Annual and Interannual Variability of Tropical–Extratropical Interaction: An Empirical Study

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ABSTRACT

In addition to regions of time-mean easterly winds, the tropical atmosphere contains substantial areas of mean westerlies in both upper and lower troposphere. Their existence is thought to be related to the large-scale atmospheric response to regional convective heating and, ultimately, to the latent heating and sea surface temperature distribution in the tropics. It has been hypothesized that regions of upper tropospheric equatorial westerlies act as efficient ducts or corridors for transient and stationary extratropical modes deep into the tropics and even to the other hemisphere. Furthermore, it has been argued that the degree of efficiency depended upon the strength of the local equatorial westerlies, thus inducing a probable distinct seasonal and interannual variability in interactions between the hemispheres and between the extratropics and low latitudes. These hypotheses are tested in the present study using an 11-year National Meteorological Center (NMC) climate data set.

Large positive pattern correlations are found between the time-mean zonal wind component ($\bar{u}$) and perturbation kinetic energy (PKE). The PKE increases substantially as $\bar{u}$ increases from small negative to large and positive values. Values of PKE measured within the mean westerlies of the central and eastern Pacific Ocean are at least a factor of 2 or 3 larger than the PKE found in the moderate and strong equatorial easterlies. If the strength of the easterlies is greater than about $-5$ m s$^{-1}$, the PKE assumes a near constant value of well less than 40 m$^2$ s$^{-2}$. Pattern correlations with the time-mean meridional velocity component ($\bar{v}$) are substantially smaller and do not appear to be significant. To test the robustness of the statistical relationship between $\bar{u}$ and PKE, individual mean months and seasons and the same months of different years are examined. In all cases, the distribution of PKE appears to be determined by the local $\bar{u}$. As arguments can be established that relate changes in the boundary forcing to changes in the mean equatorial zonal wind distributions, causal relationships can also be proposed for the variability in interannual and intraannual interhemispheric interaction.

1. Introduction

a. Background

The aim of the current study is to test the hypotheses emerging from the theoretical results of Webster and Holton (1982), Branstator (1983), and Karoly (1983), who suggested that the equatorial regions were pervious to the latitudinal propagation of extratropical disturbances because of the longitudinal variation of the basic flow. Specifically, they suggested that where the equatorial upper tropospheric flow was westerly (or even weak easterly), propagation is allowable through equatorial wave ducts. Further, Webster and Holton added that the strength of the westerlies was also important and that the stronger the westerlies, the greater the chance for an extratropical wave to propagate completely through the tropics to the other hemisphere. Finally, they argued that the latitudinal group speed of the mode went as the 3/2 power of the strength of the local mean wind field. On the other hand, where the flow is strong and easterly, propagation did not occur. We will discuss these theories in more detail at a later stage in comparison to the observed structure of the tropical atmosphere. However, it suffices to say here that the papers mentioned previously are generalizations of the zonally averaged theory of latitudinal wave propagation originally developed by Charney (1969) and extended by Mak (1969), Bennett and Young (1971), Webster (1973), and many others. Their emphasis was the apparent shielding of the tropics from the extratropics by a zonally averaged “critical latitude” where the strength of the mean state zonal wind component ($\bar{u}$) matched the phase speed of the incident wave. For typical synoptic scale waves of the extratropics and longer stationary and transient modes, the critical zonally averaged latitude occurs where $\bar{u}$ changes sign, or where $\bar{u}$ is very weak but negative. The Webster and Holton (1982), Branstator (1983), and Karoly (1983) studies question the reality of a zonally averaged critical latitude and suggest that its existence...
is longitudinally dependent, waxing and waning in its shielding capacity as the sign of the time mean flow changes with longitude.

The Webster-Holton study was motivated by implications gleaned from a number of observational studies. Many years ago, Richl (1954) observed that:

"... The intermittent appearance of high tropospheric westerlies on the equator ... is a foreign thought in classical views of the general circulation. Yet ... (there is evidence) ... that they do occur ... Since flow in the high levels is so unsteady, coupling at high altitudes between the circulations of the northern and southern hemispheres promises to provide an important link in the understanding of the fluctuations of the general circulation . . . ."

He also noted that there was considerable evidence of:

"... an intrusion of extratropical-type disturbances into the heart of the tropics (in the region of the westerlies) . . . ."

Webster and Holton received further motivation by noting that the region of maximum perturbation kinetic energy (PKE) along the equator for January and February 1971 of the Murakami and Ummayer (1977) analyses was located in the vicinity of the equatorial westerlies. Webster and Holton confirmed these observational hints theoretically and indicated that the low latitudes were porous to wave propagation from higher latitudes only in those specific regions where the zonal wind was westerly. Furthermore, the rate and extent of the interhemispheric interactions were determined by the location of the extratropical wave source relative to the equatorial westerlies and the strength of the westerlies themselves.

Webster and Holton (1982) and Branstator (1983) both considered the low frequency or quasi-stationary end of the spectrum. Karoly (1983), on the other hand, extended Charney's (1969) study to include transient modes. Thus, three criteria are needed of a data set for the present study. The data must be long period and continuous to overcome the shortness of the Riehl and Murakami-Ummayer analyses. On the other hand, they must be of sufficiently high frequency to capture the transients discussed by Karoly (1983).

b. Longitudinal variation of the mean fields

The primary motivation of the studies that generalized Charney's (1969) arguments relating to latitudinal extent of wave propagation emanate from observational evidence of considerable longitudinal variability in the mean flow, both in the extratropics and especially in the tropics. As a precursor to the empirical study, we will briefly review the evidence of longitudinal structure.

Strong longitudinal asymmetries of the atmospheric circulation within the extratropics have long been noted in both the mean and the transient domains. In fact, Rossby et al. (1939) was the first to identify distinct "centers of action" (such as the Aleutian Low) in the North Pacific region. An important extension of our knowledge of the three-dimensional structure of time-mean circulations was made by Blackmon et al. (1977) in a study that heralded a number of exhaustive diagnoses of the winter Northern Hemisphere extratropics (e.g., Holopainen, 1978, 1983; Lau and Wallace, 1979; Blackmon, et al., 1984; and others) that possessed the common result that the major cyclogenetic centers were located slightly to the north of the longitudinally dependent mean jet maxima of the Northern Hemisphere winter. Extending downstream are the major storm tracks. The longitudinally dependent structure of the Northern Hemisphere summer troposphere was studied by White (1982), who noted that the colocation of jets and transient activity of the winter is lacking in summer. White speculated that this is due to the suppression of baroclinic instability by the northern slopes of the major orographic features of the Northern Hemisphere.

The empirical studies described above have been accompanied by the development of some parallel theories. In particular, the local jet maxima have been found to correspond to regions of maximum instability (e.g., Frederiksen, 1979, 1983) and were thus identified as the source regions of extratropical disturbances.

The longitudinally dependent structure of the tropics has received less attention, both diagnostically and theoretically. With studies that emphasize the zonal average, longitudinal variability is represented as a statistical, zonally averaged covariance (e.g., Oort and Rasmussen, 1971). The strong variability in longitude was first described in a systematic manner by Newell et al. (1972) in a study that has provided a strong impetus for subsequent theoretical investigations. Examination of the Newell et al. atlas posed a very basic question: why is the tropical atmosphere so bland and relatively featureless (i.e., weak velocity fields and flat thermodynamic surfaces) from a zonally averaged perspective while, at the same time, possessing such a complex longitudinal dynamic structure?

An example of the longitudinal variation of the tropical structure is shown in Fig. 1 (Webster, 1983) where both the mean December, January and February (DJF) and June, July and August (JJA) time-mean (u) and meridional (v) velocity components are plotted as a function of height and longitude along the equator. The zonal average has been removed and the z coordinate scale has been expanded. Mean zonally averaged values of the zonal wind component at 200 mb, 500 mb and 1000 mb are -3, -4 and -2.5 m s^{-1} in DJF and -6, -5, and -5 m s^{-1} in JJA. Thus, when the zonally averaged component is added, the upper troposphere of the Western Hemisphere remains basically westerly and the Eastern Hemisphere easterly with the sense almost exactly reversed in the lower troposphere in both seasons. The lower tropospheric westerlies are smaller in magnitude and appear as isolated positive islands amid
the broad surface easterlies. The much smaller $\vec{v}$ fields (the cross-equatorial component) are also out of phase in the vertical but, unlike the $\vec{u}$ fields, they show a distinct annual variation implying a lack of temporal correlation in the seasonal cycle of equatorial values of $\vec{u}$ and $\vec{v}$.

The very different character of the $\vec{u}$ and $\vec{v}$ fields at low latitudes may be seen in the time-mean IR radiances shown in the bottom panels of Fig. 1 (scale inverted) for the equator and for 15°N and 15°S. Cold IR temperatures in the tropics correspond to regions of deep and penetrative convection and precipitation (Heddinghaus and Krueger, 1981). The most intense mean convection is in the Indonesian–Western Pacific region. In both DJF and JJA, the strongest zonal divergence (note the upper and lower tropospheric compensation in $\vec{u}$) and the IR maxima along the equator are colocated. On the other hand, the $\vec{v}$-fields, which show a distinct seasonality, appear tied to the convection in the subtropical summer hemisphere (i.e., either at 15°N in JJA or 15°S in DJF). Possibly, the equatorial $\vec{v}$-fields may be interpreted as a deep thermal response to heating in the summer monsoon regions and cooling in the winter hemisphere with a corresponding flow towards the heating in the lower troposphere and a return flow aloft. On the other hand, the near-equatorial $\vec{u}$-field appears consistent with a thermal response to the heating along the equator.

c. Physical basis of the longitudinally varying time-mean tropical atmosphere

A critical aspect of the hypotheses presented above is: why is there such a strong longitudinal component to the time-mean tropical atmosphere? Webster (1972) and Gill (1980), among others (see the review of Webster, 1983, for a more substantial bibliography), have suggested that the large-scale asymmetric structure of
the time-mean tropical circulation (i.e., the longitudinal variation) is the response of the basic zonally averaged, easterly flow of low latitudes to forcing by the concentrated regions of latent heating, induced by the distribution of sea surface temperature in the tropics (see also Geisler, 1981; and Webster, 1981, 1982). The basic mode that describes the low-latitude structure is the atmospheric equatorial Kelvin wave (Webster, 1972), although Gill (1980) has shown that the mixed Rossby–gravity wave is also important in explaining the western part of the stationary response. The “Walker Circulation” (so named by Bjerknes, 1969, but described as the “East–West Circulation” by Krishnamurti, 1971) represents the atmospheric realization of these theoretical equatorial waves. The effect of the wave composite (i.e., Kelvin and Rossby–gravity modes) is to produce a time-mean circulation that has, in addition to the mean zonally averaged flow, regions of net easterlies and westerlies in the equatorial region, as shown in Fig. 1.

The features resulting from heating centered along the equator (which shows only a small annual variation) are complemented by the cross-equatorial flow driven by heating following the annual cycle of the insolation. Confined to the Eastern Hemisphere, where the great land masses reside and consequently the largest heating gradients, are the monsoons that dominate the v profiles of Fig. 1. Again, this complicated cross-equatorial flow has been visualized in terms of a simple Rossby–gravity mode that includes a cross-equatorial component (Gill, 1980; Webster, 1983). Within such a simple structure are the upper level equatorial easterlies (the monsoon easterly jet stream), the ageostrophic cross-equatorial flow (the ・・・

2. Data

The data used in this study are from the operational tropical objective-analyses of the National Meteorological Center (NMC) in an archive maintained by the Climate Analysis Center of the NMC. They consist of daily (0000 GMT) values of zonal (u) and meridional (v) components of the 200 mb wind on a Mercator grid whose spacing is 5° in longitude and ranges in latitude from 5° to the equator at 3.5° at the northern and southern boundaries located at 48.1°N and 48.1°S. The full grid has 23 × 72 (1656) points.

The primary data used in our analyses span the period 1 March 1968 to 28 February 1979. With the exception of October and November 1972, which are entirely missing, only one month (August 1972, with 35%) has data for fewer than 80% of the days. Over the whole period, omitting October and November 1972, 97.5% of the data are available. Using the daily 200 mb wind components, mean values of the wind components, their squares and their product (u, v, u², v², and uv) were computed for each month for each grid point. From these, monthly mean values of the variances of u and v were computed for each month and grid point. Perturbation kinetic energy (PKE) was then computed as (u² + v²)/2. Where seasonal means are used, they are the arithmetic averages of the three calendar months. Data for a few more recent months are shown in Section 4. Computations were carried out as described above with the exception that the data were on a 2.5° × 2.5° latitude/longitude grid.

The NMC’s operational tropical analysis performed using all data received at NMC within the 10 hour period following the standard reporting times (0000 and 1200 GMT). This analysis is currently referred to within NMC as the “Final” analysis. While two analyses are performed each day, only one (0000 GMT) is archived by NESDIS; thus the primary data set used in this study contains no diurnal signal.

Three quite different analysis techniques were used during this period. From March 1968 through August 1974, a successive correction, or Cressman scheme, often referred to as the Bedient analysis, was used (Bedient, et al., 1967). From September 1974 through August 1978, the Hough analysis, which used a spectral representation of the first guess and data-generated corrections to the spectral coefficients, was utilized (Rosen and Salstein, 1980). From September 1978 through the present, the operational analysis has used the optimum interpolation technique (Gandin, 1963), which uses three-dimensional correlation functions to make observation-generated corrections to the first guess. Error levels are assigned to observations and the errors for observation types can be specified to have various spatial correlations (Bergman, 1979). More details can be found in Arkin (1982, 1984).

3. Mean monthly and seasonal relationships

a. Zonally averaged perspective

Figure 2a, b shows the latitudinal distribution of the mean monthly zonally averaged zonal wind component U and the mean monthly zonally averaged perturbation kinetic energy (PKE) obtained from the 11 years of the primary data set (brackets denote zonal average).

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1 The equatorial Kelvin wave, first described by Matsuno (1966), is a rotationally trapped edge wave. In the equatorial case, the edge is the change in sign of the Coriolis force about the equator. The response is zonal in nature (the meridional component of velocity is vanishingly small) and decays exponentially poleward of the equator.

2 Perturbation kinetic energy (PKE) is defined as PKE = (u² + v²)/2. If (.) and ('') refer to a time average and the deviation from a time average then: u'² = (u - 〈u〉)², = u² + u² - 2u'ū, = u² - urtles u'² - 2ūu', so that u'² = u² - ū², etc.
summer hemispheres. While the mean westerlies diminish to about 6 m s\(^{-1}\) at 33°N in August, they do not fall below 15 m s\(^{-1}\) at 30°S throughout the Southern Hemisphere summer. The larger seasonal extremes in the Northern Hemisphere may be due to its greater continentality and the associated stronger thermal gradient in winter and more vigorous monsoonal heating in summer. The former produces the stronger westerly wintertime maximum while the latter forces the extensive upper tropospheric easterlies in the tropics and subtropics (Webster, 1983). The Southern Hemisphere possesses only weaker counterparts of these two features.

The [PKE] distributions (Fig. 2b) correspond to the \([\overline{u}]\) features almost exactly. Regions of strongest mean westerlies correspond to the largest [PKE] values and a smaller seasonal variation exists in the Southern Hemisphere than in the north.

2) TROPICAL RELATIONSHIPS

Comparisons of \([\overline{u}]\) and [PKE] in Fig. 2 show that when the mean zonal flow at low latitudes is westerly (albeit quite weak in comparison with extratropical winds), the values of the [PKE] are largest, with zonally averaged values along the equator in excess of 40 m\(^2\) s\(^{-2}\) compared to values below 30 m\(^2\) s\(^{-2}\) when the mean zonal flow is easterly. It is not clear from these results whether the higher [PKE] values arise primarily from propagation into the tropics by extratropical modes, or in situ development in regions of upper level westerlies is greater than in regions of easterlies.

b. The latitude–longitude distributions

Figures 3a–d show the seasonal 200 mb distribution of \(\overline{u}\) and PKE in the 50°N–50°S strip for the seasons DJF, MAM, JJA and SON. The solid lines in all figures refer to the \(\overline{u}\) contours (m s\(^{-1}\)) and the dashed lines to the PKE fields (m\(^2\) s\(^{-2}\)). The shaded zones emphasize the mean westerlies and westerly winds of magnitude greater than 30 m s\(^{-1}\) and the heavy dashed lines show the 40 m\(^2\) s\(^{-2}\), 80 m\(^2\) s\(^{-2}\) and the 240 m\(^2\) s\(^{-2}\) PKE isopleths.

1) EXTRATROPICAL RELATIONSHIPS

The annual variation of the mean monthly values of \([\overline{u}]\) at 200 mb is fairly well known and shows maximum values of westerlies occurring in the winter hemisphere. The extreme values of the Southern Hemisphere extratropical westerlies are weaker than those of the Northern Hemisphere in winter in the NMC analyses (e.g., compare 35 m s\(^{-1}\) at ~30°S in July to 42 m s\(^{-1}\) at 33°N in February)\(^5\) but generally stronger when the comparison is made between the

\(^5\) The Southern Hemisphere values should be compared with other estimates such as those by Trenberth (1984) who, using the Australian analyses, found values of about 40 m s\(^{-1}\) in July.
heating centers of Indonesia (and northern Australia), South and Central America and Africa (Webster, 1983).

With the exception of Hoskins, et al. (1983) and Trenberth (1981, 1982) few similar studies exist for the Southern Hemisphere. Probably this lack emanates from a general paucity of data and a consequent lower degree of confidence in the archived data fields. However, there are some tantalizing observations that imply strong cross-equatorial influences relating to the time-mean fields. For example, for MAM and JJA, the only significant jet maximum in the Southern Hemisphere exists over the Australian region. Note that no orographic feature appears to be associated with the Southern Hemisphere maxima. In fact, Radok and Grant (1957) pointed out that the development of the Australian jet stream extratropical westerlies is very rapid and follows immediately the initiation of the Northern Hemisphere summer subtropical easterly jet stream which, in turn, occurs concurrently with the onset of the South Asian monsoon. Thus, by implication, the winter westerly maximum over Australia appears to be related to strong time-mean ageostrophic flow across the equator, forced by the monsoonal heating of the northern summer (see Fig. 1). These points were discussed previously in Section 1b regarding the physical basis of the longitudinal dependent basic state.

In DJF, MAM and SON, the PKE maxima are all located downstream and slightly poleward of the centers of the finite \( \bar{u} \) maxima of the Northern Hemisphere. Since Frederiksen (1979) has shown that the finite jet cores represent regions of maximum baroclinic instability, and Blackmon et al., (1977), have shown that the Northern Hemisphere winter storm tracks bear a similar relation to the jet cores, we might suppose that the PKE maxima are aggregates of transient storm loci. Specifically, our PKE coincides with the Blackmon et al., band-pass filtered results. The colocation of these maxima with the equatorial heating maxima will be important when we compare the \( \bar{u} \) and the PKE fields in years where the equatorial heating is vastly different; specifically, we will compare the winters of 1971/72 and 1972/73.

A distinctly different relationship between \( \bar{u} \) and PKE appears in the Southern Hemisphere than is found in the north. For example, in JJA (Fig. 3c), the \( \bar{u} \) and PKE maxima are in phase. It is possible that the dominant physical processes responsible for the \( \bar{u} \)-PKE relationship may be different in each hemisphere. For example, the vertical structure of the zonal flow differs between hemispheres and the large scale modes possess almost no phase change with height in the Southern Hemisphere compared to a strong westward tilt in the Northern Hemisphere. However, the colocation of the \( \bar{u} \) and PKE in the Southern Hemisphere may also relate to problems associated with the analysis of the wind field with a sparse data network rather than to a basic difference in the physical make-up of the two hemispheres. Van Loon (1980) has noted problems in Southern Hemisphere analyses where maxima in variance appear to be associated with the maximum density of observations, rather than specific physical characteristics of the flow. These features are also discussed by Trenberth (1980, 1981) and Hoskins, et al. (1983).

2) Tropical relationships

A much more straightforward relationship appears to exist between \( \bar{u} \) and PKE at low latitudes. At all seasons, in regions of strong easterlies, the PKE fields are less than 40 m² s⁻². In contrast, in regions of upper tropospheric westerlies, much larger values of PKE exist, as may be seen in Fig. 3 over the central and eastern Pacific Ocean and the Atlantic Ocean.

Scatter plots of \( \bar{u} \) and PKE for all grid points in the equatorial belt between 5°N and 5°S (Fig. 4) show a very strong and positive correlation, a result that may have been anticipated from Fig. 3. The correlation appears strongest in DJF and MAM when the equatorial westerlies achieve their maximum value. The actual spatial, or pattern, correlation coefficients (Table 1), together with the corresponding zonally averaged zonal wind-component in the 5°N–5°S latitude band, indicate that the relationship is strongest when the tropics are basically westerly and weakest in the strong easterly regime. For completeness, the correlation coefficients for each of the mean months, which indicate a similar strong relationship, are also included.

The spatial correlation between \( \bar{u} \) and PKE in the same latitude band are also entered in Table 1. Scatter plots for long-term seasonal means are not shown, but relationships between \( \bar{u} \) and PKE for specific months appear in Fig. 6. Whereas the correlations between \( \bar{u} \) and PKE are significant, \( \bar{v} \) and PKE are quite poorly correlated. What small correlation exists might well be due to a positive spatial correlation between the \( \bar{u} \) and \( \bar{v} \) components. In other words, the sense of the local mean meridional velocity component appears to have little direct impact on the magnitude of the variance energy.

Synoptic experience indicates that a large percentage of convective tropical events are located in the region of upper level easterlies, or, from Figs. 3 and 4, in regions of low PKE (see Riehl, 1954). From the IR diagrams of Fig. 1, it can be seen that the region of tropical westerlies in the eastern Pacific Ocean has relatively low levels of convective activity. Thus, the large values of PKE that exist at low latitudes in the region of equatorial upper tropospheric westerlies are probably not associated with convective systems which have developed in situ. It seems more likely that the large values of PKE are associated with propagating extratropical disturbances ducted through the equatorial westerlies (as per Webster and Holton, 1982; and Branstator, 1983).

A more careful examination of the scatter plots of \( \bar{u} \) and PKE indicate that the increase of PKE starts,
FIG. 3. Latitude–longitude distribution of the mean seasonal 200 mb $\mathbf{u}$ and $\mathbf{PKE}$ fields for (a) DJF, (b) MAM, (c) JJA and (d) SON. Solid lines and dashed lines indicate the $\mathbf{u}$ and $\mathbf{PKE}$ fields, respectively. Units are m s$^{-1}$ and m$^2$ s$^{-3}$. Shaded region indicates zone of $\mathbf{u} < 0$. 
not with the zero value of the zonal wind, but while the winds are weak and easterly. This feature is especially evident in the January 1982, the January 1983,

**TABLE 1.** Correlation coefficients $r(\bar{u}, \text{PKE})$ by season and month, together with $[\vec{u}]$ in $5^\circ\text{N}-5^\circ\text{S}$ latitude band for 216 point pairs. The number of degrees of freedom is far fewer than 216 because of spatial coherence of the fields. However, using the very conservative estimate of 15 degrees of freedom, the 5% significance level is 0.48 and the 1% level is 0.610.

<table>
<thead>
<tr>
<th>Season</th>
<th>$r(\bar{u}, \text{PKE})$</th>
<th>$r(\vec{u}, \text{PKE})$</th>
<th>$[\vec{u}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJF</td>
<td>0.838</td>
<td>-0.076</td>
<td>+1.4</td>
</tr>
<tr>
<td>MAM</td>
<td>0.825</td>
<td>0.115</td>
<td>+0.7</td>
</tr>
<tr>
<td>JJA</td>
<td>0.717</td>
<td>0.245</td>
<td>-4.8</td>
</tr>
<tr>
<td>SON</td>
<td>0.773</td>
<td>0.027</td>
<td>-1.3</td>
</tr>
</tbody>
</table>

**Month**

<table>
<thead>
<tr>
<th>Month</th>
<th>$r(\bar{u}, \text{KE})$</th>
<th>$r(\vec{u}, \text{KE})$</th>
<th>$[\vec{u}]$ $5^\circ\text{N}/5^\circ\text{S}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.799</td>
<td>-0.111</td>
<td>+1.9</td>
</tr>
<tr>
<td>Feb</td>
<td>0.829</td>
<td>-0.164</td>
<td>+0.3</td>
</tr>
<tr>
<td>Mar</td>
<td>0.867</td>
<td>-0.125</td>
<td>+0.9</td>
</tr>
<tr>
<td>Apr</td>
<td>0.676</td>
<td>0.138</td>
<td>+1.1</td>
</tr>
<tr>
<td>May</td>
<td>0.679</td>
<td>0.219</td>
<td>+0.2</td>
</tr>
<tr>
<td>Jun</td>
<td>0.717</td>
<td>0.289</td>
<td>-3.2</td>
</tr>
<tr>
<td>Jul</td>
<td>0.633</td>
<td>0.252</td>
<td>-5.3</td>
</tr>
<tr>
<td>Aug</td>
<td>0.684</td>
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<td>-6.0</td>
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<tr>
<td>Sep</td>
<td>0.663</td>
<td>0.117</td>
<td>-4.3</td>
</tr>
<tr>
<td>Oct</td>
<td>0.734</td>
<td>0.001</td>
<td>-1.2</td>
</tr>
<tr>
<td>Nov</td>
<td>0.766</td>
<td>-0.078</td>
<td>+1.6</td>
</tr>
<tr>
<td>Dec</td>
<td>0.810</td>
<td>0.039</td>
<td>+1.9</td>
</tr>
</tbody>
</table>

and the March 1982 $\bar{u}$–PKE plots of Fig. 6. A probable explanation of the association of $\bar{u} \approx 0$ and larger values of PKE is that high frequency transients that are included in the data set are propagating through the weak easterlies, as may be anticipated from Charney (1969) and dealt with explicitly by Karoly (1983).

A third possibility should be mentioned for the general relationship of $\bar{u}$ and PKE in the tropics. Rather than merely propagating through the equatorial westerly duct, it is possible that the extratropical disturbance may initiate equatorially trapped modes that would possess relatively small vertical wave scales. Such possibilities were implicitly raised in the study of Webster and Holton (1982) (see their Fig. 12, especially the perturbation height field), and explicitly by Chang and Lim (1983).

**4. Shorter-term relationships**

Figures 5a–d show scatter plots between PKE and $\bar{u}$ for four individual months, January 1982, March 1982, August 1982 and January 1983. The earlier result, that large values of PKE can occur as long as the tropospheric flow is basically westerly, is reemphasized for shorter mean periods. An interpretation may be that we can probably assume that a large part of the mean seasonal PKE illustrated in Figs. 3 and 4 is an aggregate of synoptic transient effects. Indeed, Reed (1981) has shown that transient features propagating eastward across the Pacific appear to distend south into the equatorial westerly wind region of the upper tropo-
sphere of the central and eastern tropical Pacific Ocean. Scatter diagrams for $\bar{v}$ and PKE are shown in Fig. 6 for the four individual months. Unlike the correlations between $\bar{u}$ and PKE, the relationship between $\bar{v}$ and PKE is very weak at best.

5. Interannual relationships

During warm episodes (El Niño events) in the central and eastern tropical Pacific Ocean, the mean wind deviates strongly from its climatological mean structure.

Fig. 6. As in Fig. 5, but for the meridional component $\bar{v}$ and PKE.
(e.g., see Trenberth, 1976, 1980; Arkin, 1982). At low latitudes, the mid-Pacific upper tropospheric westerlies diminish and are sometimes replaced with mean easterlies. In the winter season, the Northern Hemisphere east Asia jet stream elongates substantially in an eastward direction. If the hypothesis posed earlier regarding the relationships between $\bar{u}$ and PKE is correct, then we should expect corresponding changes to occur in

![Diagram](image)

**Fig. 7.** The latitudinal distribution of the mean Northern Hemisphere winter (DJF) zonally averaged (a) zonal wind component ($\bar{u}$) and (b) the perturbation kinetic energy (PKE), for the period 1968/69–1978/79.

![Diagram](image)

**Fig. 8.** As in Fig. 7 except for Northern Hemisphere summer (JJA).

the distribution of PKE. We shall therefore use the anomalous warm episode years as effective controls to test the hypothesis.

### a. Zonally averaged interannual variability

Figure 7a, b shows the interannual variability of the mean zonally averaged $u$ and PKE fields for DJF as a function of latitude and time for the years between 1968/69 and 1978/79. Similar diagrams for JJA are shown in Fig. 8a, b. The relationships follow those noted in the earlier discussion with maximum values of [PKE] and [$\bar{u}$] coinciding in time and location. For
Table 2. Comparison of the $\bar{u}$ and [PKE] values of the extratropics and tropics for two Northern Hemisphere winter seasons (DJF).

<table>
<thead>
<tr>
<th></th>
<th>28°N–38°N</th>
<th>5°N–5°S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{u}$</td>
<td>33.7</td>
<td>39.3</td>
</tr>
<tr>
<td>[PKE]</td>
<td>163.0</td>
<td>195.0</td>
</tr>
</tbody>
</table>

For example, the three maxima of $\bar{u}$ in the Northern Hemisphere extratropics in 1969/70, 1972/73 and 1976/77 are colocated with [PKE] extrema. Likewise, periods of weak easterly mean winds in the equatorial zone correspond to low values of [PKE], while larger values of [PKE] are associated with more westerly mean zonal winds.

One should be cautious in seeking explanations of the strong differences between the early part of the data set and the latter part, especially at low latitudes due to the substantial changes in analysis procedures discussed in Section 2. Consequently, we should view Figs. 7 and 8 as adding some credence to the relationships found earlier for the extratropics and merely note that at low latitudes, irrespective of the analysis scheme, the same relationship found in Fig. 3a, b appears to hold.

b. Longitude–latitude interannual relationships

Table 2 compares the extratropical and tropical $\bar{u}$ and [PKE] fields for an El Niño (or warm episode) DJF season (1972/73) and a non-El Niño DJF (1971/72). The El Niño season is characterized by much larger values of $\bar{u}$ and [PKE] at higher latitudes, but much weaker values of both quantities at low latitudes when compared to the non-El Niño year. In order to discern the asymmetric features which contributed to these differences, the full longitude–latitude representations of the two seasonal $\bar{u}$ and PKE charts at 200 mb are shown in Fig. 9. It should be noted that Arkin (1982) and Quiroz (1983) present extensive discussions of the variations of the local and zonally averaged wind fields during El Niño.

Certain very specific differences are apparent between the two seasons. In 1971/72 the equatorial westerlies reached from west of the dateline to South America. During 1972/73 the easterlies extended 45° eastward from their climatological position, "eliminating" the east Pacific equatorial westerlies. The extension of the easterlies and the diminution of the westerlies is consistent with the eastward migration of the major convective zone which is known to occur during warm episodes, as described by Rasmusson and Wallace (1983). At the same time, the East Asian jet

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**Fig. 9.** As in Fig. 4 except for the 1971/72 and 1972/73 winters.
stream had intensified and stretched eastward over the entire Pacific Ocean, probably because of the northerly ageostrophic flow out of the tropics that had moved eastward following the migration of the equatorial heat source mentioned above (see Webster, 1981, 1982, 1983; and Arkin, 1984).

Variations of the PKE consistent with the two differing $\vec{u}$ fields are also apparent. Mid-Pacific tropical

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**Fig. 10.** Time–longitude section of the seasonal values of the (a) zonal wind component $\vec{u}$ and (b) perturbation kinetic energy (PKE) for the equatorial channel $5^\circ$N–$5^\circ$S. Values of $\vec{u} < 0$ are shaded as are regions where PKE $> 40$ m$^2$ s$^{-2}$. 
values range up to 80 m$^2$ s$^{-2}$ over a large area during 1971/72, but only up to 40 m$^2$ s$^{-2}$ during the El Niño event. It is worth noting that the winter middle latitude \( \bar{u} \) maxima (and hence, storm tracks) are also moved eastward. These changes probably reflect alterations in the regions of maximum hydrodynamic instability of the local or finitely extending jet stream, in addition to the eastward displacement of the wind maxima themselves.

The full variation with time of all the seasonal mean distributions of \( \bar{u} \) and PKE are shown in Fig. 10 in the form of time sections along the equator for both quantities. Both exhibit relative maxima during the Northern Hemisphere winters in the east Pacific (120°W–180°). Smaller, but similarly correlated maxima, are seen in the Atlantic sector (0°–60°W). Seasons with stronger westerlies in these regions (i.e., DJF 1971/72, DJF 1975/76) are also those with the largest values of PKE. Again, this relationship only seems to be valid in regions of weak easterly and westerly zonal wind.

6. Concluding remarks

This study compared the perturbation kinetic energy with the sign and magnitude of the zonal wind component. The data set used was the NMC climatological archive consisting of mean monthly and mean seasonal statistics from March 1968 through February 1979, together with selected recent months. The purpose of the study was to gauge the validity of strong correlations between the perturbation kinetic energy and the strength of the westerly (positive) zonal wind component. Furthermore, it was suggested that the reason the perturbation kinetic energies did maximize in the equatorial westerlies of the upper-troposphere was that the westerlies formed a duct for the propagating dispersive rotational modes of the extratropics.

With respect to the correlations between the zonal wind component and the magnitude of the perturbation kinetic energy, the following conclusions can be drawn:

(i) A strong and positive relationship exists between the zonally averaged fields of \( \bar{u} \) and [PKE]. In the equatorial regions of the upper-troposphere, months when westerly winds dominate tend to have considerably higher values of perturbation kinetic energy than those with easterly mean winds.

(ii) The correlations noted in (i) are also apparent in the zonally asymmetric zonal wind component at low latitudes. Regions where upper tropospheric westerlies predominate (e.g., the mid- and eastern Pacific Ocean and the Atlantic Ocean) are also regions of large PKE values.

(iii) The increase of PKE with increasing zonal wind speed appears to commence at relatively low values of easterly wind and increase as the winds become westerly, as indicated in (i). Very small values of PKE exist for stronger easterlies.

(iv) There appears to be no meaningful correlation between the time-mean meridional component \( \bar{v} \) near the equator and the PKE in the equatorial regions. Where cross-equatorial flow is maximized (e.g., into the winter Southern Hemisphere over the Indian Ocean and into the winter Northern Hemisphere over Indonesia), the PKE field is indistinguishable from values associated with the deep easterlies.

(v) A strong variability on interannual timescales of the basic wind structure at low latitude appears to impose a similar variability on the upper tropospheric PKE field.

Overall, the study lends some credence to the theoretical suggestions of Webster and Holton (1982) for low frequency modes and also to the suggestions that high frequency transients may propagate through weak easterlies. However, the determining factor regarding local low-latitude perturbation kinetic energy concentrations appears to be the magnitude of the local westerly wind. Invariably, PKE values are stronger in westerly winds at the equator than in easterly winds of equal magnitude. The absence of organized convection in the regions of PKE maxima along the equator probably deemphasizes the role of \textit{in situ} development of transients which make up the PKE maximum.

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