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COMPARISON OF TROPICAL SYNOPTIC-SCALE WIND
SPECTRA AND SEASONAL PARAMETERS

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A. Introduction

The purpose of this study is to calculate regional synoptic wind component spectra and relate these results to properties of the long period flow. If this parameterization can be accomplished, then spectra may be indirectly estimated in remote regions where data are collected infrequently, or may be prognosticated where larger scale changes are predictable. Ultimately, diffusion coefficients could be estimated in terms of such non-stationary flow parameters.

The Caribbean was chosen as an initial analysis region as it contains some of the better low-latitude wind data and also because it has characteristics of both mid-latitude and tropical wind variability. To date, all spectra and basic flow properties have been computed. So far we have been able only to analyze the gross features of the spectral variability with respect to pilot derived parameters of the flow. Once the optimum flow parameters are determined an automated comparison will be made between the two large sets of data.

B. Procedure

Seasonal wind component spectra from twice-daily rawinsonde data have been computed for 15 stations in the Caribbean and tropical Atlantic for a seven-year period, 1964-1970. Cross spectra for each wind component have been determined among the stations within the following groupings:

- (1) Gold Rock Creek, Miami, Key West, Monterrey
- (2) San Juan, Santo Domingo, Kingston, Grand Cayman, San Andreas, Merida
- (3) Trinidad, Curacao, Balboa, Swan Island
- (4) Dakar, Ascension

The above analyses have been performed for 850, 500, 200, 70 and 30 mb, based on preliminary inter-level cross spectra from several individual stations, which determined those levels which were relatively unrelated, and also included the level of maximum kinetic energy.

1. Filtering

The entire period of data was first filtered with a Gaussian filter to remove the effect of long-term variations from the spectra. The filter is similar to those used by Maruyama (1968) and Wallace (1971) and its

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frequency response is shown in Figure 1. A filtered wind component value is the difference between the observed value and the sum of the weighted data beneath the filter during convolution, the latter normalized to account for missing observations. Missing observations in the filtered time series were not interpolated

2. Spectra

The spectra, smoothed by Hanning, were determined from estimates of autocovariance from the partially complete wind component series. The number of data pairs for the lagged autocovariances is considerably reduced from that of a complete time series and an error in the spectrum occurs as a result. In order to estimate this error, an examination of spectral variability was made as a function of increasing degradation of actual, complete time series. Resulting confidence limits for computed spectral values were estimated as a function of the number of missing observations, the variance of the time series and the spectral values, themselves. Details of the spectral verification are given in the Appendix and a diagram for estimating confidence limits is shown in Figure 2.

The frequency spectrum of coherence and phase between two time series can also be computed from estimates of covariance between the series, and autocovariance of each series, based on incomplete data. The rms variation of coherence and phase were also estimated as a function of the joint distribution of missing observations in both series, the variance of both series, and the spectral values. Again the details are given in the Appendix and shown in Figure 3.

One consequence of the spectral verification study was to revise the initially planned spectral computations. Originally it was desired to relate monthly flow patterns to spectra with a bandwidth resolution of $(30 \text{ days})^{-1}$. However, an inventory indicated there was too much missing data to permit this degree of resolution. In order to detect naturally-occurring, spectral non-stationarity from the existing data, either or both the length of time series or the spectral bandwidth must be increased. Based on the spectral results from the tropical Pacific (Maruyama, 1968, and Wallace, 1971), it was concluded that the maximum permissible spectral bandwidth was $(12 \text{ days})^{-1}$. Using this resolution and seasonal periods of record, it was concluded that cross spectra for most frequencies of interest

would be reliable for time series which were approximately 70% complete.

C. Preliminary Results

The following analyses for two seasons constitutes only a very small fraction of the total computed parameters (28 seasons). Accordingly, the results presented are not final but typify only the kinds of analyses that are now taking place.

1. Sample Spectra

Typical variance spectra for summer (June, July, August) and winter (Dec., Jan., Feb.) are shown in Figures 4 and 5 for zonal and meridional wind components. The analyzed time series are relatively complete so that the spectra are reliable. At all stations the intensity of the spectra is greatest at 200 mb. The intensity is also greater in the winter than summer and is largest for the northernmost station. The relative amplitude of the zonal and meridional spectra is approximately the same.

With the exception of 30 mb, the maximum spectral energy occurs at periods of 12 or 6 days and then decreases rapidly to a period of approximately 2 days. For shorter periods (higher frequencies) the spectral energy generally increases slightly to the 1 day period of maximum resolution. At 30 mb, the spectral energy is very small. There is a tendency for the spectral peak to occur near 1 day at 30 mb, no doubt the result of the diurnal tidal variation. It would appear that although the intensity of the spectra varies with station, level, and season, the variation with frequency remains nearly uniform.

Time sections of the zonal spectral energy for the primary frequency of $(12 \text{ days})^{-1}$ reveal significant nonstationary time variations. This parameter, shown for San Andreas and Miami in Figure 6, indicates that considerable non-seasonal variability occurs and needs to be explained.

2. Sample Cross Spectra

Horizontal cross spectral parameters are indicated in Table I for summer, 1969 and winter, 1970. The results are for the frequency $(12 \text{ days})^{-1}$. These quantities are somewhat more unreliable than the basic spectra as they are functions of two time series with missing observations.

The easternmost station of each pair is underlined in Table I. Positive phase indicates that fluctuations occur earlier at the underlined

Station Pairs	wind comp	850 mb			500 mb			200 mb		
		coh ²	Θ	λ	coh ²	Θ	λ	coh ²	Θ	λ
		Summer 1969								
<u>Miami</u> -Key West	U	.79	6°	30°	.94	3°	60°	.96	9°	20°
	V	.80	9°	20°	.75	3°	60°	.87	0°	
(Mean Flow Direction)				SE			SW			W
<u>San Juan</u> -Santo Domingo	U	.48	0°		.90	24°	56°	.47	27°	50°
	V	.65	34°	40°	.38	34°		.47	28°	48°
(Mean Flow Direction)				E			E			N
<u>Balboa</u> -San Andreas	U	.20	49°		.26	-5°		.52	21°	34°
	V	.50	12°	60°	.04	82°		.46	-2°	
(Mean Flow Direction)				E						NE
		Winter 1970								
<u>Miami</u> -Key West	U	.86	-8°	68°	.85	9°	60°	.91	-7°	76°
	V	.99	-9°	60°	.94	-6°	90°	.88	-14°	38°
(Mean Flow Direction)				W			W			W
<u>San Juan</u> -Santo Domingo	U	.69	-13°	90°	.93	-7°	175	.99	4°	316°
	V	.74	10°	120°	.73	-7°	175	.71	3°	420°
(Mean Flow Direction)				E			W			W

Table I. Horizontal cross spectral parameters, [coherence squared (coh²), phase (Θ) and wavelength (λ)] for frequency (12 days)⁻¹.

station and thus may be interpreted as moving from east to west. The phase is determined independently for both zonal and meridional winds.

The coherence for a particular frequency varies from 0 to ± 1 and is analogous to the correlation coefficient. Thus, the coherence squared which is shown here, indicates the percentage of the spectral energy of time series 1 which can be described from time series 2 at that respective frequency. The reliability of the phase between two series is proportional to the coherence². Small values indicate dissimilar variations in the two series of data at that particular frequency. If values of the coherence² below .5 are ignored in Table I, reasonable phase consistency occurs as measured from zonal and meridional wind components at the same stations and level.

Often it is desirable to try to interpret the horizontal wavelength (λ) of the fluctuation from the phase and knowledge of the distance between stations. Ideally, this can be done only if one, and identical, wave exists at each station. Practically, one determines an average horizontal scale as the spectrum of atmospheric motion results from many horizontal waves travelling with varied velocities. The determination of wavelength also depends on whether one assumes the wave pattern progresses in a prescribed direction, or in the direction of the mean flow, itself. In Table I there are occasions where the mean flow is westerly at high levels, yet waves propagating from east to west are observed for both zonal and meridional winds. In such cases the spectral energy could result from disturbances propagating in the easterly flow at lower levels. Also, during periods of transitional flow, waves which have considerably different properties with respect to direction of propagation when added together may produce inconsistencies between flow direction and wave propagation. Thus, the estimation of wavelength from phase may only be permissible for certain conditions. In Table I, reasonably consistent estimates of wavelength appear where the low-level summer easterlies and winter westerlies are well developed, i.e. extended to a neighboring level.

3. Relations between spectra and large scale flow parameters

The zonal and meridional wind spectra are measures of the distribution of kinetic energy of the flow. Kinetic energy may be generated in situ

by baroclinic, barotropic and convective instabilities or may be transported from another region through horizontal advection. In this kinetic energy analysis, we cannot directly measure the effects of eddy processes, but only infer their result from the large scale wind, temperature and moisture patterns.

As the amplitude of the spectra undergo a considerable south to north increase and also a seasonal variation, the large-scale baroclinicity due to the latitudinal distribution of solar heating would be expected to be an important mechanism. Through the thermal wind relation, this effect can be directly related to the vertical shear of the zonal wind. Song (1971) has shown that the conversion from zonal to eddy potential energy is proportional to the square of the vertical zonal wind shear. For seasonal time scales, this same parameter should also be proportional to the conversion of zonal potential to eddy potential to eddy kinetic energy.

Figure 7 indicates the 200 mb seasonal mean flow pattern, kinetic energy for the frequency $(12 \text{ days})^{-1}$, and zonal wind shear for winter-1966. This frequency band $(12 \text{ days})^{-1}$ while containing the most energy, is also the neighboring scale to the mean flow, and thus most likely to be related to the seasonal mean patterns. A substantial north-south gradient of kinetic energy and zonal wind shear exists and it would appear that the parameters are approximately related by the previously mentioned (square) relationship. Figure 8 indicates the kinetic energy pattern at 850 mb is very similar to that at 200 mb only reduced in scale. Convective instability, as defined from the equivalent potential temperature lapse, occurs equatorwards of 20°N during the winter months. Thus, the small kinetic energy observed at low latitudes may primarily result from convective processes.

During the summer 1966, the kinetic energy appears mostly related to the large-scale features of convective instability, figures 9 & 10. The 850 mb kinetic energy maxima coincides with the pattern of maximum convective instability. The large kinetic energy over southern Florida at 200 mb also appears to be inversely related to the vertical wind shear. These are the appropriate conditions for the growth of towering cumulus which can transport energy to higher levels (Gray, 1970).

In the accompanying kinetic energy diagrams, the direction of the kinetic energy vector (plotted in the first quadrant) is also shown at the individual stations. At 850 mb, it would appear that the presence of topography results in more of the kinetic energy being distributed in the meridional plane. This effect is largest for Central American stations bordering the Caribbean and Gulf of Mexico. At 200 mb the zonal and meridional kinetic energies are more nearly the same.

4. Summary

The preceding indicates samples of the analyses now taking place. The relationship between spectra and both large-scale zonal wind shear and convective instability, noted for individual cases, has physical justification. The effect of barotropic instability has yet to be investigated. In the near future, we will be performing statistical comparisons over our entire spectral data base. The objective measures of spectral reliability as a function of missing observations, developed earlier, will be used to help interpret the results.

References

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APPENDIX

Spectral Variability Resulting From Random Missing Observations

The rms error of variance spectra for various frequency bands was determined as a function of the number of randomly- distributed missing observations. Briefly, a given complete time series of evenly spaced values was randomly sampled using the computer algorithm for generating random numbers. A series with 10% randomly missing data was produced; the spectrum of this series was determined from the estimated auto-variance function and saved internally. This procedure was repeated ten times with spectra for 10 distinctive distributions of 10% missing data being produced. The rms departure of these estimates from the spectrum of complete data was then computed for each frequency band (i). These rms deviations (σ_i) were then normalized with respect to the standard deviation of the original time series (σ).

The above technique was repeated for series containing 20, 30, 40, 50, 60 and 70% missing observations. Also, the ratio of spectral energy to white noise energy (S_i/N) was computed for each frequency band of the complete series. The white noise energy (N) is the variance of the time series (σ^2) divided by the number of frequency bands in the spectrum (12).

Figure 2 indicates the normalized variation of spectral values (σ_i/σ) as a function of the ratio (S_i/N) and the percentage of missing observations. Confidence limits (σ_i) for a spectral value may be estimated from the number of missing observations, the spectral value itself, (S_i) and the variance of the time series (σ^2). Figure 2 was found to describe the spectral variability of several varied series of actual wind data and some fictitious series (combinations of sinusoidal waves and random numbers) as well. The diagram can only be used for seasonal time series, sampled twice daily, with a spectral bandwidth resolution of $(12 \text{ days})^{-1}$. If either the length of time series, or the spectral bandwidth is changed, the magnitude of the curves in Figure 2 will be inversely changed, but their shape appeared unaltered.

Cross Spectral Variability Resulting From Random Missing Observations

The covariance function between two series and the autocovariance functions of each series can also be estimated from incomplete data and used to compute

coherence and phase. The respective rms variation of these parameters, σ_{coh} and σ_{e} , as a function of the simulated joint distribution of missing observations in both series was determined in the same manner used to estimate the spectral variability.

The ratios (S_i/N) were determined for both time series. For a given frequency band, the rms variation of coherence and phase seemed most sensitive to the smallest ratio, $(S_i/N)_{\text{min}}$, of either series. Figure 3 indicates the largest value of $(S_i/N)_{\text{min}}$ that was detected among the various frequency bands for fixed coherence and phase accuracy criteria as a function of the joint distribution of missing data for both time series.

To use 3a and 3b to estimate the confidence in coherence and phase for a given frequency band, the spectral values (S_i) and variances (σ) of both series are required. The ratios (S_i/N) are determined for each series and the smallest is $(S_i/N)_{\text{min}}$. If this value is smaller than the value indicated on the diagram for the joint distribution of missing observations being considered, the specified accuracy criteria is satisfied.

As for the case of spectral variability, Figure 3 can only be used for seasons (184 points) and a bandwidth resolution of $(12\text{days})^{-1}$. The results appeared nearly independent for various time series analyzed in this manner.

Figure 1. Gaussian filter response function

Figure 2. Normalized variation of spectral estimates (σ_i/σ) as a function of percent of complete data and (S_i/N) ratio, based on seasonal records, sampled twice daily, and a spectral resolution of $(12 \text{ days})^{-1}$.

Figure 3. As a function of the joint distribution of missing observations in two time series, the largest $(S_i/N)_{\min}$ ratio is indicated (a) for which the rms variation of coherence equals 0.2; (b) for which the rms variation of phase angle equals $22\frac{1}{2}^\circ$. Both diagrams can be used only for seasonal records, sampled twice daily, and for a spectral resolution of $(12 \text{ days})^{-1}$.

Figure 4. Zonal wind component variance spectra for Miami (.), San Juan (o), and San Andreas (x).

Figure 5. Meridional wind component variance spectra for Miami(.), San Juan (o), & San Andreas (x)

Figure 6a. Zonal spectral energy for 12 day period at San Andreas ($\text{m}^2 \text{s}^{-2}$ per $2\pi/12 \text{ days}^{-1}$)

Figure 6b. Zonal spectral energy for 12 day period at Miami ($\text{m}^2 \text{s}^{-2}$ per $2\pi/12 \text{ days}^{-1}$)

Figure 8. Winter 1966 - 850 mb flow (top), 850 mb kinetic energy for 12 day spectral period (middle) and lapse of equivalent potential temperature between 850 and 500 mb (bottom).

Figure 10. Same as Figure 8, except for Summer 1966.