SPECTRAL CORRELATION TESTS OF AN EDDY HEAT FLUX PARAMETERIZATION

by

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ABSTRACT

A two-layer model processes eight years of twice daily geopotential height data to compute the total eddy flux of sensible heat and its combination of predictors in a parameterization representative of those used in climate models. The parameterization assumes that the eddy flux is proportional to a stability coefficient, X, times the square of the meridional temperature gradient. Zonal Fourier decomposition and temporal analysis of covariance are employed to determine the correlation spectra of the parameterization, thereby testing its validity for various zonal spatial and temporal scales. This procedure is performed for four 10 degree wide latitude bands centered at 35,45,55, and 65 degrees north.

The results show that the parameterization models the seasonally forced zonally averaged eddy flux well, in agreement with previous studies, and reveals additional seasonal forcing on a few other large zonal scales as well. We cannot determine whether the stability coefficient improves the parameterization in comparison with another which does not include it.

Baroclinic adjustment, whereby the eddies adjust the gradient as a result of baroclinic instabilities. is revealed in the negative correlations found on short time scales. It is shown that adjust-

ment may be occurring on zonal scales as small as the relevant zonal scale of the eddies themselves. By identifying the most favored time scale as that scale which exhibits the most negative correlation for a given zonal scale, we can show that that time scale retrogresses as the eddy size decreases. Eventually the eddies become too small, and hence too short-lived, to be observed. We identify four days as an overall favored time scale in which baroclinic eddies adjust the gradient.

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CHAPTER ONE

INTRODUCTION

1.1 The Eddy Flux Parameterization Problem

In seeking a closed system of equations to describe climate, the equations of motion along with the thermodynamic equation must be solved in time averaged form. Often the climate is defined as a zonal mean process, and the equations may be spatially averaged as well. Each independent variable is usually thought of as the sum of average and eddy parts which are substituted into the equations, then the equations themselves are averaged. In the case of the mean Navier-Stokes equations, the average product of stochastic variables appears. These terms are known as Reynold's stresses, which describe the transport of turbulent momentum. Similar terms appear in the thermodynamic equation; these are known as eddy heat fluxes. In principle the eddy heat fluxes can be solved for from the original equations. It is, however, a difficult process because the non-linear terms in the momentum equations generate higher order deviations. To get around this closure problem, current research focuses on parameterization of the eddy heat flux in terms of the mean atmospheric structure. Usually the parameterizations include the mean meridional temperature gradient and other quantities derived from the

physical reasons for the existence of the eddies.

Climate models which include the total heat transport must contain parameterizations which accurately measure the contribution of the eddies to that total. Current parameterizations only roughly model the gross eddy transport. The key problem is thus finding improved parameterizations. In order to accomplish this, the physical behavior of the eddies in relation to their predictors must be examined.

Because the eddy behavior is a function of spatial and temporal scales, one parameterization may work well when the averaging time is long, say, several months, but wouldn't work at all for short time scales, say, less than a month. Furthermore, zonal averaging smooths out the contributions of eddies of smaller zonal scale which exist because of locally unstable baroclinic zones. Because differing regions of the earth exhibit differing climates, parameterizations without zonal dependence yield little information for specific geographic regions. Hence no parameterization can capture all of the physics of the growth and decay of eddies.

Solutions to the problem hinge on several approaches. First, what does theory (particularly baroclinic instability theory and scale analysis) suggest? Secondly, what does the data reveal? Finally, how well do particular theories describe the actual behavior of the eddies, and what can we learn about the eddies from them? Our study will focus on answers to this last question.

1.2 Forced Versus Free Eddy Behavior and Baroclinic Adjustment

Much is already known about the behavior of the eddies. Lorenz (1979) showed that for the zonally averaged case, modelling eddy transport as heat diffusion works well only for the meridional planetary scale when the time scale is inclusive of seasonal forcing. For shorter or longer time scales and smaller meridional scales, the variations in eddy flux were free--unrelated to external seasonal forcing--and thus unable to be accounted for by diffusive theory alone. When we speak of free variations, we will be talking about the short period (less than a month) variety.

Stone (1978) has termed the zonally averaged free eddy behavior "baroclinic adjustment." In this process, the eddies grow in response to baroclinic instabilities unrelated to the absolute local value of the temperature gradient--but ultimately affect it by efficiently transporting heat. In contrast for the seasonal case, changes in the sun's inclination force changes in the gradient which force the eddies--a diffusive type transport. Lorenz was the first to identify this difference between forced and free regimes.

Current theories of parameterization are derived for forced variations only and in general apply to the zonally averaged case. Hence, heat transported by eddies as a result of free variations is not well modelled. In most

instances the parameterization seeks to account for the gross effect of the transport due to free variations by defining an eddy diffusivity (in analogy to a thermal diffusivity) which weights the forcing by the gradient. The form of this coefficient may be simple or elaborate depending on which theory was used to derive it.

One by product of these theories, and baroclinic instability theory in general, is the prediction of the relevant zonal scales of the eddies. Held (1978a) suggests, for instance, that the zonal extent of an eddy may depend upon the vertical extent of its associated baroclinic wave. Another by-product is the well-known result that the β-effect serves to stabilize the growth of baroclinic waves. In the two-layer model (Phillips, 1954), β is important in determining the shear at which the model becomes baroclinically unstable. "Two-layer" eddies can grow and transport heat when the actual shear exceeds the critical shear. Both of these considerations have been taken into account in theories which adjust the form of the eddy diffusivity mentioned above.

1.3 Objectives of this Research

By using actual data to test a particular parameterization, much can be learned about (1) the parameterization itself, and (2) the behavior of the eddies in relation to its predictors.

By studying one particular parameterization we are limited in our ability to compare with other parameterizations. However, we can assess its ability to model the eddy flux in comparison to that for which it was designed. To determine how a particular parameterization functions is to determine the spatial and temporal scales over which actual data assess its validity. That is, for what space and time scales is the eddy flux well-positively correlated with its combination of predictors in the parameterization of question?

The eddy behavior in relation to its predictors can be understood, on the other hand, by examining the entire range of correlations through the various space and time scales available in the data base.

Previous studies have concentrated on zonally averaged data. Stone (1978) identified the negative correlations on short time scales between the eddy flux and meridional temperature gradients as baroclinic adjustment, but used only a small data base--three Januaries. Lorenz (1979), although making use of 10 years of twice daily data, again studied the zonally averaged case in looking at meridional scales.

Eddies adjust on short time scales (free variations) and are forced on long time scales. The zonal scale of an eddy can be significantly smaller (determined by the relevant radius of deformation) than the planetary. By studying the zonally-dependent space-time correlation spectrum be-

tween the eddy flux and its predictors, we should be able to observe adjustment on short time scales within several zonal wavenumbers in the form of significant negative correlations. Adjustment has never been observed on scales smaller than wavenumber 0. Also, we should be able to observe forced eddy behavior on seasonal time scales for at least wavenumber 0. No study has sought to tie together adjustment and flux-gradient forcing so succinctly. Furthermore, we can look at the correlation spectrum as a function of latitude and gain knowledge about the relationship between adjustment regimes, forced regimes and the scales of the eddies themselves.

The primary advantage of a spectral correlation test is that it will uncover which zonal spatial scales yield the most significant temporal correlations. Available to us are 10 years of twice daily geopotential height observations at 850 mb, 500 mb and 300 mb (see Section 3.1). By arranging the data in a two-layer format, modelling a parameterization based on the two-layer model and constructing its correlation spectrum as a function of latitude, the free-forced space-time behavior of the "two-layer" eddies should be adequately revealed.

CHAPTER TWO

MODELLING THE EDDY FLUX AND ITS PREDICTORS

2.1 Choice of Specific Parameterization for Study and Analysis Method

In choosing the particular parameterization for this study, we must select one that can be adapted to the two-layer model, since our data are available in that format. The parameter dependences should include meridional temperature gradient and an eddy diffusivity which accounts for the β-effect (because we are interested in latitudinal variations), and which takes into account the zonal scale of the free regime eddies. A priori, then, we choose a parameterization which is likely to reveal the free-forced regime eddy behavior as a function of zonal scale and latitude.

It is convenient to follow Held (1978b). We write the eddy heat flux as

$$\overline{v'\theta'} = -D \frac{\partial \overline{\theta}}{\partial y} \qquad (2.1)$$

where D is the eddy diffusivity with units of velocity time length.

$$D = V \cdot L \qquad (2.2)$$

Stone (1972) assumes the velocity scale is determined by the vertical shear times the scale height, $V = H \frac{\partial \overline{u}}{\partial z}$ and the length scale is approximated by L = NH/f. Here N is the

Brunt-Väisälä frequency, $N \alpha \left(\frac{\partial \bar{\theta}}{\partial z}\right)^{1/2}$, and f is the Coriolis parameter. Stone's choice of length scale is the Rossby radius corresponding to the scale height. By the thermal wind relation, $\frac{\partial \bar{u}}{\partial z} \alpha \frac{\partial \bar{\theta}}{\partial y}$ so that when D is substituted into (2.1),

$$\overline{v'\theta'} \alpha \left(\frac{\partial \bar{\theta}}{\partial y}\right)^2 \left(\frac{\partial \bar{\theta}}{\partial z}\right)^{1/2} \tag{2.3}$$

Because $\beta = \frac{\partial f}{\partial y}$ affects the growth of baroclinic waves, one would expect it to affect the form of the diffusivity (2.2). Held (1978b) has argued using scale analysis that (2.3) should be modified such that

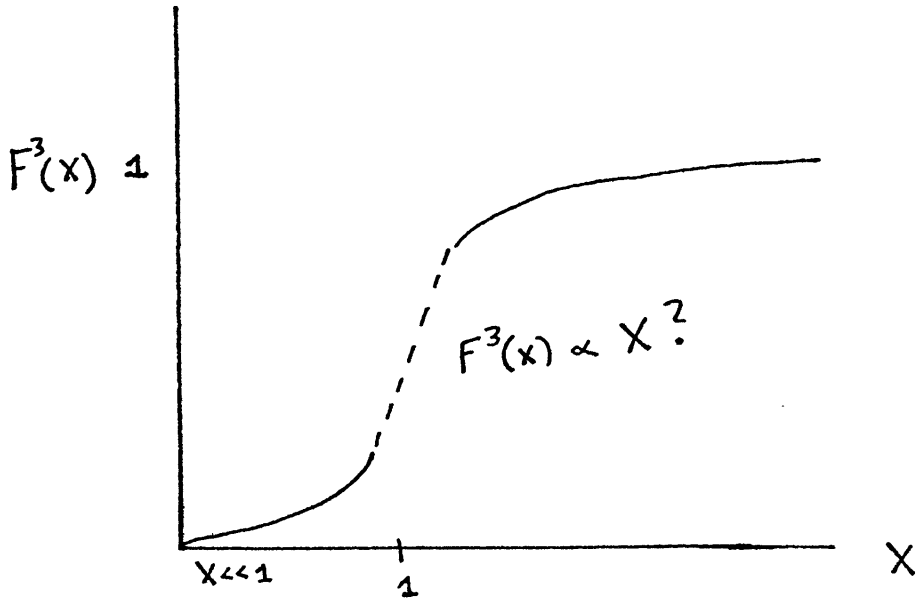
$$\overline{v'\theta'} \alpha \left(\frac{\partial \bar{\theta}}{\partial y}\right)^2 \left(\frac{\partial \bar{\theta}}{\partial z}\right)^{1/2} F^3(x) \tag{2.4}$$

where $X = \frac{h}{H}$, H being the scale height, and h is the vertical scale of the most unstable baroclinic mode. This vertical scale is defined by $h = (f^2 \frac{\partial \bar{u}}{\partial z})/\beta N^2$. When β is small $X >> 1$; conversely $X << 1$ for large β. Held's arguments proceed to deduce the following form for $F^3(X)$ in the limits $\beta \rightarrow$ large and $\beta \rightarrow$ small:

$$F^3(X) = \begin{cases} 1 & \beta \text{ small} \\ X^3 & \beta \text{ large} \end{cases}$$

For small β (β decreases northward) (2.4) reduces to (2.3); for large β (2.4) is changed significantly. The problem

arises because scale analysis doesn't predict the form of $F^3(X)$ for realistic atmospheric values of β. In the real atmosphere, $h \approx H$ so that X is near 1. A plot of F^3 vs. X looks as follows:



Assume for the real atmosphere that $F^3(x) \alpha X$. If this is the case, (2.4) becomes

$$\overline{v'\theta'} \alpha \left(\frac{\partial \bar{\theta}}{\partial y}\right)^2 \left(\frac{\partial \bar{\theta}}{\partial z}\right)^{1/2} \left(\frac{\partial u}{\partial z}\right) \left(\frac{\partial \theta}{\partial z}\right)^{-1} \qquad (2.5)$$

This is a complex parameterization to attempt to study with a large data set. If we ignore the contribution of the static stability to the 1/2 power in (2.5), it both simplifies the form of the diffusivity and leads us to Saltzman's (1967) parameterization, which says

$$D \alpha \left(\frac{\partial \bar{\theta}}{\partial y}\right) \cdot B \qquad (2.6)$$

where B is a stability coefficient. In the two layer model, B is directly analogous to X. Thus we choose to test

$$\overline{v'\theta'} \alpha \left(\frac{\partial\bar{\theta}}{\partial y}\right)^2 \left(\frac{\partial\bar{u}}{\partial z}\right) \left(\frac{\partial\theta}{\partial z}\right)^{-1} \qquad (2.7)$$

both because it is simpler than (2.5) and representative of (2.6). In (2.7), the zonal scale is no longer explicitly NH/f. This is a concession, but we expect it to make little difference in our analysis.

Equation (2.7) is easily adapted to suit a two-layer model. Let subscripts 1 and 3 denote the upper and lower layers respectively. Then $X \alpha \left(\frac{\partial\bar{u}}{\partial z}\right) \left(\frac{\partial\theta}{\partial z}\right)^{-1}$ is given by $\frac{U_1 - U_3}{U_c}$, where $U_c = \frac{\beta R(\theta_1-\theta_3)}{f^2}$ is the critical shear. (See Stone, 1978.) When $(U_1-U_3)/U_c > 1$ the model is baroclinically unstable and waves may grow. Hence X is just a Saltzman stability coefficient in the two-layer sense.

In order to test (2.7) spectrally, we must be able to compute the instantaneous values of each side as functions of λ, ϕ, t. For the left hand side, we want the mass weighted vertically integrated eddy flux of sensible heat--call it $\hat{V^*T^*}$. Here $V = [V] + V^*$, $T = T^* + [T]$ where $[(\ )]$ indicates a zonal average. Thus $\hat{V^*T^*}(\lambda,\phi,t)$ is the instantaneous transport desired. Let ΔT be the mass weighted tropospheric temperature gradient. Then

$$\hat{V^*T^*}(\lambda,\phi,t) \alpha (\Delta T)^2 \cdot \frac{U_1 - U_3}{U_c}(\lambda,\phi,t) \qquad (2.8)$$

Equation (2.8) is appropriate for testing with our data set and accurately represents the physics in (2.7) provided the correlations are not performed point by point. To avoid this, the quantities in (2.8) will each be smoothed latitudinally over the width of 4 independent 10^{o} wide latitude bands. The term $\hat{V^{*}T^{*}}$ will represent the average flux through the band. Similarly $(\Delta T)^{2}$ will be defined as 20^{o} ΔT centered at the band center, and $(U_1-U_3)/U_c$ will also be smoothed across the band width. The smoothing process, along with a 20^{o} wide ΔT, is necessary because small scale gradients do not force eddy fluxes to any great degree. It also eliminates noise.

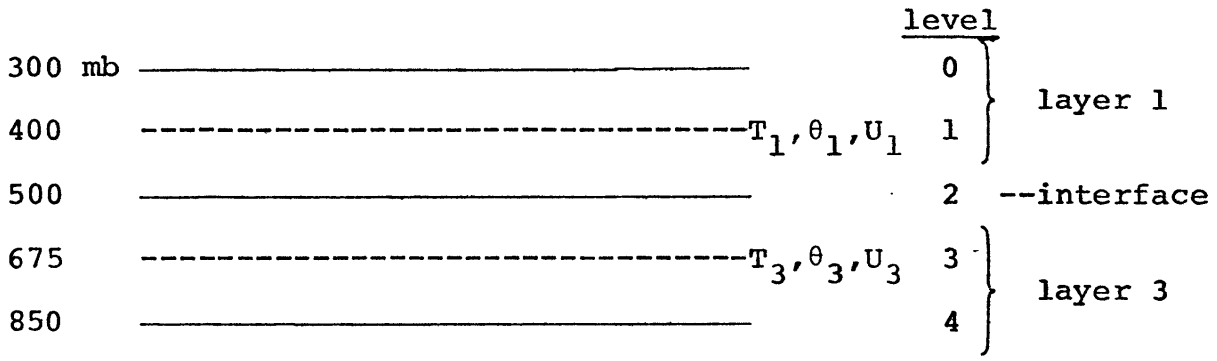
Spectral decomposition of (2.8) will thus take place in 4 latitude bands chosen to be centered at 35^{o}, 45^{o}, 55^{o}, and 65^{o} N. Fast Fourier analysis will be used to compute the zonal Fourier coefficients of each side of (2.8) as functions of time. Then, the poor man's time spectral analysis described by Lorenz (1979) will be used to construct the correlation spectrum of Fourier coefficients as functions of time. Thus, the spatial scales will be resolved as well--the zonally averaged case so often studied just falls out as the wavenumber 0 correlation spectrum. Identically calculated spectra are produced independently for the four latitude bands, allowing interpretation of results to span the midlatitudes. Sections 3.4.1 and 3.4.2 will discuss this analysis in detail.

A priori we can say something about what we expect to learn from studying (2.8). First of all, we would expect it to model forced variations for the zonally averaged case very well. We suspect that the X parameter by itself is not a very good eddy diffusivity, because diffusive assumptions like (2.6) are simpler than those derived from complex baroclinic theory. Because X is on average near 1 (the long-term mean shear approximates the long term critical shear), we can project that for seasonally forced variations our correlations will resemble these between the flux and gradient squared alone. We hope that they would be slightly better, but we have limited means with which to verify this.

We expect that (2.8) will reveal nicely baroclinic adjustment. Because X automatically includes β in its critical shear, we believe the negative correlations indicative of adjustment may be enhanced by the inclusion of X. We expect to be able to detect adjustment for a range of wavenumbers, but perhaps not as well as if the zonal scale were explicitly included as in (2.5). On this last point, however, we can only conjecture.

2.2 A Two-Layer Format for Processing Geopotential Height Data

We seek to compute all of the quantities in (8) using a two-layer model given height data at 300, 500 and 850 mb. We model the atmosphere as follows:



In some sense it is a crude model because there is some eddy transport above 300 mb. (particularly when the tropopause is higher than that) and below 850 mb. We are actually looking at a slice which includes about 80% of the mass of the troposphere

2.2.1 Critical Shear

To compute this we must compute the temperature hydrostatically:

$$T_1 = \left(\frac{g}{R}\right) \frac{\Delta_{0,2}z}{\ln \frac{5}{3}} \tag{2.9}$$

$$T_3 = \left(\frac{g}{R}\right) \frac{\Delta_{2,4}z}{\ln(\frac{8.5}{5})} \tag{2.10}$$

where $\Delta_{i,j}$ stands for the height difference between the i,j layers. The potential temperatures θ_1 and θ_3 are just

$$\theta_1 = T_1 \left(\frac{p_s}{p_1}\right)^{R/C_p} \tag{2.11}$$

$$\theta_3 = T_3 \left(\frac{p_s}{p_3}\right)^{R/C_p} \tag{2.12}$$

where p_1 = 400 mb, p_s = 1000 mb, and p_3 = 675 mb. The critical shear, given by $U_c = \frac{\beta R}{f^2}(\theta_1 - \theta_3)$ is then determined as a function of latitude.

2.2.2 Mass Weighted Meridienal Temperature Gradient

Let ΔT_i stand for the temperature difference at layer i along a 20^o latitude stretch of a given longitude λ_o. The mass weighted gradient is given by

$$\Delta T_m = \frac{2\Delta T_1 + 3.5\ \Delta T_3}{5.5} \tag{2.13}$$

Eq. (2.13) is computed using (2.9) and (2.10).

2.2.3 Actual Shear

We want to compute the velocities U_1 and U_3 in the two layers from the geopotential height data. It is convenient to follow Lorenz (1979) in first computing a geostrophic streamfunction and then getting the velocity fields.

From the divergence equation,

$$\frac{\partial \delta}{\partial t} = -\hat{k} \times \vec{u} \cdot \nabla(f+\zeta) - \omega \frac{\partial \delta}{\partial p} + (f+\zeta)\zeta - \nabla\omega \cdot \frac{\partial \vec{u}}{\partial p}$$

$$- \nabla^2[(gz) + \frac{1}{2}\vec{u} \cdot \vec{u}] + \nabla \cdot \vec{F} \tag{2.14}$$

include only the terms

$$0 = -\hat{k} \times \vec{u} \cdot \nabla f + f\zeta - \nabla^2 gz \tag{2.15}$$

where $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = k \cdot (\nabla \times \vec{u})$. Assuming that we can represent the velocity by a stream function ψ such that $\vec{u} = \left(\frac{-\partial \psi}{\partial y}, \frac{\partial \psi}{\partial x}\right)$, we have $\nabla \cdot \vec{u} = \delta = 0$. Then $\zeta = \nabla^2 \psi$ by definition. Hence,

$$g\nabla^2 z = (-\hat{k} \times \vec{u}) \cdot \nabla f + f\nabla^2 \psi \tag{2.16}$$

Now $\beta = \frac{\partial f}{\partial y}$ and $\frac{\partial f}{\partial x} = 0$. Then

$$g\nabla^2 z = - u\beta + f\nabla^2 \psi \tag{2.17}$$

$$g\nabla^2 z = \frac{\partial \psi}{\partial y} \beta + f\nabla^2 \psi \tag{2.18}$$

or $$g\nabla^2 z = \nabla \psi \cdot \nabla f + f\nabla \cdot \nabla \psi = \nabla \cdot (f\nabla \psi) \tag{2.19}$$

Finally, $$g\nabla^2 z = 2\Omega \nabla \cdot (\sin \phi \nabla \psi) \tag{2.20}$$

A procedure for solving (2.20) for ψ when z is expressed in spherical harmonics is described in Lorenz (1978). Equation (2.20) is more complex than the simple geostrophic relationship $gz = f\psi$ because it includes β effects--this is exactly what we desire.

To get the stream function at levels 1 and 3 we compute

$$\psi_1 = \frac{\psi_0 + \psi_2}{2}, \quad U_1 = \frac{-\partial \psi_1}{\partial y} \tag{2.21}$$

$$\psi_3 = \frac{\psi_2 + \psi_4}{2}, \quad U_3 = \frac{-\partial \psi_3}{\partial y}$$

We can then use a centered finite difference scheme to get the velocities u_1 and u_3 from ψ_1 and ψ_3. Hence, finally, $(u_1 - u_3)$ is the actual shear desired. Combining the results of (2.21) with the critical shear calculation yields $\frac{u_1 - u_3}{u_c}$, one part of the right hand side of (2.8).

2.2.4 Eddy Flux

We want to compute the total eddy flux representing the integrated value through the depth of the model:

$$\hat{V^*T^*} = \int_{850}^{300} \frac{c_p}{g} V^*T^* dp \qquad (2.22)$$

As before $[(\ )] = \frac{1}{2\pi} \int_0^{2\pi} (\ ) d\lambda$ so that

$$V^* = V - [V] \qquad (2.23)$$

$$T^* = T - [T].$$

T^* is simply computed from (2.9) and (2.10). The choice of a stream function to represent the velocity presupposes a non-divergent field; hence there is no mean meridional signal resolved by this method. This is convenient again because we are only interested in the eddy part of the V field. Hence

$$V_1^* = \frac{\partial \psi_1}{\partial x} \qquad (2.24)$$

$$V_3^* = \frac{\partial \psi_3}{\partial x}$$

hold for the eddy velocities at levels 1 and 3. Combining (2.23) and (2.24), we compute the two-layer finite sum representing (2.22):

$$\hat{V^*T^*} = \sum_{i=1}^{3} \frac{C_p}{g} V_i^* T_i^* \Delta_i p, \qquad \Delta_1 = 200 \qquad \Delta_3 = 350 \qquad (2.25)$$

This completes all of the model equations needed to process the height data into the quantities found in (2.8). The next chapter will discuss data acquisition and handling, the programming of these equations, and the equations and programming of the statistical analysis by spectral decomposition.

CHAPTER THREE

DATA ACQUISITION, MODEL, AND STATISTICAL ANALYSIS

3.1 Data Sources and Description

All the data were derived from synoptic analyses of the 850, 500 and 300 mb geopotential height field made at the National Meteorological Center, although it originated in the different formshaving been stored on tapes at the NCAR computing facility. Initially available to us were previously analyzed height fields at 500, 850 mb in the form of triangularly truncated spherical harmonics (Leight, 1974). The series are defined by:

$$Z(\lambda,\phi,t) = \sum_{n=0}^{L} \sum_{m=0}^{n} \left[C_{mn}(t)\cos m\lambda + S_{mn}(t)\sin m\lambda \right] \times P_n^m(\sin\phi) \qquad (3.1)$$

Lorenz (1978) documents the spherical harmonic data set at 500 mb completely, the 850 mb set is identical in structure. Here Z is the geopotential height, λ is longitude, ϕ latitude, t time, and P_n^m the associated Legendre function of degree n and order (or wavenumber) m. The series were truncated triangularly at L = 18. Maurice Blackmon provided NCAR tapes B6902 and B10618 containing the coefficients C_{mn} and S_{mn}, 100 cosines and 90 sines represent each field.

These two datasets spanned 10 years and 1 month beginning Dec 1, 1962.

In order to employ our model, data was acquired through the NCAR tape library for the 300 mb geopotential heights in 400 word packed binary. Tape C4650 was used; the dataset on this tape began before Dec 1, 1962 and extended through 12z Nov 21, 1971.

3.2 Initial Computational Work

The task of organizing the massive quantity of data (over 13 million data pieces) needed for this study was formidable. Over half the computing time was consumed by this stage of the project. In order to calculate, via the model, the quantities in (2.8) six tapes--3 of the heights themselves and 3 of their spherical harmonic representations--were needed.

The grid size was chosen to be 5^{o} x 5.625^{o} (latitude x longitude) extending from 25^{o}N to 75^{o}N. This provided 11 latitudes and 64 longitudes. The longitudinal spacing was chosen because fast Fourier analysis is convenient for powers of 2, and in foresight of the upcoming longitudinal Fourier decomposition. The latitudinal range was chosen so that 20^{o} wide ΔT's were available for the four latitude bands, centered at 35^{o}, 45^{o}, 55^{o}, 65^{o}.

For convenience the length of the study was chosen to begin Dec 1, 1962 and end Nov 21, 1971 so that the datasets

were exactly compatable. This meant that observations were lopped off the beginning of tape C4650, and lopped of the end of the two spherical harmonics tapes.

A program was written to reconstruct the height grids (5^{o} x 5.625^{o}) from their spherical harmonic coefficients. These grids then became inputs to the parts of the model which used direct heights for calculation. Thus, tapes of the 850 and 500 mb height grids and their spherical harmonic coefficients (4 tapes total) were acquired rather easily.

Producing the raw 300 mb data was much more tedious. Package routines at NCAR were used to unpack the binary data on tape C4650 and convert it to grids like those at the other two levels. It was then discovered that the 300 mb data contained 200 (out of 6556) missing observations. Programs were then written to hydrostatically interpolate the 300 mb heights for the scattered missing observations from the 850 and 500 mb grids, and then insert the interpolated data into their missing slots. Once this was accomplished, we had a complete tape of the 300 mb height grids spanning 6556 observations.

The reverse procedure then had to be undertaken to produce the spherical harmonic coefficients from the height grids at 300 mb. Maurice Blackman provided a program suited for our needs, and after adapting it to our data structure, it was used to accomplish our purpose.

The problems presented by massive quantities of data were significant. For example, the 300 mb spherical harmonics

had to be produced in 5 separate pieces because of the limitations on tape storage capacity. Program efficiency was a high priority because somewhat complex calculations were repeated thousands of times. Hence, small test data sets were constructed and used to test almost every program of significant length. Ensuring that each data set was identically formatted was a must, so that in merging the levels we could be certain that all 3 levels always contained observations made at the same date and hour.

3.3 Computation by the Two-Layer Model

Three programs, named CRTSHR, DAGRI3, and FINAL, were used to compute and store the quantities in (2.8). Table 3.1 describes the functions of the programs CRTSHR and DAGRI3.

Program CRTSHR produced the quantities from the input height grids as shown in Table 3.1 A sample section of an input height grid is shown in Fig 3.1. The programming algorithms used in CRTSHR are quite simple and available from the author.

Sample outputs of critical shear, $20^{\circ}\Delta T$, T_1^* and T_3^* are shown for 5/9/64 at 00Z in figures 3.2 - 3.5 respectively. One item to be noted is that the critical shear is a much stronger function of latitude, due to the β-effect, than longitude. Variations in U_c longitudinally are solely due to static stability differences. Sample outputs were thoroughly checked for consistencies with realistic meteorological

Table 3.1

Two-Layer Model Programming,

Programs CRTSHR, DAGRI3

Quantity	Equation in Text	Input	Produced by Program
Critical Shear	(2.11), (2.12)	Height Grids	CRTSHR
20^{o} Temperate Gradients	(2.13)	Height Grids	CRTSHR
T* Level 1	(2.23), (2.9)	Height Grids	CRTSHR
T* Level 3	(2.23), (2.10)	Height Grids	CRTSHR
V* Level 1	(2.24)	Spherical Harmonics	DAGRI3
V* Level 3	(2.24)	Spherical Harmonics	DAGRI3
Actual Shear	(2.21)	Spherical Harmonics	DAGRI3

Fig. 3.1 Sample Section of an Input Height Grid
Dec. 1,1962, 00Z

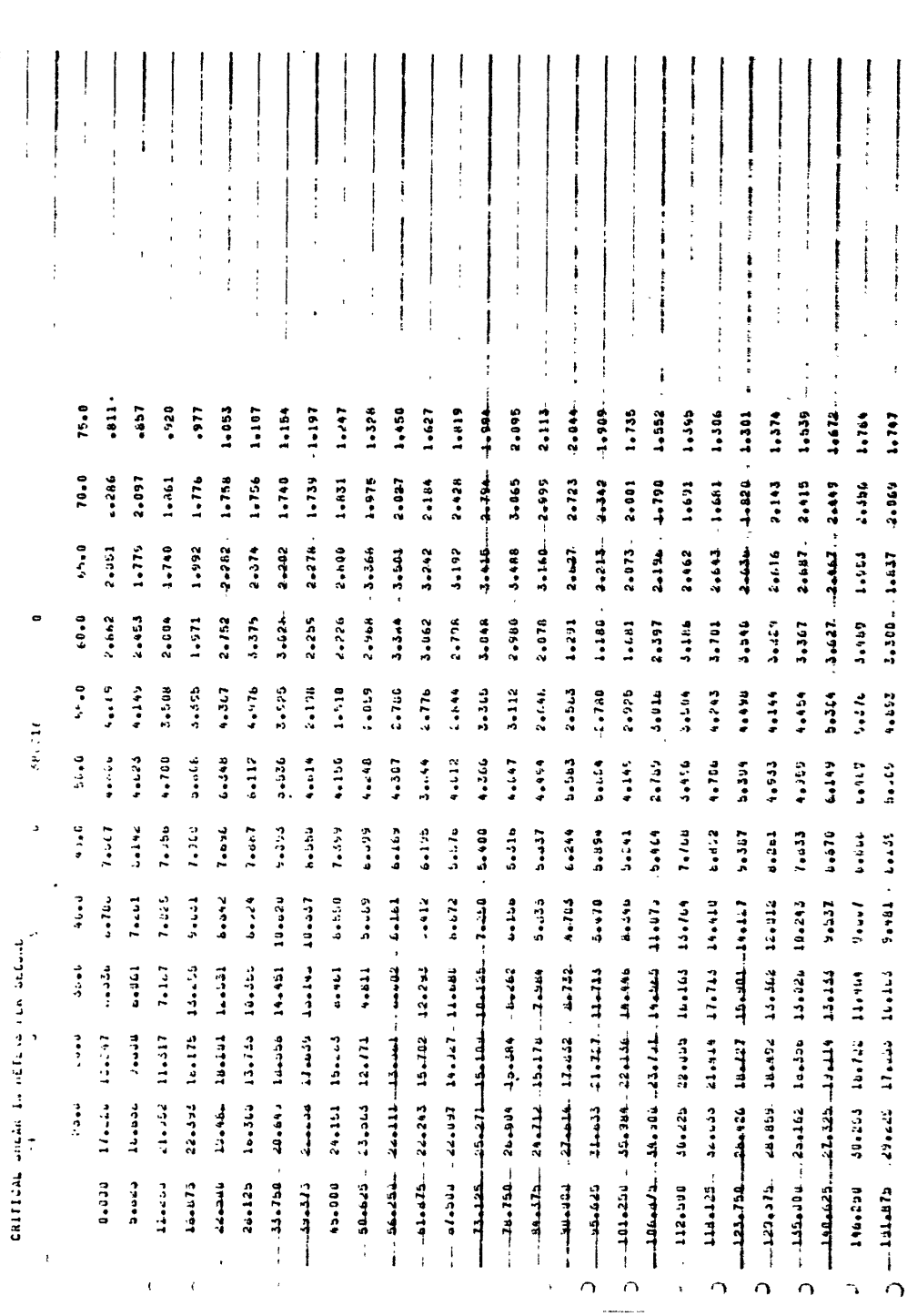


Fig 3.2 Critical Shear, Sample Output, 5/9/64 00Z

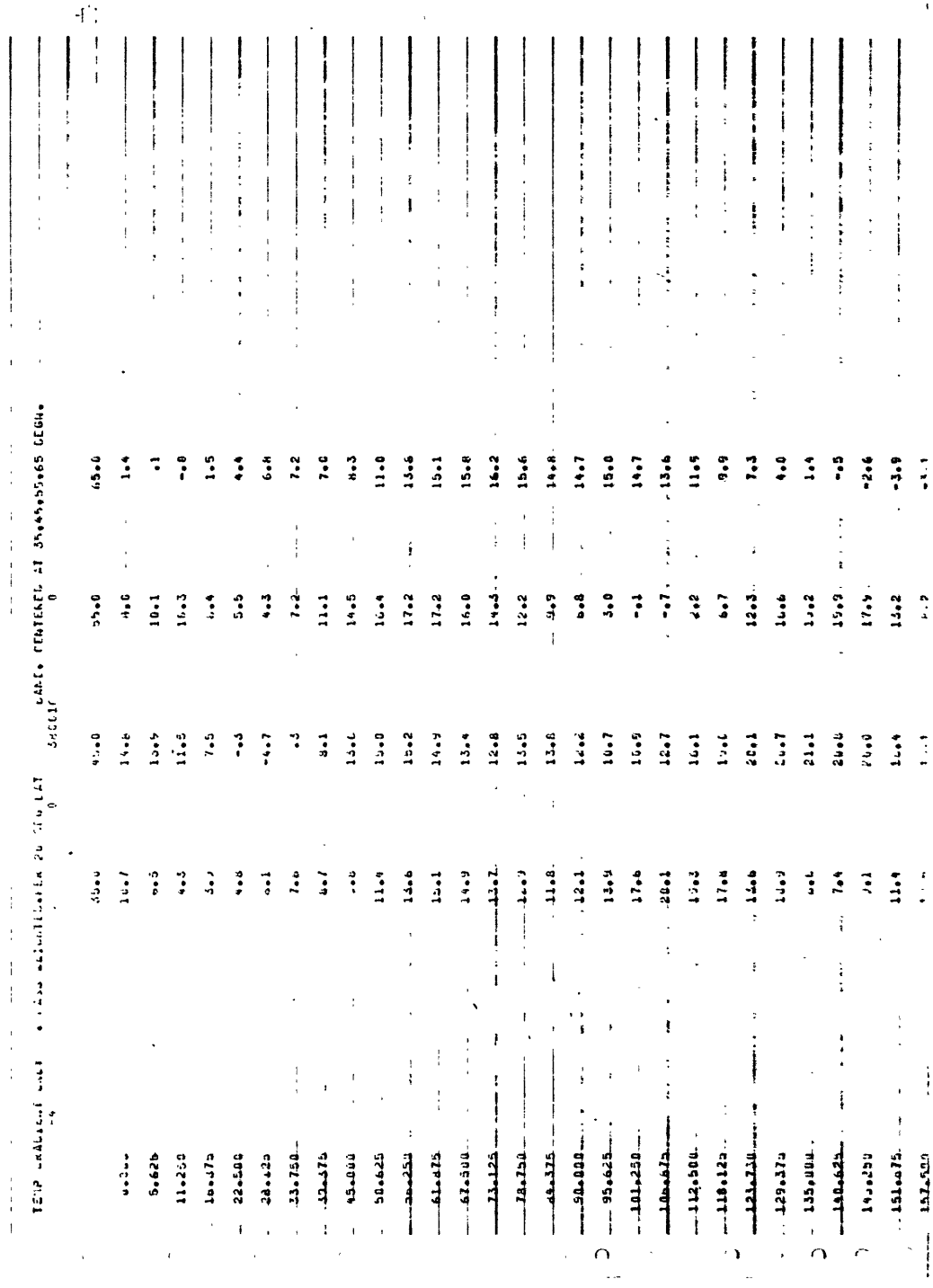


Fig. 3.3 Sample Output 20^0 Temp. Gradient, 5/9/64 00Z

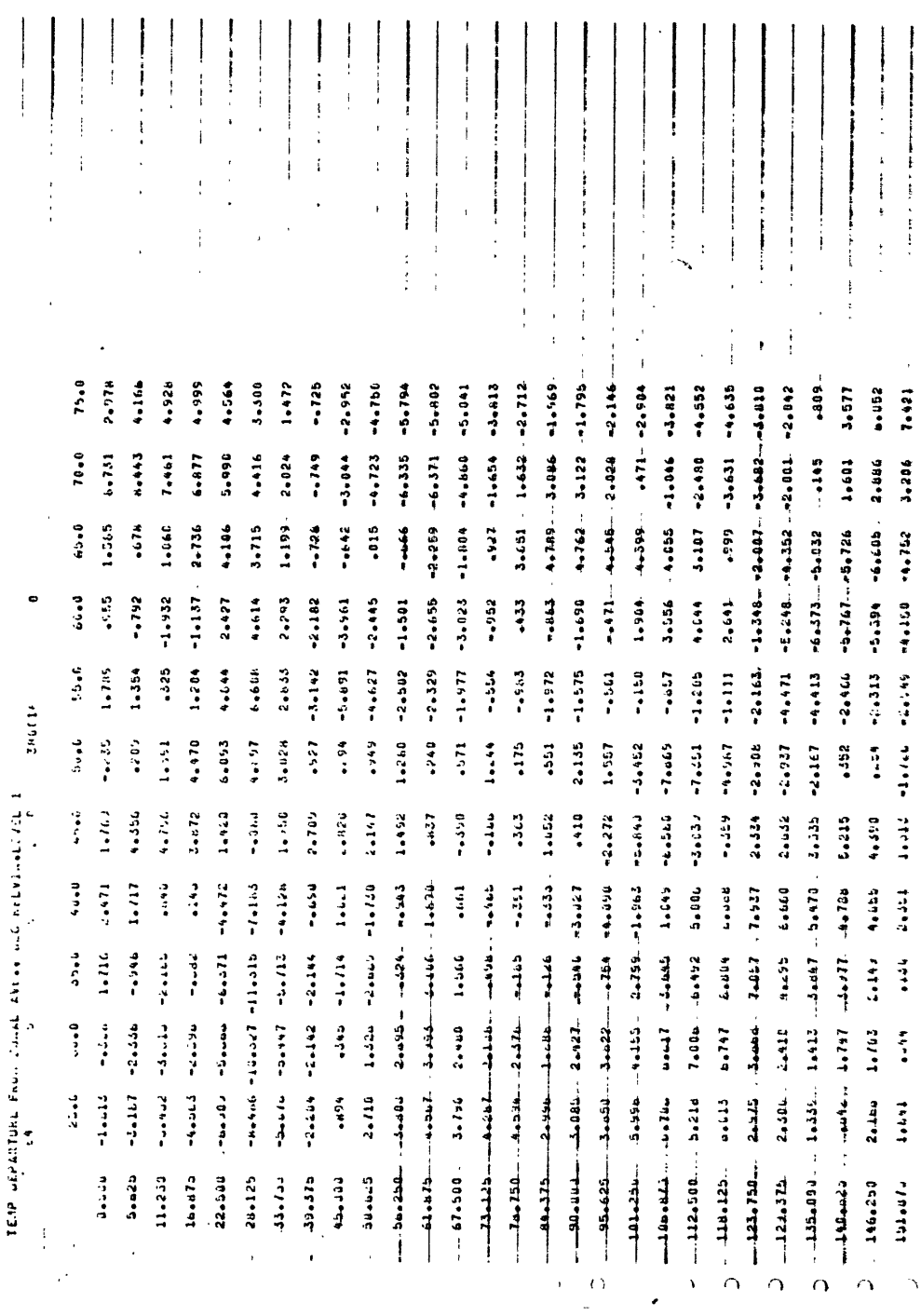
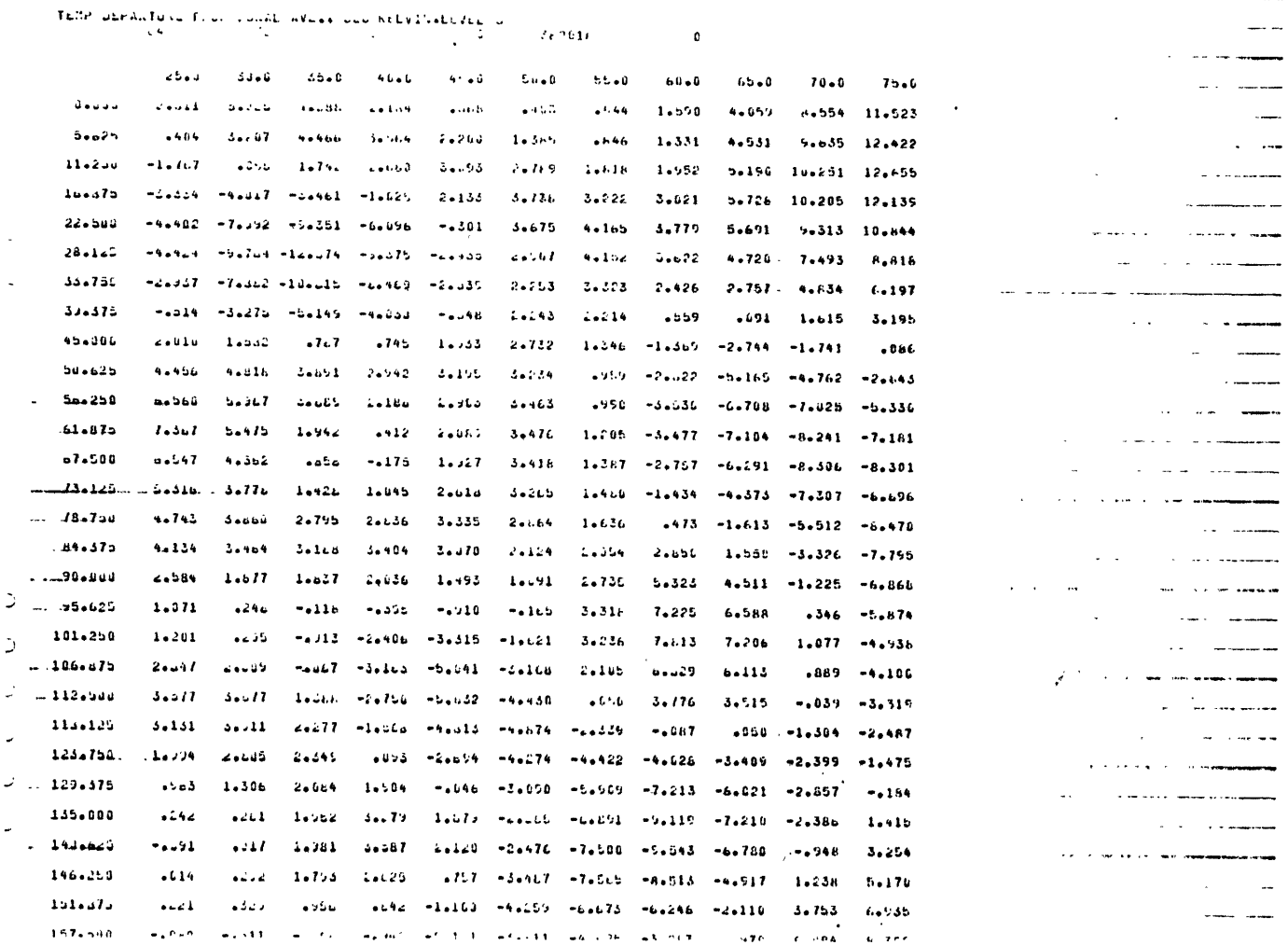


Fig. 3.4 Sample Output T_1*, 5/9/64 00Z

Fig.3.5 Sample Output T3*, 5/9/84 007



	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0
0.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.444	1.590	4.059	8.554	11.523
5.625	.404	3.107	4.466	3.964	2.200	1.385	.446	1.331	4.531	9.635	12.422
11.250	-1.767	.355	1.741	[illegible]	3.193	2.719	1.418	1.952	5.196	10.251	12.455
16.875	-2.334	-4.347	-3.461	-1.625	2.133	3.736	3.822	3.021	5.726	10.205	12.135
22.500	-4.402	-7.192	-5.351	-6.096	-.301	3.675	4.165	3.779	5.691	9.313	10.844
28.125	-4.424	-9.764	-12.174	-5.875	-2.433	2.147	4.192	3.822	4.720	7.493	8.816
33.750	-2.337	-7.462	-10.115	-4.469	-2.135	2.253	3.303	2.426	2.757	4.834	6.197
39.375	-.314	-3.275	-5.149	-4.853	-.148	1.243	2.214	.559	.491	1.615	3.195
45.000	2.010	1.552	.747	.745	1.733	2.732	1.346	-1.369	-2.744	-1.741	.086
50.625	4.456	4.816	3.651	3.942	3.195	3.234	.959	-2.122	-5.165	-4.762	-2.443
56.250	5.560	5.367	5.085	4.188	4.963	3.463	.959	-3.536	-6.708	-7.025	-5.336
61.875	7.367	5.475	1.942	.912	2.087	3.476	1.705	-3.477	-7.104	-8.241	-7.181
67.500	6.547	4.362	.656	-.175	1.527	3.418	1.387	-2.757	-6.291	-8.306	-8.301
73.125	5.316	3.776	1.428	1.845	2.618	3.265	1.480	-1.434	-4.373	-7.307	-6.696
78.750	4.743	3.660	2.795	2.836	3.335	2.864	1.636	.473	-1.613	-5.512	-6.478
84.375	4.134	3.464	3.168	3.404	3.870	3.124	2.304	2.850	1.558	-3.326	-7.795
90.000	2.584	1.677	1.827	2.036	1.493	1.491	2.730	5.325	4.511	-1.225	-6.868
95.625	1.071	.246	-.116	-.355	-.910	-.165	3.316	7.225	6.588	.346	-5.874
101.250	1.201	.235	-.313	-2.406	-3.515	-1.621	3.236	7.813	7.206	1.077	-4.936
106.875	2.347	.389	-.467	-3.163	-5.041	-2.168	2.105	6.529	6.113	.889	-4.106
112.500	3.377	3.077	1.588	-2.756	-5.032	-4.450	.646	3.776	3.515	-.039	-3.319
118.125	3.151	3.211	2.277	-1.956	-4.813	-4.674	-2.439	-.887	.950	-1.304	-2.487
123.750	1.794	2.648	2.641	.893	-2.694	-4.274	-4.422	-4.026	-3.409	-2.399	-1.475
129.375	.563	1.306	2.684	1.504	-.846	-3.050	-5.909	-7.213	-6.621	-2.857	-.184
135.000	.242	.261	1.552	1.779	1.673	-.255	-5.891	-9.119	-7.210	-2.386	1.415
140.625	-.591	.147	1.381	1.387	2.120	-2.476	-7.588	-9.543	-6.788	-.948	3.254
146.250	.614	.252	1.753	1.625	.757	-3.417	-7.565	-8.513	-4.917	1.238	5.170
151.875	.221	.329	.956	.642	-1.103	-4.259	-6.675	-6.246	-2.110	3.753	6.935
157.500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

values. The program accurately produced temperature departures such that $[T^*] = 0$.

The logic involved in program DAGRI3 was quite a bit more complex than CRTSHR. DAGRI3 handled all of the spherical harmonic inputs. Programming for the solution of (2.20) followed the algorithm for its solution described in Lorenz (1978). Once the stream functions were produced, DAGRI3 used a centered-finite difference scheme to produce zonal velocities and the meridional velocity departures. Figures 3.6 - 3.8 show sample outputs for V_1^*, V_3^* and the actual shear between the layers, U_1-U_3, for July 9, 1966 at 00Z.

A good check on the accuracy of the algorithm for solving (2.20) is the sum of V_1^* or V_3^* around a latitude circle, because $\left[\frac{\partial \psi}{\partial x}\right] = 0$. In all cases checked, that sum was zero or within .1 or .2 meters/second of zero.

Program FINAL merged the outputs of CRTSHR and DAGRI3 into the quantities of eq. (2.8), those outputs having been stored separately on the NCAR computing facility mass store device (TMS-4). Table 3.2 shows how this was accomplished. The X parameter, hereafter referred to as X, defined by $X = \frac{U_1 - U_3}{U_c}$ for the two layer model, was calculated after the shear and critical shears were smoothed latitudinally. Once this was done, the 20° ΔT was squared and multiplied by X to produce the right hand side of (2.8) for each of the four latitude bands. Statistics were kept on U_c because numerous small U_c's would have abnormally dominated the

Fig. 3.6 Sample Output V_1*, 7/9/66 00Z

Fig. 3.7 Sample Output V_3*, 7/9/66 00Z

Fig. 3.8 Sample Output, U_1-U_3, 7/9/66

Table 3.2

Two-Layer Model Programming, Program FINAL

Quantity Produced	Equation in Text	Inputs
Eddy Flux	(2.25)	V_1^*, V_3^*, T_1^*, T_3^*
X Parameter Times Temperature Gradient Squared	(2.8)	$20^{\circ}\Delta T$, $U_1 - U_3$, U_C

Fourier spectrum to be produced. It was found that only .0015% of the smoothed U_c's were less than .1 in absolute value. (A small percentage were negative.)

FINAL calculated the eddy flux from (2.25) for each grid point, then did the 10^o smoothing for each latitude band. In each case, the smoothing was performed by averaging the three values at, and 5^o either side of, the latitude at the center of the band.

Figures 3.9 and 3.10 display sample output from FINAL, eddy flux in joules/m/sec and X times $(\Delta T)^2$ in $^oK^2$, for April 1, 1963 at 00Z.

3.4 Spectral Decomposition and Analysis of Variance

Program SPECTRA was written to produce the variance, covariance, and correlation coefficient spectra for eq. (2.8). Two major algorithms are found within. SPECTRA first produces the zonal Fourier representations of the left and right hand sides of (2.8). Then, using the coefficients as inputs, it produces the space-time spectra desired by making use of Lorenz' (1979) poor man's spectral analysis of variance. In order to make use of the poor man's analysis technique, the time series were required to be in powers of two. Following Lorenz, we truncated the output data of the program FINAL for input into the program SPECTRA. Each year thus became 256 days in length (Dec 1 - Aug 13, except in leap years),

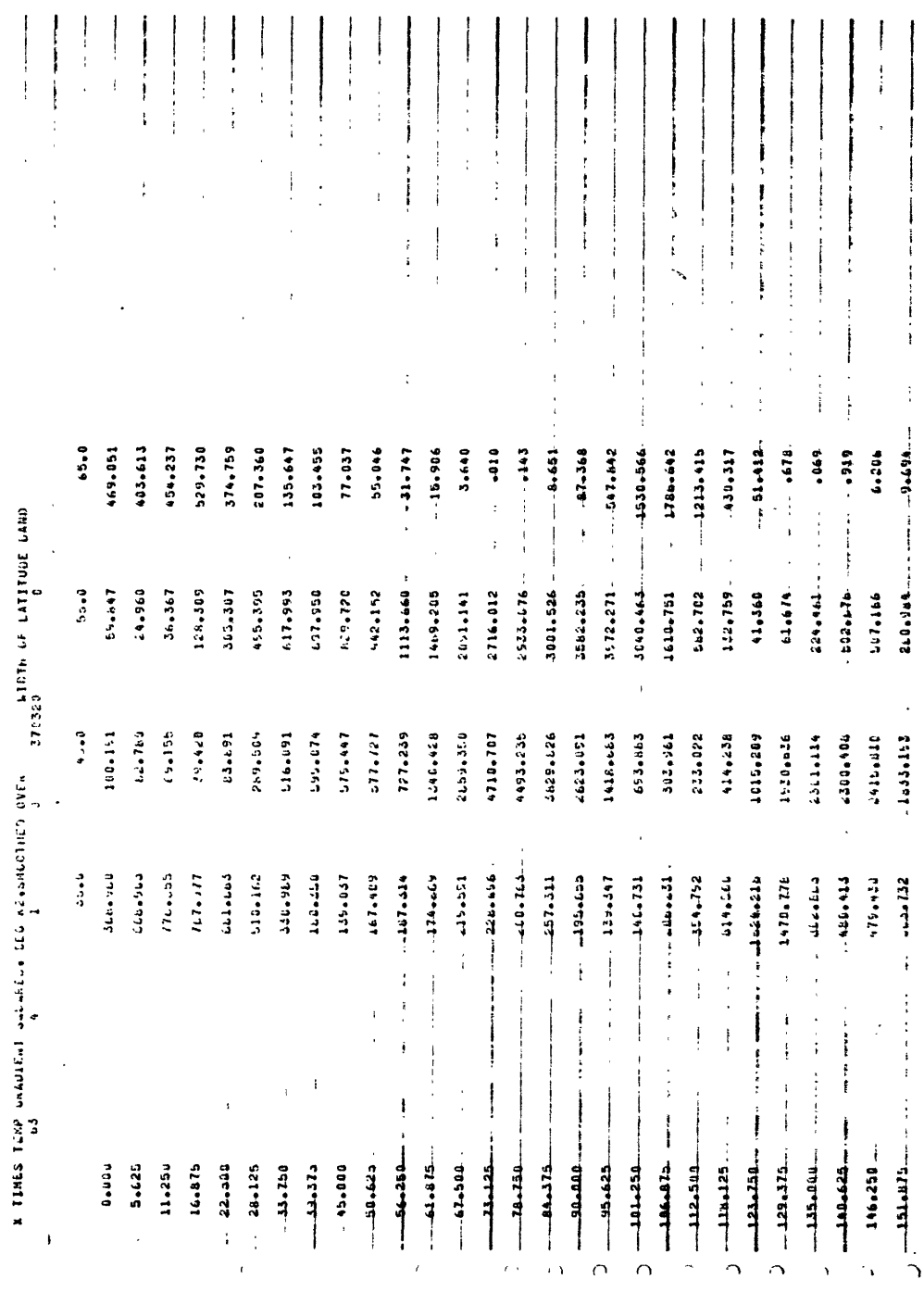


Fig. 3.9 Sample Output, X times Temp. Gradient Squared, 4/1/63 00Z

Fig.3.10 Sample Output, Eddy Flux, 4/1/63 00Z

and we made use of the first four and last four years only, discarding Dec 1, 1966 - Aug 13, 1967. More discussion about this point follows below.

3.4.1 Fourier Analysis in Latitude Bands

The left and right hand sides of (2.8) were analyzed into zonal Fourier series as follows, where m = zonal wavenumber, λ = longitude, ϕ = latitude, t = time.

$$X \cdot (\Delta T)^2(\lambda,\phi,t) = A_o(\phi,t) + \sum_{m=1}^{N} (A_m(\phi,t) \cos m\lambda + B_m(\phi,t) \sin m\lambda) \qquad (3.2)$$

$$\text{Eddy Flux } (\lambda,\phi,t) = C_o(\phi,t) + \sum_{m=1}^{N} (C_m(\phi,t)\cos m\lambda + D_m(\phi,t) \sin m\lambda) \qquad (3.3)$$

Figures 3.9 and 3.10 show the exact input structure of the data in (3.2) and (3.3), which is also just the output of program FINAL. Fast Fourier analysis yields the Fourier transforms for 32 wavenumbers (1/2 the number of input points) from which the coefficients can be directly calculated. For each observation and latitude band, 32 sine coefficients and 32 cosine coefficients are produced. The A_o and C_o terms are the zonally averaged cases, the sine coefficients being zero for m = 0 and m = 32. Hence, (3.2) and (3.3) produce time series of Fourier coefficients for introduction into

the temporal analysis scheme.

3.4.2 Poor Man's Time Spectral Analysis

Lorenz (1979) describes this nifty analysis of variance which is performed separately for each spatial wavenumber and latitude band. The reader should refer to his paper for more complete details; we shall just summarize it here.

Assume that the data to be processed consists of a 2^K successive values, and we wish to find the covariance spectrum of the scalar variables X and Y. We define

$$[X,Y]_k = J^{-1} \sum_{j=0}^{J-1} \left[\ell^{-1} \sum_{L=0}^{\ell-1} X_{(\ell j+i)} \right] \left[\ell^{-1} \sum_{L=0}^{\ell-1} Y_{(\ell j+i)} \right], \quad (3.4)$$

where k = 0,....K; L = 2^K; and the data are subscripted beginning at 0 running through L - 1. We note that $\ell = 2^k$ and J =L/ℓ. Then

$$(X,Y)_k = [X,Y]_k - [X,Y]_{k+1} \quad (3.5)$$

by definition, for k < K. Observing that $[X,Y]_o$ is the mean product of X and Y, while $[X,Y]_K$ is the product of the means, we find the covariance as a sum:

$$\sum_{k=0}^{K-1} (X,Y)_k = [X,Y]_o - [X,Y]_K. \quad (3.6)$$

when Y = X, we calculate the variance spectrum. Our observations are twice daily so that $(X,Y)_k$ is the covariance of 2^{k-1} day averages within 2^k day periods, k=0,...,K-1. The

analysis scans the spectrum with overlapping filters whose corresponding periods center about 1 day, 2 days, etc. up to 1024 days for our data set. The components $(X,Y)_8$, $(X,Y)_7$ down to $(X,Y)_o$ select contributions to the covariance within years, higher order components average between years. In this way the seasonal cycle (forced eddy behavior) is pronounced, and there is no interruption in the spectrum as there would be in a conventional time series analysis. It is for this reason the data was organized into 2^8 day (2^9 observations) blocks stacked year to year. The seasonal cycle is thus represented as the contrast between winter (Dec 1 - April 7) and summer (April 8 - Aug 13). Shorter period cycles are represented as contrasts between, for example, the first and last halves of summer and winter, etc. Longer period cycles--2^9, 2^{10} and 2^{11} days--are contrasts between years.

For our case, the X's are the $A_m(\phi,t)$ and $B_m(\phi,t)$, and the Y's are the $C_m(\phi,t)$ and $D_m(\phi,t)$. The components of variance of the eddy flux can thus be written as $((C_m,C_m) + D_m,D_m))_k$, in analogy with (3.6). (This is <u>not</u> the eddy flux energy spectrum.) The components of variance of $X \cdot (\Delta T)^2$ are $((A_m,A_m) + (B_m,B_m))_k$, and the components of the covariance are just $((A_m,C_m) + (B_m,D_m))_k$. Finally, the relevant correlation coefficient is given by

$$r_{mk} = \left(\frac{(A_m,C_m) + (B_m,D_m)}{\sqrt{((A_m,A_m) + (B_m,B_m)) \cdot ((C_m,C_m) + (D_m,D_m))}} \right)_k \quad (3.7)$$

It should be understood that no statistics are produced across scale: only coefficients with the same zonal wavenumber are correlated. Thus, in producing analyses of variance in time for each zonal scale, the spatial scales are resolved as well.

We can, however, produce correlation coefficients representing the sum over all zonal wavenumbers for a given time scale, or, the sum over all k for a given m. We can also produce a total correlation coefficient by computing the total variances and covariances, which are their respective sums over all space and time scales analyzed. These sum and total statistics will be discussed in the next chapter.

Lorenz (1979) describes the algorithm by which the analysis is programmed. SPECTRA follows his logic by introducing the proper Fourier coeffiicents as they are produced directly into the analysis of variance. Once the dataset is read, the entire analysis is complete. This eliminates the need to store the coefficients before processing by the analysis of variance. Appendix A provides a FORTRAN IV listing of the code.

CHAPTER FOUR

DESCRIPTION OF CORRELATION SPECTRA

In this and the next chapter we will describe and discuss the results of our study. This chapter will be devoted to determination of the degrees of freedom in the various space and time scales in the problem, a description of the raw output of the program SPECTRA, and an organized graphical presentation of the correlation spectra themselves. Chapter Five will discuss the results and conclusions to be drawn from the output and grahpical analyses.

4.1 Determination of Degrees of Freedom and Description of Spectral Tables

In order to have some measure of the statistical significance of the correlation spectra, it is necessary to analyze the number of degrees of freedom involved in calculating the coefficients. The most simple approach is to assume statistical independence in the observations. Recalling that for our case the observations are time series of Fourier coefficients, we see that to accurately measure the interdependence of successive observations is difficult. Meteorological data sets are known to exhibit autocorrelation in time because, for instance, today's 500 mb map is not independent of yesterday's. In our case, however, except for the smallest time scales ($k = 0,1,2$ where the period $= 2^k$), we can

assume independence, because processes whose characteristic scales are about 4 days or greater are essentially independent. With thousands of observations at short time scales in our data set, an adjustment in degrees of freedom via calculation of an autocorrelation function would increase the 95% and 99% confidence values only a small amount. Hence we choose to assume statistical independence and use caution in making our conclusions.

The analysis ((3.4), (3.5) and (3.6)) computes the contribution of the covariance of pairs of data to the total covariance. Each pair has one degree of freedom for zonal wavenumber $m = 0$ or $m = 32$, and 2 degrees of freedom for $0 < m < 32$. This is because only cosine coefficients contribute when $m = 0$ or 32, but both sine and cosine coefficients contribute (independently) to the covariance when $0 < m < 32$. Hence, for $k = 0$, there are 2048 pairs of observations, and when $m = 0$ or 32 there are 2048 degrees of freedom. When, for $k = 0$, $0 < m < 32$, we have 4096 degrees of freedom.

Figures 4.1 - 4.11 display the spectral tables output by the program SPECTRA for latitude band 1 ($\phi = 35^{o}$). Selected tables for latitude bands 2, 3, and 4 ($\phi = 45^{o}$, 55^{o} and 65^{o}, respectively) may be found in Appendix B. The first nine tables consist of the analyses of variance and covariance, and the last two of the correlation spectrum. In each case wavenumber m proceeds down the left-hand column, time period k proceeds across the top. In the analyses of variance

Fig.4.1 Components $((A_m, A_n)+(B_r, B_m))_k$ in Analysis of Variance of X times Temp. gradient squared for Latitude Band 1.

Fig. 4.2 Continuation of Fig. 4.1

Fig. 4.3 Continuation of Fig. 4.1

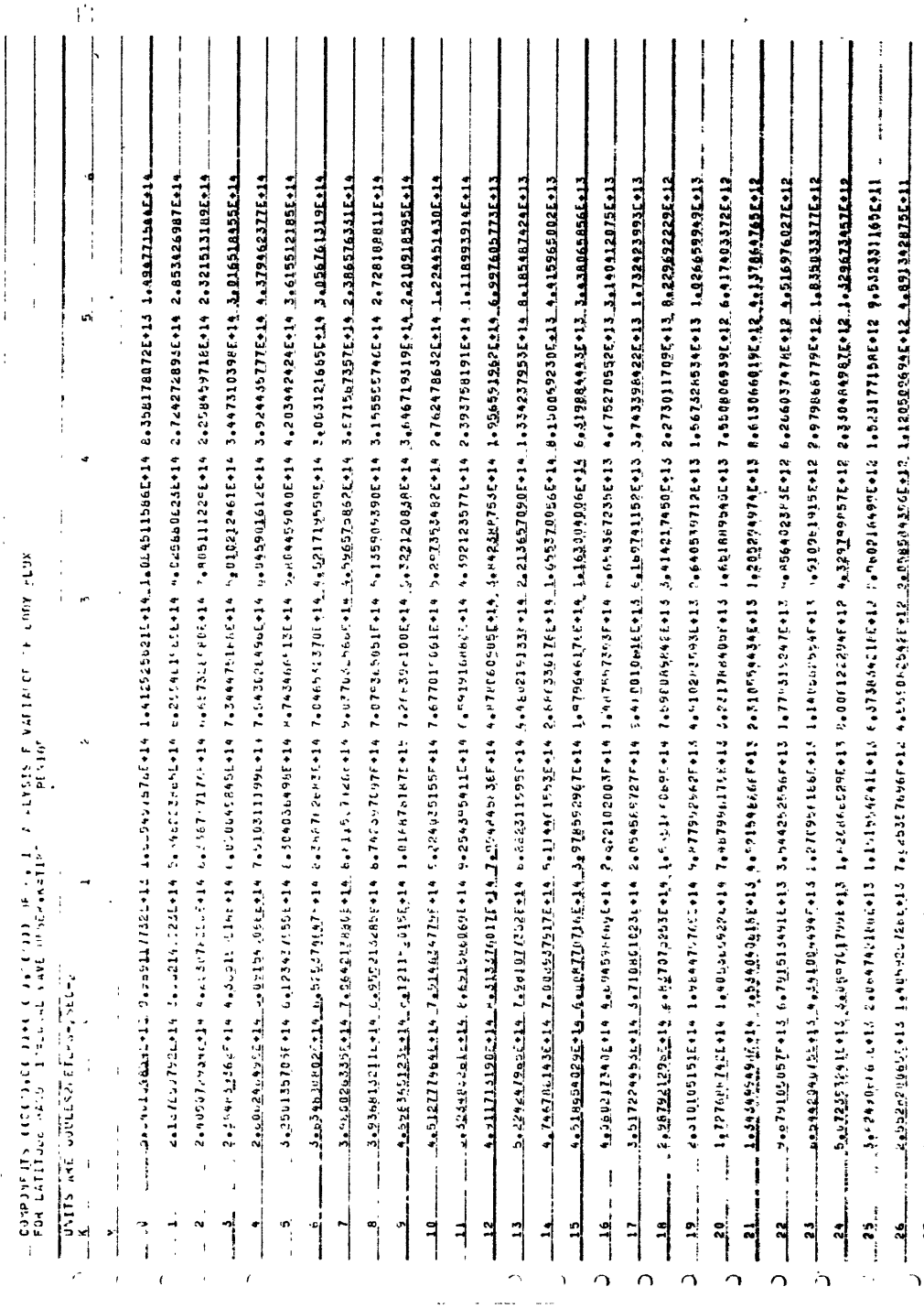


Fig. 4.4 Components $((C_m,C_n)+(D_m,D_m))_k$ in Analysis of Variance of eddy flux for latitude band 1.

28	[illegible]	[illegible]	[illegible]	[illegible]	1.521730299E+12	8.629036900E+11	8.721534833E+11
29	[illegible]	[illegible]	[illegible]	[illegible]	1.984124209E+12	5.710971683E+11	4.457955949E+11
30	[illegible]	[illegible]	[illegible]	[illegible]	8.983590831E+11	6.543544506E+11	3.749624000E+11
31	[illegible]	[illegible]	[illegible]	[illegible]	7.258022426E+11	5.452677360E+11	2.960770572E+11
32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.609426894E+11	2.920765419E+11
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.229568842E+15	3.360801966E+15

CONTINUATION

K	7	8	9	10	11	12	TOTAL
0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.093511615E+14	2.495821990E+15
1	[illegible]	[illegible]	[illegible]	1.360311151E+13	[illegible]	8.043922427E+13	3.743066265E+15
2	[illegible]	[illegible]	[illegible]	4.447517729E+13	1.135214625E+14	1.244968336E+14	3.597860448E+15
3	[illegible]	[illegible]	[illegible]	[illegible]	1.177511809E+13	1.828683733E+13	3.746594618E+15
4	[illegible]	[illegible]	[illegible]	[illegible]	7.488720274E+13	3.324677017E+14	5.437223108E+15
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.720836185E+13	4.635653222E+15
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.304074052E+13	4.106803557E+15
7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.172601717E+14	4.603354635E+15
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.526600135E+13	4.070119209E+15
9	[illegible]	[illegible]	[illegible]	[illegible]	1.185614983E+13	2.452254205E+13	4.421794777E+15
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.834630883E+13	4.173411825E+15
11	[illegible]	7.105760255E+13	[illegible]	[illegible]	1.024066153E+13	4.468275207E+13	3.964567067E+15
12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.610039977E+12	3.358790921E+15
13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.905954393E+12	2.961788053E+15
14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.916025228E+11	2.329426020E+15
15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.897070775E+12	1.903179342E+15
16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.382723622E+12	1.479527917E+15
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.647351788E+12	1.176350388E+15
18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.525322592E+11	9.042391097E+14
19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.379441158E+11	6.429486550E+14
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.123156121E+12	4.614285651E+14
21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.746310074E+11	3.335830540E+14
22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.345603720E+11	2.460581488E+14
23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.944074256E+11	1.592861434E+14

Fig 4.5 Continuation of Fig. 4.4

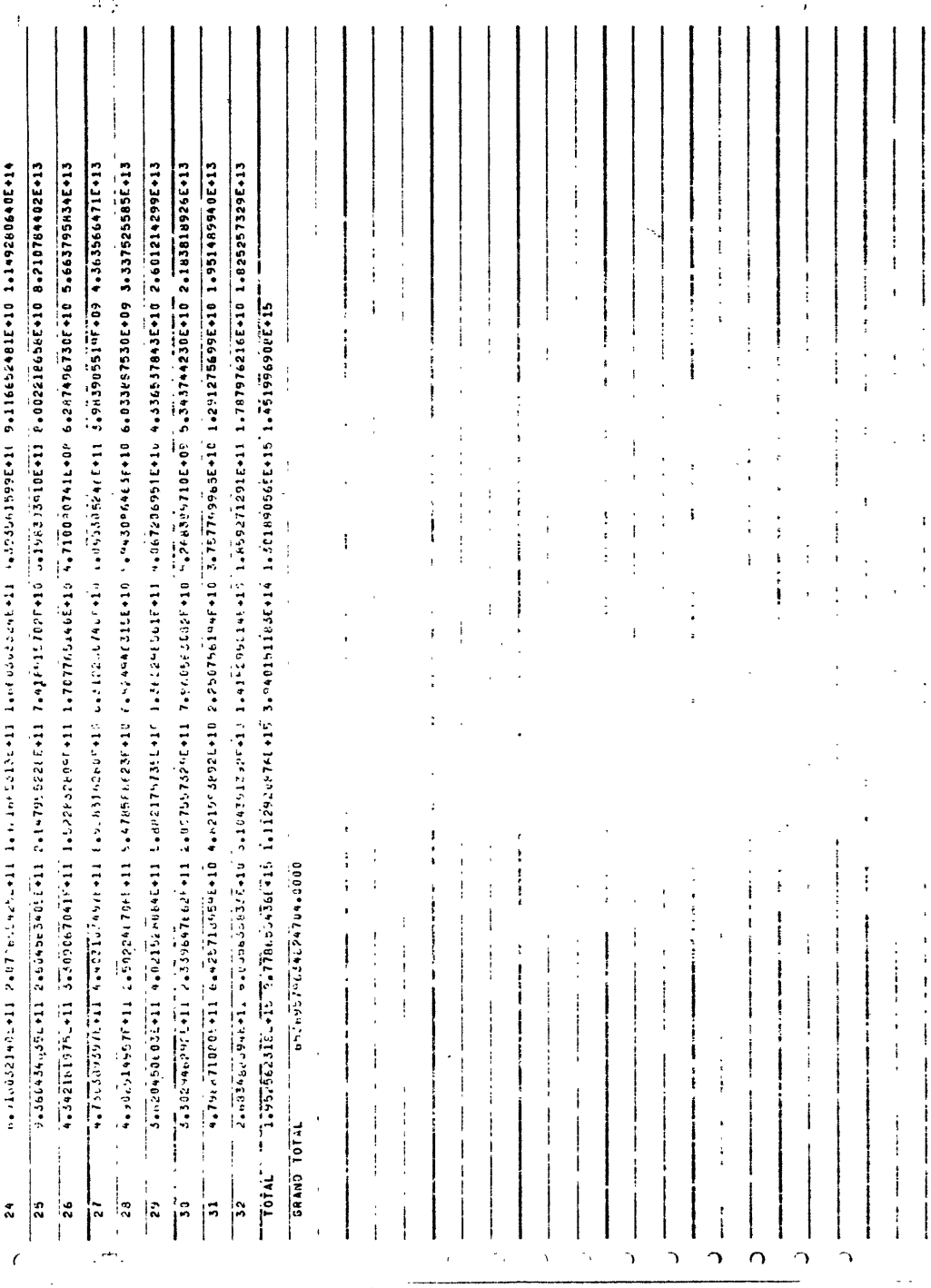


Fig. 4.6 Continuation of Fig. 4.4

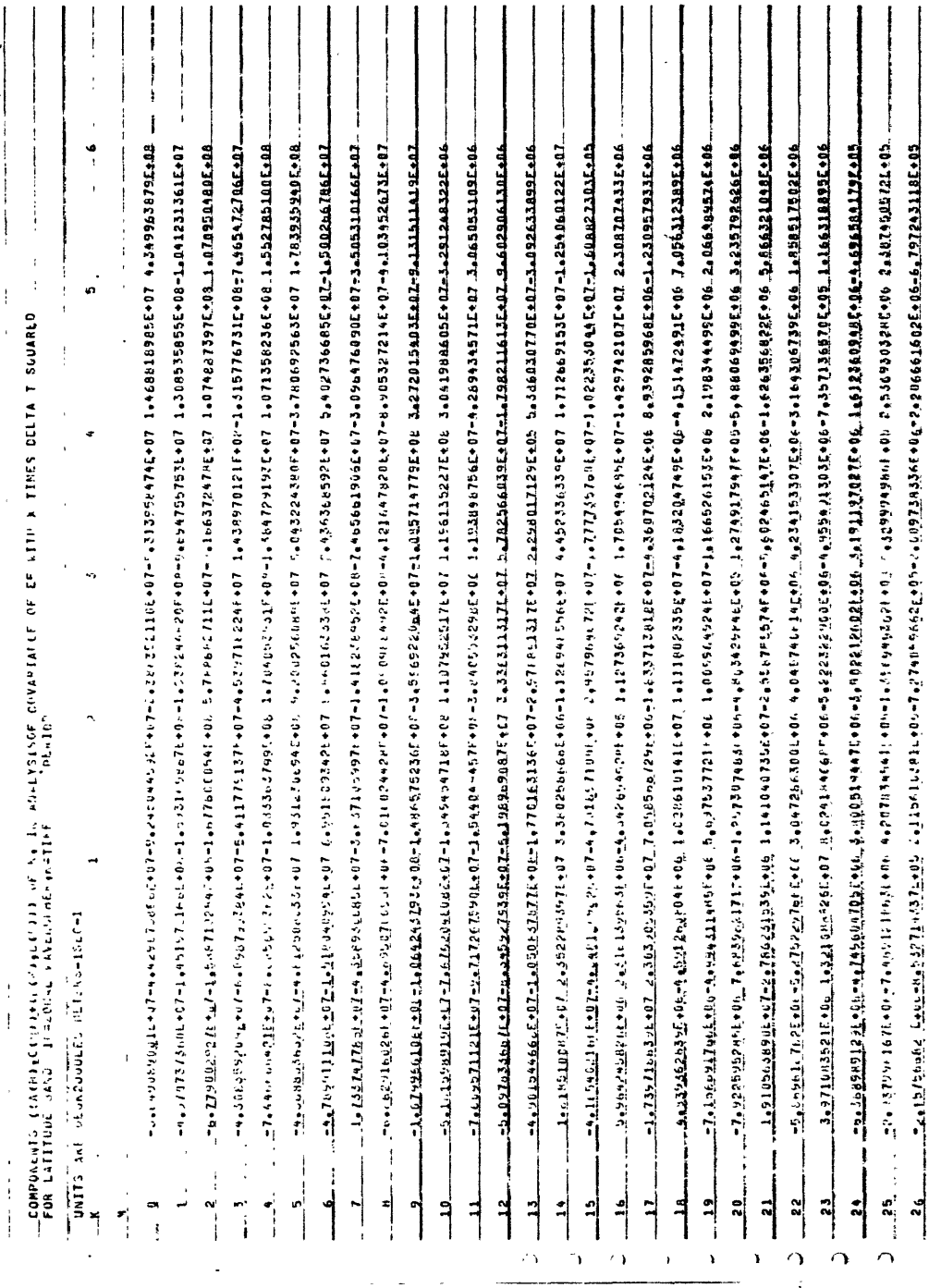


Fig. 4.7 Components $((A_m,C_m)+(B_m,D_m))_k$ in Analysis of Covariance of eddy flux with X times temp. gradient squared for latitude band 1.

28												
29												
30												
31												
32												
TOTAL												

CONFIGURATION

	7				11	12	TOTAL
0	4.5149C0322E+0A	5.010716880E+05	1.6573984C2EE+0A	-1.3044454496E+07	2.9262375837E+06	7.7749107506+09	1.4725614176+10
1	2.5632452436+0	1.3566407676E+09	8.1561124201E+07	-7.5239233636E+07	3.5755415596+08	3.0186495836+08	1.7641875006+09
2	1.4715370622E+0	1.4460454A86E+05	2.2242284803E+08	-8.7668217956+07	5.0935224866+08	1.1434204506+09	3.4180142056+09
3	-4.3512109536+07	-6.0631741126+06	-3.3016A49163E+07	-1.0423109256+06	-3.1838228676+07	3.2832006336+08	-1.1337961226+09
4	1.9752978216+07	-2.5043A37523E+07	-9.8607497356+07	-1.0872169796+08	2.9717458956+07	-1.1185978356+08	-1.4849961986+08
5	-4.3103660406+07	2.5068P65196+07	-9.7327851256+07	-5.6592855536+07	-4.6066496926+07	3.8246024716+07	2.2215784816+08
6	3.8588217356+07	-5.5043A152E+07	-1.0975011826+08	-4.6P14746116+07	-7.4742928666+07	2.1300653236+07	-2.1132826166+07
7	-2.2481328816+07	1.1728A42A6E+08	2.0762350766+07	-4.2507876126+07	-6.5738177176+07	2.0134556276+08	-1.6725248486+08
8	-2.4199A467AE+06	5.0268571736+07	-1.2120A61876+07	2.1335706366+07	4.3853851136+07	7.3625J33476+06	-3.1580742666+08
9	1.5237399926+07	-4.4874410626+07	5.4498004046+06	3.6235790956+07	2.8661239196+07	-1.1771222236+07	-5.3917957466+08
10	-9.7096461406+06	1.F4C2101076+06	4.6557790336+07	5.6324054136+07	-1.1C61152696+05	-9.7047400886+07	-1.2458289126+08
11	1.0449618616+07	1.5291C5147E+07	-2.3487132666+06	8.8285277846+06	-2.8377944456+06	-5.5572364556+06	-3.3657908596+08
12	3.0572011176+06	3.0596654846+05	-A.3917796326+06	3.0574281146+06	4.3844750696+06	6.0323374016+06	-9.5652036916+07
13	-1.6854817226+06	4.7092622576+06	3.0261239546+06	7.3166470016+06	2.2759866276+06	4.4206066616+06	-1.3046580456+08
14	-3.4286093222E+05	-1.5957E46896+06	-P.6414706926+05	-1.6710041156+06	7.3380445776+06	-1.6014336176+06	7.9401307416+07
15	1.4066124346+01	-6.0203759756+06	-7.0249427476+06	-1.7971406266+06	2.4109567826+05	8.5174153946+06	-8.6924492486+07
16	9.1195311826+06	3.7439102366+06	1.6934245866+06	-2.7702011186+06	-8.0180291756+05	-2.6506429866+06	2.2253933136+07
17	1.4591175536+06	1.6190076266+06	-1.2390953106+06	-1.9438173146+06	7.9900750986+05	-2.1728143126+06	-3.4876686026+06
18	-1.4519610706+06	-2.1484A37036+06	-3.0A50F9162E+06	-2.2605346826+06	-1.7853646426+06	-1.0613520446+06	6.5720913646+06
19	1.7183246466+06	-2.1357A5306E+06	-2.5974851446+06	-4.1839611576+06	-3.4035156246+06	1.3057450296+06	-3.1241440226+06
20	-2.2126806396+06	-2.7177522006+04	1.2322564036+06	-6.5012643086+04	-1.1291855576+06	-2.8538270446+06	-9.1568038696+06
21	-5.5736552206+05	2.1046A3A766+06	-2.9116183756+06	-9.4056838A06+05	9.1923368006+05	-7.6388888906+05	2.2377516196+07
22	-5.1895900826+06	-3.0977192676+05	1.4637153326+06	-3.8474377976+05	4.5253995216+05	-7.4902907566+05	-3.0203434886+06
23	-1.0370715116+06	5.3478E2019E+05	3.6072541596+05	-2.7044475336+04	-6.2542950866+04	-3.6841032106+05	1.4668391966+07

Fig. 4.8 Continuation of Fig. 4.7

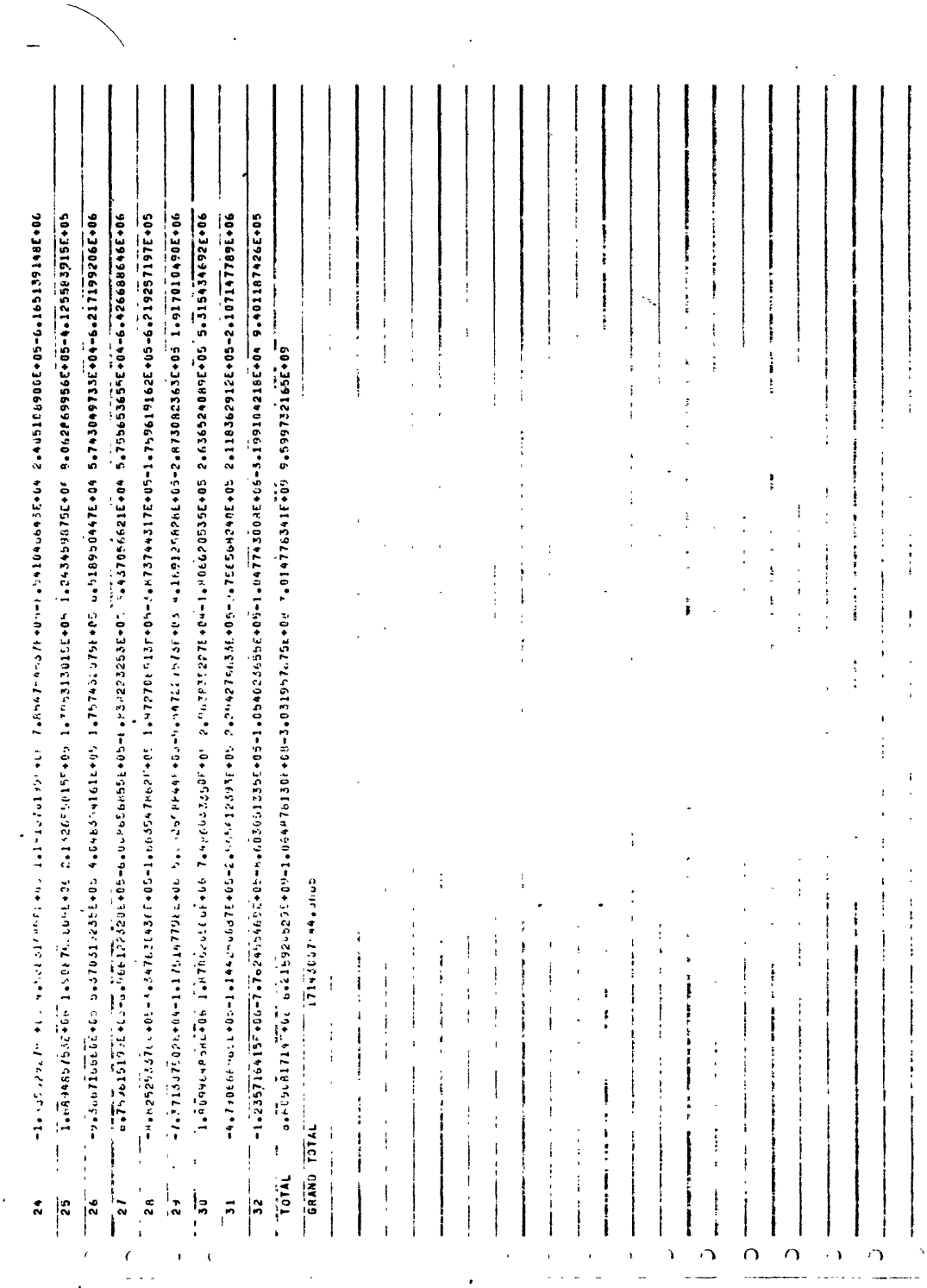


Fig. 4.9 Continuation of Fig.4.7

Fig. 4.10 Correlation Coefficient Spectrum, Latitude Band 1.

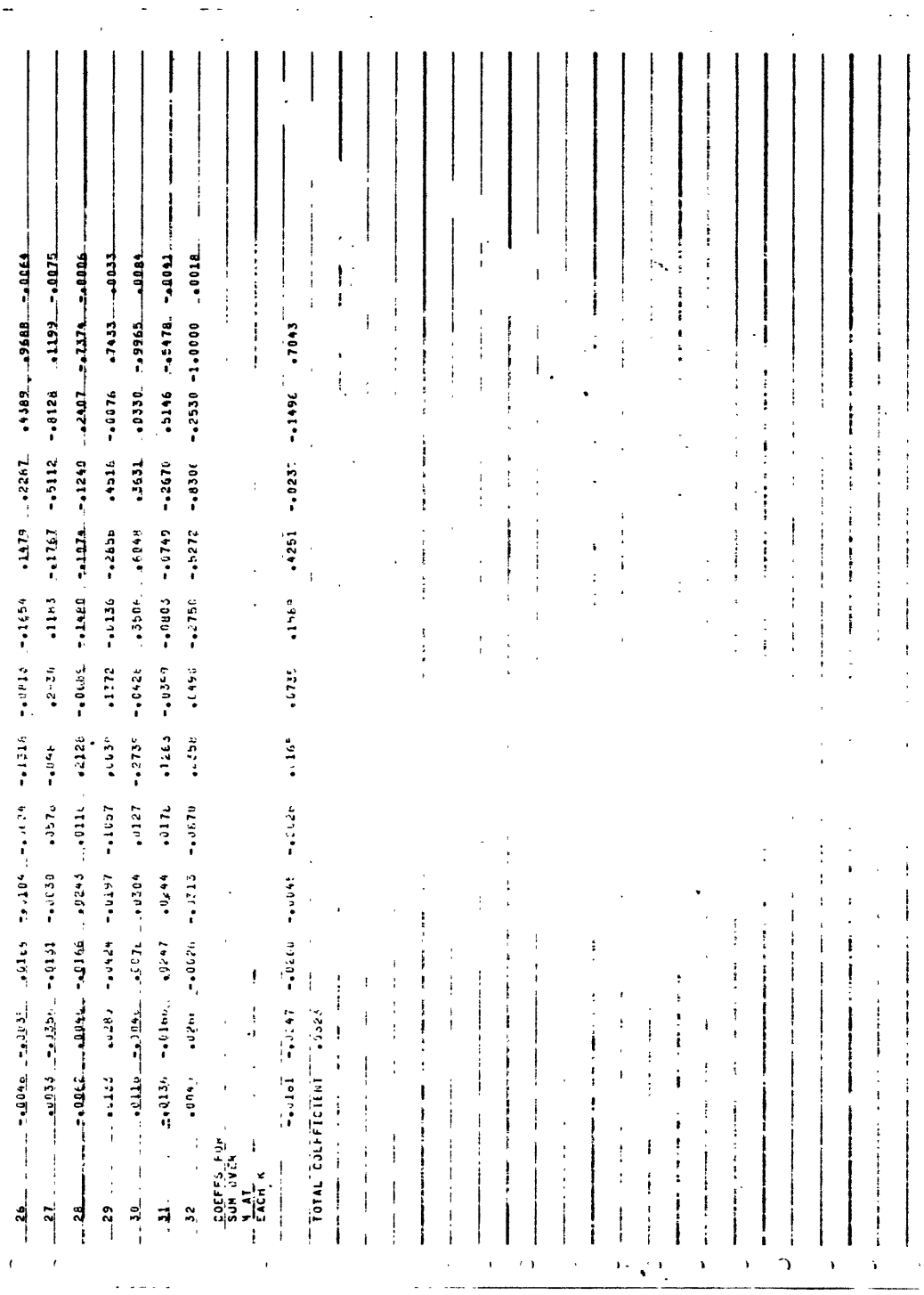


Fig. 4.11 Continuation of Fig. 4.10

and covariance, k = 12 is actually the squares or products of the means, and to its right TOTAL shows the mean products for the wavenumbers. At the bottom of the wavenumber column, TOTAL gives the sum of the variances or covariances over all wavenumbers for a given k. Looking down column k = 12, and over from row TOTAL, we find the grand square or product of the means, and the grand total is just the total mean product. The total variance or covariance is just the grand total minus the grand square or product. We will briefly discuss the variance and covariance spectra in section 4.6.

Figures 4.10 and 4.11 display the correlation spectrum for the band centered at $\phi = 35^{o}$. The rightmost column entitled COEFFS FOR SUM OVER k FOR EACH WAVENUMBER contains the coefficients derived from the two rightmost columns of the analyses of variance and covariance (see discussion above.) The bottom most row contains the coefficients for the sum over m at each k, these being derived from the bottom TOTAL row mentioned above. The TOTAL COEFFICIENT results from the grand totals in the other analyses. The correlation coefficients are all calculated according to (3.7) or modifications thereof.

Before describing all of the correlation spectra in the next few sections, we should conclude our discussion about degrees of freedom, and indicate the 95% and 99% confidence limits on the correlation coefficients. To determine the degrees of freedom assuming independence for the sums

of the k's at each m, just add them up for the individual k's. Similarly add to get the total for the sum over the m's at each k (again assuming independence). The total number of degrees of freedom is computed by adding once again across the other scale. Table 4.1 lists the degrees of freedom in all possible combinations and the total, which is 253890. It also gives the value of the correlation coefficient significant at the 95% and 99% confidence limits for an equal-tails test of hypothesis $r_{mk} = 0$. These limits are either taken directly or interpolated using the inverse square root formula from G.W. Snedecor, Statistical Methods, 4th ed., Ames, Iowa, Iowa State College Press, 1946, p. 351. Thus, a correlation coefficient exceeding one or both limits is significant at the given limit assuming statistical independence.

4.2 Correlation Spectra for Individual Wavenumbers and Time Scales by Latitude Band

In this and the next three sections, the important parts of the correlation spectra will be described by means of graphical analysis. Because there is a massive amount of information to be studied, this section will fully describe only spectra for wavenumbers 0 through 5. Wavenumber 5 includes zonal scales ranging from about 6600 KM at 35^{o} to 3400 KM at 65^{o}. This analysis should adequately justify the conclusions to be discussed in the next chapter.

Figures 4.12.1 - 4.12.24 present the correlation spectra by individual wavenumber and time scale for latitude bands 1

Table 4.1

Degrees of Freedom and 95%, 99% Confidence

Limits for Correlation Coefficients

M	K→	0	1	2	3	4	5	6	7	8	9	10	11	Sum Over K	
0 or 32	D.O.F.	2048	1024	512	256	128	64	32	16	8	4	2	1	4095	D.O.F.
	95%	.043	.061	.087	.122	.172	.242	.338	.468	.632	.811	.950	.997	.031	95%
	99%	.057	.080	.114	.160	.225	.315	.435	.590	.765	.917	.990	1.000	.040	99%
0<M<32	D.O.F.	4096	2048	1024	512	256	128	64	32	16	8	4	2	8190	D.O.F.
	95%	.031	.043	.061	.087	.122	.172	.242	.338	.468	.732	.811	.950	.022	95%
	99%	.040	.057	.080	.114	.160	.225	.315	.435	.590	.765	.917	.990	.028	99%
Sum over M	D.O.F.	126976	63488	31744	15872	7936	3968	1984	992	496	248	124	62	Total 253890	D.O.F.
	95%	.0056	.0078	.011	.016	.022	.032	.044	.063	.088	.123	.175	.246	.0039	95%
	99%	.0072	.0102	.014	.020	.029	.041	.058	.081	.115	.162	.229	.320	.0050	99%

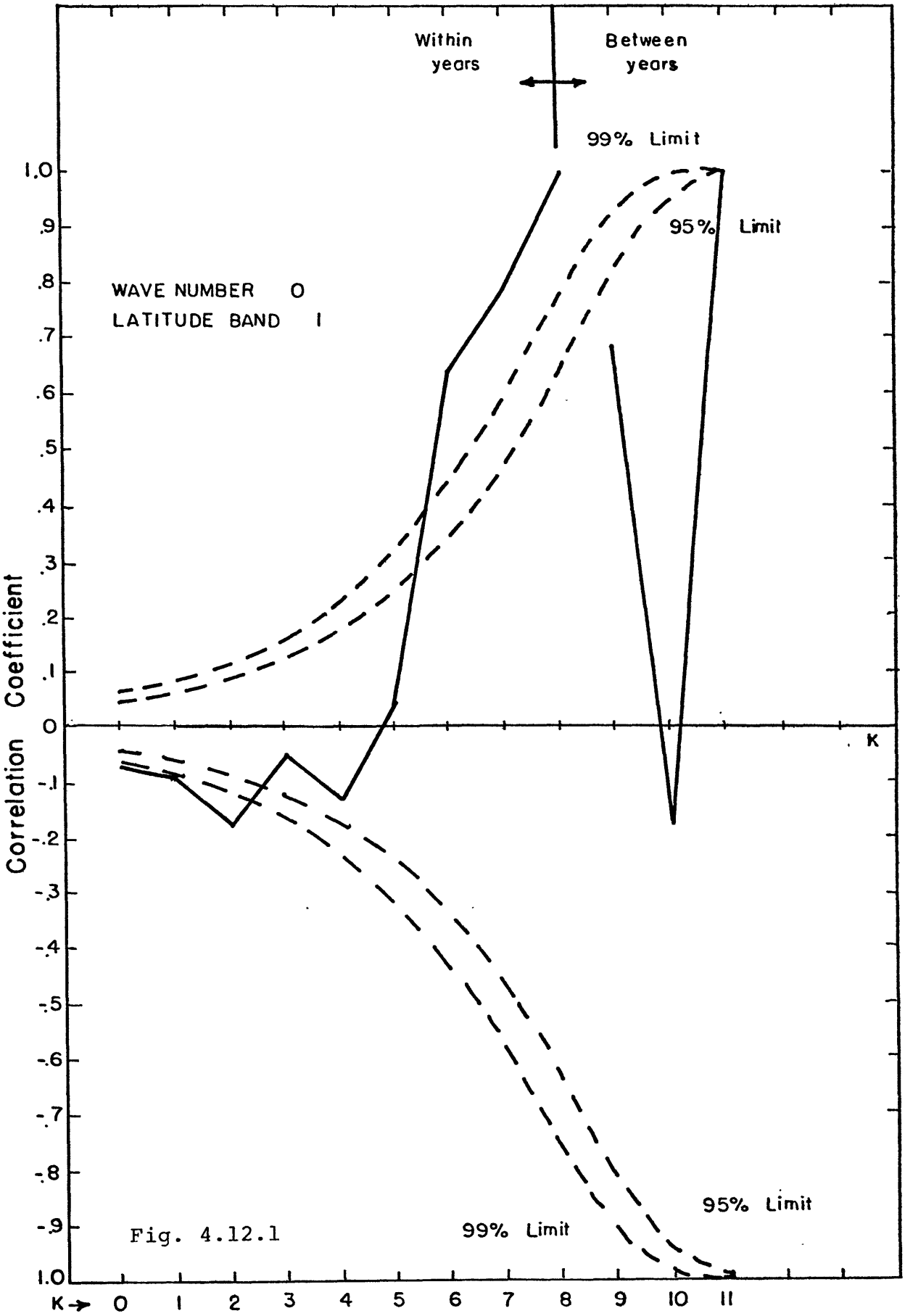


Fig. 4.12.1

Figs. 4.12: Correlation Spectra by Individual Wavenumber and Time Scale K.

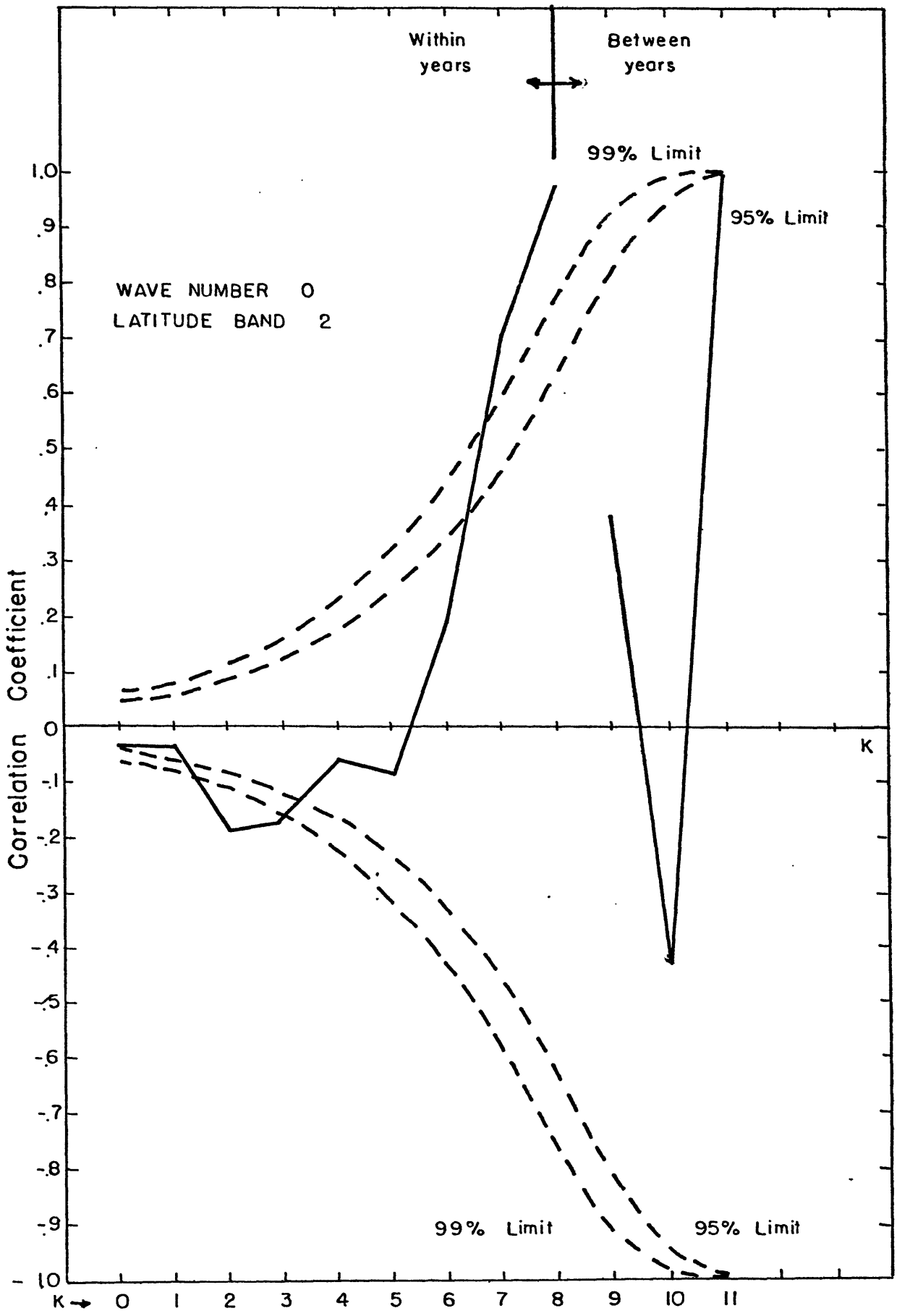

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 0
LATITUDE BAND 2
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
99% Limit
95% Limit
K → 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.2

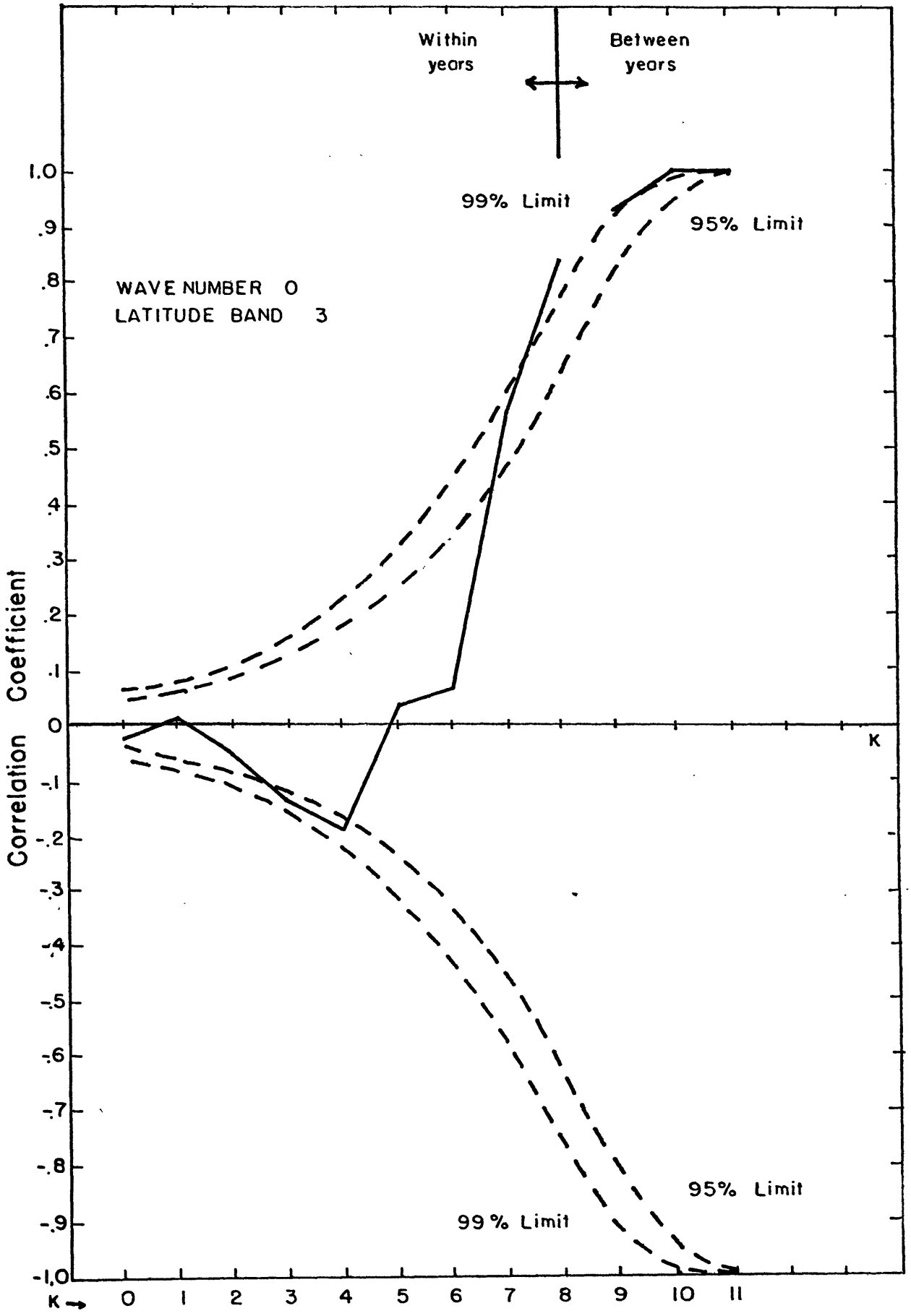
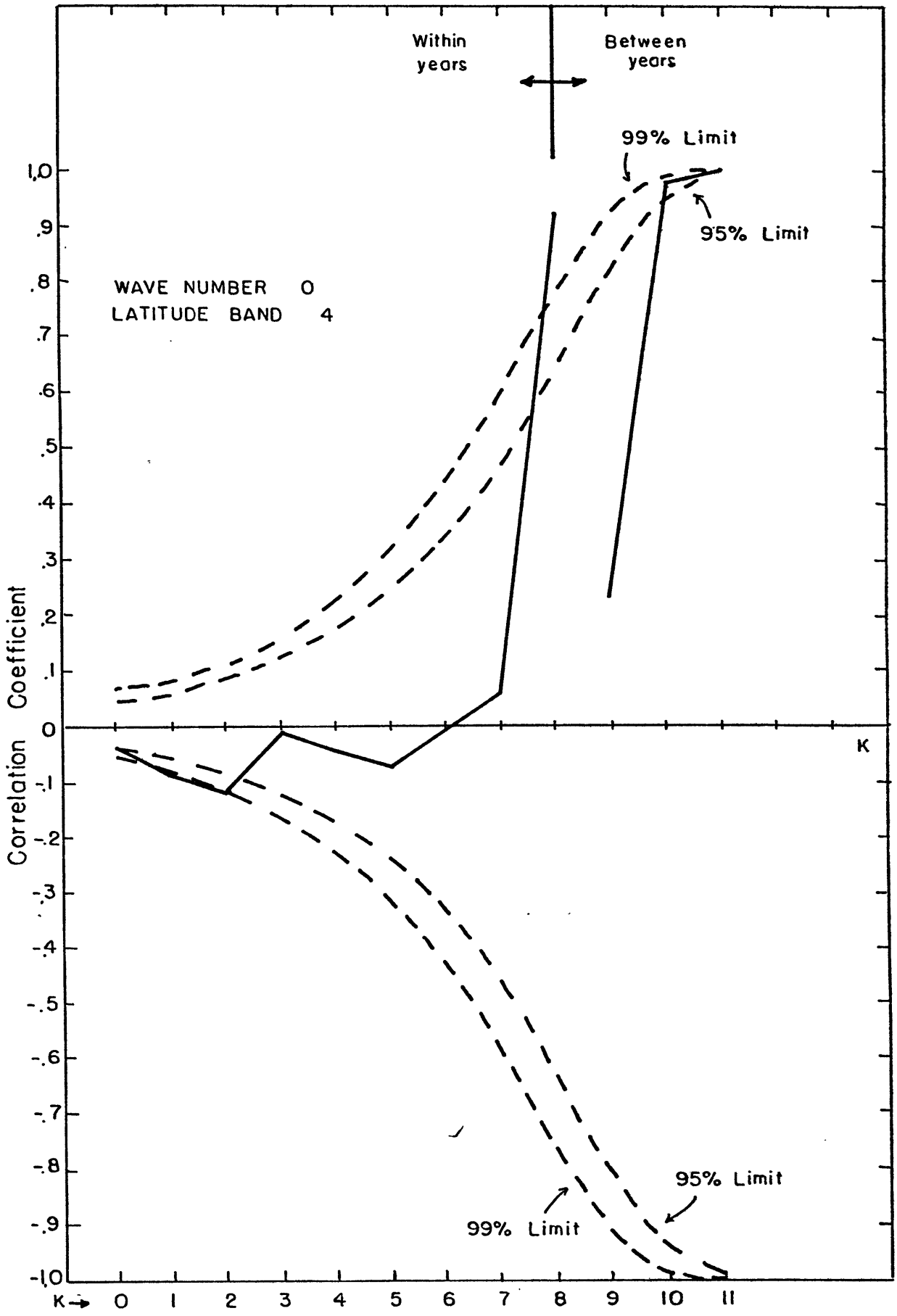

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 0
LATITUDE BAND 3
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.3


Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 0
LATITUDE BAND 4
Correlation Coefficient
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.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95% Limit
99% Limit
K→ 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.4

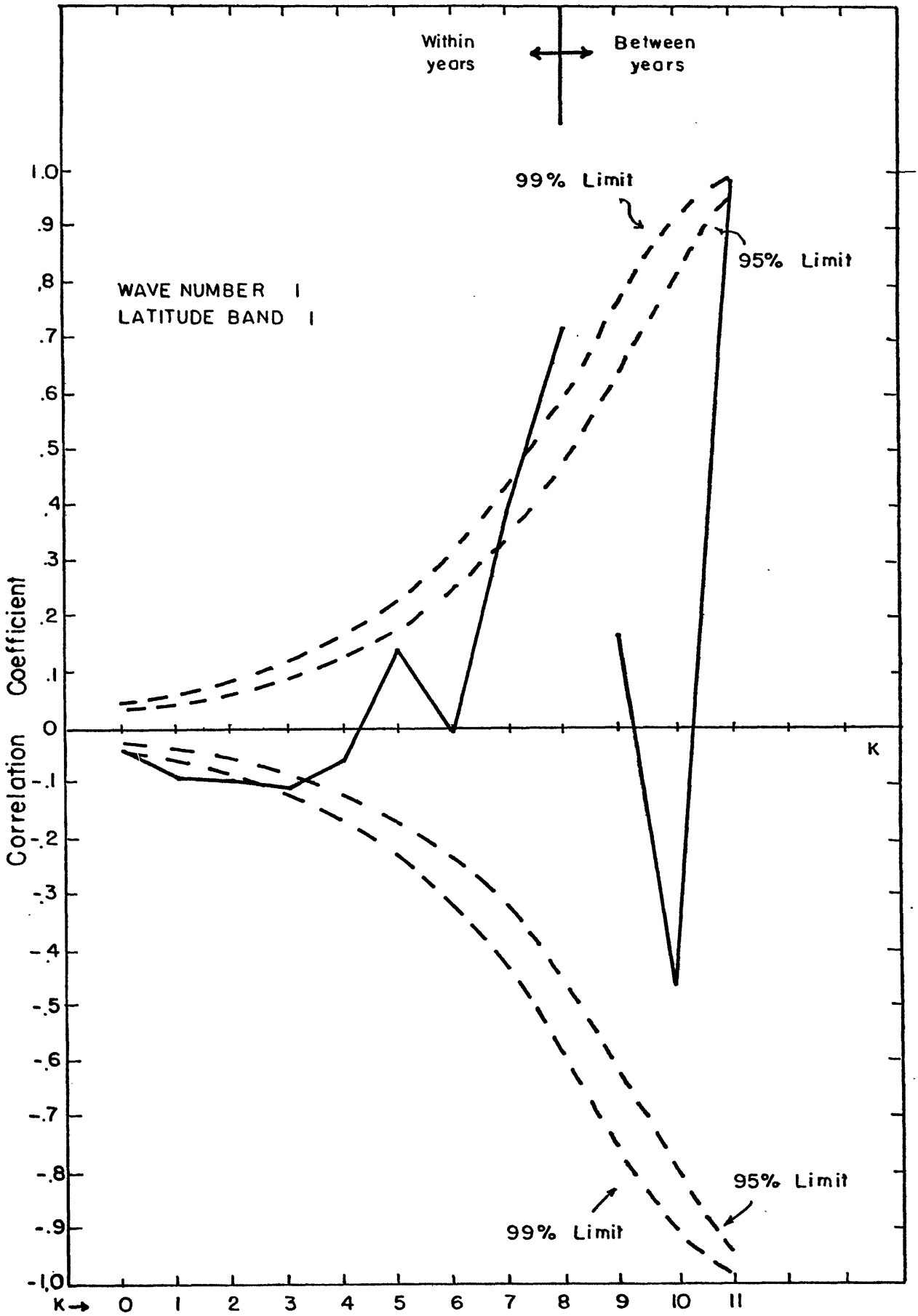

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 1
LATITUDE BAND 1
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95% Limit
99% Limit
K→ 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.5

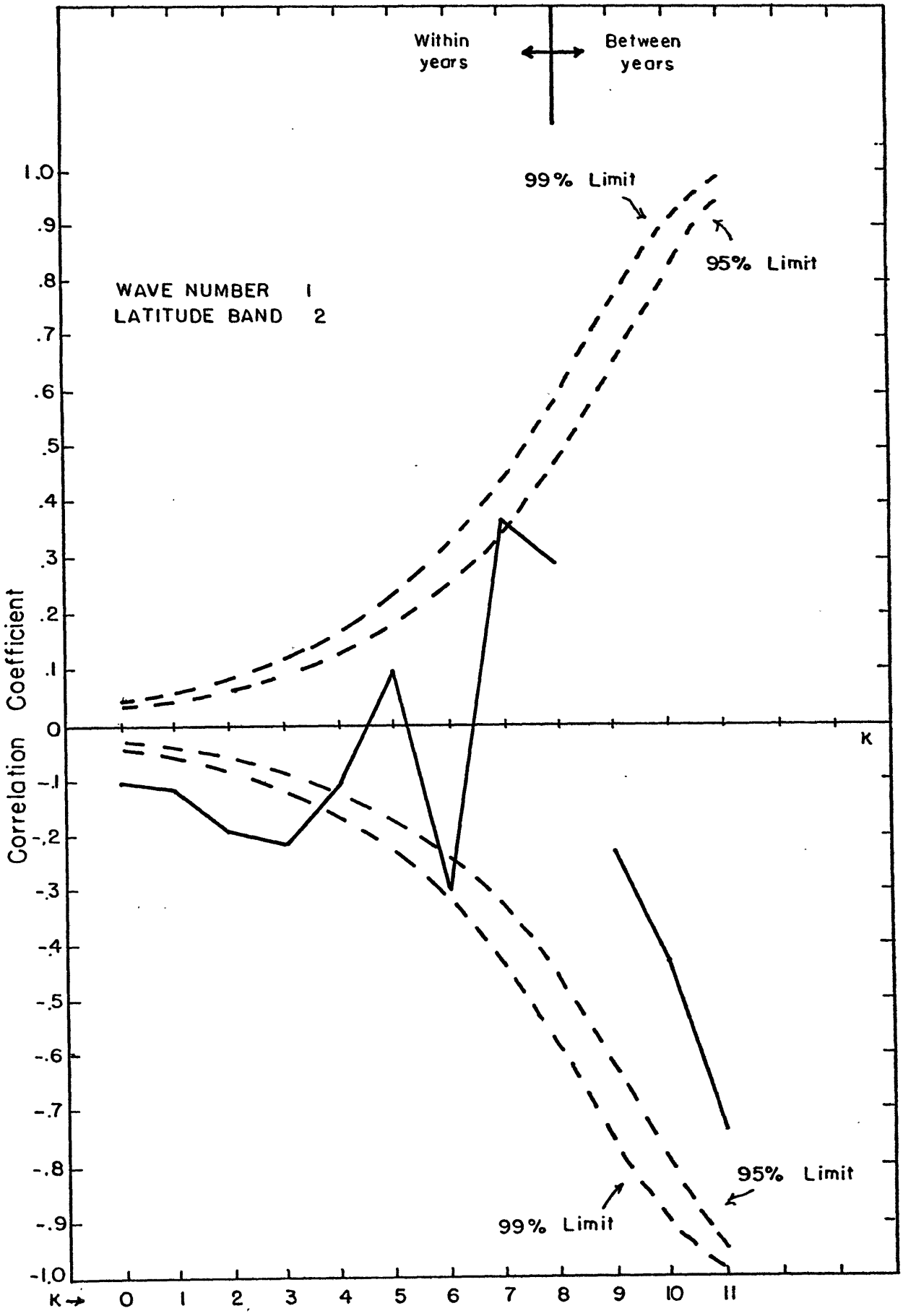

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 1
LATITUDE BAND 2
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.6

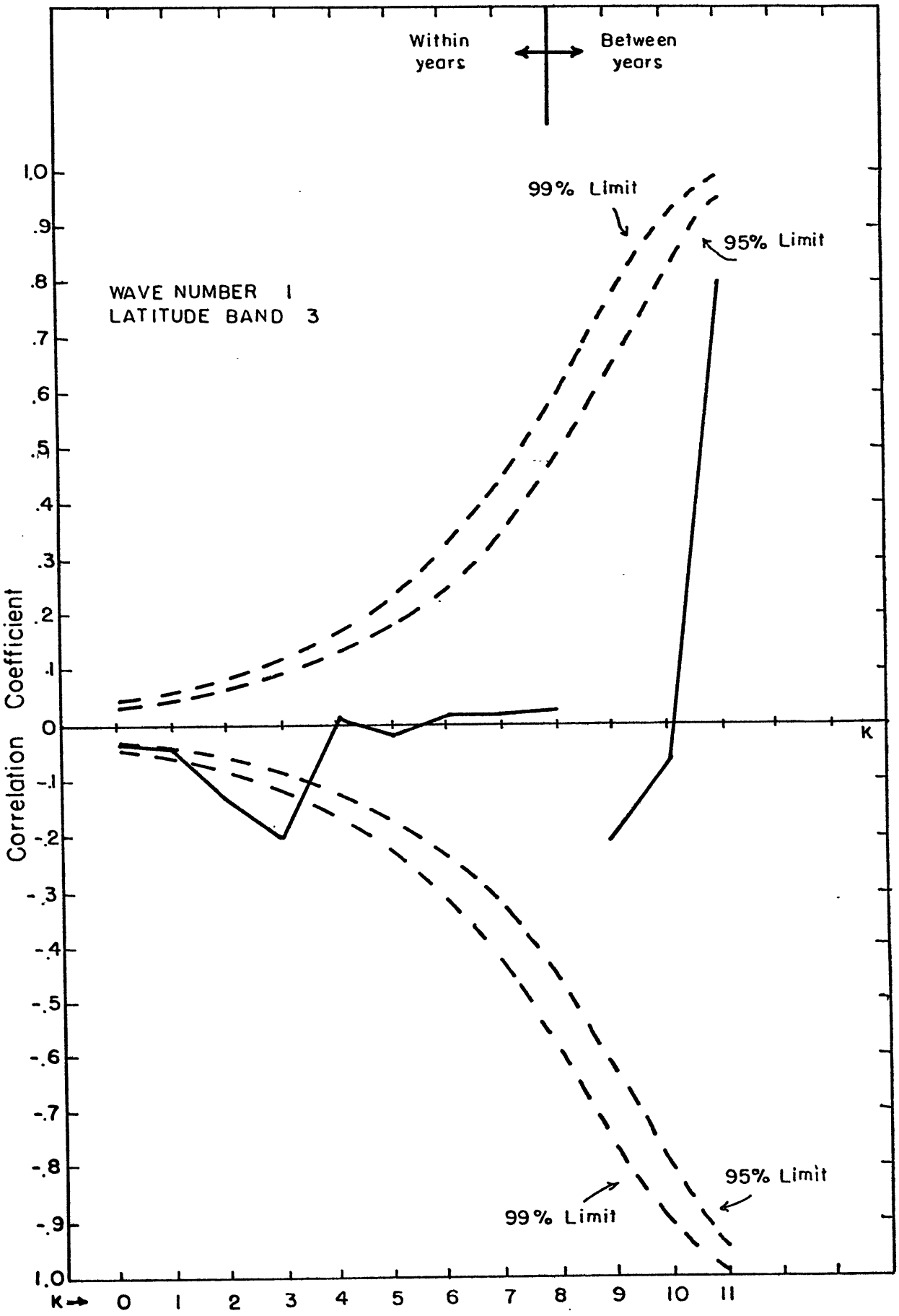

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 1
LATITUDE BAND 3
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.7

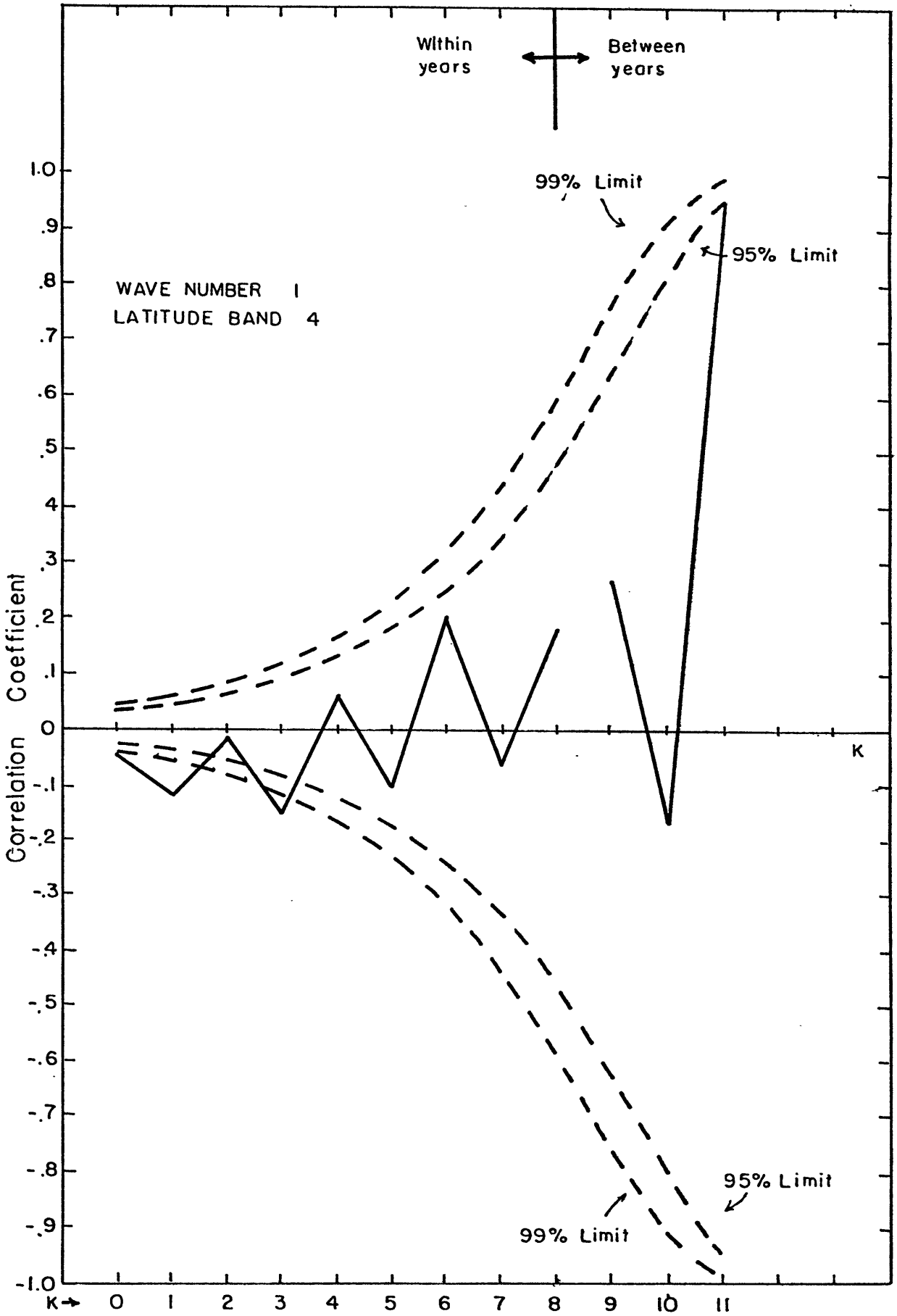

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 1
LATITUDE BAND 4
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95% Limit
99% Limit
K→ 0 1 2 3 4 5 6 7 8 9 10 11

Fig.4.12.8

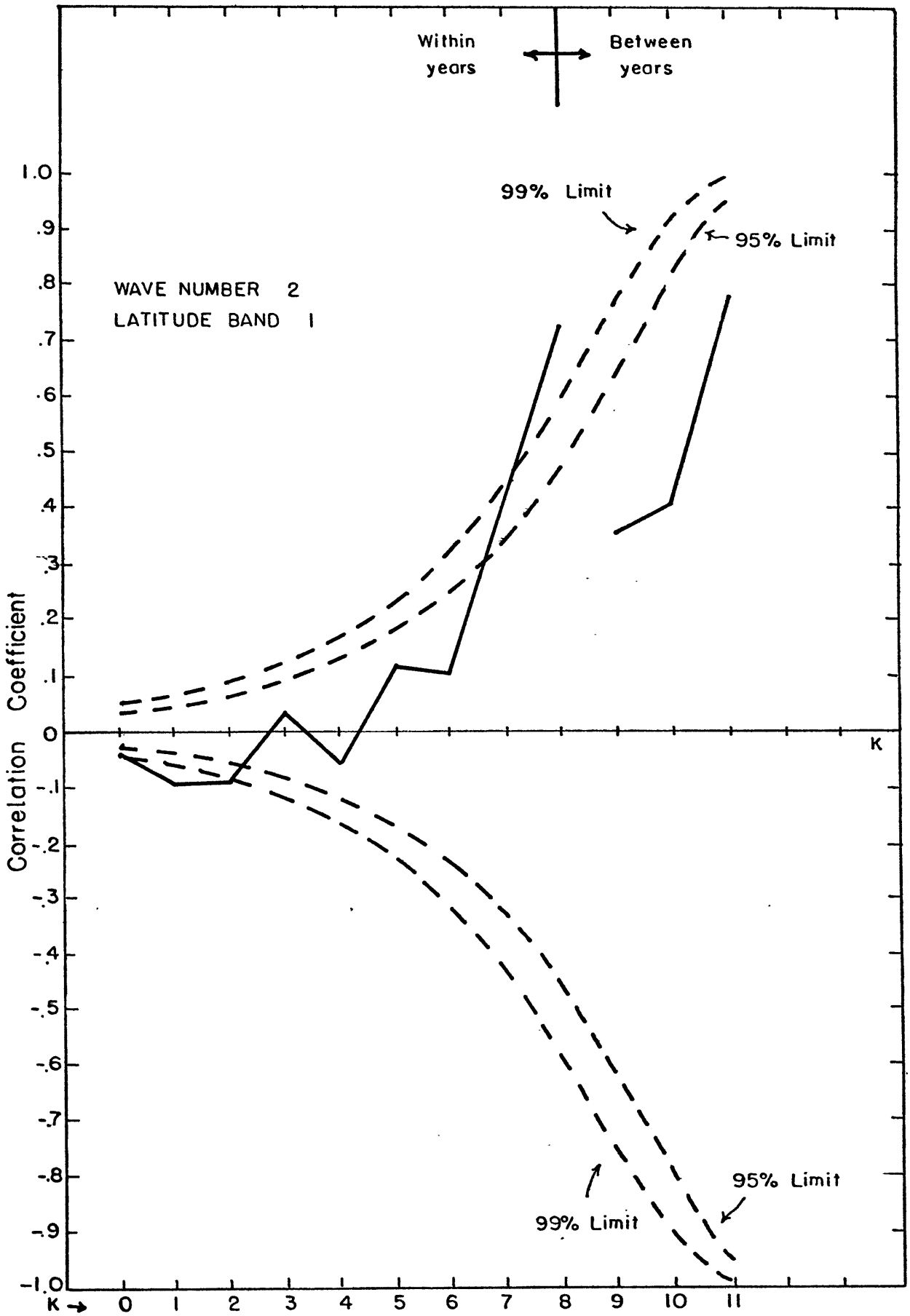
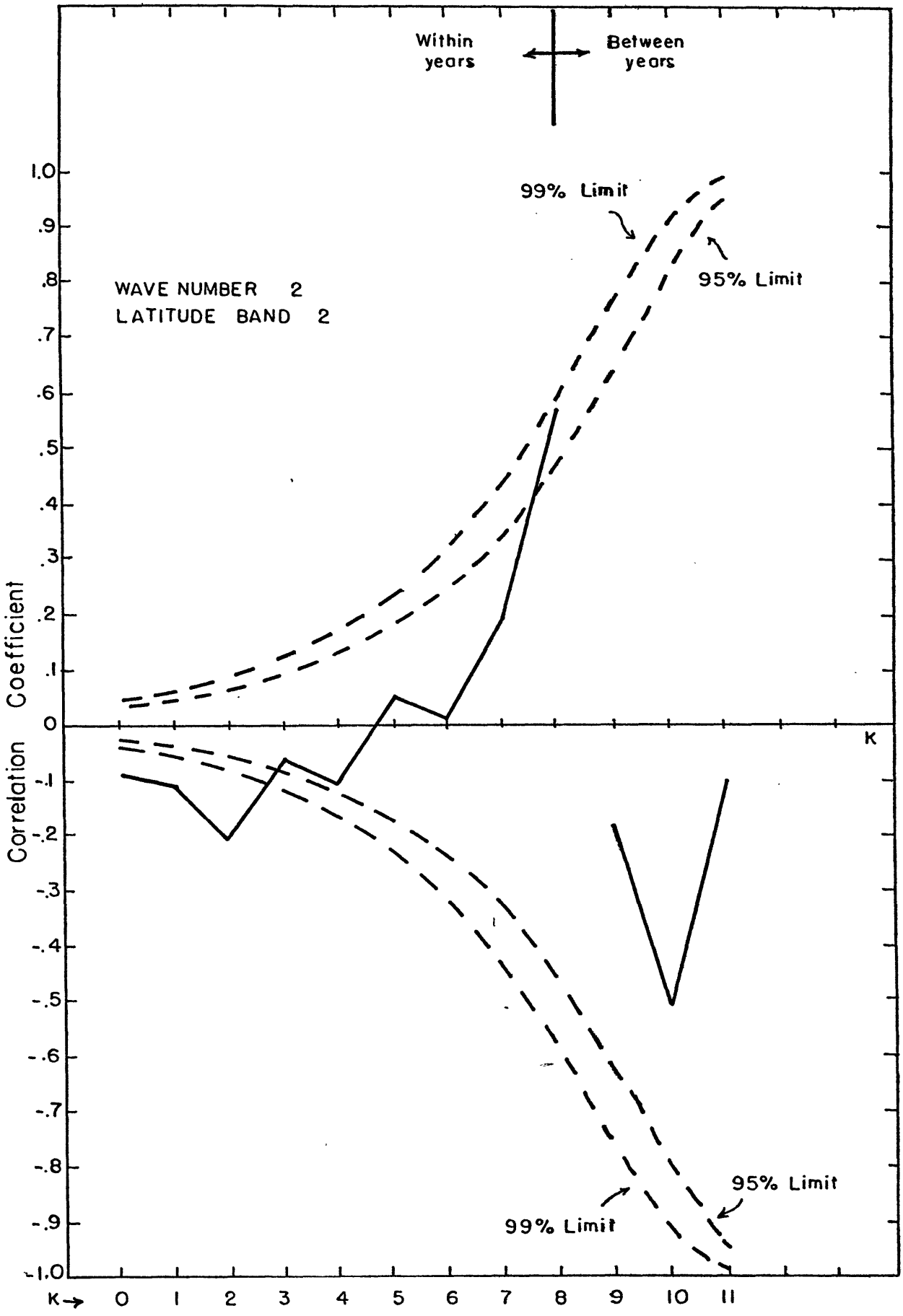

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 2
LATITUDE BAND 1
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
0 1 2 3 4 5 6 7 8 9 10 11
K →
95% Limit
99% Limit

Fig. 4.12.9


Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 2
LATITUDE BAND 2
Correlation Coefficient
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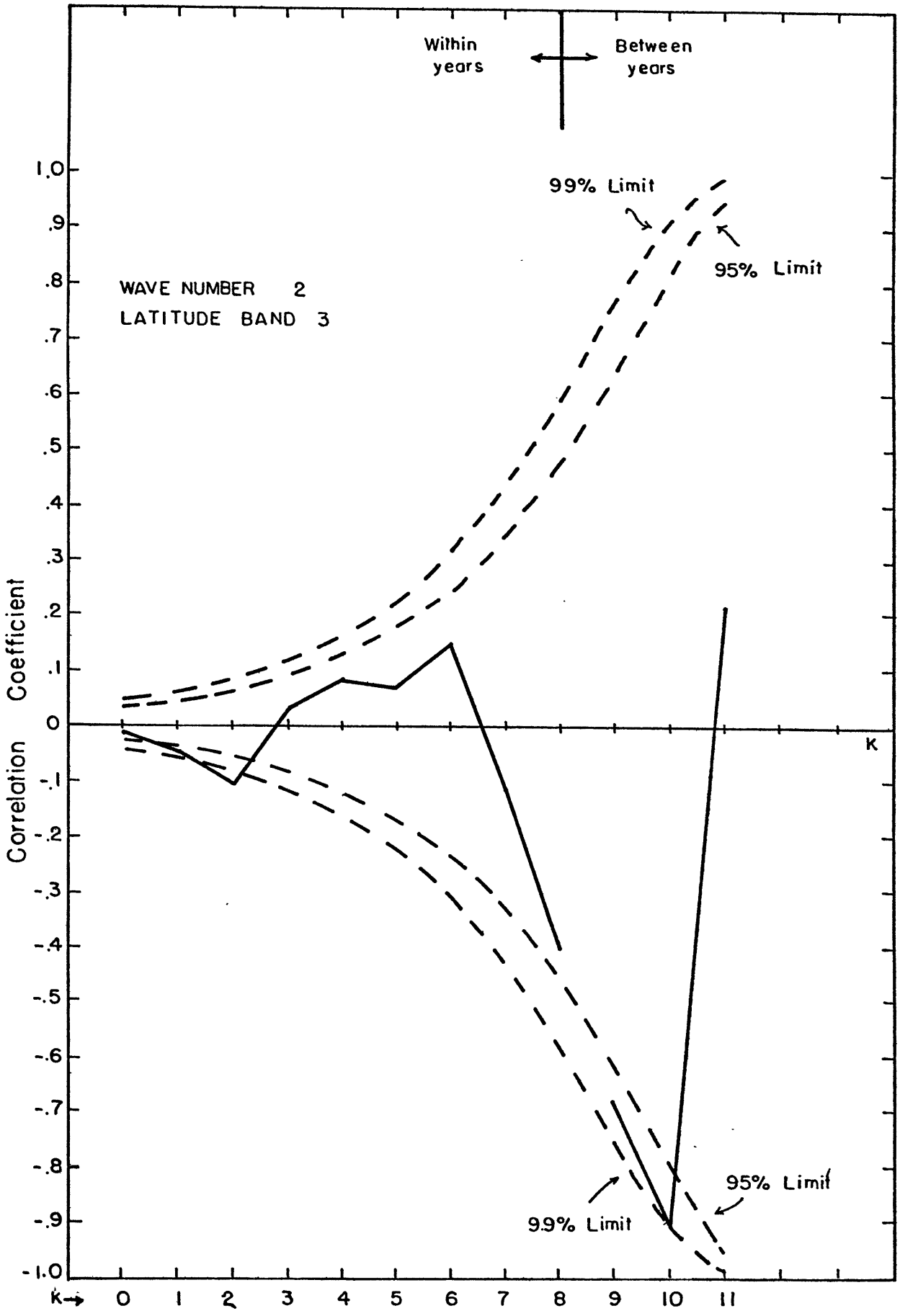
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.10


Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 2
LATITUDE BAND 3
Correlation Coefficient
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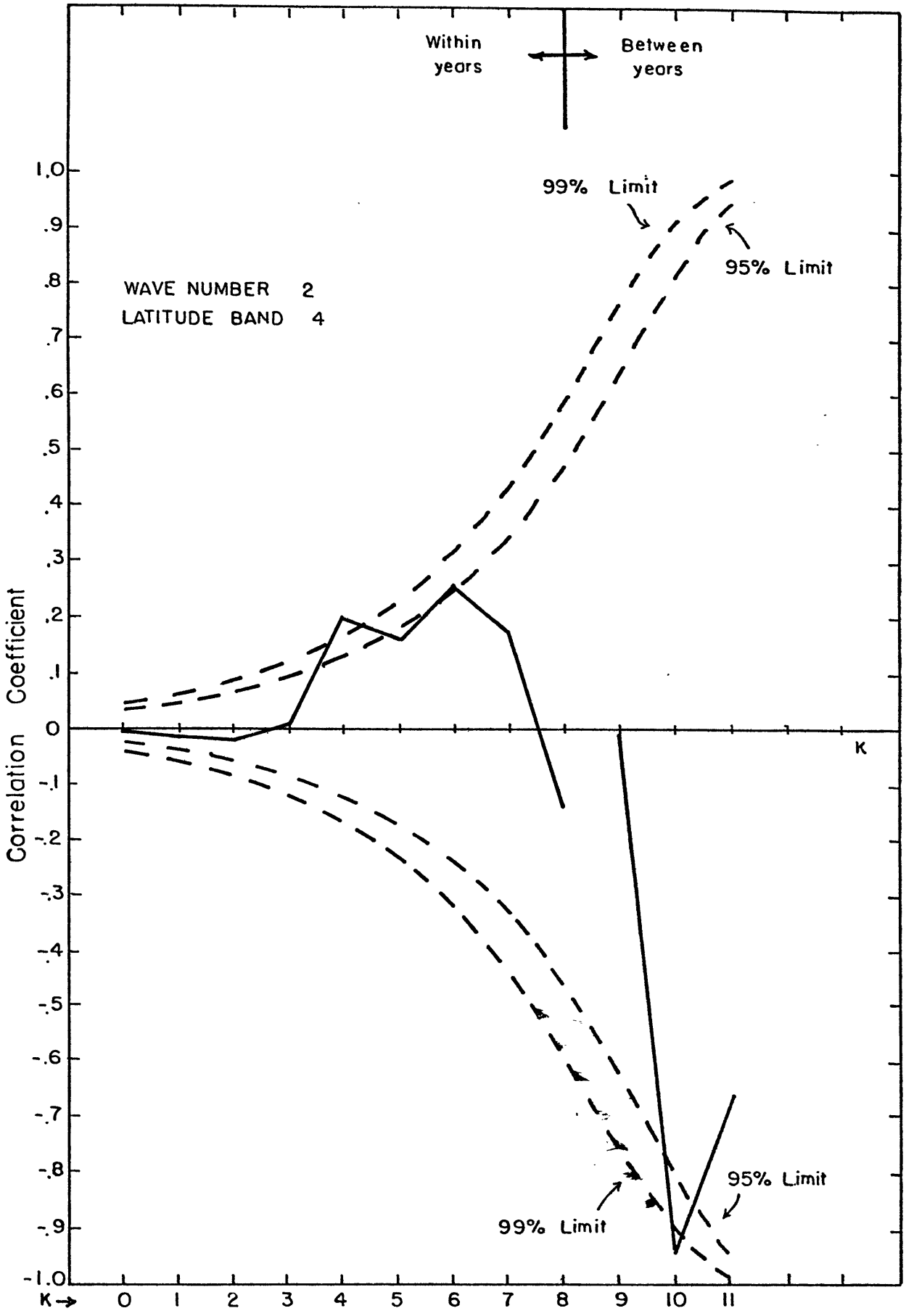
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95% Limit
99% Limit
k→ 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.11


Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 2
LATITUDE BAND 4
Correlation Coefficient
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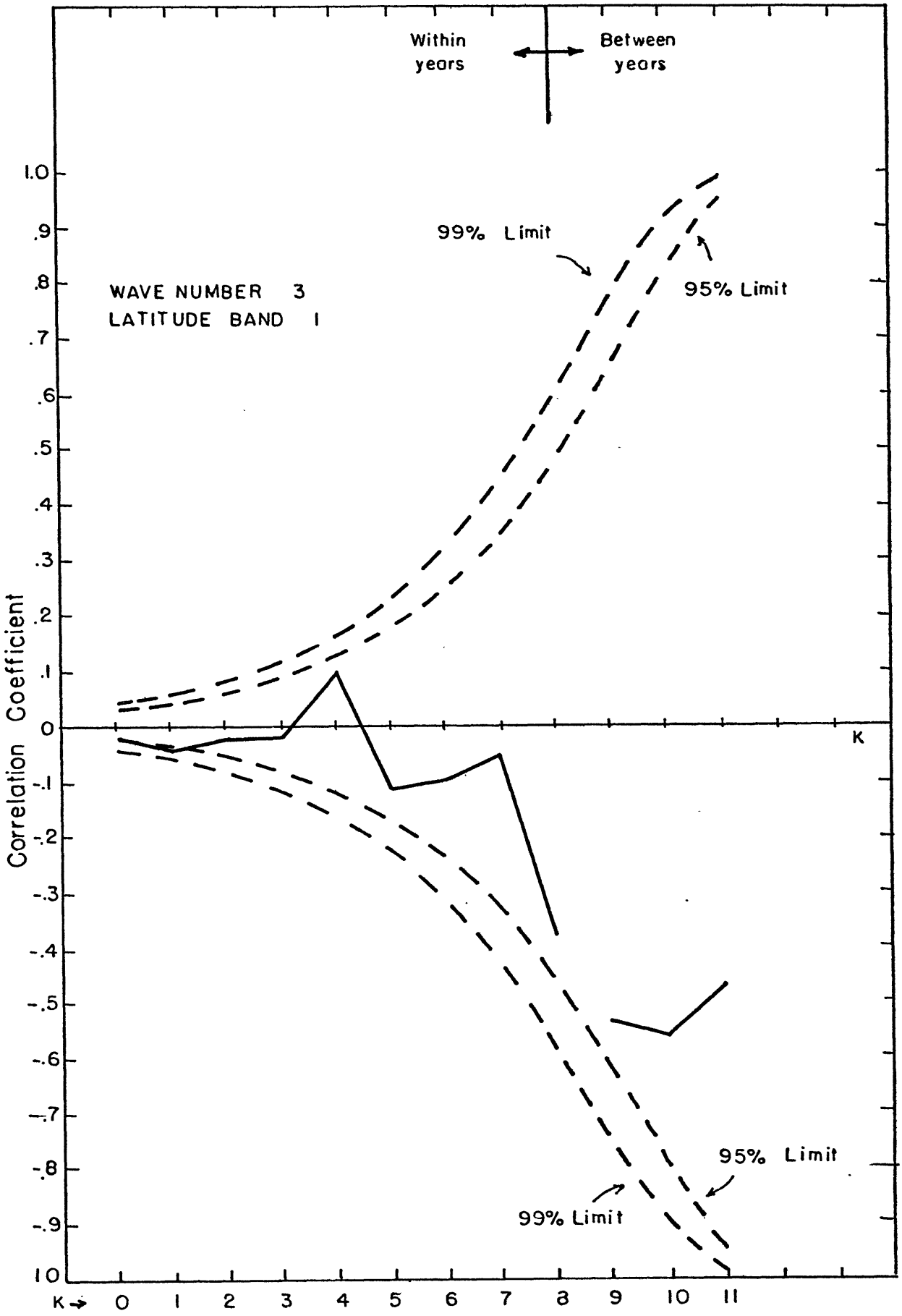
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.12


Within years
Between years
WAVE NUMBER 3
LATITUDE BAND 1
99% Limit
95% Limit
95% Limit
99% Limit
Correlation Coefficient
K
K→
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
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-.3
-.4
-.5
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-.7
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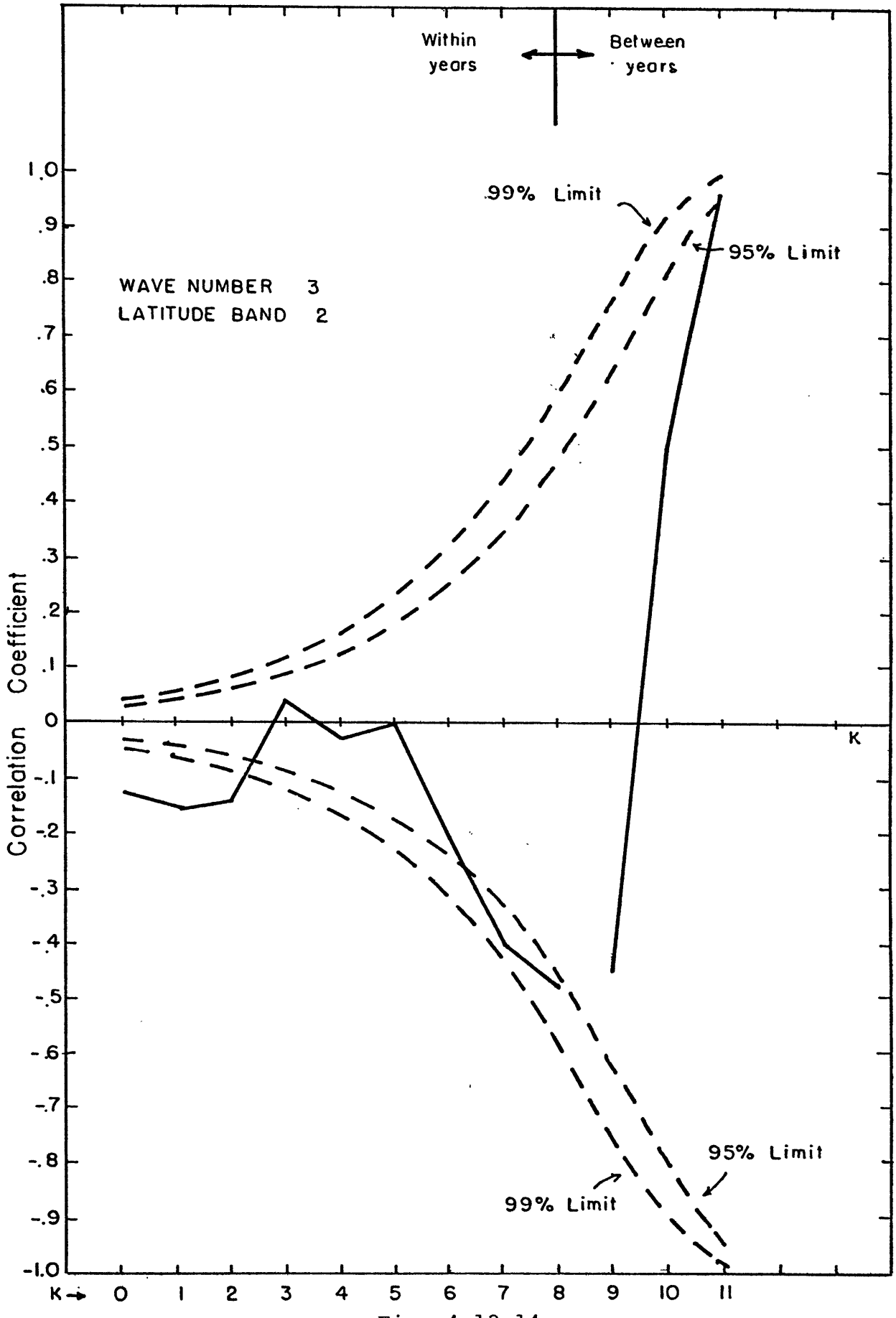
-.9
10
0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.13


Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 3
LATITUDE BAND 2
Correlation Coefficient
1.0
.9
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.7
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.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
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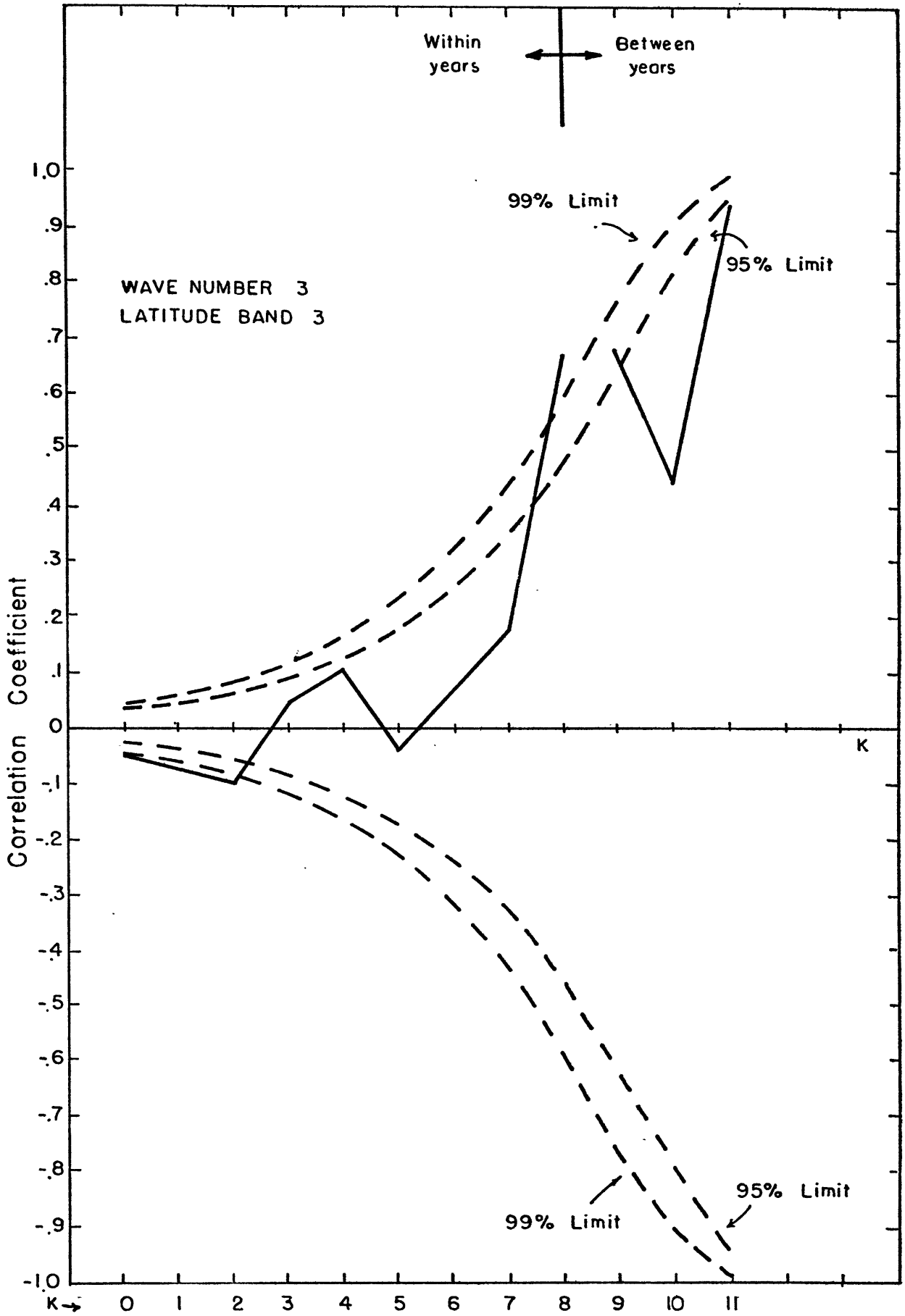
-.9
-1.0
K
95% Limit
99% Limit
K → 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.14


Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 3
LATITUDE BAND 3
Correlation Coefficient
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.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.15

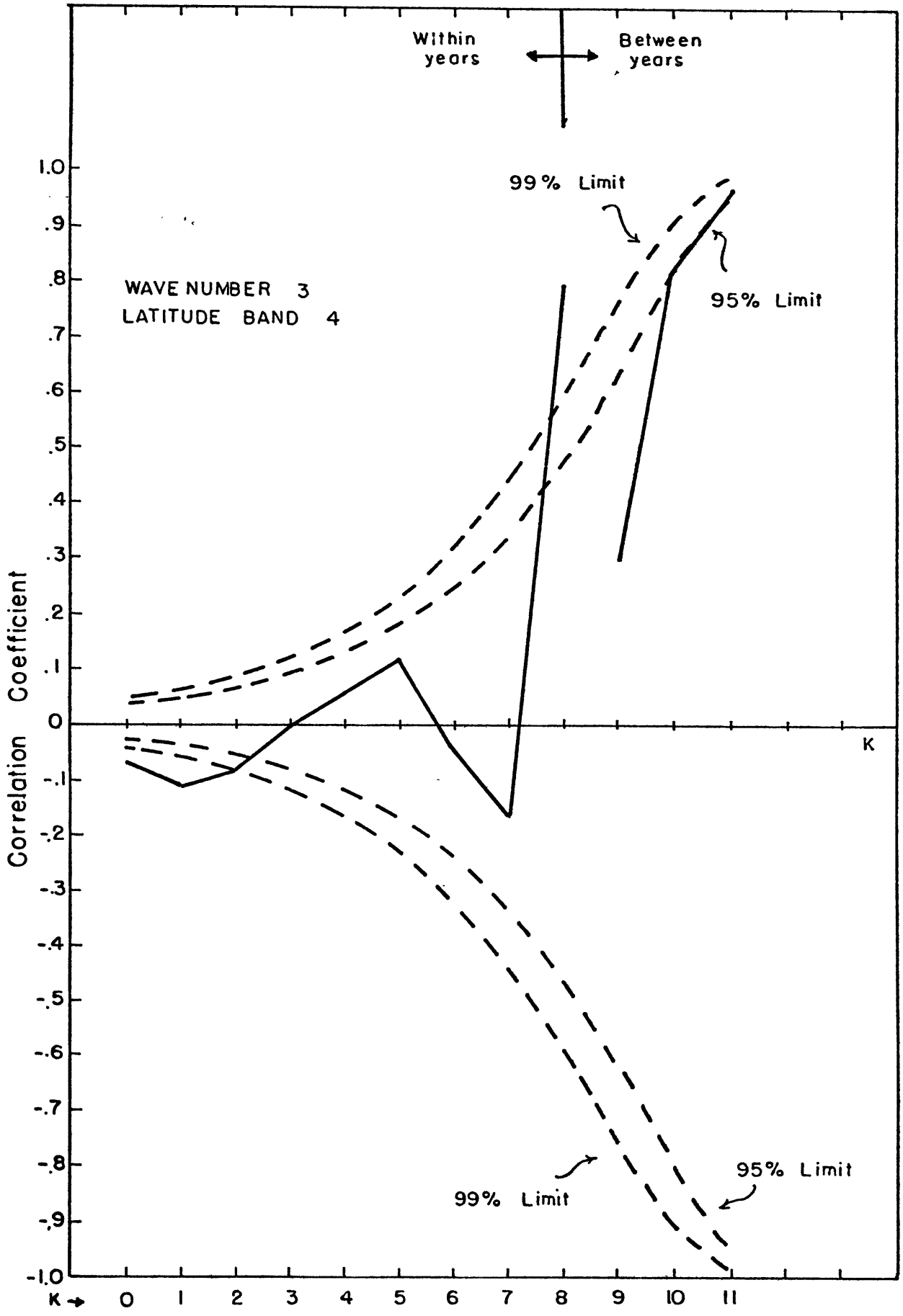

Within years
Between years
99% Limit
95% Limit
WAVE NUMBER 3
LATITUDE BAND 4
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
99% Limit
95% Limit
K → 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.16

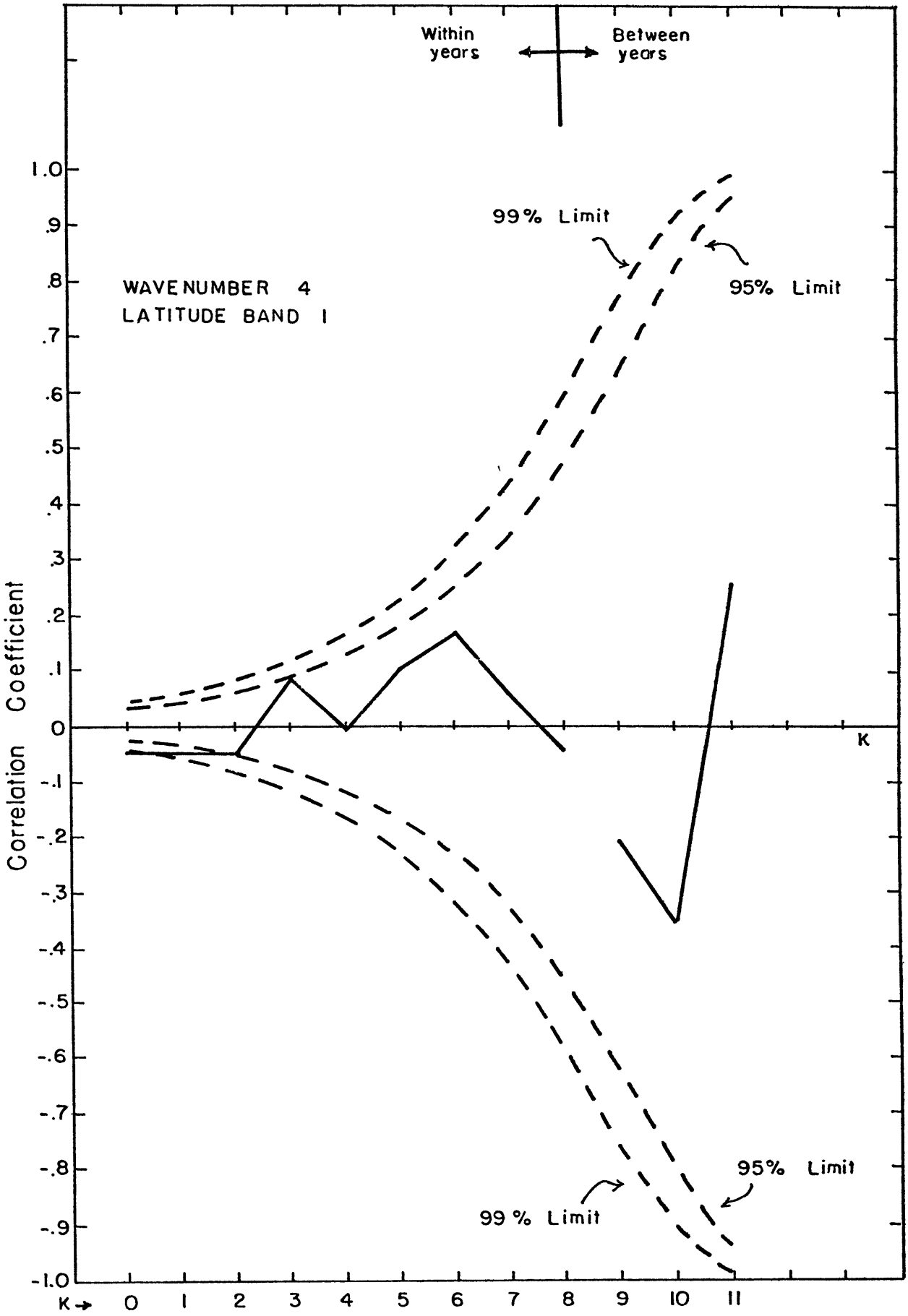

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 4
LATITUDE BAND 1
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K → 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.17

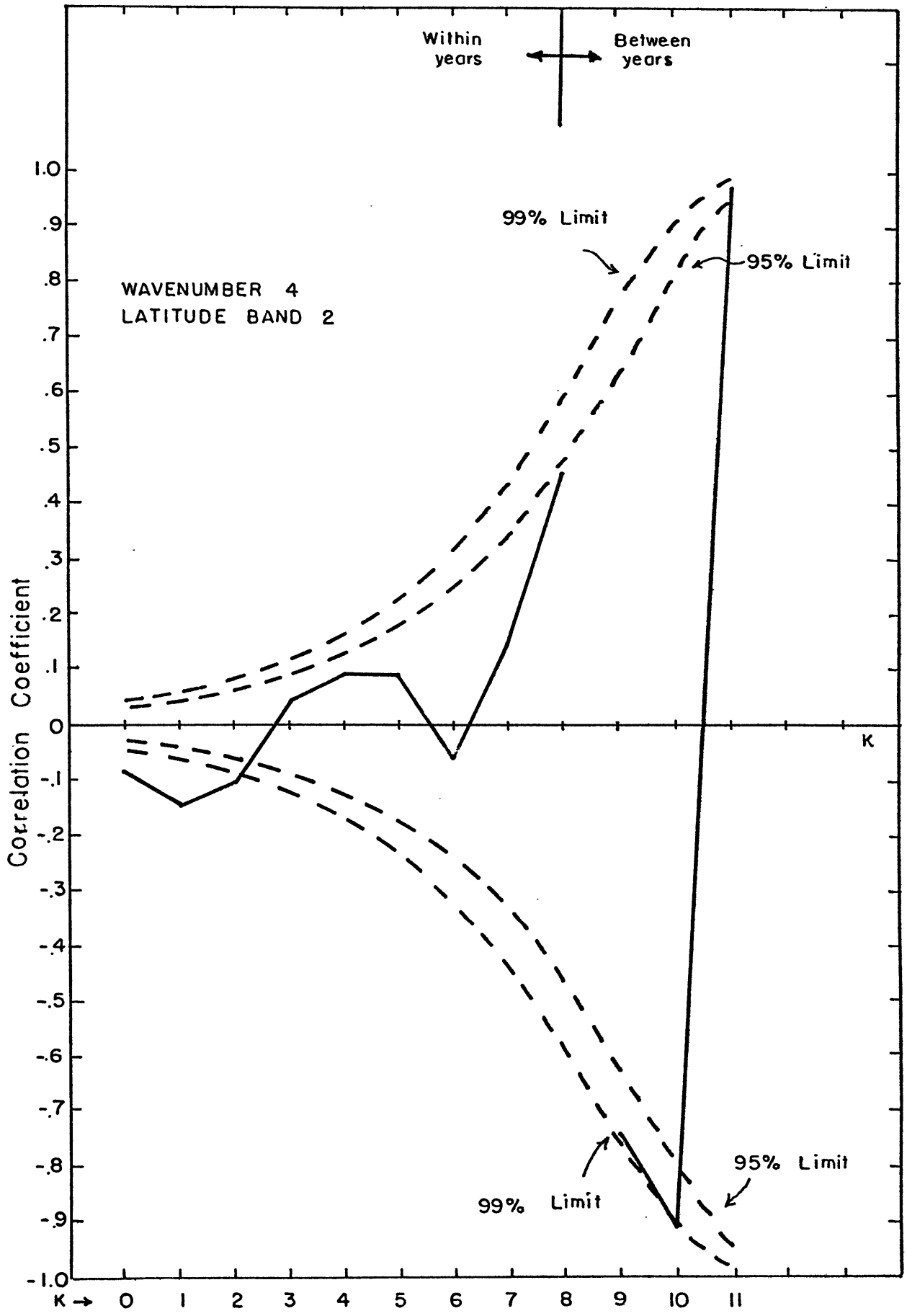

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 4
LATITUDE BAND 2
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K → 0 1 2 3 4 5 6 7 8 9 10 11
99% Limit
95% Limit

Fig. 4.12.18

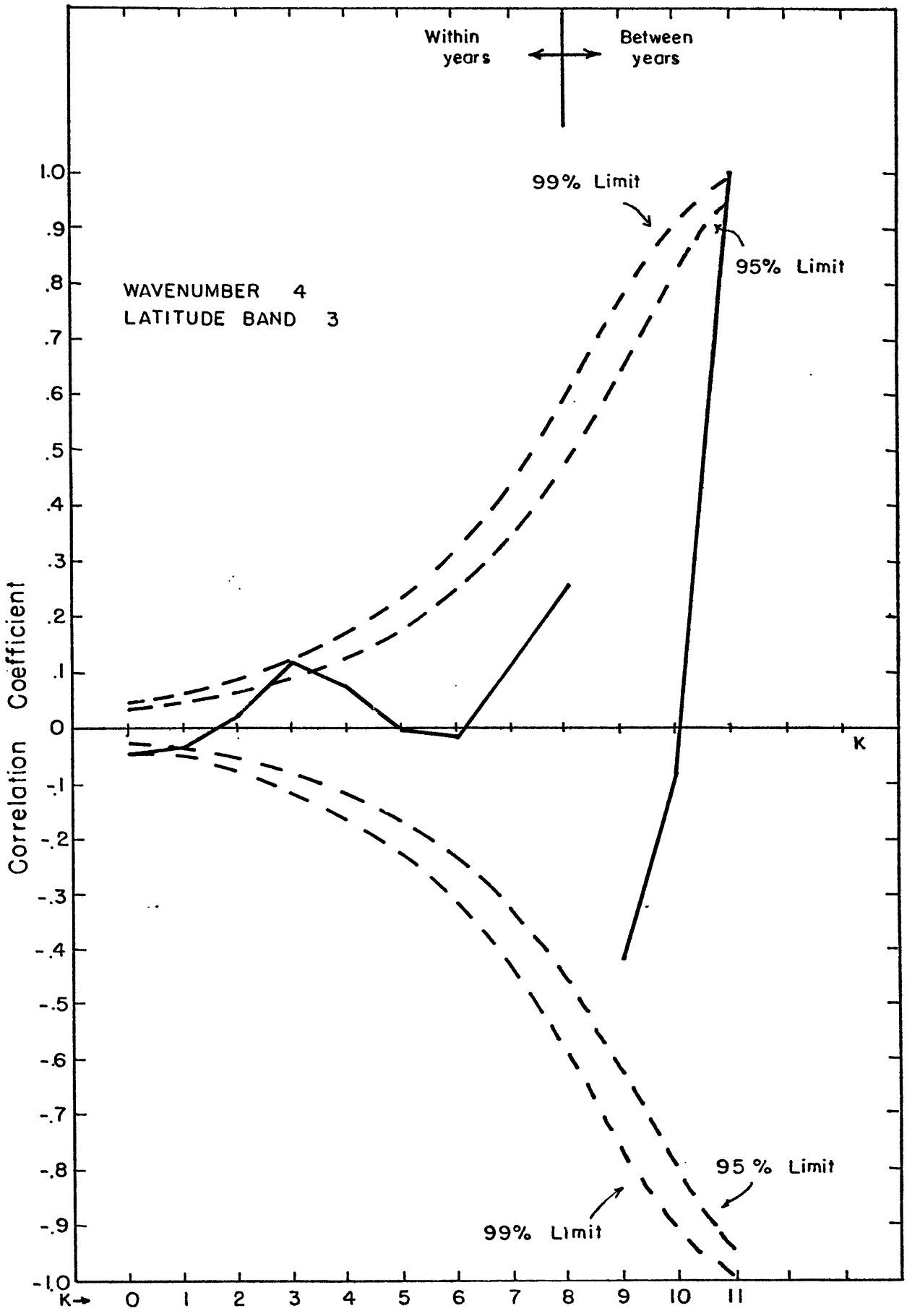

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 4
LATITUDE BAND 3
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95 % Limit
99% Limit
K→ 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.19

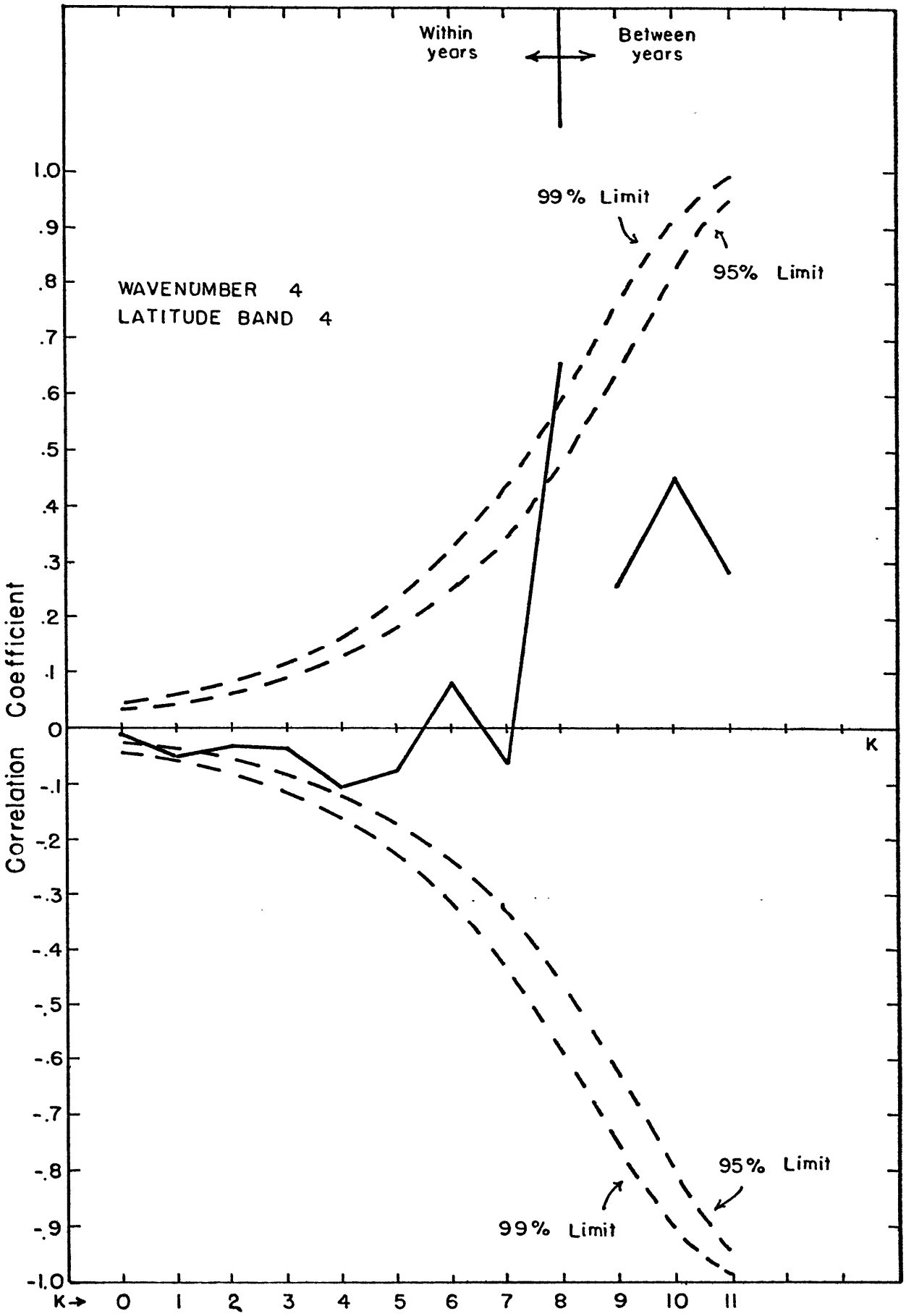

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 4
LATITUDE BAND 4
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.20

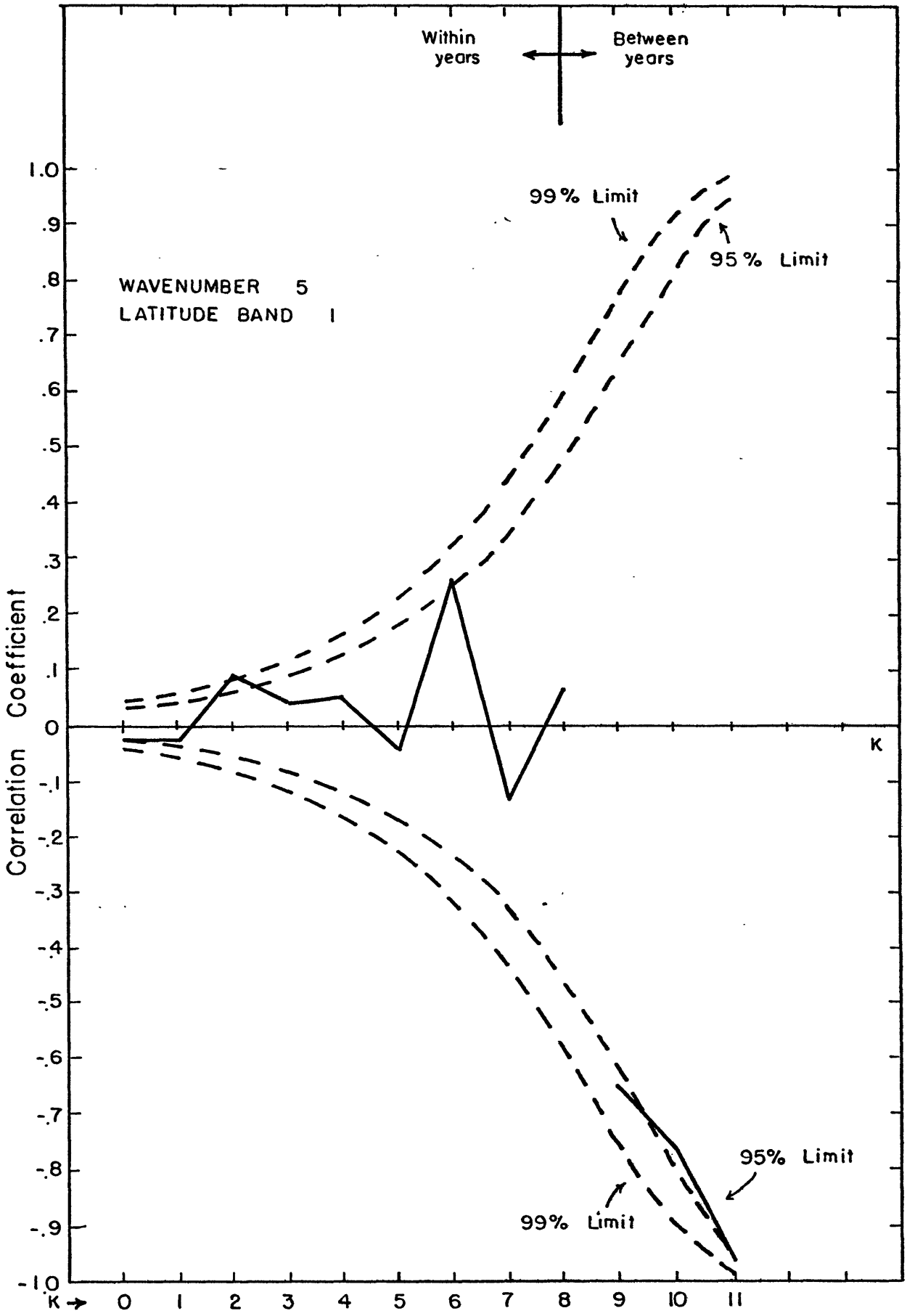

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 5
LATITUDE BAND 1
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95% Limit
99% Limit
K → 0 1 2 3 4 5 6 7 8 9 10 11

Fig. 4.12.21

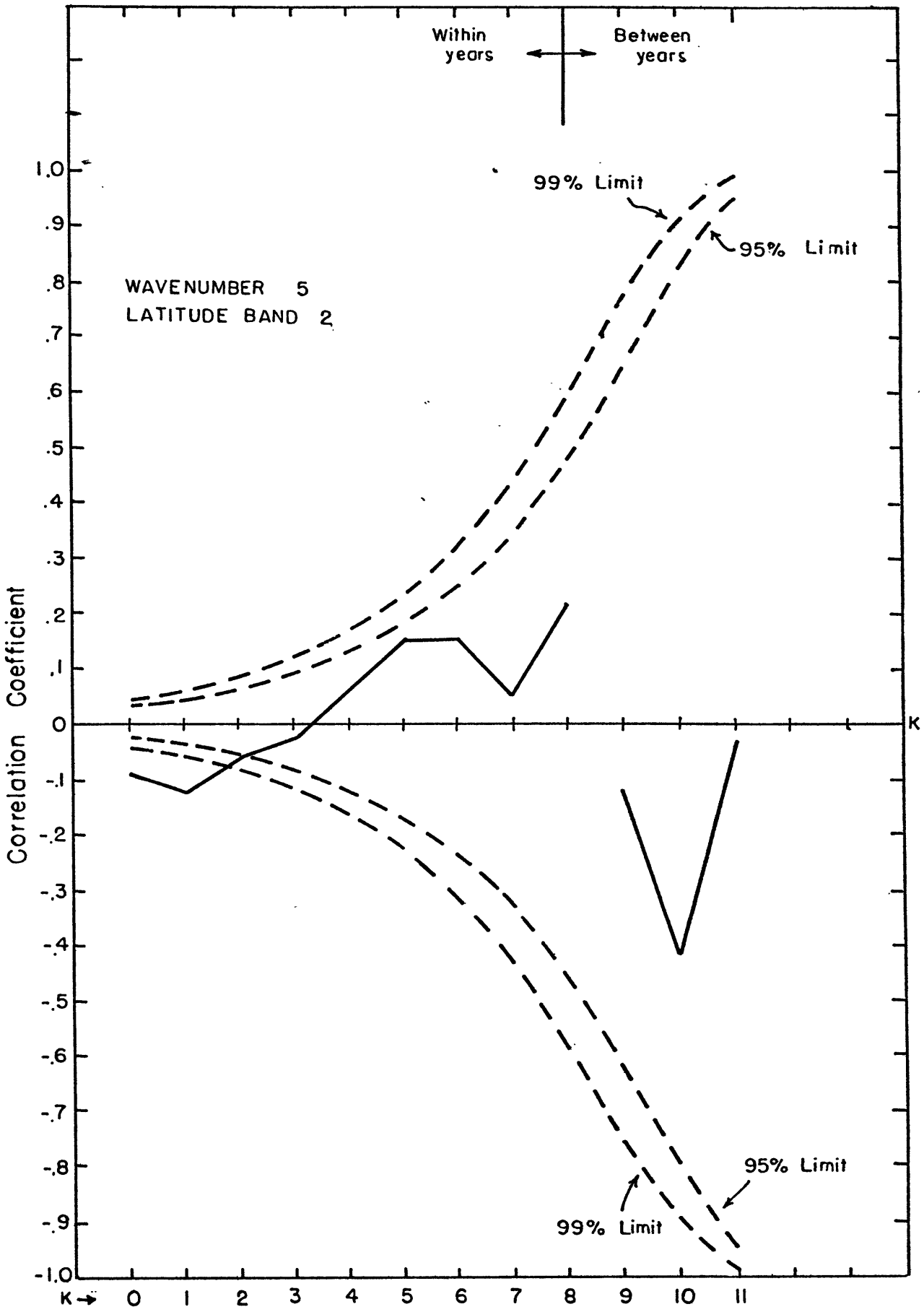

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 5
LATITUDE BAND 2
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.22

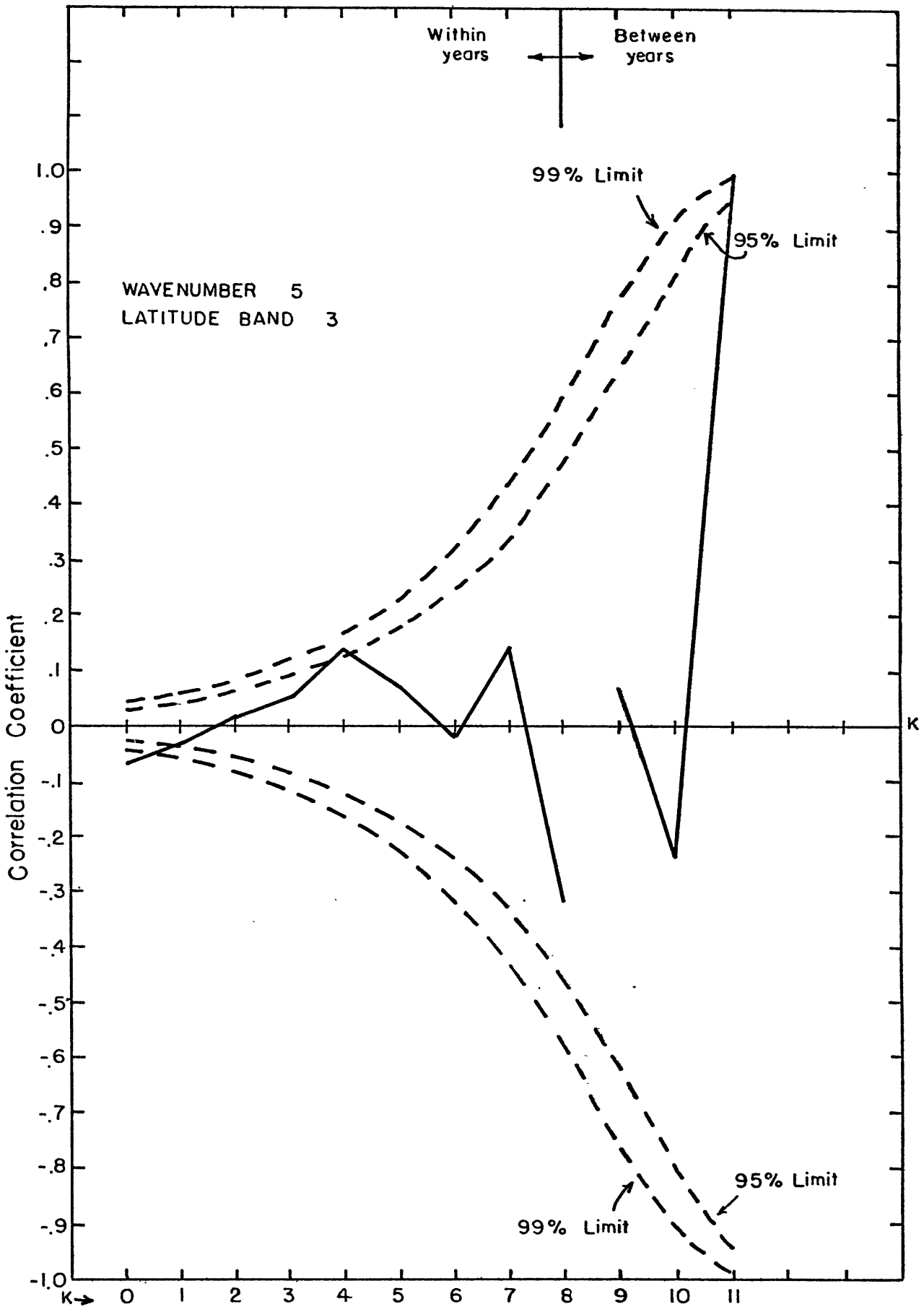

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 5
LATITUDE BAND 3
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

Fig. 4.12.23

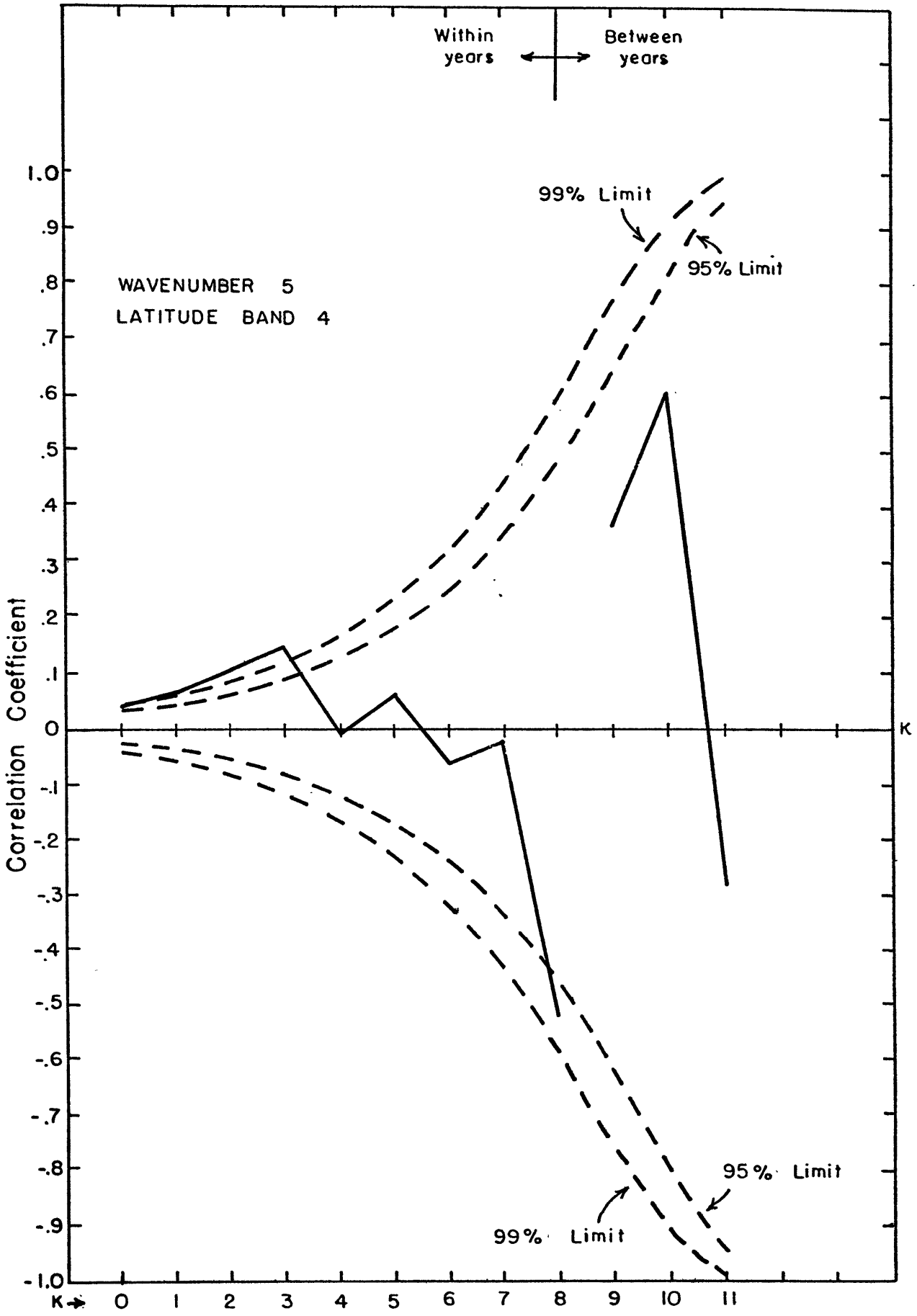

Within years
Between years
99% Limit
95% Limit
WAVENUMBER 5
LATITUDE BAND 4
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
K
95% Limit
99% Limit
K→ 0 1 2 3 4 5 6 7 8 9 10 11

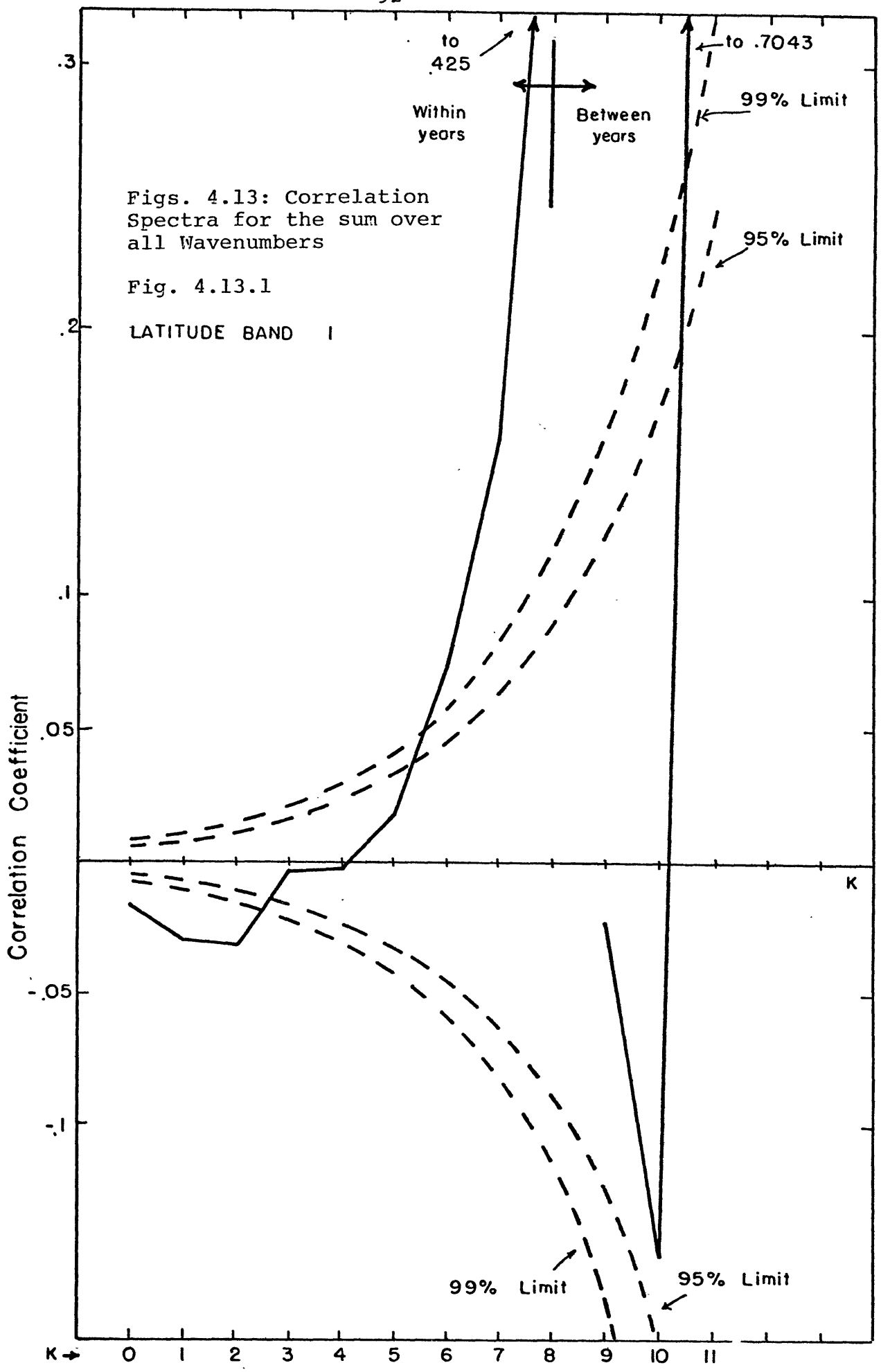
Fig. 4.12.24

through 4. The confidence limits appear dashed while the coefficients have been connected by solid lines. When $k \leq 8$ the coefficients describe within year processes, when $k > 8$ they are interannual. Hence, we have separated the solid lines to denote these two temporal areas. Fig 4.12.1 shows three significant negative coefficients and two more negative ones for $k \leq 4$, 3 significant positive coefficients and another small positive one for $8 \leq k \leq 5$. For $k > 8$ nothing significant occurs. The coefficient for $k = 11$, $m = 0$ must be 1.0 because there is only 1 degree of freedom there. For large k, say $k \geq 9$, there are fairly few degrees of freedom so that decisive conclusions about statistical trends are difficult to make.

Rather than discuss each graph we will point out a few recognizable traits. In all cases except fig 4.12.24 (wavenumber 5, latitude band 4), we observe negative correlations on short time scales. Many are significant at the 99% level. Secondly, we observe significant positive correlations (exception: fig 4.12.24) only on long time scales ($k = 6,7,8$), and only for selected zonal scales. Finally, there is little evidence for significant correlation in the $k > 8$ range of the spectrum.

4.3 Correlation Spectra for the Sum Over All Wavenumbers

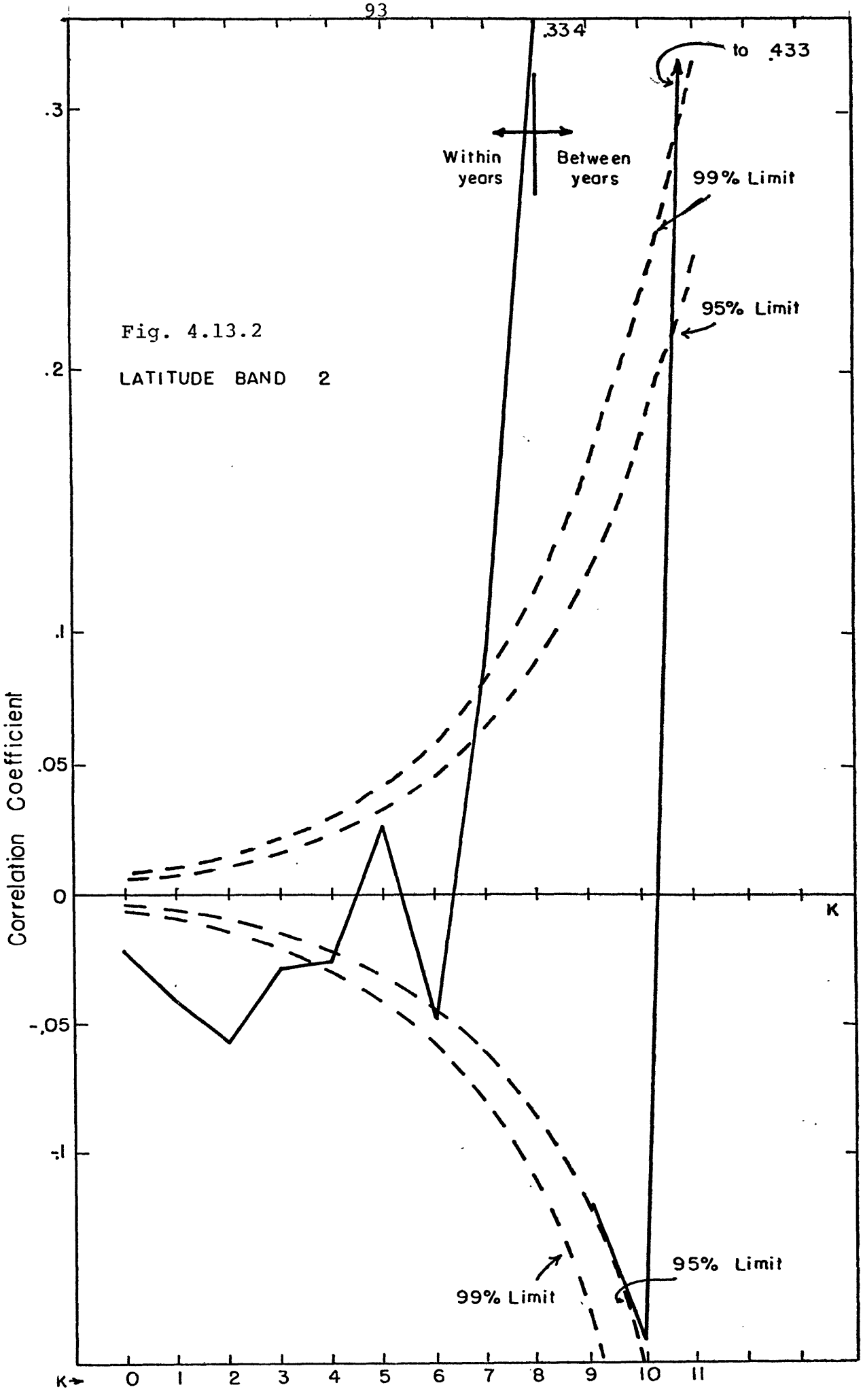
Figures 4.13.1 - 4.13.4 display these spectra summed over all wavenumbers. The graphs are identical in structure

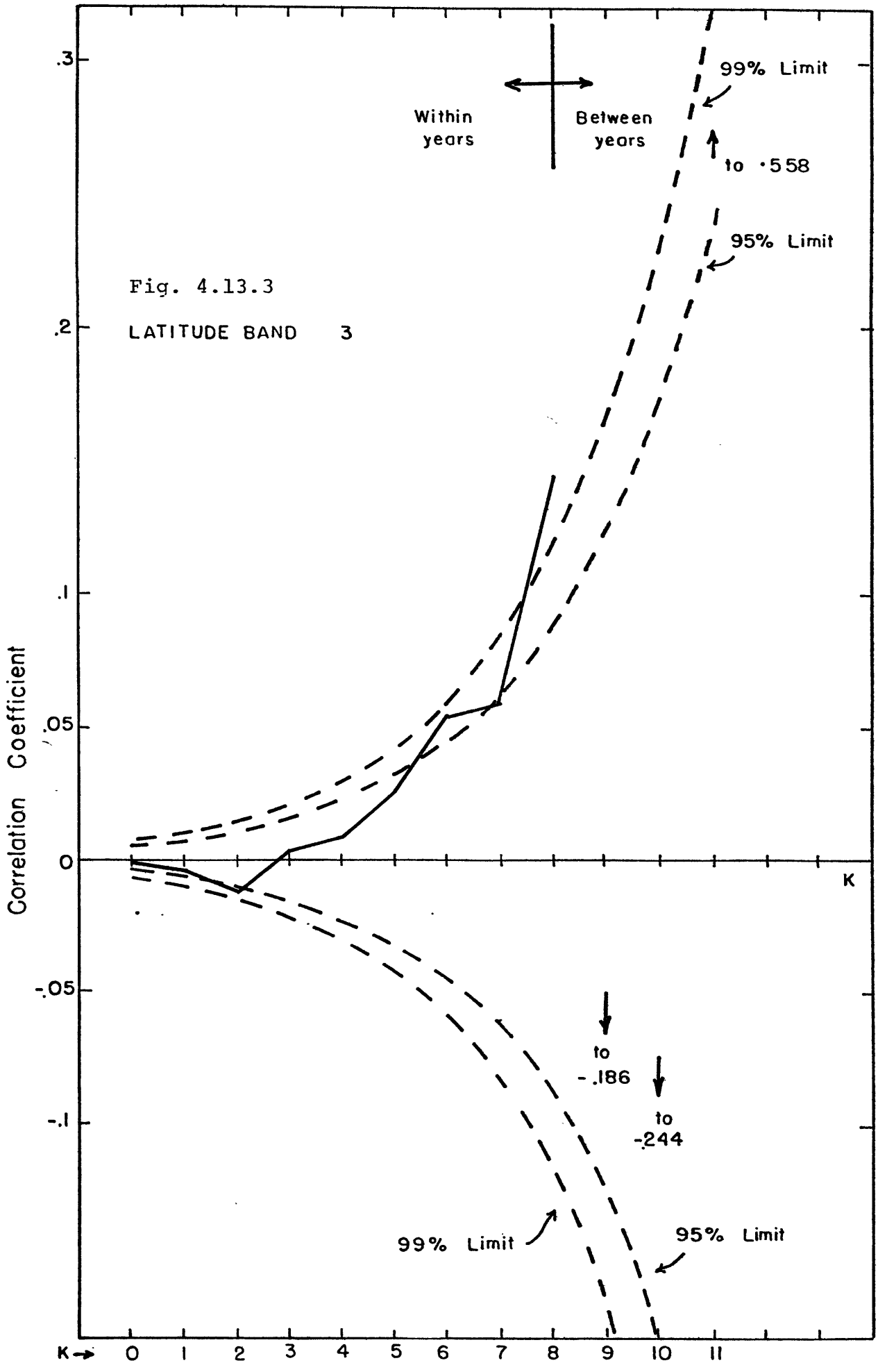


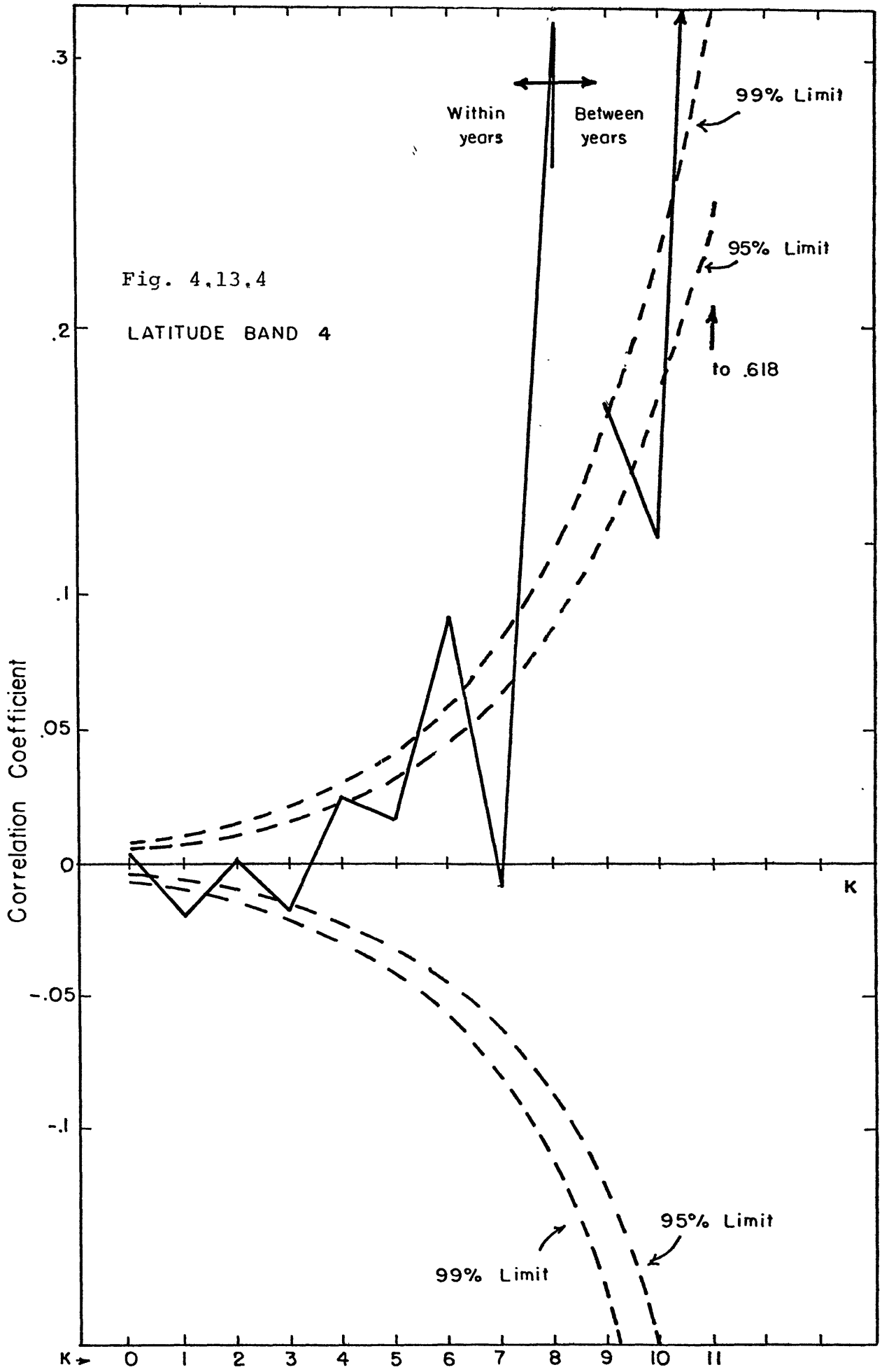
Figs. 4.13: Correlation Spectra for the sum over all Wavenumbers

Fig. 4.13.1

LATITUDE BAND I


.334
to .433
Within years
Between years
99% Limit
95% Limit
Fig. 4.13.2
LATITUDE BAND 2
Correlation Coefficient
.3
.2
.1
.05
0
-.05
-.1
K
99% Limit
95% Limit
K→ 0 1 2 3 4 5 6 7 8 9 10 11


Within years
Between years
99% Limit
to ·558
95% Limit
Fig. 4.13.3
LATITUDE BAND 3
Correlation Coefficient
.3
.2
.1
.05
0
-.05
-.1
K
to -.186
to -.244
99% Limit
95% Limit
K → 0 1 2 3 4 5 6 7 8 9 10 11


Within years
Between years
99% Limit
95% Limit
to .618
Fig. 4.13.4
LATITUDE BAND 4
Correlation Coefficient
.3
.2
.1
.05
0
-.05
-.1
K
K→ 0 1 2 3 4 5 6 7 8 9 10 11
95% Limit
99% Limit

to those of figure 4.12. Strikingly, all four latitudes show negative correlations on short time scales and positive correlations on long time scales (k = 6,7,8), although the trend is less distinct in the two higher latitudes. In contrast to figures 4.12, we do observe significant correlations for the between years scales; however, caution is the word here because of the small number of degrees of freedom.

4.4 Correlation Spectra for the Sum Over All Time Scales

These four spectra, depicted in figs. 4.14.1 - 4.14.4, display correlation coefficient as a function of wavenumber for the sum over all time scales. The reader should observe the expanded ordinate scale between 0 and .1. They describe, in essence, whether positive or negative correlations dominate for the entire range of time scales. Each spectrum is somewhat different; however, in all cases positive correlations are the rule for the zonally averaged flow. Negative correlations are observed to dominate in the 2-5 wavenumber range with a few exceptions. Caution should be taken in broadly interpreting these spectra because they include between year processes (k > 8) which are not of significance for this particular study. Latitude band 4 (65^{o}) departs from the patterns established at lower latitudes with high positive correlations between wavenumbers 9 and 17. Referring to Appendix B, output for latitude band 4, we can see that this is caused by a concentrated group of high positive

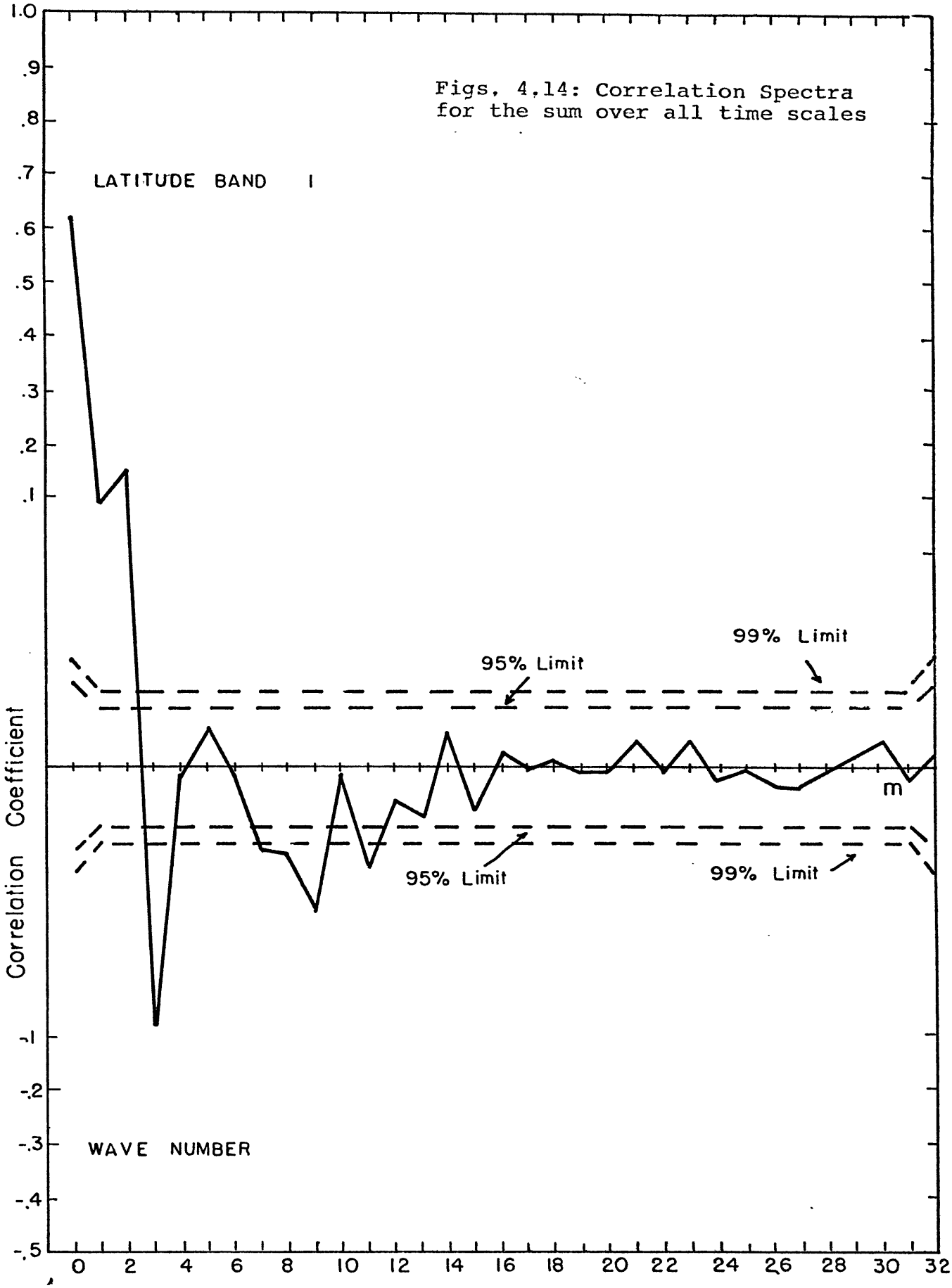

Figs. 4,14: Correlation Spectra
for the sum over all time scales
LATITUDE BAND I
99% Limit
95% Limit
95% Limit
99% Limit
m
Correlation Coefficient
WAVE NUMBER
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
-.3
-.4
-.5
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32

Fig. 4.14.1

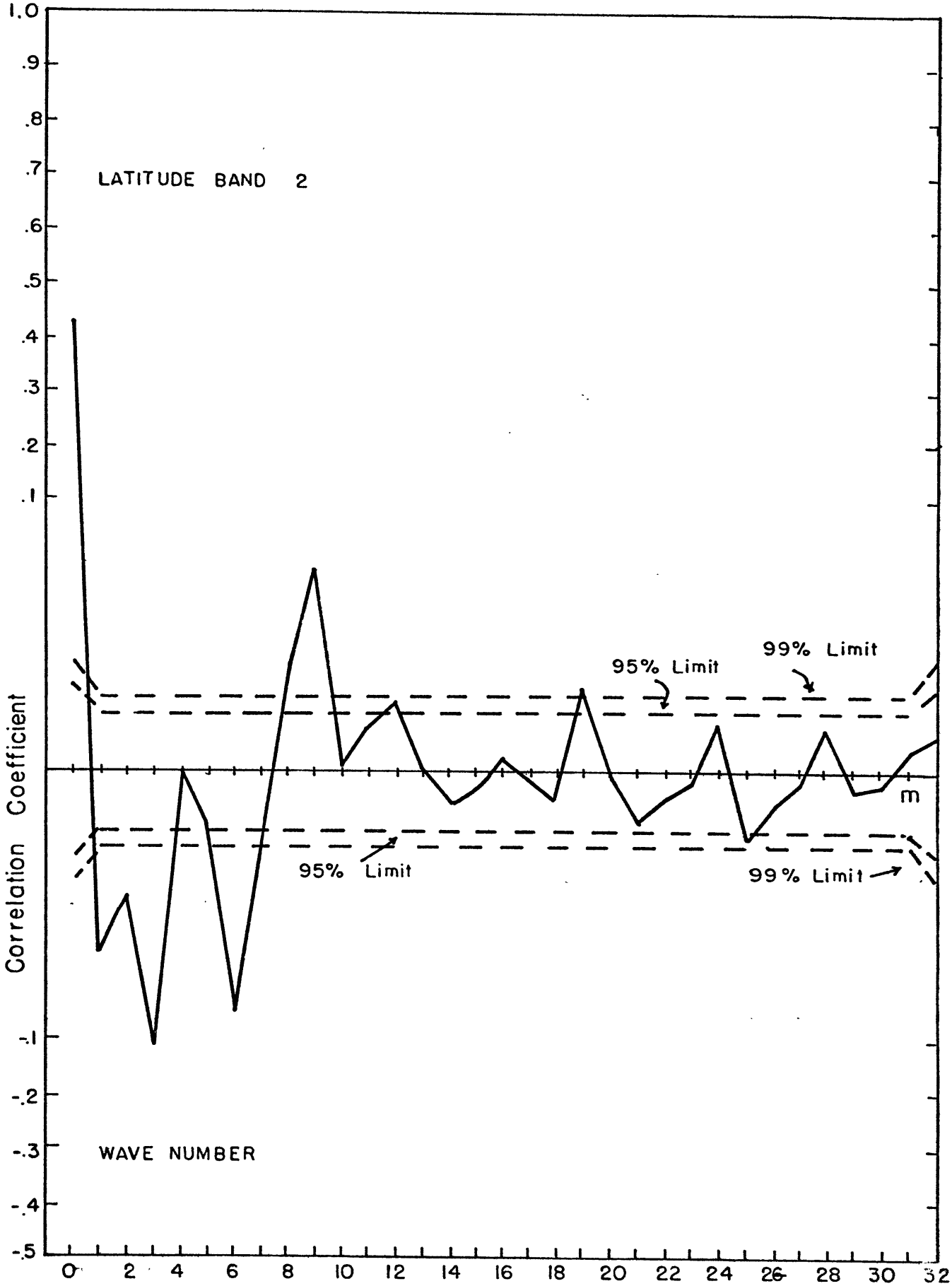

LATITUDE BAND 2
95% Limit
99% Limit
95% Limit
99% Limit
m
WAVE NUMBER
Correlation Coefficient
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
-.3
-.4
-.5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Fig. 4.14.2

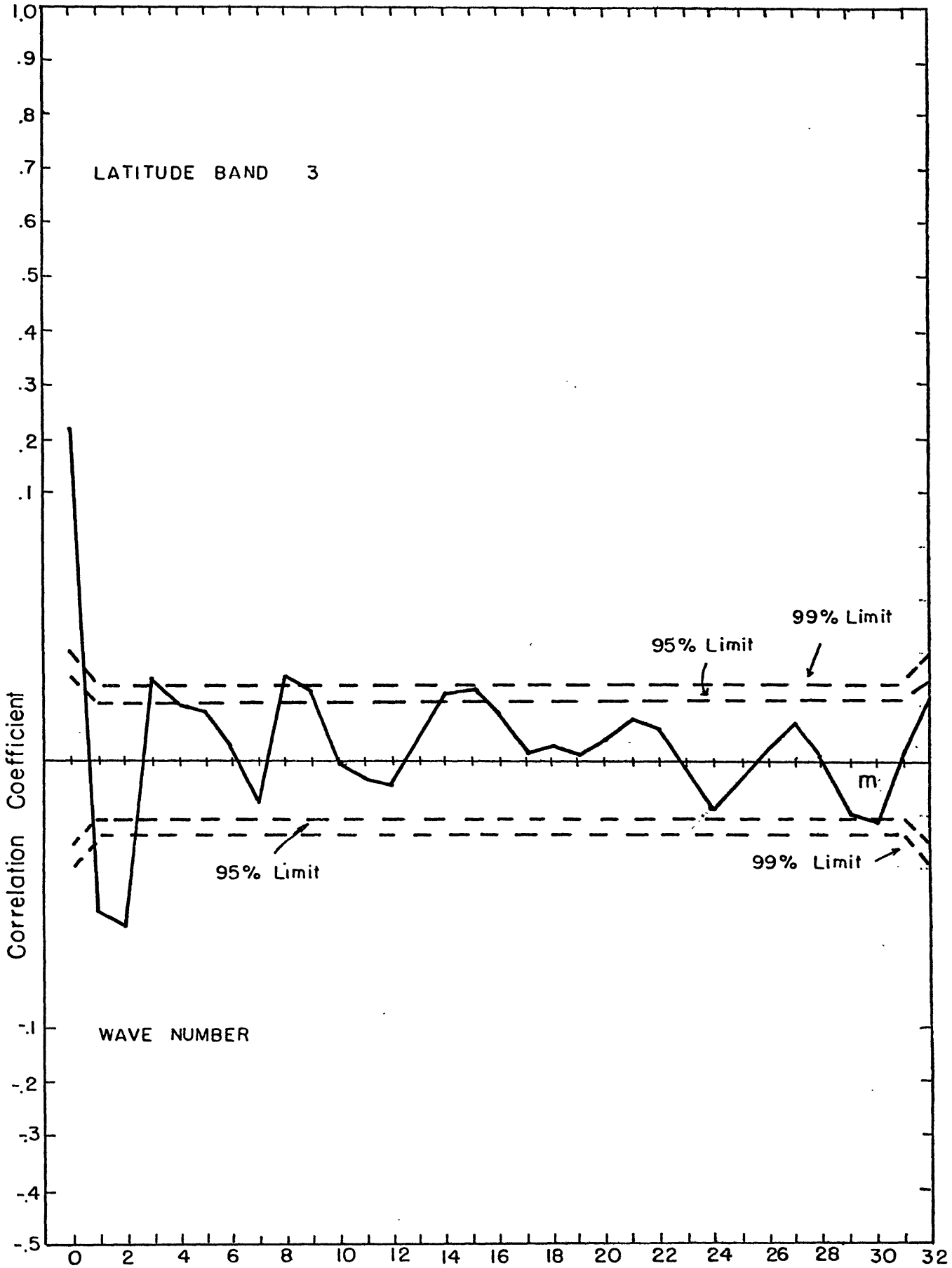

LATITUDE BAND 3
Correlation Coefficient
WAVE NUMBER
99% Limit
95% Limit
95% Limit
99% Limit
m
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
-.3
-.4
-.5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Fig. 4.14.3

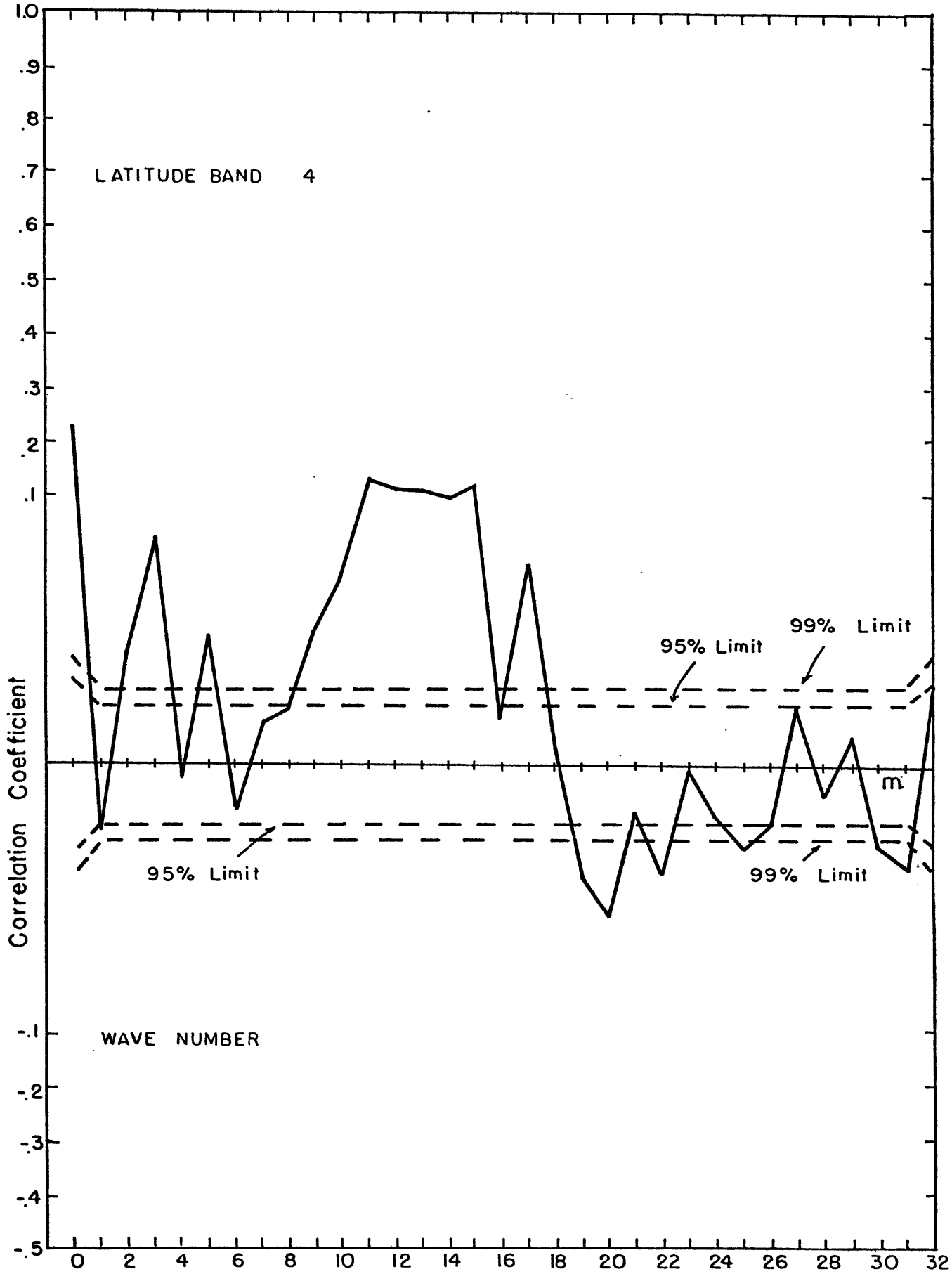

LATITUDE BAND 4
Correlation Coefficient
WAVE NUMBER
95% Limit
99% Limit
95% Limit
99% Limit
m
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
-.3
-.4
-.5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Fig. 4.14.4

correlations within these wavenumbers on short time scales. At 65^{o}, the Zonal Scale is at most 1800 KM (m = 9) which approaches the reliable resolution limit of the data. (Hypothetically that limit is $\frac{2\pi a \cos 65^{o}}{32}$ = 512 KM, but realistically it is probably twice or even three times that large.) Hence, not too much stock can be placed in significant correlations near this resolution limit. (See Table 5.1, which gives the physical size of the wavenumber domains as a function of latitude.)

4.5 Total Correlations by Latitude Band

Figure 4.15 depicts the total correlation coefficient between the eddy flux and $X \cdot (\Delta T)^2$ as a function of latitude. Little information is to be drawn from this graph because the absolute values of the coefficients are so small, even though they exceed the 99% confidence limit twice. One would not expect a high positive correlation between datasets which are negatively correlated on certain scales and positively correlated on others. These are probably the least meaningful results.

4.6 Variance and Covariance Spectra

Here we will briefly touch on the variance and covariance spectra found in Figures 4.1 - 4.9. In general, the variance of both $X \cdot (\Delta T)^2$ and the eddy flux drops off with increasing wavenumber. Relative maxima may be found, for

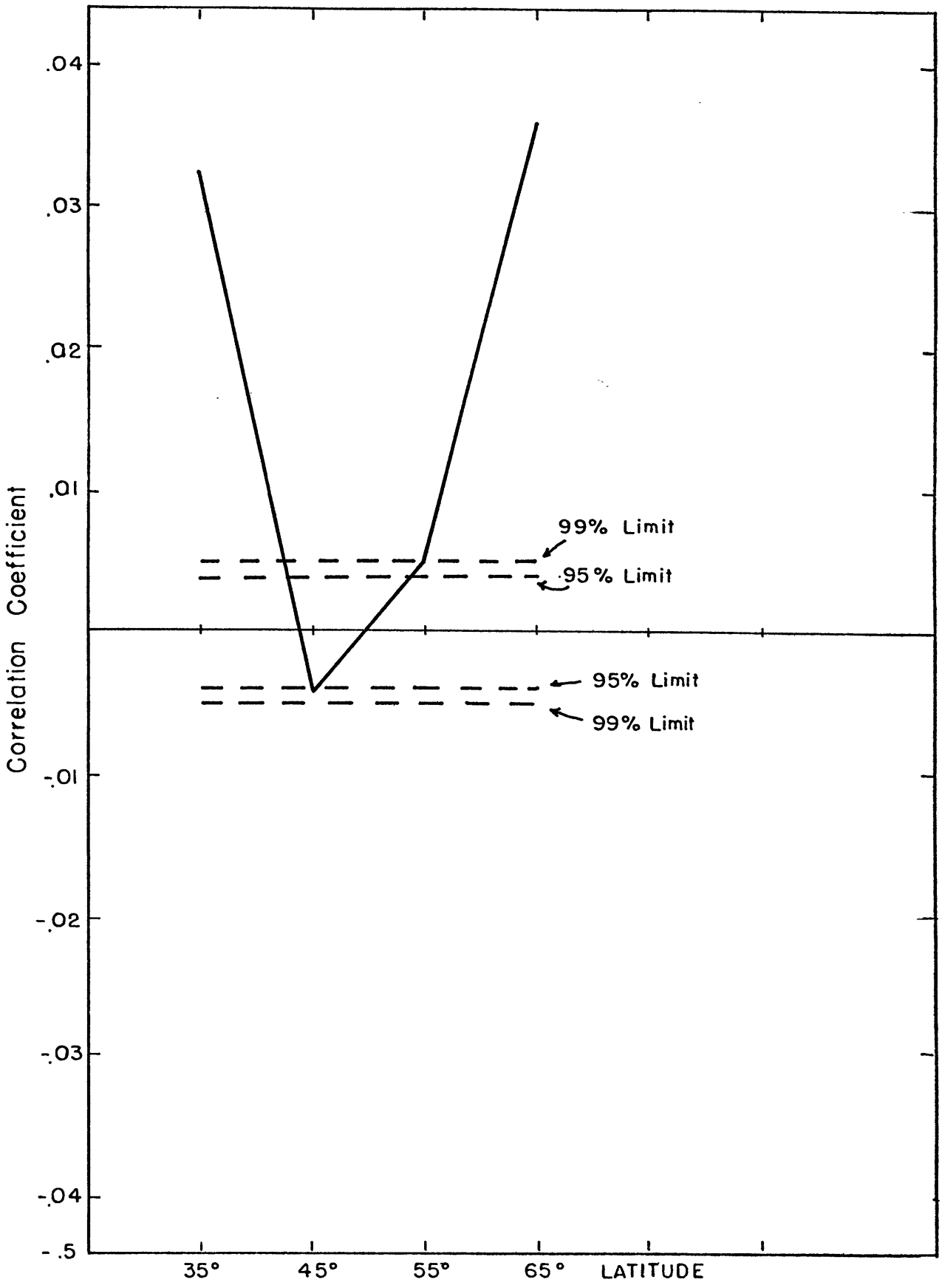


Fig. 4.15 Total Correlations by Latitude Band

instance, for $1 \leq m \leq 9$ and $k = 0$ in the $X \cdot (\Delta T)^2$ variance. Another relative maximum may be found at $m = 0$, $k = 8$. In the eddy flux case, the variance maximum occurs at $k = 2$, $m = 9$. The relative maxima described here refer to latitude $35^{\circ}N$ only. Lorenz (1979) reports similar findings. In his case the variance in zonally averaged temperature decreased as the meridional scale decreased. Figures 4.7 - 4.9 reveal that the components of the covariance also decrease in magnitude as wavenumber increases. Positive maxima occur near $m = 0$ and $k = 8$, while negative maxima occur near $m = 0$, $k = 2$.

CHAPTER FIVE

DISCUSSION OF RESULTS AND CONCLUSIONS

5.1 Forced and Free Regimes

We can make use of the figures in the last chapter to draw some conclusions about the forced and free regimes revealed in the parameterization (2.8). In our case, because we correlate the eddy flux with the square of the temperature gradient, positive correlations imply that the variations are forced. For free variations the correlation must be negative, although it is possible to have a negative correlation even though some forcing is present (Lorenz, 1979). For the zonally averaged case, free regimes appear on short time scales and forced regimes appear on seasonal scales. This result solidly verifies both baroclinic adjustment and seasonal forcing within the spectre of the same data set.

For planetary and smaller scale wavenumbers (through $m = 5$), forcing at the seasonal time scale is confined to: wavenumber 1 at 35^{o} and 45^{o}, wavenumber 2 at 35^{o} and 45^{o}, wavenumber 3 at 55^{o} and 65^{o} and wavenumber 4 at 45^{o} (marginal). Because the total eddy flux is modeled, both stationary and transient eddies are included. The wavenumber 3 forcing at high latitudes may very well be due to the topographical (land mass/ocean) forcing of the stationary eddies.

Flux variations which can be explained by this para-

meterization (i.e., which have significant correlations, either positive or negative) are, however, primarily free. At the seasonal time scale, many of the figures reveal no significant correlations. Wavenumber 5 at 65^{o} and wavenumber 3 at 45^{o} are the only seasonal time scales which are marked by negative correlations. As mentioned briefly in the last chapter, it is striking that significant negative correlations occur on all short period time scales except one. We conclude that we have observed what we set out to observe: the eddies also adjust the gradient on scales smaller than the zonally averaged scale!

We feel that we have been successful in effectively displaying the behavior of the eddies by spectrally testing (2.8) on real data. Additionally, we can assess more completely baroclinic adjustment, and make some general conclusions about the validity of (2.8). This we will do in the next two sections.

5.2 Baroclinic Adjustment: A Free Regime Process

By studying the latitudinal and temporal dependence of the eddies for short time scales we can learn a great deal about baroclinic adjustment. First, we will discuss the favored time scale. This is the period at which the eddies are most negatively correlated with $X \cdot (\Delta T)^2$. Secondly, we can examine the zonal scale of the eddies as a function of latitude. Finally we will describe how the

characteristic adjustment period (= 2^k days) is affected by the zonal scale on which the adjustment is occurring.

With the exception of the zonally averaged case, the peak negative correlation begins at k = 3 (8 days) and retrogresses with increasing wavenumber until it reaches 1 day for m = 5, and finally dissappears altogether at 65^o for m = 5. For the zonally averaged case, the favored time scale is 4 days. This agrees with Lorenz' (1979) results. An average of the zonal and smaller scales could very well suggest 4 days as an overall favored time scale as well. We can offer a simple explanation for the observed retrogression, but most do so in light of the zonal scale of the eddies as a function of latitude.

Table 5.1 illustrates the physical size of the various wavenumber domains as a function of latitude. Referring to Fig 4.10, we see that adjustment is observed up to m = 11 for k = 0. Here, we define observation of adjustment to include the highest wavenumber exhibiting significant negative correlations for time scales such that $k \leq 4$, and within the reliable resolution limit of the data. This corresponds to a physical scale of about 3000 KM. Comparing this with the highest wavenumber for which adjustment is observed at 65^o (see Appendix B) on the <u>same time scale</u>, we get m = 3. This corresponds to the physical scale of about 5600 KM. Doing the same for the middle two latitudes yields physical scale "lower limits" of about 3800 KM ($\phi = 55^o$) and 4000 KM

Table 5.1

Wavenumber Scales (KM.)*

	$\phi = 35^{o}$	45^{o}	55^{o}	65^{o}
m =				
1	32780	28300	22980	16930
2	16390	14150	11490	8465
3	10927	9433	7660	5643
4	8195	7075	5745	4232
5	6556	5660	4596	3386
6	5463	4717	3830	2822
7	4683	4043	3283	2419
8	4098	3537	2872	2116
9	3642	3144	2553	1881
10	3278	2830	2298	1693
11	2980	2573	2089	1539

* Computed using $a = 6.371 \times 10^{6}m$

$2\pi = 6.28318$

($\phi = 45^{o}$). A reasonable conclusion is that the zonal scale of the eddies has a lower size limit at around 4000 KM, for time scale k = 0 (1 day fluctuations). This result is consistent with baroclinic theory.

As the time scale increases, so does the "lower limit" on the eddy size observed to baroclinically adjust. This is exemplified very nicely at 55^{o} where for k = 0, m = 6 represented the smallest adjusting eddy, whereas for k = 3, m = 1 is the smallest adjusting eddy. This transition is very smooth (refer to Appendix B) for $\phi = 55^{o}$ and less smooth but still quite noticeable at all other latitudes.

In light of this we can offer an explanation for the retrogression observed in the preferred time scale. As we move north, the time scale of an eddy at any given wavenumber decreases because the eddy size at that wavenumber decreases towards its lower physical size limit. At any one latitude, the time scale of an eddy decreases as zonal wavenumber increases because the physical size decreases with increasing wavenumber. Two limitations on this process exist. First, the eddies cannot be smaller than their characteristic length scale. In (2.5) that scale is HN/f, where H is the scale height, N the Brünt-Väisälä frequency and f the coriolis parameter. Hence, in fig. 4.12.24, the physical size may be (m = 5, $\phi = 65^{o}$ or ~ 3300 KM) too small and no baroclinic eddy is observed. Secondly, their time scale cannot greatly exceed k = 3 (k = 4 is about maximum) because other physical processes (e.g. stationary eddies) take over the burden of

the heat transport.

We can think of this retrogression in a different way. An eddy of small size is rapidly mixed into eddies of larger sizes -- hence to observe their transport we must search on short time scales. However, a large eddy retains its singular features longer. The largest baroclinic eddies thus exhibit the longest time scales--up to the limit of about $k = 4$ (16 days).

We are satisfied that we have learned a great deal about the zonal scales on which adjustment takes place, and realize that this is due in part to the unique spherical geometry of the earth. In conclusion of this section, Figure 5.1 displays a parametric plot of the preferred eddy time scale in baroclinic adjustment, revealing its retrogressive behavior.

5.3 Validity of the Eddy Flux Parameterization: Eddy Flux Predictors

We can make some general conjectures about the validity of (2.8) in modelling forced variations, which is what it is designed to do. Lorenz (1979) correlated (essentially) the eddy transport with the temperature gradient only, whereas our correlations involved an eddy diffusivity which is supposed to correct for the effect of the free variations by weighting the forced variations. By comparing his correlations with ours we will get a gross measure of the effect of the X parameter on the eddy flux parameterization.

Before doing this we should make clear that the two

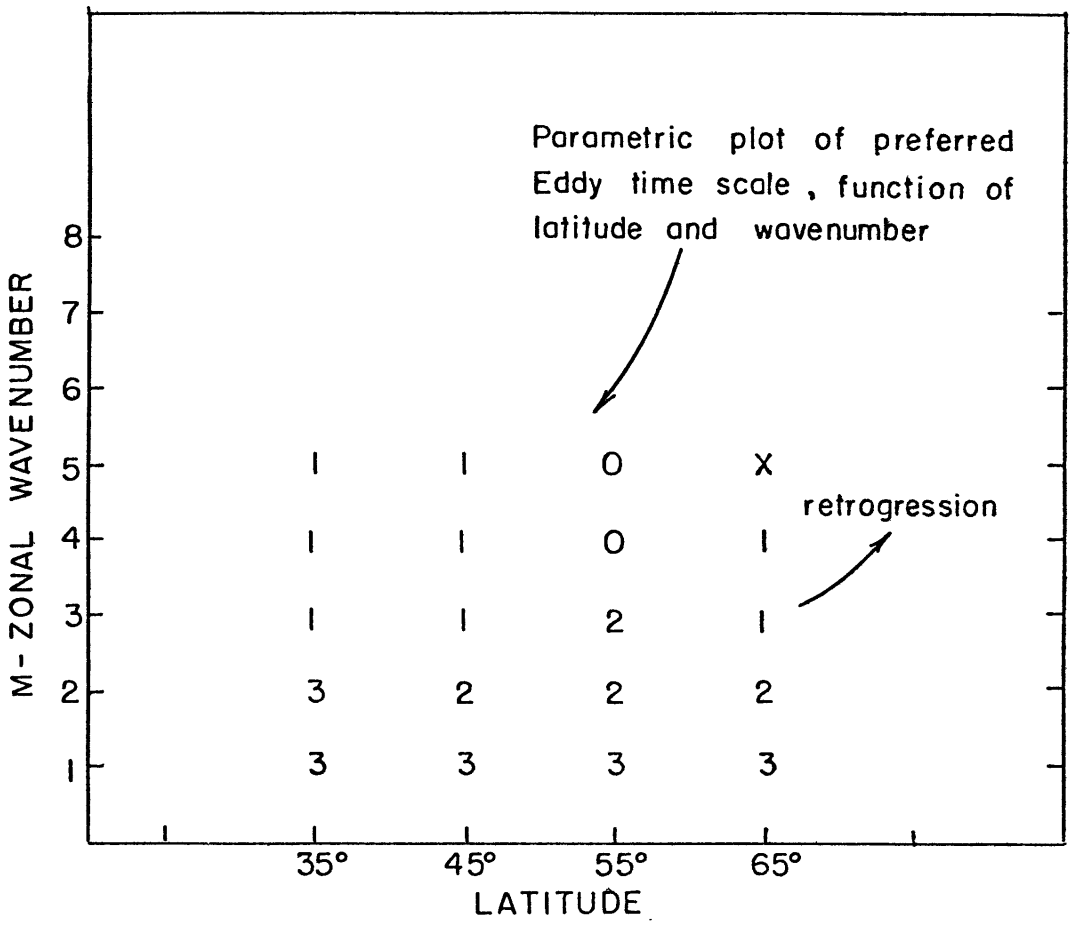


Fig. 5.1 Parametric Plot of preferred eddy time scale in Baroclinic Adjustment*

*K is plotted, time scale is 2^K days

studies are not perfectly compatible. First, Lorenz correlated the two quantities by meridional spectral analysis making use of the Legendre representations of the heat transport and temperature gradient. This effectively isolated the meridional planetary scale ($n = 2$, where n is the degree of the Legendre polynomial) which proved to be the scale at which forced variations dominated. Our study correlated the quantities directly within latitude bands, without spectral meridional analysis. Stone and Miller (1979) point out that the characteristic meridional scale of the fluxes is basically the planetary scale when the fluxes are zonally and monthly averaged. Hence, we can be certain that the basic scale involved in our data for $m = 0$ and $k = 7$ or 8 (greater than month-long averages) is the planetary--but our data do not isolate this scale from the others. Hence, small contributions from other scales would decrease our correlations relative to Lorenz's.

Secondly, our data admit latitudinal dependences which Lorenz's does not. Noting that we can compare only the $m = 0$ results, for each time scale we have four correlation coefficients to Lorenz's one. Table 5.2 presents the comparison, where Lorenz's coefficients have been calculated from the tables in his paper. In his case, negative correlations indicate forcing of the flux by the gradient.

Lorenz's coefficients are markedly higher than ours for both time scales. We cannot assess whether this is because

Table 5.2

Correlation Coefficient Comparison:

Lorenz (1979) vs. McHenry

m = 0

	ϕ	McHenry	Lorenz	N
k = 8	35^{o}	.9834	-.996	2
	45^{o}	.9653		
	55^{o}	.8935		
	65^{o}	.9131		
k = 7	35^{o}	.7813	-.893	2
	45^{o}	.6983		
	55^{o}	.5688		
	65^{o}	.0596		

his parameterization is better than ours, though, because of the above mentioned reason. What we had hoped to show--that ours is better than his--we cannot do either.

We should conclude by mentioning that we set out to test a parameterization which both took account of the β-effect and contained some measure of the zonal scale in its eddy diffusivity. In fact, (2.8) neglects this horizontal scale. We have shown, though, that (2.8) models forced variations well, but cannot determine the impact of X on its ability to model those variations.

In addition, we have presented a graphical analysis which displays both adjustment and seasonal forcing succintly. We have documented the retrogressive behavior of the characteristic adjustment time scale with the physical eddy size. Finally, we believe the inclusion of X in (2.8) enabled us to better detect the overall behavior of the free regime eddies.

CHAPTER SIX

SUGGESTIONS FOR CONTINUING RESEARCH

In this chapter we will outline several ideas for research related to our study. In the first two sections we will discuss proposals directly related to this research, and in the last section we'll talk about general uses of the program SPECTRA.

6.1 Regional Analysis

Instead of performing correlations in wavenumber space, they could be performed by defining a regional eddy flux and examining specific geographic regions of varying size. The primary advantage of this would lie in better understanding of free variations, because forced variations occur on only the two or three largest longitudinal scales (m = 0,1,2).

In this analysis the eddy fluxes are defined regionally and correlations are performed only over the regions of definition. This procedure is undertaken because it is logical to assume that eddy transport (primarily due to transient eddies, in this case) in a region on one side of the globe is not a result of instabilities on the other side, and therefore does not adjust the gradient on the other side. So long as the regions are greater in extent than the appropriate length scale of the transport, illuminating results should be expected.

In order to begin, we define

$$\langle ( ) \rangle = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \frac{1}{a \cos \phi} ( ) \, d\lambda \qquad (6.1)$$

as an average over the part of a latitude circle spanned by longitudes λ_1, λ_2. The regions are thus of extent $a \cdot \cos \phi \cdot (\lambda_2 - \lambda_1)$ in the zonal direction. We now define:

$$T^X = T - \langle T \rangle$$
$$V^X = V - \langle V \rangle \qquad (6.2)$$

where the $( )^X$ denotes the departure of the field from its average $\langle \rangle$. Assuming a non-divergent geostrophic solution, as before, we find that $\langle V \rangle \neq 0$, and the eddy flux for the region, call it EF_R, now applies only to the region between λ_1 and λ_2.

To perform the correlations, we might average EF_R over the region, getting $\langle EF_R \rangle$ as a function of time. We could compute and average X over the region, and define ΔT to span its meridional extent. Each region would yield two time series to be correlated. If we chose $\lambda_2 - \lambda_1 = \frac{2\pi}{m}$, we could perform correlations over regions of identical size, obtaining one correlation table for each <u>set</u> of regions of the same size studied. By choosing $\lambda_2 - \lambda_1 = \frac{2\pi}{m}$, we could also directly compare results with the present study for the free variations of short period.

In defining a regional flux, we must account for the fact that the total eddy flux, $\int_0^{2\pi} V^*T^*d\lambda$, is not conserved when the definitions (6.2) are used. A simple expression is now derived which relates the total eddy fluxes as defined each way. As before, let

$$\langle() \rangle = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \frac{1}{a \cos \phi} (\,) d\lambda$$

$$(\,)^X = \text{departure from regional average}$$

$$[\,] = \text{zonal average} \qquad (6.3)$$

$$(\,)^* = \text{departure from zonal average}$$

The total fluxes are

$$\langle VT \rangle = \langle V \rangle \langle T \rangle + \langle V^X T^X \rangle \text{ (region)} \qquad (6.4)$$

and

$$[VT] = [V][T] + [V^*T^*] \text{ (zonal)} \qquad (6.5)$$

Now,

$$[VT] = [\langle VT \rangle] = [\langle V \rangle \langle T \rangle] + [\langle V^X T^X \rangle]$$

$$= [\langle V \rangle][\langle T \rangle] + [\langle V \rangle^* \langle V \rangle^*] + [\langle V^X T^X \rangle] \qquad (6.6)$$

Combining the expressions (6.5) and (6.6) we get

$$[VT] = [V][T] + [\langle V \rangle^* \langle T \rangle^*] + [\langle V^X T^X \rangle] \qquad (6.7)$$

Again combining, this time (6.7) and (6.5) we arrive at the result desired:

$$[V^*T^*] = [\langle V\rangle^*\langle T\rangle^*] + [V^X T^X] \qquad (6.5)$$

We have made use of the fact that $[\langle\ \rangle] = [\ ]$. As it stands (6.8) relates the eddy fluxes as defined both ways, integrated around a latitude circle. The difference term $[\langle V\rangle^*\langle T\rangle^*]$, is the eddy flux resulting from the departure of the regional averages from the zonal averages. We suspect this term involves zonal planetary scale waves, and hence would reveal forced variations if studied over seasonal time scales.

6.2 Multiple Correlation Studies

Because our research did not reveal the affect of the inclusion of an eddy diffusivity on the parameterization (2.8), we feel that a multiple correlation study would be of value. It would be a simple modification to produce three time series: eddy flux, X, and $(\Delta T)^2$, analyze their zonal Fourier components, and correlate them jointly and by pairs. We suspect the results would indicate that X enhances the negative correlations on short time scales, but has only a small effect on seasonal scales since on average X is close to unity. This would confirm the suspected inability of X by itself to model short period free variations, and would point to more complex parameterizations for improved results.

6.3 General Uses of the Program SPECTRA

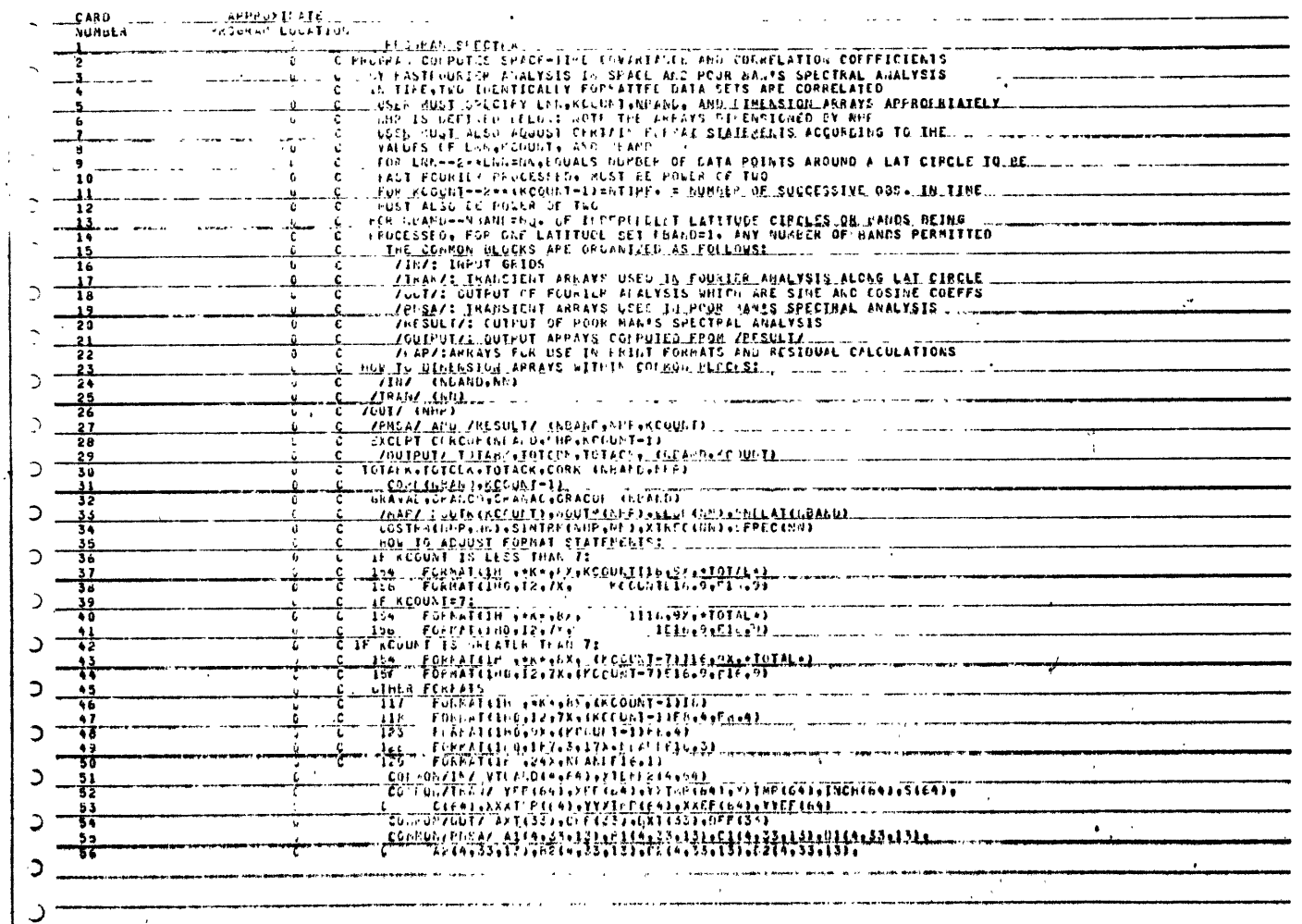
SPECTRA is a very versatile computer program which can be used to temporally correlate the Fourier coefficients of any two datasets. It is listed in FORTRAN IV in Appendix A. The restrictions are such that the number of datapoints in a set be in powers of two, and that the number of sets in a time series be in powers of two. It is generally easy to interpolate, or truncate, meteorological data sets to fit these requirements.

Instructions are provided in the comment cards on the meaning of the control parameters--there are only three--and on how to adjust the FORMAT statements to fit these parameters. We have found the program to be highly efficient and therefore inexpensive to use.

SPECTRA produces the variance, covariance and correlation coefficient spectra of the input data sets. We can think of many opportunities for its use which would involve only adjustment of the input data sets themselves. For instance, little is known about the cross-correlation spectrum of the eddy heat flux itself. By inputing V*(t) and T*(t), this spectrum would be produced in the output table entitled COMPONENTS IN THE ANALYSIS OF COVARIANCE.

APPENDIX A

COMPUTER PROGRAM SPECTRA: LISTING



```
CARD      APPROXIMATE
NUMBER    PROGRAM LOCATION
1                          FFT/RAN SPECTRA
2                     C PROGRAM COMPUTES SPACE-TIME COVARIANCE AND CORRELATION COEFFICIENTS
3                     C  BY FAST FOURIER ANALYSIS IN SPACE AND POOR MAN'S SPECTRAL ANALYSIS
4                     C  IN TIME, TWO IDENTICALLY FORMATTED DATA SETS ARE CORRELATED
5                     C     USER MUST SPECIFY LNA,KCOUNT,NPAND, AND DIMENSION ARRAYS APPROPRIATELY
6                     C     NNP IS DEFINED BELOW: NOTE THE ARRAYS DIMENSIONED BY NNP
7                     C     USER MUST ALSO ADJUST CERTAIN FORMAT STATEMENTS ACCORDING TO THE
8                     C     VALUES OF LNA,KCOUNT, AND NBAND
9                     C     FOR LNA=2**L, LNA=NA, EQUALS NUMBER OF DATA POINTS AROUND A LAT CIRCLE TO BE
10                    C     FAST FOURIER PROCESSED, MUST BE POWER OF TWO
11                    C     FOR KCOUNT=2**(KCOUNT-1), NTIME = NUMBER OF SUCCESSIVE OBS. IN TIME
12                    C     MUST ALSO BE POWER OF TWO
13                    C     FOR NBAND=NBANDS=NO. OF EQUIDISTANT LATITUDE CIRCLES OR BANDS BEING
14                    C     PROCESSED, FOR ONE LATITUDE SET (NBAND=1, ANY NUMBER OF BANDS PERMITTED
15                    C       THE COMMON BLOCKS ARE ORGANIZED AS FOLLOWS:
16                    C         /IN/: INPUT GRIDS
17                    C         /TRAN/: TRANSIENT ARRAYS USED IN FOURIER ANALYSIS ALONG LAT CIRCLE
18                    C         /OUT/: OUTPUT OF FOURIER ANALYSIS WHICH ARE SINE AND COSINE COEFFS
19                    C         /PMSA/: TRANSIENT ARRAYS USED IN POOR MAN'S SPECTRAL ANALYSIS
20                    C         /RESULT/: OUTPUT OF POOR MAN'S SPECTRAL ANALYSIS
21                    C         /OUTPUT/: OUTPUT ARRAYS COMPUTED FROM /RESULT/
22                    C         /AP/:ARRAYS FOR USE IN PRINT FORMATS AND RESIDUAL CALCULATIONS
23                    C     HOW TO DIMENSION ARRAYS WITHIN COMMON BLOCKS:
24                    C       /IN/  (NBAND,NA)
25                    C       /TRAN/ (NN)
26                    C       /OUT/ (NNP)
27                    C       /PMSA/ AND /RESULT/ (NBAND,NPF,KCOUNT)
28                    C       EXCEPT CORCOF(NEAD,NNP,KCOUNT-1)
29                    C       /OUTPUT/ TOTAM,TOTCOR,TOTACO, (NEAD,KCOUNT)
30                    C     TOTALM,TOTCLM,TOTACK,CORK (NBAND,NPF)
31                    C       COR(NNP,KCOUNT-1),
32                    C     GRAVAL,SPACOR,SPARAC,GRACOR (NEAD)
33                    C       /MAP/ IOUT(KCOUT),XOUT(NPF),YOUT(NNP),ALLAT(NBAND)
34                    C     COSTH(NNP),SINTH(NNP),XTHCC(NN),FREC(NN)
35                    C     HOW TO ADJUST FORMAT STATEMENTS:
36                    C     IF KCOUNT IS LESS THAN 7:
37                    C       124   FORMAT(1H ,*K*,6X,(KCOUNT-1)I16,9X,*TOTAL*)
38                    C       126   FORMAT(1H0,I2,7X,     (KCOUNT-1)E16.9,E14.9)
39                    C     IF KCOUNT=7:
40                    C       154   FORMAT(1H ,*K*,6X,      1116,9X,*TOTAL*)
41                    C       156   FORMAT(1H0,I2,7X,       1E16.9,E14.9)
42                    C     IF KCOUNT IS GREATER THAN 7:
43                    C       154   FORMAT(1H ,*K*,6X, (KCOUNT-7)I16,9X,*TOTAL*)
44                    C       156   FORMAT(1H0,I2,7X,(KCOUNT-7)E16.9,E14.9)
45                    C     OTHER FORMATS
46                    C       117   FORMAT(1H ,*K*,6X,(KCOUNT-1)I16)
47                    C       11R   FORMAT(1H0,I2,7X,(KCOUNT-1)E16.9,E14.9)
48                    C       125   FORMAT(1H0,9X,(KCOUNT-1)E16.9)
49                    C       145   FORMAT(1H0,1P7,3,17X,(KCOUNT-1)E16.9)
50                    C       129   FORMAT(1H ,24X,NLAT,E16.1)
51                          COMMON/IN/ VTL(4004,64),XTL(4004,64)
52                          COMMON/TRAN/ XPP(64),XPF(64),XTMP(64),YTMP(64),INCH(64),SIG(64),
53                         1     C(64),XXAT P(64),YYAT P(64),XXPF(64),YYPF(64)
54                          COMMON/OUT/ AXT(33),CPF(33),QX1(33),QPF(33)
55                          COMMON/PMSA/ A1(4,33,13),B1(4,33,13),C1(4,33,13),D1(4,33,13),
56                         C     A2(4,33,13),B2(4,33,13),C2(4,33,13),D2(4,33,13),
```

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CARD
NUMBER        APPROXIMATE
              PROGRAM LOCATION
   57                      C      ADR2(4,33,13),ACCD(4,33,13),C2D2(4,33,13),WLOAD(4,33,13)
   58                            COMMON/RESULT/ CRACCD(4,33,13),VRA2D2(4,33,13),VRC2D2(4,33,13),
   59                      C     C
   60                      C     COMMON/OUTPUT/ TOTAC(4,13),TOTCDR(4,13),TOTACM(4,13),
   61                      C     TOTAC(4,33),TOTCDR(4,33),WTECC(4,33),GRANAM(4),GRANCM(4),
   62                      C     GRANAC(4),CORR(4,33),CORR(4,13), RACOR(4)
   63                            COMMON/MAP/ NOUTK(13),NOUTK(33),WLON(64),WLAT(64),COSTRN(33,64),
   64                      C     C     SINTRN(33,64),XTRECC(64),ETRECC(64)
   65                      C  INITIALIZE PROGRAM PARAMETERS
   66                            LL=6
   67                            KCOUNT=14
   68                            NBAND=4
   69                            NMINUS=KCOUNT-1
   70                            LA=2**LL
   71                      10    NH=NN/2
   72                      10    NHP=NH+1
   73                      10    NTIME=2**NMINUS
   74                      10    C  INITIALIZE ARRAYS AND COUNTERS
   75                      17    ICOU=0
   76                      17    XXLON=0.0
   77                      17    YYLAT=90
   78                      17    RAD=3.14159265359/180.0
   79                      17    DO 236 LBAND=1,NBAND
   80                      17    BNDLAT(LBAND)=YYLAT
   81                      17    YYLAT=YYLAT-10
   82                      17 236 CONTINUE
   83                      36    DO 237 LON=1,NH
   84                      36    WLON(LON)= XXLON
   85                      36    XXLON=XXLON+5.625
   86                      36    EFREC(LON)=0.0
   87                      36    XTRECC(LON)=0.0
   88                      36 237 CONTINUE
   89                      51    XXLON=0.0
   90                      51    DO 238 LON=1,NH
   91                      51    DO 239 K=1,NHP
   92                      53    COSTRN(K,LON)=COS((K-1)*RAD*XXLON)
   93                      53    SINTRN(K,LON)=SIN((K-1)*RAD*XXLON)
   94                      53 239 CONTINUE
   95                      75    XXLON=XXLON+5.625
   96                      75 238 CONTINUE
   97                     102    DO 233 K=1,KCOUNT
   98                     102    NOUTK(K)=K-1
   99                     102    DO 234 LBAND=1,NBAND
  100                     104    TOTACM(LBAND,K)=0.
  101                     104    TOTCDM(LBAND,K)=0.
  102                     104    TOTAC(LBAND,K)=0.
  103                     104    IF(K.EQ.KCOUNT) GO TO 234
  104                     104    CORR(LBAND,K)=0.
  105                     104 234 CONTINUE
  106                     121 233 CONTINUE
  107                     124    DO 230 LBAND=1,NBAND
  108                     124    DO 231 M=1,NHP
  109                     126    DO 232 K=1,KCOUNT
  110                     127    ACC2(LBAND,M,K)=0.0
  111                     127    ACD2(LBAND,M,K)=0.0
  112                     127    C2D2(LBAND,M,K)=0.0
```

```
CARD      APPROXIMATE
NUMBER    PROGRAM LOCATION
  113          137          NLOAD(LLA1(,A,K)=0
  114          147     222  CONTINUE
  115          142          CORR(LBALD,K)=0.
  116          143          TOTAR(LLBA(D,K)=0.
  117          144          TOTOR(LLBA(D, K)=0.
  118          145          TOTACK(LBA(D),K)=0.
  119          146     251  CONTINUE
  120          151          GBAR(LLBA(D)=0.
  121          152          GBAR(LLBA(D,K)=0.
  122          153          GBAR(LLBA(D)=0.
  123          154          GBAC(BA(D)=0.
  124          155     230  CONTINUE
  125          156          DO 235 M=1,NHF
  126          157          NOUT(M)=M-1
  127          163     235  CONTINUE
  128          167     C    CONCLUDES ARRAY AND COUNTER INITIALIZATION
  129          167     C      FOURIER ANALYSIS INITIALIZATION
  130          166          IR(M(1)=1
  131          167          C(1)=1.
  132          168          S(1)=0.
  133          169          U=1.
  134          170          V=0.
  135          168          MU=MM
  136          169          DO 12 LN=1,LMM
  137          170          NU=MU/MM
  138          171          NL=NU/2
  139          172          DO 12 L=1,NL
  140          173          M=IR(M(L)
  141          174          ME=M+NU
  142          175          MF=M+MU
  143          176          IR(M(ME)=MF
  144          176          C(MF)=C(M)*U-S(M)*V
  145          176          S(MF)=C(M)*V+S(M)*U
  146          176     12   CONTINUE
  147          264          U=SQRT((U+1.0)/2)
  148          265          IF(LN.EQ.1) V=1.0
  149          267          IF(LN.GT.1) V=V/(U+U)
  150          242     10   CONTINUE
  151          242     C    CONCLUDE FOURIER ANALYSIS INITIALIZATION
  152          244          PRINT 120
  153          244     C    FROM SIFT. 300 TO 390 WE INPUT GRIDS,FOURIER ANALYZE,AND
  154          244     C    TOOK MAX SPECTRALLY ANALYZE
  155          256     300  READ (1) DA1,DB1,DC1,DD1,NE,IFF1,VTBAND
  156          270          READ (2) DA1,DB1,DC1,DD1,NFF1,NTEMP2
  157          300          NCOUNT=NCOUNT+1
  158          320     C    SAMPLE OUTPUT OF GRID INPUT
  159          326          IF(NE.EQ.3674416) GO TO 310
  160          332          IF(NF.EQ.26R160.OR.NF.EQ.370320.OR.NE.EQ.3725044) GO TO 310
  161          335          IF(NE.EQ.9450.0) GO TO 310
  162          337          GO TO 311
  163          337     310  PRINT 130
  164          345          PRINT 126,,DA1,NF1,NB1,ND1,NE ,IFF1
  165          364          PRINT 127
  166          372          PRINT 129, (DELLAT(LSAT(),LEAND=1,LSAND)
  167          407          PRINT 128,(VLON(LON),(VTBAND(LLAND,LOND,LEANDE1,NBANDE),LOWE1,NB1
  168          433          PRINT 140
```

```
CARD NUMBER   PROGRAM LOCATION
                449          PRINT 131
170             449          PRINT 132,((A(I,J),I=1,NC1),J=1,NE),NF1
171             461          PRINT 127
172             475          PRINT 128,((NF,L),(LEAND),L=1,NBAND)
173             487          PRINT 129,((NA,L),(LON),(XTEMP(I,L),I=1,NA),L=1,NBAND),L=1,NBAND),LON=1,NN)
174             511      511 GO TO 100
175             532          LO 200 LEAND=1,NBAND
176             536          DO 201 LON=1,NN
177             544          YEF(LON)=0.0
178             934          XEF(LON)=YTEMP(LEAND,LON)
179             934          YXTEP(LON)=0.0
180             934          XXTEP(LON)=YTEMP2(LEAND,LON)
181             934      201 CONTINUE
182             947          NC=NA
183             947          DO 350 LP=1,LPN
184             947          NT=10
185             947          NF=NT/2
186             947          NF=NN/NT
187             947          NG=1
188             947          DO 350 M=1,NM*NT
189             952          NP=M+1
190             954          DO 350 N=1,NA*NT
191             961          NP=N+NP
192             961          UEF=XEF(N)-XEF(NP)
193             961          VEF=YEF(N)-YEF(NP)
194             961          UXTEP=XXTEP(N)-XXTEP(NP)
195             961          VXTEP=YXTEP(N)-YXTEP(NP)
196             961          XEF(N) = XEF(NP)+XEF(NP)
197             961          YEF(N)=YEF(N)+YEF(NP)
198             961          XXTMP(N)=XXTMP(N)+XYTMP(NP)
199             961          YXTMP(N)=XXTMP(N)+YXTEP(NP)
200             961          XEF(NP)=UEF*S(M)-V*F*S(M)
201             961          YEF(NP)=UEF*S(M)+VEF*C(M)
202             961          XXTMP(NP)=UXTMP*C(M)-VXTEP*C(M)
203             961          YXTMP(NP)=UXTEP*S(M)+VXTEP*C(M)
204             961      350 CONTINUE
205             970          DO 210 N=1,NN
206             974          P=T(N)
207             975          XXXTEP(N)=XXTEP(N)
208             975          YYXTEP(N)=YYTEP(N)
209             975          XXEF(N)=XEF(N)
210             975          YYEF(N)=YEF(N)
211             975      210 CONTINUE
212             980          DO 212 I=1,NNP
213             984          IF(N.GT.1) GO TO 213
214             990          AXT(N)=XXXTEP(1)/NN
215             990          CEF(N)=XXEF(N)/NN
216             990          EXT(N)=0.
217             996          DEF(N)=0.
218             998          GO TO 212
219             998      213 AXT(N)=(2.0*A)*XTMP(N))/NN
220            1008          BXT(N)=(2.0*YYXTMP(N))/NN
221            1018          CEF(N)=(2.0*XXEF(N))/NN
222            1028          DEF(N)=(2.0*YYEF(N))/NN
223            1038      212 CONTINUE
224            1047      C   SAMPLE OUTPUT OF FOURIER COEFFICIENTS AND RECONSTRUCTED GRIDS
```

```
CARD      APPROXIMATE
NUMBER    PROGRAM LOCATION
225                 734          IF(NE.EQ.537916) GO TO 312
226                 713          IF(NE.EQ.366166.OR.NE.EQ.370320.OR.NE.EQ.372504) GO TO 312
227                 716          IF(NE.EQ.443676) GO TO 312
228                 720          GO TO 313
229                 720    312   DO 241 LON=1,NN
230                 724          DO 240 M=1,NHP
231                 722          EFREC(LON)=EFREC(LON)+(CEF(M)*COSTRM(M,LON)+DEF(M)*SINTRM(M,LON))
232                 724          XTREC(LON)=XTREC(LON)+(AXT(M)*COSTRM(M,LON)+BXT(M)*SINTRM(M,LON))
233                 726    240   CONTINUE
234                 742    241   CONTINUE
235                 745          PRINT 100
236                 753          PRINT 132,NA1,NB1,NC1,ND1,NE ,NF1,LBAND
237                 776          PRINT 134
238                1003          PRINT 134
239                1016          PRINT 135,(KOUTM(M),CEF(M),DEF(M),M=1,NHP)
240                1032          PRINT 136
241                1037          PRINT 137,(XLON(LON),EFREC(LON),LON=1,NN)
242                1050          PRINT 138
243                1063          PRINT 134
244                1070          PRINT 135,(KOUTM(M),AXT(M),BXT(M),M=1,NHP)
245                1112          PRINT 136
246                1117          PRINT 137,(XLON(LON),XTREC(LON),LON=1,NN)
247                1134          DO 242 LON=1,NN
248                1136          EFREC(LON)=0.
249                1136          XTREC(LON)=0.
250                1136    242   CONTINUE
251                1144    313   CONTINUE
252                1144    C     , POOR MANS SPECTRAL ANALYSIS
253                1145          DO 235 M=1,NHF
254                1145          K=1
255                1145    C     IF ACCOUNT IS EVEN GO TO 360
256                1145          IF(MOD(ICOUNT,2).EQ.0) GO TO 360
257                1145          A1(LBAND,M,K)=AXT(M)
258                1145          B1(LBAND,M,K)=BXT(M)
259                1145          C1(LBAND,M,K)=CEF(M)
260                1145          D1(LBAND,M,K)=DEF(M)
261                1145    355   A2R2(LBAND,M,K)=A2R2(LBAND,M,K)+(A1(LBAND,M,K)**2)+
262                1145    C           (E1(LBAND,M,K)**2)
263                1145          AC2D1(LBAND,M,K)=AC2D1(LBAND,M,K)+(A1(LBAND,M,K)*C1(LBAND,M,K))+
264                1145    C           (B1(LBAND,M,K)*D1(LBAND,M,K))
265                1145          C2D2(LBAND,M,K)=C2D2(LBAND,M,K)+(C1(LBAND,M,K)**2)+
266                1145    C           (D1(LBAND,M,K)**2)
267                1145          NLOAD(LBAND,M,K)=NLOAD(LBAND,M,K)+1
268                1145          GO TO 370
269                1145    360   A2(LBAND,M,K)=AXT(M)
270                1145          B2(LBAND,M,K)=BXT(M)
271                1145          C2(LBAND,M,K)=CEF(M)
272                1145          D2(LBAND,M,K)=DEF(M)
273                1145    365   A2R2(LBAND,M,K)=A2R2(LBAND,M,K)+(A2(LBAND,M,K)**2)+
274                1145    C           (B2(LBAND,M,K)**2)
275                1145          AC2D1(LBAND,M,K)=AC2D1(LBAND,M,K)+(A2(LBAND,M,K)*C2(LBAND,M,K))+
276                1145    C           (B2(LBAND,M,K)*D2(LBAND,M,K))
277                1145          C2D2(LBAND,M,K)=C2D2(LBAND,M,K)+(C2(LBAND,M,K)**2)+
278                1145    C           (D2(LBAND,M,K)**2)
279                1145          NLOAD(LBAND,M,K)=NLOAD(LBAND,M,K)+1
280                1145    370   IF(MOD(NLOAD(LBAND,M,K),2).NE.0) GO TO 235
```

```
CARD       APPROXIMATE
NUMBER     PROGRAM  LOCATION
 281          1139          IF(I.GT.(ILBAND(LBA(L,"yr+1),2),+L+0) GO TO 272
 282          1140          K=K+1
 283          1141          A1(LBA(L,K)=A1(L-A(L,yr,K-1)+A2(LBAND,yK-1)
 284          1142          B1(LBA(L,K)=B1(L-A(L,yr,K-1)+B2(LBAND,yK-1)
 285          1143          C1(LBA(L,yr)=C1(L-A(L,yK-1)+C2(LBAND,yK-1)
 286          1144          D1(LBA(L,yr)=C1(L-AND,yK-1)+D2(LBAND,yK-1)
 287          1145          GO TO 272
 288          1146      372 K=yr+1
 289          1147          A2(LBA(L,yK)=A1(L-AND,yK-1)+A2(LBAND,yK-1)
 290          1148          B2(LBA(L,yr)=B1(L-AND,yK-1)+B2(LBAND,yK-1)
 291          1149          C2(LBA(L,yr)=C1(LBAND,yr-1)+C2(LBAND,yK-1)
 292          1150          D2(LBA(L,K)=D1(LBAND,yK-1)+D2(LBAND,yK-1)
 293          1151          GO TO 365
 294          1152      235 CONTINUE
 295          1312      260 CONTINUE
 296          1313          IF(LCOUNT.EQ.NTIME) GO TO 360
 297          1314          GO TO 300
 298          1315      361 CONTINUE
 299          1316      C   FROM HERE IF IF IS STMT 250 WE COLLECT AND STORE COMPONENTS IN THE
 300          1317      C   ANALYSIS OF VARIANCE
 301          1318          DO 251 K=1,KCOUNT
 302          1319          FAK=0.0**(KCOUNT+yr-2)
 303          1320          FAK=0.5**(KCOUNT+yr-1)
 304          1321          DO 250 LBAND=1,NBAND
 305          1322          DO 251 M=1,MM
 306          1323          IF(K.EQ.KCOUNT) GO TO 350
 307          1324          COVACB(LBAND,M,K)=(FAK*ACCD(LBA(L,M,K))-(RUK*ACBD(LBAND,M,K+1))
 308          1325          VARA2(LBAND,M,K)=(FAK*A2B2(LBA(L,M,K))-(RUK*A2B2(LBAND,M,K+1))
 309          1326          VARC2D2(LBAND,M,K)=(FAK*C2D2(LBA(L,M,K))-(RUK*C2D2(LBAND,M,K+1))
 310          1327          GO TO 251
 311          1328      C   PRODUCTS  F THE MEANS
 312          1329      350 COVACB(LBAND,M,K)=FAK*ACBD(LBAND,M,K)
 313          1330          VARA2(LBAND,M,K)=FAK*A2B2(LBAND,M,K)
 314          1331          VARC2D2(LBAND,M,K)=FAK*C2D2(LBAND,M,K)
 315          1332          IF(K.EQ.KCOUNT) GO TO 251
 316          1333          CORCOF(LBAND,M,K)=COVACB(LBAND,M,K)/SQRT(VARA2B2(LBAND,M,K)*
 317          1334      C       VARC2D2(LBAND,M,K))
 318          1335      251 CONTINUE
 319          1400      250 CONTINUE
 320          1401      252 CONTINUE
 321          1402      C   DATA TABLES OUTPUT--REST OF PROGRAM
 322          1403          WRITE (61) COVACB,VARA2B2,VARC2D2,CORCOF
 323          1404      C       COMPUTE OVERALL COVARIANCES,MEANSQUARES,AND CORRELATION  COEFFS.
 324          1405          DO 261 LBAND=1,NBAND
 325          1406          DO 261 M=1,MM
 326          1407          DO 262 K=1,KCOUNT
 327          1408          TOTACB(LBAND,M)=TOTACB(LBAND,M)+VARA2B2(LBAND,M,K)
 328          1409          TOTCOR(LBAND,M)=TOTCOR(LBAND,M)+VARC2D2(LBAND,M,K)
 329          1410          TOTACB(LBAND,M)=TOTACB(LBAND,M)+COVACB(LBAND,M,K)
 330          1411          TOTABB(LBAND,M)=TOTABB(LBAND,M)+VARA2B2(LBAND,M,K)
 331          1412          TOTCOR(LBAND,M)=TOTCOR(LBAND,M)+VARC2D2(LBAND,M,K)
 332          1413          TOTACB(LBAND,M)=TOTACB(LBAND,M)+COVACB(LBAND,M,K)
 333          1414      262 CONTINUE
 334          1415      261 CONTINUE
 335          1416          DO 263 K=1,KCOUNT
 336          1417          GRANAB(LBAND)=GRANAB(LBAND)+TOTABB(LBAND,K)
```

```
CARD                APPROXIMATE
NUMBER              PROGRAM LOCATION
  337                1454          GRANCO(LBAND)=CHANCO(LBAND)+TOTCOM(LBAND,K)
  338                1454          GRANAC(LBAND)=GRANAC(LBAND)+TOTACM(LBAND,K)
  339                1454          IF(K.EQ.KCOUNT) GO TO 267
  340                1454          CORR(LBAND,K)=TOTACM(LBAND,K)/SQRT(TOTACM(LBAND,K)*
  341                1454         C     TOTCOM(LBAND,K))
  342                1454     265  CONTINUE
  343                1501          GO 271 K=1,NHP
  344                1501          CORR(LBAND,K)=(TOTACK(LBAND,M)-COMCOR(LBAND,M,KCOUNT))/
  345                1501         C     SQRT((TOTABK(LBAND,M)-VRA2P2(LBAND,M,KCOUNT))*
  346                1501          C(TOTCOK(LBAND,M)-VRC2D2(LBAND,M,KCOUNT)))
  347                1501     271  CONTINUE
  348                1522          GRACOR(LBAND)=(GRANAC(LBAND)-TOTACM(LBAND,KCOUNT))/
  349                1522         C     SQRT((GRANAB(LBAND)-TOTABM(LBAND,KCOUNT))*
  350                1522         C     (GRANCO(LBAND)-TOTCOM(LBAND,KCOUNT)))
  351                1543     260  CONTINUE
  352                1543         C     PRINT SCHEME
  353                1544          IF(KCOU+1.GE.7) GO TO 395
  354                1544          GO TO 396
  355                1544     395  KCOU=7
  356                1545          KCOU2=KCOU+1
  357                1545          IF(KCOU.EQ.KCOUNT) KCOU=KCOUNT
  358                1553          KPOPT=1
  359                1553          GO TO 397
  360                1554     396  KPOPT=2
  361                1554          KCOU2=1
  362                1555     397  DO 250 LBAND=1,NBAND
  363                1555          PRINT 100
  364                1565          PRINT 101
  365                1572          PRINT 102,LBAND
  366                1581          PRINT 103
  367                1606          IF(KPLPT-2) 400,401,401
  368                1610     400  PRINT 104, (NOUTK(K),K=1,KCOU)
  369                1625          PRINT 105
  370                1632          PRINT 106, (NOUTM(M),(VRA2P2(LBAND,M,K),K=1,KCOU),M=1,NHP)
  371                1657          PRINT 107, (TOTAPP(LBAND,K),K=1,KCOU)
  372                1674          PRINT 129
  373                1741     401  PRINT 104,(NOUTK(K),K=KCOU2,KCOUNT)
  374                1741          PRINT 105
  375                1723          PRINT 156,(NOUTK(K),(VRA2P2(LBAND,M,K),K=KCOU2,KCOUNT),
  376                1723         C     TOTAPK(LBAND,K),M=1,NHP)
  377                1756          PRINT 107,(TOTAPM(LBAND,K),K=KCOU2,KCOUNT)
  378                1773          PRINT 108, GRANAB(LBAND)
  379                2003          PRINT 109
  380                2010          PRINT 109
  381                2015          PRINT 102, LBAND
  382                2024          PRINT 110
  383                2031          IF(KPOPT-2) 402,402,403
  384                2035     402  PRINT 104, (NOUTK(K),K=1,KCOU)
  385                2046          PRINT 105
  386                2055          PRINT 106, (NOUTM(M),(VRC2P2(LBAND,M,K),K=1,KCOU),M=1,NHP)
  387                2102          PRINT 107, (TOTCOM(LBAND,K),K=1,KCOU)
  388                2117          PRINT 129
  389                2124     403  PRINT 104, (NOUTK(K),K=KCOU2,KCOUNT)
  390                2141          PRINT 105
  391                2146          PRINT 156,(NOUTK(K),(VRC2P2(LBAND,M,K),K=KCOU2,KCOUNT),
  392                2147         C     TOTCOK(LBAND,M),M=1,NHP)
```

```
CARD      APPROXIMATE
NUMBER    PROGRAM LOCATION
  393          2200          PRINT 107,(TOTCOM(LBAND,K),K=KCOU2,KCOUNT)
  394          2216          PRINT 108, CRANCO(LBAND)
  395          2225          PRINT 109
  396          2233          PRINT 111
  397          2241          PRINT 102,LBAND
  398          2247          PRINT 112
  399          2254          IF(MAPOPT-2) 404,405,405
  400          2256      404 PRINT 104,(NOUTK(K),K=1,KCOU)
  401          2274          PRINT 105
  402          2300          PRINT 106,(NOUTH(M),(COACOF(LBAND,M,K),K=1,KCOU),M=1,NHP)
  403          2325          PRINT 107, (TOTACM(LBAND,K),K=1,KCOU)
  404          2342          PRINT 139
  405          2347      405 PRINT 154,(NOUTK(K),K=KCOU2,KCOUNT)
  406          2364          PRINT 155
  407          2371          PRINT 156,(NOUTH(M),(COACOF(LBAND,M,K),K=KCOU2,KCOUNT),
  408          2371      C     TOTALK(LBAND,M),K=1,NHP)
  409          2421          PRINT 107,(TOTACM(LBAND,K),K=KCOU2,KCOUNT)
  410          2441          PRINT 108,GRANAC(LBAND)
  411          2451          PRINT 160
  412          2456          PRINT 113
  413          2463          PRINT 102,LBAND
  414          2472          PRINT 114
  415          2477          PRINT 115
  416          2504          PRINT 116
  417          2511          PRINT 117,(NOUTK(K),K=1,KMINUS)
  418          2525          PRINT 105
  419          2534          PRINT 118,(NOUTH(M),((COPCOF(LBAND,M,K),K=1,KMINUS),
  420          2552      C     COAK(LBAND,M),M=1,NHP)
  421          2567          PRINT 119
  422          2576          PRINT 120
  423          2605          PRINT 121
  424          2602          PRINT 122
  425          2607          PRINT 123,(COPK(LBAND,K),K=1,KMINUS)
  426          2624          PRINT 124,GRACOK(LBAND)
  427          2634     200  CONTINUE
  428          2636     100  FORMAT(1H1)
  429          2636     101  FORMAT(1H ,*COMPONENTS ((A(P),A(M)+(B(M),B(M))) OF K, IN ANALYSIS
  430          2636      C OF VARIANCE OF X TIMES DELTA T SQUARED*)
  431          2636     102  FORMAT(1H ,*FOR LATITUDE BAND*,I3,*M=ZONAL WAVENUMBER,K=TIME
  432          2636      CPERIOD*)
  433          2636     103  FORMAT(1H0,*UNITS ARE DEGK TO THE FOURTH*)
  434          2636     104  FORMAT(1H ,*K=*,8X,7I16)
  435          2636     105  FORMAT(1H0,*K*)
  436          2636     106  FORMAT(1H0,I2,7X,7E16.8)
  437          2636     107  FORMAT(1H0,*TOTAL*,4X,7E16.8)
  438          2636     108  FORMAT(1H0,*GRAND TOTAL=*,F30.8)
  439          2636     109  FORMAT(1H ,*COMPONENTS ((C(M),C(M))+(D(M),D(M))) OF K, IN ANALYSIS
  440          2636      C OF VARIANCE OF EDDY FLUX*)
  441          2636     110  FORMAT(1H0,*UNITS ARE JOULES2METERS-2SEC-2*)
  442          2636     111  FORMAT(1H ,*COMPONENTS ((Z(M),C(M))+(D(M),D(M))) OF K, IN ANALYSIS
  443          2636      C OF COVARIANCE OF EF WITH X TIMES DELTA T SQUARED*)
  444          2636     112  FORMAT(1H0, *UNITS ARE (ESP2JOULES METERS-1SEC-1*)
  445          2636     113  FORMAT(1H ,*CORRELATION COEFFICIENTS, EF WITH X DELTA T SQUARED,
  446          2636      CFOR INDIVIDUAL SPACE-TIME COMPONENTS,FOR COLUMN AND ROW TOTALS,
  447          2636      CAPS FOR GRAND TOTAL*)
  448          2636     114  FORMAT(1H0, *UNITLESS*)
```

```
CARD      APPROXIMATE
NUMBER    PROGRAM LOCATION
  449          2e4E    115   FORMAT(1H0,  9HX1 *COEFFS FOR SUM OVER K*)
  450          2e5E    116   FORMAT(1H ,  96X,*FOR EACH LATITUDE NUMBER*)
  451          2e6E    117   FORMAT(1H ,*K*,8X,12I5)
  452          2e7F    118   FORMAT(1H0,I2,7X,12F8.4,F8.4)
  453          2e8F    119   FORMAT(1H0,*COEFFS FOR*)
  454          2e9F    120   FORMAT(1H ,*SUM OVER*)
  455          2eAF    121   FORMAT(1H ,*I AT*)
  456          2eBF    122   FORMAT(1H ,*EACH K*)
  457          2eCF    123   FORMAT(1H0,9X,12F8.4)
  458          2eDF    124   FORMAT(1H0,*TOTAL COEFFICIENT*,F8.4)
  459          2eEF    125   FORMAT(1H1,*SAMPLES OF INPUT GRIDS AND THEIR FOURIER COMPONENTS
  460          2eFF          CARRIAGE RELOAD*)
  461          2F4E    126   FORMAT(1H0,6I12)
  462          2F5F    127   FORMAT(1H )
  463          2F6F    128   FORMAT(1H0,1F7.3,17X,4F16.3)
  464          2F7F    129   FORMAT(1H ,24X,4F16.1)
  465          2F8F    130   FORMAT(1H ,*EDDY FLUX SMOOTHED OVER WIDTH OF BAND,JOULES/M-1SEC-1*)
  466          2F9F    131   FORMAT(1H ,*K TIMES DELTA T SQUARED,SMOOTHED,DEG K2*)
  467          2FAF    132   FORMAT(1H ,*FOURIER COEFFICIENTS*,6I12,9X,*LATITUDE BAND*,I3)
  468          2FBF    133   FORMAT(1H0,*FOR EDDY FLUX*)
  469          2FCF    134   FORMAT(1H0,2X,*M*,11X,*COSINES*,11X,*SINES*)
  470          2FDF    135   FORMAT(1H0,I3,2X,F14.8,5X,F14.8)
  471          2FEF    136   FORMAT(1H0,40X,*LONGITUDE*,10X,*RECONSTRUCTED FIELD*)
  472          2FFF    137   FORMAT(1H0,40X,F10.4,10X,F10.3)
  473          3e3F    138   FORMAT(1H0,*FOR > TIMES TEMP GRADIENT SQUARED*)
  474          3e4F    139   FORMAT(1H0,*CONTINUATION*)
  475          3e5F    140   FORMAT(1H ,*K*,8X,6I16,9X,*TOTAL*)
  476          3e6F    141   FORMAT(1H0,I2,7X,6E16.9,E16.5)
  477          3e7F          CALL EXIT
  478          3e8F          END
```

LENGTH OF ROUTINE SPECTRA 3251

VARIABLE ASSIGNMENTS

VTBAND	=	0C 0	XTEMP2	=	4e0C 0	YEI	=	0C 1	XEF	=	120C 1	YXTMP	=	200C 1	XXTMP	=	300C 1
INCH	=	400C 1	S	=	500C 1	C	=	600C 1	XXXTMP	=	700C 1	YYXTMP	=	1000C 1	XXEF	=	1100C 1
YYEF	=	1200C 1	ANL	=	0C 2	CEF	=	41C 2	EXT	=	102C 2	DEF	=	143C 2	A1	=	0C 3
B1	=	3.640C 3	C1	=	6550C 3	D1	=	120340 3	A2	=	153200 3	B2	=	204040 3	C2	=	240700 3
D2	=	270340 3	A2E2	=	320400 3	ACHI	=	361240 3	C2E2	=	414100 3	NLOAD	=	446740 3	COACBD	=	0C 4
VRA232	=	32640 4	VNC2L2	=	0C 4	CORCOF	=	127240 4	TOTAFC	=	0C 5	TOTCDM	=	0C 5	TOTACM	=	150C 5
TOTA6K	=	254C 5	TOTCDM	=	440C 5	TOTACX	=	644C 5	CRADAI	=	1050C 5	GRADCD	=	1054C 5	GRADAC	=	1060C 5
CORK	=	1064C 5	CORK	=	1270C 5	GRACDX	=	1350C 5	NOUTM	=	0C 6	NOUTM	=	15C 6	NLON	=	56C 6
BNDLAT	=	130C 6	COSTH1	=	1e6C 6	SINTH	=	4262C 6	XTREC	=	1036C 6	CFREC	=	104620 6	LNP	=	2712
KCOUNT	=	2711	NLANE	=	2710	KHIAUS	=	2707	NM	=	2706	NM	=	2705	NMP	=	2704
NTIME	=	2703	COUNT	=	2702	XXLON	=	2701	YYLAT	=	2700	RAD	=	2677	LBAND	=	2676
LON	=	2675	K	=	2674	K	=	2673	U	=	2672	V	=	2671	MC	=	2670
LN	=	2667	NU	=	2666	N	=	2665	NP	=	2664	MP	=	2663	MAI	=	2662
NU1	=	2661	NC1	=	2660	NA1	=	2657	NE	=	2656	NF1	=	2655	NT	=	2654
NT	=	2653	NO	=	2652	DEF	=	2651	VEF	=	2650	VXTMP	=	2647	VXTMP	=	2646
RAK	=	2645	KCK	=	2644	KCOU	=	2643	KCOU2	=	2642	KPOPT	=	2641			

SUBROUTINES CALLED

IGAIEX	COSF	SINF	SQRTF	OUTPTC	INPUTS	MAIEX	OUTPTS	EXIT

COMMON BLOCKS AND LENGTHS

IN	=	1000	INAN	=	1300	OUT	=	200	PHSA	=	ERIGO	RESULT	=	11114	OUTPUT	=	1354

APPENDIX B

ADDITIONAL SPECTRAL OUTPUT

Below we provide the output tables of correlation coefficient spectra for latitude bands 2, 3 and 4, (45^{o}, 55^{o}, 65^{o}).

CORRELATION COEFFICIENTS, FF WITH X DELTA T SQUARED, FOR INDIVIDUAL SPACE-TIME COMPONENTS, FOR COLUMN AND ROW TOTALS, AND FOR GRAN
FOR LATITUDE BAND ZONAL WAVENUMBER,K=TIME PERIOD

UNITLESS

K	0	1	2	3	4	5	6	7	8	9	COEFFS FOR SUM OVER K FOR EACH WAVENUMBER 10	11
M												
0	-.0342	-.0352	-.1897	-.1747	-.0694	-.0936	.1783	.6983	.9653	.3794	-.4371	1.0000 .4262
1	-.1021	-.1203	-.1976	-.2184	-.1110	.0592	-.3030	.3655	.2875	-.2329	-.4310	-.7909 -.8690
2	-.0957	-.1120	-.2073	-.0609	-.1071	.0535	.0163	.1930	.5671	-.1898	-.5103	-.1000 -.0470
3	-.1222	-.1540	-.1456	.0415	-.0255	-.0050	-.2165	-.4062	-.4898	-.4531	.4941	.9568 -.1137
4	-.0843	-.1479	-.1039	.0046	.0446	.0924	-.0630	.1500	.4517	-.7467	-.9092	.9745 -.0004
5	-.0964	-.1221	-.0658	-.0229	.0598	.1436	.1506	.0509	.2135	-.1235	-.4211	-.0318 -.0208
6	-.1098	-.1209	-.0675	-.0070	-.1387	-.1580	-.2490	-.3669	.4433	-.0425	.0905	-.7168 -.0897
7	-.0740	-.0823	.0497	.0075	-.0083	.0188	-.0590	-.1705	.1441	-.1121	-.5041	-.4420 -.0212
8	.0025	.0236	.0768	-.0405	-.0409	-.0002	.2355	.0425	.0907	.6685	.8203	.6582 .0386
9	.0637	.0742	.0364	-.0375	.1562	-.0653	.1820	.1646	.3955	.4307	.6889	.5343 .0736
10	.0304	.0363	-.0137	-.0204	-.1023	-.1080	.1363	-.1153	.5884	-.1027	-.6358	.5108 .0026
11	.0409	.0047	.0307	.0624	.0291	.0481	.0639	-.5098	-.1376	.0714	-.7300	-.4121 .0160
12	.0044	.0240	.0127	.0240	-.0055	.0285	.0294	.0393	-.3485	-.1796	.5683	-.0417 .0252
13	.0096	-.0134	-.0525	.0863	-.0548	.0040	.1383	-.0364	.0286	-.0318	.2268	.6282 .0004
14	-.0268	-.0179	-.0134	.0160	-.0161	.0476	.0548	.0689	.3206	-.2613	-.8802	.9387 -.0106
15	-.0123	-.0085	-.0198	-.0134	.0424	.0387	.1411	-.2934	.4561	-.0418	-.1831	.3000 .0073
16	-.0245	.0206	.0359	-.0402	.0849	-.1494	.1381	-.3736	.6459	.5946	.4583	-.3898 .0032
17	-.0219	.0172	-.0030	-.0097	.1238	.0055	.0578	-.2902	.2253	.1116	.0915	-.7447 -.0027
18	.0121	-.0159	-.0111	-.0417	-.0246	-.0382	-.1545	-.3871	-.4569	-.7818	-.5869	.2075 -.0109
19	.0215	.0245	.0496	-.0082	-.0325	.1594	.2254	-.0161	-.1187	.6229	.7701	.6473 .0287
20	-.0016	-.0011	.0335	-.0699	.0465	.0319	-.1095	-.0028	-.2011	-.1944	-.2005	-.2775 -.0018
21	-.0213	.0122	-.0199	-.0458	.0111	.1284	-.0667	-.1519	-.0485	-.5284	-.6066	-.5684 -.0196
22	-.0293	.0075	-.0083	.0031	-.0444	.1462	-.0892	.0609	.2522	.3992	-.1826	-.6931 -.0110
23	.0156	-.0370	-.0052	-.0417	-.0378	.0845	.0221	-.0559	-.3242	.6355	.2893	.3338 -.0050
24	.0199	-.0024	.0417	.0715	-.1458	.1408	-.1183	-.1748	-.1984	.0379	.2763	.9986 .0167
25	-.0328	-.0090	.0325	-.0516	-.0489	.1257	-.1343	-.3015	-.2931	-.4360	-.2016	-.0563 -.0204

26	-.31 [illegible]	-.1152	-.[illegible]	-.[illegible]171	.1249	.0765	-.0952	.1459	.2018	.5284	.6994	-.9272	-.0137
27	-.0014	-.[illegible]	.0209	.0220	-.333	.0244	-.1745	-.0914	.0571	.4304	.5285	.8755	-.0050
28	.0208	.0071	.0105	-.0172	-.0086	-.1441	.0339	-.0572	.1134	-.4821	-.2754	.5355	.0144
29	-.0115	-.0247	-.0173	.0455	.1004	-.0211	.[illegible]984	-.0213	.0296	.1074	-.6829	-.7415	-.0080
30	-.0124	.0562	-.0[illegible]32	-.0[illegible]241	-.1[illegible]85	.1798	.0816	-.1351	-.6174	-.5814	.4034	-.6006	-.0058
31	-.0002	.0397	-.0043	-.0428	.0063	-.0381	.0[illegible]40	.0270	.[illegible]336	.5031	.5154	.4655	.0079
32	.0234	-.0963	.0165	.0592	.1603	.0700	-.1092	.2113	.1082	-.2630	.8927	1.0000	.0129

COEFFS FOR
SUM OVER
M AT
EACH K

-.0239 -.0411 -.0568 -.0296 -.0262 .0244 -.0488 .0925 .3340 -.1208 -.1723 .4326

TOTAL COEFFICIENT -.0041

CORRELATION COEFFICIENTS, EE WITH > DELTA T SQUARED, FOR INDIVIDUAL SPACE-TIME COMPONENTS, FOR COLUMN AND ROW TOTALS, AND FOR GRAN
FOR LATITUDE BAND REGIONAL WAVENUMBER-KETIME PERIOD

UNITLESS

K \ M	0	1	2	3	4	5	6	7	8	9	COEFFS FOR SUM OVER K FOR EACH WAVENUMBER 10	11
0	-.0438	.0090	-.0529	-.1299	-.1974	.0334	.0665	.5684	.8395	.9300	.9979	1.0000	.2153
1	-.0346	-.0442	-.1379	-.2056	.0028	-.0233	.0203	.0203	.0262	-.2019	-.0712	.7927	-.0563
2	-.0198	-.0442	-.1009	.0330	.0747	.0643	.1485	-.1129	-.4147	-.6893	-.9158	.2198	-.0624
3	-.0497	-.0687	-.0916	.0437	.1026	-.0325	.0662	.1717	.6672	.6749	.4354	.9359	.0308
4	-.0464	-.0378	.0249	.1121	.0752	-.0022	-.0169	.1224	.2555	-.9220	-.0845	.9247	.0208
5	-.0681	-.0365	.0260	.0598	.1576	.0719	-.0297	.1397	-.3209	.0696	-.2335	.9908	.0185
6	-.0370	-.0200	.0737	.0491	-.1025	.1512	.1711	-.2970	-.0303	.2060	-.0405	-.2735	.0056
7	-.0154	-.0003	-.0380	-.0251	-.1301	.0946	.2383	.1160	-.2394	-.3804	-.8543	.2966	-.0162
8	.0271	.0442	.0549	-.0267	-.0538	.0939	.2238	.0516	-.1780	.8677	.8837	-.9435	.0312
9	.0104	.0665	.0253	.0492	-.1571	.0621	-.0680	.2365	.2427	-.0125	.1050	.5268	.0262
10	.0299	-.0021	.0094	.0408	-.0572	-.0620	-.0040	-.0345	-.2303	-.9874	-.7068	-.4790	-.0017
11	.0163	-.0267	-.0329	.0227	.0355	-.1073	.0769	-.2156	-.3833	.7413	.1023	.0317	-.0075
12	.0350	-.0458	-.0162	-.0905	.0676	-.0644	-.0924	.3434	.1017	.0839	-.3252	.9748	-.0097
13	.0514	.0002	-.0433	.0240	-.0360	.0172	-.0310	.0213	-.2621	-.1907	-.0228	.1276	.0095
14	.0580	.0196	.0077	.0256	-.0146	.0660	-.1017	.0798	-.0669	-.2463	.1095	-.4865	.0255
15	.0206	.0395	.0125	.0428	.0246	.0105	.0450	.1495	.1240	-.1020	.1190	-.9905	.0269
16	-.0077	.0464	.0261	.0204	.0588	.0443	.0153	-.2549	.3719	-.2949	-.7941	-.5512	.0175
17	-.0248	.0276	.0178	.0200	.1027	-.0641	.4766	.0558	-.0956	-.0110	-.0553	.9811	.0027
18	-.0191	.0371	.0061	-.0036	.0680	.0317	.0158	.0020	.0091	.4867	-.7486	-.5172	.0050
19	-.0166	.0220	.0182	.0235	-.0367	.0324	-.0595	.1013	-.0221	-.0243	.0465	.8909	.0018
20	.0075	.0261	-.0121	-.0312	-.0301	.0656	-.0415	.0164	.0265	-.0075	.3596	.9498	.0072
21	.0260	.0053	.0041	-.0416	.0573	.0701	.0427	.2364	-.0682	.0775	.2382	-.9580	.0156
22	.0015	.0532	-.0162	.0226	.0544	-.0711	-.0697	-.1319	-.2014	.1116	-.6958	-.1076	.0113
23	-.0001	.0036	-.0124	-.0111	.0850	-.0927	-.0760	.0093	-.2573	.0271	-.4879	-1.0000	-.0032
24	-.0173	-.0089	-.0375	.0097	.0571	-.0982	-.2870	-.2868	.3556	-.2363	-.7712	.9994	-.0180
25	.0046	-.0519	.0171	.0433	.0588	-.0261	-.0299	.0804	.0587	-.1568	-.0305	-.9388	-.0050

26	.0184	-.0655	-.0130	.0021	.0079	-.0491	-.0756	-.1117	.2205	-.4350	-.5162	.9523	.0045
27	.0123	-.0441	.0729	.0525	.1433	-.0591	.0152	-.0767	.0676	.5593	-.3946	.9033	.0134
28	-.0008	-.0175	.0197	.0352	.0509	-.1691	.0711	-.1389	-.0102	-.0133	.7112	.9951	.0003
29	-.0168	-.0574	.0121	-.0327	.1524	-.0950	-.0709	-.1786	.0794	.1458	.0252	-.5412	-.0207
30	-.0210	-.0099	-.0565	-.0463	.0701	-.0299	-.0435	-.9581	.0411	.1665	-.4703	.8196	-.0235
31	.0021	.0295	-.0234	-.0057	-.0078	-.0062	-.1133	-.2267	.9410	-.0113	-.0009	.8442	.0026
32	-.0058	.0780	.0223	.0241	.1766	-.0273	.3797	-.0730	-.5926	-.6606	-.0427	-1.0000	.0277

COEFFS FOR SUM OVER M AT EACH K

-.0018 -.0052 -.0122 .0033 .0083 .0243 .0539 .0589 .1428 -.1885 -.2437 .5577

TOTAL COEFFICIENT .0046

CORRELATION COEFFICIENTS OF (U1 * DELTA T SQUARED) FOR INDIVIDUAL SPACE-TIME COMPONENTS, FOR COLUMN AND ROW TOTALS, AND FOR GRAN
FOR LATITUDE BAND 44 ZONAL WAVENUMBER KETIC PERIOD

UNITLESS

K	0	1	2	3	4	5	6	7	8	9	COEFFS FOR SUM OVER K FOR EACH WAVENUMBER 10	11
0	-.0411	-.0420	-.1180	-.0140	-.0425	-.0770	-.0027	.0596	.0131	.2283	.9780	1.0000	.2257
1	-.0461	-.1130	-.0150	-.1553	.0575	-.1060	.1962	-.0699	.1778	.2620	-.1716	.9427	-.0223
2	-.0038	-.0108	-.0184	.0076	.1552	.1503	.2444	.1739	-.1416	-.0175	-.9489	-.6611	.0419
3	-.6745	-.1087	-.0621	-.0077	.0567	.1167	-.0479	-.1711	.7962	.2977	.8137	.9690	.0831
4	-.0177	-.0481	-.0230	-.0375	-.1003	-.0785	.0788	-.0616	.0525	.2601	.4469	.2725	-.0045
5	.0374	.0631	.1055	.1435	-.0154	.0513	-.0638	-.0294	-.5287	.3661	.6004	-.2854	.0467
6	.0017	-.0094	-.0042	-.0762	-.0764	.1288	.1185	-.2211	-.0066	.2167	.1973	-.9984	-.0178
7	.0459	.0076	.0185	.0526	-.0424	.1261	.0158	.0835	-.0520	-.3527	-.7691	.0634	.0163
8	.0101	.0033	.0458	-.0185	.1231	-.1027	-.0087	-.3440	.3754	-.0331	.3358	.7860	.0206
9	.0540	.0204	.1393	.0832	-.0329	.0802	-.2123	.1284	-.3172	-.0225	.0681	.4379	.0490
10	.0491	.0429	.0976	.1544	.1501	.0522	-.0690	.0274	-.1598	.5673	.8357	.9984	.0698
11	.0619	.1122	.1781	.1217	.0853	.1075	.2044	.0199	.2928	.1787	.5039	.6602	.1286
12	.0785	.1170	.1294	.1191	.1333	.1432	.0653	.1876	.2056	.3641	.3999	.1014	.1105
13	.1000	.1353	.1111	.0301	.0690	.0636	.1027	.1667	.1611	.0749	.2336	.8092	.1877
14	.0955	.1296	.1219	.0791	.0882	.3850	-.0116	-.1619	-.0991	.0686	-.5303	.3643	.0987
15	.1162	.1297	.0459	.0020	.1307	.0216	.1510	.1016	.0205	.4280	.3495	-.0917	.1882
16	.0183	.0619	.0936	.0016	-.0110	-.0582	-.0164	-.1671	-.6507	-.1895	.5177	-.9280	.0175
17	.0561	.0997	.0884	.0191	.0525	.1577	.0868	-.1569	.3290	.4113	-.3349	.1980	.0739
18	.0277	.0570	-.0287	.0074	.0463	-.1170	-.0460	-.1365	.4274	-.6751	-.9818	-.9177	.0046
19	-.0407	-.0202	-.0171	-.0501	-.1522	-.1647	-.1631	-.0443	-.4932	.0781	.4116	.6298	-.0424
20	-.0338	-.0235	-.0585	-.1107	-.1405	-.0091	-.1383	-.1979	.1563	-.5707	-.0303	-.9705	-.0567
21	.0053	-.0197	-.1128	.0084	-.2173	.0640	-.1594	.0030	.4221	-.0134	.5113	.0216	-.0196
22	-.0454	-.0192	-.0374	-.0141	-.1203	.1482	-.2037	-.2625	-.3944	-.0928	-.3587	.6588	-.0402
23	-.0943	.0117	-.0897	.0948	.0105	-.0114	.2157	.1858	-.0604	.2699	-.2937	.7610	-.0029
24	-.0271	-.0501	.0161	-.0404	-.0081	-.0110	-.1703	-.1317	.4247	.7638	.6137	.2848	-.0200
25	.0145	-.0581	-.0585	.0257	.0455	-.0172	-.1658	-.2534	.1902	-.0409	.8952	-.6751	-.0307

26	-.0[illegible]	-.[illegible]	-.[illegible]	-.[illegible]	-.121	-.[illegible]	.118	-.0005	.0072	-.2327	.3672	.9882	-.0226
27	.0061	.001	.0582	.0578	-.077.	-.0671	.1160	.1120	.5764	.0984	-.1640	.9249	.0208
28	-.0410	.0[illegible]	-.0[illegible]	.0150	-.[illegible]	.1671	.04e2	.2367	-.2534	-.3285	.1370	-.0170	-.0112
29	-.0124	.0[illegible]	-.0[illegible]	.2604	-.0527	.1185	-.2023	-.0859	-.2211	.0195	.3286	.0825	.0094
30	-.0396	.0183	-.0[illegible]	.0177	-.0041	-.2045	-.0515	-.3051	-.1795	-.1184	.0783	.2461	-.0318
31	-.0133	-.[illegible]	-.[illegible]	-.2244	-.1553	-.1057	-.1501	-.0448	-.0012	-.4092	.1261	.5939	-.0390
32	.0107	-.[illegible]	-.0[illegible]	.0713	-.0438	-.0124	.0474	.3794	.1013	-.7096	.2786	1.0000	.0310

COEFFS FOR SUM OVER M AT EACH K

.0022	-.0193	.0007	-.0178	.0240	.0183	.0507	-.0104	.3202	.1713	.1284	.6162	

TOTAL COEFFICIENT .1359

TERMINATION DATE = 04/17/80
TERMINATION TIME = 19/01/21

TOTAL CPU TIME IN MILLISECONDS = 47962
PPU TIME IN MILLISECONDS = 17536
PAGES PRINTED = 221
TOTAL JOB RESOURCES USED = 19.62

DISK BLOCK USAGE SUMMARY

	ODD UNITS	EVEN UNITS
	DISK 0	DISK 1
LIMIT OF BLOCKS ALLOWED	256	256
MAXIMUM BLOCKS USED	37	28
PLIB BLOCKS FOR THIS PROJECT	0	

TAPE ACTIVITY SUMMARY

TAPE LABEL	PHYSICAL UNIT	CHANNEL	PARITY ERRORS	READ ERRORS	WRITE ERRORS	RECORDS READ	WORDS READ	FILE MARKS READ	RECORDS WRITTEN	WORDS WRITTEN	FILE MARKS WRITTEN
RD	0	0	0	0	0	484	3912	1	0	0	0
P3	0	0	0	0	0	0	0	0	6445	53130	0
SL10	0	1	0	0	0	50	257280	0	0	0	0
SYSTAPE	0	0	0	0	0	16	66745	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	73	1132800	0	4	2304	0
304399	0	0	0	0	0	4096	1011344	0	0	0	0
2	0	1	0	0	0	73	1132800	0	4	2304	0
B10046	0	0	0	0	0	4096	1011344	0	0	0	0
3	0	0	0	0	0	4	33920	0	10	36272	0
RESULTS	0	0	0	0	0	0	0	0	14	6760	0
SSCH1	0	0	0	0	0	21	5376	0	21	5376	0
SSCH1	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	29	59392	0
RD	0	0	0	0	0	2	4096	0	0	0	0
LGO	0	0	0	0	0	4	5972	2	2	2736	0
LGO	0	0	0	0	0	0	0	0	0	0	0
RANFU	0	0	0	0	0	1	5110	0	1	5110	0
SSCRD	0	1	0	0	0	0	0	0	0	0	0
3567	0	0	0	0	0	0	0	0	0	0	0

REFERENCES

Blackman, M.L., 1976: A climatological spectral study of the 500 mb geopotential height of the northern hemisphere. J. Atmos. Sci., 33, 1607-1623.

Held, I.M., 1978a: The vertical scale of an unstable baroclinic wave and its importance for eddy heat flux parameterizations. J. Atmos. Sci., 35, 572-576.

Held, I.M., 1978b: Theories for transient baroclinic eddy fluxes. The General Circulation: Theory, Modelling and Observations, NCAR/CQ-6+1978-ASP, 224-235.

Holton, J.R., 1972: An Introduction to Dynamic Meteorology, Academic Press, Inc., 319 pp.

Leith, C.E., 1974: Spectral statistical-dynamical forecast experiments. Proc. Intern. Symp. Spectral Methods in Numerical Weather Prediction, CARP Programme on Numerical Experimentation, Rep. No. 7.

Lorenz, E.N., 1978: An experiment in non-linear statistical weather forecasting. Mon. Rev., 105, 590-602.

Lorenz, E.N., 1979: Forced and free variations of weather and climate. J. Atmos. Sci., 36, 1367-1376.

Phillips, N.A., 1954: Energy transformations and meridional circulations associated with simple baroclinic waves in a two-level quasigeostrophic model. Tellus, 6, 273-286.

Saltzman, B., 1967: Steady-state solutions for axially-symmetric climatic variables. Research on the theory of climate. Contract Cwb-11389, Rept., Travelers Research Center, 1-38.

Stone, P.H., 1972: A simplified radiative-dynamical model for the static stability of rotating atmospheres. J. Atmos. Sci. 29, 408-418.

Stone, P.H., 1978: Baroclinic adjustment. J. Atmos. Sci., 35, 561-571.

Stone, P.H., and Miller, D.A., 1979: Empirical relations between seasonal changes in meridional temperature gradients and meridional fluxes of heat. MIT Dept. of Meteorology, awaiting publications, 41 pp.

St. Pierre, R., 1979: Correlations between eddy heat fluxes and baroclinic instability. MIT Dept. of Meteorology Master's Thesis, 83 pp.