracting the solar radiation absorbed between 100 and 1 000 mb then yields the net short-wave radiation at the surface. Limitations inherent in this computational procedure are recognized, but estimates thus obtained are considered adequate for the purposes of the present study.

Combining these computed short-wave radiation values with the directly measured long-wave radiation finally leads to an estimate of R_o and R_{oa} considered representative of the Christmas region. These estimates are also included in Table 5. Computatios will be described in more detail elsewhere (Cox & Hastenrath, 1970).

Whatever the uncertainties in the tentative estimates of R_0 and R_{oa} listed in Table 5, the following characteristics relevant in the further discussion can be stated clearly: (1) the ocean-troposphere column at both Palmyra and Christmas gains heat by radiation; (2) the net radiation at the tropopause, $-R_{oa}$, over Christmas has the same general magnitude as at Palmyra; (3) the net radiation at the ocean surface, $-R_o$, during LIE is considerably larger than the values computed in Wyrtki's (1965, 1966) study; this agrees with findings of Quinn & Burth (1967) and Vonder Haar & Hanson (1969).

Values of the total heat exported by horizontal motions for the tropospheric column, Q_{va}, listed in Table 5 are taken from Tables 2, 3, and 4. It will be appreciated from the above discussion that Wyrtki's (1966) residual $(Q_{vo} + S_o)$, should be considered as underestimates, unless there is reason for an upward adjustment of the bulk-aerodynamic calculations of Q_e and Q_s. The residual $(Q_{vo}+S_o)$ resulting from the LIE estimates of R_o described above and Wyrtki's values of (Q_e+Q_s) are presented in Tables 5 and 4, respectively. It will be recalled that long-wave radiation values for the surface were obtained from evening radiation-sondes at Palmyra and Christmas. Comparison with continuous surface measurements during LIE at Palmyra suggests that the daily mean of downward directed long-wave radiation may be about 90×10^{-5} cal cm^{-2} sec^{-1} smaller than the evening sonde value (cf. Cox & Hastenrath, 1970). This would lead to a somewhat smaller value of $-R_o$ and hence of the residual $(Q_{vo}+S_o)$. However, the corresponding daily variations of $-R_{oa}$ and $(R_o - R_{oa})$ are not known. For consistency with the radiation budget of the atmospheric column (cf. Tables 2 and 3), only radiation-sonde values were used here.

Partitioning of the residual $(Q_{vo}+S_o)$ requires an estimate of the seasonal heat storage within the ocean, S_o. Gabiets (1950) lists a climatic mean value of 45×10^{-5} cal cm^{-2} sec^{-1} for the entire latitude belt 0–5° N in March and April. Gabites' data are derived from monthly mean maps of sea surface temperature (U.S. Weather Bureau, 1938), assuming an identical temperature change from month to month from the sea surface down to a depth of 25 m, and beneath this a linear decrease of the temperature change, reaching a value of zero at 125 m; phase is assumed to be constant with depth. Using Gabites' procedure and the available monthly mean maps of sea surface temperature (U.S. Weather Bureau, 1938), the heat storage term S_o in the Line Islands region during March and April was estimated to be of the order of 100×10^{-5} cal cm^{-2} sec^{-1} or smaller. It will be recalled that the validity of Gabites' method has been questioned by Patullo (1957), on the basis of bathythermograph measurements obtained in selected ocean areas.

At any rate, S_0 appears to be small in this equatorial region. The seasonal heat storage within the troposphere, S_a, was estimated from the radiosondes of the LIE period and Operation Dominic. S_a was was found to be insignificant and it was therefore not included in Table 5.

In the rain belt (Palmyra), export of potential energy and sensible heat exceeds the import of latent heat in the lower layers, and the troposphere acts as an exporter of heat to other parts of the globe ($Q_{va} > 0$). However, it is noticed that an appreciable portion of the total radiative surplus of the ocean-troposphere system, $-R_{oa}$, is carried away within the ocean.

The heat budget of the ocean-troposphere column in the equatorial dry zone shows a contrastingly different pattern. Lateral import of potential energy and sensible heat far exceeds the export of latent heat. Although the ocean-atmosphere system can boast of a large radiative surplus in this region ($R_{oa} < 0$), the troposphere still imports heat from other parts of the globe ($Q_{va} < 0$)! Thus the ocean is left with the entire job of disposing of the regional heat surplus. From a study of the heat budget it can be concluded that, in a region with positive net radiation at the tropopause, the atmospheric circulation in a meridional-vertical plane considered as characteristic of the equatorial dry zone could only exist over the ocean, not a continent.

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О МЕРИДИОНАЛЬНОЙ ЦИРКУЛЯЦИИ И ТЕПЛОВОМ БАЛАНСЕ ТРОПОСФЕРЫ НАД ЦЕНТРАЛЬНОЙ ЧАСТЬЮ ТИХОГО ОКЕАНА В РАЙОНЕ ЭКВАТОРА

Измерениями осадков и ежедневными мозаичными облачными снимками со спутников ЭССА III и ЭССА V обраружено существование сухой экваториальной зоны в центральной части Тихого океана, заключённой между двумя влажными поясами в обоих полушариях. Режим ветра в тропосфере изучается, главным образом, на основе аэрологического зондирования во время эксперимента в районе о-вов Лайн (ЭОЛ) весной 1967 г. и более ранних наблюдений. Во время ЭОЛ зона западных ветров в верхней тропосфере простиралась непрерывно через экватор. На нижних уровнях в экваториальном поясе доминировали восточные ветры. Меридиональная компонента ветра в районе о-вов Лайн направлена на север в нижних слоях и на юг в верхних. По вертикальным профилям теплосодержания и распределению источников и стоков тепла во время ЭОЛ построены вертикальные профили дивергенции в предположении баланса тепла и влажности в атмосфере. Конвергенция на нижних уровнях и дивергенция на верхних образуются в поясе дождей (о. Пальмира), в то же время обратная картина получается в экваториальной сухой зоне (о. Рождества). Циркуляция в среднем меридиональном сечении, выводимая из этих профилей при некоторых предположениях, характеризуется потоком к полюсу на нижних уровнях, восходящим движением в поясе дождей, потоком к экватору в верхней тропосфере и нисходящим движением в экваториальной сухой зоне. Система океан–тропосфера приобретает тепло за счёт излучения как в зоне дождей, так и в сухой экваториальной зоне. В поясе дождей экспорт потенциальной энергии и тепла превосходит импорт скрытого тепла на нижних уровнях; в этой области как тропосфера, так и океан действуют как экспортёры тепла в другие части Земного шара. В экваториальной сухой зоне импорт потенциальной энергии и тепла превосходит экспорт скрытого тепла. В результате получается чистый импорт тепла для тропосферной колонны в целом. Избыток тепла в районе накапливается океаном.