The Wavenumber-Frequency Spectra of the 200 mb Wind Field in the Tropics

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ABSTRACT

The wavenumber-frequency spectra of the 200 mb wind field from 28.7°N to 28.7°S were examined for the 128-day period from mid-May to mid-September of 1970 and 1971. Evidence was presented that supported the existence of Rossby and mixed Rossby-gravity waves. Westward-propagating waves, with periods of about 10 days and wavenumber 10, centered at about 24°N were also observed. These waves appear to be associated with the tropical upper troughs.

There were indications of equatorward transfers of energy from the mid-latitudes at periods of 9–10 and about 5 days.

1. Introduction

Over the past several years there has been renewed interest in the character and structure of the tropospheric and stratospheric circulation of the tropics, both from observational and theoretical viewpoints. Theoretically predicted waves, such as westward propagating Rossby waves and eastward propagating Kelvin waves (Matsuno, 1966) have been confirmed observationally by a number of investigators studying the time spectra of rawinsonde data over limited geographical areas for both the tropical troposphere and stratosphere. The reader is referred to Wallace (1971, 1973) for reviews of the theoretical and observational aspects of tropical waves in the troposphere and stratosphere.

There has also been considerable study of the circulation of the tropical upper troposphere at about 200 mb (Krueger and Winston, 1974; Krishnamurti, 1971a, b; Krishnamurti *et al.*, 1973). These studies are quasi-global in the sense that the circulation of the entire tropical belt is studied. Interest in the upper level circulation has been stimulated, in part, by the addition of commercial aircraft wind reports and satellite-derived wind estimates supplementing the sparse conventional data networks. The usefulness of satellite-derived wind estimates in depicting circulation features was demonstrated by Gruber *et al.* (1971).

Of fundamental importance in studies of the tropical circulation are the dominant temporal and spatial scales of the flow field. One objective of this research was to investigate the spatial and temporal scales by an examination of the space-time spectra of zonal and meridional velocity. By examining the detailed structure of the spatial and temporal scales, it was possible to compare the results with the theoretical predictions of wave modes in the tropics (e.g., Matsuno, 1966; Hayashi, 1970).

Space-time spectral analysis procedures have been used previously to study the structure of the atmosphere. Gruber (1974) used those analysis techniques on satellite-observed cloud brightness to study the dominant scales of latent heating in the tropics. Hayashi (1974) used the same procedures to study the output of general circulation models. Kao and Wendell (1970) have performed space-time spectral analyses of the geostrophic winds in mid-latitudes, and more recently Kao and Kuczek (1973) have examined the space-time spectra of the wind field tropics.

2. Data and analysis techniques

The wavenumber-frequency spectra were computed by a method that was analogous to the one developed by Kao (1968). It makes use of the two-dimensional Fourier transform of a real single-valued function $f(\lambda,t)$ which is piecewise continuous in the interval $(0,2\pi)$ for both λ and t, where λ is longitude and t time. Such a transform is given by

$$F(k,\omega)=\frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} f(\lambda,t)e^{-i(k\lambda+\omega t)}d\lambda dt, \qquad (1)$$

and its inverse transform by

$$f(\lambda,t)=\frac{1}{4\pi^2}\sum_{k=-\infty}^{\infty}\int_{-\infty}^{+\infty} F(k,\omega)e^{i(k\lambda+\omega t)}d\omega, \qquad (2)$$

where F is the complex coefficient, k the wavenumber, and ω the frequency. Kao has shown that in wave-

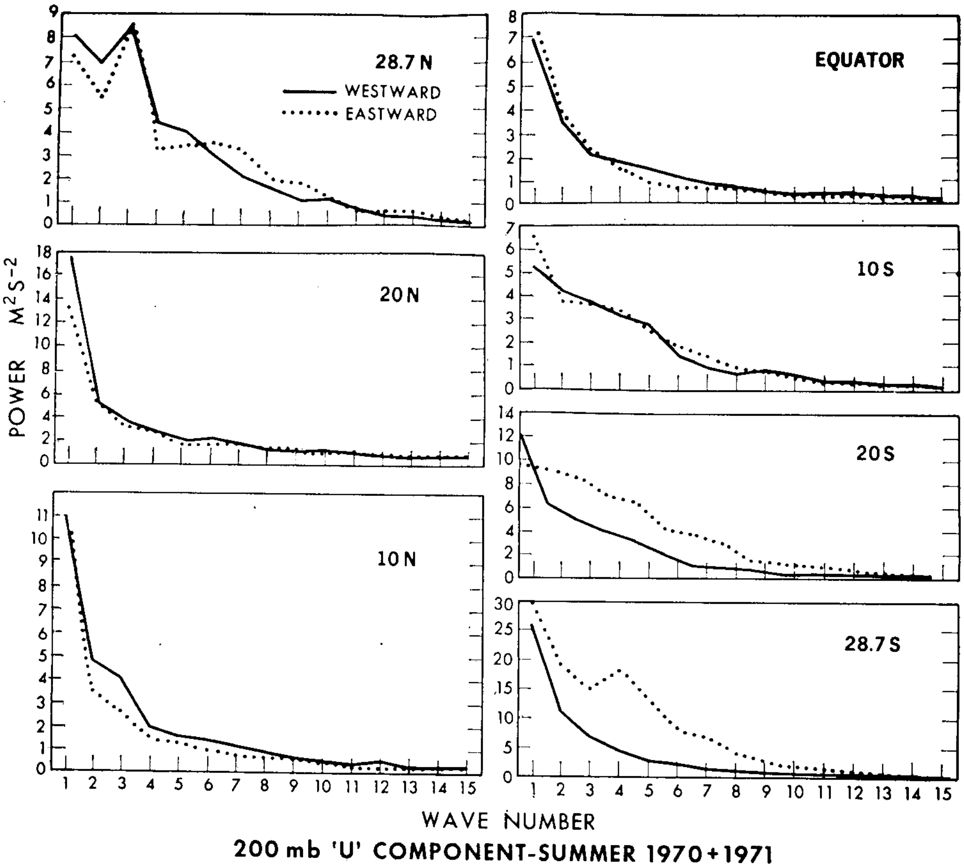

FIG. 1. The wavenumber distribution of zonal wind. Eastward propagating waves (dotted line) are separated from the westward propagating waves (solid line).

number-frequency space the power spectrum at wavenumber k and frequency ω moving from west to east $(+\omega)$ and from east to west $(-\omega)$ can be expressed as

$$\left.\begin{aligned} P(0,\pm\omega)&=F(0,\pm\omega)F^*(0,\pm\omega)\\ P(k,\pm\omega)&=2[F(k\pm\omega)F^*(k,\pm\omega)]\end{aligned}\right\},$$

where $F^*(k,\omega)$ is the complex conjugate of $F(k,\omega)$. The power spectrum of wavenumber k and all frequencies is given by

$$P(k,\pm)=\int_0^\infty P(k,\pm\omega)d\omega,$$

and the power spectrum at frequency ω and all wavenumbers is given by

$$P(\pm\omega)=\sum_{k=0}^{\infty} P(k,\pm\omega).$$

The data sample consisted of daily values of 200 mb zonal and meridional winds obtained from the NMC tropical analysis program (Bedient *et al.*, 1967). These data are produced objectively and incorporate aircraft-determined winds and satellite estimates of winds as well as conventional rawinsonde data. The analysis scheme and data processing method are described in Bedient *et al.* (1967) and in Bedient and Vederman (1964). Briefly, the analysis scheme uses the method of successive corrections with a grid distance of 5° of longitude on a Mercator map. The data are scanned four times, the first scan at a radius of 4.7 grid lengths and the last scan decreasing to 1.5 grid lengths. The northern boundary is at 48°N and the southern boundary at 48°S. Since the time of the Bedient *et al.* (1967) paper, geostationary satellite estimates of wind speed and direction have been included in the analysis.[1] These are much more accurate than the previous satellite estimate of winds, which were obtained by estimating speed and direction from cirrus blow-off of cumulonimbus cloud systems.

Because of the scarcity of observations in the region between 12.4°S and 48°S, the constant pressure wind vectors in the final analysis exhibit a 10% return to

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[1] The geostationary satellite ATS-1 which viewed the Pacific Ocean was operational starting in the spring of 1969 and continued to October 1972. The ATS-3 satellite which viewed the Atlantic Ocean was operational in the spring of 1970 and ceased in November 1974.

the climatological wind. There is apparently little or no direct climatological influence outside this region.

Despite the addition of aircraft- and satellite-estimated winds there are still deficiencies in the data coverage and thus in the subsequent analysis. Nevertheless, Krueger and Winston (1974) feel that the large-scale circulations are well represented.

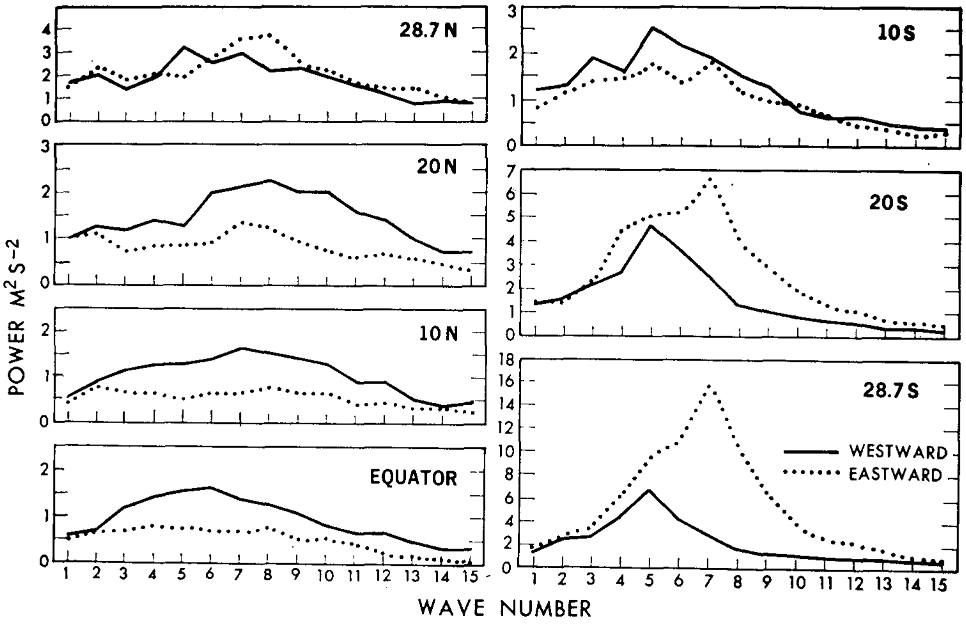
A 128-day period from mid-May to mid-September of 1970 and 1971 was selected for analysis. During this period both geostationary satellites ATS-1 and ATS-3 were operating, thus providing good coverage over the Pacific and Atlantic Oceans. Daily data for the 0000 GMT observing time were used and missing data were linearly interpolated. The linear trend in time of the zonally averaged data was removed. Wavenumber-frequency spectra were obtained by performing fast-Fourier transforms, first on winds for each day to obtain the zonal wavenumber spectra and then on each of the 36 wavenumbers to obtain the frequency spectrum. A 1, 2, 1 smoothing was applied to the frequency spectra. This results in slightly less than three degrees of freedom for each spectral estimate in the frequency domain for a given wavenumber and propagation direction. When summed over all wavenumbers for both years, the total number of degrees of freedom for each spectral estimate in the frequency domain is approximately 200. The spatial structure (wavenumber spectra, all frequencies), temporal structure (frequency spectra, all wavenumbers), and the wavenumber-frequency spectra were examined separately. Results in wavenumber space are presented only for the first 15 wavenumbers.

3. Wavenumber domain

The distribution of variance in the wavenumber domain for both the zonal and meridional wind components for latitudes 28.7°N to 28.7°S are shown in Figs. 1 and 2, respectively. The eastward propagating waves are separated from the westward propagating waves and the distribution represents the summation over all frequencies excluding the zero frequency. Thus, the wavenumber distribution represents the contribution of all propagating waves.

The zonal component has most of its variance in the low wavenumbers (planetary-scale waves). At the latitude belts from 28.7°N to 10°S, the contributions from eastward and westward propagating waves are about equal. Southward of 10°S, however, the eastward propagating waves dominate the spectra. This is a manifestation of the equatorward extent of the strong westerlies during the winter season of the Southern Hemisphere. This is further illustrated in Fig. 3 which shows a profile of the zonal wind component zonally averaged over the time period. The mean zonal wind is asymmetrically distributed about the equator with strong westerly winds extending much further equatorward in the Southern Hemisphere than in the Northern Hemisphere. The average zonal wind speed is 6 m s^{-1} at 28.7°N as compared to 31 m s^{-1} at 28.7°S.

The meridional wind component (Fig. 2) indicates considerable variance in the wavenumber range 3–10. The westward propagating waves dominate in the region 20°N to 10°S, with a shift toward higher wavenumbers to the north. At 10°S, wavenumber 5 makes



200 mb 'V' COMPONENT - SUMMER 1970+1971

Fig. 2. As in Fig. 1 except for the meridional wind component.

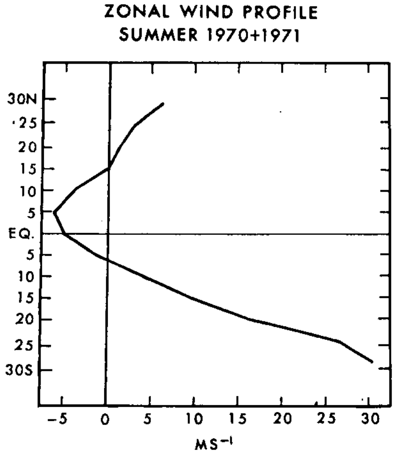


FIG. 3. Profile of the mean zonal wind.

the largest contribution and at 20°N wavenumber 8 makes the largest contribution.

It is of interest to examine the spatial structure of the stationary waves, i.e., the zero frequency. Table 1 compares the stationary waves with the total energy of the propagating waves (i.e., westward plus eastward propagating waves) for the zonal and meridional wind components for wavenumbers 1 through 5 from 28.7°N to 28.7°S. The stationary wave makes its largest contribution at the first few wavenumbers in both the zonal and meridional wind components. In some cases, the contribution from the stationary waves exceeds that of the propagating waves (e.g., wavenumber 1 of the zonal component 10°N). By wavenumber 5, however, the stationary wave component is greatly reduced and its contribution to the spatial variance is not of great significance.

Krishnamurti (1971a) presented wavenumber spectra for the 200 mb zonal and meridional wind components from 30°N to 20°S for the summer of 1967. His results are for the total motion, i.e., the sum of the westward and eastward propagating motion and the stationary wave component. Allowing for the differences in the analysis methods, the present results are in qualitative agreement with the spatial structure presented by Krishnamurti. That is, the zonal wind component shows a large contribution of variance with significant contributions between wavenumbers 3 to 10. Hayashi (1974), analyzing the output from a general circulation model, found a similar distribution.

4. Frequency domain

The distribution of variance in the frequency domain is shown in Fig. 4 for both the zonal and meridional wind component between 28.7°N and 28.7°S. The 95% confidence level is indicated on all the peaks that appeared significant.

Between 10°S and 28.7°N, the zonal component of motion indicates about as much wave activity eastward as westward. The exceptions to this occur at the equator, 10°N and 20°N where the westward propagating wave activity is slightly greater than the eastward propagation at frequencies higher than about 10 cycles per 128 days. At the equator there is an indication of wave activity at close to 5 days. At 20°N there is an indication of significant spectral peaks at 16.0 days and at 8.5 days. These peaks are not well represented at the equator or 10°N, although there is a suggestion of enhanced variance at or near those periods. At 20°S and 28.7°S the situation is reversed. That is, there is considerably more eastward propagating wave activity than westward wave activity—a factor of 2 or more at frequencies higher than 3 cycles per 128 days.

In contrast to the zonal wind, the meridional wind (Fig. 5) indicates considerably greater westward propagating wave activity than eastward propagating wave activity between the latitudes of about 10°S and 20°N. At 28.7°S, eastward propagating wave activity dominates and at 28.7°N there is about as much westward as eastward wave activity.

There are several spectral peaks in the meridional component confined primarily to the region 10°S to 20°N in the westward propagating wave activity. The most prominent are the peaks located at periods of 7.1 days and 4.9 days at both 10°S and the equator. At 10°N and 20°N the activity at those periods is not well marked although there is a suggestion of enhanced power at periods of about 7 days.

There are prominent spectral peaks at about 10 days at 10°N and 20°N which were not evident at 10°S or the equator. The separation in both latitude and period suggests that this activity should not be considered as evidence of an equatorial wave mode. This point is

TABLE 1. Contributions of variance ($m^2 s^{-2}$) from propagating (P) and stationary (S) waves.

	Zonal wind component										Meridional wind component									
	Wavenumber										Wavenumber									
	1		2		3		4		5		1		2		3		4		5	
Latitude	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S
28.7°N	15.5	10.0	11.8	3.5	16.9	10.5	7.6	1.5	7.4	0.5	2.9	3.8	4.1	5.6	3.0	1.3	3.8	1.5	5.0	0.3
20°N	30.5	42.8	10.6	10.5	6.75	2.75	5.4	2.0	3.5	0.3	2.0	2.8	2.3	2.8	1.9	1.0	2.3	0.8	2.1	0.3
10°N	21.3	31.8	8.3	8.0	6.6	4.3	3.4	.75	2.8	0.5	1.0	0.5	1.6	1.3	1.6	0.5	1.9	0.3	1.8	0.1
Equator	14.0	14.3	7.4	3.8	4.5	0.75	3.3	1.0	2.4	0.3	1.0	0.5	1.4	0.5	1.9	0.8	2.3	0.3	2.4	0.3
10°S	12.4	7.0	8.0	1.0	7.3	0.75	6.5	1.5	5.3	0.8	2.0	1.5	2.4	1.0	3.3	0.8	2.0	0.3	4.3	0.3
20°S	22.0	14.3	15.6	8.5	13.1	3.2	11.3	1.3	9.8	0.8	2.8	2.3	3.1	0.5	4.6	0.3	7.3	0.5	9.8	0.5
28.7°S	56.1	66.5	30.4	12.3	22.1	2.8	22.5	3.3	16.0	1.0	2.8	1.3	4.5	1.0	5.6	0.3	10.1	1.5	15.8	0.8

discussed more fully when the frequency spectra of individual wavenumbers are examined.

There is an indication of longer period oscillations in the meridional wind component centered about the equator. At both 10°N and the equator there is an indication of wave activity at about 14 days, and at about 10°S there is an indication of activity at about 16 days, although it is not statistically significant at the 95% confidence level.

It is interesting to note that the spectral peaks observed in the meridional wind components do not, in general, have counterparts in the zonal wind component. This has been observed in the spectra presented by Wallace and Chang (1969) for the lower troposphere and is also evident in the upper troposphere in the results presented by Yanai and Murakami (1970a, b). The prominent periods observed in the data presented have also been observed by others investigating wave

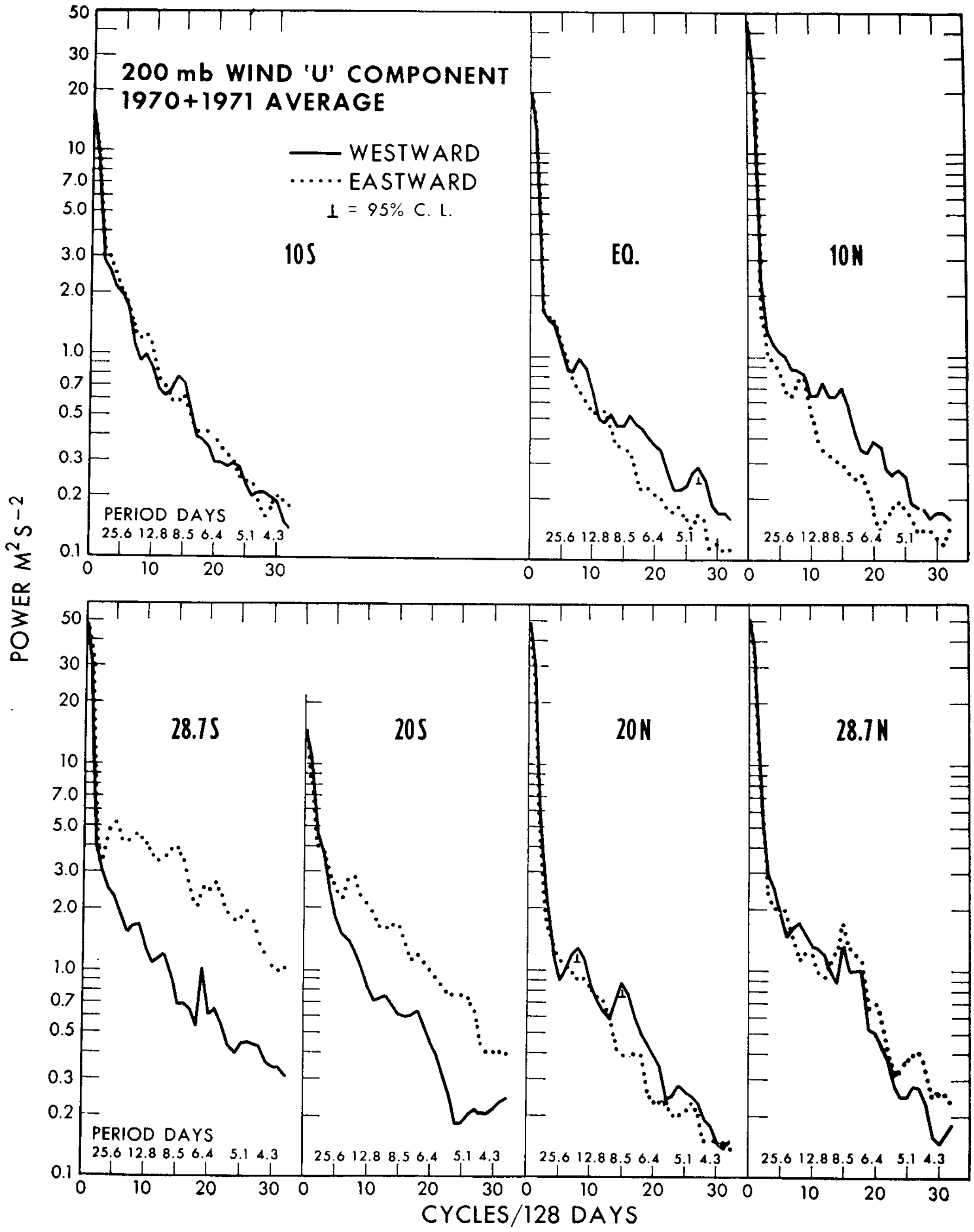


Fig. 4. Frequency spectra of the zonal wind component between 28.7°N and 28.7°S. Dotted line is eastward propagating, solid line is westward propagating.

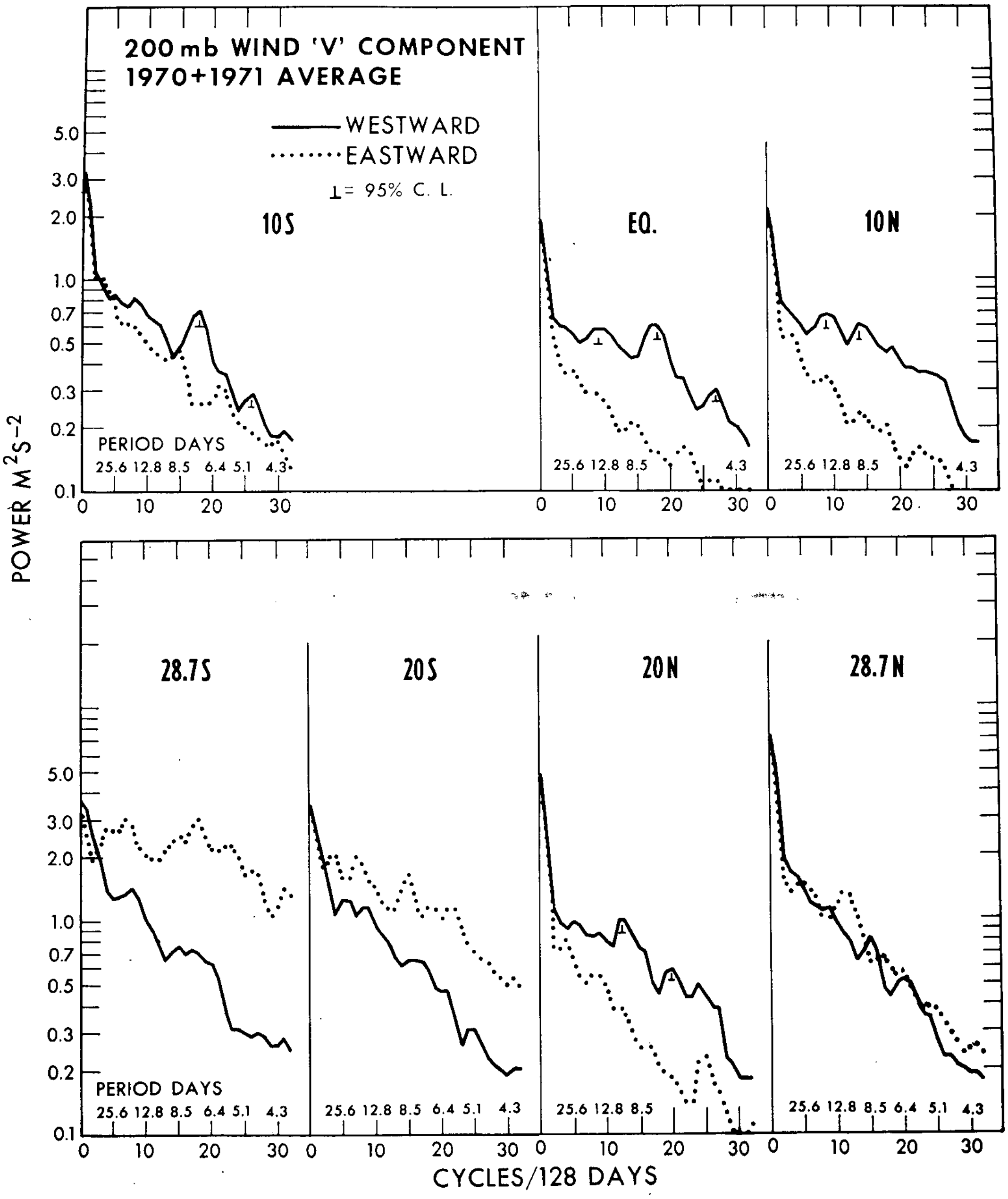


FIG. 5. As in Fig. 4 except for the meridional wind component.

activity in the tropics. For instance, Yanai and Murakami (1970b) in their spectral analysis of equatorial station data in the Pacific, observed westward propagating wave activity in the meridional wind component with periods of 16.7, 7.1 and at about 5 days near 200 mb. Although their analysis was confined to the tropical Pacific while this analysis is global, the similarity in the observed spectral peaks suggests that these wave modes are not necessarily confined to a particular geographic location.

Yanai and Murakami identified the wave activity with theoretical Rossby wave modes on an equatorial beta plane as described by Matsuno (1966). According to theory there are two types of westward propagating Rossby waves expected in the equatorial region. They are identified as $n=0$ corresponding to mixed-Rossby gravity waves and $n=1$ corresponding to Rossby waves where n is the order of the Hermite polynomial which expresses the latitudinal variation of the meridional wind. The mixed-Rossby gravity waves behave as a gravity wave at low zonal wavenumber and as a Rossby wave at high zonal wavenumber.

The theoretical distribution of winds and pressures indicates that the mixed Rossby-gravity waves ($n=0$)

should exhibit a power spectrum which is a maximum at the equator for the meridional wind, and a maximum away from the equator for the zonal wind component. Rossby waves ($n=1$) tend to exhibit the reverse distribution, that is, a power maximum in the zonal wind at the equator and a power maximum in the meridional wind component away from the equator.

In the next section the westward propagating frequency spectra for specific wavenumbers which exhibited large contributions at the periods just discussed are examined. Emphasis is placed on the horizontal structure of these waves to determine if they have any relevance to the theoretical wave modes previously mentioned.

5. Wavenumber-frequency distribution

Examination of wavenumber-frequency plots for the westward propagating wave activity in the equatorial region showed that wavenumbers 5 and 6 made significant contributions to the activity at 7.1 days and 10 days and that wavenumbers 6 and 7 made significant contributions at about 5 days. In the region 20°N–28.7°N, wavenumbers 7 and 10 made significant contributions at about 10 days.

In contrast to the other periods, the wavenumbers that contributed to periods at 14–16 days were quite variable. For example, at 10°S the wavenumbers that contributed most were 5, 6 and 8, whereas at 10°N wavenumbers 3, 4 and 5 made the most significant contributions.

Wavenumbers 5, 6 and 7 and their associated periods are generally consistent with some of the free wave modes discussed theoretically by Matsuno (1966), and more recently by Hayashi (1970). It is important to determine if they are mixed Rossby-gravity waves or Rossby waves. As indicated previously, it is possible to distinguish the type of wave by an examination of the latitudinal variation of power in the wavenumber and frequency band of interest. The individual periods identified, and their corresponding horizontal structure for the wavenumbers that exhibited significant contributions to the variance, are discussed separately.

6. Periods of 7 and 10 days

The distribution of power for wavenumbers 5 and 6 as a function of latitude for the meridional and zonal wind components is shown in Fig. 6 for the westward propagating wave modes. A period range of about 6 to 11 days is covered. There is a well-defined maximum in the meridional wind at 7.1 days located at 10°S and a maximum located at about 15°N close to 7.1 days; however, it is much less in magnitude than the maximum located in the Southern Hemisphere. The spectra of the zonal wind component shown in Fig. 6b indicates a maximum over the equator centered at a period of 7.1 days. The observed distribution of power with latitude is for the most part consistent with westward propagating Rossby waves. The discrepancies with the theory are that the maxima in the meridional winds are not symmetric with respect to the equator either in

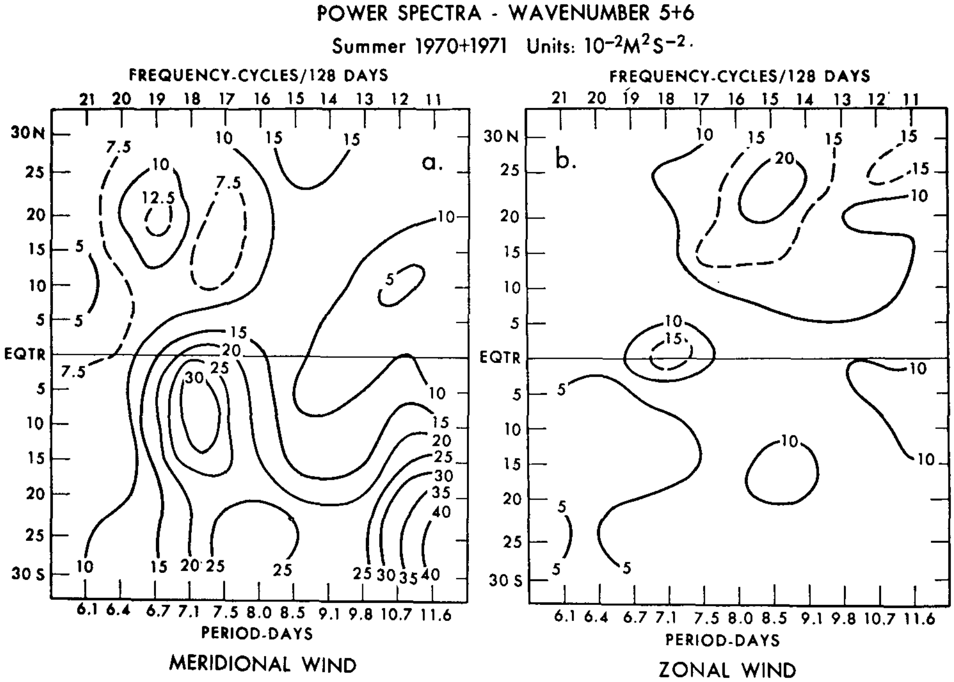


Fig. 6. The latitude-frequency distribution of power for wavenumbers 5 and 6, westward propagating. Period ranges from 6.1 to 11.6 days. (a) meridional wind component; (b) zonal wind component.

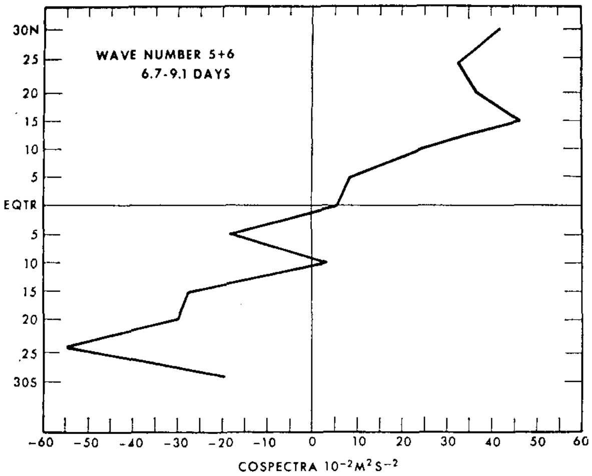


FIG. 7. Profile of momentum transport for wavenumbers 5 and 6 averaged over the frequency band of 14–19 cycles per 128 days, corresponding to Rossby waves.

magnitude or location. This may be related to the asymmetric distribution of zonal wind speed (Fig. 3). The momentum transports associated with these waves was examined for further evidence that they may be related to the theoretical equatorial Rossby waves. According to the theory of Hayashi (1970) the momentum transport of Rossby waves is away from the equator and the phase between the zonal and meridional wind components is close to 90° indicating that the momentum transport is small. The cospectra between u and v is shown in Fig. 7 for wavenumbers 5 and 6 averaged over the period range of 6.7 to 9.1 days. The cospectra is generally small in the equatorial regions and indicates transport of momentum away from the equator in both the Northern and Southern Hemispheres. These results are consistent with theory and it is reasonable to conclude that the wave activity at 7.1 days and wavenumbers 5 and 6 represent equatorial Rossby waves of the $n=1$ type.

It is interesting to note that Yanai and Murakami (1970b) observed westward propagating Rossby waves with periods of about 7 days and wavelength of about 8800 km in the western Pacific. These results are in essential agreement with theirs.

There is also evidence shown in Fig. 6 of wave activity at periods of about 9 days in both the zonal and meridional wind components. The distribution of power for the meridional wind, however, suggests a connection to mid-latitudes. Because of the indication of a connection to latitudes further north, this activity may be related to lateral energy transfers. This aspect is being studied and will be reported on separately.

As indicated earlier, there was a contribution by wavenumbers 7 and 10 which contributed significantly to the periods at about 10 days, primarily at 20°N–28.7°N. The distribution of power for wavenumber 10 meridional and zonal wind components is shown in Fig. 8. A clearly defined maximum in the meridional wind component is located at about 20–25°N at periods of about 10 days. There is a weak, but corresponding maxima in the zonal wind component. It is believed that these peaks are representative of westward propagating disturbances found in the tropical upper troughs. During the Northern Hemisphere summer season the tropical upper troughs are well developed, and are most evident just north of 20°N (Sadler, 1967; Krishnamurti, 1971a). Associated with these large-scale circulation features are smaller disturbances which generally move westward. For example, Sadler (1967) analyzed a series of disturbances on the upper trough in the Pacific. They had a wavelength of about 30° of longitude, consistent with a wavenumber of 10.

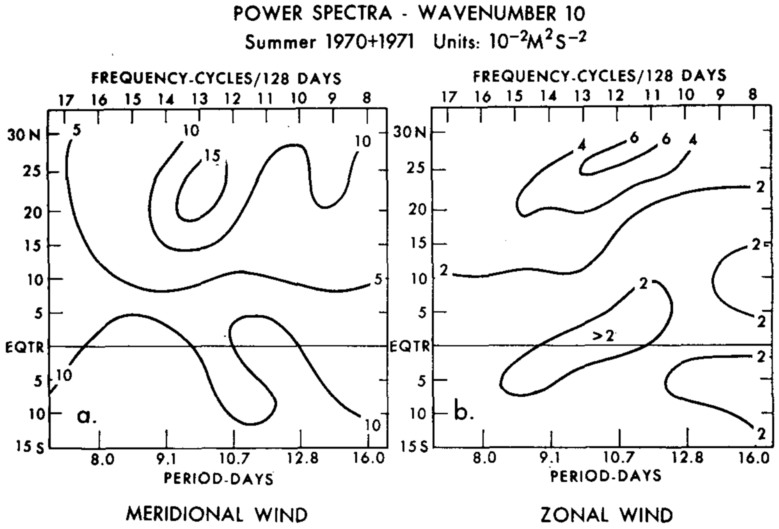


FIG. 8. As in Fig. 6 except for wavenumber 10. Periods range from 8.0 to 16.0 days.

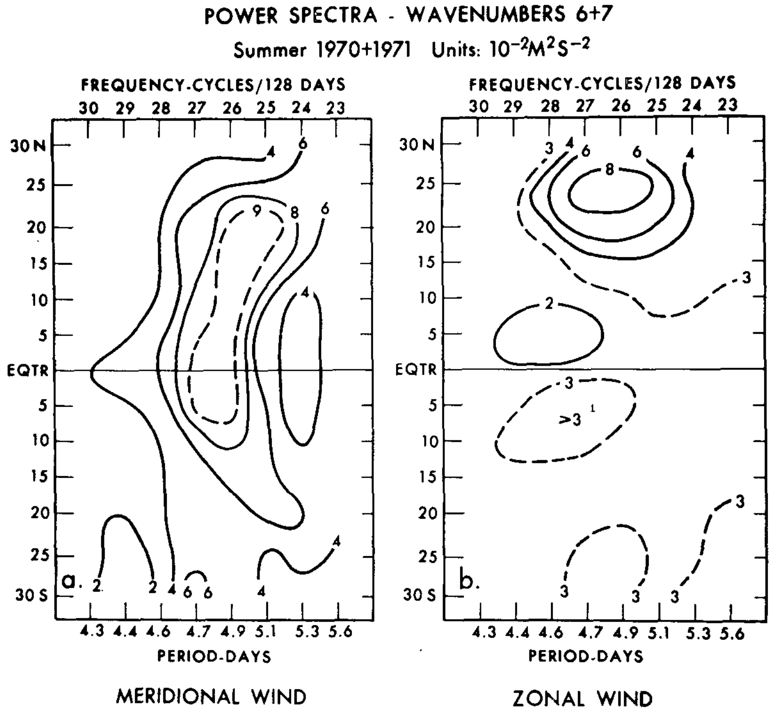


FIG. 9. As in Fig. 6 except for wavenumbers 6 and 7. Periods range from 4.3 to 5.6 days.

7. Periods of 4.92 days

The wavenumbers which contribute to the wave activity at 4.92 days were primarily 6 and 7. The latitudinal distribution of power for both and *u* and *v* components are shown in Fig. 9. There is an elongated maximum in the meridional component at about 5 days which extends from about 5°S to about 20°N. Close examination of the data suggests that there are actually two maxima—one centered on the equator and one located at 15–20°N. This is not well shown in Fig. 9a, but only hinted at by the hourglass shape of the contours.

The zonal wind component shows maxima away from the equator, at about 5–10°S in the Southern Hemisphere and at about 25°N in the Northern Hemisphere. The maximum in the Northern Hemisphere has about twice the magnitude of the one in the Southern Hemisphere and, as in some of the previous spectra examined, there is an indication of a connection to the middle latitudes. Nevertheless, the latitudinal distribution of power is in part consistent with what one might expect to find with mixed Rossby-gravity waves. As in the case of the Rossby waves, the cospectra between the zonal and meridional velocity components (Fig. 10) is consistent with theory. Zonal momentum transport is small in the equatorial region and directed poleward in both hemispheres. These results can be compared with Nitta's (1970) study. He showed very weak zonal momentum transports in the latitude belt 15°S–15°N in the 100–250 mb layer for the period range of 3.12–5.36 days. In the Northern Hemisphere he indicates a poleward directed transport of zonal momentum, but in the Southern Hemisphere he calculates a small equatorward momentum transport. In view of the different period ranges and levels between Nitta's study and this one, the results appear to be consistent with each other. Nitta implicitly identified these disturbances with mixed Rossby-gravity waves.

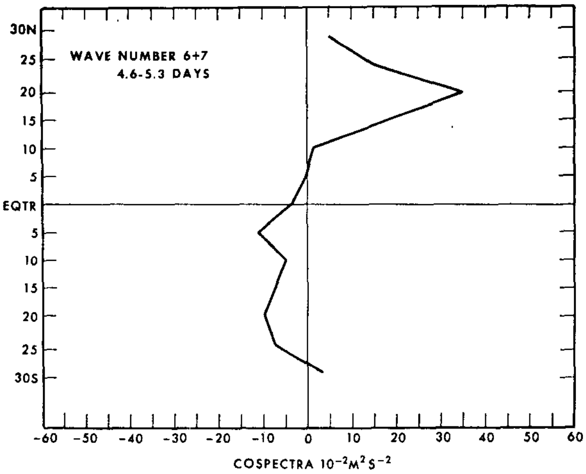


FIG. 10. Profile of momentum transport for wavenumbers 6 and 7 averaged over the frequency band of 23–28 cycles per 128 days corresponding to the mixed Rossby-gravity waves.

While the period of about 5 days calculated in this work is consistent with previous observations of mixed Rossby-gravity waves using station data (Wallace, 1971; Yanai and Murakami, 1970a, b; Yanai *et al.*, 1968, and Yanai and Hayashi, 1969) the wavelength appears to be smaller than previously reported for the upper troposphere (6000–7000 km versus about 10,000 km). However, Wallace (1972) has presented evidence suggesting that mixed Rossby-gravity waves have wavelengths that vary vertically from about 4500 km in the lower troposphere to about 10,000 km in the upper troposphere. Thus the wavelength calculated in this study (~7000 km) is not inconsistent with previously reported values.

Despite this evidence in favor of a mixed Rossby-gravity waves interpretation, the lack of a clear maximum in the spectra of the meridional wind at the equator and the implied connection with the mid-latitudes indicated by the spectra of zonal wind make that interpretation somewhat uncertain. It is possible that lateral transfers from the mid-latitude at periods of about 5 days, as suggested by Mak (1969), are operating such that an unambiguous identification of a mixed Rossby-gravity wave is not possible with these data.

8. Period of 14–16 days

As previously indicated, the wavenumber distribution that contributes to the observed spectral peaks at 14–16 days was quite variable. Thus it is difficult to identify the activity at those periods with any of the equatorial wavemodes. This is contrary to observations made by Yanai and Murakami (1970b) who observed waves with periods of 16.6 days and wavelengths of about 8000 km. Since these observations were based on station data confined to the western Pacific, it is possible that what they observed was a local phenomena and so would not appear in this type of analysis which utilized observations from entire latitude belts.

However, Miller (1974) has observed 14–16 day periodicities in energy parameters averaged from 20°N to the Pole. This suggests that the 14–16 day period observed in the tropics in this study may be part of a hemispherical or perhaps global oscillation in the period range of 14–16 days. This aspect requires considerably more investigation.

9. Concluding remarks

Analysis of the wavenumber-frequency spectra of the 200 mb wind field in the tropics has revealed several interesting aspects of the structure of the upper tropical troposphere.

In the wavenumber domain good agreement with Krishnamurti's work was observed. This was gratifying since his results were based on data from a different year and consisted of aircraft and rawinsonde reports, and were subjected to very careful analysis. The data set used in this analysis was objectively produced in an operational setting and in addition to aircraft and conventional rawinsonde data, included satellite-derived wind estimates.

Evidence was presented that supported the existence of Rossby and mixed Rossby-gravity waves. The former had a period of about 7 days and wavelengths of 7000–8000 km, and the latter period of about 5 days and wavelengths of about 6000–7000 km. Unfortunately, some discrepancies in the analysis prevented unambiguous identification of these waves. Some possible sources of these discrepancies were the asymmetric character of the mean zonal wind and a suggestion of energy transfer from mid-latitudes which may have influenced the distribution of power in the equatorial region, making the isolation of the equatorial wave modes somewhat more difficult. This was particularly true for the mixed Rossby-gravity waves. Nevertheless, the momentum transports seem to agree with what one would expect from theory lending credence to the interpretation of equatorial Rossby waves.

There was also evidence for equatorward transfer of energy from the mid-latitudes at periods of 9–10 and about 5 days. The problem of lateral energy transfers and their influence on tropical motions is currently under investigation.

Finally, there was strong indication of westward propagating waves with periods of about 10 days and wavenumber 10 centered at about 24°N. This was interpreted as being indicative of westward tracking disturbances found in the tropical upper troughs.

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