Some Features of Synoptic-Scale Waves Based on a Compositing Analysis of GATE Data

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ABSTRACT

A compositing technique has been used to analyze the wind field of easterly waves in the GATE region of western Africa and the eastern Atlantic. The compositing analysis is similar to the method of Reed and Recker (1971), but this study includes variations of the waves as a function of latitude in addition to variations as a function of east–west wavelength and height. A wave composited for the summer of 1974 has been isolated from the mean flow and analyzed on constant pressure maps. From these analyses, kinematic vertical motion has been computed in the lower and middle troposphere. The results show that the pattern of vertical motion calculated from the compositing agrees quite well with satellite cloud patterns.

1. Introduction

Several different synoptic-scale waves have been identified in the tropical troposphere and stratosphere since the early investigations of easterly waves in the Caribbean region by Riehl (1945). Most of these early studies of tropical wave motion used the case study approach. This method is limited, however, because adequate upper air observing networks exist only in the Caribbean and the western Pacific and because the amplitude of the waves is small compared with the mean flow. Rosenthal (1960) and Yanai *et al.* (1968) showed that power-spectrum methods could be used successfully to define the properties of these waves. Subsequent power-spectrum computations with upper air data have produced a much better understanding of the structure and energetics of several waves in both the troposphere and the stratosphere. The spectral technique has been particularly useful in analyzing data from widely spaced stations and in isolating statistics of the wave structure from the mean flow. A basic assumption of the spectral method, however, requires that the phenomenon being investigated have a nearly constant period. In the atmosphere the period of the waves varies considerably; therefore, the accuracy of the quantities determined by the power-spectrum method is uncertain.

Compositing analyses have also been used frequently to study atmospheric wave motion. For example, Schedler (1921) has investigated mid-latitude cyclones with compositing analyses and López (see Fig. 8 of Graves, 1951) and Reed and Recker (1971) have studied synoptic-scale wave motion in the tropics. Compositing requires a method for tracking individual waves so that the data can be normalized relative to a particular wave feature; thus the analysis is not limited by the assumption of a nearly constant period. Both power-spectrum and compositing techniques, however, give results that are representative of an average wave. Those waves that differ greatly from the average will not be adequately described by either of these methods. This paper shows how the compositing methods used by López and Reed and Recker can be extended to determine wave structure in two horizontal dimensions. The method is applied to the easterly waves observed in the lower and middle troposphere of western Africa and the eastern Atlantic during the GARP Atlantic Tropical Experiment (GATE).

2. Data

The wind observations used in this study were taken from 25 June to 24 September 1974 during GATE. The data were obtained with radar equipment twice each day for nine land stations in western Africa and four times daily from ten of the GATE ships whenever these ships were within 100 km of their assigned positions. Figure 1 shows the location of each station. During Phase I of the experiment the positions of the *Vanguard* and *Vize* were interchanged from those shown in this figure. All of the wind observations are preliminary, unvalidated data from the surface, 850, 700, 500, and 200 mb.

3. The compositing method

During July the easterly waves of western Africa and the eastern Atlantic were most easily followed on the 700 mb maps near 15°N. From mid-August through September, when the waves reach their maximum amplitude, they were also observed on the 850 and 500 mb

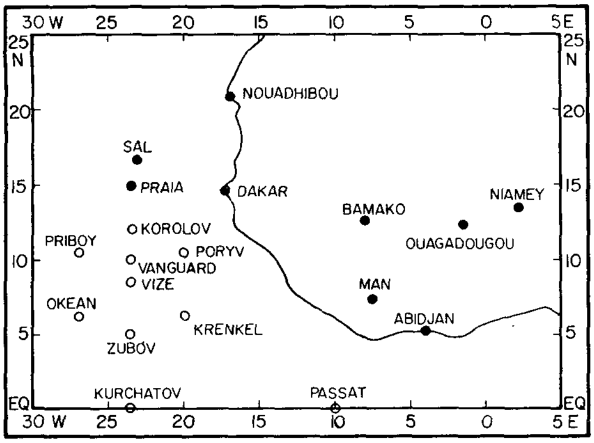

FIG. 1. The nine land stations and ten ships that were used in the compositing analyses. Open circles indicate ship locations and solid circles indicate land stations.

charts and sometimes at the surface as well. During the experiment an uninterrupted series of waves propagated through the GATE region. Analysis of the preliminary data indicate that 24 waves crossed the West African coast from late June until mid-September. Two others were followed across western Africa, but merged with another wave, or weakened just west of the coast. The average period for these waves was 3.5 days and the average wavelength was 2500 km. Considerable variations in both the period and wavelength were evident, however, as the period ranged from 2.5 to 5.5 days and the wavelength from 1500 to 4000 km.

In order to specify the location of the waves, a diagram was prepared with the 700 mb meridional wind at five stations near 15°N plotted as a function of longitude and time. Before the 700 mb meridional wind was plotted, it was filtered to remove periods shorter than 1.5 days and longer than 10 days. At all of the stations the maximum northerly wind associated with each wave was specified, and a second diagram was made which shows the maximum northerly wind of the waves as a function of longitude and time. The time of passage of the maximum northerly wind was recorded at each 5 degrees of longitude from 5°E to 30°W and was linearly interpolated for stations at other longitudes. The time interval between successive maxima of the 700 mb northerly wind near 15°N was divided into eight equal parts and the wind data were then categorized according to these eight equal time intervals. Category 1 was centered on the time of the northerly wind maximum and the seven other categories were equally spaced between the times designated as category 1. Thus category 5 corresponds approximately to the southerly wind maximum, while categories 3 and 7 correspond to the trough and ridge axes respectively. Categories 2, 4, 6, and 8 occupy intermediate positions. Every station from 2°E to 27°W has been categorized according to the category number for its longitude in the 700 mb meridional wind analysis at 15°N. Before the compositing results were calculated, mean values for all available observations in the time interval from the beginning of the first wave to the end of the last wave were subtracted from the data at each station and level. The compositing analysis was carried out by averaging all of the zonal and meridional winds in each category and then computing the mean wind direction and speed for each of the eight categories. Since the mean has been subtracted from each time series, the results show the structure of the waves without any influence from the mean flow. The statistics from the composited data represent a wave that has been normalized in time. Surface and upper air data for stations at all latitudes have been composited on the basis of the wave analysis at 15°N. Because the wave features slope in the vertical and with latitude, category 1 at other latitudes and other pressure levels is not necessarily associated with the maximum northerly wind.

4. Results

The composited surface and upper air observations of the land stations were compared with the ship data and very little difference was found for stations at nearly the same latitude; therefore, it was decided to combine the results of both land and ocean stations.[1] The vertical structure of the meridional wind of the waves near 15°N is shown in Fig. 2a. This figure is an average for Dakar, Praia, Sal, and the Korolov. The trough and ridge axes tilt eastward with height (i.e., toward a higher category) where there is easterly shear of the mean zonal wind from the surface to 600–700 mb, then they tilt westward with height where there is westerly shear of the mean

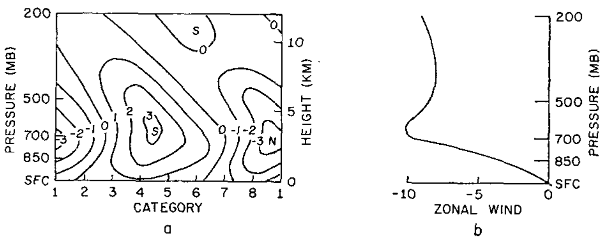

FIG. 2. Compositing results for (a) the meridional wind of the easterly waves near 15°N with the data from Dakar, Praia, Sal, and the *Korolov* and (b) the mean zonal wind as a function of pressure at these same stations. All winds are in m s^{-1}.

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[1] The small difference between the composited wind data in western Africa and the eastern Atlantic is somewhat surprising because the north-south gradient of surface temperature is oriented in opposite directions in these two areas. Examination of north–south cross sections of zonal wind in extreme western Africa near 7.5°W and in the eastern Atlantic at 23.5°W (Burpee and Dugdale, 1975) shows that the differences between the two cross sections tend to be small when compared to the monthly mean surface temperature patterns. Apparently the mean zonal wind and the wind associated with the waves require a greater horizontal distance to adjust to the change in surface temperature gradient.

zonal wind (Fig. 2b). The maximum amplitude of 3.5 m s^{-1} occurs at 700 mb. There is no obvious evidence of the waves at 200 mb, but they are very clearly present at the 500 mb level with an amplitude of 2.5 m s^{-1}. Diagrams similar to Fig. 2a were first computed by Reed and Recker (1971), who analyzed observations from several stations near 10°N in the Western Pacific. In this study upper air observations are available at several different latitudes. It is possible, therefore, to plot the composited data on a map of constant pressure with latitude as the north-south coordinate and the wave categories (i.e., an average wavelength of 2500 km) as the east-west coordinate. The composited results for the zonal and meridional winds have been averaged for those stations near the equator, 6, 10, 14 and 19°N and the averaged wind direction and speed plotted as a function of category and latitude. Each of the composited winds is an average of at least 25 observations and, at two of the latitudes, the composited winds have been averaged for nearly 150 observations. The winds have been analyzed with streamlines and isotachs. Figure 3 shows examples of the streamline analyses for the surface and 700 mb. Even though the wind speeds associated with the waves are generally less than 20% of the mean flow and many of the wind speeds at the surface are less than 1 m s^{-1}, the composited wind directions have a definite pattern and the streamlines are easily drawn. It should be remembered that the compositing analysis has been based on the subjective

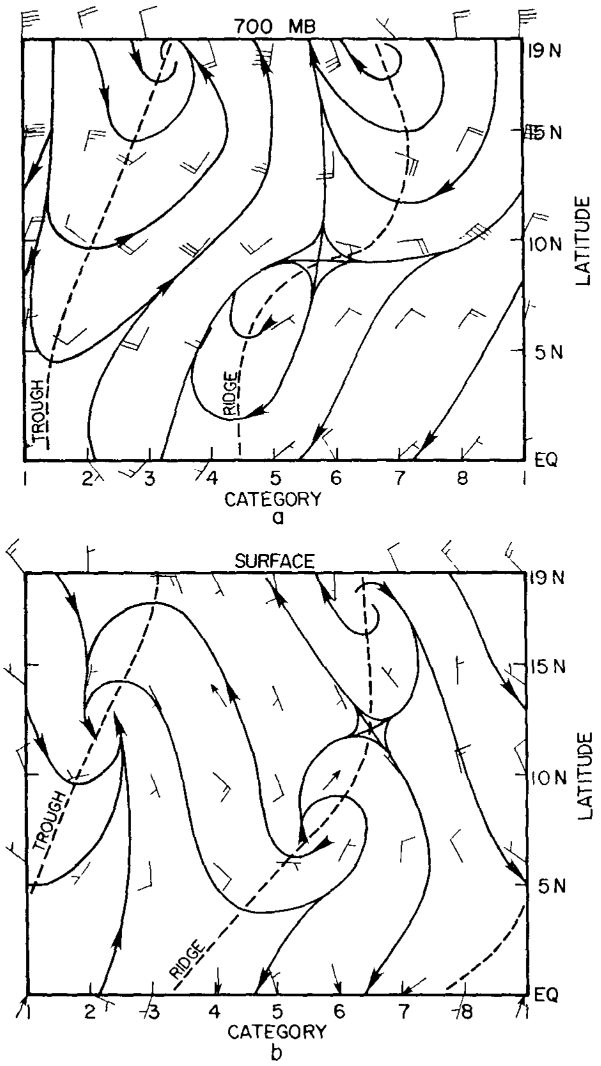


Fig. 3. Streamline analyses of easterly waves and composited wind direction and speed at (a) 700 mb and (b) the surface. The solid lines are the streamlines and the dashed lines are the trough and ridge lines. The wind barbs show the composited wind speed. Each full barb indicates a speed of 1 m s^{-1} and half a barb indicates 0.5 m s^{-1}. Wind speeds less than 0.3 m s^{-1} are shown by wind vanes without any barbs.

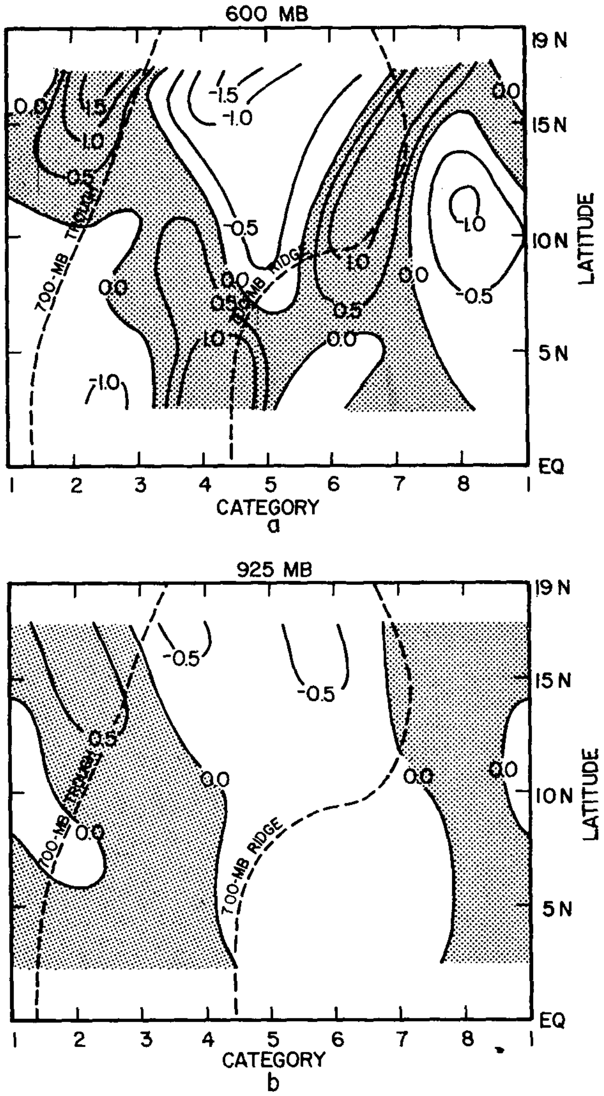


Fig. 4. The kinematic vertical velocity (cm s^{-1}) for the composited waves at (a) 600 mb and (b) 925 mb.

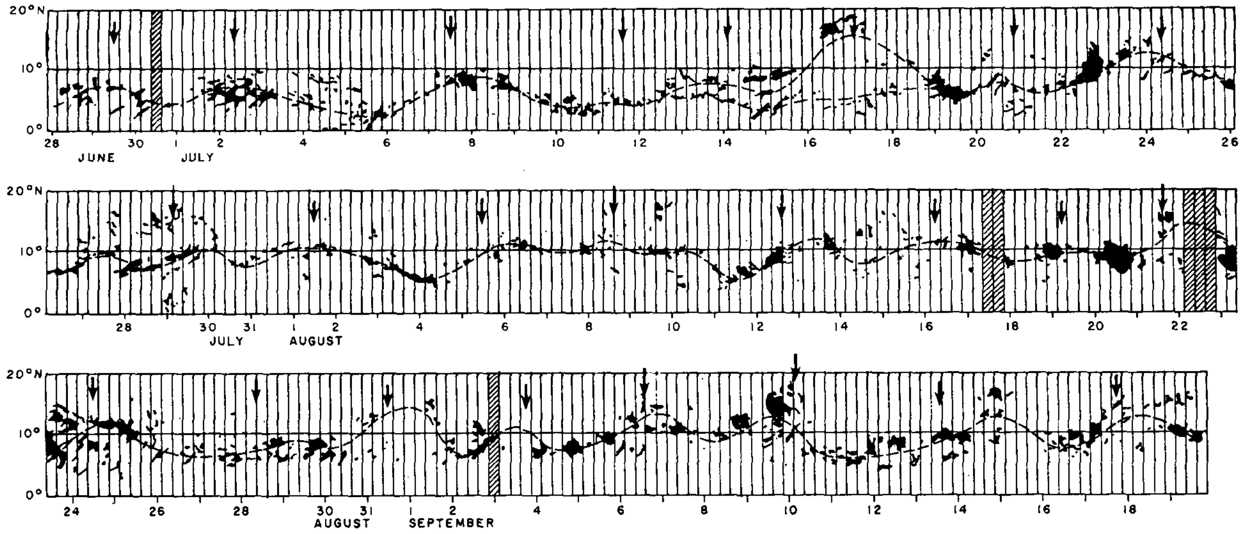


FIG. 5. Time section of the upper level cloud in a 1.5 degree longitude band centered on 23.5°W from 28 June through 19 September 1975. The dates are placed under the sketch of the 0000 GMT picture. This figure was provided by George Dugdale, Reading University, Reading, England.

analysis of the 700 mb meridional wind near 15°N. The wind analyses at all other pressure levels and at the other latitudes have been computed objectively according to the 700 mb analysis near 15°N.

At both the surface and 700 mb there is a horizontal tilt of the trough and ridge axes from southwest to northeast. The 700 mb amplitude of the composited wave at the equator is 1 m s^{-1} and at 19°N it is 3.5 m s^{-1}. The maximum 700 mb amplitude is north of the GATE ships near 15–20°N. The streamline maps indicate that the waves extend south of the equator and north of 19°N.

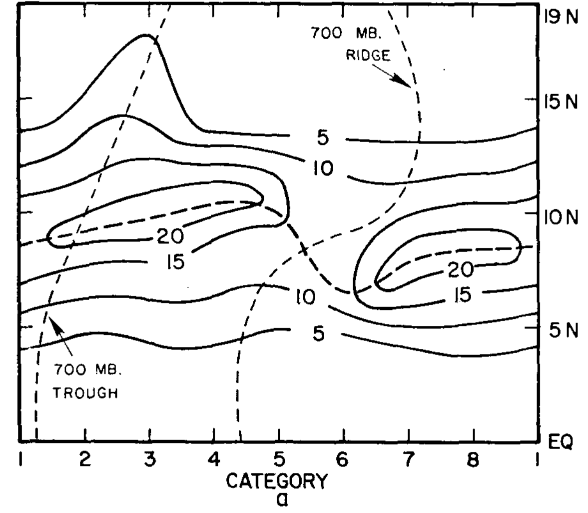
The wind data at the surface, 850, 700, and 500 mb were used to compute kinematic vertical motion for the composited wave at 925, 775, and 600 mb. The 925 mb pattern of vertical motion is fairly simple, with upward motion generally in categories 8, 1, 2, and 3 and descent in categories 4 to 7 (Fig. 4). The maximum value of the vertical motion at 925 mb is about 0.5 cm s^{-1}. Since the wind speeds are quite small near the surface, confluence and diffluence are more important than velocity gradients in determining the vertical motion at low levels. At 700 and 500 mb the gradients of wind speed are more important in the divergence calculations. As a result, the pattern of vertical motion at 600 mb (Fig. 4) is more complicated. The maximum value of vertical motion at 600 mb is 1.5 cm s^{-1}.

The easterly waves were important in modulating the convection in the Intertropical Convergence Zone near the GATE ships. This is shown in Fig. 5, a latitude-time cross section of the upper level or brightest cloud in the infrared satellite pictures of SMS-1. In this diagram the brightest clouds in the satellite pictures have been subjectively reproduced at 6 h intervals in the strip between the equator and 20°N from 22.75°W to 24.25°W. Each satellite strip in the figure is 1.5° wide and is centered on 23.5°W, the central longitude of the GATE ship array. The satellite images at the nearest possible time to 0000, 0600, 1200, and 1800 GMT were used to prepare Fig. 5. The arrows near 15°N indicate the time that the 700 mb troughs of each easterly wave crossed 23.5°W at 15°N.

Each strip of the satellite pictures was composited in the same manner as the wind data, and the percent of the area covered by the brightest cloud was determined for each 2.5° of latitude. Since the mean latitude of the convective activity during the first month of GATE was farther south than that for the remainder of GATE, the pictures before 0000 GMT 20 July were adjusted northward in order to be compatible with the later pictures. The composited satellite picture (Fig. 6a), which includes the latitudinal mean, shows that most of the brightest cloud occurred between 5 and 15°N. This figure also reveals that both the amount and location of the upper level cloudiness were modulated by the passage of the waves. The brightest cloud occurred farthest to the north between the 700 mb trough and the next ridge to the east (category 4) and farthest to the south in category 6 which is near or just to the west of the 700 mb ridge. Category 6 is also the region where the least amount of cloudiness occurred. Since convective areas are positively correlated with the upper level cloud, the variations in time and latitude of the brightest cloud in the infrared pictures should be closely related to similar variations of convective activity.

Kinematic vertical motion for the mean flow at 23.5°W was calculated so that the total vertical motion near the surface could be compared with the composited satellite picture. There were some difficulties specifying the mean flow for the divergence calculations because only two stations were available west of 23.5°W. Despite this problem the sign and magnitude of the kinematic vertical motion seem to be reasonable. At 925 mb the maximum upward motion of the mean flow was 0.7 cm s^{-1} just south of 10°N, while the maximum upward motion associated with the wave near 10°N was 0.5 cm s^{-1}. The diagram of total vertical velocity at 925 mb was constructed by adding the mean vertical motion for each latitude at 23.5°W to the wave vertical motion. The variations in the total vertical motion at 925 mb (Fig. 6b) are very similar to those of the composited satellite picture. Those areas with upward motion in excess of 0.5 cm s^{-1} are positively correlated with greater than average brightness on the infrared pictures. Category 5 near 5–10°N has very slight upward motion. This is approximately the same region as the relative minimum in cloud amount. Farther north in the region near 15°N, the maximum amount of cloudiness occurred in categories 2 and 3, just west of the 700 mb trough.

PERCENT OF AREA COVERED BY UPPER-LEVEL CLOUD



TOTAL VERTICAL MOTION AT 925 MB

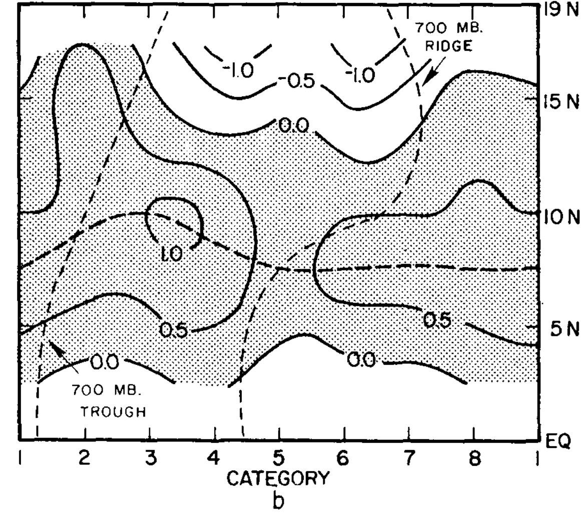


Fig. 6. The compositing results of (a) the upper level cloud amount as determined from the infrared satellite pictures of SMS-1 and (b) the total vertical motion in cm s^{-1} at 925 mb. Both figures have been computed at 23.5°W.

5. Conclusions

This study has described a compositing technique for analyzing synoptic-scale wave motion; the technique is similar to that used by Reed and Recker (1971). The method has isolated a composited wave from the mean flow even at pressure levels where the wave amplitude was only 1 m s^{-1}. Kinematic vertical motion has been calculated from the composited wind data and the resulting pattern of vertical motion is consistent with the cloudiness observed on the satellite pictures. Although only wind data were available for these calculations, the results indicate that temperature, geopotential, and humidity can also be investigated by this method. A complete description of the structure and properties of synoptic-scale waves may be possible with this compositing technique by analyzing the GATE data or even by analyzing some of the regular upper air networks.

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REFERENCES

Burpee, R. W., and G. Dugdale, 1975: A summary of weather systems affecting western Africa and the eastern Atlantic during GATE. Report on the Field Phase of the GATE Scientific Programme, GATE Report No. 16, 2.1–2.42.

Graves, M. E., 1951: The relation between the tropopause and convective activity in the subtropics (Puerto Rico). *Bull. Amer. Met. Soc.*, 32, 54–60.

Reed, R. J., and E. E. Recker, 1971: Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific. *J. Atmos. Sci.*, 28, 1117–1133.

Riehl, H., 1945: Waves in the easterlies and the polar front in the tropics. Misc. Rept. No. 17, Dept. of Meteorology, University of Chicago, 79 pp.

Rosenthal, S. L., 1960: Some estimates of the power spectra of large-scale disturbances in low latitudes. *J. Meteor.*, 17, 259–263.

Schedler, A., 1921: Die Beziehung zwischen Druck und Temperatur in der Freien Atmosphäre. *Beitr. Physik Freien Atmosphäre*, 9, 181–201.

Yanai, M., T. Maruyama, T. Nitta, and Y. Hayashi, 1968: Power spectra of large-scale disturbances over the tropical Pacific. *J. Meteor. Soc. Japan*, 46, 308–323.