Observational Study on the 30–60 Day Variations in the Geopotential and Temperature Fields in the Equatorial Region

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Abstract

Using seven-year (1979–1985) rawinsonde data in the equatorial region, the 30–60 day variation in the geopotential height (H) and the temperature (T) fields and their relations with fluctuations in the zonal wind (U) field are studied. After examining in detail the 30–60 day variation in the time series, the lag-correlation method is applied to the seven intervals of four month duration which show active variation. The main results are as follows: (i) In the H field of all the troposphere and the T field in the upper troposphere, the zonal standing-wave-like structures with a little phase differences are found in the wide region from India to Central America through the date line. (ii) In the lower troposphere, the 30–60 day variations of H and U are in phase near the date line, but the signal of U leads that of H by about 120° over the Maritime Continent. In the upper troposphere, the signal of U leads that of H by about 120° near the date line. (iii) Though the vertical structure has a large year-to-year variability, the upper tropospheric H leads the lower one by 70° – 120° in the phase over the western and mid Pacific.

The properties of the H field obtained in the present work are considerably different from well-known ones in the U field. These results suggest that the simple Kelvin mode which has an out-of-phase structure between the upper and lower troposphere is not dominant in the 30–60 day variation.

1. Introduction

It is well known that the zonal wind (U) and the outgoing longwave radiation (OLR) have strong signals in the period range of 30–60 days in the equatorial region. It has been shown that they have the structure of an eastward-moving wavenumber-one wave (Lorenc, 1984; Krishnamurti *et al.*, 1985; Nakazawa, 1986). There is such a close relation that the filtered-anomaly of OLR is negative in the region where the filtered U field in the upper (lower) troposphere is divergent (convergent) (Murakami and Nakazawa, 1985; Knutson *et al.*, 1986).

Although the 30–60 day variation can also be found in the geopotential height (H) field, only a few and still fragmentary studies on this aspect are available, as described below. The purpose of the present study is to investigate the behavior of the equatorial 30–60 day variation of H and temperature (T) and their relation to that of U :

The zonal phase structure of sea level pressure (SLP) is different from that of U as shown by Madden and Julian (1972). Though the eastward-

moving characteristic is also seen on SLP from the Indian Ocean to Central America across the date line, its phase speed is about 30° /day, much faster than that of U (about $5^\circ \sim 10^\circ$ /day). They considered that the 30–60 day variation of H has a zonally standing characteristic in order that it may be reflected by a period of about 45 days detected in time series at a single station. On the composite maps of the low frequency variation based on a 18 month record of SLP, they found that the phase of the variation is nearly the same over two thirds of the equatorial belt, though a weak systematic phase propagation was found. The longitudinal extension of such a zonal standing-wave-like structure to South America and to the Atlantic should be examined, because this was not evident in their analysis. Maruyama (1982) examined the zonal phase structure of U and H at 150 mb only for three month grid data of FGGE IIb. He concluded that the 30–60 day variation of H has an almost zonal wavenumber-zero structure, while that of U showed the structure corresponding to an eastward-moving wavenumber-one. However, the data length in his work is too short to confirm the zonal structure in the upper troposphere. Fur-

Table 1. Stations used in the present analysis.

Station name	Latitude (°)	Longitude (°)	Elevation (m)	Observationl Time (GMT)
Nairobi	1.30S	36.75E	1798	00
Diego Garcia	7.30S	72.40E	2	00
Minicoy	8.30N	73.00E	2	00
Trivandrum	8.48N	76.95E	64	00
Penang	5.30N	100.27E	4	12
Songkhla	7.20N	100.60E	5	00
Kuala Lumpur	3.12N	101.55E	17	12
Kota Bahru	6.17N	102.28E	5	00
Kuantan	3.78N	103.22E	16	12
Singapole	1.33N	103.90E	32	00
Kuchine	1.48N	110.33E	27	00
Kota Kinabaru	5.95N	116.05E	7	00
Koror	7.33N	134.48E	30	00
Yap	9.48N	138.08E	14	00
Truk	7.47N	151.85E	3	00
Ponape	6.97N	158.22E	39	00
Honiara	9.42S	159.97E	56	00
Kwajalein	8.73N	167.73E	4	00
Majuro	7.08N	171.38E	3	00
Tarawa	1.35N	172.92E	4	00
Funafuti	8.52S	179.22E	2	00
Atuona	9.80S	139.03W	52	00
Haward AFB	8.92N	79.60W	66	12
Manaus	3.15N	59.98W	84	12
Cayenne	4.83N	52.37W	6	12
Belem	1.38S	48.48W	16	12
San Luiz	2.53S	44.28W	51	12
Fortaleza	3.72S	38.55W	26	12
Natal	5.92S	35.25W	49	12
Recife	8.13S	34.92W	7	12
Fernando	3.85S	32.42W	57	12
Ascension	7.97S	14.40W	79	12
Abidjan	5.25N	3.93W	11	12

ther study should be made about the behavior of the 30–60 day variation of H in the middle and upper troposphere.

The vertical structure of the 30–60 day variation is another interesting feature. Maruyama (1982) showed the vertical structure of the 30–60 day variation from 8 year data at Gan in the central Indian Ocean: the signal of U was almost out of phase between the upper and lower troposphere, while that of H was almost barotropic. Longitudinal extensions of such vertical structure must be examined.

As for the T field, Madden and Julian (1971) showed that the phase of the 30–60 day variation of T in the upper and middle troposphere leads that of SLP by about 150° at Canton. Madden and Julian (1972) analyzed the zonal structure of the 30–60 day variation of T at 100 mb and 300 mb statistically, but the coherence is not large enough to offer

a clear conclusion about the zonal phase structure of T .

Chen (1987) analyzed the 30–60 day variation of H at 850 mb and T at 200 mb in 1979 northern-summer by using FGGE IIIb data by ECMWF, concentrating on the behavior over the subtropics. His results of EOF components imply the dominance of the standing-wave-like structure.

Madden and Julian (1971) also showed that the signals of H and U are in phase in the lower troposphere at Canton. Results on the zonal and vertical structures mentioned above raise questions about the spatial extension of the relationships. We should confirm the phase relation between H and U of the 30–60 day variation in every region in the tropical belt with extreme care.

One of the most remarkable points in the present study is the use of the station rawin-sonde data only.

After Madden and Julian (1972), most studies utilized grid data for the initial field of the numerical prediction. However, the quality of such grid data is rather questionable for the analysis of the equatorial region (Sanga, 1986). This is more serious in the H and T field where we can get less information because satellite-derived data, like cloud wind vectors in the wind field, are not available for these variables. It is not appropriate to utilize grid point data for the present purpose because we cannot distinguish regions with poor data coverage.

The time series shows that the intensity of the 30–60 day variation changes severely from-season-to-season or from-year-to-year and the properties of the 30–60 day variation are recognized only with a little reliability during the weak-intensity intervals as described in Section 3. Furthermore, some of the properties of the 30–60 day variation of T and H in a certain active interval are quite different from those of another active interval. Therefore we have to look at each case separately with extreme care. Case studies are made for some active intervals of the 30–60 day variation, instead of statistical or composite analyses like Madden and Julian (1972).

2. Data and analysis method

We utilize the rawinsonde station data over the equatorial region for seven years (January 1979–December 1985). The data of the first eleven months (January–November 1979) are from FGGE IIb data set and the remaining are from real time station data collected by Japan Meteorological Agency (JMA).

The station data used here consist of H , T and U at the 10 levels of 1000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 mb. The 33 stations with the small number of missing or erroneous data are selected from 10°N to 10°S . The list of the utilized stations is given in Table 1 with some information. More data are available at 00Z than 12Z for most of the stations in the Maritime Continent and the Pacific, whereas the opposite prevails in South America and in the Atlantic Ocean. For variations with periods longer than 20 days, no systematic difference can be found between the two time data at the stations where there are sufficient data at 00Z and 12Z.

Data quality control is performed as follows: First, the data with value four times greater than the standard deviation from the annual mean are removed. Then, the data three times greater than the standard deviation from the monthly mean are removed. The missing values are interpolated linearly.

Since the present study focuses on the variation in the tropics on a time scale of one to two months, we applied Lanczos band-pass filter (Duchon, 1979) to all the time series. The response of the band-pass filter is 0.5 at the period of 30 and 60 days.

This filtering was made with weighting range of 240 day point centered on a month of interest (say n -th month). Then the missing data in the original time series spanning over this weighting range were flagged. When the total number of the flagged data is larger than 135 or the consecutive number larger than 20, the filtered data of the n -th month were considered as missing and were rejected.

One of the remarkable properties of the 30–60 day variation is the variability of the period (Anderson *et al.* 1984). Therefore, we also applied the 20–80 day broader band-pass filter in order to clarify whether the results depend on the cut-off frequency of the filter. It is found that the most conclusive results with the 30–60 day filter can be also obtained with the 20–80 day filter.

In order to clarify the structure of the variation discussed here, the lag-correlation method is utilized. We introduce a lag-correlation coefficient of the filtered time series x_i referring to y_i . A positive(negative) lag means that the phase of x_i lags (leads) that of y_i .

The length of the intervals for calculating the lag-correlation is 120 days and it is too short to establish whether most of the results are statistically significant. However, a property can be considered as meaningful if it is found at all the adjacent stations which represent independent time series.

3. Results

3.1 Activity of the 30–60 day variation for seven years

First, we shall examine the activity of the 30–60 day variation averaged over the seven years though the variation is not uniform throughout the seven years, as described below. The power spectra of H and U are computed with an FFT method for the stations from India to the central Pacific with available data for the entire record of the seven years. Fig. 1 shows the power spectra of H at 1000 mb and U at 200 mb at Kuala Lumpur and Ponape. The spectrum of H at 1000 mb at Kuala Lumpur has a significant peak at about 45 days (Fig. 1a), and similar results are also found at Trivandrum and Kuantan in the Maritime Continent (not shown). On the other hand, the spectrum of Ponape has a broad peak in the 30–60 day period range (Fig. 1b), and this broadening of the peak is common at the stations in the western and central Pacific (130°E -the date line) (not shown). The spectral peaks for H in the lower troposphere are more significant than those in the middle and upper troposphere. Concerning the spectra of U , it should be noted that the seven year mean activity of the 30–60 day variation of U at 200 mb is not as strong as could be anticipated from previous studies (*e.g.* Madden and Julian, 1972).

Fig. 2 shows the time series of the 30–60 day fil-

Fig. 1. Power spectra determined from seven-year time series (1979–1985), (a) for H at 1000 mb at Kuala Lumpur, (b) for H at 1000 mb at Ponape, (c) for U at 200 mb at Kuala Lumpur and (d) for U at 200 mb at Ponape. The bandwidth and 95 % significant limits at the peak are indicated by the crosses.

tered H at 1000 mb (hereafter $H1000$) and U at 200 mb (hereafter $U200$) during the seven years. The origin of the scale is located at the longitude of the station. The signal of H is active over some intervals (e.g. April–August 1979) and non-active over other intervals (e.g. June–September 1980). In active intervals, the time series are fairly coherent among the stations over a wide region, indicating a zonally systematic structure at least between 60°E and the date line. Because the time series at a station is given independently from that of another station, this coherence should be evidence that the large scale events dominate in this period range. The coherence is smaller in the period range shorter than 30 days. The signals of H in the middle and upper troposphere are less coherent in the zonal direction, as well as T in the whole troposphere (not shown).

In the illustration of $U200$ shown in Fig. 2b, the zonally coherent signals can sometimes be seen in wide region (e.g. April–August 1979). However, these are confined in the limited time-intervals, and the spatial coherence is less strong than $H1000$. Similar features are also seen in $U850$ (not shown).

In order to select the active intervals, the variances of the filtered time series are calculated over a sampling interval of four months at each sta-

tion. These variances are averaged over the following five stations: Trivandrum, Kuala Lumpur, Koror, Truk and Majuro, where the zonal phase structure of 1000 mb is the most coherent. These averaged variances are computed with one month shift. We adopt the variance of $H1000$ as a measure of the activity because we are mostly interested in the behavior of the H field and its phase structure is the most coherent at this level. The five-station mean of the variance of $H1000$ has the following seven clear local maxima in the seven years (Fig. 3): May–August 1979, January–April 1980, February–May 1981, February–May 1982, August–November 1982, November 1983–February 1984 and November 1984–February 1985. The analyses are made for these intervals which we call Case 1–7, respectively. The zonal coherence is very large over those intervals (Fig. 2a); therefore, it is considered that the large scale events are dominant. We treat each case separately because some of the properties may be different from one case to the next. The largest variance is found in Case 1 (May–August 1979), when many authors studied the 30–60 day variation (e.g. Murakami and Nakazawa 1985) and the variation of U is also active and zonally coherent (Fig. 2b). First, we exam-

Fig. 2. Bandpass filtered (30–60 days) values at each station. The data are signified by vertical deflection, giving the position of zero value at the longitude of the station: (a) is for $H1000$ and (b) for $U200$. Values in the ordinate denote longitude (E). Scale of vertical deflection is given in the panel.

ine the properties of the 30–60 day variation in this case in detail about (i) zonal phase structure, (ii) vertical phase structure and (iii) the phase relation between H and U at the same height level. Next, similar analyses are performed for each property in the other six cases.

3.2. Zonal structure

(1) Characteristics during 1979 Northern Summer

Fig. 2b shows that the phase of the 30–60 day variation of $U200$ in May–August 1979 propagates eastward and that the zonal wavenumber-one structure appears around the equator with almost the same amplitude. Similar properties can be also seen in the signal of U in the lower troposphere. In contrast, the property in the H field (Fig. 2a) is quite different from that of U . In $H1000$ from Trivandrum (the curve near 75°E) to Haward AFB (that

near 280°E) across the date line, a little phase lag appears in May and it is almost in an in-phase situation in June, July and August. On the panel, the curves for most of the stations in this region are very similar to one another, although the variation loses the sinusoidal forms in August. The phase at the stations between 60°W and 0° is quite different from those in the Indian Ocean, the Maritime Continent and the Pacific Ocean.

In order to see more clearly these characteristics of the phase structure, lag-correlation method is applied to the filtered time series, taking as a reference $H1000$ at Majuro where the 30–60 day variation is very well defined. The lag-correlations are calculated for H , T and U at the ten levels in the troposphere.

In Fig. 4a exhibiting the zonal phase relation of $H1000$, it is seen that most correlation peaks are

Fig. 2. (Continued)

Fig. 3 Five-station averaged variance of four-month data of filtered $H1000$ (30-60 day period), which is an average of those at Trivandrum, Kuala Lumpur, Koror, Truk and Majuro. Abscissa denote the first month for each interval.

systematically on a near vertical line with small scattering. The dominant period is estimated to be about 40-45 days from the figure. The lag-time is about 7 days (60° in the phase) between Trivandrum (77.0°E) and Haward AFB (79.6°W), for which the eastward difference of longitude is about 200° . Considering this period and phase speed, the 30-60day

variation seems to have a standing-wave-like structure. At 500 mb (Fig. 4b), the systematic zonal phase difference cannot be seen except over South America and the Atlantic. Though the phase structure is more scattered at 200 mb than at 1000 mb, the zonally standing feature is still strongly apparent (Fig. 4c).

Fig. 4. The lag-day when maximum and minimum of lag-correlation of filtered (30-60 days) variables appears at each station in May-August 1979, the filtered H at 1000 mb at Majuro being taken as a reference: (a) H 1000, (b) $500H$, (c) H 200, (d) T 500, (e) T 200, (f) U 850 and (g) U 200. The shape and size of the symbols denote the magnitude of correlation, with details shown under the panel (b). Abscissa and ordinate denote lag-day and longitude (E), respectively.

Fig. 4. (Continued)

Concerning the T field, we can see the almost eastward-propagating wavenumber-one structure at 500 mb (Fig. 4d). On the other hand, at 200 mb a nearly zonally in-phase structure is found at almost all stations (Fig. 4e).

We can see a well-defined eastward-moving wavenumber-one structure in the signal of U in the upper and lower troposphere except in the region between 90°W and 0° where the phase are nearly the same (Figs. 4f and g).

In summary, it should be noted that even when the very clear eastward-moving wavenumber-one structure appears in the U field, H and the upper tropospheric T predominantly show a zonally standing-wave-like structure.

(2) Case studies in 7 years

Fig. 2a shows that $H1000$ is zonally very coherent and almost in phase over a wide region; also in the other intervals of Case 2~7. Fig. 5 shows the lag-correlation of $H1000$ referring to $H1000$ at Majuro for Case 2~7, while that for Case 1 is shown in Fig. 4a. The lag or lead time is within 10 days (about 90° – 110° in the phase) from the Indian Ocean to Central America across the date line except for Case 5. The standing-wave-like structure can be seen over more than half of the equator. Although some eastward-moving properties can be seen in Cases 2 and 3 over the Indian and western Pacific ocean, the phase speed is faster ($15^\circ/\text{day} \sim 20^\circ/\text{day}$) than that of U shown later. In Case 5, the region of in-phase structure is located to the east of those in other cases. It might be related to the fact that Case 5 corresponds to the beginning stage of the remarkable 1982–83 El-Niño and the region of the convective activity moves to the central and eastern Pacific (Lau and Chan, 1986). The behavior of the 30–60 day variation in Case 5 is fairly different from

other cases in many aspects, as will be shown later.

The lag-correlations of H , T and U in some levels referring to $H1000$ at Majuro are summed up in Table 2. The eastward phase lag from 90°E to 90°W is shown by drawing the phase line subjectively on the lag-longitude section using all stations between the stations over the Maritime Continent and Haward AFB in central America through the date line. The values are not given in the table when the phases in that region are less coherent.

As for $H500$, the zonal in-phase structure is obvious in all the cases except for Case 5. A standing-wave structure is also seen in $H200$, though there is a little eastward-moving tendency in Case 3. Concerning $H100$, the in-phase structure is also remarkable. Although the correlation coefficients for $H200$ and $H100$ are not as large as those for $H1000$, the lag-days at many independent stations are less scattered and therefore this in-phase structure is meaningful.

As for the T field, the phase structure is not so clear in the lower troposphere in most cases. For $T500$, the eastward-moving characteristic can be seen and the phase speed is fairly small (about 10° – $15^\circ/\text{day}$) in Cases 4 and 6 and similar to that of Case 1. On the other hand, though the eastward-moving property can be seen in $T200$, the standing-wave-like structure is very clear and the eastward phase speed is more than $15^\circ/\text{day}$. It implies that the behavior of T in the mid-troposphere is a little different from that of the upper one.

The zonal phase structure of the U field near 200 mb and 850 mb is clear enough to discuss in some cases, although it is not evident over much of the seven years (Fig. 2b). In $U200$, the eastward-moving wavenumber-one structure with a slow phase speed of about $6^\circ/\text{day}$ is seen for Case 2 (shown in Fig. 2). In Cases 3 and 4, the eastward-moving tendency with a speed of $5^\circ \sim 10^\circ/\text{day}$ appears, though

Fig. 5. The lag-day when a maximum or minimum of the lag-correlation of filtered (30-60 days) $H1000$ appears at each station with a reference $H1000$ at Majuro for Case 2-Case 7, respectively. The symbols are the same as in Fig. 4.

Table 2. Zonal phase structure which is given by the phase lag from 90°E to 90°W through the date line for seven cases. Values within brackets are less reliable. Crosses denote values which could not be estimated. Units are (degrees). See text for the details.

Case	H1000	H500	H200	H100	T500	T200	U850	U200
2	60°	-30°	60°	0°	110°	10°	150°	180°
2	110°	0°	*a	(-30°)	*b	*c	(80°)	280°
3	90°	50°	110°	40°	(-10°)	80°	130°	(200°)
4	40°	-40°	x	x	130°	(-50°)	210°	(270°)
5	*d	x	x	340°	x	-270°	100°	100°
6	30°	10°	0°	(-100°)	110°	(0°)	x	(0°)
7	0°	-10°	(90°)	(80°)	x	(10°)	230°	(120°)

*a,*b,*c There is large phase gap near 130°E

*d 0° between the western Pacific and South America

the scattering of the lag-day among the stations is large and the correlation coefficient is small. In U850, the eastward-moving wavenumber-one structure with a phase speed of 5°~8°/day can be seen in Cases 3, 4 and 7. We also compute lag-correlations with referring to U200 at Majuro as a reference, but the phase structure of U is still not clear. This implies that the weak correlations and their large spatial scattering in the U field are not caused by taking geopotential height as a reference, but by the unclear structure of U itself.

The above results for the seven cases can be summarized as follows: (i) The standing-wave-like structure in the H field can be recognized in all the troposphere. Though the eastward-moving properties appear in the lower and upper troposphere in some cases like those in the U field, its phase speed is much faster than that of U. (ii) The standing-wave-like structure is seen in T200, while fairly slow eastward-moving ones are found in T500.

The extension of these standing-wave-like structure to South America and the Atlantic is different among the cases: For example, in H1000 shown in Fig. 4a and Fig. 5, a rather out-of-phase structure with a node near 80°W appears in Case 1; rather in-phase structures in Cases 2, 5 and 7. A similar analysis using as a reference H1000 at Natal (South America) instead of Majuro shows that the correlations between the stations of South America and the region from India to the Pacific are not so high. A systematic phase relation cannot be found between the 30–60 day variation over the region from the Maritime Continent to the Pacific and that over the region from South America to the Atlantic.

3.3. Vertical structure

(1) Characteristics during 1979 Northern Summer

In order to examine the vertical phase structure of the 30–60 day variation, the time-height sections of a filtered time series of H and U at Koror are shown in Figs. 6a and b respectively. In the active

interval of May~August 1979 (Case1), the upper tropospheric U is clearly out of phase with the lower tropospheric U and there is a node at about 400–500 mb (Fig. 6b). On the other hand, the vertical phase difference is far less than 180° in the signal of H (Fig. 6a). We compute the vertical correlations of H and U, taking H1000 and U850 at the same station as references respectively. First, we examine the behavior in the western and mid Pacific where the data are available at many stations in Case 1. Fig. 7 shows the average of the lag-correlation at the following six stations located from 134°E to 172°E: Koror, Yap, Truk, Ponape, Kwajalein and Majuro.

The 30–60 day variation of U has the clear out-of-phase structure between the upper and lower troposphere (Fig. 7b), in agreement with previous studies (e.g. Murakami and Nakazawa, 1985). On the other hand, the upper tropospheric H leads the lower tropospheric one by about 15 days (120° in the phase) (Fig. 7a). This phase difference is apparently less than that in U and shows neither an out-of-phase structure nor a vertical node. Similar analyses are made for the time series of H and U at Kuala Lumpur, Kuantan and Kota Kinabaru in the Maritime Continent: The 30–60 day variation of U is also out of phase between the upper and lower troposphere with an abrupt phase change between 300 mb and 500 mb in this region; the downward phase propagation in the H field can be seen; and the phase lead of the upper troposphere is about 15 days (120° in the phase) (not shown). It is obvious that the vertical structure of H is different from that of U over the Maritime Continent and over the western and mid Pacific.

The longitudinal dependence of the vertical structure is depicted in Fig. 8: Figs. 8a and b represent the correlations of H200 with 1000H as a reference and that of U200 with U850 as a reference at each station, respectively. A nearly out-of-phase structure is seen in the U field at almost all stations; Over the Maritime Continent and South America

Fig. 6. Time-height cross sections of the bandpass filtered (30–60 days) value at Koror: (a) H with a contour interval 10 m; and (b) U with a contour interval of 3 m/s. The ordinate denotes pressure (mb). The heavy line and broken line denote zero and negative values, respectively.

Fig. 7. Lag-height cross sections of the mean correlation averaged at the stations in the western and mid Pacific (Koror, Yap, Truk, Ponape, Kwajalein and Majuro) in May–August 1979: (a) H with the reference H_{1000} and (b) U with the reference U_{850} at each station. Abscissa and ordinate denote lag-day and height (mb), respectively. The contour interval is 0.2. The heavy line and broken line denote zero values and negative values, respectively.

Fig. 8. The lag-day when maximum and minimum of the lag-correlation of filtered variable appears at each station: (a) H_{200} with the reference H_{1000} and (b) U_{200} with the reference U_{850} at each station. The position of the symbols denotes the lag-day and the space and size denote the value of the correlation. The symbols are the same as in Fig. 4. Abscissa and ordinate denote the lag-day and longitude (E), respectively.

the lag-time is close to half of the period, while in the mid-Pacific it is somewhat smaller (Fig. 8b). Fig. 8a shows that in the western Pacific the phase lead of H is about 18 days and a nearly out-of-phase structure appears, and that near the date line and the Maritime Continent the signal of H in the upper troposphere leads that of the lower troposphere by 12–14 days ($90^\circ \sim 120^\circ$ in the phase).

(2) Case studies in 7 years

First, the mean vertical structures at 6 stations in the western and central Pacific, Koror, Yap, Ponape, Truk, Kwajalein and Majuro are compared for Case 1. Table 3 gives the phase lead of H_{200} for H_{1000} and that of U_{200} for U_{850} , which are obtained from the averaged correlation among the stations in the western and mid Pacific from the panels as Fig. 6. The almost vertical out-of-phase structures appear

Table 3. Vertical phase structure which is given by the phase lead of (a) $H200$ for $H1000$ and (b) $U200$ for $U850$ averaged at six stations in the western and mid Pacific, Koror, Yap, Truk, Ponape, Kwajalein and Majuro for the seven cases. Values within brackets are less reliable. Crosses denote values which could not be estimated. Units are (degrees). See text for the details.

Case	(a) the phase lead of $H200$ for $H1000$	(b) The phase lead of $U200$ for $U850$
1	120°	-160°
2	70°	-120°
3	90°	-150°
4	x	-110°
5	-140°	140°
6	80°	(150°)
7	110°	160°

between $U200$ and $U850$ in many cases although the correlation is somewhat small (Table 3b). On the contrary, the phase lead of $H200$ for $H1000$ shown in Table 3a is about 70°~120° and the vertical out-of-phase structure like that of U does not appear except in Case 5. The correlations between H in the lower and mid troposphere are not low so that the evidence of the nodes is not confirmed. The downward phase shift is apparent in the H field, though the amplitude of 30–60 day variation is somewhat small in mid-troposphere (Fig. 6a).

A similar analysis in the U field over the Maritime Continent gives different results depending on the cases, and the correlations are small. The phase lead of $H200$ for $H1000$ also varies among the cases, and the phase shift is downward in Cases 3 and 6 and upward in Cases 2 and 4 (not shown).

3.4. Phase relation between H and U

(1) Characteristics during 1979 Northern Summer

The phase relation of the 30–60 day variation between U and H seems rather complex as was suggested by the previous results: (i) A standing-wave-like structure appears in H , in contrast to that of eastward-moving wavenumber-one in U ; and (ii) In the western and mid Pacific region, $H200$ leads $H1000$ (or $H850$) by 70°–120°, whereas $U200$ is out of phase with $U850$. However, as the phase relation between U and H is very important for the understanding of the mechanism of the 30–60 day variation, we closely examine the phase relation of the 30–60 day variation between U and H over the region from India to the eastern Pacific across the date line where $H1000$ has standing-wave-like structure in this subsection 3–4. Fig. 9a represents the lag-correlation coefficient of $U850$ for $H1000$ at the same station. $U850$ is also expected to have a similar phase relation to $H850$, because the behavior of $H850$ is very similar to that of $H1000$. The time lag of $U850$ to $H1000$ almost vanishes near the date

line as shown by Madden and Julian (1972), while $U850$ leads $H1000$ by 10~15 days (80°~120° in the phase) from India to the western Pacific. On the other hand, although $U200$ and $H1000$ are out of phase near the date line, the lag of $U200$ for $H1000$ is about 14 days (130° in the phase) in the western Pacific, 11 days (90° in the phase) over the Maritime Continent and 27 days (240° in the phase) in central America (not shown). These facts indicate that the in-phase relation between $H1000$ and $U850$ and the out-of phase relation between $H1000$ and $U200$ do not hold except near the date line.

From Fig. 9b, it is seen that $U200$ leads $H200$ with about 12 days (about 100° in the phase) from the western Pacific to the date line, although the phase lag cannot be estimated with sufficient reliability over India and the Maritime Continent because of the somewhat small correlations and large spatial scattering.

(2) Case studies in 7 years

We examine hereafter the phase relation between the signal of U and H in the upper and lower troposphere over the Maritime Continent and the western and mid Pacific for each case during the 7 years.

Table 4a shows the phase lead of $U850$ for $H1000$ for each case, subjectively determined from the panels such as Fig. 9. The correlation coefficient is not large in Cases 3, 6 and 7 due to the weakness of the signal of U . In Case 2, $U850$ is nearly in phase with $H1000$ in the mid Pacific. This result coincides with Case 1. On the other hand, the phase lead of $U850$ for $H1000$ increases westwards; and the phase lead over the Maritime Continent is larger than that in the mid Pacific in Case 2. Table 4b shows $U200$ seems to lead $H200$ by about 90°~140° in the western and mid Pacific except in Case 5, although the reliability is not sufficient because of the weakness of U signal and the noisy properties of H . The phase relation in the upper troposphere is remarkably dif-

Fig. 9. The same as Fig. 8 except (a) $U850$ with the reference $H1000$ and (b) $U200$ with the reference $H200$ at each station.

Table 4. The phase lead of (a) $U850$ for $H1000$ and (b) $U200$ for $H200$ at the same stations in the Maritime Continent, the western and mid Pacific, respectively. Values within brackets are less reliable. Crosses denote cases when the value could not be estimated. Units are (degrees). See text for the details.

(a) The phase lead of $U850$ for $H1000$

Case	Maritime Continent	Western Pacific	Mid Pacific
1	110°	80°	-10°
2	110°	-10°	10°
3	(-20°)	(-30°)	(10°)
4	70°	40°	50°
5	260°	150°	110°
6	(30°)	(-40°)	180°
7	(0°)	(140°)	(-70°)

(b) The phase lead of $U200$ for $H200$

Case	Maritime Continent	western Pacific	Mid Pacific
1	(-160°)	100°	110°
2	20°	x	140°
3	-120°	(120°)	90°
4	(90°)	80°	140°
5	(-30°)	x	50°
6	70°	50°	140°
7	(60°)	(110°)	90°

ferent from that in the lower one.

4. Discussion

In the present work, a careful analysis of tropical station data has picked up several notable features about the 30–60 day mode, particularly concerning the zonal phase structure and the phase relation between U and H at the same level. One of the most noticeable structures is the zonally standing-wave-like one in the H field over more than half of the globe, along the equator.

The zonally standing-wave-like structure is detected in $H1000$ during most of the cases which have been considered. The phase lag in $H1000$ from India to central America through the Pacific hardly varies from case to case, though both the zonal phase lag at upper level and the vertical structure vary. This phase lag in $H1000$ coincides with that of SLP in Madden and Julian (1972) and is one of the most representative features of the 30–60 day variation. It should be noted that a phase lag of the same magnitude is found even in the case when the zonal wavenumber-one structure can be clearly seen in the U field.

Madden and Julian (1972) showed that the correlation between the SLP signal at Canton and those in South America and over the Atlantic are weak, while Maruyama (1982) showed that H at 150 mb has the zonal-wavenumber-zero structure in 1979 northern summer. The present analysis showed that the phase lag between the signal at Majuro and those in South America and over the Atlantic varies considerably from one case to another at any height level. We should study in what situation the 30–60 day variation zonally extends to South America and to the Atlantic in a future analysis.

One of the other remarkable features shown by the present work is the difference between the zonal phase structure of T in the upper troposphere and that in the middle troposphere for Case 1. $T200$ shows a nearly standing-wave-like structure, but $T500$ has structure of nearly wavenumber one similar to that of the U field in the lower and upper troposphere. For the other cases such a difference is not obvious because of the weakness of the signal. It should be confirmed with using a longer data series, because there is a possibility that two or more vertical modes contribute to the variation of the time scale.

In the theoretical and model studies, the horizontal phase-structure found in the present analysis should be taken into account. In particular, the following facts have to be explained: in the lower troposphere, the signals are evident both for U which has a nearly eastward-moving wavenumber-one structure and H which has a zonally standing-wave-like structure. They are in phase in the mid Pacific, while the signal of U leads that of H by about 120° from the Indian Ocean to the western Pacific.

In the theoretical work, Yamagata and Hayashi (1984) tried to give a consistent explanation of the behavior of the 30–60 day variation in both U and H by using a linear shallow-water diagnostic model with the localized heat source pulsating with a 40-day period. This form of forcing partly represents the observational fact that the signal of OLR is in the limited region from 60°E to 180°E (Nakazawa, 1986), though it does not represent the eastward-moving property and the interaction with the large scale flow of the cumulus cluster. While the signal of U has a phase jump of about 180° at the eastern part of the forcing region, the pressure field is not associated with a phase jump and the center of low pressure is at the east part of the forcing region. Since this is a linear model and the forcing is symmetric about the equator, the wind and the pressure fields consist of the Kelvin and Rossby modes. The Kelvin mode is dominant to the east of the forcing region and the signals of U and H are in phase there, while the Rossby wave is dominant to the west of the forcing region, and signals of U and H are out of phase there. These results are in good agreement with our observational facts that the signals of U and H are in phase over the mid-Pacific in the east of the forcing region, while U and H are rather out of phase in India and over the Maritime Continent in the western part of the forcing region.

However the Rossby mode with the eastward-moving forcing should be weaker than that with the standing forcing from a theoretical consideration (Yamagata, 1987) and in the other authors' observational studies the Rossby mode seems to be very weak. The possibility of dominance of the Rossby

mode as well as the Kelvin mode in the real atmosphere should be closely examined to confirm whether the observed behavior of the H field can be interpreted by the model results of Yamagata and Hayashi (1984) or not.

If the above-mentioned interpretation is acceptable, the 30–60 day variation in the H field with a standing-wave-like structure should be negative when the 30–60 day variation of the total cumulus activity in the forcing region is large (OLR is negative). The phase of the 30–60 day variation in the H field at each longitude depends on the 30–60 day variation of the amount of the total heating over the tropics rather than the longitudinal position of the convective center at each time. This relationship will be examined by analysis of OLR data together with the station data in a following work.

In some GCM experiments, a part of the results of the present study were simulated. Chiba (1986) made a simulation with GCM based on realistic conditions. The signal of U and precipitation (corresponding to the cumulus activity) clearly indicates an eastward-moving wavenumber-one structure, while those of SLP and upper tropospheric T shows an almost zonally in-phase structure along the equator similar to those in the present work. The behavior of the signal of H in this model is similar to that of the present analysis as a whole. Lau and Lau (1986) also made a simulation experiment with GCM, and obtained the eastward-moving wavenumber-one properties. Though the zonal phase difference of SLP was fairly small compared with that of U in the Pacific region, the wavenumber-one structure in the H field seems to be too prominent by comparison with the present analysis. Moreover, in Hayashi and Sumi (1986)'s aqua-planet GCM simulation, the signals of U and H are in phase in all the regions along the equator and it is likely that the Kelvin mode becomes too predominant in this simulation. Further investigations are required to survey the cause of the difference among the GCM results mentioned above.

Another interesting feature in the present work is the vertical structure of the 30–60 day variation in the H field. Maruyama (1982) shows statistically that at Gan in the Indian ocean the 30–60 day variation of the H field has a barotropic structure. In the present analysis, at the stations over India and the Maritime Continent near Gan, the vertical structure of the 30–60 day variation in these regions changes from one case to the next and the barotropic structure is not clearly identified.

The well-known vertical structure of U (upper tropospheric U is out of phase with lower one) can be explained with the heating centered in the middle troposphere. However, the structure of H found clearly in the western and mid Pacific cannot be explained with such a location of the heating. Un-

derstanding this vertical structure is indispensable in order to clarify the mechanism of the 30–60 day variation.

5. Summary and conclusion

The structure of the 30–60 day variation in the H and T fields and their relationship with that of the U field have been observationally investigated in the equatorial region with the use of seven-year long station rawinsonde data. The following features are found:

- (i) The 30–60 day variation of the H field is significant for the seven year spectral analysis. However, there are fairly large varieties in the activity of the mode and the systematic zonal and vertical phase structure is apparently recognized only during the active intervals. Furthermore, there are large variations in the properties of the H and T fields among the intervals.
- (ii) The 30–60 day variation in the H field has a standing-wave-like structure over more than half of the globe along the equator from India to the Pacific Ocean, although the phase of $H1000$ delays a little eastward from India to the eastern Pacific. The extension of the standing-wave-like structure to South America in the H field is not found in many cases. A similar zonal structure is also found in the signal of H in the upper and middle troposphere and in that of T in the upper troposphere.
- (iii) The following phase relations between U and H are found:
 - (a) In the lower troposphere, the signals of U and H are in phase in the mid Pacific, while the phase of U leads that of H by about 120° over India and the Maritime Continent.
 - (b) In the upper troposphere, the signal of U leads that of H by about 120° in the western and mid Pacific, while the phase relation is not clear over India and the Maritime Continent.
- (iv) Concerning the vertical structure, the signal of H in the upper troposphere is not out of phase with that of the lower troposphere, but leads that of lower troposphere by only $70^\circ \sim 120^\circ$ in the phase over the western and mid Pacific.

The properties of the H field are considerably different from well-known ones of the U field. These

results suggest that the simple Kelvin mode which has an out-of phase structure between the upper and lower troposphere is not dominant in the 30–60 day variation. Since these conspicuous properties of the H field should be taken into consideration in any theoretical and modeling studies on the mechanism of the 30–60 day variation.

Further investigations of the properties of the 30–60 day variation in the H and T fields are necessary together with much more detailed analyses of OLR data. The latitudinal structure should be examined to confirm what mode is dominant. Furthermore, due to the rather large year-to-year and season-to-season variations of some properties, the use of a much larger time series is required to elaborate the conclusions of our the present work.

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赤道域の高度場および温度場における 30–60 日変動の観測的研究 西 憲敬

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赤道付近の 33 地点のレーウィンゾンデのデータを用いて高度と温度の場の 30–60 日変動の特性および東西風のそれとの関係を調べた。まず 7 年間の時系列を調べ、次に変動が活発な 7 つの時期に対してずらし相関の手法を用いて解析を行った。主要な結果は以下のとおりである。

(i) 対流圏全層の高度および上部対流圏の温度において、インドから日付変更線を越えて東太平洋までの広い領域で東西の位相のずれが小さい定常波のような構造が認められた。

(ii) 対流圏下層の高度と東西風の変動は日付変更線付近では同位相であるが、インドネシア付近では東西風が高度より約 120° 進んでいる。上層では日付変更線付近で東西風が高度より約 120° 進んでいる。

(iii) 高度の鉛直分布は年によって変化が大きい、西および中部太平洋では上層は下層より約 $70^\circ \sim 120^\circ$ 進んでいる。

これらの高度場の特徴はよく知られている東西風の場の構造とは大きく異なっている。30–60 日変動においては、単純に対流圏の上・下層で逆位相のケルビン・モードが卓越しているとは考えがたい。