Spectral Analysis of Tropical Disturbances Appearing in a GFDL General Circulation Model[1]

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ABSTRACT

A space-time cross spectrum analysis is applied to the 11-layer, 2.4° mesh GFDL general circulation model with seasonal variation, extending the work of Manabe *et al.* A statistical study is made of the model's tropical disturbances during the period July through October with respect to their wave characteristics, three-dimensional structure, energetics, and their role in the general circulation.

Four types of equatorial traveling waves are isolated from stationary waves and ultra-long waves extending from middle latitudes. They are identifiable with observed mixed Rossby-gravity waves (Yanai waves), Kelvin waves, equatorial Rossby-type waves, and easterly waves.

All these traveling waves are maintained primarily by the conversion of available potential energy generated by condensational heating. This heat is associated with traveling rainfall disturbances localized, in particular, in the western Pacific of the northern summer hemisphere where the sea surface is relatively warm.

1. Introduction

In recent years remarkable progress has been made both in the analysis and in the linear theory of tropical disturbances. However, little is known about the characteristics of tropical disturbances appearing in general circulation models despite their abundant output of data. All of these studies should go hand in hand toward a better understanding of the tropics.

This study is a comprehensive spectral analysis[3] of the tropical part of a GFDL general circulation model with seasonal variation (Manabe *et al.*, 1973), extending the work of Manabe *et al.* (1970b). The method and the preliminary results are described in Hayashi (1971e, 1973).

In the following we shall briefly review the observational and theoretical background relevant to the present study. For details the reader is referred to Yanai (1967, 1971), Yanai and Maruyama (1969), Syono and Yanai (1970), Wallace (1969, 1971, 1972b, 1973), Bates (1972), Krishnamurti (1972), Lindzen (1972b), and Holton (1972a). Among them, Yanai's review (1971) is the most comprehensive and relevant to the present paper.

It was the discovery of large-scale equatorial waves in the stratosphere over the Pacific by Yanai and Maruyama (1966) that renewed interest in the tropical atmosphere, where disturbances were observed only in the troposphere (Riehl, 1945, 1948b; Palmer, 1951; Yanai, 1963) and were believed to have weak coupling in the vertical according to the scale analysis of Charney [(1963); see Holton's comment (1969)]. These planetary-scale waves move westward with periods of about 5 days and wavenumber 4, tilting westward with height (Maruyama and Yanai, 1967). Maruyama (1967) further showed that they take the form of vortices centered over the equator and identified them as mixed Rossby-gravity waves which were discussed theoretically by Rosenthal (1965) and Matsuno (1966), independently. Yanai *et al.* (1968) established a quantitative analysis of tropical disturbances both in the troposphere and the stratosphere by a systematic application of time-series power spectra, extending the pioneering work of Rosenthal (1960a).

Maruyama (1968b) and Yanai and Hayashi (1969) further showed that the observed mixed Rossby-gravity waves carry both momentum and energy upward into the stratosphere. Nitta (1970c, 1972a) proved that these waves are associated with the energy conversion from available potential energy generated by tropospheric heating.

Their research was followed by that of Wallace and Kousky (1968a), who found another type of an equatorial stratospheric disturbance. It is characterized by the absence of meridional component and with a period

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[3] A similar spectral analysis is in progress at the National Center for Atmospheric Research, where the author first introduced his preliminary results informally while attending the GATE workshop on cumulus parameterization in July 1972.

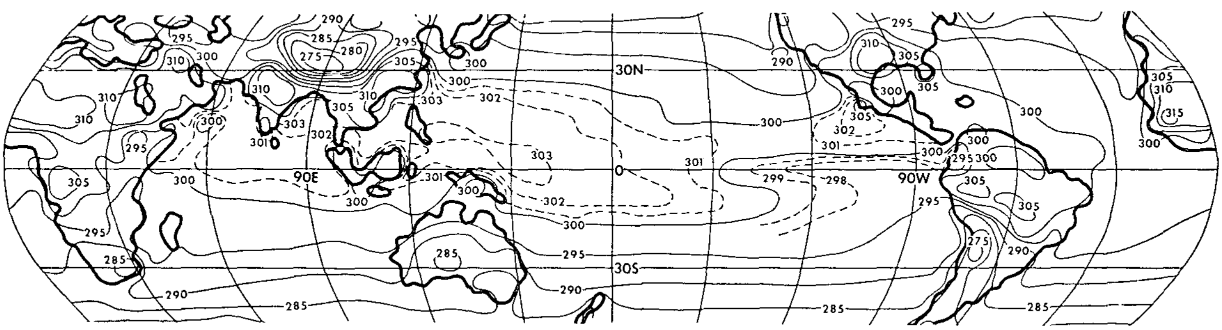

FIG. 1. Geographical distribution of the mean surface temperature during the period June through August in the model (after Manabe *et al.*, 1973). Ocean temperatures were adapted from the *World Atlas of Sea Surface Temperature* (Hydrographic Office, 1964).

of 15 days, and may correspond to the atmospheric Kelvin wave discussed theoretically by Matsuno (1966). They further suggested that this disturbance is likely to be associated with wavenumber 1 and move eastward with its phase lines tilting eastward with height. The wave also transports momentum and energy upward in the stratosphere (Wallace and Kousky, 1968b; Maruyama 1969).

Theoretically, Lindzen and Matsuno (1968) and Holton and Lindzen (1968) proved that the above stratospheric waves are consistent in terms of wavenumber and frequency with equatorial normal modes, which were discussed by Rosenthal (1965) and Matsuno (1966) and also by Lindzen (1967) and Longuet-Higgins (1968). They further interpreted these stratospheric waves with vertical tilt as forced from the troposphere. However, these wave theories do not explain how these waves are generated and selected among many possible wave modes.

Mak (1969) demonstrated by his two-layer theoretical model that tropical free oscillations with wavenumber 4 and a 5-day period are resonant to excitations by middle latitude disturbances. However, these internal free waves result from artificial rigid upper boundary condition (see Lindzen *et al.*, 1968). Moreover, his conclusion is contrary to the result of a general circulation model by Manabe and Smagorinsky (1967) who pointed out that a major energy source in the tropical troposphere is the latent heat release. In order to confirm this result, Manabe *et al.* (1970b) compared a moist and a dry model of general circulation and concluded that the kinetic energy of tropical disturbances is significantly enhanced by the convective heating parameterized by the moist convective adjustment. They also presented time sections which suggest the passage of mixed Rossby-gravity waves.

Meanwhile, Yamasaki (1969, 1971b) studied the instability of tropical disturbances by extending the linear theory (Syono and Yamasaki, 1966) of tropical cyclones based on the CISK parameterization. It was assumed that latent heat is released by cumulus convection in proportion to the low-level moisture convergence associated with large-scale traveling waves. He found four types of unstable disturbances corresponding to tropical cyclones, fast and slow moving easterly waves and stratospheric waves. Hayashi (1970, 1971a, b, d) re-examined the stratospheric wave mode by using a three-dimensional primitive equation model and demonstrated that mixed Rossby-gravity waves and Kelvin waves with observed wavenumbers and periods exist as unstable waves. He further showed that these waves strikingly resemble the observed waves in

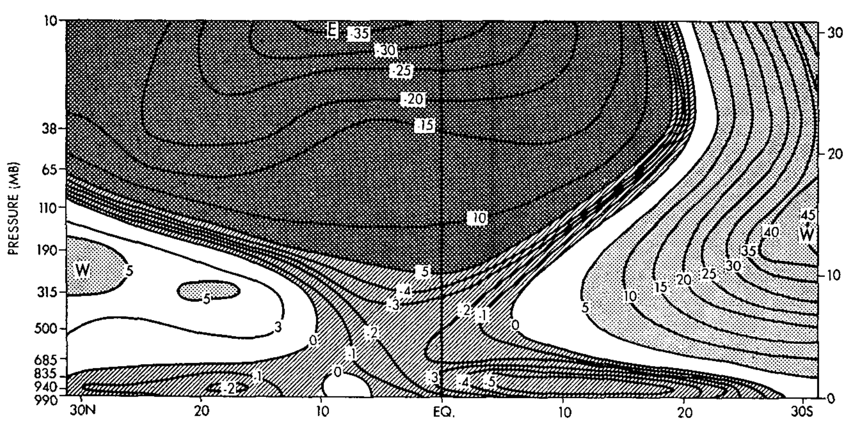

FIG. 2. Latitude-height section of the mean zonal wind during the period from July through October of the model atmosphere.

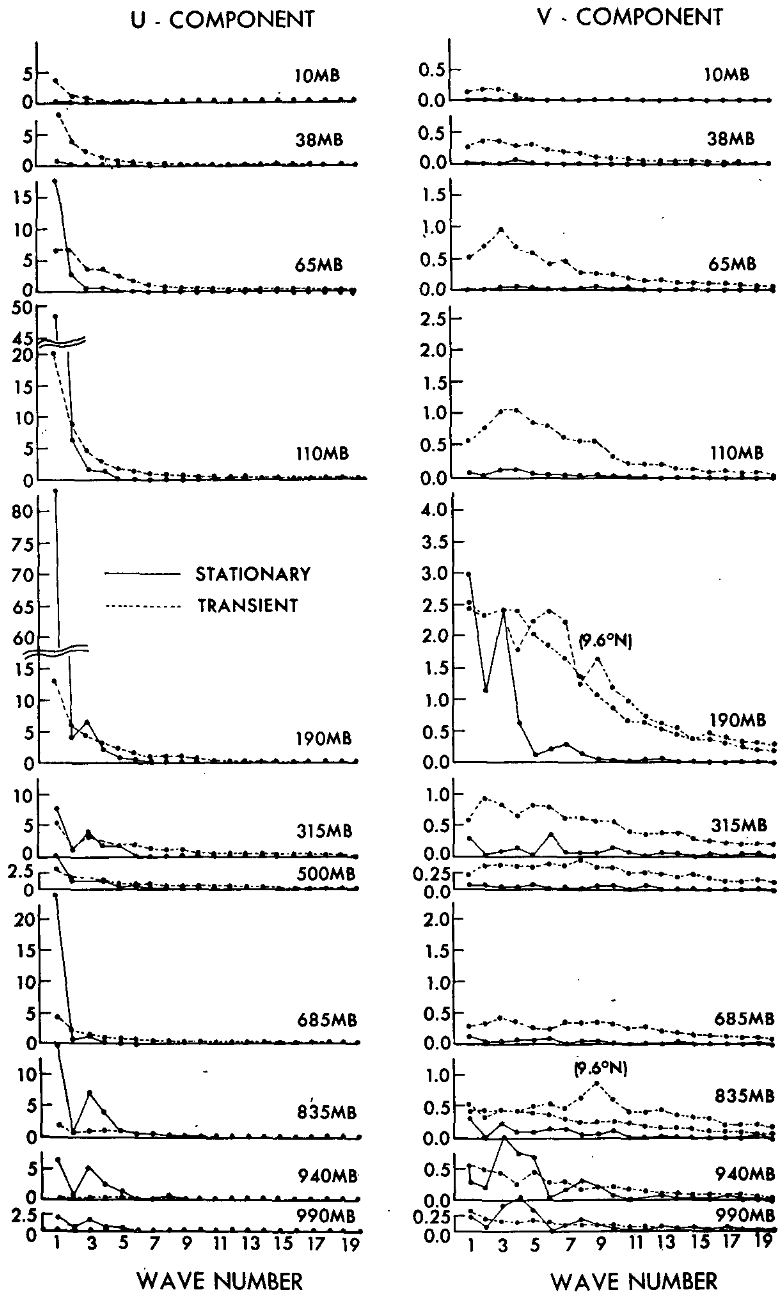

FIG. 3a. Wavenumber spectra ($m^2 sec^{-2}$) of zonal component (left) and meridional component (right) of wind at the equator. Full and dashed lines show variance spectra for stationary and transient waves, respectively. Spectral curves of the meridional component at 835 and 190 mb at 9.6N are shown in addition to those at equator.

three-dimensional structure. However, he encountered a serious difficulty in that gravity waves with periods of less than one day are most unstable and that mixed Rossby-gravity waves and Kelvin waves do not attain their maximum growth rate at the observed scales. Subsequently, T. Murakami (1972) showed that mixed Rossby-gravity waves attain their preferred scale at wavenumber 4 in a balance equation CISK model. However, this conclusion is misleading, since a balance approximation is not valid for mixed Rossby-gravity waves with wavenumbers lower than 4 which behave more like gravity waves and are highly divergent.

The effect of vertical shear on the structure and the vertical propagation of equatorial waves generated by

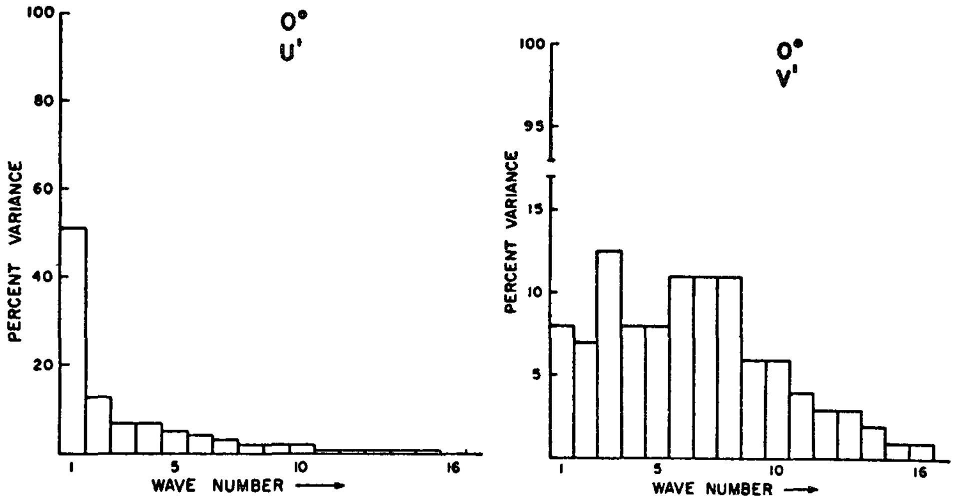

FIG. 3b. Observed wavenumber spectra of zonal component (left) and meridional component (right) of wind at the equator, during the period from June through August, 1967. No separation is made between stationary and transient components. (After Krishnamurti, 1971a.)

tropospheric heating was examined by Holton (1971) and Murakami (1972b,c) by externally imposing traveling heat waves.

Recently, Holton (1972b) demonstrated that both eastward and westward moving waves are excited in the troposphere by a localized tropospheric heat source pulsating with an imposed periodicity, while either eastward moving Kelvin waves or westward moving mixed Rossby-gravity waves with observed wavenumber are selected depending on the vertical shear as the waves propagate into the stratosphere. Holton (1973) further showed that a 10∼20 day spectral peak in tropospheric forcing is not required to account for the observed spectral distribution of stratospheric Kelvin waves, since the atmosphere acts as a bandpass filter. However, there is as yet no satisfactory theoretical explanation for the periodicity of mixed Rossby-gravity waves.

It will be of interest to examine the general circulation model with the convective adjustment in the light of the above observational and theoretical studies.

2. Brief description of the model

This global circulation model was constructed by Manabe and Holloway primarily to simulate the seasonal variation of climate by time integration of a system of prognostic equations; i.e., the equations of motion, the thermodynamical equations, the hydrologic equations for atmospheric water vapor, and the schemes for determining soil moisture and snow cover. The horizontal grid mesh is 2.4° with a vertical resolution of 11 layers to represent both the troposphere and the stratosphere. The finite-difference forms of the equations of motion are those developed by Kurihara and Holloway (1967) and modified by Holloway and Manabe (1971).

For the computation of radiative fluxes, the seasonal variation of solar radiation is given at the top of the atmosphere. However, its diurnal variation is not incorporated. The temperature at the ground is determined in such a way that it satisfies a condition of heat balance at the land surface. Over the sea, the seasonal variation of sea surface temperature is given as a lower boundary condition. The prognostic equations for the hydrologic cycle are highly simplified. It is assumed that condensation takes place whenever the relative humidity exceeds 100%. The macroscopic effect of moist convection is represented by the moist convective adjustment (Manabe *et al.*, 1965). This parameterization assumes that the moist convective process releases the heat of condensation if the air is saturated and transfers heat upward in such a way as to neutralize the lapse rate. For more detailed description of the model, see Manabe *et al.* (1973).

The mean surface temperature during the period June through August is presented in Fig. 1. Maximum sea surface temperature occurs north of the equator in the western Pacific, while a local minimum appears over the equator in the eastern Pacific. It is well known that the sea surface temperature is an important factor for the formation of tropical cyclones (Palmén, 1948) and the Walker circulation (Bjerknes, 1969). Manabe *et al.* (1973) demonstrated by a general circulation model that it is also a crucial factor for determining the location of the ITCZ (intertropical convergence zone) as suggested numerically by Pike (1971a, 1972). The present paper will prove that it is also important in the generation of stratospheric waves.

Since travelling waves are sensitive to the basic flow with respect to their phase velocity and structure (Lindzen, 1970a, 1971, 1972a; Holton, 1970, 1971,

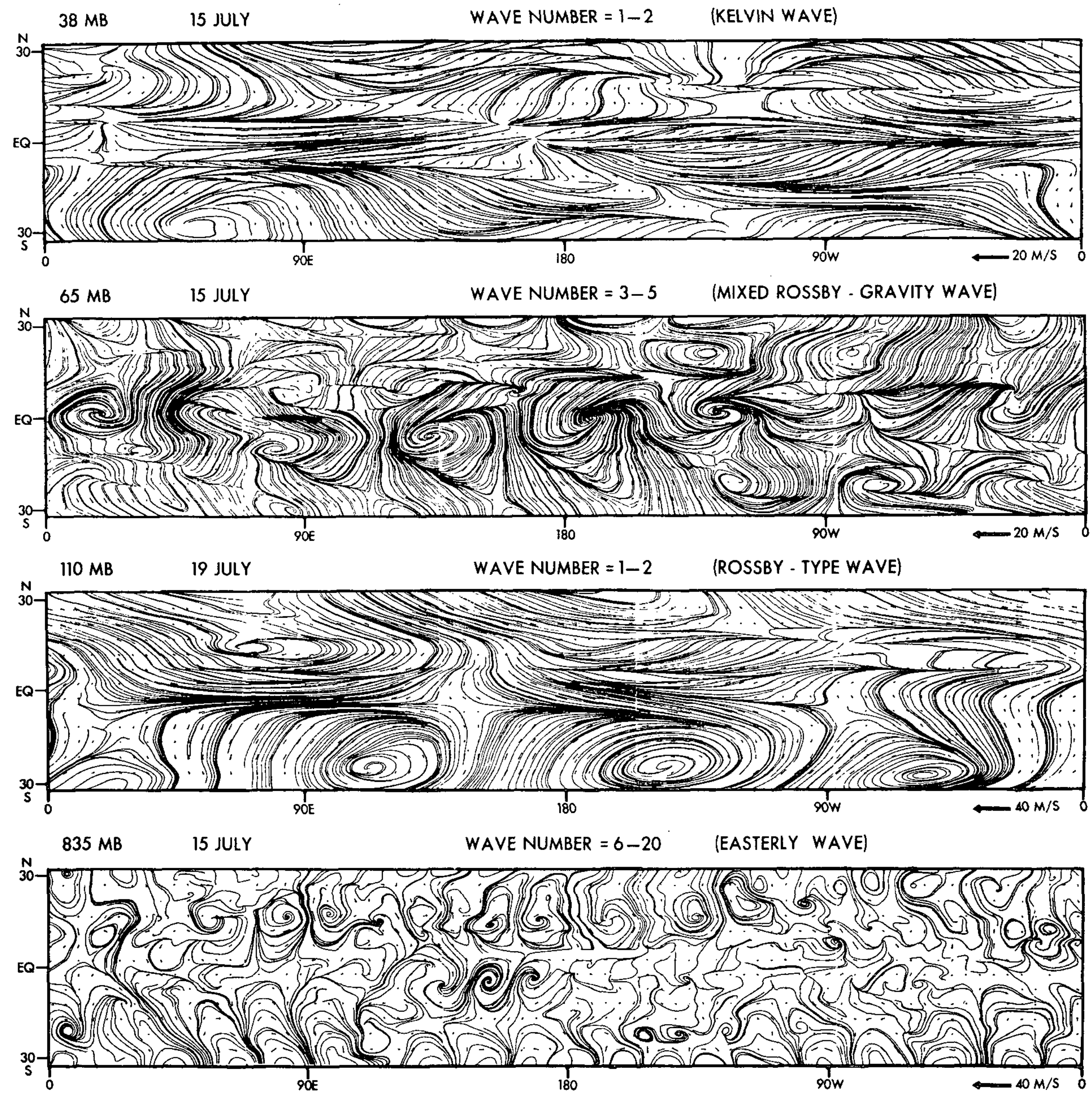

FIG. 4a. Streamlines and wind vectors composed of characteristic wavenumbers appearing at 38, 65 and 835 mb on 15 July and at 110 mb on 19 July. Four-month mean is subtracted out.

1972b; T. Murakami, 1972c), the basic wind field of the model atmosphere is presented in Fig. 2. This figure shows a latitude-height section of the mean zonal wind during the period from July through October of the model atmosphere, demonstrating that easterlies are prevailing throughout all levels over the equator. This mean zonal wind is in good agreement with the seven-year seasonal average of observed winds by Newell *et al.* (1970), except that the easterlies at the top level are too strong [see Manabe *et al.* (1973) for comparison with observation].

The output data used for the wave analysis are the daily time-series during the period July through October. The wind data have been averaged daily before the spectra are computed. However, for the other variables only instantaneous values were stored. The heating and vertical velocity, which contain a high-frequency noise associated with abrupt convective adjustment, may be significantly affected by an aliasing error, if instantaneous daily values are used. In order to assess this error, a comparison was made between the vertically integrated instantaneous condensational heating and the daily accumulation of precipitation which is rather free from high-frequency

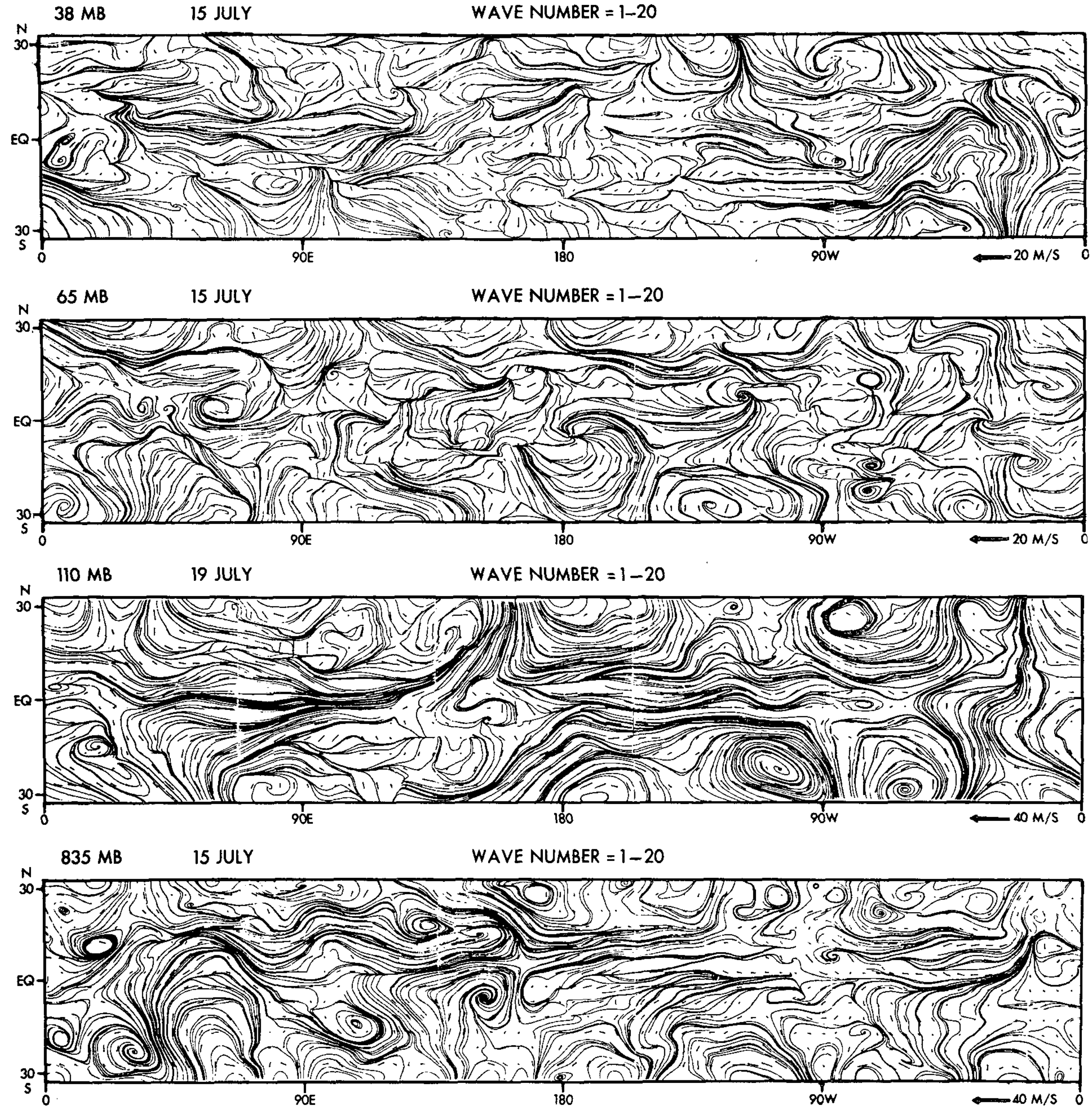

FIG. 4b. Streamlines and wind vectors composed of wavenumbers 1∼20. No time mean is subtracted out.

noise. It is found that the power spectra of heating and vertical velocity are overestimated, especially for periods of less than 5 days. However, the spectral peaks occur at the right frequencies.

3. Classification of tropical waves

a. Wavenumber analysis

The first point of interest is what scale of stationary and transient waves are typical of the model tropical atmosphere. Fig. 3a shows wavenumber spectra of stationary and transient waves at various levels over the equator. The zonal component (left) with lower wavenumbers has much more variance than the meridional component (right). (Note the difference in the scale of the variance.) In the troposphere stationary waves are predominant at wavenumber 1 with a secondary maximum at wavenumber 3. For these wavenumbers stationary waves are much stronger than transient waves with respect to both the zonal and the meridional component. However, for higher wavenumbers the reverse is true. According to Manabe

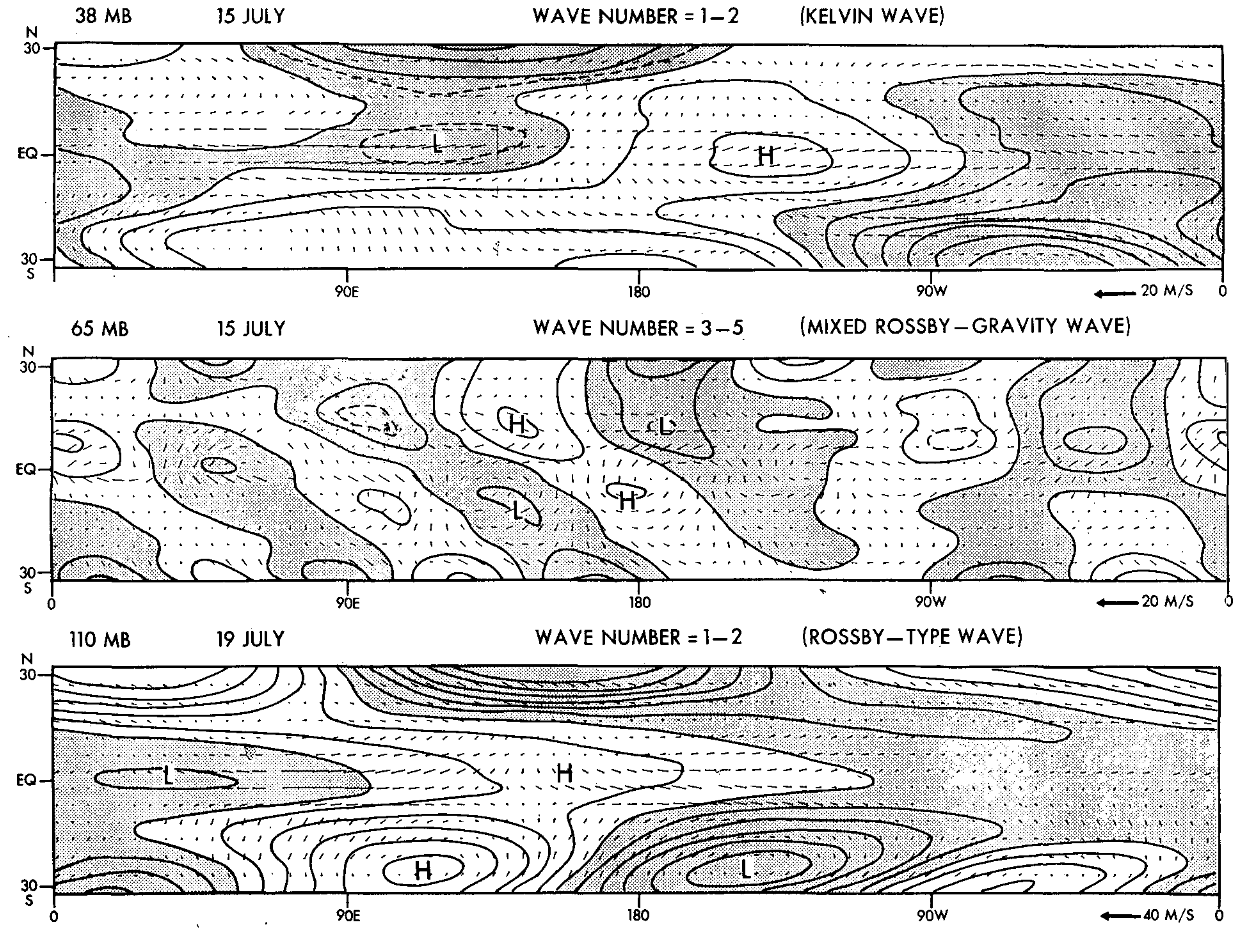

FIG. 4c. Geopotential height contour (interval 10 m) with wind vectors composed of characteristic wavenumbers. Four-month mean is subtracted out.

et al. (1974), the kinetic energy of the model stationary eddies are comparable[4] to that of the transient eddies except for the summer season in which stationary eddies are especially strong over the equator.

The wavenumber spectra at 190 mb resemble the observed wavenumber spectra at 200 mb by Krishnamurti (1971a) shown in Fig. 3b. At this level (190 mb), stationary waves attain their maximum variance. Time-mean streamlines (see Manabe *et al.*, 1973) suggest that they are related to the Indian monsoon and the Walker circulation in the Pacific.

For the transient waves at 38 mb there is a spectral peak at wavenumber 1 in the zonal component. It will be shown later that this peak is a manifestation of Kelvin waves. For the zonal component at 110 mb, a spectral peak at wavenumber 1 is also found. It will be seen that this peak is associated with equatorial Rossby-type waves. For the meridional component at 110 mb a spectral peak around wavenumber 4 occurs, which is a reflection of mixed Rossby-gravity waves. For the meridional components at 835 and 190 mb a peak at wavenumber 9 is observed at 9.6N rather than over the equator. It will be shown that this peak is associated with easterly waves.

Visualization is made of the four types of transient waves represented by these spectral peaks. Fig. 4a shows streamlines and wind vectors composed of several wavenumbers characteristic of the four types of transient waves appearing on a particular day. At 38 mb near the equator, streamlines are seen running parallel to the equator. This wave pattern resembles that of Kelvin waves described theoretically by Matsuno (1966). At 65 mb, vortices are found centered over the equator. This wave pattern resembles that of mixed Rossby-gravity waves described theoretically by Rosenthal (1965) and Matsuno (1966) and synoptically by Maruyama (1967) and Yanai and Hayashi (1969). At 110 mb, vortices can be seen centered off the equator. This wave pattern resembles that of equatorial Rossby-type waves described theoretically by Matsuno (1966)

[4] According to Oort and Rasmusson (1971), tropical stationary eddies are much weaker than transient eddies both for the zonal and the meridional component. This discrepancy seems to result partly from lack of observations in the eastern Pacific where the Walker circulation is prevailing.

and Koss (1967); synoptically by Riehl (1948b, 1954), Yanai (1963) and Yanai and Hayashi (1969); and statistically by Yanai and Murakami (1970b) and Nitta (1972b). At 835 mb are synoptic-scale vortices mostly centered off the equator. They may correspond to easterly waves observed by Riehl (1945, 1948a, 1954, 1967) in the Caribbean and Palmer (1951, 1952) in the Pacific, and discussed theoretically by Rosenthal (1960b).

It will be interesting to see how these waves look in the original wind fields with only the basic flow subtracted out. Fig. 4b shows the streamlines composed of wavenumbers 1~20, illustrating that the model tropical disturbances are a mixture of several wave modes and look rather chaotic without filtering. At 835 mb, westerlies are prevailing in the Eastern Hemisphere and easterlies are prevailing in the Western Hemisphere. Superimposed upon these stationary flows are synoptic-scale easterly waves.

Fig. 4c shows wavenumber-filtered geopotential height contours with wind vectors. At the 38-mb level a typical pattern of Kelvin waves is seen with their winds blowing across the height contours centered over the equator. At 65 mb we find a typical pattern of mixed Rossby-gravity waves with their winds blowing across the height contours centered off the equator. A typical pattern of Rossby-type waves is seen at 110 mb with their winds blowing along the height contours centered off the equator. The high and low over the equator at 110 mb are again due to Kelvin waves which attain their maximum geopotential height over the equator.

b. Frequency analysis

Since most of the statistical studies of tropical disturbances are based upon time-series power spectrum analysis, a direct comparison of the model with observation requires the same technique.[5] Figs. 5a and 5b are frequency-height sections of power spectra of winds of the model and observation, respectively. It should be noted that they are strikingly similar in the following points. The meridional winds exhibit spectral peaks of comparable magnitude around a 4-day period in the stratosphere, corresponding to mixed-Rossby gravity waves. Also, the power spectra are similar around a 15-day period both in zonal and meridional components. Later they will be interpreted as a mixture of eastward moving Kelvin waves and westward moving equatorial Rossby-type waves together with ultra-long waves extending from middle latitudes. Around the 20-km level the computed power spectra of the zonal wind is too large compared with the observation. This discrepancy may be explained as follows. The period of the observation (April–July, 1962) is the year in which westerlies lie below easterlies and Kelvin waves are supposed to be weak (Wallace and Kousky, 1968b; Maruyama, 1969; Kousky and Wallace, 1971; Angell *et al.*, 1973); the model, however, has easterlies throughout the levels and Kelvin waves are free to penetrate into the stratosphere.

[5] The space-time power spectra (Fig. 6) are one order of magnitude smaller than the local time-power spectra (Fig. 5a), since the former is one of the wavenumber components of the longitudinal average of the latter which are small (see Fig. 15) in some longitudes.

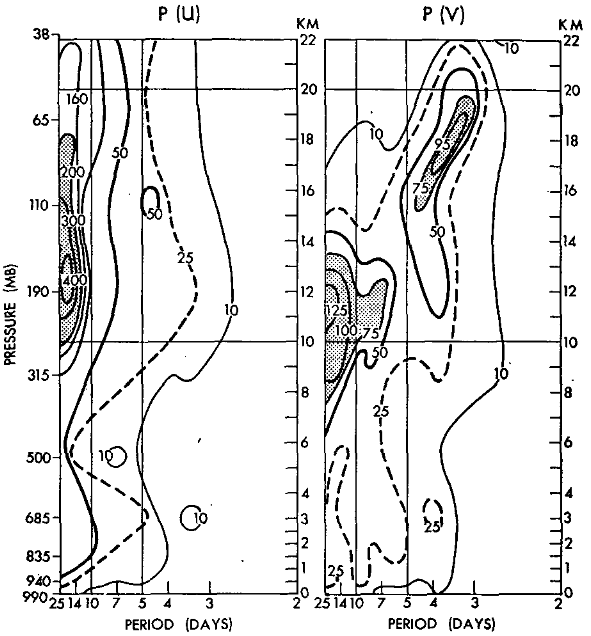

FIG. 5a. Frequency-height section of time-power spectra ($m^2\ sec^{-2}$) per unit frequency (day^{-1}) of zonal component (left) and meridional component (right) of the model atmosphere at 180° longitude over the equator, for July through October.

c. Wavenumber-frequency analysis

Abundant output data both in time and space make it possible to make an extensive application of a wavenumber-frequency analysis which resolves disturbances into progressive and retrogressive waves. The Appendix gives formulas (Hayashi, 1971e, 1973) for computing space-time cross spectra through conventional time-series cross spectra. In the present paper a 30-day lag correlation with a lag window (see Blackman and Tukey, 1958) was used to compute time-series cross spectra. [Note that these time spectra may also be computed by the direct Fourier method with a spectral window.] Prior to spectral analysis, only the time mean was subtracted out; a high-pass filter (see Holloway, 1958) was not applied.

Fig. 6a shows space-time power spectra of the zonal wind at 38 mb over the equator. Frequency spectra are plotted for each wavenumber. We find that the peak

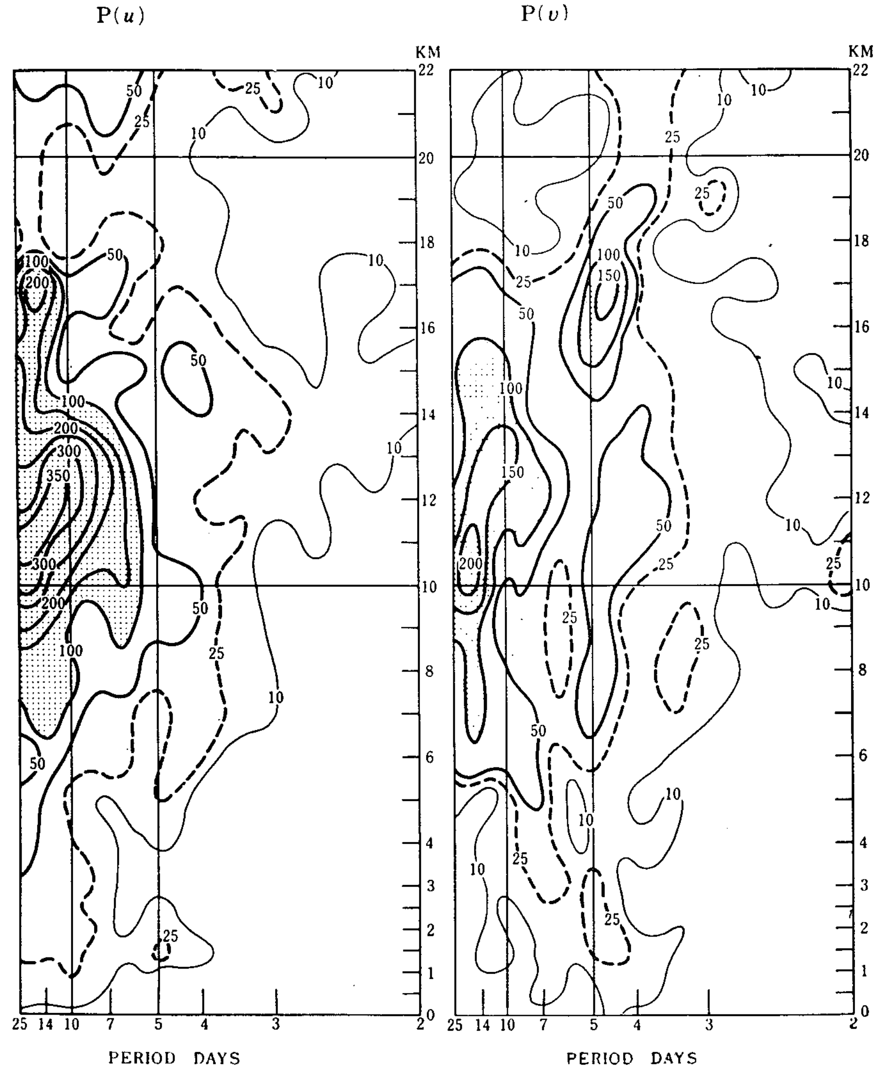

FIG. 5b. As in Fig. 5a except for observations at Canton Island (02°46′S, 171°43′W) during the period April through July, 1962 (after Yanai and Murakami, 1970a).

of wavenumber 1 described in the previous section is associated with waves moving eastward with a period of 15 days in agreement with Kelvin waves observed by Wallace and Kousky (1968a). Wavenumber 1 has also a westward moving component with 30-day period. This is associated with westward moving stratospheric ultra-long waves extending from middle latitude as will be seen in Fig. 11b in Section 4.

Fig. 6b shows the same diagram at 110 mb. It is seen that the peak of wavenumber 1 at this level is associated with waves moving westward with periods of 15 days corresponding to Rossby-type waves. They are identifiable with the large-scale westward moving waves with periods of 10∼20 days observed by Wallace and Chang (1969), Yanai and Murakami (1970b) and Nitta (1972b).

Fig. 6c shows the space-time power spectra of meridional winds at 110 mb over the equator. The peak of wavenumber 4 found at this level is associated with westward moving waves with periods of about 4 days, exactly in agreement with mixed Rossby-gravity waves analyzed by Yanai *et al.* (1968). These waves appeared in the former moist model of Manabe *et al.* (1970b). Fig. 6c also reveals a secondary peak for wavenumber 3 and periods of 20 days (eastward moving). This is associated with eastward moving tropospheric ultra-long waves extending from the Southern Hemisphere. This peak may correspond to the meridional wind with wavenumber 3 which appeared in a dry model of Manabe *et al.* (1970b).

Fig. 6d shows space-time power spectra of the meridional wind at 835 mb at 9.6N. It is found that the

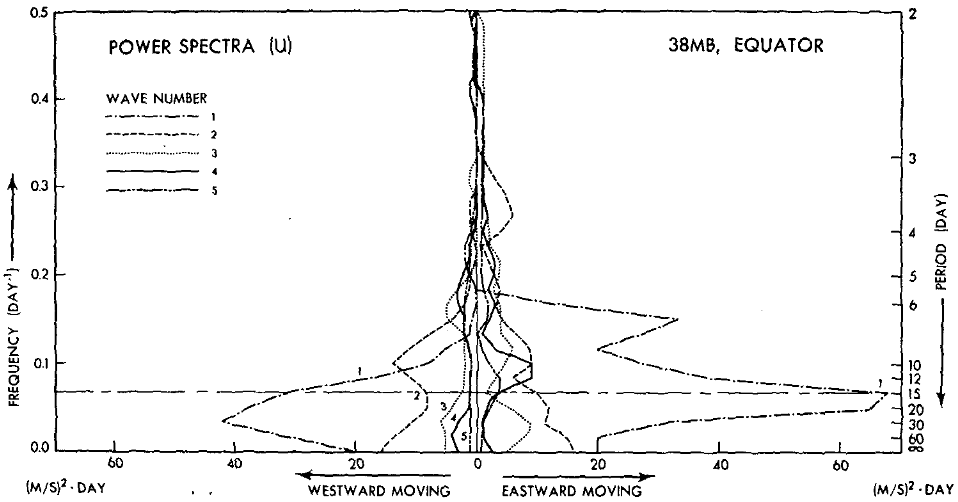

Fig. 6a. Space-time power spectra of zonal wind at 38 mb over the equator from July through October. Power spectra per unit frequency (day^{-1}) are shown by each wavenumber-line. Left- and right-hand side curves distinguish between westward and eastward moving waves, respectively. The peak for wavenumber 1 and period of 15 days (eastward moving) corresponds to Kelvin waves.

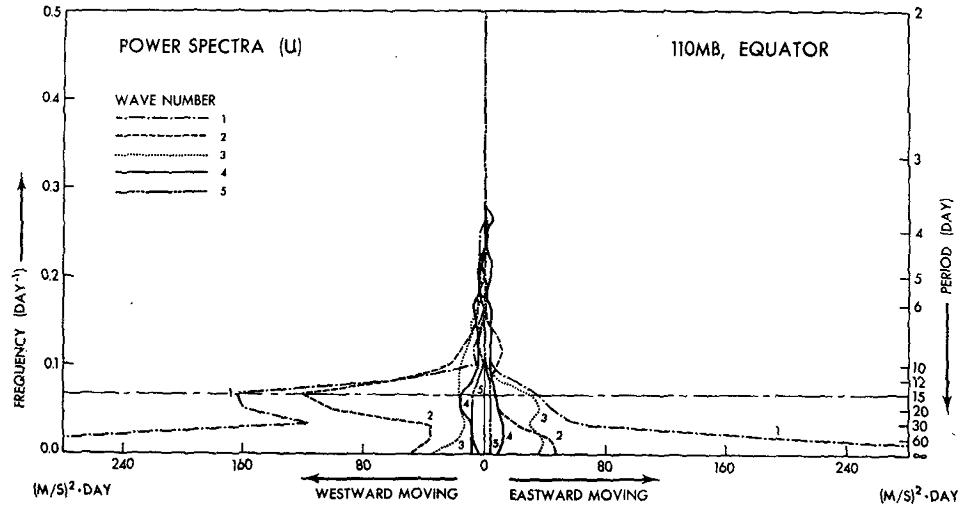

Fig. 6b. As in Fig. 6a except for 110 mb. The peak for wavenumber 1 and a period of 15 days (westward moving) corresponds to equatorial Rossby-type waves.

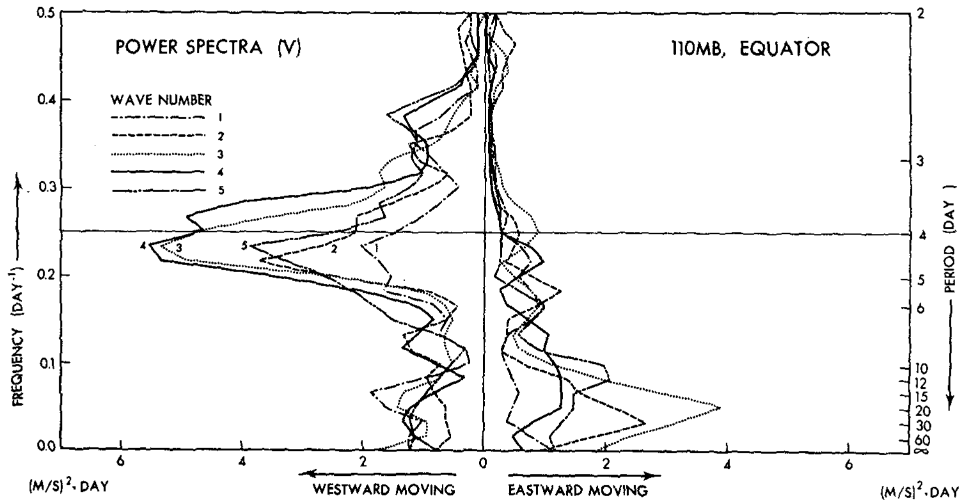

Fig. 6c. As in Fig. 6a except for the meridional component at level 110 mb. The peak for wavenumber 4 and period 4 days (westward moving) corresponds to mixed Rossby-gravity waves.

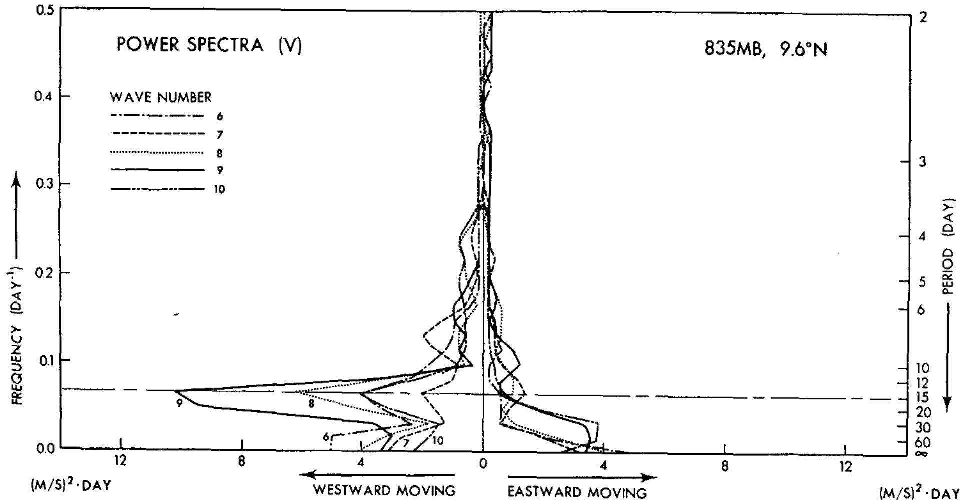

FIG. 6d. As in Fig. 6a except for the meridional component at level 835 mb at 9.6N.

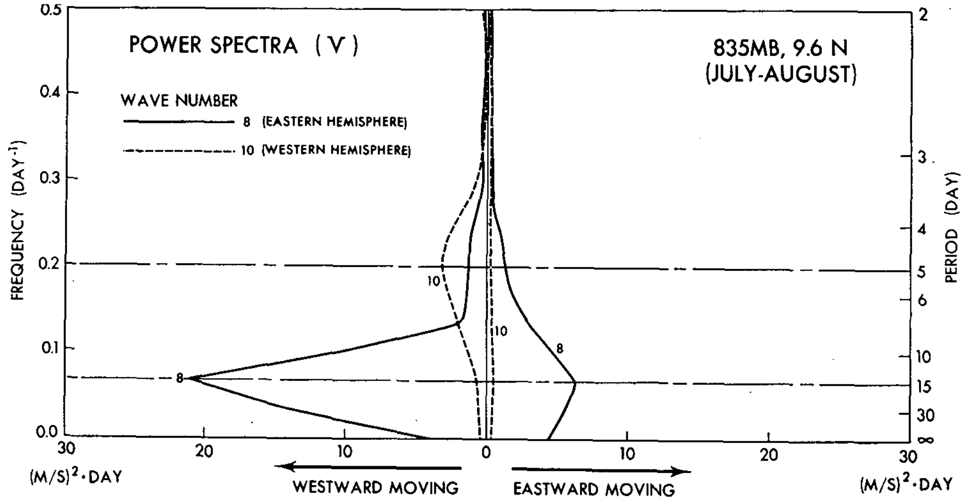

FIG. 6e. As in Fig. 6d except that space-time power spectra are computed in the Eastern (full lines) and Western (dashed lines) Hemispheres, separately. Two-month data are used for technical convenience. The peak for wavenumber 8, period 15 days (westward moving) corresponds to easterly waves in the westerly region (Eastern Hemisphere). The peak for wavenumber 10, period 5 days (westward moving) corresponds to easterly waves in the easterly region (Western Hemisphere).

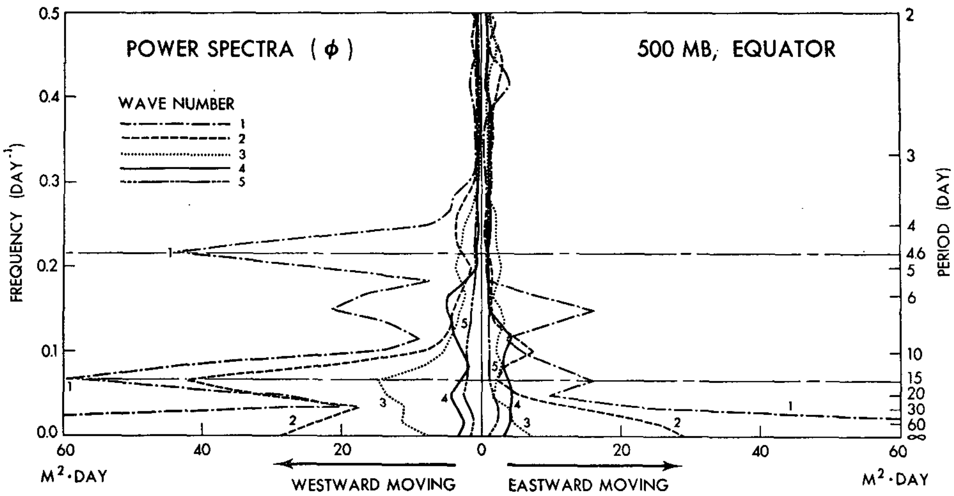

FIG. 6f. As in Fig. 6a except for geopotential height at 500 mb. The peak for wavenumber 1, period 4.6 days (westward moving) corresponds to the observed pressure waves.

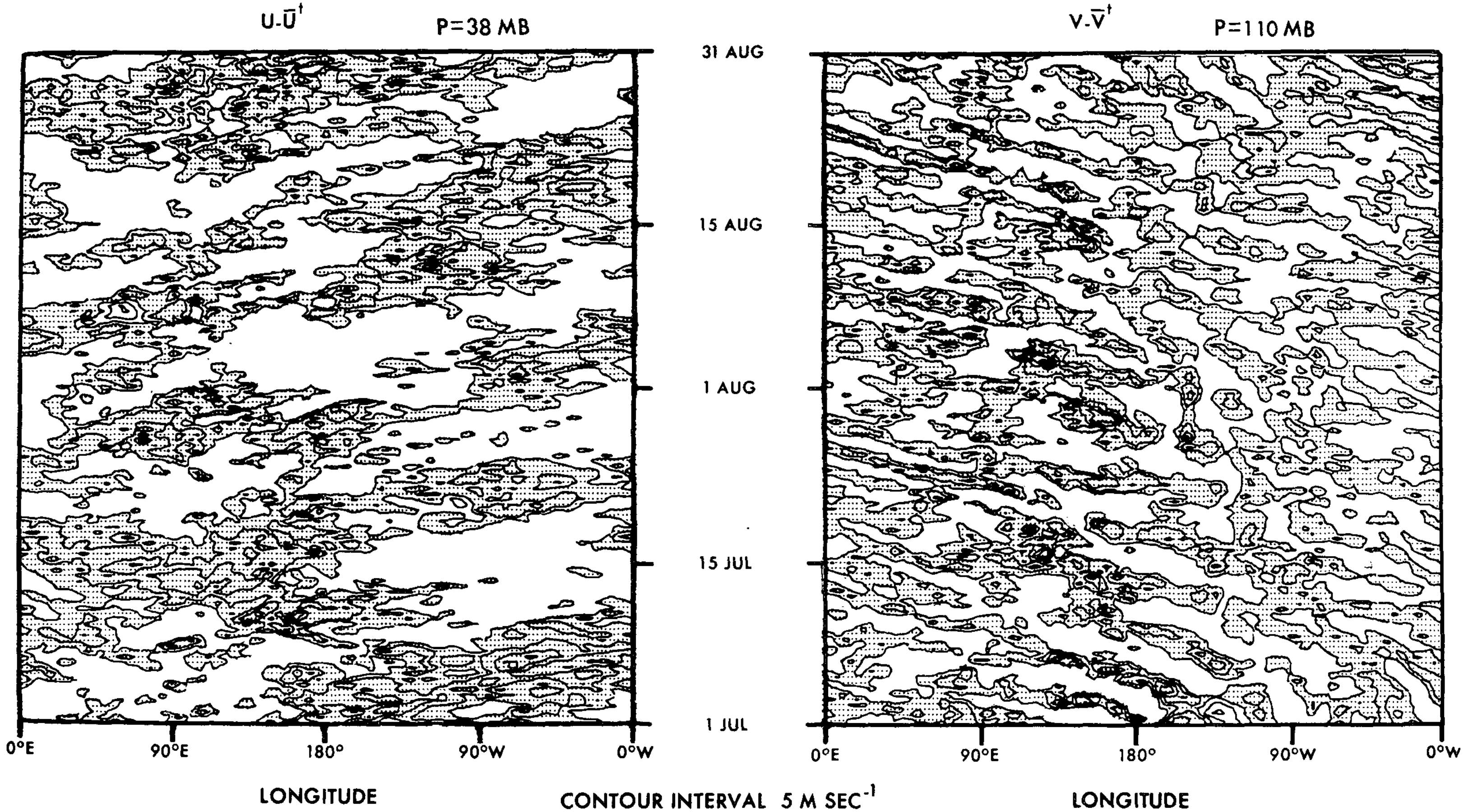

Fig. 7a. Longitude-time sections of zonal wind at 38 mb over the equator (left) and of meridional wind at 110 mb over the equator (right). Two-month mean is subtracted out. Contours are drawn only for negative areas (shaded). Left- and right-hand side time sections show the passage of Kelvin waves and mixed Rossby-gravity waves, respectively.

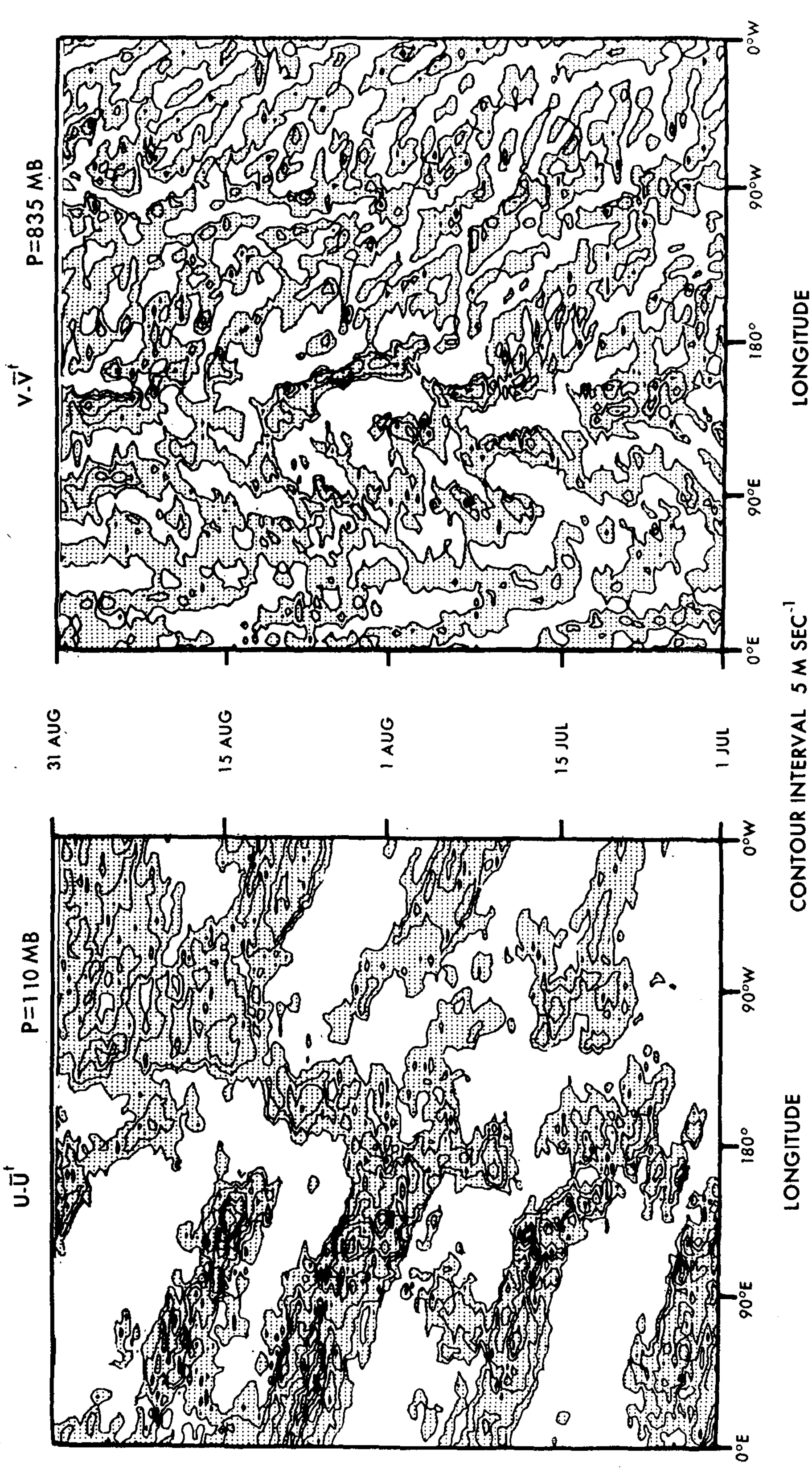

FIG. 7b. As in Fig. 7a except for zonal wind at 110 mb over the equator (left) and of meridional wind at 835 mb at 9.6N (right). Left- and right-hand side time-sections show the passage of Rossby-type waves and easterly waves, respectively.

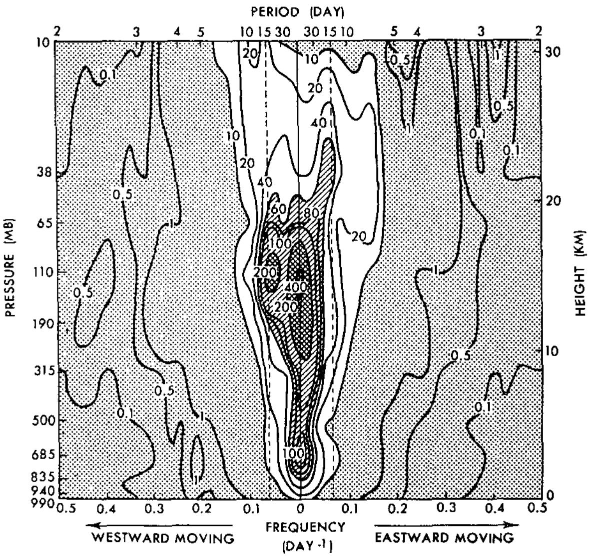

FIG. 8a. Frequency-height section of space-time power spectra of zonal wind at equator. Power spectra ($m^2 sec^{-2}$) per unit frequency (day^{-1}) are integrated over wavenumbers of 1∼2. Two maxima around 15-day period (westward and eastward moving) correspond to Rossby-type waves and Kelvin waves, respectively.

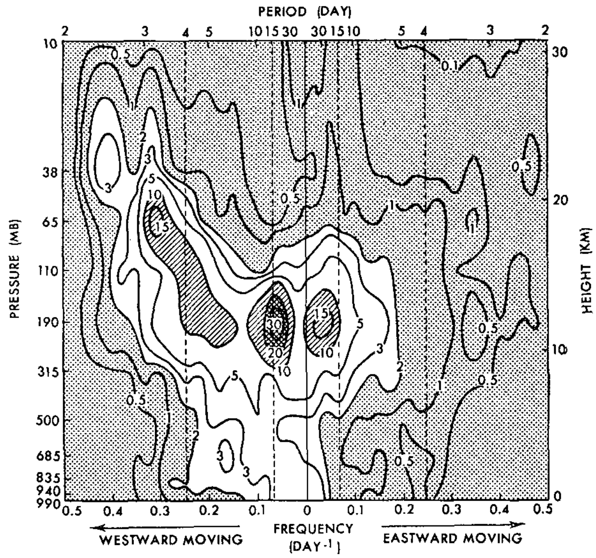

FIG. 8b. As in Fig. 8a except for meridional component. Power spectra are integrated over wavenumbers 3∼5. Maximum around 4-day period corresponds to mixed Rossby-gravity waves.

peak of wavenumber 9 is associated with westward moving waves with periods of 15 days. This period is, however, too long compared with the observed easterly waves which are usually associated with periods of 3∼6 days. This discrepancy may be due to the fact that the periodicity of travelling waves with higher wavenumber is very sensitive to the Doppler shift of the basic flow. In order to examine this possibility, Fig. 6e separates a region of westerlies (Eastern Hemisphere) from a region of easterlies (Western Hemisphere) as seen in the streamlines at 835 mb in Fig. 4b. Observationally, however, easterlies extend further westward into the western Pacific (see Yanai *et al.*, 1968). In the model, the easterlies are blocked by stationary typhoon-like eddies which are generated too frequently in the western Pacific. Fig. 6e shows that the waves prevailing in the Eastern Hemisphere are those of wavenumber 8 moving westward with periods of 15 days. On the other hand, waves prevailing in the Western Hemisphere are those of wavenumber 10, moving westward with periods of 5 days in agreement with observations. The amplitude of the former is much larger than the latter. This suggests that the model easterly waves intensify as they move toward the west. The regional variation of the period of easterly waves rules out the speculation by Holton (1972b) and Wallace (1972b) that mixed Rossby-gravity waves with 4-day periods may be excited by easterly waves with 4-day periods.

In addition to the four types of equatorial waves shown above, there is also evidence of 5-day pressure waves. These waves were first observed by Eliasen and Machenhauer (1965) and Deland and Lin (1967) in middle latitudes and by Wallace and Chang (1969), Misra (1972) and Madden and Julian (1972, 1973) in the tropics. They are classified as a non-divergent barotropic wave type discussed by Haurwitz (1940). Fig. 6f shows space-time power spectra of geopotential height at 500 mb with a spectral peak at wavenumber 1 and a period of 4.6 days (westward moving) in addition to the 15-day peak associated with Rossby type waves. In the present paper, however, no further description of these pressure waves will be given.

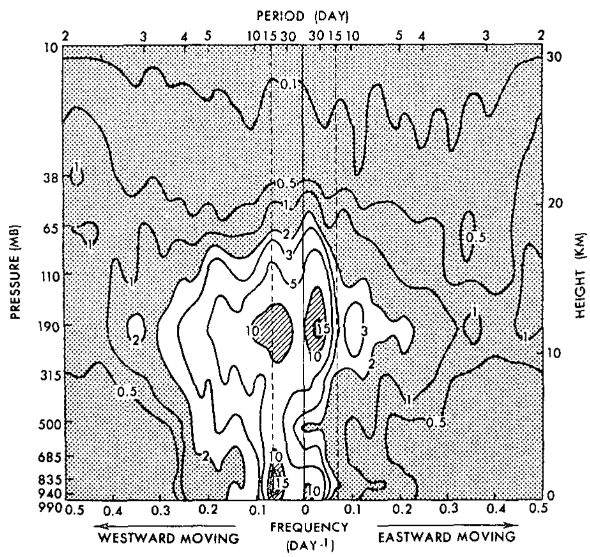

FIG. 8c. As in Fig. 8a except for meridional component at 9.6N. Power spectra are integrated over wavenumbers of 8∼10. Maximum at 15-day period corresponds to easterly waves.

The longitudinal propagation and the local intensity of the four types of waves are visualized by longitude-time sections (Figs. 7a, b). The regional variation of local amplitude will be discussed in Section 4.

It is of interest now to see how the periodicity of these waves varies with height. Fig. 8a is a frequency-height section of space-time power spectra of the zonal wind at the equator integrated over wavenumbers 1 and 2. A peak at a 15-day period for eastward moving Kelvin waves is clearly seen in the stratosphere but not in the troposphere. This suggests that these disturbances are filtered as they penetrate into the stratosphere as theoretically demonstrated by Holton (1973) for Kelvin waves. Around 110 mb, westward moving equatorial Rossby-type waves can be detected. In the lower troposphere westward moving waves have distinct 15-day periods in northern latitudes (not shown by Fig. 8a at the equator) and are dominant over eastward moving waves with the same periods (see Figs. 11a, b). This means that the tropospheric waves with wavenumbers 1 and 2 are not standing wave oscillations as Holton (1972b) assumed. Above 38 mb, westward moving waves at periods of 15~30 days are an extention of stratospheric ultra-long waves in the Southern Hemisphere (see Fig. 11b in Section 4).

Fig. 8b shows space-time power spectra of the meridional component at the equator integrated over wavenumbers 3~5. In the stratosphere a spectral peak is observed around a 4-day period for westward moving mixed Rossby-gravity waves. Although their spectral peak is rather vague in the lower troposphere, it clearly indicates a westward phase velocity and becomes sharper and shifts from a 5-day to a 3-day period and also from wavenumber 5 to 3 as it penetrates into the stratosphere. This is not quite in agreement with Holton's (1972b) model in which mixed Rossby-gravity

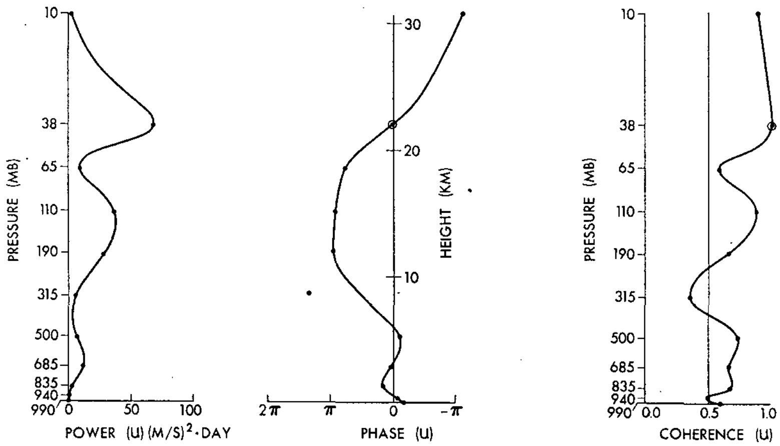

FIG. 9a. Vertical structure of Kelvin waves (zonal component at equator) with wavenumber 1 and period 15 days (eastward moving). Vertical profiles of power spectra (left), vertical phase difference (middle), and vertical coherence (right), with respect to the reference level indicated by circles.

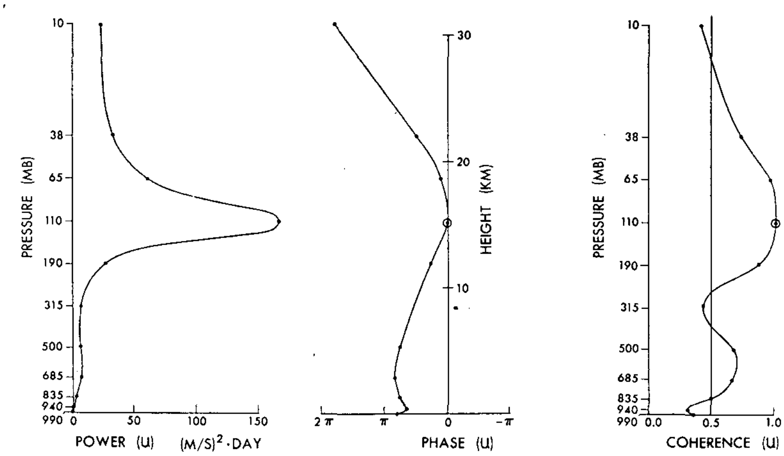

FIG. 9b. As in Fig. 9a except for Rossby-type waves (meridional component at equator) with wavenumber 1 and period 15 days (westward moving).

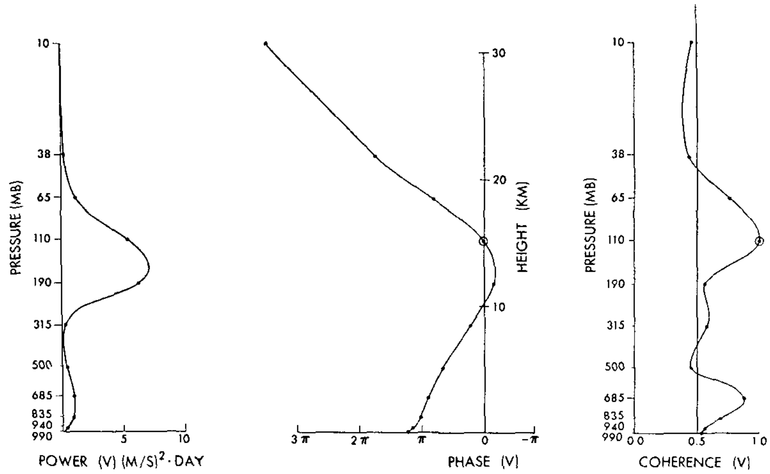

FIG. 9c. As in Fig. 9a except for mixed Rossby-gravity waves (meridional component at equator) with wavenumber 4 and period 4.3 days (westward moving).

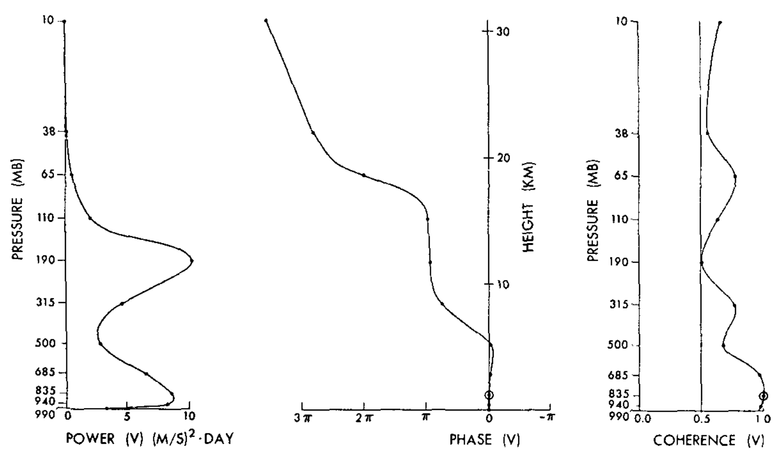

FIG. 9d. As in Fig. 9a except for easterly waves (meridional component at 12N) with wavenumber 9 and period 15 days (westward moving).

waves have a dominant wavenumber 1 in the troposphere and wavenumber 3 in the stratosphere. At about 190 mb, two maxima are found at periods of 15 days (westward moving) and 30 days (eastward moving). The former is a reflection of westward moving equatorial Rossby-type waves, while the latter is an extension of tropospheric ultra-long waves in the Southern Hemisphere.

Fig. 8c shows space-time power spectra of the meridional component at 9.6N integrated over wavenumbers 8~10. Two maxima of 15-day period (westward moving) are found both in the lower and the upper troposphere, corresponding to easterly waves travelling especially in the westerly flow region. In addition, 30-day period maxima (eastward moving) are seen at 190 and 940 mb. This is an extension of the subtropical, eastward moving synoptic-scale waves.

The vertical structure of these four types of waves will now be investigated. Fig. 9a shows that eastward moving Kelvin waves tilt eastward with height in the stratosphere and westward in the troposphere, while the reverse is true for westward moving Rossby-type waves (Fig. 9b) and mixed Rossby-gravity waves (Fig. 9c).

Mixed Rossby-gravity waves have a short vertical wavelength (8 km) in the stratosphere and a rather long vertical wavelength (15 km) in the troposphere. This agrees with observations (Yanai *et al.*, 1968) and the CISK model (Hayashi, 1970) but not with Holton's (1972b) model in which mixed Rossby-gravity waves have a very short vertical wavelength (3 km) in the troposphere. Kelvin waves in the stratosphere have a somewhat larger vertical wavelength (15 km) than that observed (6~10 km) by Wallace and Kousky (1968a, b). However, much higher vertical resolution is required to simulate the vertical structure correctly. The vertical tilt of phase lines indicates a vertical propagation of wave energy (Lindzen and Matsuno, 1968; Yanai and Hayashi, 1969).

The vertical structure of Rossby-type waves resembles a diagnostic model of large-scale tropospheric waves induced by diabatic heat sources (T. Murakami, 1972b), which have a large wave amplitude in the upper troposphere and a rather large vertical wavelength.

In contrast to the above three waves, easterly waves (Fig. 9d) show only a slight eastward tilt in the lower troposphere in agreement with observations (Yanai and Nitta, 1967; Yanai, 1968; Wallace and Chang, 1969; Nitta, 1970a; Chang *et al.*, 1970; Reed and Recker, 1971) and also with the CISK models (Yamasaki, 1969, 1971b; T. Murakami, 1972) and a diagnostic model (Holton, 1971).

It is interesting that all of these waves in the lower troposphere show rather high coherence with respect to the reference levels in the upper troposphere, in agreement with the analysis by Yanai *et al.* (1968). This suggests the waves are well coupled in the vertical.

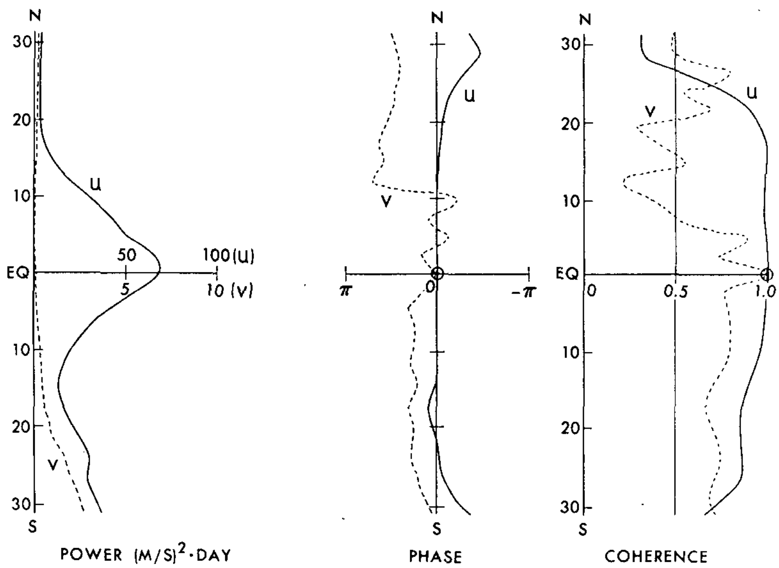

FIG. 10a. Horizontal structure of Kelvin waves (zonal component, 38 mb) with wavenumber 1 and period 15 days (eastward moving). Meridional profiles of power spectra (left), meridional phase difference (middle), and meridional coherence (right) with respect to the reference latitude indicated by circles.

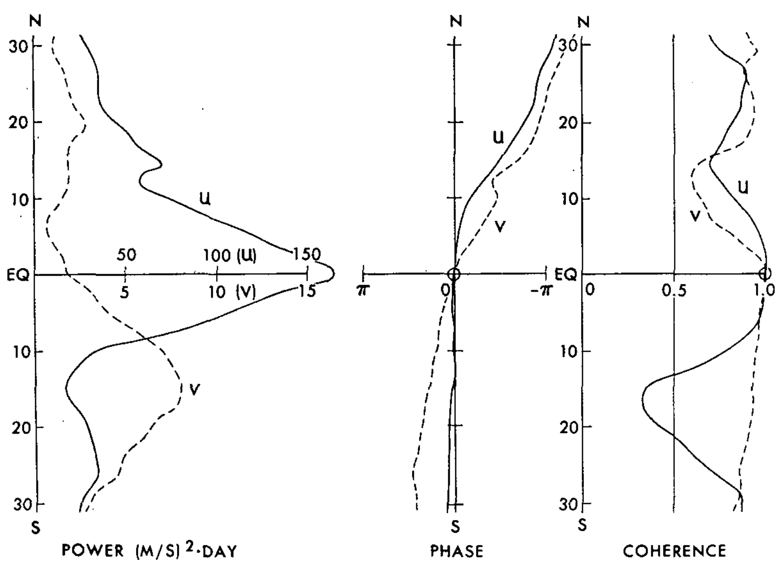

FIG. 10b. As in Fig. 10a except for Rossby-type waves (zonal component at 110 mb) with wavenumber 1 and period 15 days (westward moving).

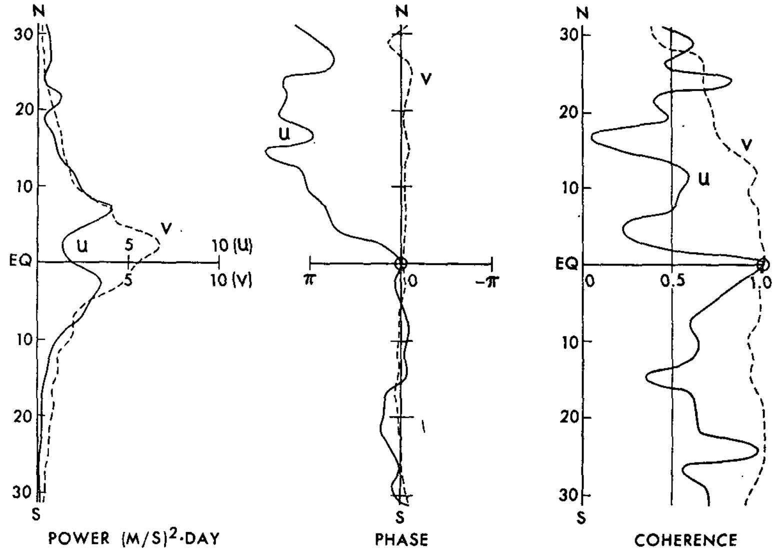

FIG. 10c. As in Fig. 10a except for mixed Rossby-gravity waves (v-component at 110 mb) with wavenumber 4 and period 4.3 days (westward moving).

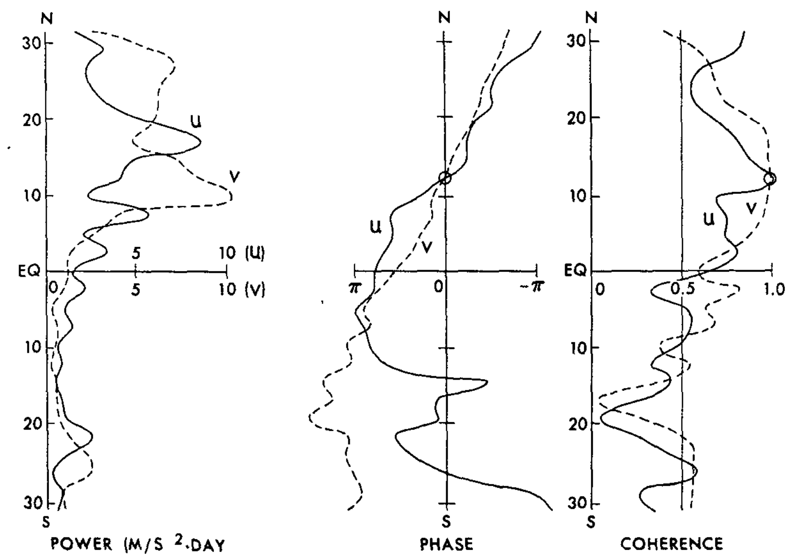

FIG. 10d. As in Fig. 10a except for easterly waves (meridional component at 835 mb) with wavenumber 9 and period 15 days (westward moving).

Fig. 10 shows the horizontal structure of the four types of waves. Kelvin waves (Fig. 10a) have their maximum zonal component over the equator with hardly any meridional component. Rossby-type waves (Fig. 10b) have their maximum zonal component over the equator and maximum meridional component off the equator indicating that they have their vortices centered off the equator. Their phase lines tilt from southwest to northeast. Mixed Rossby-gravity waves (Fig. 10c) have their maximum zonal component off the equator and maximum meridional component almost on the equator, indicating that their vortices are centered on the equator. The phase line of their zonal component jumps by 180°, crossing the equator. On the other hand, the phase line of their meridional component shows hardly any tilt at this level. However, at lower levels (not shown) mixed Rossby-gravity waves tilt slightly eastward with increasing latitudes in both hemispheres. Easterly waves (Fig. 10d) have both their zonal and meridional component maxima in the Northern Hemisphere with their phase lines tilting southwest to northeast. All these waves exhibit high coherence in the horizontal.

4. Three-dimensional structure of waves

In this section a three-dimensional view of these four types of waves is presented together with their temperature, vertical velocity and heating.

Fig. 11a shows a latitude-height section of power spectra of the zonal component integrated over wavenumbers 1∼2 and over periods of 10∼20 days (eastward moving). A maximum is seen corresponding to Kelvin waves over the equator in the stratosphere. In the upper troposphere eastward moving ultra-long waves extend from the Southern Hemisphere. Their dominant wavenumber is 3 rather than 1∼2 (see also Fig. 4b and Fig. 6c).

Fig. 11b is the same as Fig. 11a except for westward moving waves. A maximum of the zonal wind spectra corresponding to Rossby-type waves exists over the equator below the tropopause. In the stratosphere, westward moving ultra-long waves reach as far as the equator from the Southern Hemisphere. [Their dominant wavenumber is 1 (see also Fig. 4a and Fig. 6a).] This is consistent with the theoretical results by Dickinson (1968), Charney (1969) and Benett and Young (1971) who showed that the propagation of Rossby waves becomes possible in an easterly regime, only if their phase velocity is westward relative to the basic flow. These westward moving waves appeared in the time section (16 mb) of Manabe *et al.* (1970b), and they may correspond to those described by Fritz (1970) and Deland (1973) using infrared spectrometer measurements.

Fig. 11c shows the meridional section of mixed Rossby-gravity waves. In contrast to Fig. 11a and Fig. 11b, there is hardly any influence from middle-latitude disturbances. This feature is consistent with the recent theoretical results by Gambo (1971) and M. Murakami (1973) that wavenumbers 4 or higher cannot penetrate into the tropics, if the horizontal shear exceeds 10 m sec^{-1} (10°)$^{-1}$. Fig. 11d shows that easterly waves with periods of 10∼20 days have their root around 15N.

Fig. 12 shows the power spectra of temperature associated with the four types of waves. Kelvin waves

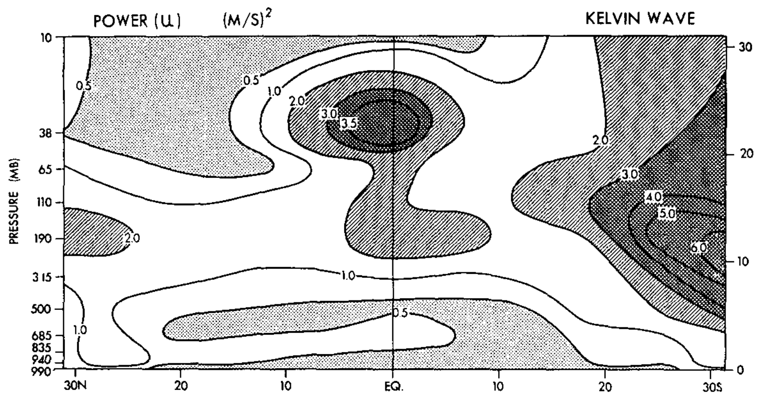

FIG. 11a. Latitude-height section of power spectra of zonal component integrated over wavenumbers of 1∼2 over periods of 10∼20 days (eastward moving). Maximum over the equator corresponds to Kelvin waves.

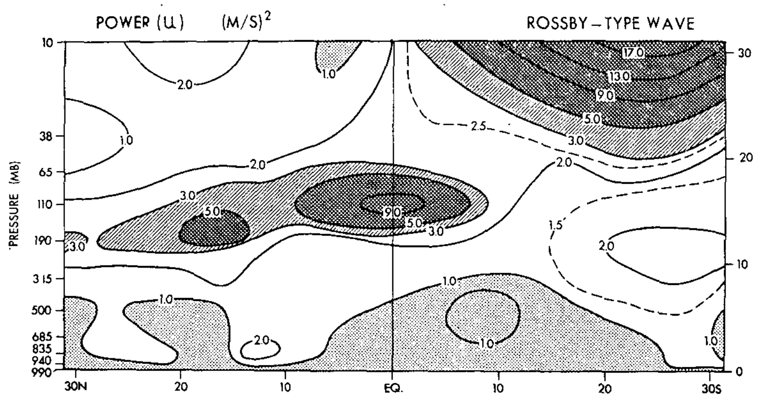

FIG. 11b. As in Fig. 11a except for zonal component integrated over wavenumbers of 1∼2 and over periods of 10∼20 days (westward moving). Maximum over the equator corresponds to equatorial Rossby-type waves.

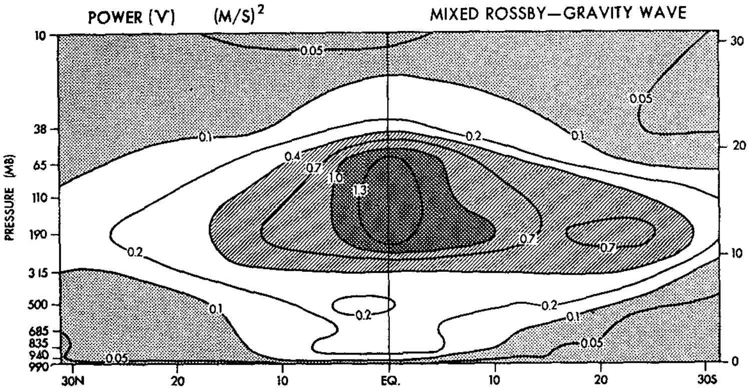

FIG. 11c. As in Fig. 11a except for meridional component integrated over wavenumbers of 3∼5 and over periods of 3∼5 days (westward moving). Maximum over the equator corresponds to mixed Rossby-gravity waves.

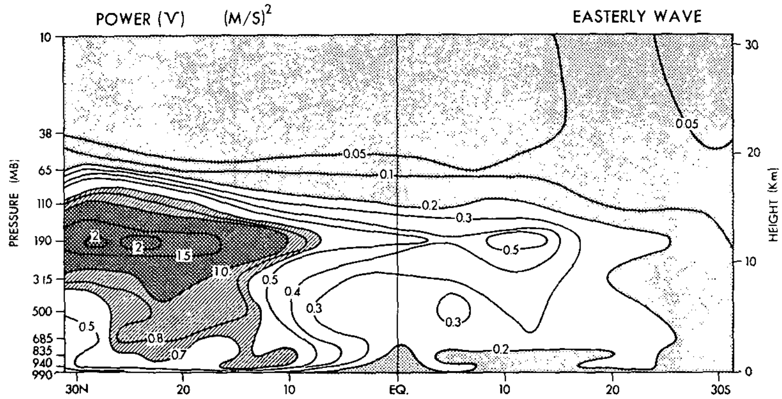

Fig. 11d. As in Fig. 11a except for meridional component integrated over wavenumber 8∼10 and over periods of 10∼20 days (westward moving). Maximum around 15N corresponds to easterly waves.

have their temperature maxima over the equator, while Rossby-type and mixed Rossby-gravity waves have their temperature maxima away from the equator. This feature also holds for the geopotential height spectra (not shown) and is consistent with the height patterns shown by Fig. 4c in Section 3. Mixed Rossby-gravity waves have their temperature maxima in the stratosphere rather than in the troposphere, in agreement with Yanai and Hayashi (1969) observationally, and with Hayashi (1970) theoretically.

Figs. 13 and 14 show power spectra of vertical velocity and heating associated with the four types of waves, respectively. Their heating maxima occur around the 500-mb level which is a little lower than observed (400 mb) by Nitta (1970c, 1972a). It is interesting that in the troposphere all of these waves have their maximum vertical velocity and heating away from the equator in the summer (northern) hemisphere. In this respect this model is more similar to the models by T. Murakami (1972b, 1973c) and Holton (1972) who assumed a heat source situated away from the equator. In the case of CISK theories (Hayashi, 1970), Kelvin waves attain their heating maximum over the equator, unlike the other types of equatorial waves.

The geographical distribution of these waves is further examined. Fig. 15 shows the longitude-latitude sections of the time-power spectra of wind disturbances which are spatially filtered according to their characteristic wavenumber range. Though this method does not distinguish between eastward and westward moving waves, Kelvin waves and Rossby-type waves are separated according to their preferred level, 38 and 110 mb, respectively. Easterly waves are further classified into two groups according to their period ranges of 10∼20 days and 3∼6 days.

Kelvin waves at 38 mb in Fig. 15 exhibit their maximum local amplitude in the mid-Pacific and the Atlantic. Mixed Rossby-gravity waves at 65 mb attain their maximum in the mid-Pacific (see also Fig. 5). However, at lower levels (not shown) their maximum is situated in the western Pacific. This shifting of the maximum amplitude of wave packets has been theo-

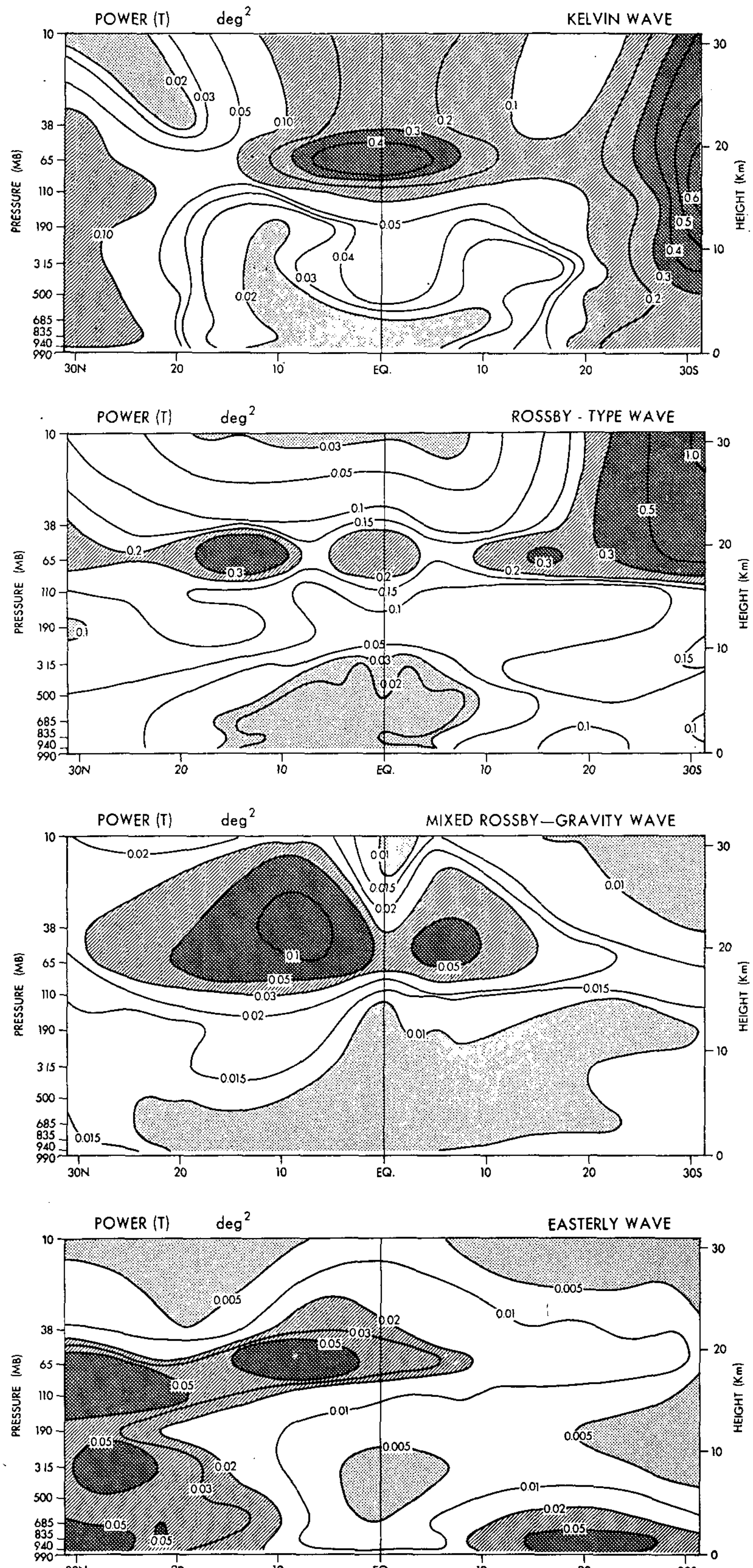

FIG. 12. As in Fig. 11 except for temperature.

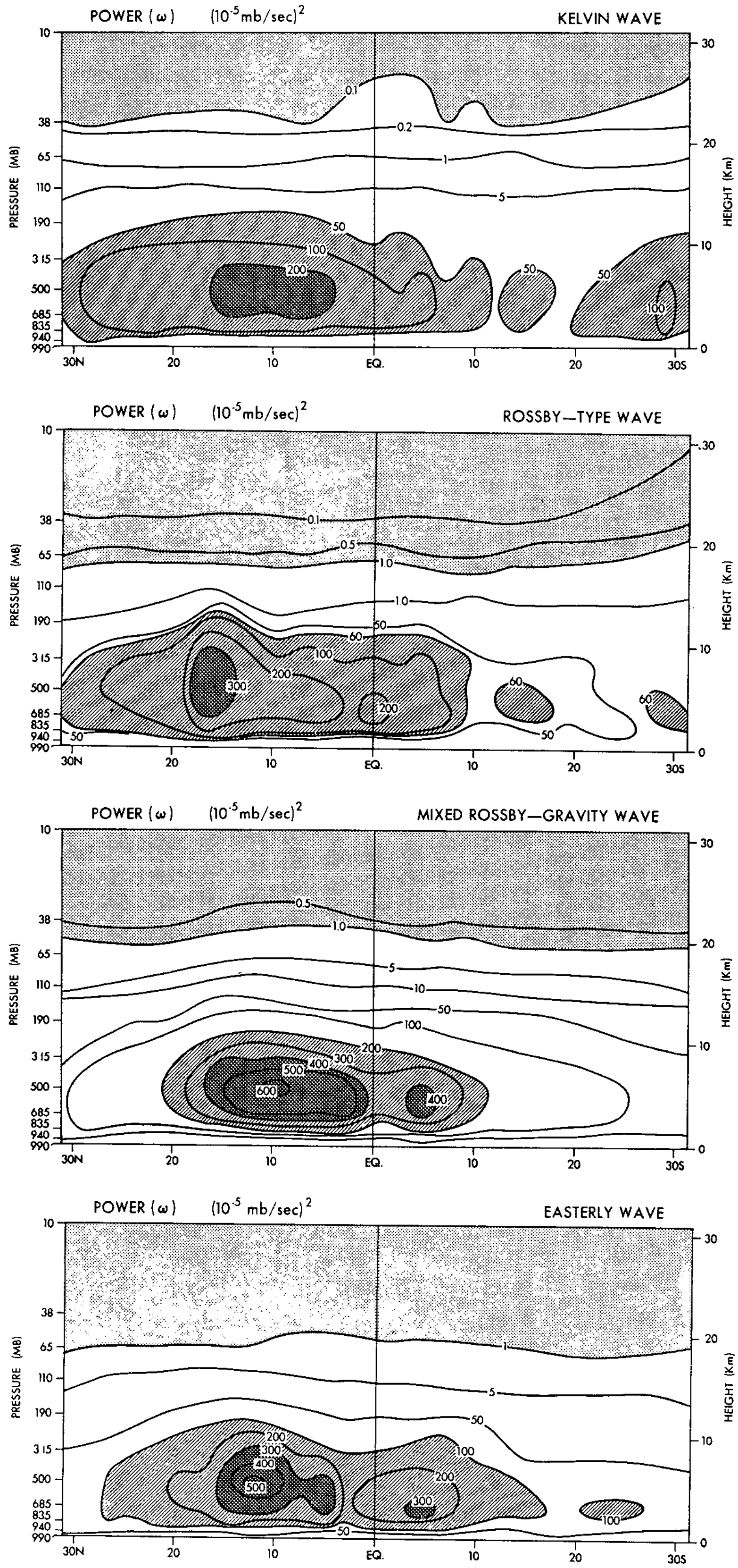

FIG. 13. As in Fig. 11 except for p-velocity.

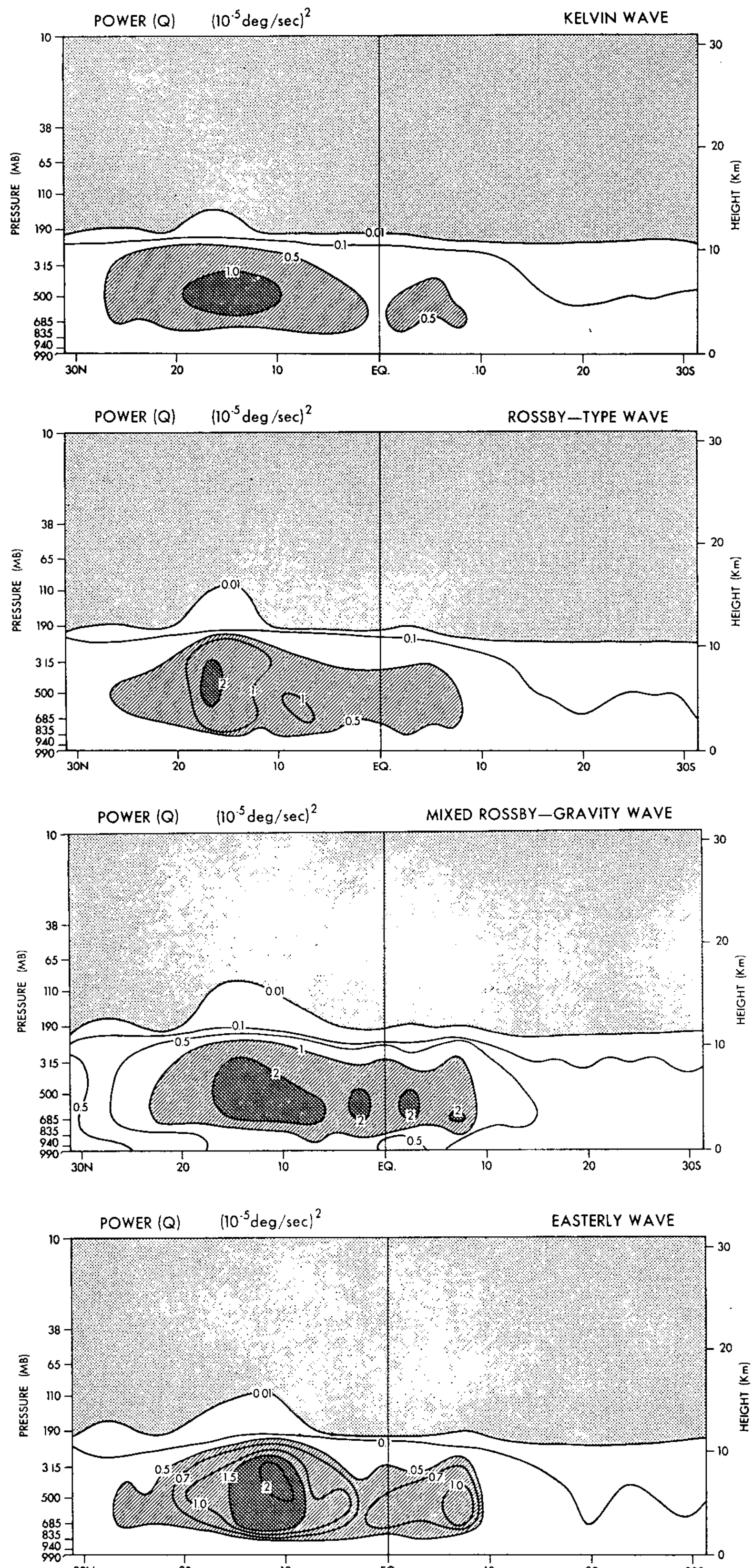

FIG. 14. As in Fig. 11 except for convective heating.

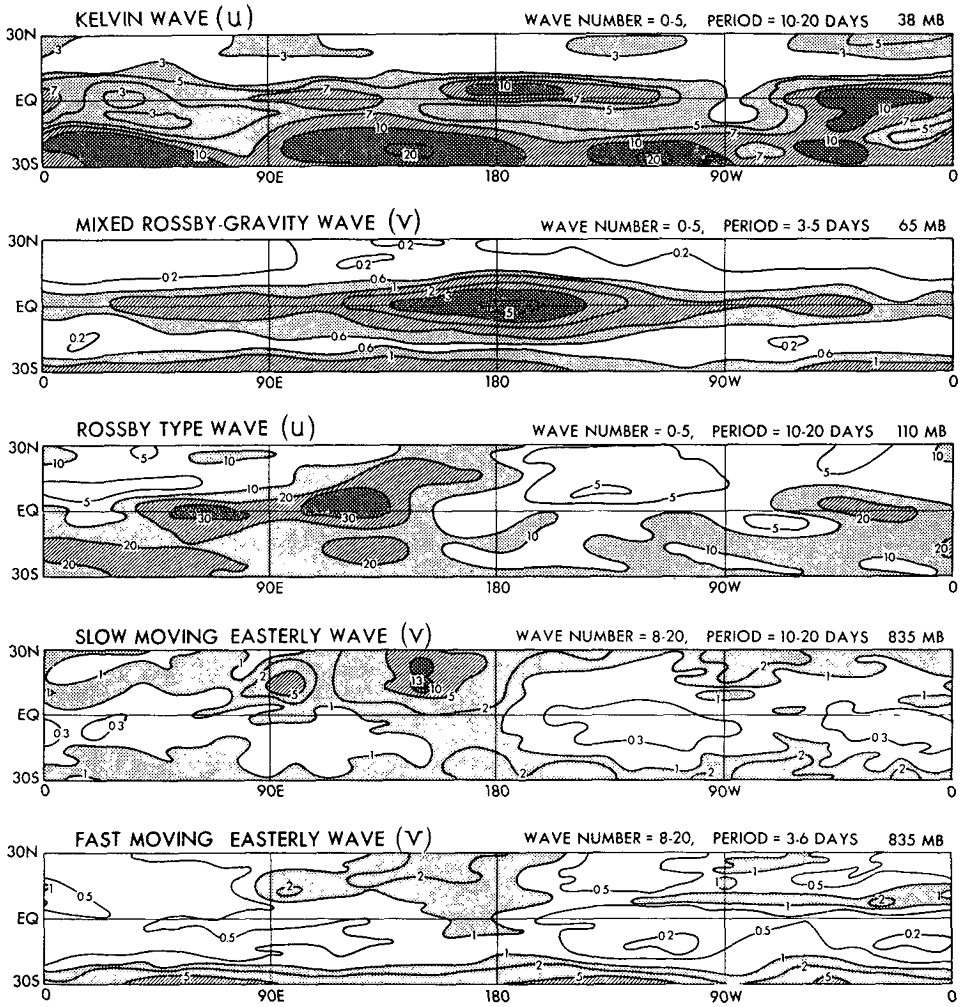

FIG. 15. Longitude-latitude section of time-power spectra ($m^2 sec^{-2}$) of winds filtered spatially according to the characteristic wavenumber range of waves.

retically pointed out by Holton (1972b). Observational evidence of mixed Rossby-gravity waves in the Indian Ocean has been given by Rao and Murty (1972) and Parker (1973a). It is interesting that Fig. 15 suggests mixed Rossby-gravity waves extend as far as the Atlantic where the GATE experiment (1974) is scheduled (see GATE Report No. 1, 1972). Rossby-type waves at 110 mb have their maximum amplitude over the western Pacific. Easterly waves with periods of 10∼20 days have their maximum in the western Pacific in the Northern Hemisphere, where some of them appear to form typhoon-like disturbances as observationally suggested by Yanai (1961a, b, 1963, 1964). Easterly waves with periods of 3∼6 days form the ITCZ around 7N in the eastern Pacific. Similar results were obtained by Bates (1970) and Chang (1973a) who made a CISK model of the ITCZ. Observational evidence of easterly waves in the Atlantic was given by Frank (1969), Carlson (1969a, b) and Burpee (1972).

Longitudinal differences of the local amplitudes are also revealed by the time sections (Figs. 7a, b).

5. Energetics

This section briefly examines the relative importance of the transient waves in the energetics of the tropics and their major energy sources.

Fig. 16 shows a wavenumber-frequency section of kinetic energy spectra integrated over the mass in the stratosphere (upper diagram) and in the troposphere (lower diagram) between 10S∼20N. This latitudinal range was chosen so as not to include the very large kinetic energy between 10∼20S associated with the ultra-long waves extending from higher latitudes.

In the stratosphere, maximum kinetic energy is contained in westward moving waves of wavenumbers 1∼2 and periods $\gtrsim$15 days. This kinetic energy is associated partly with equatorial Rossby-type waves and partly with westward moving ultra-long waves extending from middle latitudes (see Fig. 11b). A secondary peak occurs for eastward moving Kelvin waves at wavenumbers 1∼2 and periods of 15∼20 days. There is also an isolated peak for westward moving mixed

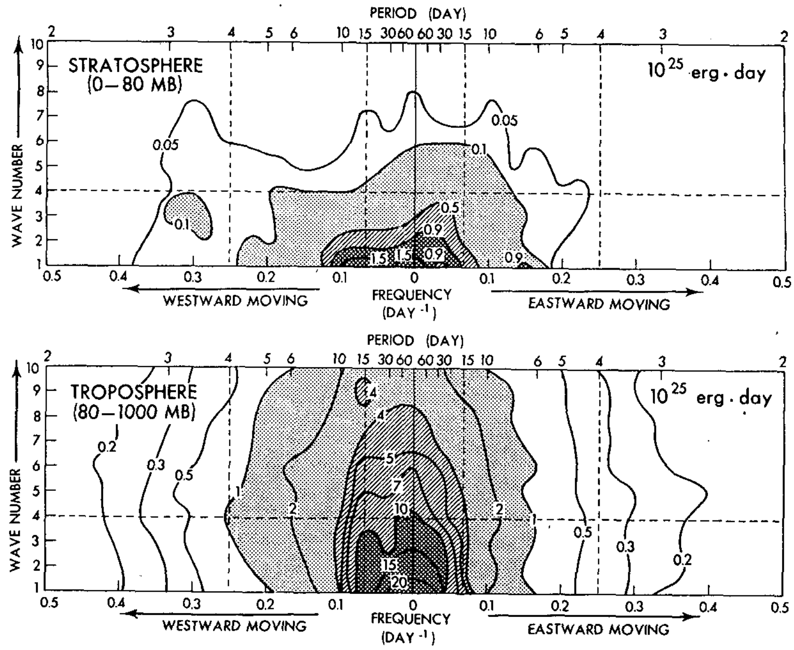

FIG. 16. Wavenumber-frequency section of kinetic energy spectra integrated longitudinally, latitudinally over 10S~20N, and vertically over 0~80 mb (upper diagram) and 80~1000 mb (lower diagram).

Rossby-gravity waves at wavenumber 3 and periods of 3~4 days.

In the troposphere (lower diagram) the maximum kinetic energy is primarily contained by long-period oscillations related to the seasonal variation.[6] In addition, there is a large amount of kinetic energy associated with westward moving Rossby-type waves with wavenumbers 1~4 and with a period of around 15 days. Eastward moving Kelvin waves and westward moving mixed Rossby-gravity waves show their characteristic wavenumbers 1 and 4, respectively, but their periodicity is not as distinct as those in the stratosphere. This suggests that these waves are filtered as they penetrate into the stratosphere. There is also an isolated kinetic energy maximum for slow moving easterly waves with wavenumber 9 and periods of 15 days.

Fig. 17 shows a wavenumber-frequency section of energy conversion (upper diagram) and meridional convergence of energy (lower diagram) between 10S~20N integrated over the mass throughout the levels. A comparison between the two diagrams shows that energy conversion is quantitatively more important than the energy flux converging from middle latitudes for all the types of equatorial transient waves. This result is consistent with that of Manabe *et al.* (1970b) who obtained a similar conclusion for eddy kinetic energy as a whole.

[6] Power spectra at zero frequency computed through lag correlation is contributed by trends with time scales longer than the record. The time mean, however, is subtracted out.

The vertically integrated energy conversion spectra are more similar to the kinetic energy spectra in the troposphere than to those in the stratosphere. Rossby-type waves have their spectral peak at wavenumber 3 in the energy conversion spectra, and at wavenumber 1 in the kinetic energy spectra. This, however, is not inconsistent since there is a peak at wavenumber 3 in the energy dissipation spectra (not shown), which should directly balance with the energy conversion together with nonlinear energy loss (Manabe *et al.* 1970a, b; 1974). It is also confirmed that the energy conversion balances with the generation of available potential energy due to latent heat release.

The meridional convergence (Fig. 17) of energy has a maximum for wavenumbers 2~3 and periods of 30 days (eastward moving) corresponding to tropospheric ultra-long waves extending from the Southern Hemisphere. According to Manabe *et al.* (1973), the transient eddies account for most of the energy flux from the Southern Hemisphere, while the stationary eddies are mainly responsible for the energy flux from the Northern Hemisphere. Fig. 17 also reveals a slight peak at wavenumber 1 and periods of 4~5 days (westward moving) corresponding to the pressure waves described by Fig. 6f in Section 3.

Exchange of energy between the zonal mean winds and the disturbances turns out to be small for all the four types of waves (not shown). However, this result is based on the space-time mean statistics and does

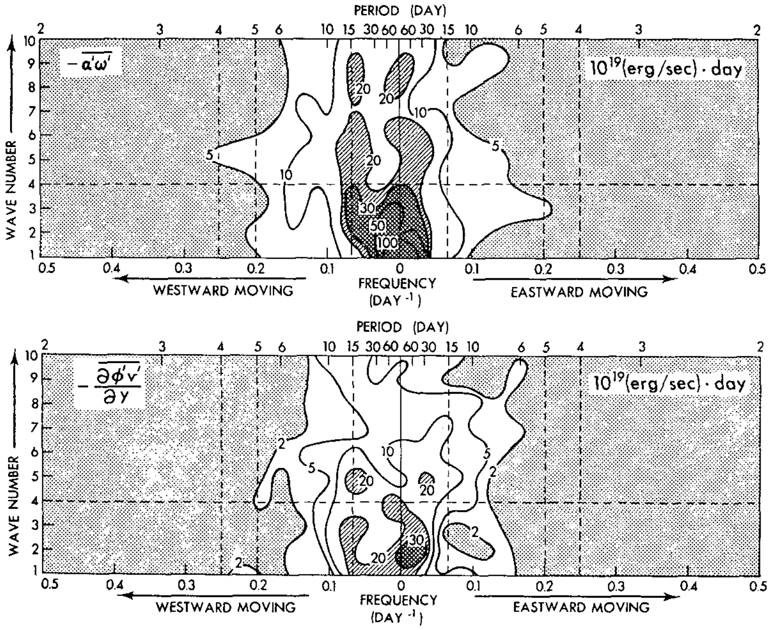

FIG. 17. Wavenumber-frequency section of co-spectra of energy conversion (upper diagram) and meridional convergence of energy flux (lower diagram) integrated longitudinally, vertically over 0∼1000 mb, and latitudinally over 10S∼20N.

not necessarily rule out the possibility of local and sporadic amplification of easterly waves through barotropic instability (Nitta and Yanai, 1969; Lipps, 1970; Bates, 1970; Williams *et al.*, 1971; Yamasaki and Wada, 1972a, b; T. Murakami, 1972; Padro, 1973; Colton, 1973).

Finally, the energetics of the stratosphere are examined separately. Fig. 18 shows the spectra of the

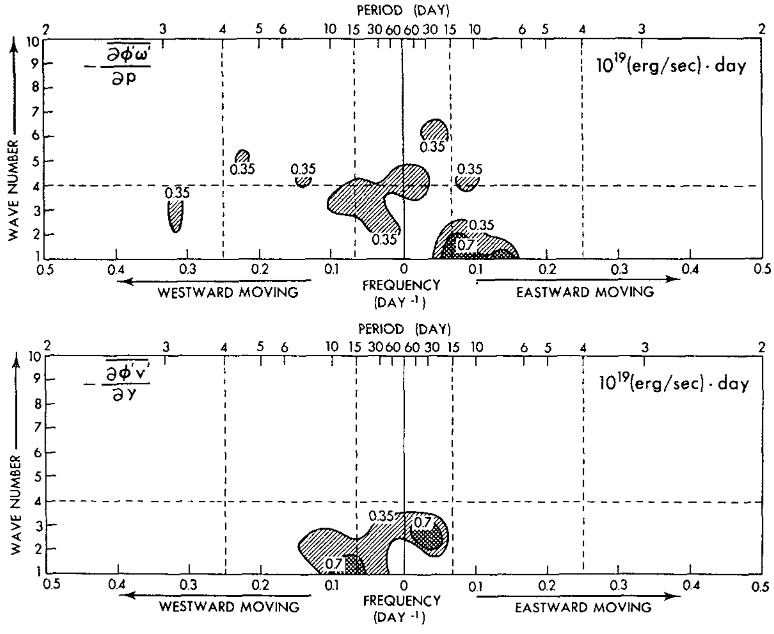

FIG. 18. Wavenumber-frequency section of co-spectra of vertical convergence of energy flux (upper diagram) and meridional convergence of energy flux (lower diagram) integrated longitudinally, vertically over 0∼80 mb and latitudinally over 10S∼20N.

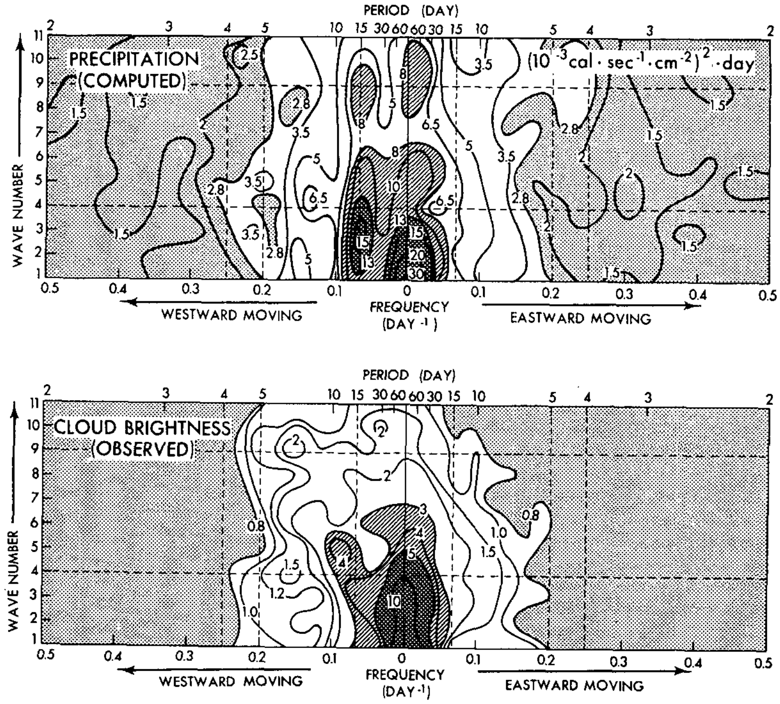

FIG. 19. Wavenumber-frequency section of averaged (0∼20N) power spectra of model precipitation (upper) and observed cloud brightness during the period May through October, 1967 (lower). The cloud brightness spectra are adapted from Gruber (1973).

vertical convergence of energy flux (upper diagram) and the meridional convergence of energy flux (lower diagram) integrated over the mass in the stratosphere between 10S∼20N. Contours are drawn for the values above the level of noise due to the aliasing error from high-frequency noise mentioned in Section 2. [There may be other errors due to the coarse vertical resolution of this model which has only three layers above 65 mb: 1) stratospheric waves are not sufficiently resolved, 2) the spurious reflection at the top boundary (Lindzen *et al.*, 1968; Hayashi, 1970, 1971b) is directly felt at lower layers, and 3) the output data are interpolated from sigma coordinates to constant-pressure levels.] These diagrams suggest that Kelvin waves and mixed-Rossby gravity waves in the stratosphere are maintained by a vertical flux of energy from the troposphere. The kinetic energy of wavenumbers 1∼4 and periods of ∼15 days in the stratosphere (westward moving equatorial and middle latitude Rossby-type waves) is maintained by both a vertical and a meridional flux of energy. These results, however, must be confirmed by a model with much finer vertical resolutions.

6. Relation between waves and convective heating

In this section a comparison is made between the model precipitation spectra and observed cloud brightness spectra to see whether or not the condensational heating resulting from such idealized convective adjustment is too unrealistic. Also, relations between waves and convective heating are examined in order to clarify similarity and dissimilarity of this model to CISK theories (Yamasaki, 1969; Hayashi, 1970) and to the thermal forcing theories (Holton, 1972b; T. Murakami, 1972b, c).

Fig. 19 shows wavenumber-frequency sections of power spectra of the model precipitation[7] and observed satellite brightness.[8] The brightness spectra are adapted from Gruber (1973) who used the author's method. [Since these spectra have significant latitudinal variations, they are averaged between 0∼20N in order to be more consistent with the latitudinally integrated energy spectra in the preceding section.] These spectra resemble each other in the following respects. Both of them are associated with more westward than eastward phase velocity except for very long- and short-period oscillations which are standing wave pulsations. Distinct spectral peaks are seen, corresponding to westward moving Rossby-type waves at wavenumbers 1∼5

[7] M. Murakami (1971, 1972) found three spectral peaks at periods of 15, 4 and 3 days in precipitation in the Marshall Islands area, corresponding to planetary scale, synoptic-scale and intermediate-scale travelling waves, respectively.

[8] Regional analysis of cloud brightness have been made by Chang (1970), Wallace (1970, 1971), Tanaka and Ryuguji (1971, 1973), Sikdar and Suomi (1971), Sikdar *et al.* (1972), T. Murakami and Ho (1972a, b), Wallace and Chang (1972) and Young and Sikdar (1973).

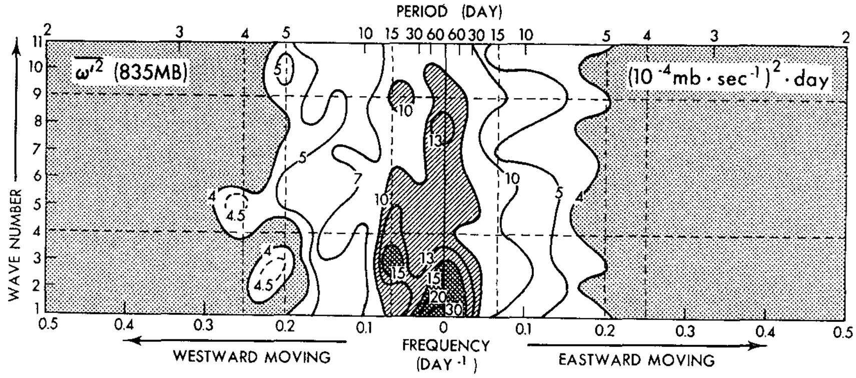

FIG. 20. Wavenumber-frequency section of power spectra of vertical p-velocity at 835 mb averaged latitudinally between 0∼20N.

and slow and fast moving easterly waves at wavenumbers 9 and 10. Also, vague spectral peaks can be seen corresponding to westward moving mixed Rossby-gravity waves at wavenumber 5 and eastward moving Kelvin waves at wavenumbers 1∼3. In this respect both this model and observation are more similar to the CISK theories in which condensational heating itself has phase velocities than to the thermal forcing theories (Holton, 1972; T. Murakami, 1973a) in which heating is assumed to be a standing pulsation with a dominant wavenumber of 1. However, the precipitation has no 15-day peak corresponding to Kelvin waves. In this respect, this model is more similar to the thermal forcing theory (Holton, 1973) in which no periodicity is required in heating itself to excite Kelvin waves with 15-day periods. The peak for mixed Rossby-gravity waves with wavenumber 4 and 4-day periods is more clearly seen at 12N (not shown) than that shown by the latitudinal mean spectra (Fig. 19).

It is also of interest to examine whether convective heating is related to the vertical velocity of the waves in the lower troposphere, as in the case of CISK parameterization (Ooyama, 1964, 1969; Charney and Eliassen, 1964; Ogura, 1964; Kuo, 1965). Fig. 20 shows a wavenumber-frequency section of the averaged (0∼20N) power spectra of vertical p-velocity at 835 mb. It should be noted that the precipitation spectra correspond very well to the vertical velocity spectra.

Next it will be profitable to estimate the traditional CISK heating parameter defined by the ratio of heating to the vertical velocity at 900 mb as

$$\eta(p) \equiv \frac{R}{S_p C_p P} \frac{Q(P)}{\omega(900\text{ mb})}, \qquad (1)$$

where η is the parameter of the vertical distribution of convective heating, R the gas constant, S_p the mean static stability, C_p the specific heat at constant pressure, Q the latent heat release, and ω the vertical p-velocity. For a modern definition of the heating parameter, the reader is referred to Ooyama (1971), Arakawa and Schubert (1974) and Yanai *et al.* (1973). Fig. 21 gives vertical profiles of the heating parameter determined from the wave amplitudes for the four types of waves with their wavenumber-frequency range defined in Section 4. All of these waves have similar vertical profiles and have a larger heating parameter in the Northern (summer) Hemisphere than in the Southern (winter) Hemisphere. It has also been confirmed (not shown) that the latent heat is released almost in phase with the lower vertical velocity. The profiles in the Northern Hemisphere are similar to those obtained statistically by Nitta (1972a) in the Marshall Islands area except that his profiles attain their maximum at a higher level, around 350 mb. In the CISK theories the computed value of the heating parameter (2 or 3) is large enough to give instability.

The difference between the profiles in the Northern and Southern Hemispheres may be attributed, in part, to the sea surface temperature and the mixing ratio which will control the convective adjustment. Another factor responsible for this difference is that the convective heating may also be related to the large-scale vertical velocities at levels higher than 900 mb. Fig. 21b shows that the vertical velocity relative to that at 900 mb is larger in the Northern Hemisphere (5∼10N) than in the Southern Hemisphere (5∼10S). This result is interesting in connection with the analysis by Williams and Gray (1973) who found a deep convergence layer extending to 400 mb in the western North Pacific.

Next an examination is made of the geographical relation between the vertical velocity and the convective heating. Fig. 22 shows a geographical distribution of the local power spectra of precipitation for three wavenumber-frequency ranges. The top figure shows precipitation spectra with wavenumbers 0∼5 and periods of 10∼20 days, corresponding to both westward moving Rossby-type waves and eastward moving Kelvin waves. The middle figure shows precipitation spectra with wavenumbers 0∼5 and periods of 3∼5 days, corresponding to mixed Rossby-gravity waves. The bottom figure shows precipitation spectra with wavenumbers

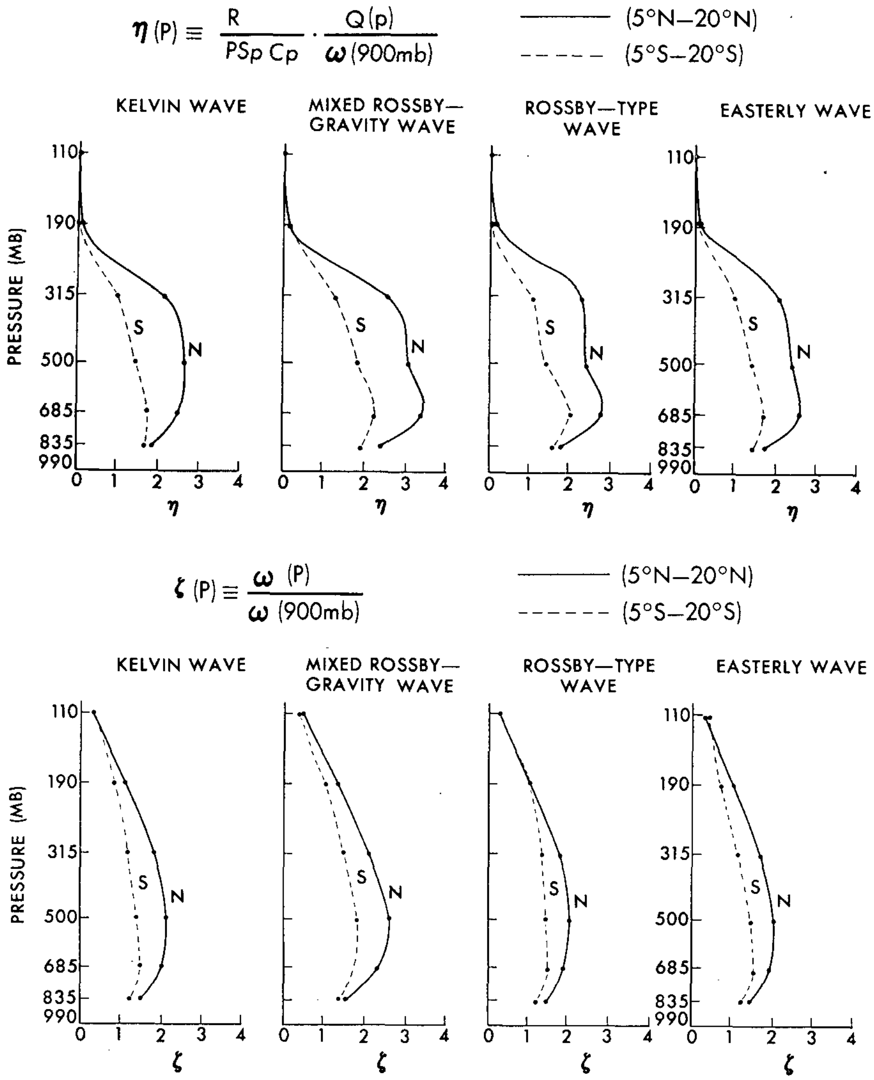

FIG. 21. Vertical profiles of CISK heating parameter η, a., and ζ (defined as amplitude of vertical velocity relative to that at 900 mb), b., for four types of waves as classified in Fig. 11. Full and dashed lines show values obtained from power spectra of vertical velocity and convective heating averaged over 5~20N and 5~20S, respectively.

8~20 and periods of 3~20 days, including both the slow moving easterly waves in the western Pacific and the fast moving easterly waves in the eastern Pacific. Fig. 23 shows a geographical distribution of the power spectra of the vertical velocity at 835 mb. A comparison between Figs. 22 and 23 shows that both the precipitation and the vertical velocity associated with these waves attain their maximum particularly in the western Pacific and in the ITCZ in the eastern Pacific in the Northern Hemisphere. In this respect, this model in this season is more similar to the thermal forcing theories (Holton, 1972b) which assume heating is localized and situated away from the equator than it is to the CISK theory (Hayashi, 1970, 1971d) in which heating is not localized and the vertical velocity of Kelvin waves attains its maximum on the equator.

The location of the vertical velocity maximum in the present model seems to be directly related to the sea surface temperature (see Fig. 1) rather than the effect of the critical latitude (where the wave frequency is equal to the Coriolis parameter), as discussed by Holton *et al.* (1971a), Yamasaki (1971a), Hayashi (1971c) and Chang (1973b), and the effect of stable stratification (Kuo, 1973a, b). If the latter effects were primary, the vertical velocity should attain its two maxima equally in the Northern and Southern Hemispheres. Manabe *et al.* (1973) demonstrated that the model ITCZ shifts its location and sometimes forms even over the equator [also see Gruber (1972) for observational evidence] following the seasonal variation of the sea surface temperature.

Quantitatively, however, a regional difference is found

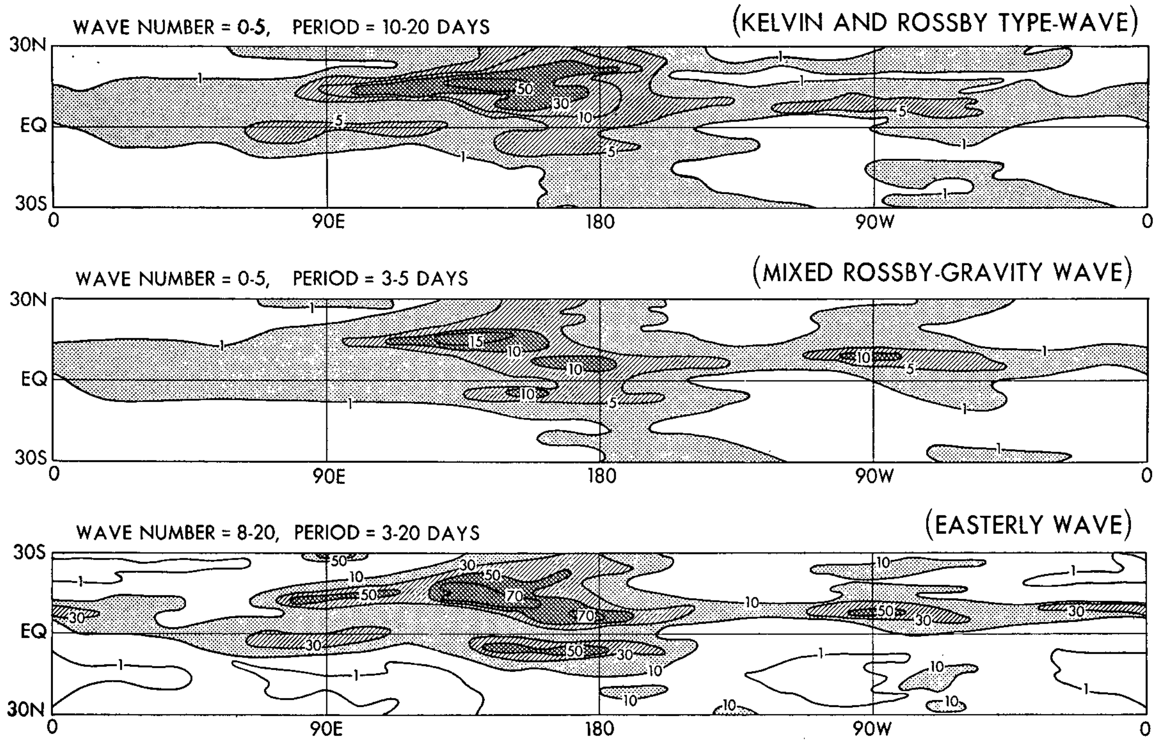

Fig. 22. Longitude-latitude section of time-power spectra (10^{-3} cal sec^{-1} cm^{-2})^2 of precipitation for three wavenumber-frequency regimes.

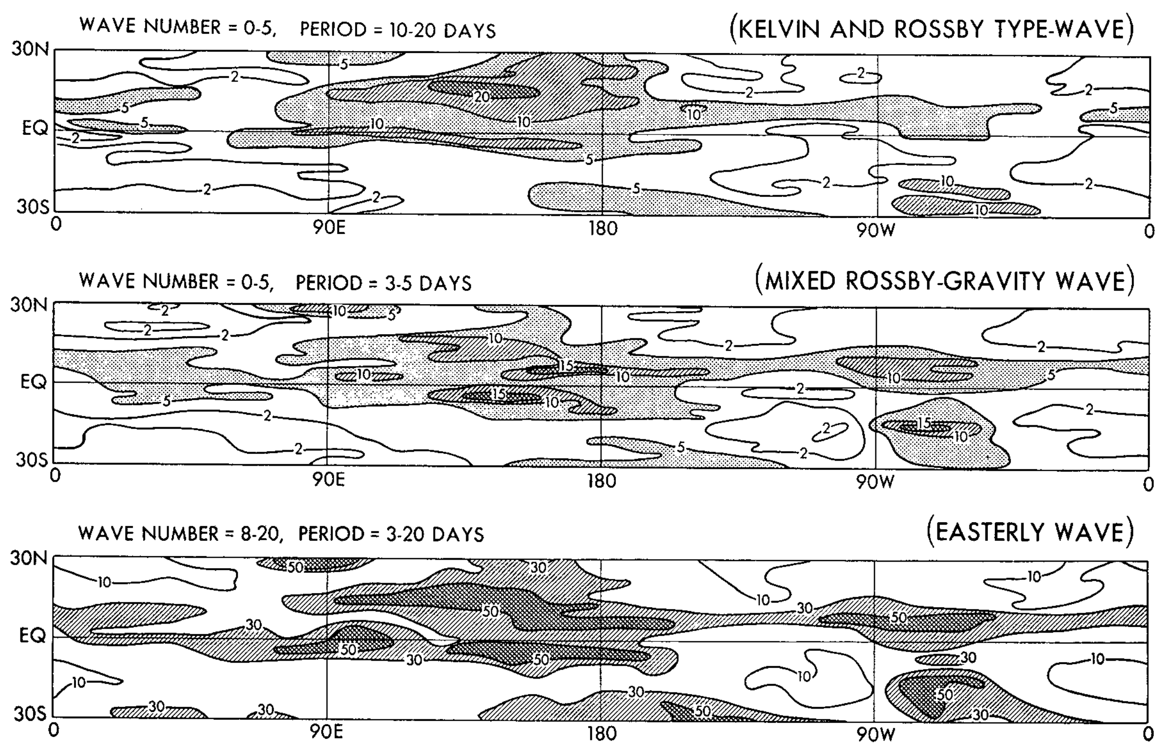

Fig. 23. Longitude-latitude section of time-power spectra (10^{-4} mb sec^{-1})^2 of vertical velocity ω at 835 mb for three wave-number-frequency regimes.

in the relation between the convective heating and the vertical velocity disturbances as follows. Table 1 shows longitude-latitude diagrams of the CISK heating parameter defined by Eq. (1) by using time-power spectra of heating and vertical velocity averaged over each longitude-latitude domain. This shows that a maximum of the heating parameter occurs in the western Pacific in the Northern Hemisphere where the sea surface is warmest.

In the above estimate of the heating parameter, no distinction was made between upward and downward motion. It may be more natural to assume that condensational heating is related to only upward motion. Table 2 compares the heating parameters at 500 mb obtained by using the original vertical velocity (unconditional) with that obtained by putting the downward vertical velocity to zero (conditional). The wavenumber and period range was taken as 0~20 and 2~20 days, respectively. It is seen that the relative geographical distribution of the heating parameter remains the same except that their absolute values are doubled.

These results suggest that latent heat release resulting from convective adjustment is related to the vertical velocity in the lower layer as in the case of the CISK parameterization except for regional variation of the heating parameter. It is of interest to reexamine CISK models with a regional variation of their heating parameter. Bates (1970) showed that the ITCZ forms away from the equator in his CISK model in which the heating parameter vanishes over the equator [also see comment by Pike (1971b)]. In a similar manner Kelvin waves might attain their vertical velocity maximum away from the equator in the troposphere, if the heating parameter is assumed to be large away from the equator.

The most important dissimilarity between the present model and the CISK theory is that the convective adjustment does not unrealistically excite gravity waves[9] with periods of days or less which are found most unstable in the linear theory (Hayashi, 1970, 1971d) with CISK parameterization.

TABLE 1. Heating parameter at 500 mb.
Kelvin and Rossby-type waves.*

Latitude	Longitude 0~90E	90E~180	180~90W	90W~0
20N~ 5N	1.8	2.4	1.9	1.9
5N~ 5S	2.0	1.8	1.9	1.8
5S~20S	1.2	0.9	1.5	0.7

* Wavenumber = 0~5, period = 10~20 days.

Mixed Rossby-gravity waves.*

Latitude	Longitude 0~90E	90E~180	180~90W	90W~0
20N~ 5N	2.9	3.7	2.7	2.8
5N~ 5S	2.9	2.4	2.7	2.3
5S~20S	1.7	2.2	2.4	1.2

* Wavenumber = 0~5, period = 3~5 days.

Easterly waves.*

Latitude	Longitude 0~90E	90E~180	180~90W	90W~0
20N~ 5N	2.3	3.0	2.3	2.4
5N~ 5S	2.5	2.1	2.4	2.2
5S~20S	1.4	1.9	2.0	1.0

* Wavenumber = 8~20, period = 3~20 days.

TABLE 2. Heating parameter at 500 mb
(see text for definition of cases).
Unconditional case

Latitude	Longitude 0~90E	90E~180	180~90W	90W~0
20N~ 5N	2.6	3.1	2.3	2.7
5N~ 5S	2.6	2.1	2.5	2.2
5S~20S	1.6	2.0	2.2	1.0

* Wavenumber = 0~20, period = 2~20 days.

Conditional case

Latitude	Longitude 0~90E	90E~180	180~90W	90W~0
20N~ 5N	4.6	5.7	4.0	5.0
5N~ 5S	4.9	4.0	5.3	4.0
5S~20S	3.0	4.2	4.9	2.0

* Wavenumber = 0~20, period = 2~20 days.

7. Role of tropical waves in the general circulation model

This section will examine what role these tropical disturbances play in the tropical general circulation model.

It is important to estimate the momentum transport of these waves especially in relation to the quasi-biennial oscillation of the mean zonal wind [see Ebdon (1960) and Reed *et al.* (1961) for observational studies, and Wallace and Holton (1968), Lindzen and Holton (1968) and Holton and Lindzen (1972) for current theoretical models]. Fig. 24 shows wavenumber-frequency sections of the vertical convergence of momentum flux (upper diagram) and the meridional convergence of momentum flux (lower diagram) integrated over the mass in the stratosphere between 10S~20N. Mixed Rossby-gravity waves and Kelvin waves are shown to transport westerly momentum upward into the stratosphere in agreement with observation (Maruyama, 1968b; Wallace and Kousky, 1968b). Fig. 24 also shows that equatorial Rossby-type waves and

[9] In the present model eastward and westward moving waves with wavenumbers 1~2 and periods of 1.5 days are clearly detected for the meridional component at the 10-mb level. However, their amplitudes are very small. Gravity waves with periods of hours or less are suppressed computationally by the Matsuno scheme.

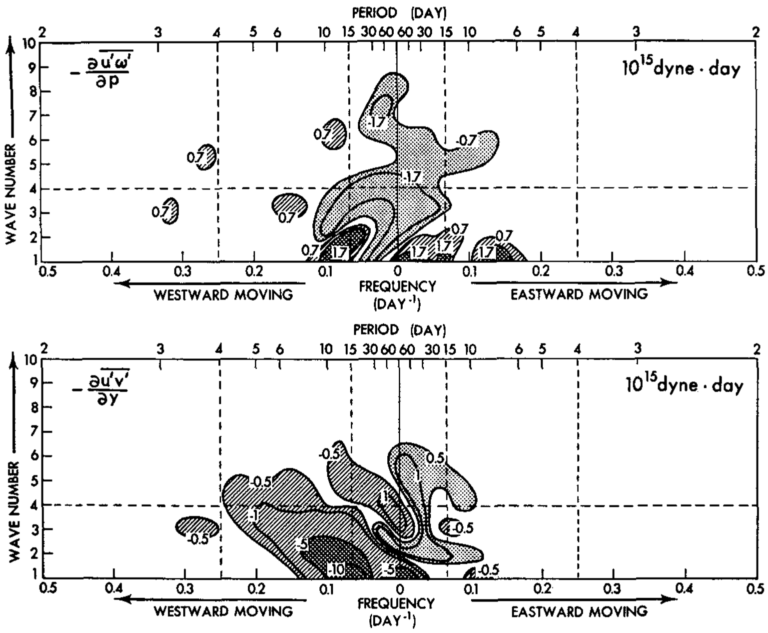

FIG. 24. Wavenumber-frequency section of co-spectra of vertical convergence of momentum flux (upper diagram) and meridional convergence of momentum flux (lower diagram) integrated longitudinally and vertically (0∼80 mb) over 10S∼20N.

ultra-long waves extending from middle latitudes (described in Section 5) are responsible for transporting westerly momentum away from the equator. This meridional flux of momentum may correspond to that observed by Tucker (1964, 1965b) and Wallace and Newell (1966). Their meridional flux of momentum is more effective than their vertical flux. These results, however, must be confirmed by a model with much finer vertical resolutions and by output data without aliasing errors.

Fig. 25 gives a latitude-height section of the meridional flux of momentum integrated over wavenumbers 1∼2 and periods of 10∼20 days corresponding to westward moving Rossby type waves. Momentum is found to be transported southward in the stratosphere and northward in the upper troposphere across the equator. This cross equatorial transport of momentum was observed by Rao (1960), Obasi (1963), Tucker (1965), Iida (1968) and Kidson *et al.* (1969), and has been simulated by Manabe *et al.* (1970, 1973), and theoretically interpreted by Dickinson (1971).

Fig. 26 shows a wavenumber-frequency section of meridional flux of sensible heat at 65 mb at 9.6N. Rossby-type waves and mixed Rossby-gravity waves

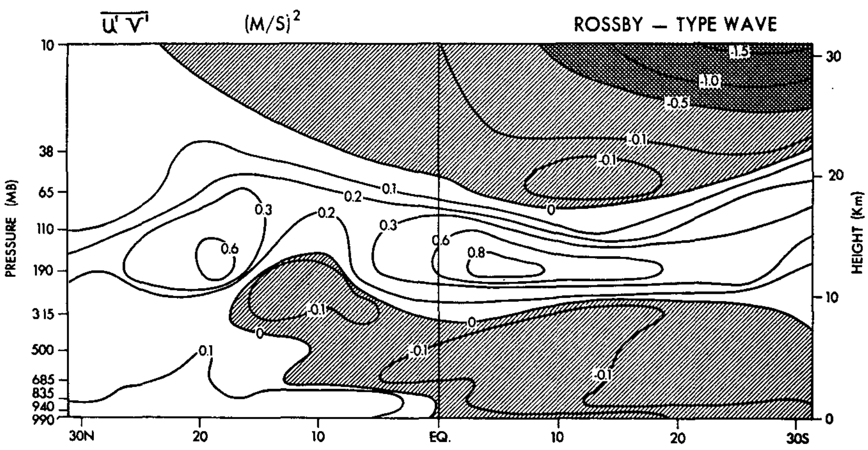

FIG. 25. Latitude-height section of co-spectra of meridional flux of momentum integrated over wavenumbers 1∼2 and over periods of 10∼20 days (westward moving).

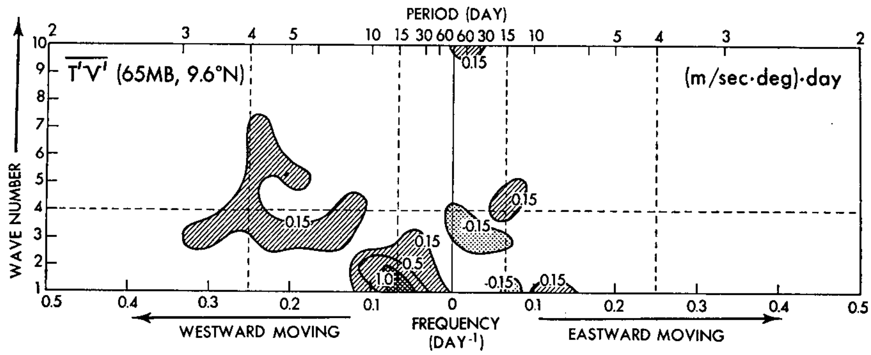

FIG. 26. Wavenumber-frequency section of co-spectra of meridional flux of sensible heat at 65 mb at 9.6N.

are found mainly responsible for transporting sensible heat away from the equator in the stratosphere as observed by Maruyama (1968b) and Yanai and Hayashi (1969) for mixed Rossby-gravity waves. Poleward flux of sensible heat is also a measure of upward flux of wave energy (Eliassen and Palm, 1960; Yanai and Hayashi, 1969).

Fig. 27 shows a latitude-height section of meridional flux of sensible heat integrated over wavenumbers 1∼2 and periods of 10∼20 days, corresponding to westward moving Rossby-type waves. This shows that the sensible heat flux reverses its sign just below the tropopause where the vertical phase line (see Fig. 9a) bends, consistent with the well-known relation by Eliassen and Palm (1960). This fact may partly be responsible for the maintaining of the minimum temperature at the tropical tropopause (see also Manabe *et al.*, 1973).

This poleward sensible heat flux also plays an important role in the momentum balance. It induces a secondary mean meridional circulation in such a way as to counterbalance its effect adiabatically (Charney and Drazin, 1961). In the presence of dissipation or a critical level (Booker and Bretherton, 1967), this induced circulation results in an easterly acceleration of the mean zonal wind, as discussed by Dickinson (1968, 1969) and Matsuno (1971) for middle-latitude Rossby waves and by Hayashi (1970) and Lindzen (1970b) for equatorial waves.

8. Conclusions and remarks

Based on a space-time cross spectral analysis, the following information has been gained concerning the tropical disturbances appearing in the GFDL general circulation model during the period July through October.

a. Analysis of wind

Four types of traveling waves are isolated from stationary waves and ultra-long waves extending from middle latitudes:

1) Kelvin waves with wavenumbers 1∼2, a period of 15 days, moving without a meridional component. They attain their maximum amplitude at 38 mb with their phase lines tilting eastward and

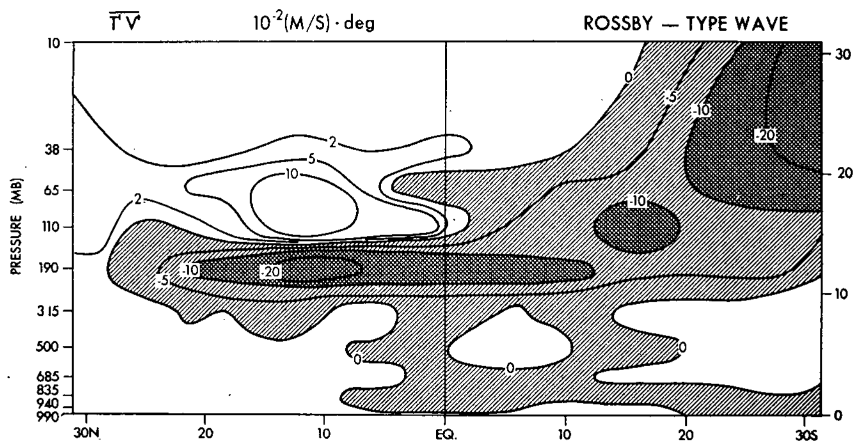

FIG. 27. Latitude-height section of co-spectra of meridional flux of sensible heat integrated over wavenumber 1∼2 and over periods of 10∼20 days (westward moving).

westward with height in the stratosphere and the troposphere, respectively. Their spectral peak is sharper in the stratosphere than in the troposphere.

2) Mixed Rossby-gravity waves with wavenumbers 3~5, a period of 3~5 days, moving westward with their vortices centered over the equator. They attain their maximum at 110~190 mb with their phase lines tilting westward and eastward in the stratosphere and the troposphere, respectively. Their spectral peak is sharper in the stratosphere than in the troposphere.

3) Rossby-type waves with wavenumbers 1~5, a period of 15 days, moving westward with their vortices centered off the equator. They attain their maxima at 110~190 mb with their phase lines tilting westward and eastward in the stratosphere and the troposphere, respectively. They have a distinct spectral peak in the troposphere.

4) Easterly waves with wavenumbers 8~10, moving westward with a period of 15 days in the Eastern Hemisphere and 5 days in the Western Hemisphere. They attain their maximum at 835 mb and 190 mb in the summer hemisphere, with their phase line tilting very slightly eastward in the lower troposphere. They have a distinct spectral peak in the troposphere.

b. Analysis of rain

1) Rainfall disturbances with periods of 4~20 days are associated with a more westward phase velocity than an eastward velocity. They are localized particularly in the western Pacific in the Northern (summer) Hemisphere where the sea surface temperature is comparatively high.

2) Rainfall disturbances are closely related to the vertical velocity in the troposphere. They have similar wavenumber-frequency spectra, in-phase relationships and similar geographical distribution.

3) Rainfall disturbances have distinct wavenumber-frequency spectra corresponding to Rossby-type waves and easterly waves, while they have rather vague spectra corresponding to Kelvin and mixed Rossby-gravity waves.

4) Latent heat release is a primary energy source to maintain the kinetic energy of the tropical transient disturbances.

c. The primary role of tropical disturbances in the general circulation model

1) Kelvin waves transport westerly momentum upward into the stratosphere, resulting in a westerly acceleration of the zonal flow.

2) Mixed Rossby-gravity waves transport sensible heat away from the equator in the stratosphere, implying an easterly acceleration of the zonal flow by the induced mean meridional circulation.

3) Rossby-type waves transport both westerly momentum and sensible heat away from the equator in the stratosphere. They are partly responsible for the cross-equatorial flux of momentum.

4) Easterly waves are an important constituent of the ITCZ.

The above results may be interpreted as follows. There seems to be a mutual interaction between large-scale disturbances and convection, presumably through moisture convergence as in the case of the CISK theories. Due to this coupling, a broad spectrum range of waves are generated and maintained by the latent heat released by the rainfall in the region where the sea surface temperature is comparatively high. Among them are easterly waves and Rossby-type waves which are associated with distinct spectral peaks in the troposphere. Others are mixed Rossby-type gravity waves and Kelvin waves which are associated with rather vague spectra in the troposphere, but attain a sharper spectral peak and a more distinct normal mode pattern as they penetrate into the stratosphere as in the case of the thermally forced wave theories.

However, we still do not know why rain spectra are not random noise but, instead, exhibit certain characteristic wavenumbers and phase velocities. Convection and large-scale waves may be efficiently coupled at some scale and periods. The preferred scale may also be influenced by the disturbances extending from middle latitudes as suggested by a dry model of Manabe (1970b). It may also be due to geographical effects such as the distribution of the sea surface temperature. This problem will be left for a future control experiment.

In this study more interest was placed in transient than stationary waves. However, large-scale stationary waves have significant kinetic energy in the tropics. It will be important to make a more detailed analysis of the model and the observed stationary waves especially in relation to the monsoon and the east-west circulation (see Krishnamurti, 1971b, and Krishnamurti *et al.*, 1973) and also in connection with the theoretical studies of equatorial stationary waves (Matsuno, 1966; Webster, 1972, 1973a, b; Holton and Colton, 1972).

For a better description of the model's easterly waves it is necessary to make a detailed regional analysis. A further description of the 5-day period pressure waves and the ultra-long waves extending from middle latitudes will require an extension of this analysis to middle latitudes. In order to isolate 40–50 day period oscillations reported by Madden and Julian (1971, 1972) and Parker (1973b), a much longer time series must be analyzed. On the other hand, a time series with a much shorter time step must be analyzed in order to extend the analysis of tidal oscillations appearing in a general circulation model by Hunt and Manabe (1968). It is also important to clarify the nonlinear wave-wave interaction in the tropics, as studied numerically by Manabe *et al.* (1971a), Colton (1973) and T. Murakami (1973b), and observationally by Kanamitsu *et al.* (1972).

Since Maruyama (1971) showed that observed equatorial disturbances vary significantly with seasons, it is of interest to analyze other seasons with different sea surface temperature distributions and different wind shear.

For a better simulation, it is of primary importance to increase the horizontal and (especially) vertical resolutions in the stratosphere in order to resolve equatorial waves sufficiently. The multi-layered structure of the wind disturbances observed by Madden and Zipser (1970) may be completely missing in the present model.

Compared with a numerical simulation of the general circulation, however, much higher accuracy will be required in a numerical prediction of tropical weather, such as attempted by Krishnamurti (1969) and Miyakoda *et al.* (1973). Moreover, errors in the tropics can significantly influence middle latitudes, as numerically demonstrated by Gordon *et al.* (1972), Miyakoda and Umsheid (1973) and M. Murakami (1973). It is hoped that further improvement will be made by a more advanced parameterization, such as those being developed theoretically by Arakawa (1969), Ooyama (1971) and Arakawa and Schubert (1973) and observationally by Yanai *et al.* (1973).

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APPENDIX

Computation of Space-Time Cross Spectra

The following is a brief description of a technique of computing space-time cross spectra employed in this paper. For details the reader is referred to Hayashi (1971e, 1973).

Initially, we compute the space-Fourier cosine and sine coefficients of two sets of space-time series $W(x,t)$ and $W'(x,t)$ at each time step, where

$$\left.\begin{aligned} W(x,t) &= \sum_k C_k(t)\cos kx + S_k(t)\sin kx \\ W'(x,t) &= \sum_k C'_k(t)\cos kx + S'_k(t)\sin kx \end{aligned}\right\}.$$

In the present analysis the four-time fast-Fourier transformation (FFT) method of G. P. Williams (1969) was employed. This technique only requires that the number of data be a multiple of 4, while the ordinary FFT (Cooley and Tukey, 1965) requires a power of 2.

Next, space-time cross spectra are obtained by applying conventional time series cross spectrum analysis to these Fourier coefficients as follows:

Power spectra

$$4P_{k,\pm\omega}(W) = P_\omega(C_k) + P_\omega(S_k) \pm 2Q_\omega(C_k,S_k)$$

Co-spectra

$$4K_{k,\pm\omega}(W,W') = K_\omega(C_k,C'_k) + K_\omega(S_k,S'_k) \pm Q_\omega(C_k,S'_k) \mp Q_\omega(S_k,C'_k)$$

Quadrature spectra

$$4Q_{k,\pm\omega}(W,W') = \pm Q_\omega(C_k,C'_k) \pm Q_\omega(S_k,S'_k) - K_\omega(C_k,S'_k) + K_\omega(S_k,C'_k)$$

Phase difference

$$\text{Phase}_{k,\pm\omega}(W,W') = \tan^{-1}[Q_{k,\pm\omega}(W,W')/K_{k,\pm\omega}(W,W')]$$

Coherence

$$\text{Coh}_{k,\pm\omega} = \left[\frac{K^2{}_{k,\pm\omega}(W,W') + Q^2{}_{k,\pm\omega}(W,W')}{P_{k,\pm\omega}(W)P_{k,\pm\omega}(W')}\right]^{\frac{1}{2}}.$$

In the above k and ω are wavenumber and frequency, respectively, and the plus and the minus signs correspond to westward and eastward moving waves, respectively. P_ω, K_ω and Q_ω are time-series power spectrum, co-spectrum and quadrature spectrum, respectively.

The advantage of this method is that a ready-made program of time-cross spectra can easily be converted to that of space-time cross spectra. The time-cross spectra can be computed either by the lag correlation method (Panofsky and Brier, 1958; Munk *et al.*, 1959; Maruyama 1968a) or by the fast Fourier method (Bingham *et al.*, 1967; Julian, 1971). The present method is more general than the quadrature spectrum method (Deland, 1967, 1972a; Eliasen and Machenhauer, 1969) and more reliable and flexible than the two-dimensional Fourier method (Kao, 1968; Kao and Kuczeck, 1973).

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