C00-2153-3

SEASONAL VARIATIONS
OF
TROPICAL WIND SPECTRA
VOLUME II: Analysis

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Final Report
Contract AT-1-2153

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Prepared for
U. S. Atomic Energy Commission
Washington, D. C.

May 15, 1974

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Abstract

The seasonal variation of properties of synoptic wind spectra are described from time series of rawinsonde data in the tropics. Spectral properties include total kinetic energy, ratio of meridional to zonal kinetic energy, and the slope of the spectrum for both meridional and zonal wind components. Horizontal and vertical cross spectrum properties are also examined on a regional basis. The intraseasonal variation of kinetic energy of the synoptic eddies at 850 and 200 mb is examined with respect to various properties of the seasonal flow. At 850 mb, in the easterly trades of the western Pacific, kinetic energy varies inversely with resultant wind speed and also, inversely with divergence. In the Caribbean during winter and spring, kinetic energy is proportional to vertical wind shear. On a global basis, kinetic energy at 200 mb is proportional to vertical wind shear during the winter and spring seasons. Finally, a statistical diffusion model is formulated that numerically uses the spectral properties described above.

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SEASONAL VARIATIONS OF TROPICAL WIND SPECTRA

VOLUME III: Analysis

I. OBJECTIVE

The spectra and cross spectra of synoptic scale wind variability is investigated in the tropics for the purpose of characterizing large-scale diffusion. Such spectral properties can be used to describe the relative diffusion of particles as a function of time scale.

Initially, properties of synoptic wind spectra and cross spectra for tropical stations are analyzed with respect to regional and seasonal variability. The spectral properties for the frequency range $2\pi/12 - 2\pi/2 \text{ day}^{-1}$ include kinetic energy of the horizontal wind, the ratio of the kinetic energy of meridional wind to the kinetic energy of zonal wind, and the slopes of the power spectrum for both wind components. A description of kinetic energy of the horizontal wind for the frequency range $2\pi/2 - 2\pi/1 \text{ day}^{-1}$ is also included. In addition such cross spectrum properties as phase and coherence are indicated horizontally and vertically at prominent spectral frequencies for selected groups of tropical stations. All statistical parameters are determined from a base of raw spectral wind component data for various tropical stations at 850, 500, 200, 70, and 30 mb for the period September 1963 to December 1970.

An attempt is made to describe the intraseasonal variability of kinetic energy among tropical stations in terms of variations of properties of the seasonal mean flow such as vertical shear of the horizontal wind, resultant wind speed, vorticity, divergence and lapse of equivalent potential temperature. Such relationships may be useful for extrapolating diffusion parameters into remote regions where synoptic data do not exist. This comparison of kinetic energy and flow parameters is confined to the 850 and 200 mb levels. ~~The purpose of the present study was distorted by errors~~
of a tentative two particle horizontal diffusion model that could be used.

~~The use of the wind statistics is discussed in terms of a tentative two~~
particle horizontal diffusion model that could be used to compute numerically the mean square separation of two particles as a function of particle separation and the nonhomogenous variation of wind variance along the particles' trajectories. While the primary use of the model is to describe diffusion on a climatological basis, there are real-time and prognostic applications for diffusion resulting from nondeterministic wind components. The advocated diffusion model is only described on a theoretical basis and has not been practically evaluated.

II. PROCEDURE

The spectral parameters have been computed from time series of 12 and 24-hourly rawinsonde winds that have been prefiltered to isolate synoptic waves with periods of 1 to 25 days. There was no interpolation of missing observations. Filtering was accomplished in terms of a convolution of a series of Gaussian weights with the observational time series. The resulting weights are normalized so that their sum is always equal to 1.0 for all distributions of data beneath the filter. Auto-variances and covariances are then computed from the resulting filtered time series. Hanned spectral estimates are formulated from the auto-variances and covariances in the traditional manner, although corrections are added to the first two and the last two frequency components of the spectrum to help preserve the basic shape of the spectrum that was distorted by Hanning. The spectrum was computed with a resolution of $2\pi/12 \text{ day}^{-1}$ and consists of thirteen components. This was the most detailed resolution that was permissible on an individual seasonal basis as determined from the number of missing data at high levels for many tropical stations. A complete description of the computation procedure is provided in Volume I of this report.

The above analysis is similar to that of Wallace (1971) and Yanai, et al. (1968), except that the current study contains spectral characteristics for longer periods and also tropical stations outside the Pacific. This enables a comparison of spectral properties on a global basis and also allows an examination of year to year variability.

A preliminary examination of power spectra plotted on a logarithmic scale revealed that the energy decreases approximately linearly in the frequency range $2\pi/12 - 2\pi/2 \text{ day}^{-1}$. In the frequency range $2\pi/2 - 2\pi/1 \text{ day}^{-1}$, the energy was small and was distributed nearly uniformly with frequency, except for the occurrence of a small peak corresponding to the diurnal variation. Thus, the power spectrum of each wind component (13 values) was reduced to three essential properties: (1) The energy in the band $2\pi/12 - 2\pi/2 \text{ day}^{-1}$, (2) the power variation of energy with frequency (slope) within this frequency range, and (3) of less importance, the

(slope) within this frequency range, and (3) of less importance, the energy in the frequency range $2\pi/2 - 2\pi/1 \text{ day}^{-1}$.

In the frequency range $2\pi/12 - 2\pi/2 \text{ day}^{-1}$, the spectra were fitted with the expression:

$$\ln\{\hat{S}(\omega_k)\} - \ln\beta = m \ln\{k\}$$

$$\hat{S}(\omega_k) = \beta k^m \quad (1)$$

The values m and β that were determined minimized the mean square difference between (1) and the first six spectral values beginning with the frequency $2\pi/12 \text{ day}^{-1}$. The magnitude (β) indicates the crossing point of the ordinate for $k = 1$. The total spectral energy (A) in the frequency band can be determined from (β) and the slope (m) as:

$$A = \beta[(2\pi/2)^{m+1} - (2\pi/12)^{m+1}]/(m+1) \quad (2)$$

Values of β are not given in this report as they can be derived from (2) in terms of the total energy (A) and slope (m). Further, the energy of the zonal and meridional winds is combined for analysis to produce the total horizontal kinetic energy, $u^2 + v^2$. A pilot study (Dartt, et al, 1972) indicated this parameter was better related to flow parameters than the energy of either wind component separately. The distribution of total energy between the meridional and zonal wind components is analyzed as the ratio of v^2/u^2 for the frequency range $2\pi/12 - 2\pi/2 \text{ day}^{-1}$. Thus, the independent variables to be considered for analysis are the kinetic energy ($u^2 + v^2$), the ratio v^2/u^2 and slope (m) of the zonal and meridional winds for this primary frequency band. The total energy in the frequency band $2\pi/2 - 2\pi/1 \text{ day}^{-1}$ is a secondary variable.

III. SPACE-TIME VARIABILITY OF SPECTRAL PARAMETERS

Primary regional properties of spectra and cross spectra of tropical winds are indicated below. These statistics are based on seasonal auto-variances and covariances determined for a consolidated seven-year period. (Winter includes December, January, February; Spring includes March, April, May; etc.) The primary frequency band $2\pi/12 - 2\pi/22\text{day}^{-1}$ contains most of the kinetic energy of wind for this study and hereafter is termed band 1. A secondary frequency band is the range $2\pi(7)/12 - 2\pi(12)/12\text{ days}^{-1}$ and is termed band 2.

A. KINETIC ENERGY - BAND 1

1. Patterns for Consolidated Seasons

Table 1(1) indicates the primary height-season distribution of kinetic energy for key tropical stations with the most upper air data in different regions of the tropics. Kinetic energy per unit mass increases from 850 mb to a maximum at 200 mb for all stations. From 200 to 30 mb, kinetic energy decreases rapidly, with kinetic energy at the 70 mb level usually larger than at 30 mb. As discussed in Volume I, the energy at 30 and 70 mb includes aliased contributions from frequencies greater than the sampling rate, especially at those stations with only 24-hourly data (Singapore, Canton, and Bangkok). Consequently, any spectral results for these three stations should not be considered particularly reliable at stratospheric levels. The longitude-season distribution of kinetic energy at 200 mb and 850 mb is also indicated for the Caribbean and Pacific (Tables 2a-7a). An analysis of these diagrams and the height-season patterns at individual stations indicates the following significant characteristics of the tropical kinetic energy distribution. (In these diagrams principal maxima are underlined solidly while minima are underlined with dashes.)

a. 200 mb

- (1) A general annual variation of kinetic energy occurs with amplitude largest at highest latitudes, i.e. Miami ($227-114\text{ m}^2/\text{sec}^2$).

- (2) Globally, at 14-18°N (San Juan, Swan, Dakar, Bangkok) the phase of the kinetic energy pattern is similar. However, the summer minimum is smaller at Dakar ($40 \text{ m}^2/\text{sec}^2$) and Bangkok ($36 \text{ m}^2/\text{sec}^2$) than at San Juan ($99 \text{ m}^2/\text{sec}^2$) or Swan ($84 \text{ m}^2/\text{sec}^2$). The winter maximum is also smaller at Bangkok than other stations.
- (3) In the Caribbean a general winter maximum and summer minimum of kinetic energy exists. Kinetic energy is greater in the eastern than western Caribbean for practically all seasons (Tables 2 and 3).
- (4) At 8°N in the western Pacific, the seasonal pattern is almost 180° out of phase with the Caribbean with a summer or autumn maximum and winter minimum (Table 4). However, the magnitude in the western Pacific is similar to that observed at these latitudes in the Caribbean (Table 3).
- (5) In the Indian Ocean at 8°N, Trivandrum indicates the seasonal variation of kinetic energy is similar to the Caribbean but out of phase with the western Pacific.
- (6) Ascension Island, 8°S, has a winter (southern hemisphere) maximum of kinetic energy. The pattern, which is out of phase with the Caribbean and Indian Ocean, may reflect the change of seasons between the northern and southern hemisphere.
- (7) Near the equator, Singapore, 1°N, indicates a pattern similar to the western Pacific; Canton Island, 3°S, indicates large values of kinetic energy, similar in magnitude to those at Ascension.

b. 850 mb

- (1) A generally weaker annual variation of kinetic energy is observed than at 200 mb. The magnitude is largest at highest latitudes, i.e. Miami ($59\text{--}24 \text{ m}^2/\text{sec}^2$).
- (2) Globally, at 14-18°N (San Juan, Swan, Dakar, Bangkok) a phase reversal occurs outside the Caribbean. Both Bangkok and Dakar indicate winter minima and summer or autumn maxima.
- (3) In the Caribbean a winter maximum and summer minimum of kinetic energy exists. Kinetic energy is greater in the western than eastern Caribbean (Tables 5 and 6) which is opposite of the pattern at 200 mb.

- (4) At 8°N in the western Pacific, an autumn maximum and spring minimum is indicated (Table 7). The amplitude of these variations is strongest at Koror and Yap, decreasing both eastward and westward from their meridian. The amplitude in the Pacific is stronger than is observed in the Caribbean at these latitudes.
- (5) In the Indian Ocean at 8°N , Trivandrum indicates a variation which is similar in phase to Dakar and Bangkok in (2) above.
- (6) Ascension has a weak spring maximum (southern-hemisphere) of kinetic energy.
- (7) Both Singapore and Canton indicate weak seasonal variations. Canton has a larger variation with summer (southern-hemisphere) maximum.

c. Other Levels

No detailed analysis of variability was undertaken at 500, 70 and 30 mb. However, Table 1 indicates that generally the stratospheric levels have summer minima and winter maxima which are reduced in magnitude from the variation observed at 200 mb. Canton and Ascension in the southern hemisphere show a phase reversal from stations in the northern hemisphere.

The kinetic energy at the 500 mb level does not appear to be independent of the pattern at 850 and 200 mb. The 500 mb pattern appears to be a composite of both the upper and lower levels. An interesting feature is that when the 200 mb and 850 mb patterns are completely out of phase, the 500 mb pattern may indicate a semiannual variation (Singapore; Table 1).

The features just described indicate much irregular variability on a seasonal and regional basis. As the kinetic energy patterns are based on seven years of data, such characteristics must be regarded as

real features of tropical synoptic variability. In Section IV of this report, the space-time variability of synoptic kinetic energy is explored with regards to seasonal patterns of wind and other variables.

2. Extreme Variations for Individual Seasons

Table 8 indicates the range of kinetic energy at 200 mb for individual seasons. These values include kinetic energy variations caused by missing observations as well as naturally occurring seasonal variability. The variability caused by missing observations was simulated by eliminating observations from actual time series with a random number generator. The rms difference between the spectral energy of the simulated and original time series were then computed for ten distinct distributions of missing observations as discussed in Volume I, Section IV. This value, when normalized with respect to the energy in the frequency band of a zonal or meridional wind component spectrum, gives a measure of spectral variability as a function of the number of complete data. This variability caused by sampling variations was computed separately for zonal and meridional wind components and then combined on a mean square basis to produce the sampling error of kinetic energy.

The $\pm 2 \sigma$ values in Table 8 are an indication of the sampling error of kinetic energy determined for autumn. The $+2 \sigma$ value is the value of the kinetic energy for the consolidated period plus two times the rms sampling error determined by the corresponding number of data points for the autumn maxima ($252 \text{ m}^2/\text{sec}^2$ for Miami). Similarly, the -2σ value is the value of the kinetic energy for the consolidated period minus two times the rms sampling error determined by the number of data points for the autumn minima ($136 \text{ m}^2/\text{sec}^2$ for Miami). When the number of data points are different for the extreme values, $+2 \sigma$ is not equal to -2σ .

If we hypothesize that the kinetic energy is the value for consolidated autumn, and the individual season extremes are caused by sampling variations, then we would expect to find 96% of the cases between the $\pm 2 \sigma$

limits. For seven seasonal values, perhaps one would occasionally occur outside the $\pm 2 \sigma$ limits. The autumn extreme values in Table 8 are consistently greater than the $\pm 2 \sigma$ limits for most stations. Thus, the hypothesis is rejected that all the calculated seasonal variability is caused by the varied distribution of observations for individual seasons. Conversely, a large portion of the yearly variability occurs naturally and is thus subject to later analysis (See Section IV).

Table 9 indicates the range of kinetic energy at 850 mb for individual seasons. For many stations, the variability for individual seasons would exceed the annual variation. As at 200 mb, the hypothesis can be made that the extremes are caused by variations in the distribution of data within a season. Again for most stations, this hypothesis would be rejected as the autumn extremes are generally outside the $\pm 2 \sigma$ limits. Thus, a large portion of inter-seasonal variability occurs naturally and is not caused by sampling variations.

B. KINETIC ENERGY - BAND 2

1. Patterns for Consolidated Seasons

Table 10 indicates the kinetic energy in the high frequency portion of the spectrum for the primary tropical stations. The kinetic energy is noticed to increase with height to a general maximum at 200 mb. At 70 mb the values of this parameter are smaller than at 200 mb, but an increase in kinetic energy occurs between 70 mb and 30 mb. Contributing to the kinetic energy at 30 mb is the diurnal tide which is one of the primary components of this frequency band. Some of the important space-time characteristics of the band 2 kinetic energy pattern are:

a. 200 mb

The seasonal pattern of kinetic energy for frequency band 2 is very similar in phase to that observed for band 1 (Table 1). However, the magnitude of the energy in band 2 is only 10-30% that found in band 1. Bangkok and Ascension are exceptions to the above description as the seasonal

pattern is out of phase with that described earlier for band 1.

b. 850 mb

Similar to 200 mb stations at a latitude greater than 13°N indicate a band 2 kinetic energy pattern that reflects the seasonal band 1 variation. The magnitude of the energy in band 2 is 10-40% that found in band 1. Stations near the equator have small values of band 2 kinetic energy and no annual variation.

c. Other Levels

At 30 mb, the phase of the band 1 pattern does not appear related to the band 2 kinetic energy pattern.

C. RATIO OF MERIDIONAL TO ZONAL KINETIC ENERGY - BAND 1

1. Patterns for Consolidated Seasons

The distribution of kinetic energy between the meridional and zonal components is indicated in Table 11 and in Tables 2-7b. This parameter appears to exhibit less systematic seasonal variability than was observed for kinetic energy. In the vertical, however, zonal kinetic energy exceeds meridional kinetic energy at all levels except at 200 mb, where the two components are often nearly equal. At 70 and 30 mb, the kinetic energy of the zonal component is two or three times greater than the kinetic energy for the meridional component.

a. 200 mb

- (1) Caribbean stations generally indicate more meridional kinetic energy than zonal kinetic energy, while in the western Pacific, the opposite is true.
- (2) Most stations in the central and southern Caribbean have a tendency for a maximum v^2/u^2 ratio in spring (Tables 2 and 3). However, there is no consistent seasonal variation for other stations.

b. 850 mb

- (1) The Caribbean has more energy distributed in the meridional component than the Pacific (Tables 5, 6 and 7). Seasonal variations appear small and inconsistent from one station to the next.
- (2) Some interesting standing variations appear between neighboring stations. For example, Balboa - San Andreas, Santo Domingo - Kingston are stations pairs where neighboring abnormal high and low ratios of meridional to zonal kinetic energy are observed simultaneously. These local variations probably reflect the influence of an orographic circulation.

c. Other Levels

At 30 and 70 mb the v^2/u^2 ratio is largest in summer-autumn and smallest in winter. The v^2/u^2 ratio was also

The v^2/u^2 ratio was also analyzed at both 850 and 200 mb with respect to such seasonal horizontal flow parameters as divergence, vorticity and $\bar{v}/\bar{u}$. The respective ratio of the components of the vertical shear, $\Delta\bar{v}/\Delta\bar{u}$ was also considered as a dependent variable for analysis. No consistent relation was found that would be useful for relating v^2/u^2 to seasonal flow patterns.

For later applications to diffusion (Section V), it is desirable to parameterize as much of the space and time variability of the spectral properties as possible. For the ratio v^2/u^2 , stratification by height and region would reduce a large portion of the overall variability. However, no useful relationships were found that could be used in estimating this parameter from properties of the seasonal mean flow. Seasonal values of σ_v^2 and σ_u^2 such as are available in tropical atlases (Newell, et al, 1972) also might be used to help define the v^2/u^2 ratio. This presumes that the ratio of component energies for the entire spectrum is similar to the respective ratio for one of its primary frequency bands.

is similar to the respective ratio for one of its primary frequency bands.

2. Extreme Variations for Individual Seasons

Table 12 indicates extreme values of the ratio v^2/u^2 for autumn. The $\pm 2 \sigma$ range was determined from:

$$2\sigma = [\{\Delta(v^2/u^2)\}^2]^{\frac{1}{2}} = 2[(\Delta v^2)^2 + (\Delta u^2)^2(v^2/u^2)^2]^{\frac{1}{2}}/u^2 \quad (3)$$

Where u^2 and v^2 are the zonal and meridional kinetic energy in band 1 of the spectrum. The parameters Δu^2 and Δv^2 are the simulated errors calculated for zonal and meridional components resulting from missing observations as described previously. The $\pm 2 \sigma$ range of variability of v^2/u^2 is determined from the value for autumn for consolidated years and the limits are based on the number of missing observations for individual season extreme values. It would appear that for most stations sampling variations are less than the observed variability, and thus, much of the intraseasonal variability occurs naturally.

D. SPECTRAL SLOPES FOR WIND COMPONENTS - BAND 1

1. Patterns for Consolidated Seasons

The power variation of energy with frequency is indicated in Table 13 and 2-7c for the zonal component and Table 14 and 2-7d for the meridional component. Both components show a transition from large negative slopes in the middle troposphere (500 and 200 mb) to smaller negative or even positive slopes in the stratosphere. The space-time pattern for the zonal component is similar to that of the meridional component. However, the zonal component slope is generally more negative (steeper) than for the meridional component.

a. 200 mb

- (1) On a global basis, the slope of the spectrum appears quite well correlated with the kinetic energy at 200 mb.

Figure 1 indicates that as the slope increases the kinetic energy also increases, which implies that the largest values of kinetic energy are associated with the lowest frequency components of the spectrum. This figure is based on seasonal values of kinetic energy (Table 1) and slope (Tables 13-14).

- (2) Seasonal variability of slope is small and nearly random for both zonal and meridional components in the Caribbean (Tables 2 and 3). However, both wind components indicate more negative slope in the eastern than western Caribbean (Merida and San Juan, San Andreas and Trinidad).
- (3) At 8°N in the Pacific (Table 4) slope increases (becomes more negative) from southeast Asia towards the central Pacific. Also, stations in the western Pacific have minimum slopes in the summer for the meridional component.

b. 850 mb

- (1) A more consistent annual variation appears than observed at 200 mb.
- (2) In the eastern Caribbean, a summer minimum generally occurs in the spectral slope of both wind components (Tables 55 and 66). Maximum slopes usually occur in autumn.
- (3) In the Pacific at 8°N maximum slopes occur in autumn (Table 7). A progressive phase reversal with season is indicated for meridional slope from southeast Asia towards the central Pacific. Also, greater slopes occur in the western Pacific (Koror-Yap) than in the central Pacific (Kwajalein-Majuro) during all times of year.
- (4) Globally, the slope of the zonal and meridional component spectrum is minimum (least negative) in either summer or winter and occasionally exhibits a semiannual variation. Practically all stations indicate summer minima for the meridional component (exceptions are Miami and Trivandrum). Winter minima for the zonal component occur in the western Pacific and Indian Ocean and at Miami. Summer slope minima occur for the zonal component in the Caribbean and Atlantic Oceans.

c. Other Levels

The slopes of the zonal and meridional component spectrum indicate a strong annual variation at most stations with the most positive (least) slope occurring in the summer at 70 and 30 mb.

2. Extreme Variations for Individual Seasons

The calculated range in seasonal variability of spectral slope at 200 mb is indicated for autumn in Table 15. The rms variability caused by missing observations was simulated by degrading the time series, as discussed earlier. The $\pm 2 \sigma$ limits for sampling variations with respect to the slope for the consolidated period are larger than the respective extreme values of slope for most stations. Therefore, most year to year variations could be caused by the distribution of missing observations within individual seasons. Natural intraseasonal variability of slope could only be investigated for time series with very complete data. No doubt sampling variability also contributes to the ~~interseasonal variability~~ of the patterns in Tables 13 and 14.

Table 16 indicates the range of individual autumn values for slope at 850 mb. As was the case for 200mb, most of the seasonal variability could be the result of incomplete data as the $\pm 2 \sigma$ limits are outside the range of the respective extreme values for many stations.

The increased sensitivity of slope to sampling variations as compared to the previous kinetic energy parameters is not unexpected. Slope depends on the resolution of each spectral component in the range $2\pi(1)/12 - 2\pi(6)/12$, while kinetic energy depends only on the total energy in this frequency band. Also, the high frequencies, which contribute little to kinetic energy but are weighted equally for slope, deteriorate first with regard to sampling errors.

The dependency of slope on properties of the seasonal flow was not substantially investigated. However, grouping the data by height,

season and region would greatly reduce the variability of the parameter for diffusion applications. Also, the relationship between kinetic energy and slope should be useful for extrapolating slope to regions of no data, provided the kinetic energy itself can be estimated (Section IV).

E. CROSS SPECTRUM PROPERTIES

Horizontal patterns of coherence and phase at 850 and 200 mb were computed in the western Pacific (7-9°N), middle Caribbean (15-18°N), and extreme south Caribbean (7-11°N). In addition, these spectral properties were determined vertically for time series at various standard pressure levels for selected tropical stations. In the following tables and diagrams, coherence and phase are indicated both for zonal and meridional components at periods of 12 and 4 days. These periods are independent components where appreciable spectral energy of wind occurs. Further, known wave phenomena have been investigated for these frequency bands in the tropics (Wallace, 1971). These are the long period Kelvin wave observed primarily in the zonal component at stratospheric levels, the short period mixed Rossby-gravity wave in the meridional component at upper tropospheric levels and the easterly wave in the lower troposphere.

All ~~cross spectrum parameters were~~ computed with a spectral resolution of $2\pi(1)/12 \text{ day}^{-1}$, thus the values for a period of 12 days encompasses periods ranging from 24-8 days, while values for the period of four days encompasses the range 4.8 - 3.4 days. Also, because the cross spectra were Hanned, there are contributions from the nearest neighboring frequencies. This crude resolution must be considered in the interpretation of results.

With regards to diffusion, coherence indicates spatial dependence and is a measure of the horizontal or vertical distance along a particles' trajectory for which the particle remembers its past for that particular scale of motion. Phase indicates the relative change of eddy flow between two positions along the particles' trajectory as a function of the scale of motion.

of motion. On a statistical basis both coherence and phase describe the space-time correlation pattern of wind variability as a function of scale. Such correlation functions are necessary for describing both one and two particle diffusion on a statistical basis (Taylor, 1921; Batchelor, 1952; Buell, 1972).

1. Horizontal Coherence for Consolidated Seasons

The indicated coherence is the squared value of that given in some texts. The value here represents the fraction of variability in a given frequency band between two time series that can be explained by the technique of linear regression. In the accompanying diagrams, coherence is plotted as a function of difference in longitude between stations that are located nearly along the same parallel of latitude. At 8°N in the Pacific, the pattern is based on Ponape, Majuro, Kwajalein and Truk; at 11°N in the Caribbean, the stations are San Andreas, Balboa, Curacao and Trinidad; at 17°N in the Caribbean, the stations are San Juan, Santo Domingo, Kingston, Grand Cayman, Swan, and Merida. Underlined stations were master stations to which the remaining stations were correlated. Also, only spring and autumn seasons are shown in Figures 2-5. These two seasons typify the annual variation of this parameter. Values of horizontal coherence and phase for all seasons are given in Appendix IV in Volume I of this report.

a. 200 mb

- (1) Figures 2 and 3 show that the longitudinal pattern in the western Pacific, 8°N , is quite similar to that observed in the central Caribbean, 17°N , for both 12 and 4 day periods, and both wind components. In the southern Caribbean, 11°N , coherence is smaller than observed above.
- (2) Larger values of coherence are observed for the 12-day than the 4-day period.
- (3) Seasonal changes appear minimal for all regions.

b. 850 mb

- (1) Regional variations are more apparent than observed at 200 mb. Figures 4 and 5 indicate that in the Pacific coherence decreases uniformly with distance; in the central Caribbean, coherence decreases more rapidly with distance than in the Pacific. Coherence in the southern Caribbean is smaller than either of ~~the~~ above regions.
- (2) Coherence for the 12-day period exceeds that for 4-days except for the meridional component during autumn in the Pacific.
- (3) In the Pacific for the 4-day period, coherence is larger in autumn than spring. For the central Caribbean, spring coherences are larger than those for autumn for a period of 12-days.

2. Vertical Coherence for Consolidated seasons

Both 850 and 200 mb were used as primary levels to be examined with respect to 500, 70 and 30 mb. Figures 6 and 7 indicate the primary variations for three Caribbean and three Pacific stations for spring and autumn seasons. (Additional values of vertical coherence and phase for more stations and all seasons are given in Appendix v in Volume I of this report.)

a. 850 mb

- (1) In the lowest latitudes the vertical coherence between 850 and 500 mb is larger in autumn than spring for both wind components and 12 and 4-day periods. Vertical coherence increases with latitude northward for all seasons.
- (2) The coherence between 850 and 500 mb is generally larger for the 12-day than 4-day period.
- (3) Locally, some stations may indicate considerably better vertical 850-500 mb coherence than others within a region. For example, Koror has larger values of vertical coherence than either Kwajalein or Songkhla.

b. 200 mb

- (1) The 200-500 mb coherence is very small within ten degrees of the equator and thus is not shown. At higher

latitudes, coherence for the 12-day period has a seasonal variation with a minimum in the summer. (For details, see Appendix v in Volume I?)

- (2) The 200-70 mb coherence pattern is very similar to (1) above.

3. Horizontal and Vertical Phase Progression for Consolidated Seasons

The interpretation of cross spectrum phase in terms of a physical moving wave is very difficult. For such an interpretation it must be assumed that there is one moving wave propagating with uniform velocity which is responsible for the energy in a given frequency band. Actually, during a season there may be many waves of various wavelengths moving with different velocities and directions contributing to the energy of a given frequency band. When this occurs, the phase pattern becomes quite random and its interpretation in terms of a single wave is meaningless. Phases in the previous tables (Appendices iv and v in Volume I) suggest both regular and irregular patterns depending on location, level and season. Tables 17 and 18 attempt to summarize the meaningful phase information along the three parallels of latitude discussed previously. In these tables, only systematic properties are given. Horizontal phase has been converted to phase velocity (degrees of longitude per day). Extreme values of phase progression are given along with underlined mean values when phase progression can be determined for more than two stations. If the horizontal direction of propagation among regional stations is inconsistent, no values are indicated in the accompanying tables. The direction toward which the waves appear to be propagating is indicated horizontally, W (west) and E (east), and vertically, (U) (up), D (down) and N (no vertical progression). Upward and downward progression at both 850 and 200 mb are defined with relation to the 500 mb level. For upward or downward progression, phase angles must be greater than 10° between the two levels. If the phase is between $\pm 10^\circ$ or if the phase changes sign from one location to the next along a given parallel of latitude, then

no phase progression (N) occurs. No phases are included in Tables 17 and 18 for horizontal or vertical coherences smaller than .1.

At 850 mb, Table 17, the meridional component for the 4-day period indicates westward propagation in the Pacific at a rate of $7-11^{\circ}$ day⁻¹. These westward progression rates are slightly larger than the $6-8^{\circ}$ day⁻¹ discussed by Wallace (1971). In the Caribbean these westward propagating waves have smaller phase velocity ($4-5^{\circ}$ day⁻¹). In terms of phase velocity for the westward propagating waves, there appears to be a better correspondence between values for both 4 and 12 days for either the zonal or meridional component than between both wind components for the same wave period. This suggests that the 12 and 4 day waves for a given wind component may propagate jointly, but the zonal and meridional components may be independent of each other. Phase velocities for the zonal component are approximately two times greater than for the meridional component for both 12 and 4 day periods for westward propagating disturbances.

~~The eThe westward propagating disturbances for a period of 4 days are~~ those of higher latitudes in the winter hemisphere. Easterly progression extends southward to 13° N in the Caribbean in the winter and spring but is not observed in the Pacific at 8° N.

At 200 mb, Table 18, the westward propagating meridional 4 day wave in the Pacific shows an increase in phase velocity from the wave phenomena observed at 850 mb. This is somewhat consistent with characteristics of the mixed Rossby-gravity wave discussed by Wallace (1971) although the wave observed here exhibits very poor vertical coherence. The phase velocity of this westward propagating wave is smaller in the Caribbean than in the Pacific. A very slow westward propagating wave is also observed for the 12 day meridional component and its horizontal phase characteristics are similar among the analysis regions and at 850 and 200 mb. The similarity in phase velocity of westward propagating waves for 4 day and 12 day periods

for individual wind components that was observed at 850 mb is not apparent at 200 mb.

Eastward propagating disturbances are prevalent in the spring for the 12 day zonal and 4 day zonal and meridional waves. The 4 day period indicates similar phase velocity for both wind components. However, phase velocity for the 12 day zonal component is considerably larger than for the 4 day period.

There is a tendency for the zonal component to indicate upward progression and the meridional component downward progression for the 12 day period for westward propagating waves at both 850 and 200 mb. Downward phase progression is indicated for both wind components for the 4 day period for westward and eastward propagating disturbances.

Finally, it should be stressed that because of the previously discussed problems of seasonal averages with regard to mixing of wavelengths, velocities and directions of propagation, it may be impossible to attribute any of the above phase parameters to a particular distinct model of a disturbance.

IV. DISTRIBUTION OF KINETIC ENERGY AS RELATED TO FLOW PARAMETERS

Climatically, kinetic energy of the synoptic eddies can be regarded as large-scale turbulence and investigated with regard to parameters characterizing instabilities of the seasonal mean flow, occurring either internally within the flow or at the boundary of the flow with the earth's surface. Examples of internal instabilities are barotropic instability for which the magnitude of the eddies may be related to horizontal shear in the mean flow (vorticity), or baroclinic instability for which the magnitude of the eddies could be related to vertical wind shear. Also, in the tropics, thermal instability causes the vertical transport of sensible and latent heat from tropical oceans to higher altitudes where the resulting potential energy may be converted to kinetic energy. Parameters which may be important for this instability mechanism include convergence, vorticity, vertical wind shear, wind speed, sea surface temperature, and lapse of equivalent potential temperature.

However, seasonal kinetic energy patterns need not be a function of local instabilities. For instance, Kung (1967) found that a large portion of the kinetic energy generated over North America is advected to the western Atlantic Ocean, where it is dissipated. Also, instability mechanisms tend to destroy the flow condition that is responsible for their existence. Thus, while there may be good relationships between kinetic energy and physical properties of the flow on a real-time basis, these same relationships need not be evident in terms of ~~long-term~~ seasonal averages of the basic parameters.

Further, seasonal periods are long time intervals for large-scale flow patterns to remain stationary, even in the tropics. If flow reverses or undergoes major changes in speed within a season, the important relations between kinetic energy production and properties of the flow may be lost in the seasonal averaging process. Also, if two or more distinct energy

processes occur within a season, it would be very difficult to resolve the physical parameters characteristic of each process. However, the basic seasonal period was chosen for investigating the wind spectra because of the problem of missing observations. It was the shortest interval over which non-stationary variations of the time spectra, with $2\pi/12 \text{ day}^{-1}$ frequency resolution, could be investigated for a large number of global stations.

In the following analysis the individual seasonal kinetic energy values were first stratified by region (Caribbean, Pacific and Southeast Asia), season and vertical wind shear category. The vertical wind shear classification used was the method described by Riehl (1950) using seasonal mean zonal winds at two levels in the atmosphere. For 850 mb, a 500-1000 mb shear was used for classification and for 200 mb the 200-850 mb shear was used. Four basic shear regimes occur in the tropics: (a) Westerly shear with strongest east winds at the lowest level, (b) easterly shear with strongest east winds at the highest level, (c) westerly shear with west winds at the upper level and east winds at the lower level and (d) easterly shear with west winds at the lower level and east winds at the highest levels. In the Caribbean, shear regimes (a) and (c) are most common with (c) occurring at highest latitudes in winter and spring and (a) occurring at lowest latitudes during most times of the year. In the Pacific at 8°N , (a) and (b) shear regimes are common during the entire year, although (d) occurs in the extreme western Pacific in summer and autumn and defines the monsoon circulation. In Southeast Asia and India (d) is common in summer and autumn and either (a), (b) or (c) occurs in winter and spring. The various kinetic energy relations that were analyzed did not seem particularly sensitive to wind shear classification except for the (d) shear regime. Therefore, in the following analyses, (a), (b), and (c) shear regimes were combined and in most instances were analyzed separately from (d). The lapse of equivalent potential temperature was also originally considered for stratification. However, this

parameter exhibited considerable variability from one year to the next for a given season when defined in terms of seasonal mean temperature and humidity at many tropical stations. These variations did not appear correlated with intraseasonal kinetic energy variability; therefore, this variable was not considered further in the analysis.

In each category the kinetic energy distributions for individual seasons were analyzed with respect to parameters derived from seasonal mean zonal and meridional winds. The parameters include the square of the vector ~~wind shear, with height, resultant wind speed, divergence, vorticity,~~ and meridional wind speed. In the following diagrams only the positive results are graphically indicated. The procedure is to indicate the primary important variable relationship as a two parameter plot. If another parameter is important for describing additional variability then this secondary variable is plotted as a function of the primary variable and kinetic energy, thereby preserving the previous relationship.

A. KINETIC ENERGY RELATIONS AT 850 MB

1. Pacific

Resultant wind speed is the primary parameter related to kinetic energy in the Pacific, Figures 8-11. On these diagrams divergence is plotted as the independent variable, which is of secondary importance compared to the relation between kinetic energy and the speed of the resultant wind. On these figures, one unit of divergence is equivalent to $2 \times 10^{-6} \text{ sec}^{-1}$. Divergence and vorticity were determined by mapping seasonal winds, analyzing the patterns, and measuring wind differences at 5° latitude intervals from the analyzed maps. On Figures 8-11, the $\pm \sigma$ limits for individual seasonal values indicating the simulated variability caused by missing observations is given for Koror. The small (x)'s indicate the kinetic energy and resultant wind speed at Canton Island. At Canton

and Koror there was not enough surrounding data to estimate divergence. An inverse relationship between kinetic energy and vector mean wind speed exists for all four seasons of 1000 mb easterly winds (a, b, c shear regimes). (Stations where the 1000 mb flow was westerly did not behave in this manner and these cases are discussed later.) A superposition of the patterns for individual seasons indicates a general behavior indicated by the lines on Figures 8-11. Thus, much of the seasonal variability of kinetic energy at 850 mb is inversely related to the strength of the trade wind easterlies in the Pacific at 7°N .

The divergence field is a secondary parameter that can be used to further reduce the variability remaining after the kinetic energy and resultant wind speed relationship is removed. On Figures 8-11 the largest positive departures from the best fit line are usually associated with convergence of the mean flow. Cyclonic vorticity is also weakly correlated with kinetic energy particularly for extreme values. However, it would be the third choice of a dependent variable in so far as the analysis of over-all variability is concerned.

The inverse relationships between resultant wind speed and eddy kinetic energy implies a barotropic energy conversion from mean to eddy flow. More combined kinetic energy of mean flow and eddies occurs at large wind speeds than small wind speeds so there is no conservation law. For a barotropic instability mechanism, vorticity should be an important parameter. This was not observed on a seasonal basis, although this parameter could be important for smaller time scales. (The gradient of relative vorticity was not examined with regard to kinetic energy in this study.)

An alternate explanation is in terms of the CISK mechanism. Williams and Gray (1973) indicate that low level frictional convergence, cyclonic vorticity, and weak vertical wind shear are correlated with maintenance of cloud clusters in the trades of the Western Pacific. Wind

speed is a factor in the advection of sensible and latent heat away from the source of production at the ocean surface. Strong, steady winds could have the effect of restricting convection and the associated production of kinetic energy which would give a relationship not unlike that observed in Figures 8-11.

2. Caribbean

The broad range of kinetic energy at 850 mb observed in the Caribbean during winter and spring is primarily related to the square of the vector shear of the horizontal wind. Figures 12-13 indicate the seasonal distribution of kinetic energy as a function of vector shear computed between 1000 and 500 mb. The largest vertical shears on these diagrams occur at latitudes beyond 20°N . The superimposed line indicates a composite relationship for both winter and spring seasons. On this figure the $\pm \sigma$ limits of error due to missing observations within a season are indicated for Swan Island. This gives some indication of the scatter in the statistics caused by sampling variations and also indicates the station variability for individual seasons. A secondary variable is the vector mean wind speed, which is plotted as the independent variable. Its relationship to kinetic energy, however, is not independent of vertical shear. An inverse relationship is observed between resultant wind speed and kinetic energy, similar to that observed in the Pacific. Wind speed becomes the primary variable related to kinetic energy in autumn (Figure 15). The data appear to support the same relationship as observed in the Pacific, which is superimposed on the diagram. For summer, a substantially weaker relation between kinetic energy and vector mean wind speed occurs (Figure 14).

① Other variables that were analyzed for relationships to kinetic energy in the Caribbean include 850 mb vorticity, divergence and meridional wind. There was no apparent relation between any of these parameters and kinetic energy.

The square of the vertical shear is an indicator of the large-scale baroclinic energy of the seasonal flow (To Song, 1971). This energy must be converted to available potential energy of the eddies to be realized as eddy kinetic energy. Over a seasonal period, this apparently occurs, producing a fairly good relationship between eddy kinetic energy and vertical shear during winter and spring.

3. Southeast Asia

The kinetic energy in the region of southeast Asia does not appear related to either vertical wind shear or horizontal wind speed. The strongest relation appears between kinetic energy and horizontal convergence. A weaker relation may exist between kinetic energy and cyclonic vorticity. Table 19 indicates the average distribution of kinetic energy as a function of these two parameters. Here all seasons and wind shear regimes have been included together, as this additional stratification did not appreciably reduce the variability of kinetic energy within the above framework. On a seasonal basis, winter and spring are associated with westerly wind shear, divergence and anticyclonic vorticity, while summer and autumn have easterly shear, convergence and cyclonic vorticity. Hence, larger amounts of kinetic energy usually occur in autumn and summer than in winter and spring for most stations. However, the variability within any one vorticity-divergence category is considerable. Table 19 contains data for all seasons from Bangkok, Songkhla, Singapore, Penang, Trivandrum, Gan, Djakarta, Cocos and Lae. The sign of vorticity in the southern hemisphere has been changed so values can be compared with those for the northern hemisphere. In addition, Table 19 includes seasonal values of kinetic energy for Koror, Yap, and Truk for the low level easterly shear regime (d), which did not fit into the previous analysis of these stations.

Sea surface temperature could also be a primary variable related to kinetic energy throughout this region. However, no values of this parameter were available to compare with kinetic energy on an individual

seasonal basis. Long term values for consolidated seasons are given by the Naval Oceanographic Office, Atlas SP-99 (1967). These are indicated in Table 20 for select locations where kinetic energy was analyzed on a consolidated basis (Table 1). Sea surface temperature may be regarded as an indirect measure of convective forcing at the ocean surface. However, the actual transfer of latent and sensible heat to the air depends also on humidity and wind speed. A comparison of sea surface temperature from Table 20 and 850 mb Band 1 kinetic energy in Table 1 indicates a correspondence of maxima at Koror, Kwajalein and Trivandrum. However, there does not appear to be any relationship between the spatial variation of kinetic energy at 850 mb and the spatial variation of sea surface temperature for summer and autumn seasons. Thus, while sea surface temperature may be related to the seasonal maximum of kinetic energy on a large areal basis, this parameter does not appear useful for describing local kinetic energy variations. These appear most likely to be described by such flow properties as indicated in Table 19.

B. KINETIC ENERGY RELATIONS AT 200 MB

The winter and spring dependence of 200 mb kinetic energy on vertical wind shear between 850 and 200 mb is indicated for the Caribbean in Figures 16 and 17. The $\pm \sigma$ limits resulting from missing observations are shown for individual seasonal values at Swan Island. An approximately linear relationship occurs between kinetic energy and the square of the vertical wind shear. A superposition of the pattern for winter and spring indicates that the relationship is similar for both seasons although there is certainly more scatter in winter than spring. The straight line on the diagrams indicates the best ~~subjective fit for both~~ seasons.

Figures 18 and 19 indicate the kinetic energy-vertical wind shear relationship in the western Pacific. These diagrams also include individual seasonal values from southeast Asia and the Indian Ocean. Estimated errors resulting from missing observations are not indicated on these

figures so as not to obstruct actual values. The natural range of variability of both kinetic energy and vertical wind shear is considerably reduced in this region as compared to the Caribbean. There is a tendency for kinetic energy to increase with wind shear as was observed in the Caribbean. The linear relationship that was observed in the Caribbean primarily for much larger values of kinetic energy is superimposed on Figures 18 and 19. Based on this relationship, seasonal values of kinetic energy in the Pacific would be larger than in the Caribbean for comparable values of wind shear.

An attempt to further reduce the variability in Figures 15-19 by the introduction of secondary variables was conducted by examining relative vorticity, divergence and meridional wind. Meridional wind has some virtue as a secondary parameter, in the Caribbean, with southerly winds indicating less kinetic energy than northerly winds for comparable values of wind shear. Vorticity and divergence had no kinetic energy correlation that was independent of vertical shear.

Vorticity gradients were not considered here because of areal data limitations. However, Webster (1973) recently produced a modeled global standing tropical wave pattern of zonal wind at 250 mb with preferred zones that are likely to amplify barotropic waves due to shear instability. There was no correlation of the 200 mb kinetic energy pattern for consolidated seasons computed here and the preferred locations of the shear zones from his diagrams.

No variable could be found that was related to kinetic energy at 200 mb during the summer on an individual seasonal basis. The variables included vertical wind shear and the 200 mb patterns of resultant wind speed, vorticity and divergence. In the summer the natural range in kinetic energy variability observed among stations during the seven year period is from 40-100 m^2/sec^2 in the Pacific and 50-200 m^2/sec^2 in the Caribbean. All the larger values of kinetic energy in the Caribbean occurred at latitudes greater than 20°N , otherwise the Caribbean distribution would have been much the same as in the Pacific.

Autumn is much the same as summer in the Pacific with no variables indicating any relation to kinetic energy on a consistent basis. In this region, the natural range in variability among stations for different years is similar to that observed in summer, $30-100 \text{ m}^2/\text{sec}^2$. Figure 20 indicates a weak relationship between kinetic energy and vertical wind shear in the Caribbean. Kinetic energy appears to increase with wind shear at a greater rate than was observed in either winter or spring (linear relationship indicated on Figure 20). In the Caribbean, autumn is a season of active convection. This convection is often associated with wave patterns of synoptic-scale, and thus, variables indicating convective instability should be good parameters to relate to the vertical transport of kinetic energy. However, such variables as the lapse of equivalent potential temperature, 200 mb divergence or vertical wind shear based on seasonal averages do not explain the intraseasonal variability of kinetic energy among stations. The autumn kinetic energy pattern in the Caribbean is perhaps characteristic of a mixed convective and large-scale baroclinic energy regime. Kinetic energy produced by convective instability is inversely proportional to vertical wind shear, while kinetic energy produced by large-scale baroclinic instability is proportional to wind shear. These two mechanisms, both prominent within the broad limits of the autumn season, could produce a pattern similar to Figure 20 when the vertical wind shear is computed for seasonal averages.

C. DISCUSSION

All of the relations that are shown in Figures 8-20, both at 850 and 200 mb, are rather mediocre for reducing the intraseasonal variability of kinetic energy among stations, as indicated by the scatter in the diagrams. Part of this scatter may be the result of statistical errors arising from the problem of missing observations in the seasonal spectra. However, the greater portion of unexplained variability is probably the result of the inability of seasonal parameters to describe the eddy properties of the flow. As stated previously, this may be the result of several separate kinetic energy producing mechanisms occurring within a season and the current

statistical analysis cannot separate the contributing factors. This appears to be demonstrated in the above analysis as the best relationships between synoptic kinetic energy and independent variables occur in seasons and regions where one type of flow condition is predominant. For example, the best kinetic energy-flow parameter relationships occur in the Pacific at 850 mb for the easterly trades and in the Caribbean at 200 mb during the spring baroclinic regime.

The above analysis can be used, however, to help describe much of the interseasonal variability of kinetic energy in Section IIIA(1):

(1) In the subtropics the primary variation of kinetic energy both at 850 and 200 mb is the result of baroclinic waves in winter and spring whose intensity is proportional to local vertical wind shear.

(2) At low latitudes in the easterly tradewind regime, much of the seasonal-space variability of kinetic energy is inversely proportional both to resultant wind speed and to divergence.

(3) For the monsoon westerly wind regime, the 850 mb kinetic energy is proportional to sea surface temperature, low level convergence and possibly cyclonic vorticity. These are factors in the CISK mechanism of generating kinetic energy at upper levels by convective instability.

With regards to diffusion, the relationships indicated in this section possibly could be used as a first approximation to the parameterization of synoptic kinetic energy in remote tropical regions. Using the nearest station where the statistical parameters are available as a base value, kinetic energy could be extrapolated to a new position in terms of changes of the large-scale flow parameters between the two locations.

V. APPLICATIONS OF SPECTRAL PARAMETERS TO DIFFUSION

One of the most promising applications of the computed statistical parameters is modeling Lagrangian two-particle horizontal diffusion. It now becomes possible to incorporate non-homogeneous variations of diffusion caused by changes in turbulence intensity with position along a particle's trajectory and include the effects of initial particle separation. While it is beyond the scope of this report to quantitatively discuss any such application, an approach is described that should be feasible for diffusion modeling.

Briefly, we consider two particles that are initially separated by a distance (x_0), Figure 21. The respective equations describing their position $x(T)$ as a function of a number (T) of discrete equal time steps (i) are:

$$x_1(T) = \sum_{i=0}^T u_1(i) \Delta t(i) \quad 4(a)$$

$$x_2(T) = x_0 + \sum_{i=0}^T u_2(i) \Delta t(i) \quad 4(b)$$

Here, $u(i)$ are the respective zonal velocities each particle experiences along its trajectory. The time interval, $\Delta t(i)$, is uniform except for the terminal values, $\Delta t(0) = \Delta t(T) = \Delta t(i)/2$. (However, for $T=0$, $\Delta t(0)=0$). Only one-dimensional motion is considered for simplicity; however, the procedure holds also for other components of motion. Progressively subtracting 4(a) from 4(b), squaring, and taking the ensemble average (over bar) results in:

$$\overline{\{x_2(T) - x_1(T)\}^2} = x_0^2 + \overline{\Delta t(i) \Delta t(j)} \quad (a)$$

$$+ \sum_{i=0}^T \sum_{j=0}^T \overline{u_1(i) u_1(j) \Delta t(i) \Delta t(j)} \quad (b)$$

$$+ \sum_{i=0}^T \sum_{j=0}^T \overline{u_2(i) u_2(j) \Delta t(i) \Delta t(j)} \quad (c)$$

$$+ 2x_0 \sum_{i=0}^T \overline{u_2(i) - u_1(i)} \Delta t(i) \quad (d)$$

$$- 2 \sum_{i=0}^T \sum_{j=0}^T \overline{u_1(i) u_2(j)} \Delta t(i) \Delta t(j) \quad (e)$$

This is a discrete form of the two particle diffusion equation, which gives mean square particle separation as a function of initial separation (a), of autovariance of velocity along each particle's trajectory, (b) and (c), covariance of velocity between the particles, (e), and mean horizontal wind shear between the particles along their trajectories, (d). Forms of this relative diffusion equation were first considered by Batchelor (1952). It is assumed that there is no mean horizontal wind shear, (d)=0, and that both particles are close enough together so that the autovariance of velocity along each particle's trajectory is identical, (b)=(c). These assumptions are not necessary for the overall solution of (5), but it makes the remaining mathematics less complicated. Further, assumptions are:

$$\begin{aligned} \overline{u_1(i) u_1(j)} &= \overline{u_2(i) u_2(j)} = \sigma(i) \sigma(j) R(k, \tau) \\ \overline{u_1(i) u_2(j)} &= \overline{u_2(i) u_1(j)} = \sigma(i) \sigma(j) R_{12}(k, \tau) \\ k &= |i - j| \end{aligned}$$

The Eulerian space-time correlation function, $R(k, \tau)$, is considered to be homogeneous and stationary (on a seasonal basis). However, the standard deviation of velocity is considered to be a function of time step (i) and is defined in terms of position along the mean trajectory of the two particles. The single particle Lagrangian autovariance of velocity, (b) or (c), is to be estimated by considering the probable distance separating the particle between time steps, $k = i - j$, along its trajectory. This distance and the time interval, τ , between the discrete steps can be used as dependent variables to define the specific Lagrangian correlation from the general Eulerian space-time correlation pattern. Buell (1972) discusses

how the Lagrangian correlation function can be approximated from the Eulerian correlation pattern in terms of the mean trajectory of the particle for small time lags. An example of the downstream space-time correlation pattern at 200 mb in the Caribbean is given in Figure 22. The standard deviations of particle velocity, $\sigma(i)$ and $\sigma(j)$, are a function of position and can be read from maps. The Lagrangian two-particle covariance is determined in similar manner as the one particle autovariance with the correlation in terms of particle separation, $R_{12}(k, \tau)$, as a function of time. Rewriting (5) with the above considerations:

$$\begin{aligned} \overline{\{x_2(T) - x_1(T)\}^2} &= x_0^2 + 2 \sum_{i=0}^T \sum_{j=0}^T \sigma(i) \sigma(j) R(k, \tau) \Delta t(i) \Delta t(j) \\ &\quad - 2 \sum_{i=0}^T \sum_{j=0}^T \sigma(i) \sigma(j) R_{12}(k, \tau) \Delta t(i) \Delta t(j) \end{aligned} \quad (6)$$

This is a discrete representation of an implicit integral equation which can be solved, iteratively, as a function of time (T). It is implicit because the root mean square particle separation which is to be found is also needed to define the distance over which the two particle covariance function needs to be found for solution. For a possible method of solution, consider (6) for $T=1$:

$$\begin{aligned} \overline{\{x_2(T) - x_1(T)\}^2} &= x_0^2 + 2(\Delta t/2)^2 \{ \sigma^2(0)R(0,0) + 2\sigma(0)\sigma(1)R(1,1) + \sigma^2(1)R(0,1) \} \\ &\quad - 2(\Delta t/2)^2 \{ \sigma^2(0)R_{12}(0,0) + 2\sigma(0)\sigma(1)R_{12}(1,1) + \sigma^2(1)R_{12}(0,1) \} \end{aligned} \quad (7)$$

The initial particle separation, x_0 , is known and the terms in the first brackets on the right side can be easily found by advecting the particles with the mean wind over the time interval Δt . The Lagrangian correlation $R(1,1)$ is found by displacing the particles downstream a distance $\bar{u}(1)\Delta t$ and reading the respective time-space correlation for $\tau=1$, Figure 22.

(Here, $\Delta t=24$ hours is used only to describe the method.) The standard

deviation of velocity as a function of particle position can be estimated from the lower diagram.

The terms in the second brackets on the right side are the two particle correlations, and while $R_{12}(0,0)$ can be found from the initial particle separation, x_0 , both $R_{12}(1,1)$ and $R_{12}(0,1)$ depend on knowing the probable separation of the particles at a time of $(T=1)$. In the manner shown in Figure 21, we let the relative separation of particle 1 at time $i=0$ and particle 2 at time $i=1$ to be:

$$R_{12}(1,1) = R_{12}(x_0 + \bar{u}(1)\Delta t + \Delta x(1), 1) \quad (8)$$

where x_0 is the initial particle separation, $\bar{u}(1)\Delta t$ is the separation resulting from particle advection and $\Delta x(1)$ is the probable separation resulting from diffusion in the time interval $(1)\Delta t$. In a similar manner, the relative separation of particle 1 and particle 2 at time $i=1$ is:

$$R_{12}(0,1) = R_{12}(x_0 + \sqrt{2}\Delta x(1), 0) \quad (9)$$

There is no advective separation as both particles have been carried along the trajectory; the distance $\sqrt{2}\Delta x(1)$ is a result of equal diffusion in a mean square sense of both particles relative to their initial position. Equation (7) may then be rewritten as:

$$(\sqrt{2}\Delta x(1))^2 = K(1) + [2\sigma(0)\sigma(1)R_{12}(x_0 + \bar{u}(1)\Delta t + \Delta x(1), 1) + \sigma^2(1)R_{12}(x_0 + \sqrt{2}\Delta x(1), 0)] \quad [-2(\Delta t/2)^2] \quad (10)$$

where $K(1)$ are all the terms that are directly evaluated as described previously. The solution of (10) is to iteratively find the value of $\Delta x(1)$ so that the right and left sides balance. Descriptively, we follow down the curves of Figure 22 for $\tau=0$, the distance $x_0 + \sqrt{2}\Delta x(1)$, and for $\tau=1$, the distance $x_0 + \bar{u}(1)\Delta t + \Delta x(1)$, evaluating the correlations until (10) is

satisfied. When that occurs, we ~~havet jointly~~ evaluated the mean square particle separation over the first time interval and also defined $R_{12}(1,1)$ and $R_{12}(0,1)$ for the next time step. For $T=2$, equation (6) can be written as:

$$\begin{aligned} \overline{\{x_2(2)-x_1(2)\}^2} = & 2(\Delta t/2)^2 \{ \sigma^2(0)R(0,0) + \sigma^2(2)R(0,2) + 2\sigma(2)\sigma(0)R(2,2) \} \\ & + 2(\Delta t)(\Delta t/2) \{ 2\sigma(0)\sigma(1)R(1,1) + 2\sigma(1)\sigma(2)R(1,2) \} + 2(\Delta t)^2 \{ \sigma^2(1)R(0,1) \} \\ & - 2(\Delta t/2)^2 \{ \sigma^2(0)R_{12}(0,0) + \sigma^2(2)R_{12}(0,2) + 2\sigma(2)\sigma(0)R_{12}(2,2) \} \\ & - 2(\Delta t)(\Delta t/2) \{ 2\sigma(0)\sigma(1)R_{12}(1,1) + 2\sigma(1)\sigma(2)R_{12}(1,2) \} \\ & - 2(\Delta t)^2 \{ \sigma^2(1)R_{12}(0,1) \} \end{aligned} \quad (11)$$

As for $T=1$, the single particle Lagrangian correlation can be found by considering the separation of points along the downstream trajectory. In Figure 22, with constant wind direction and velocity, $R(1,1)=R(1,2)$. In the same manner as for $T=1$, Figure 21 indicates that:

$$\begin{aligned} R_{12}(2,2) &= R_{12}(x_0 + \bar{u}(1)\Delta t + \bar{u}(2)\Delta t + \Delta x(1) + \Delta x(2), 2) \\ R_{12}(1,2) &= R_{12}(x_0 + \bar{u}(2)\Delta t + \sqrt{2}\Delta x(1) + \Delta x(2), 2) \\ R_{12}(0,2) &= R_{12}(x_0 + \sqrt{2}\Delta x(1) + \sqrt{2}\Delta x(2), 2) \end{aligned} \quad (12)$$

Thus, (11) can be rewritten as (13) and solved, iteratively, for $\Delta x(2)$ as was the case for $\Delta x(1)$,

$$\begin{aligned} (\sqrt{2}\sigma x(2))^2 = & K(2) + [2\sigma(0)\sigma(2)R_{12}(x_0 + \bar{u}(1)\Delta t + \bar{u}(2)\Delta t + \Delta x(1) + \Delta x(2), 2)] [-2(\Delta t/2)^2] \\ & + [2\sigma(1)\sigma(2)R_{12}(x_0 + \bar{u}(2)\Delta t + \sqrt{2}\Delta x(1) + \Delta x(2), 2)] [-2(\Delta t)(\Delta t/2)] \\ & + [\sigma^2(2)R_{12}(x_0 + \sqrt{2}\Delta x(1) + \sqrt{2}\Delta x(2), 2)] [-2(\Delta t/2)^2] \end{aligned} \quad (13)$$

The number of terms that are necessary to iteratively evaluate increases arithmetically with the number of time steps. Practically, there is a reasonable limit as the time space correlation between particles becomes zero after three or four days (see Figure 22). With a strong advective wind component, this decrease would occur even more rapidly. After a finite number of time steps the two particles would be also separated by a distance large enough so that their diffusion proceeds independently. In this case their separation is described only by terms (b) and (c) in (5). At this point in time their separation proceeds according to the one particle Lagrangian autocorrelation first described by G. I. Taylor (1921).

The procedure just described is suitable for numerical evaluation on a digital computer using correlation and variance data along with an advective field from which to compute a trajectory. Meridional diffusion, $\{y_2(T) - y_1(T)\}^2$, would be evaluated by replacing $\overline{u_1(i)u_2(j)}$ with $\overline{v_1(i)v_2(j)}$ in equation (5) and following the same procedure.

It is to be noted that the zonal and meridional diffusion components do not necessarily correspond to the primary horizontal diffusion axes, as defined by a two dimensional bivariate elliptical distribution function. To find this axis it is also necessary to examine the space-time zonal-meridional wind correlation $\overline{u_1(i)v_2(j)}$. These values would be used in place of $\overline{u(i)u(j)}$ in equation (4) to define the separation $\{y_2(T) - x_1(T)\}^2$. No cross spectral analysis of u and v was conducted in this study, so the importance of this term with respect to diffusion in the tropics is difficult to evaluate. Kao and Al Gain (1968) have indicated that in middle latitudes the principal diffusion axis is inclined to the zonal direction by a few degrees in a NE-SW direction. Analyses of seasonal $\overline{uv}$ correlations in the tropics are given by Newell, et al, 1972. It would appear that generally the $\overline{uv}$ correlation is small in the lower troposphere; however, near the tropopause values of this parameter may be significant. (These correlations include the contributions of periods longer than 25 days which was the upper limit of variability for the current study.) However, on a global

basis the relative importance of this term should be smaller in the tropics than in middle latitudes. By neglecting this term, diffusion in directions NW-SE and SW-NE is most likely to be modeled incorrectly. Diffusion along the north-south and east-west directions would not be affected.

The alternative method of investigating two particle diffusion is by using hypothetical particle pairs and following them with a synoptic map series of winds. This simulation approach to large-scale diffusion has been taken by Murgatroyd (1969) and Kao, and Al Gafn (1968). However, many particle pairs at many independent time intervals must be followed in order to satisfy the requirements of ensemble averages. The statistical approach utilizes correlations and variances in which the ensemble averaging is already inherent; thus only one particle pair needs to be considered. The vast decrease in computer time makes the statistical approach particularly appealing for investigating differences in large-scale diffusion patterns as a function of release location and particle separation.

Using the space-time statistical data presented in Volumes I and II of this report, both climatological and real-time applications to diffusion modeling are apparent. The primary difference in the two applications is a matter of time scale. For climatological applications, a statistical representation of the effects of all scales of motion is desirable. Thus, complete seasonal space-time covariances encompassing all scales of motion would be utilized. On a real-time basis, a deterministic representation of particle separation in terms of actual wind data would be better than the statistical results. However, if an existing diffusion pattern were to be prognosticated, there should be a gradual trade-off as a function of time scale of deterministic versus statistical description of wind variability. The statistical description would be originally useful for the shortest time scales and would progressively be more valuable for longer time scales as the forecast interval increased. The space-time covariance of the wind as a function of averaging interval (T) can be shown to be approximated by:

$$\text{cov}_T(x_1, x_2) \approx \sum_{i=T}^{i=N} \sigma(x_1, \omega_i) \sigma(x_2, \omega_i) \text{coh}(\Delta x, \omega_i) \cos\{\theta(\Delta x, \omega_i)\} \quad (14)$$

$$T = 2\pi/W$$

The values $\sigma(x_1, \omega_i)$ and $\sigma(x_2, \omega_i)$ can be determined from the power spectrum of wind for time series at locations x_1 and x_2 . The coherence, $\text{coh}(\Delta x, \omega_i)$ and phase, $\theta(\Delta x, \omega_i)$, are derived from the cross spectrum of the time series between the two locations. The summation extends from the highest frequency (N) to the frequency (W) representing the longest time scale (T) for which a statistical representation of wind variability is needed. The required correlations and variances in equation (6) can be readily computed from (14) in terms of spectral properties of wind as a function of time scale (T). The statistical data on tapes AECT and AECX and in Volumes 1 and 2 of this report can be used for estimating the above parameters for the spectral range $2\pi/12 - 2\pi/1 \text{ day}^{-1}$ for various tropical regions.

Initially, for numerically evaluating equation (6), it would be desirable to assume that the space-time correlation function is stationary (on a seasonal basis) and homogeneous for each wind component. The coherence and phase patterns of Section IIIE, for the primary spectral components, indicate that when these statistics are stratified by height, season and direction of flow, regional variations are usually quite small. The variance of the wind as a function of time scale would be allowed to vary along the particle's trajectory. These values could be determined from such spectral properties as total kinetic energy, ratio of meridional to zonal kinetic energy, and spectral slope that were computed in Section IIIA, C, D using equations (1) and (2). Some of the relations in Section IV perhaps could be used to help extrapolate kinetic energy into regions where no detailed data on wind variability exists.

VI. CONCLUSIONS

In this study three interrelated tasks were conducted involving spectral and cross spectral properties of synoptic wind variability in the tropics. These included:

(1) A climatology of basic wind spectrum properties is provided for tropical stations that indicates height, season, regional and year to year variability. The spectra encompass wind variations ranging from 1 to 25 days. Spectral properties include total horizontal kinetic energy, the ratio of meridional to zonal kinetic energy, and the spectrum slope for each individual wind component. Cross spectral properties include coherence and phase determined both horizontally and vertically for 12 day and 4 day periods. These statistical data are useful for a variety of practical problems, including diffusion, objective analysis, network analysis, etc.

(2) Relations were investigated between kinetic energy of the synoptic eddies and basic properties of the seasonal mean flow. This was done at 850 and 200 mb using kinetic energy and flow parameters computed for individual seasons over a seven year period.

At 850 mb, it was found that in the easterly trades of lower latitudes (Pacific and Caribbean) much of the time-space variability of kinetic energy is inversely proportional to resultant wind speed and to divergence. In subtropical latitudes during winter and spring, kinetic energy is also proportional to vertical wind shear. Over Southeast Asia and the Indian Ocean, 850 mb kinetic energy was best related to large-scale patterns of convergence.

At 200 mb, the kinetic energy in all regions was found to be proportional to vertical wind shear during the winter and spring seasons. During the summer and autumn, no good relations were found between kinetic energy and any wind or temperature parameter.

(3) A tentative two particle statistical diffusion model is discussed that uses the statistical parameters from (1) above. The model follows one particle pair and evaluates its separation as a function of time in terms of statistical properties of wind along the particles' trajectories. A primary advantage of the model is that repeated simulation with many particle pairs is not needed to describe the resultant diffusion pattern. Thus, it might be used to describe intermediate scale global diffusion as a function of release location and particle separation. The model can be applied to describe diffusion as a function of time scale and thus has both real-time and climatological applications. The above model has not been programmed or validated. It is recommended that this ~~task is~~ worthwhile effort for future investigations.

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MIAMI (26N, (80W), 80W)					
mb					
30	18.6	12.6	7.2	13.6	18.6
70	41.5	24.1	6.5	116.0	226.5
200	226.8	199.8	113.7	180.7	226.8
500	87.1	68.8	30.0	52.6	87.1
850	59.1	39.7	23.8	40.8	59.1
	W	SP	SU	A	
SWANS (17N, (184W), 84W)					
mb					
30	15.6	13.1	9.3	10.7	15.6
70	30.0	16.6	7.6	10.8	30.0
200	110.8	104.1	84.3	95.4	110.8
500	48.9	35.1	18.0	23.9	48.9
850	32.5	20.7	17.6	21.1	32.5
	W	SP	SU	A	W
SAN JUAN (18N, (66W), 66W)					
	18.4	13.0	10.5	10.8	
	134.4	125.0	7.4	11.6	
	165.8	141.5	99.2	134.4	165.8
	54.5	41.8	18.5	28.6	54.5
	20.7	15.7	11.5	17.0	20.7
	W	SP	SU	A	
SAN ANDREAS (13N, (82W), 82W)					
	21.6	24.7	19.6	30.4	21.6
	25.0	22.2	11.2	13.0	25.0
	101.7	55.1	59.0	55.8	101.7
	36.3	23.6	19.9	27.1	36.3
	17.2	13.0	12.9	17.9	17.2
	W	SP	SU	A	W
KWAJALEIN (9N, (168E), 8E)					
mb					
30	19.9	16.5	13.2	16.7	19.9
70	27.2	20.7	16.9	17.5	27.2
200	55.2	66.4	66.1	84.0	55.2
500	37.7	26.7	18.1	27.0	37.7
850	12.5	12.0	13.0	21.3	12.5
	W	SP	SU	A	W
KOROR (7N, (134E), 134E)					
	27.1	21.1	17.7	20.2	27.1
	19.1	19.8	18.8	18.5	19.1
	39.8	53.8	62.1	63.7	39.8
	33.2	21.8	29.7	43.5	33.2
	25.3	20.9	29.4	41.6	25.3
	W	SP	SU	A	W

Table 1. Height-season distribution of kinetic energy per unit mass (m^2/sec^2) for frequency band 1, $2\pi/12 - 2\pi/2$ day.

ASCENSION I (8S, 814W) 4W)

mb					
30	20.0	20.5	20.3	18.3	20.0
70	20.0	19.2	22.8	21.1	20.0
200	99.7	76.9	112.0	98.6	99.7
500	22.4	19.2	29.9	22.5	22.4
850	12.5	11.3	13.8	16.6	12.5
	W	SP	SU	A	W

DAKAR (15N, 17W) 5N, 17W)

	63.4	33.1	31.6	32.2	63.4
	75.5	38.1	27.4	26.1	75.5
	147.5	116.5	40.1	880.1	147.5
	35.7	28.5	28.2	27.5	35.7
	19.7	19.8	27.9	20.1	19.7
	W	SP	SU	A	W

BANGKOK (14N, 100E) 100E)

mb					
30	37.7	35.6	44.2	44.9	37.7
70	27.2	20.5	16.0	16.8	27.2
200	70.1	61.4	36.4	47.6	70.1
500	27.7	20.6	23.7	24.7	27.7
850	10.6	11.6	17.1	18.6	10.6
	W	SP	SU	A	W

SINGAPORE (1N, 104E) 1N, 104E)

	37.5	39.7	36.7	50.1	37.5
	56.4	42.1	38.9	62.0	56.4
	53.3	43.8	66.3	47.7	53.3
	22.4	15.0	21.9	19.7	22.4
	19.5	13.9	14.1	17.7	19.5
	W	SP	SU	A	W

TRIVANDRUM (8N, 77E) 77E)

mb					
30					
70	100.3	44.7		98.7	43.8
200	100.3	63.2	55.7	42.4	100.3
500	32.0	34.4	22.8	27.6	32.0
850	11.7	16.0	17.0	15.6	11.7
	W	SP	SU	A	W

CANTON (3S, 172W) 3S, 172W)

	38.4	38.8	38.1	39.8	38.4
	29.2	26.8	102.2	37.7	29.2
	76.0	104.4	76.8	64.5	76.0
	35.7	27.2	26.8	29.2	35.7
	23.5	17.4	13.6	14.7	23.5
	W	SP	SU	A	W

Table 1. (Continued) son distribution of kinetic energy per unit mass
 (m^2/sec^2) for frequency band 1, $2\pi/12 - 2\pi/2$ day⁻¹

Table ②. East-west distribution of spectral parameters at 200 mb in the Caribbean at 17°N for the frequency band $2\pi/12 - 2\pi/2$ day⁻¹.

Table 3. East-west distribution of spectral parameters at 200 mb in the Caribbean at 11°N for the frequency band $2\pi/12 - 2\pi/2$ day⁻¹.

Table 4. East-west distribution of spectral parameters at 200 mb in the western Pacific at 8°N for the frequency band $2\pi/12 - 2\pi/2 \text{ day}^{-1}$.

(a) $u^2 + v^2$ (m²/sec²) (b) v^2/u^2

(c) Minus Slope (u)

(d) Minus Slope (v)

Table 5. East-west distribution of spectral parameters at 850 mb in the Caribbean at 17°N for the frequency band $2\pi/12 - 2\pi/2$ day⁻¹.

Table 6. East-west distribution of spectral parameters at 850 mb in the Caribbean at 11°N for the frequency band $2\pi/12 - 2\pi/2$ day⁻¹.

Table 7. East-west distribution of spectral parameters at 850 mb in the western Pacific at 8°N for the frequency band $2\pi/12 - 2\pi/2$ day⁻¹.

Table 9.

<u>Station</u>	<u>Winter</u>	<u>Spring</u>	<u>Summer</u>	<u>Autumn</u>	<u>+2σ</u>
Miami	166-281(6)	159-276(6)	83-173(7)	136-252(7)	169-196
San Juan	126-232(6)	118-145(6)	57-143(7)	115-164(7)	122-144
Swan	69-139(6)	70-123(6)	59-109(6)	74-143(6)	80-109
San Andreas		59-69(4)	45-69(4)	53-60(2)	49-65
Dakar	97-165(4)	87-157(6)	34-52(5)	73-102(5)	71-89
Ascension			111-113(2)	96-103(2)	87-106
Canton	75-134(3)	75-102(3)	64-101(3)	47-71(3)	61-70
Kwajalein	53-64(3)	48-87(6)	49-92(6)	62-104(6)	72-93
Koror	31-47(3)	16-27(3)	43-77(2)	57-79(4)	54-73
Singapore			68-97(3)		
Bangkok	47-86(4)	44-83(5)	33-41(5)	35-57(6)	41-52

Table 8. Range in individual seasonal values of kinetic energy (m^2/sec^2)

at 200 mb for period 1964-1970. In parenthesis are the number of seasons forming the basis of extreme values. Results are considered for only those time series have 130 out of a possible 184 12-hourly data points, except at Canton and Singapore where 65 out of a possible 92 24-hourly data points was the limiting number.

Table 2.

<u>Station</u>	<u>Winter</u>	<u>Spring</u>	<u>Summer</u>	<u>Autumn</u>	<u>+2σ</u>
Miami	44-77(6)	34-56(7)	14-36(7)	31-48(7)	34-42
San Juan	12-25(6)	11-19(6)	7-15(7)	14-21(7)	16-18
Swan	23-51(6)	15-34(6)	12-34(6)	18-27(7)	20-24
San Andreas	14-24(3)	9-22(6)	9-20(5)	13-20(4)	16-21
Dakar	11-21(5)	14-25(6)	21-48(6)	12-23(6)	18-22
Ascension	13-13(2)		13-15(3)	16-18(3)	14-18
Canton	26-35(3)	15-20(3)	14-19(4)	11-33(3)	13-17
Kwajalein	9-18(5)	9-16(6)	11-18(6)	13-37(7)	19-24
Koror	17-32(3)	16-27(5)	19-38(5)	28-59(5)	37-45
Singapore	16-25(4)	10-17(6)	12-18(5)	14-21(6)	16-20
Bangkok	8-13(6)	9-15(6)	13-21(6)	15-24(7)	17-21

Table 9. Same as Table 8 for 850 mb.

MIAMI (26N, (80W), 80W)						SAN JUAN A (18N, 66W) 3N, 66W)					
mb											
30	9.7	8.4	9.1	6.9	9.7	8.5	10.1	11.3	8.3	8.5	
70	9.3	6.7	6.6	5.9	9.3	6.6	7.8	8.4	6.1	6.6	
200	31.1	21.0	14.6	16.5	31.1	13.9	19.6	12.7	13.1	13	
500	12.2	8.5	5.1	7.1	12.2	6.6	5.0	4.5	4.6	1.5	
850	7.5	6.3	5.2	5.2	7.5	4.3	3.9	3.9	3.2	4.5	
	W	SP	SU	A	W	W	SP	SU	A	W	
SWAN (17N, (84W), 84W)						SAN ANDREAS A (13N, 82W) 3N, 82W)					
mb											
30	7.2	8.1	10.6	7.9	7.2	17.7	20.5	18.0	13.3	17.5	
70	5.4	5.7	6.1	5.4	5.4	12.4	10.5	7.4	10.5	12.5	
200	12.8	12.6	11.8	12.9	12.8	31.5	17.3	14.8	19.8	31.5	
500	5.6	5.0	5.2	5.0	5.6	7.3	6.4	7.0	6.4	7.5	
850	3.7	3.2	4.1	3.7	3.7	4.9	3.4	4.7	4.0	4.9	
	W	SP	SU	A	W	W	SP	SU	A	W	
KWAJALEIN (9N, 168E) 9N, 168E						KOROR (7N, 134E) 7N, 134E					
mb											
30	10.0	9.0	9.1	9.4	10	16.8	12.7	9.3	11.1	16	
70	9.3	7.7	8.0	7.0	9	8.2	7.8	7.4	8.0	8	
200	8.5	10.5	8.4	9.0	8	14.1	13.9	15.6	19.2	14	
500	4.4	3.5	4.2	4.0	4	7.4	4.6	7.5	5.6	7	
850	3.7	3.0	3.0	3.8	3	5.0	5.2	5.9	3.0	5	
	W	SP	SU	A	W	W	SP	SU	A	W	

(m/sec²) for frequency band 2, 2π(7)/12 - 2π(12)/12 day⁻¹.

Table 10. Height-season distribution of kinetic energy per unit mass (m²/sec²) for frequency band 2, 2π(7)/12 - 2π(12)/12 day⁻¹.

ASCENSION (8S, 14W)S, 14W)						DAKAR (15N, 17W)R (15N, 17W)					
mb											
30	13.4	12.0	7.9	9.0	13.4	29.2	18.7	46.5	21.5		
70	5.8	8.6	5.0	5.4	5.8	41.7	29.7	14.7	16.2	41	
200	8.9	10.2	6.4	10.3	8.9	35.1	23.8	16.9	18.0	35	
500	2.5	2.6	2.6	3.3	2.5	8.5	6.5	12.6	8.5	8	
850	2.4	2.9	2.9	2.4	2.4	6.0	6.9	10.1	6.2	6	
	W	SP	SU	A	W	W	SP	SU	A	W	

BANGKOK (14N, 100E) 100E)						TRIVANDRUM (8N, 77E)N, 77E)					
mb											
30											
70	12.4		23.5	13.3	12.4	35.7					
200	18.0	16.9	21.0	15.2	18.0	43.9	26.6	32.7	21.1		
500	6.4	4.9	7.3	6.2	6.4	8.3	6.7	7.2	5.9		
850	4.5	4.6	6.6	5.4	4.5	8.6	6.2	6.6	4.9		
	W	SP	SU	A	W	W	SP	SU	A		

Table 10. (Continued)

MIAMI (26N, 80W)

mb					
30	.47	.39	.56	.34	.47
70	.46	.71	.58	.63	.46
200	.98	1.19	.77	1.31	.98
500	.85	.70	.71	.78	.85
850	.66	.50	.56	.60	.66
	W	SP	SU	A	W

SAN JUAN (18N, 66W)

	.30	.33	.57	.48	.30
	.49	.40	.57	.46	.49
	.79	1.05	1.14	1.75	.79
	.77	.59	.75	.63	.77
	.73	.68	.99	.62	.73
	W	SP	SU	A	W

SWANSON (17N, 84W)

mb					
30	.34	.37	.59	.35	.34
70	.32	.51	.53	.49	.32
200	1.12	1.31	1.17	.96	1.12
500	.63	.80	.79	.77	.63
850	1.46	1.18	.58	1.06	1.46
	W	SP	SU	A	W

SAN ANDREAS (13N, 82W)

	.35	.37	.37	.65	.35
	.43	.33	.55	.48	.43
	.99	1.23	1.02	.92	.99
	.64	.60	.55	.50	.64
	.79	.41	.35	.57	.79
	W	SP	SU	A	W

KWAJALEIN (9N, 168E)

mb					
30	.40	.48	.50	.48	.40
70	.37	.43	.44	.41	.37
200	.73	.87	.71	.82	.73
500	.51	.56	.66	.52	.51
850	.69	.57	.50	.69	.69
	W	SP	SU	A	W

KOROR (7N, 134E)

	.30	.42	.45	.48	.30
	.38	.46	.46	.31	.38
	1.01	.69	.68	1.14	1.01
	.51	.62	.57	.50	.51
	.68	.59	.59	.39	.68
	W	SP	SU	A	W

Table 11. Height-season distribution of the ratio of meridional to zonal kinetic energy for frequency band 1, $2\pi/12 - 2\pi/2$ day⁻¹.

ASCENSION (8°N, 14°W) 14°W						DAKAR (15°N, 17°W) 15°N					
mb											
30	.36	.44	.41	.57	.36	.21	.41	.26	.72		
70	.63	.48	.61	.54	.63	.39	.48	.49	.53		
200	.42	.57	.69	.85	.42	.91	1.26	.66	.89	.9	
500	.59	.76	.46	.57	.59	.64	.72	.73	.50	.6	
850	.75	.52	.68	.56	.75	.87	.66	1.13	.95	.87	
	W	SP	SU	A	W	W	SP	SU	A	W	
BANGKOK (14°N, 100°E) 100°E						SINGAPORE (1°N, 104°E) 104°E					
mb											
30	.43	.37	.49	.43	.43	.22	.38	.33	.43	.22	
70	.51	.64	.62	.49	.51	.82	.51	.32	.23	.82	
200	.79	.62	.64	.70	.79	.43	.66	1.16	.56	.43	
500	.74	.90	.57	.78	.74	.62	.73	.56	.52	.62	
850	.65	.60	.62	.46	.65	.69	.71	.86	.91	.69	
	W	SP	SU	A	W	W	SP	SU	A	W	
TRIVANDRUM (8°N, 77°E) 77°E						CANTON (23°N, 117°W) 117°W					
mb											
30						.50	.65	.54	.51	.50	
70	.25	.48		.46	.25	.44	.49	5.63	.67	.44	
200	1.02	.48	.69	.46	1.02	1.12	.90	.87	.58	1.1	
500	.55	.32	.47	.33	.55	.64	.74	.77	.83	.64	
850	.41	.76	.79	.48	.41	.48	.60	.60	.72	.48	
	W	SP	SU	A	W	W	SP	SU	A	W	

Table 14. (Continued) son distribution of the ratio of meridional to zonal kinetic energy for frequency

Table 15.

Station	850 mb		200 mb	
	Autumn	+2 σ	Autumn	+2 σ
Miami	.38-.99(7)	.54-.67	.69-1.90(7)	1.13-1.46
San Juan	.49-.79(7)	.50-.76	.42-1.10(7)	.58-.92
Swan	.73-2.08(7)	.90-1.22	.61-1.83(7)	.77-1.23
San Andreas	.42-.62(4)	.42-.79	.60-1.25(2)	.71-1.23
Dakar	.75-2.08(6)	.73-1.23	.66-1.67(5)	.69-1.12
Ascension	.55-.69(3)	.40-.69	.73-1.00(2)	.70-1.04
Canton	.37-1.05(3)	.64-.89	.50-1.00(3)	.41-.63
Kwajalein	.25-1.14(7)	.55-.77	.41-1.21(6)	.63-1.03
Koror	.28-.67(5)	.31-.46	.87-1.91(4)	.89-1.43
Singapore	.59-1.15(6)	.78-1.01	- - -	- - -
Bangkok	.32-.69(7)	.32-.54	.50-.96(6)	.54-.85

Table 12. Range in individual autumn values of the ratio of meridional to zonal kinetic energy for the frequency band $2\pi(1)/12 - 2\pi(6)/12$ day⁻¹ for the period 1964-1970. In parenthesis are the number of seasons forming the basis of extreme values. Results are considered for only those time series having 130 out of a possible 184 12-hourly data points, except at Canton and Singapore where 65 out of a possible 92 24-hourly data points was the limiting number.

MIAMI (26N, 80W), 80F)						SAN JUAN A (18N, 66W), 6F)					
mb											
30	1.01	.87	.53	1.23	1.01	1.30	.79	.58	.60	1.21	
70	1.35	1.37	.92	1.34	1.35	1.50	1.59	.49	1.02	1.0	
200	1.43	1.46	1.52	1.52	1.43	1.51	1.22	1.39	1.68	1.5	
500	1.31	1.56	1.56	1.38	1.31	1.48	1.53	1.05	1.48	1.	
850	1.12	1.25	1.52	1.48	1.12	1.02	1.20	.92	1.42	1.02	
	W	SP	SU	A		W	SP	SU	A		
SWAN (17N, 84W), 84W)						SAN ANDREAS A (13N, 82W), 82W)					
mb											
30	1.23	.48	.37	.63	1.23	.42	.08	-.12	.32	.42	
70	1.42	1.26	.67	1.00	1.42	1.07	.91	.24	.66	1.07	
200	1.48	1.59	1.02	1.37	1.48	.87	.87	.92	1.04	.87	
500	1.58	1.52	1.15	1.23	1.58	1.51	1.27	.74	1.26	1.5	
850	1.26	1.22	1.38	1.39	1.26	.99	1.28	.87	1.43	.99	
	W	SP	SU	A	W	W	SP	SU	A	W	
KWAJALEINE (9N, 168E), 8E)						KOROR (7N, 134E), 134E)					
mb											
30	1.14	.66	.60	.15	1.14	.15	.52	.68	.21	.15	
70	.69	.83	.08	.54	.69	.87	.93	.19	.72	.87	
200	1.32	1.27	1.35	1.53	1.32	.89	1.11	1.19	.73	.89	
500	1.45	1.33	1.09	1.19	1.45	1.19	1.20	1.22	1.50	1.19	
850	.91	1.01	1.08	1.45	.91	1.09	1.12	1.61	1.83	1.09	
	W	SP	SU	A	W	W	SP	SU	A	W	

Table 13. Height-season distribution of spectrum slope for zonal wind for frequency band $1, 2\pi/12 - 2\pi/2 \text{ day}^{-1}$. The signs of all tabulated values should be reversed: with increasing frequency.

ASCENSION (8S, (14W) 14W)						K. DAKAR (15N, (17W) 17W)					
mb											
30	.32	.42	.77	.48	.32	.13	.00	.24	.04		
70	.54	.63	.92	.92	.54	.33	.12	.10	.48	.3	
200	1.63	1.53	1.43	1.49	1.63	.71	1.09	.96	1.19	.71	
500	1.75	1.52	1.49	1.77	1.75	1.31	.85	.63	1.13	1.3	
850	1.35	1.37	1.34	1.44	1.35	1.00	1.47	.35	.90	1.0	
	W	SP	SU	A	W	W	SP	SU	A	W	
BANGKOK (14N, (100E) 100E)						SINGAPORE (1N, 104E) 104E)					
mb											
30	.52	.28	.36	.64	.52	.82	.42	.79	.40	.82	
70	1.23	.91	.04	.34	1.23	.80	.72	1.02	.21	.80	
200	1.12	1.34	.25	.85	1.12	.90	1.31	.76	.78	.90	
500	1.22	1.03	.94	1.03	1.22	1.32	1.09	.98	1.50	1.32	
850	1.10	1.16	1.08	1.26	1.10	1.18	1.16	.89	1.23	1.18	
	W	SP	SU	A	W	W	SP	SU	A	W	
TRIVANDRUM (8N, (77E) 77E)						CANTON (3S, (72W) 72W)					
mb											
30						.58	.45	.84	.59	.58	
70	.49	2.24	.48	.05	.49	1.45	.64	.63	.73	1.45	
200	1.25	.99	.56	.87	1.25	.98	1.09	1.24	1.53	.98	
500	.96	1.74	1.06	1.00	.96	1.46	1.30	1.07	1.44	1.46	
850	.41	1.08	1.09	1.12	.41	1.56	1.44	.99	1.11	1.56	
	W	SP	SU	A	W	W	SP	SU	A	W	

Table 13. (Continued) son distribution of spectrum slope for zonal wind for frequency band 1, $2\pi/12 - 2\pi/2$ day⁻¹. The signs of all tabulated values should be changed to reflect the power with increasing frequency.

MIAMI (26N, 80W)N, 80W)						SAN JUAN J(18N, (166W) 66W)					
mb											
30	.96	.43	-.29	.52	.96	.441	.2121	-.2525	-.0808	.4	
70	1.03	1.23	.51	1.08	1.03	1.11	1.15	-.06	.56	1	
200	1.11	1.29	1.30	1.49	1.11	1.66	1.47	1.46	1.40	1.66	
500	.85	1.14	1.20	1.19	.85	1.37	1.22	.70	1.03	1.3	
850	.85	.92	1.08	1.23	.85	1.09	1.01	.55	1.11	1.0	
	W	SP	SU	A	W	W	SP	SU	A	W	
SWAN (6N, (84W) 84W)						SAN ANDREAS (13N, 82W)N, 82W)					
mb											
30	.39	-.09	-.20	-.11	.39	-.08	-.21	-.31	.45	-.08	
70	.78	.76	-.04	.52	.78	.08	.23	-.21	.03	.08	
200	1.34	1.35	1.23	1.32	1.34	.87	.87	.81	.70	.87	
500	1.02	1.28	.71	.91	1.02	1.07	.83	.31	.53	1.0	
850	1.04	1.34	.69	1.29	1.04	.75	.70	.26	.86	.75	
	W	SP	SU	A	W	W	SP	SU	A	W	
KWAJALEIN (9N, (168E) 68E)						KOROR (7N, 134E) 134E)					
mb											
30	-.27	-.67	-.64	-.05	-.27	-.19	-.55	-.38	-.19	-.1	
70	.28	-.48	-.48	-.40	-.28	-.07	-.01	-.58	-.50	-.07	
200	1.10	.98	.77	1.10	1.10	.45	.90	.62	.79	.45	
500	.96	.94	.21	.46	.96	.69	.53	.68	.78	.69	
850	.41	.34	.07	.56	.41	.74	.77	.99	1.04	.74	
	W	SP	SU	A	W	W	SP	SU	A	W	

Table 14. Height-season distribution of spectrum slope for meridional wind for frequency band $1, 2\pi/12 - 2\pi/2 \text{ day}^{-1}$. The signs of all tabulated values should be reversed to reflect the power variation with increasing frequency.

ASCENSION (8S, 814W) (W)

mb					
30	-.36	-.40	-.35	-.34	-.36
70	-.07	-.07	.31	.12	-.07
200	1.36	1.07	1.72	1.65	1.36
500	1.00	.89	1.00	.98	1.00
850	.89	.64	.60	.71	.89
	W	SP	SU	A	W

DAKAR (15N, 17W) (17W)

	-.25	-.16	-.82	.13	.25
	-.01	-.12	.13	-.07	-.01
	1.08	1.21	.13	1.17	1.08
	1.05	.91	.05	.72	1.05
	.93	.51	.27	.67	.93
	W	SP	SU	A	W

BANGKOK (14N, 100E) (100E)

mb					
30	.38	.13	.05	-.06	.38
70	.52	.05	-.82	.01	.52
200	.86	.99	.36	.78	.86
500	.82	1.04	.59	.77	.82
850	.79	.64	.94	.76	.79
	W	SP	SU	A	W

SINGAPORE (1N, 104E) (104E)

	-.33	-.67	.30	.34	-.33
	.29	.47	.11	.25	.29
	.62	.77	.73	.54	.62
	.68	.71	.58	.93	.68
	.93	1.17	.99	1.34	.93
	W	SP	SU	A	W

TRIVANDRUM (8N, 77E) (77E)

mb					
30	0	0	0	0	0
70	-.60	-.45	.94	.41	-.60
200	.69	.22	.26	.27	.69
500	.85	.53	.23	.46	.85
850	.41	.68	.56	1.00	.41
	W	SP	SU	A	W

CANTON (3S, 172W) (3S, 172W)

	.10	.23	.12	-.04	.10
	-.06	.12	1.53	.60	-.06
	1.38	.94	1.18	.90	1.38
	1.01	.94	.94	1.12	1.01
	.93	.30	.04	.62	.93
	W	SP	SU	A	W

Table 14. (Continued) Season distribution of spectrum slope for meridional
 for frequency band $1, 2\pi/12 - 2\pi/2$ day. The signs of all
 tabulated values should be changed to reflect the power
 with frequency.

Table 20.

Station	Years	Zonal Component Zonal-Component		Meridional Component	
		200 mb Slope/U		200 mb Slope/V	
		Autumn	+2 σ	Autumn	+2 σ
Miami	(7)	-(1.82-1.16)	-(1.80-1.05)	-(2.27-1.17)	-(1.95-1.00)
San Juan	(7)	-(2.22-1.28)	-(2.30-1.10)	-(1.57-.92)	-(1.90-.90)
Swan	(6)	-(2.04-.81)	-(1.80-1.05)	-(1.68-.97)	-(1.75-.85)
San Andreas	(2)	-(1.28-.69)	-(1.50-.60)	-(1.62-.99)	-(1.05-.40)
Dakar	(5)	-(2.09-.78)	-(1.45-.60)	-(1.88-.84)	-(1.70-.70)
Ascension	(2)	-(1.84-1.08)	-(1.90-.85)	-(1.71-1.16)	-(2.10-.90)
Canton	(3)	-(1.68-.65)	-(2.40-1.35)	-(1.53-.27)	-(1.20-.75)
Kwajalein	(6)	-(2.05-1.17)	-(2.25-.75)	-(1.32-.77)	-(1.70-.50)
Koror	(4)	-(.94-.55)	-(1.10-.40)	-(.99-.60)	-(1.15-.40)
Bangkok	(6)	-(1.13-.34)	-(1.20-.60)	-(1.18-.02)	-(1.25-.45)

Table 15. Range in individual autumn values of the slope of the 200 mb wind component spectrum for the frequency band $2\pi(1)12 - 2\pi(6)/12 \text{ day}^{-1}$ for the period 1964-1970. The numbers of years for which the extremes are given is indicated in parenthesis. Results are considered for only those time series having 130 out of a possible 184 12-hourly data points, except at Canton where 65 out of a possible 92 24-hourly data points was the limiting number.

Table 21.

Station	Year	Zonal Component		Meridional Component	
		850 mb Slope		850 mb Slope	
		Autumn	+2 σ	Autumn	+2 σ
Miami	(7)	-(1.64-1.32)	-(1.80-1.40)	-(1.55-.62)	-(1.50-1.00)
San Juan	(7)	-(1.79-.84)	-(1.80-.90)	-(1.39-.95)	-(1.35-.90)
Swan	(7)	-(1.52-1.11)	-(1.60-1.10)	-(1.92-.80)	-(1.65-1.10)
San Andreas	(4)	-(1.81-1.04)	-(1.70-.90)	-(1.23-.14)	-(1.30-.30)
Dakar	(6)	-(1.84-.29)	-(1.20-.40)	-(1.24-.27)	-(1.05-.45)
Ascension	(3)	-(1.49-1.08)	-(1.80-.60)	-(.85-.82)	-(1.25-.45)
Canton	(3)	-(1.41-.84)	-(1.31-.55)	-(.89-.59)	-(.80-.30)
Kwajalein	(7)	-(2.14-1.06)	-(2.20-.95)	-(.93-.11)	-(.85-.30)
Koror	(5)	-(2.88-1.49)	-(2.85-1.20)	-(1.38-.24)	-(1.40-.70)
Singapore	(6)	-(1.55-.77)	-(1.85-.65)	-(2.61-.41)	-(2.00-.70)
Bangkok	(7)	-(1.67-.77)	-(1.75-1.00)	-(1.16-.62)	-(1.15-.60)

Table 16. Same as Table 15 for 850 mb.

<u>Season</u>	<u>Period</u>	<u>Wind</u>	<u>8° N Pacific</u>	<u>11° Caribbean</u>	<u>17° Caribbean</u>
Winter	12	u	W (18-27°)	U W	N E N
Spring	12	u	W (7-19-33°)	N W	U N
Summer	12	u	W (8-15-21°)	N W	U W (8-18-25°) N
Autumn	12	u	W (4-10-7°)	N W (5-7°)	N W (8-18-25°) U
Winter	12	v	W (6-8°)	N	D
Spring	12	v	W (5-7°)	U	U E D
Summer	12	v	W (4-5°)	D W (2-3°)	D W (3-4-5°) D
Autumn	12	v	W (3-4°)	N W (4°)	N N
Winter	4	uu	W (21°)	W (15-23°)	E (34-46°) D
Spring	4	u	W (16°)		E (34-35°)
Summer	4	u	W (13-28°)	W (2-12°)	D W D
Autumn	4	u	W (10-27°)	D W (8-17°)	N W N
Winter	4	v	W (8°)	E (20°)	E (14-18-30°) D
Spring	4	v	W (11-18°)	E (12°)	E (13-20-40°)
Summer	4	v	W (9-11°)	D W (5°)	D W (5-6-7°) U
Autumn	4	v	W (7-10°)	D W (4°)	N N

Table 17. Summary of horizontal and vertical phase progression (degrees longitude per day) at 850 mb. Eastward (E), westward (W), upward (U), downward (D) or no vertical progression (N) are indicated.

<u>Season</u>	<u>Period</u>	<u>Wind</u>	<u>8° N Pacific</u>	<u>14° Caribbean</u>	<u>17° Caribbean</u>	
Winter	12	u	E (35-58-77°) (U)			N
Spring	12	u	E (35-58-77°) N	E	N	E
Summer	12	u	W (17-24-33°)	W (4°)	W (4-15-38°)	(U)
Autumn	12	u	W (17-22-30°) (U)	W (2-13°) (U)		(U)
Winter	12	v	W (14-21°)	W (6°)		D
Spring	12	v		W (10°)		D
Summer	12	v	W (5-6-7°)	W (3-7°)	W (3-3-5°)	N
Autumn	12	v	W (4-6°)	W (3-4°)	W (3-5-7°)	(U)
Winter	(4) 4	u			E	N
Spring	4	u	E (25-35°)		E (13-22-29°)	D
Summer	4	u		W (12°)	W	
Autumn	4	u	W (12-25°) D	W (7°)		
Winter	4	v	W (12-19°)		E (10-18-27°)	N
Spring	4	v	E (16-45°)		E (7-15-29°)	
Summer	4	v	W (12-14-16°)	W (8-10°)	W (6-7-7°)	(U)
Autumn	4	v	W (12-13°)	W (5°)	W (7°)	

Table 18. Summary of horizontal and vertical phase progression (degrees longitude per day) at 200 mb. Eastward (E), westward (W), upward (U), downward (D), or no vertical progression (N) are indicated.

	<u>Div(2)</u>	<u>Div(1)</u>	<u>Div(0)</u>	<u>Div(-1)</u>	<u>Div(-2)</u>	
Vort (2)		12(3)	22(4)			18(7)
Vort (1)	15(4)	17(3)	18(6)	21(4)	19(3)	18(20)
Vort (0)	15(4)	18(5)	16(16)	20(16)	22(3)	18(44)
Vort (-1)		13(2)	14(8)	33(2)		17(12)
Vort (-2)	10(3)	13(4)	12(2)	24(3)	21(4)	16(16)
	14(11)	15(17)	16(36)	22(25)	21(10)	

Table 19. Joint and marginal distributions of 850 mb kinetic energy (m^2/sec^2) as a function of vorticity and divergence of seasonal wind patterns in the southwest Pacific and Indian Ocean. Values in parenthesis are the number of individual seasonal values contributing to each category. In one unit of divergence is $2 \times 10^{-6} \text{ sec}^{-1}$; a vorticity $4 \times 10^{-6} \text{ sec}^{-1}$.

<u>Station</u>	<u>Winter</u>	<u>Spring</u>	<u>Summer</u>	<u>Autumn</u>
TRIVANDRUM	82	84	81	82
SONGKHIA	82	85	84	83
SINGAPORE	82	84	84	84
KOROR	83	84	85	86
KWAJALEIN	83	84	84	85
CANTON	83	84	84	83

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