The Wavenumber-Frequency Spectra of Satellite-Measured Brightness in the Tropics

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ABSTRACT

The wavenumber-frequency spectra of satellite-observed brightness have been examined for the period 1 February 1967 through 29 February 1968 for the latitude belt 20N to 20S. It was found that the quasi-stationary modes and low wavenumbers contain most of the power. The propagating wave activity was located primarily in the 5–15N latitude zone. Perturbations with periods of 12.5 days and wavenumber 5 and about 6 days and wavenumber 9 were prominent. These are consistent with Rossby waves and easterly waves. Since the propagating brightness spectra are due to propagating clouds, the results indicate a traveling heat source as being important in the generation and maintenance of those waves. There was no indication in the brightness spectra of periods and wavelengths consistent with Kelvin waves. However, a tropospheric heat source is not ruled out for those waves.

1. Introduction

During the past several years there has been considerable spectral analysis of satellite-observed brightness in attempts to define tropical wave modes (Tanaka and Ryuguji, 1971; Murakami and Ho, 1971; Sikdar *et al.*, 1972; Wallace and Chang, 1972; Wallace, 1971). These studies have generally concentrated on spectra in the time domain, over limited longitudinal extent in the tropical oceanic areas, primarily the Pacific. Over the oceanic areas variations in brightness are overwhelmingly due to variations in cloudiness. The wavelengths and directions of propagation of disturbances were determined by coherence and phase analysis between two longitudinally separated grid points. The results have been mixed. Prominent periods have varied from about 5 to 50 days and wavelengths from about 4000 to 30,000 km depending on geographical location and season. Nevertheless, existence of westward propagating Rossby-type waves, which were observed in the wind field and predicted theoretically (Wallace, 1971), were generally confirmed.

The research reported upon herein differs from the previously mentioned spectral studies. It is not limited to a specific longitudinal belt, but rather examines the brightness spectra in the space-time domain. Thus, zonal wavelengths and associated periods are explicitly calculated with little or no ambiguity, a situation that is not always the case with coherence and phase analysis between longitudinally separated grid point data.

The explicit determination of the wavenumber and frequency of perturbations will also permit a realistic comparison of the observed form of the latent heating distribution[1] with the form of the tropospheric latent heat sources indicated by theoretical models. It is important to determine if the latent heating is in the form of traveling waves as indicated by instability theories (Yamasaki, 1969; Hayashi, 1970; Murakami, 1972), as standing waves as suggested by Holton (1972), or as "red noise" as recently suggested by Holton (1973). The daily time continuity and global coverage provided by satellite brightness data make this evaluation possible.

2. Data and analysis methods

The data set was composed of daily values of brightness for the period 1 February 1967 through 28 February 1968. These data were obtained from the ESSA 3 and 5 satellites and were averaged over 5°×5° squares of latitude and longitude from 20N to 20S around the globe. These data have been adjusted for instrumental and calibration variations (Taylor and Winston, 1968), and are in digital values betweeen 0 and 10. The method of analysis followed the procedures developed by Hayashi (1973), which allows for the resolution of a field of data dependent on time and longitude into its wavenumber and frequency components as well as into quasi-stationary, eastward and westward propagating waves.

In the wavenumber domain computations were made for wavenumbers up to 15 and in the frequency domain spectral estimates were obtained every 0.02 cycle per

[1] Transient oscillations in the brightness field are due principally to oscillations in cloudiness which in turn should be representative of the latent heating distribution.

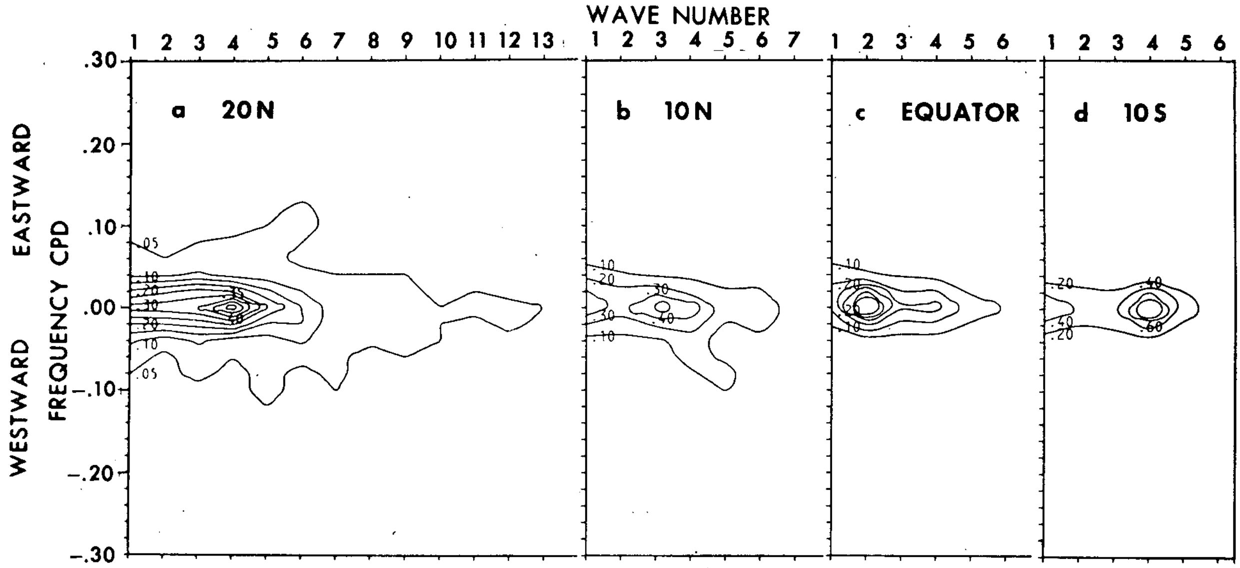

FIG. 1. Wavenumber-frequency spectra of brightness for the period 1 February 1967 through 29 February 1968. The ordinate is frequency in cycles per day (cpd) and the abscissa is wavenumber. Positive frequency represents eastward propagating waves and negative frequency westward propagating waves. Latitudes shown are: a. 20N, contour interval 0.05 unit (variance per unit frequency interval); b. 10N, contour interval 0.10 unit, c. equator, contour interval 0.10 unit; and d. 10S, contour interval 0.20 unit.

day (cpd) from 0.00 to 0.50 cpd. The lag autocorrelation method was used to attain the spectra in the frequency domain and harmonic analysis was used to obtain the spectra in the space domain.

The power at zero frequency represents the contribution of variance per unit frequency interval by those processes with frequencies less than 0.02 cpd. They will be called the quasi-stationary waves. Spectral peaks for a given wavenumber, which show symmetry about the zero frequency, will be interpreted as standing waves, that is, waves which propagate both eastward and westward with the same frequency and amplitude. Note, however, that it is not possible to determine true standing wave activity from equal amounts of eastward and westward propagating waves from spectra alone.

3. Results and interpretation

Although space-time spectra for the period 1 February 1967 through 29 February 1968 were computed at every 5° latitude from 20N and 20S, only results for representative latitudes of 20N, 10N, the equator and 10S will be presented. These are shown in Figs. 1a–1d for the frequency range 0.00 to 0.30 cpd and a wavenumber range which cover significant features in the spectra.[2]

The most striking feature is the concentration of power at zero frequency, indicating the importance of the quasi-stationary waves to the total variance of brightness. The propagating wave activity is best developed at 10N with a noticeable peak at wavenumber 5 and a period of about 12.5 days propagating westward. There was also evidence for westward propagating waves at 5 and 15N (not shown) but it was not as distinct as at 10N. The quasi-stationary and propagating wave activity will be discussed separately.

a. Quasi-stationary waves

The distribution of power with wavenumber at frequencies <0.02 cpd should be representative of the wavenumber distribution of the mean brightness. The wavenumber distribution shows that most of the spatial variance is contained in the first five wavenumbers. At 20N, wavenumber 4 dominates. South of 20N the lower wavenumbers make more of a contribution so that at 10N and 10S the distribution appears bi-modal with strong contributions from wavenumbers 1 and 4. The bi-modal distribution was also evident at 5S, 15S and 20S (not shown). At the equator, wavenumber 2 dominates. A similar distribution was observed at 5N.

The spatial distribution of variance depends to a large extent on the distribution of land and sea in the tropical belt. This can be qualitatively seen in Fig. 2 which shows the mean annual albedo (Winston, 1972) for the period March 1967 through February 1968. In the latitudinal belt from 20N to 20S the land areas exhibit high albedo and the ocean areas low albedo. At 20N most of the high albedo areas are the deserts of Africa and Arabia. In the equatorial latitudes, however, the high albedo areas are regions of wide-

[2] The frequency range will be from 0.00 to 0.30 cpd for all space-time spectra diagrams. The wavenumber range will be variable depending on significant features in wavenumber space.

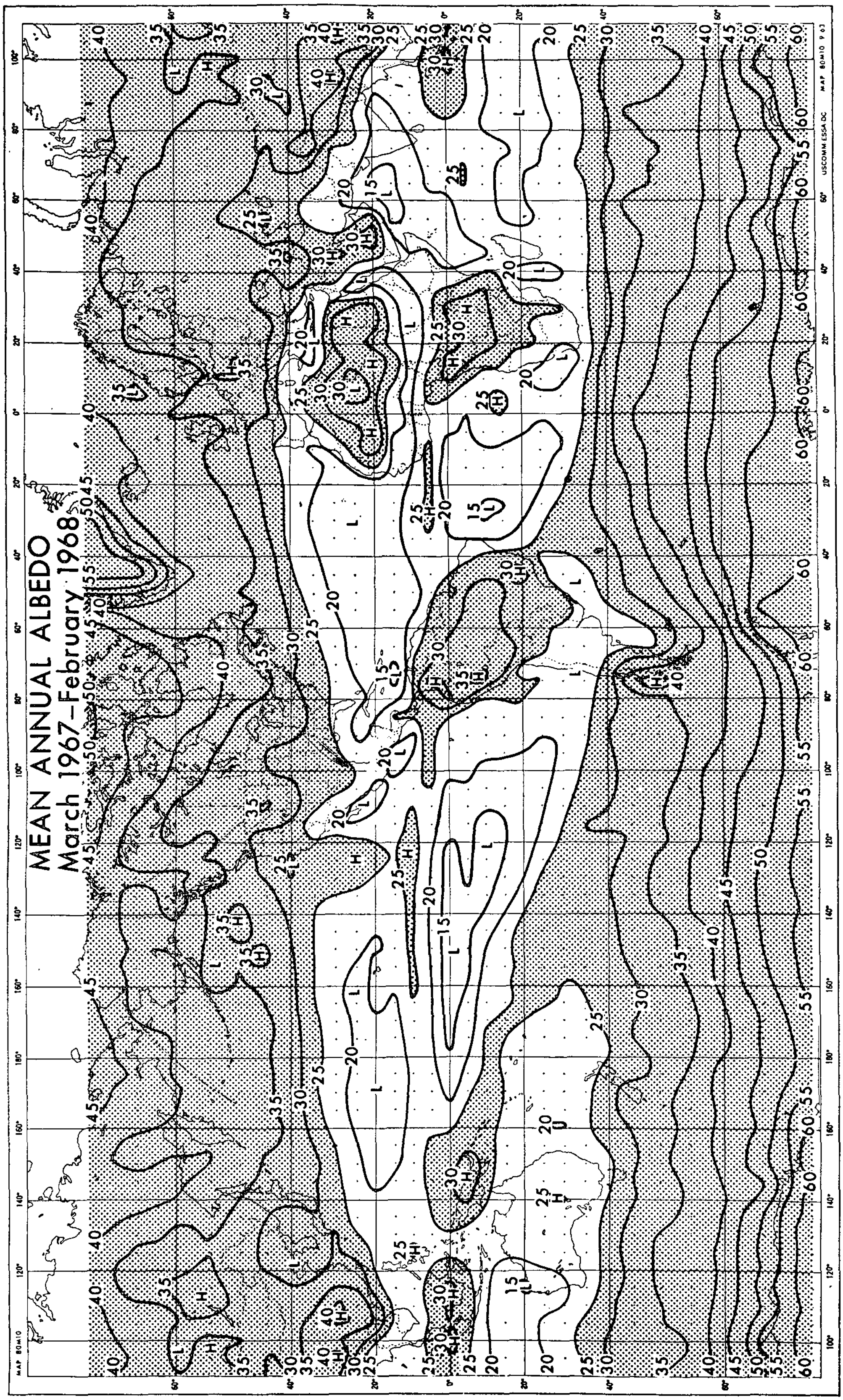

FIG. 2. Mean annual albedo for the period March 1967 to February 1968 (after Winston, 1972).

spread and intense convection. This emphasizes the importance of the equatorial continental areas as a potent diabatic heat source for the tropical atmosphere. Some implications of that heat source have been discussed by Krueger (1970).

It is also known that the convective activity over the continental regions undergoes a seasonal oscillation. However, it is not possible to adequately study the characteristics of that oscillation with only a one-year data sample.

b. *Transient waves*

Transient wave activity is quite evident at 10N (Fig. 1b). However, study of time-longitude sections of satellite-measured brightness (Wallace, 1970) indicates that the transient wave activity is considerably more pronounced during the summer months than during the winter months. Consequently, the discussion of the transient activity will concentrate primarily on spectra computed for the six-month period 1 May through 30 October 1967.

During those months the wave activity extended somewhat further north of 10N. Figs. 3a–3d show the transient activity from the equator to 15N. It is evident that both westward and eastward propagating waves are present.

The westward propagating waves appear best developed at 10N (Fig. 3c) and extend southward to 5N (Fig. 3b) and northward to 15N (Fig. 3d). At 10N the distribution of power indicates wave activity at wavenumbers 4 and 5 and periods ranging from about 6–12.5 days. The activity at 6 days, however, is considerably weaker than at 12.5 days. There is another well-defined peak at wavenumber 9 and a period of about 6 days. This activity is evident at 15N but not at 5N or the equator. In contrast, the activity wavenumber 5 and period of 12.5 days is well defined at 5N but not at 15N or the equator. This suggests two distinctly different wave modes. Wavenumber 9 with periods of about 6 days may be related to the low-level classical easterly wave whereas wavenumber 5 with periods of about 12.5 days may be related to one of the Rossby wave modes studied theoretically and observationally by many others (e.g., see Wallace, 1971).

The latitudinal extent of these waves are more clearly shown in Figs. 4 and 5, for wavenumbers 5 and 9 respectively. The concentration of power in the Northern Hemisphere is quite evident. There is no corresponding spectral peak in the Southern Hemisphere, emphasizing the asymmetric distribution of power with respect to the equator. Most of the power in the Southern Hemisphere is concentrated in the quasi-stationary waves.

The eastward propagating wave modes appear to be best developed at the equator, 5N and 10N (Figs. 3a, 3b, 3c). There are two distinct wavenumber regimes, each with its own characteristic frequency. The one indicating the larger power distribution is wavenumber 1 with periods of about 50 days. The other regime varies between wavenumber 3 and 5 and is at a period of about 10 days.

The eastward propagating waves most commonly discussed in the literature are the Kelvin waves characterized by periods of about 15 days and wavenumbers 1 and 2, and a planetary-scale disturbance with periods of 40–50 days described by Madden and Julian (1972).

Neither of the two wavenumber regimes evident in the brightness statistics appear to be related to the Kelvin wave. The former would appear to have too long a period and the latter too short a wavelength. The latter regime (wavenumber 5, 10-day period) appears to be quite similar to the waves described by Wallace and Chang (1972) in their analysis of cloud brightness.

The spectral results observed at wavenumber 1 and 50 days seem to agree with Madden and Julian's 40–50 day oscillations observed in the tropics. However,

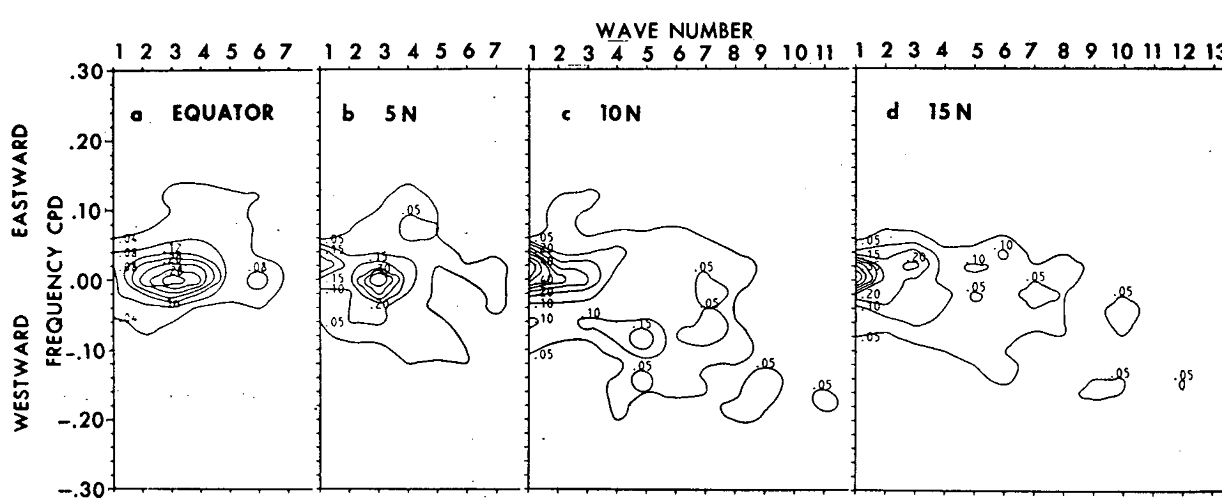

FIG. 3. As in Fig. 1 except for the period 1 May to 30 October 1967. Latitudes shown are: a. equator, contour interval 0.04 unit; b. 5N, contour interval 0.10 unit; c. 10N, contour interval 0.05 unit; and d. 15N, contour interval 0.05 unit.

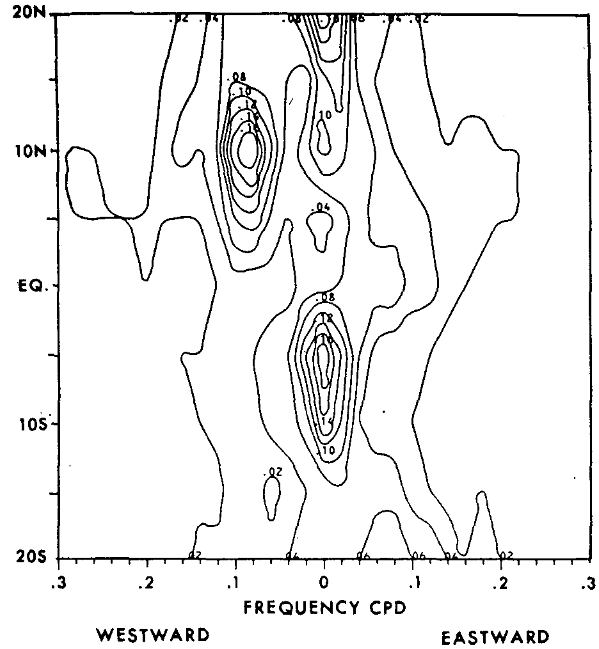

FIG. 4. Brightness spectra as a function of frequency and latitude, for wavenumber 5 for the period 1 May 1967 through 30 October 1967. Contours are variance per unit frequency interval.

there are two points which make the association between these two phenomena weak. First because this spectral peak is not clearly evident in the statistics for the period 1 February 1967 to 29 February 1968, it suggests a seasonal dependence, which is contrary to the results presented by Madden and Julian. The other point is that the six-month period which does exhibit wavenumber 1, directed eastward with a 50-day period, may be too short to yield reliable statistics.

4. Relation to latent heating

One of the purposes of this study was to deduce the relationship between the latent heating of the atmosphere and the various wave modes, treated theoretically and observed using wind data. It was seen that much of the wave activity occurs in the latitude belt within which the mean position of the ITCZ lies (Gruber, 1972). It is well known that there is considerable convective activity in this region and it seems reasonable, in the case of the westward propagating waves, that the diabatic heat source of water vapor condensation plays an important role in the generation of those wave modes. In this case the diabatic heat source is transient. In fact, there was little evidence for prominent standing-wave activity at periods of 6 and 12.5 days. It is mainly in the very low frequency oscillations that the data exhibit standing-wave oscillations. Hayashi (1974) noted similar characteristics when he averaged the data between 20N and the equator, and compared the results to precipitation generated by a GFDL general circulation model.

An interesting aspect of the heating is its asymmetric distribution with respect to the equator (Figs. 4 and 5). This is in contrast to results presented by Wallace (1971) who examined brightness data for the period July through October, 1967. He observed fluctuations at both 10N and 10S. However, his study was for a longitudinal region extending only between 160E and 170W. If this is indeed the situation it may not appear in these results with any appreciable magnitude. The latitudinal width of the implied heating for wavenumbers 5 and 9 can also be inferred from Figs. 4 and 5. In both cases it is approximately 10° latitude.

As regards a heat source for Kelvin waves, the situation is not as clear. There are no prominent spectral peaks that can be clearly identified with Kelvin waves, either standing waves or transient waves. However, at low wavenumbers the distribution of power in the time domain is of a "red noise" pattern. That is, there is large power at low frequency and a decrease in power as frequency increases. The distribution of power also tends to be symmetrical about the equator. This is shown in Fig. 6 for wavenumber 1. This is consistent with Holton's (1973) suggestion that the atmosphere, acting as a band-pass filter, is capable of extracting the required energy from this type of latent heating distribution. Thus, a tropospheric source of energy for Kelvin waves is not ruled out.

5. Summary and concluding remarks

Study of the wavenumber-frequency spectra of satellite-observed brightness between 20N and 20S has revealed some important characteristics of wave activity and latent heating distribution in the tropics.

It was shown that the quasi-stationary modes represent a potent heat source to the tropical atmosphere

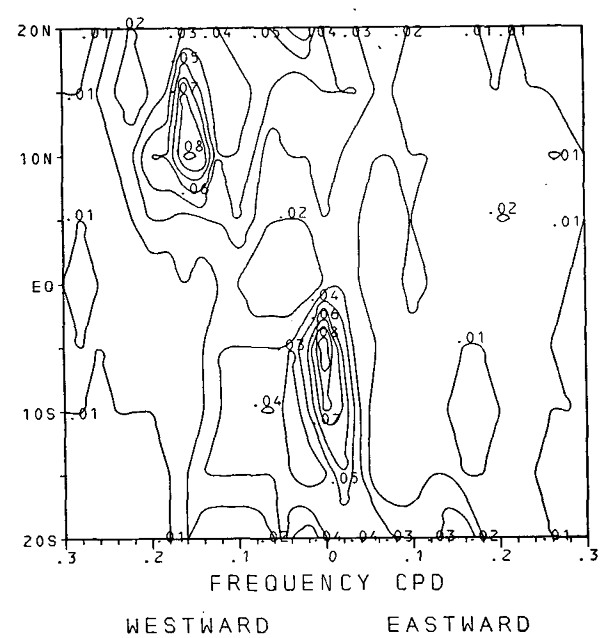

FIG. 5. As in Fig. 4 except for wavenumber 9.

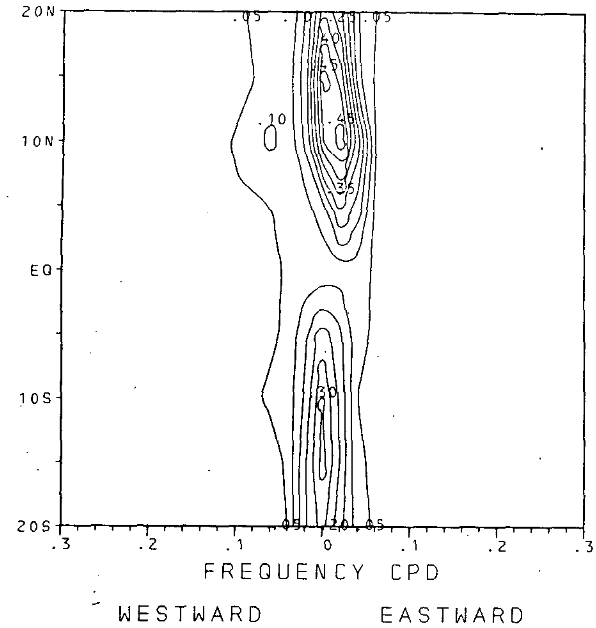

FIG. 6. As in Fig. 4 except for wavenumber 1.

particularly at low wavenumbers. Because of the large power exhibited at these very long periods they should be examined in greater detail than done in this study. Data records of several years duration will be required.

The transient wave activity was shown to be located principally in the Northern Hemisphere between 5 and 15N. The westward propagating wave activity exhibited wavelengths and periods consistent with classical easterly waves and Rossby-type waves. This indicates that the diabatic heating which may be responsible for the generation of those waves is transient in character. In contrast, there was no eastward propagating wave that could be related to stratospheric Kelvin waves. However, this does not rule out the possibility of a tropospheric heat source for the generation of these waves. The distribution of power in the equatorial region was consistent with Holton's (1973) results concerning the form of the required heating. There was no clear indication of standing waves in brightness that could be related to Kelvin waves.

In this study the variability of the cloudiness has been taken as representative of the latent heating distribution to be found in the tropics. However, the generation and organization of the cloud fields are themselves dependent on the disturbances. That the diabatic heating was found to be transient in the case of westward propagating waves is thus not surprising. Those waves are well developed in the tropical troposphere. It indicates the operation of a feedback mechanism, i.e., the disturbances organize the cloud fields which in turn help maintain the disturbances, such as in the CISK theories.

It is interesting to note that the lack of a specific wavelength and period that could be identified with Kelvin waves suggests that a similar mechanism does not operate for those waves. Kelvin waves are largely confined to the stratosphere.

Finally, it should be noted that examination of cloud brightness alone does not allow for a quantitative measure of the heating. Nevertheless, it is likely that these results are representative of the spectra of the latent heating.

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