

The Three-Dimensional Structure of Perturbation Kinetic Energy and Its Relationship to the Zonal Wind Field

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19 December 1988 and 13 April 1989

ABSTRACT

We seek relationships between the perturbation kinetic energy (PKE), the zonal wind, and outgoing longwave radiation. It is found that the mean low-level PKE extratropical maxima are located at the "atmospheric centers of action" (e.g., the Aleutian and Iceland lows), which lie beneath the high-level PKE maxima downstream of the westerly jet streams. As expected, this means that the PKE maxima in the middle latitudes are closely related to the propagating disturbances. In the tropics, however, the high-level PKE maxima and minima are located in the strongest upper tropospheric westerlies and easterlies, respectively, while the low-level PKE maxima and minima are located in the monsoon systems and the easterly trade winds, respectively. It is also found that the maxima and minima of the PKE in the middle latitudes, at least in the Northern Hemisphere, are in phase in the vertical but completely out of phase in the tropics. These features are closely linked to the structure of the zonal wind component.

The hypothesis is posed that in the tropics, the PKE maxima in the upper troposphere are related to the tropical-extratropical atmospheric interaction, to the equatorially trapped transient modes which are presumably created in the convective regions, or to a combination of both processes.

1. Introduction

The theoretical results of Webster and Holton (1982) evolving from a free surface barotropic model with a two-dimensional basic state suggest that extratropical disturbances can propagate into the tropics if the equatorial upper tropospheric flow is westerly or weak easterly. Webster and Holton also pointed out that the strength of the westerlies is important in determining the equatorial extent of the propagation as this sets the meridional group speed of the propagating modes. That is, the degree to which an extratropical disturbance can propagate into the tropics, or through the tropics into the other hemisphere, is proportional to the strength of the equatorial westerlies and is related to the location of the source of the disturbance in the middle latitudes relative to the location of the equatorial westerlies. Within the contexts of simpler barotropic models, Branstator (1983) and Karoly (1983) tended to substantiate the results of Webster and Holton.

Arkin and Webster (1985) attempted to test the theory of Webster and Holton (1982) by examining the distribution and variability of atmospheric perturbation kinetic energy (PKE). PKE was defined as the time-mean kinetic energy of those motions having time scales of less than one month. Arkin and Webster used

PKE as a measure to infer the degree of propagation of the extratropical waves into the tropics. In particular, they found that the PKE maximizes in the equatorial upper tropospheric westerlies over the central Pacific Ocean where a strong and positive relationship exists between the time-mean zonal wind component (i.e., \bar{U}) and PKE. On the other hand, there appeared to be no meaningful correlation between the time-mean meridional component (\bar{V}) near the equator and the PKE in the equatorial regions. They also found a distinct interannual variability in the \bar{U} -PKE relationship. The analysis indicated that the PKE is a minimum in the El Niño (large negative values of the Southern Oscillation Index; SOI) years when the westerly winds along the equator diminish and a maximum in the La Niña years (i.e., SOI ≥ 0) when the westerlies are strongest. The interannual variability of the two quantities is shown in Fig. 1.

A complementary theory to the Webster and Holton "westerly wave duct" theory has been advanced recently by Webster and Chang (1988). They noted that classes of latitudinally trapped transient modes, presumably created in the convective regions, are also longitudinally trapped in the regions of equatorial westerlies. Specifically, they showed that wave action flux should converge where $\partial\bar{U}/\partial x < 0$, or on the eastern side of the equatorial upper tropospheric westerlies. This implies that the PKE maxima, inside the equatorial westerlies, may be associated with the energy transfer process from the remote convective regions in

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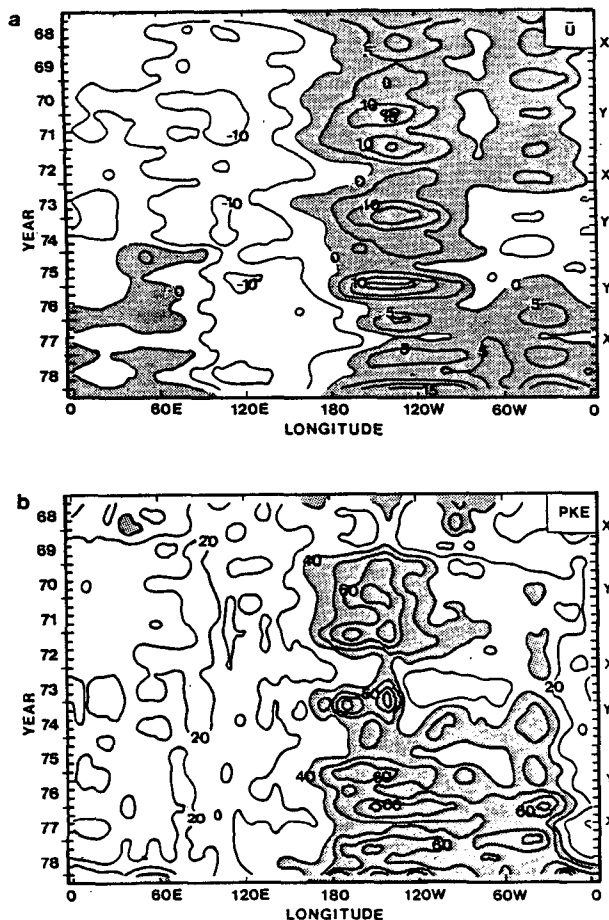


FIG. 1. Time-longitude sections of the 200 mb mean zonal velocity component (m s^{-1}) and the PKE ($\text{m}^2 \text{s}^{-2}$) averaged between 5°N and 5°S . Regions where $\bar{U} > 0$ and $\text{PKE} > 40 \text{ m}^2 \text{s}^{-2}$ are shaded. Times of maximum and minimum Southern Oscillation Index (SOI) are labeled along the abscissa as X's and Y's, respectively. (From Arkin and Webster 1985).

the tropics.¹ Webster and Chang emphasize that the two theories are not mutually exclusive and that the concentration of perturbation kinetic energy could depend on both the flux of energy from the higher latitudes through the westerly duct, as postulated by Webster and Holton (1982), and along the equator.

The results of Arkin and Webster (1985), thus, may be said to be consistent with the theories of both Webster and Holton (1982) and Webster and Chang (1988). The investigation by Arkin and Webster, however, was rather limited. For example, only data from the 200 mb level were studied. In the present study, we extend the work of Arkin and Webster by presenting the distribution of the PKE in the lower troposphere and investigating the vertical structure of the PKE along

some specific cross sections. Through this analysis, we hope to improve our understanding of the dynamics involved in the linkage of the PKE structure at the different levels and the mechanisms of the tropical-extratropical interaction.

2. Data description

The study utilizes the Climate Diagnostics Data Base (CDDDB) mean dataset from the National Meteorological Center (NMC). The dataset consists of calendar monthly mean values for the period from October 1978 to September 1985 of the three components of the wind field, temperature, geopotential height, specific humidity and vorticity and also the submonthly perturbation terms of these mean quantities. A perturbation quantity is thus defined as having a time scale of less than one month. The wind field and geopotential height data are archived at the 1000, 850, 700, 500, 300, 250, 200, 100 and 50 mb levels while the specific humidity is given only at the lowest four levels. Relative vorticity fields are calculated for the lowest seven levels. All fields are global and interpolated to a 2.5° latitude-longitude grid. In this study, we use only the mean zonal wind component, \bar{U} , and the mean monthly covariance $u'u'$ and $v'v'$ at each level. A critical review of the dataset is given by Trenberth and Olson (1988). All analyses and conclusions obtained from them must be considered relative to the caveats of Trenberth and Olson.

The outgoing longwave radiation (OLR) data used in this study are from the "Tropical Strip Wind and Outgoing Longwave Radiation" dataset from the operational tropical objective analyses of the NMC in an archive maintained by the Climate Analysis Center (CAC) of the NMC. The OLR data cover the time period from June 1974 to February 1985 with an exception of March to November 1978 and are set on a 72×23 Mercator latitude-longitude grid. The longitude spacing is 5° . In latitude, the spacing varies from 5° at the equator to 3.5° at the southern and northern boundaries at 48.1°S and 48.1°N . The details of the dataset can be found in Arkin (1982) and Arkin and Webster (1985).

3. Latitude-longitude distributions of the zonal wind component and PKE

a. The 200 mb flow field

The latitude-longitude distributions of the mean seasonal 200 mb zonal wind component (\bar{U}_{200}) and PKE have been described by Arkin and Webster (1985) using the data which covered the time period from 1968 to 1979. Similar patterns of \bar{U}_{200} and PKE_{200} for DJF (December, January and February) and JJA (June, July and August) are shown in Figs. 2 and 3, respectively, for two purposes: to compare the patterns with those of Arkin and Webster and to compare the

¹ Frederiksen and Webster (1988) show results of experiments with the NMC global spectral model which substantiate the free surface barotropic results of Webster and Chang.

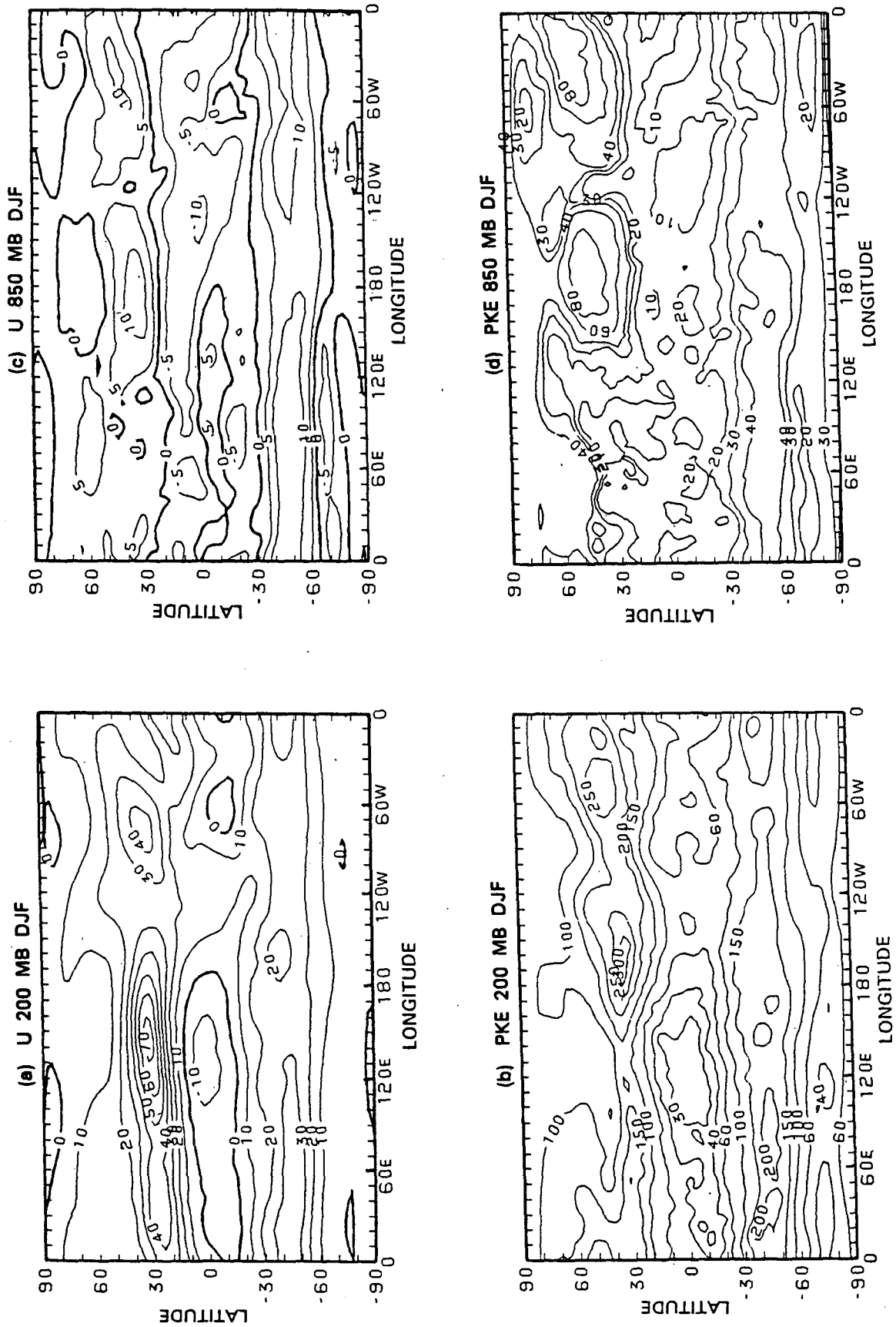


FIG. 2. Latitude-longitude distributions of the 200 mb (Panels a, b) and 850 mb (c, d) seasonal mean zonal wind component (m s⁻¹) and PKE (m² s⁻²) for DJF. Data are averaged over the period from 1978 to 1985.

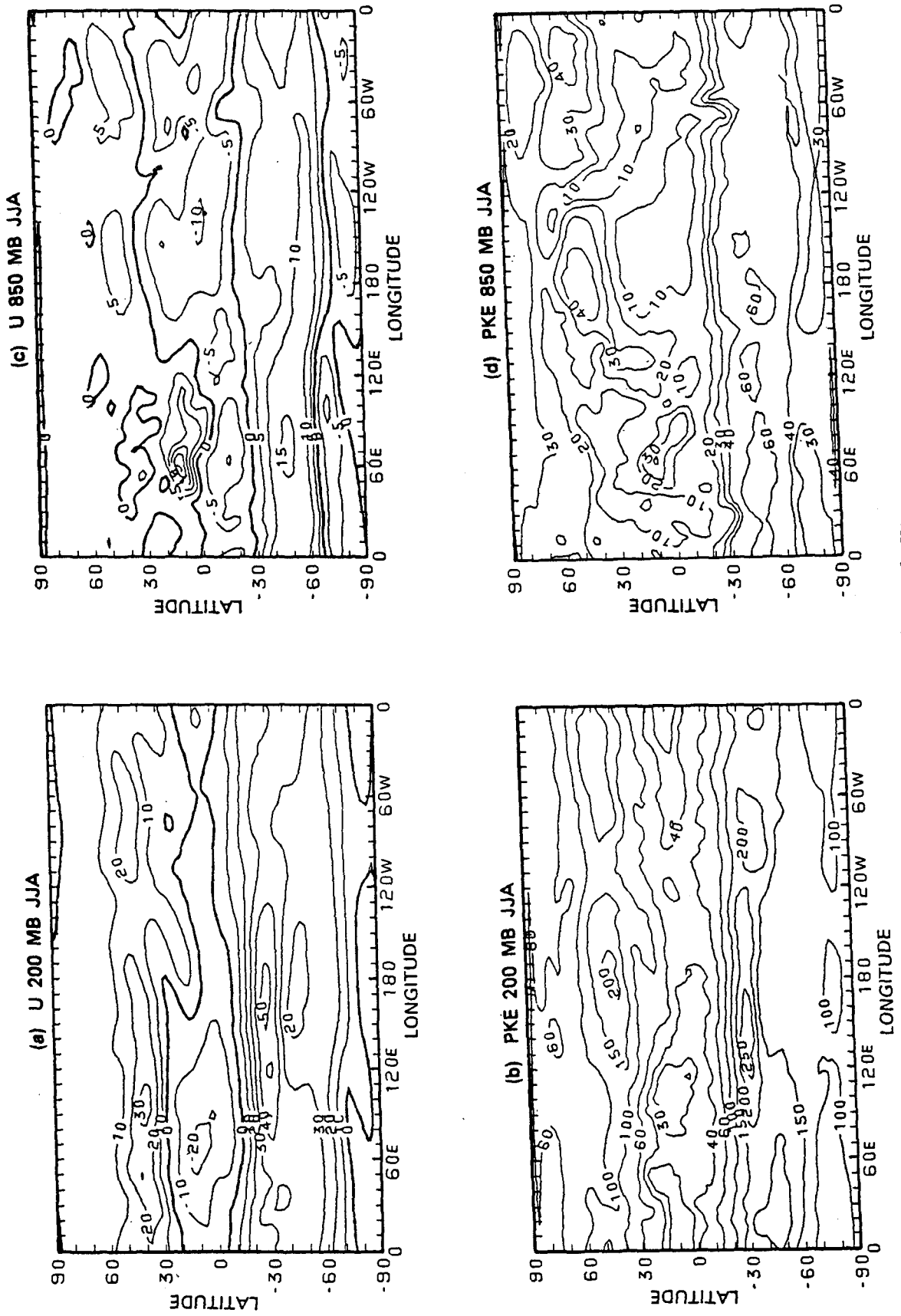


FIG. 3. The same as Fig. 2, but for JJA.

conditions at the different levels (200 mb and 850 mb) within the same dataset. The analysis shown here extends the results of Arkin and Webster for 50°N to 50°S to pole-to-pole.

From Figs. 2 and 3 we see that the 200 mb mean PKE is generally largest in the middle latitudes of both hemispheres from where it decreases both equatorward and poleward. Three minimum PKE bands can be found, one over the tropics and the other two over the high latitudes of the two hemispheres.

An interesting longitudinal structure exists in the relationship between the zonal wind component and PKE. In the middle latitudes, several maximum PKE centers are located over and downstream of the westerly jet streams. The minimum PKE centers are upstream of the jets. These features are consistent with the patterns of the band-pass filtered variance (representing fluctuations with period between 2.5 and 6 days) of the zonal and meridional wind components (Blackmon et al. 1977). This jet stream–PKE relationship is similar in both hemispheres except that the major jet stream and the largest PKE center are more in phase in the Southern Hemisphere. The difference between the hemispheres was first noted and described by Trenberth (1982, 1986). Arkin and Webster (1985) also emphasize this difference in terms of the \bar{U} -PKE but, at the same time, they suggest that the sparse data in the Southern Hemisphere may be responsible for the difference. In the tropics, the maximum PKE centers are found inside the tropical westerlies while the minimum PKE centers are located inside the tropical easterlies. That is, the maximum PKE is over the central-eastern Pacific Ocean and the Atlantic Ocean whereas the minimum PKE is over the eastern hemisphere and the central Americas. The PKE minimum over the central Americas appears more clearly than in the analysis of Arkin and Webster (see their Fig. 3a).

The different regional structure of the zonal wind–PKE relationship can be attributed to very important dynamic characteristics that occur as a function of latitude and is probably associated with the form of the circulation interactions between latitude bands. For example, the results of Webster and Holton (1982) suggest that tropical–extratropical interaction is much more likely in regions of westerlies than in regions of easterlies, which could account for the regional maxima of the tropical PKE.

Like the zonal wind component, the PKE distribution also shows significant spatial and temporal differences. In the middle latitudes, for example, the maximum westerlies become stronger and extend equatorward in the winter hemisphere while, simultaneously, they weaken and extend poleward in the summer hemisphere. Consistently, the maximum PKE band shows a similar north–south migration and a change in magnitude. In the tropics, the minimum PKE band moves southward in winter and northward in summer which appears to be linked very closely to

the changes (in both intensity and location) of the tropical easterlies and westerlies. Although from DJF to JJA the PKE over the central-eastern Pacific Ocean and the Atlantic Ocean diminishes as the zonal wind component changes from westerly to easterly, the magnitude of the PKE inside the easterlies shows very little seasonal change even though the easterlies strengthen greatly. The relationship between the changes of the tropical PKE and the tropical westerlies and easterlies will be discussed later.

So far, the major features described are consistent with the results of Arkin and Webster (1985). We will now see the extent to which they may be linked to low-level phenomena by considering the 850 mb flow characteristics.

b. The 850 mb flow field

The latitude–longitude distributions of the mean 850 mb zonal wind component and the PKE for DJF and JJA are also shown in Figs. 2 and 3, respectively. Similar to 200 mb, the 850 mb PKE also attains its maximum values in the middle latitudes of both hemispheres with minimum values in the tropics and high latitudes. In the Northern Hemisphere winter, two very distinct maximum PKE centers can be found. These are over the northern Pacific Ocean and the northern Atlantic Ocean. It would seem that these midlatitude PKE maxima are closely linked to the activity of the baroclinic eddies in these regions because they are located in the vicinity of the Aleutian Low and the Iceland Low, respectively, which were clearly identified long ago by Rossby et al. (1939) as the “centers of action.” These centers correspond to the highest variability in sea level pressure and the 500 mb geopotential height field (e.g., Blackmon 1976; Blackmon et al. 1977). It is important to notice that these PKE maxima are located downstream of the upper tropospheric westerly jet streams and are consistent in the vertical with the 200 mb PKE maxima. In the Southern Hemisphere, the maximum PKE band is collocated with the maximum westerly band in the extratropical regions. Generally, the maximum PKE band at 850 mb is poleward of that at 200 mb by about 10° of latitude.

In the tropics, the low-level PKE has its maxima and minima in the monsoon regions and the trade wind regions, respectively (also shown in Figs. 7 and 8). That is, the low-level PKE is largest in the westerlies and smallest in the easterlies, mirroring, to some extent, the relationship found at 200 mb. Thus, the PKE over the Asian monsoon regions in JJA is larger than that over the other corresponding latitudes. Similar relationships can also be found for the Australian monsoon regions in DJF.

The seasonal changes of the 850 mb PKE patterns are of considerable magnitude, especially in the Northern Hemisphere. For example, as the Aleutian Low and the Iceland Low weaken greatly from DJF to JJA,

the regional PKE consistently diminishes. Because the seasonal change of the atmospheric circulation in the Southern Hemisphere is relatively small, the PKE changes only a little from DJF to JJA there. In addition, the maximum and minimum PKE centers in the tropics also show a latitudinal migration following the seasonal swing of the monsoon systems and the trade winds.

c. PKE-OLR relationships

The latitude-longitude distribution of the mean OLR for DJF and JJA is shown in Fig. 4. PKE-OLR relationships can be examined by comparing the PKE patterns (Figs. 2, 3) and the OLR patterns (Fig. 4)

simultaneously, although the OLR data do not exactly cover the same time period.

In the extratropics, it is very difficult to find a meaningful PKE-OLR relationship based on the figures probably because the OLR distribution does not necessarily denote extratropical convection or the location of storm tracks. A much clearer PKE-OLR relationship can be seen in the tropics. There, the mean 200 mb PKE maxima (minima) are collocated with the OLR maxima (minima). For example, in winter, the OLR minima over the Indonesian regions, central Africa and the central Americas are all accompanied by PKE minima. On the other hand, the OLR maxima over the central-eastern Pacific Ocean and the Atlantic Ocean (also the western Indian Ocean) are collocated

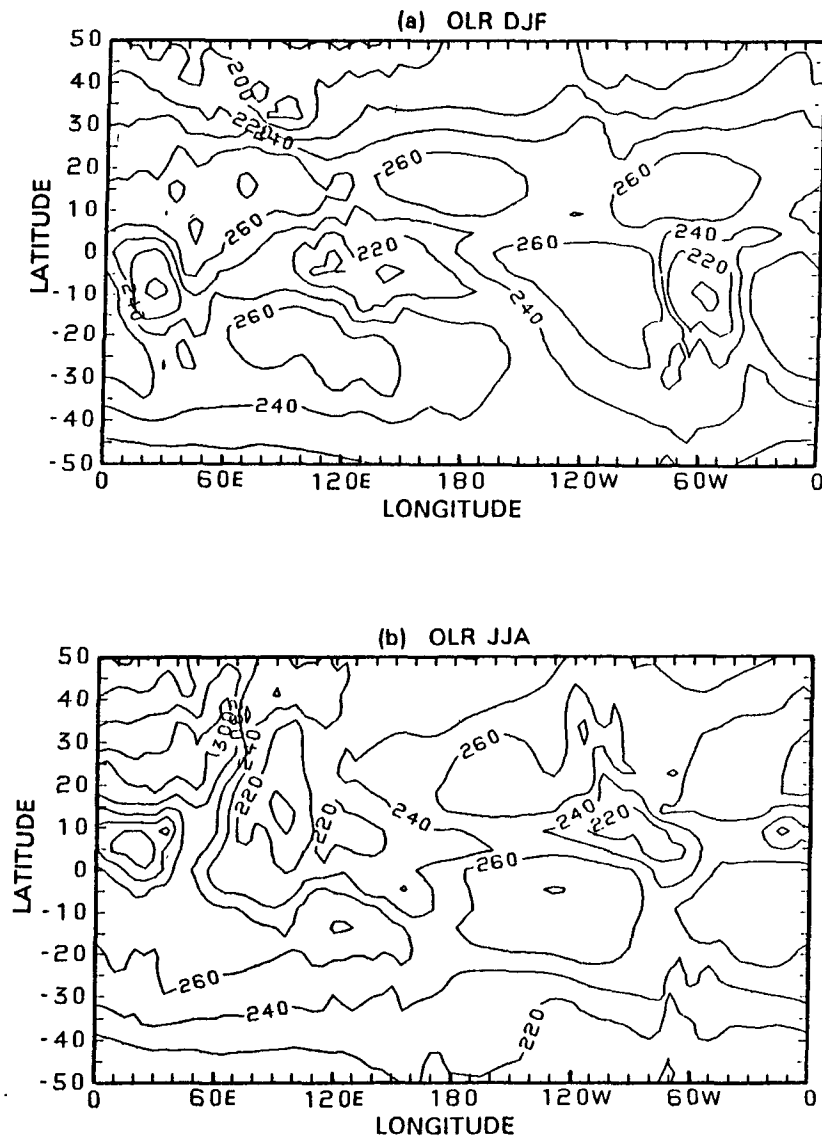


FIG. 4. Latitude-longitude distributions of seasonal mean OLR (wm^{-2}) for DJF (a) and JJA (b). Data are averaged from 1974 to 1985.

with PKE maxima. Thus, in the tropics, the relationship between the OLR and the motion field is less obvious than in the extratropics. Arkin and Webster (1985) also indicated that the central-eastern Pacific Ocean region was a minimum convective area although they did not show OLR distributions. Probably, a better comparison for the extratropics would be between the short term variance of the PKE and the OLR. Unfortunately, daily values of PKE and OLR were not available for this study.

The relationship between the mean 850 mb PKE and the OLR in the tropics is very different. In the lower troposphere, the PKE maxima appear to be collocated with the OLR minima and vice versa. For example, the OLR minima in the Asian and Australian monsoon regions are accompanied by the PKE maxima. On the other hand, the OLR maxima over the Atlantic Ocean and the central Pacific Ocean are collocated with the PKE minima.

4. Vertical structure of the zonal wind component and PKE

a. Extratropical regions

The vertical structures of the mean zonal wind component and the PKE and their departures from the zonally averaged values for DJF and JJA are shown in Fig. 5 for the Northern Hemisphere. The quantities are averaged between 25° and 35°N for DJF (Figs. 5a–d) and between 40° and 50°N for JJA (Figs. 5e–h). The different latitude belts are chosen to reflect the maximum westerlies obtained from Figs. 2 and 3.

Figure 5 shows that the extratropical PKE maxima are located between 300 mb and 200 mb, the height at which the maximum westerlies are found. Great similarity exists between the shapes of the PKE and \bar{U} fields except that the maximum PKE centers are just downstream of the maximum westerly centers. For example, in DJF three upper tropospheric westerly jet streams are found near the longitudes of 40°E, 130°E and 80°W and each is accompanied by an out-of-phase PKE maximum. In JJA, the wind field in the 25°–35°N belt weakens significantly, consistent with the northward migration of the westerly band, although the westerly maxima are still accompanied by out-of-phase PKE centers of smaller magnitude.

The structure of \bar{U} and PKE can be examined further by removing the zonally averaged values at each height. The cross sections (Figs. 5c, d, g and h: the “starred quantities” indicate the quantities with the vertically dependent zonal average removed) confirm a minimal tilt of \bar{U} and PKE in the vertical.

The vertical structures of \bar{U} and PKE and their departures from the zonally averaged values are shown in Fig. 6 for the Southern Hemisphere extratropics. Again, the maximum values of \bar{U} and PKE are located between 300 mb and 200 mb and show a noticeable

seasonal variation. The vertical structures of the PKE and \bar{U} fields, however, are not quite the same (cf. Figs. 6a, e with 6b, f). Two more differences exist between the hemispheres. First, the longitudinal variability of both \bar{U} and PKE in the Southern Hemisphere is relatively smaller. Second, the PKE maximum is collocated with the zonal wind maximum, or, alternatively, the PKE maximum downstream of the westerly jet stream is located closer to the jet maximum in the upper troposphere in the Southern Hemisphere as noticed by Arkin and Webster (1985).

b. Equatorial regions

Figures 7a–c show longitudinal variability of the mean OLR and the vertical structure of \bar{U} and PKE averaged between 5°S and 5°N for DJF, respectively. The departures of \bar{U} and PKE from the zonal averages (i.e., U^* and PKE^*) are shown in Figs. 7d and 7e.

The \bar{U} -field shows a clear demarcation between the upper and lower troposphere, which appears to be completely out of phase. Equatorial westerlies extend between 500 and 100 mb in the western hemisphere and below 700 mb over the Indian Ocean and the western Pacific Ocean. Westerly maxima exist at 200 mb over the central-eastern Pacific Ocean and the Atlantic Ocean. Equatorial easterlies prevail elsewhere with a maximum center in the upper troposphere over the Indonesian region with two others in the lower troposphere over the central-eastern Pacific Ocean and the Atlantic Ocean. Thus, the regimes of easterly and westerly winds show clearly the “Walker Circulation” along the equator. The removal of the zonal average discloses two cells, the stronger being consistent with the ascent over the warm pool regions of the western Pacific and the Indian oceans. The three PKE maxima (more easily identified in Fig. 7e) are found close to the three maximum westerly centers with the magnitude of the PKE positively proportional to the magnitude of the westerlies. The three PKE minima are collocated with easterly maxima but the magnitude of the PKE maxima does not show a simple relationship with the magnitude of the easterly maxima. These relationships correspond to those found by Arkin and Webster (1985) for the 200 mb level.

In JJA (Fig. 8), the zonal wind field in the western hemisphere diminishes significantly at all levels, especially the magnitude of the upper tropospheric westerlies which shrink in extent and change their location at higher levels. Again, the deviations from the zonal average highlight these changes. On the other hand, the zonal wind field in the summer eastern hemisphere becomes much stronger, presumably due to the increase of the latitudinal heating gradient across the equator. The magnitude of the upper level PKE maxima over the central-eastern Pacific Ocean and the Atlantic Ocean becomes correspondingly smaller while the magnitude of the low-level PKE maximum between

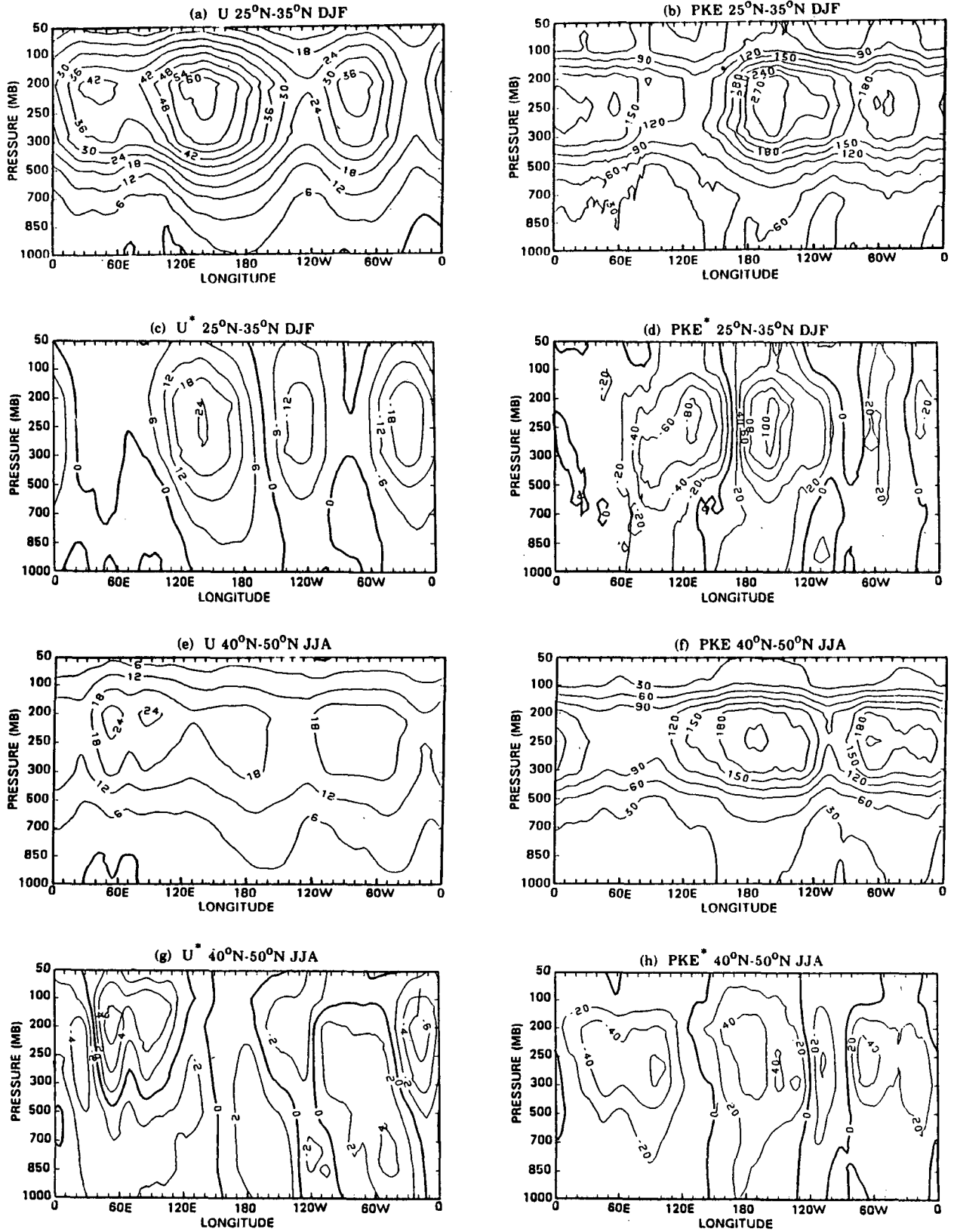


FIG. 5. Longitude-height distributions of the zonal wind component (\bar{U} , $m\ s^{-1}$) and perturbation kinetic energy (PKE, $m^2\ s^{-2}$) and for the quantities with the zonal mean removed ("starred" quantities). DJF quantities are averaged between 25° and 35°N and, for JJA, 40° and 50°N. The averaging belt is changed in order to follow the region of the maximum westerlies.

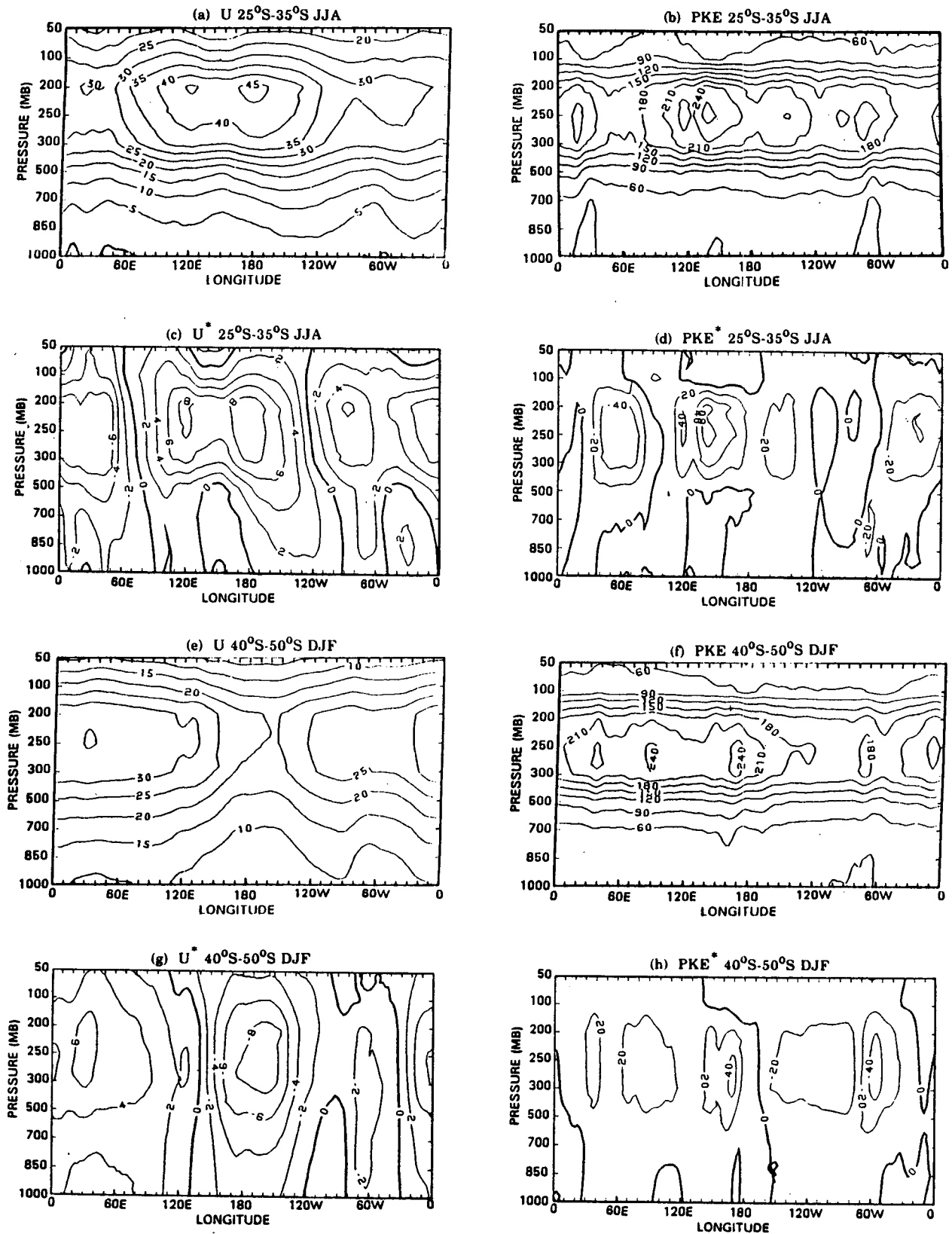


FIG. 6. As in Fig. 5 except for the Southern Hemisphere. Data are averaged between 25° and 35°S for JJA and between 40° and 50°S for DJF.

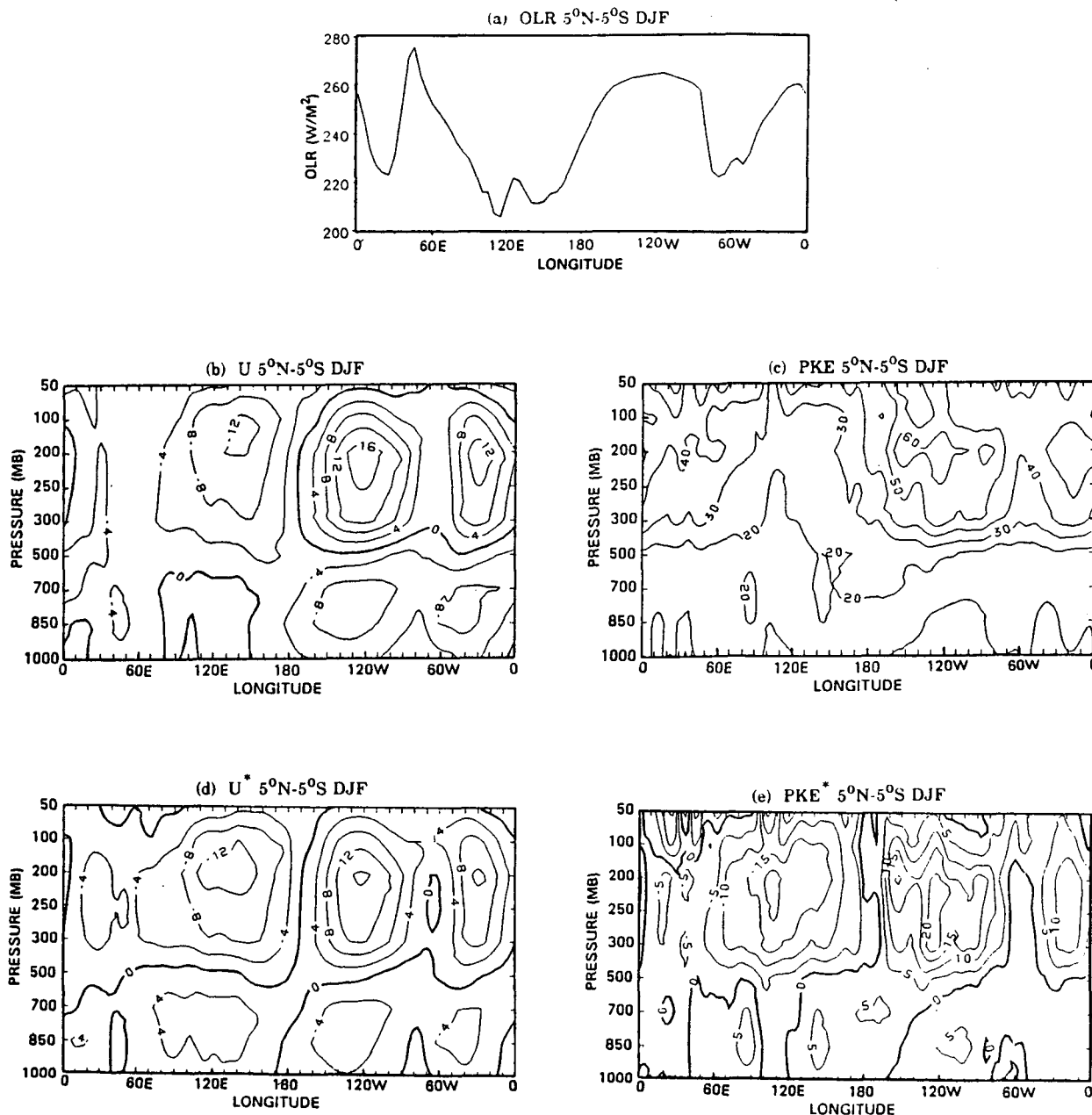


FIG. 7. As in Fig. 5 for DJF between 5°N and 5°S . Panel (a) shows the longitudinal distribution of the OLR along the equator.

the Indian Ocean and the western Pacific Ocean becomes larger.

Two other features should also be mentioned. First, even though the equatorial upper tropospheric easterlies over the Indian Ocean strengthen distinctly from winter to summer, there is no corresponding seasonal change in the magnitude of the PKE. That is, the PKE remains small in the upper troposphere of the eastern hemisphere. Second, although the equatorial upper tropospheric westerlies diminish in the upper troposphere and exist only at very high levels in summer,

the locations of the PKE maxima show very little change although the magnitudes become a little smaller. The two PKE maxima, however, are not collocated with the maximum westerlies at 100 mb but rather with the weaker easterlies at 200 mb, or with the anomalous westerlies as revealed by the U^* field in Fig. 8d.

Finally, Figs. 7d and 8d allow a comparison of the strength of the Walker Circulation between the boreal winter and summer. In the upper troposphere, the differences between the extremes of U^* at about 100°E

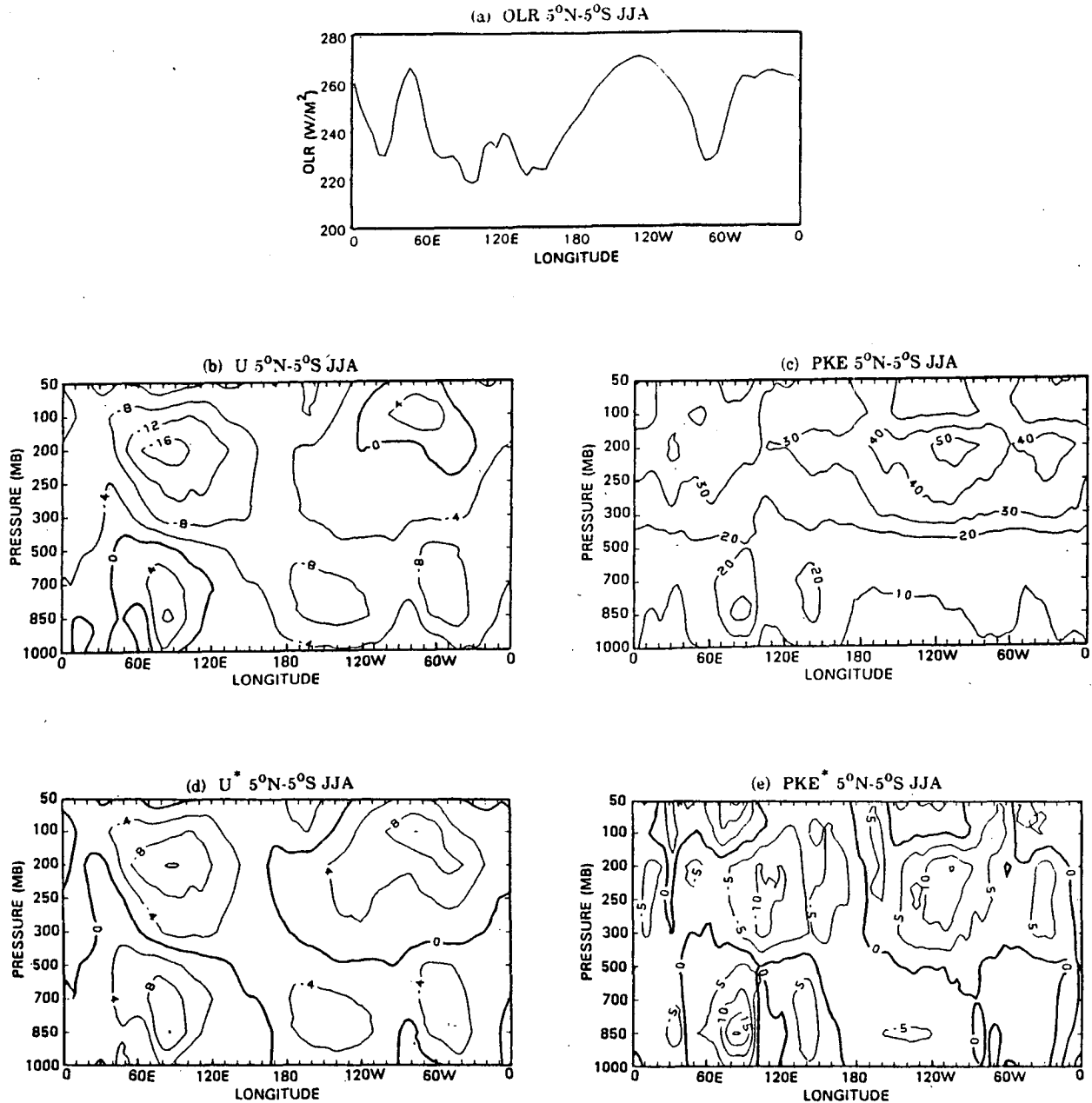


FIG. 8. As in Fig. 7, but for JJA.

and 120°W decrease from 28 m s^{-1} in DJF to 20 m s^{-1} in JJA. Although the difference is consistent with a decrease of 20 w m^{-2} in the OLR values between the western Indian Ocean and Indonesia, the decrease is small across the Pacific Ocean where the largest changes in U^* occur. At the same time, the longitudinal sea surface temperature (SST) gradients along the equator do not change much. Thus, the reason for the seasonal variation of the Walker Circulation as shown in these figures remains obscure.

5. Discussion and conclusions

We have extended the analysis of Arkin and Webster (1985) by considering the vertical distribution of the mean PKE and its relationship to the structure of the \bar{U} -field. Two important features emerge from the analysis. First, the PKE maxima (minima) are located downstream (upstream) of the westerly jet streams in the middle latitudes, particularly in the Northern Hemisphere, while the PKE maxima (minima) lie just

inside the strongest westerlies (easterlies) in the tropics. These upper level zonal wind–PKE relationships are consistent with the results of Arkin and Webster. Our analysis shows that at lower levels, the extratropical PKE is maximum in the vicinity of the semipermanent centers of action but in the monsoon circulations or in the near equatorial circulation in the vicinity of the “maritime continent” in the tropics. The PKE is a minimum in the tropical–subtropical trade wind regions. Second, the PKE structure is more in phase in the vertical in the middle latitudes, especially in the Northern Hemisphere, but completely out of phase in the tropics where it duplicates the zonal velocity distribution.

In the extratropics, the location of the PKE maxima suggests that the PKE is produced by baroclinic instability processes. This genesis would be consistent with the small tilt observed in the vertical. In the tropics, the magnitude of PKE may be assumed to be a measure of the activity of the propagating disturbances from the extratropics to the tropics, as suggested by Webster and Holton (1982), or the degree of energy accumulation along the equator as postulated by Webster and Chang (1988). *It may well be a combination of both effects.* One process that was ruled out by Webster and Chang was that the PKE maximum is produced by local hydrodynamical instability of the equatorial westerlies. They conducted a random perturbation of a basic state which contained both shearing and stretching deformation. The basic state used was very similar to the 200 mb flow shown in Fig. 2a. The integration proved stable, at least relative to a 10-day e -folding dissipation rate. This stability is to be expected, as the upper tropospheric westerlies are a region of minimal latitudinal shear.

Thus, the regional difference of the vertical structure of PKE is not simply the consequence of the structure of the zonal wind structure but, rather, associated with the dominant dynamics of the atmospheric circulation which differ as a function of latitude. The westerly jet streams are very important as a source of transient disturbances which lead to PKE maxima downstream. Disturbances associated with the PKE maxima may propagate equatorward through the westerly ducts of the tropical upper troposphere. As is shown by the PKE–OLR relationship, in the tropics the upper tropospheric PKE maxima are not collocated with local convection which suggests that the PKE maxima may have remote sources.

Arkin and Webster (1985) considered the tropical PKE maxima as being linked to tropical–extratropical interaction because the PKE maxima are located inside westerlies and the westerlies are favorable to the latitudinal interaction via Rossby wave propagation. Accordingly, the tropical PKE minima in the upper tropospheric easterlies may be due to the weakness or lack of the tropical–extratropical interaction because of the existence of a critical line poleward of the easterlies.

On the other hand, Webster and Chang (1988) suggest that the distribution of PKE may also be related to the zonal wind variation in longitude. Regions where $\partial\bar{U}/\partial x > 0$ are divergent regions of wave energy. On the other hand, where $\partial\bar{U}/\partial x < 0$, a wave energy convergence exists. According to this theory, the maximum PKE in the equatorial westerlies may be linked to the energy created in the convective regions which is transferred from the convective regions to the nonconvective regions where it accumulates and subsequently propagates to higher latitudes.

To test the Webster and Chang (1988) theory, the $\partial\bar{U}/\partial x$ and PKE* distributions, averaged between 5°N and 5°S in latitude and between 100 mb and 300 mb in height, are plotted in Fig. 9 as a function of longitude for both DJF and JJA. In winter, the PKE maxima over the central-eastern Pacific Ocean and the Atlantic Ocean are located at the vicinity of the maximum negative values of $\partial\bar{U}/\partial x$, and show a fairly convincing correlation. In summer, the longitudinal stretching de-

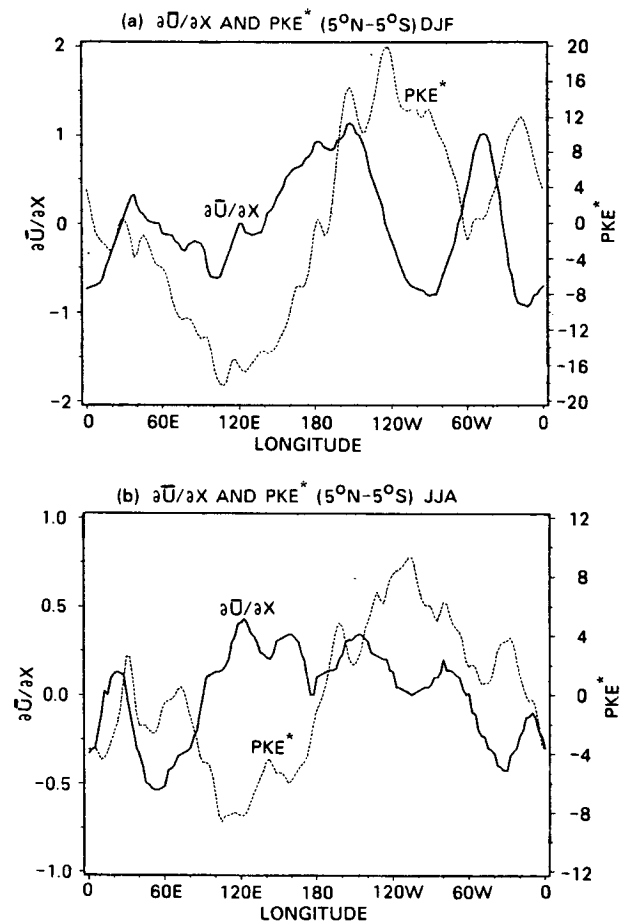


FIG. 9. Longitudinal variability of $\partial\bar{U}/\partial x$ and PKE* averaged between 5°N and 5°S in latitude and between 100 mb and 300 mb in height for DJF (a) and JJA (b). Units are in m s^{-1} per 250 km for $\partial\bar{U}/\partial x$ and $\text{m}^2 \text{s}^{-2}$ for PKE*.

formation is much weaker and, although the PKE is correspondingly weaker as well, there is still a weak correlation between $\partial\bar{U}/\partial x$ and PKE.

Both the theory of Webster and Holton (1982) and Webster and Chang (1988) could explain the existence of the tropical upper tropospheric PKE maxima by a horizontally propagating process of energy from remote regions. This study fails to differentiate between the theories, but it presents results which are consistent with both. We are currently experimenting with the Webster and Chang model with both extratropical and tropical forcing in an attempt to simulate the PKE distribution relative to the equatorial zonal velocity distribution shown in Figs. 7 and 8.

One problem which is common to both theories has not been resolved. In the regions of the upper tropospheric westerlies, the transients become vertically decoupled, but one would expect vertical coherence for the propagating deep tropical modes. Of course, one could speculate about the existence of differential dissipation in the vertical and note that the nonconvective regions are subsident, which would produce a subsequent stability change. Neither Webster and Chang (1988) nor Webster and Holton (1982), however, offered a clear explanation of how this structure transition takes place. It is obvious that many of the answers to the questions posed here and elsewhere are thwarted by the monthly mean characteristics of the data, especially the variance. The submonthly structure is now being examined using the ECMWF twice-daily dataset. In addition, the Webster and Chang experiments will be rerun with a baroclinic model.

Acknowledgments. The research reported in this study was supported by NSF Grants ATM 83-18852 and ATM 87-03267. Computing was carried out at the National Center for Atmospheric Research. We are appreciative of the Monsoon Program of the US-PRC Protocol in Atmospheric Science which supported Mr. Yang during the early period of his tenure at the Penn-

sylvania State University. We acknowledge discussions with our colleagues, Mr. Min Dong and Dr. Hai-Ru Chang. We also thank Dr. P. A. Arkin of the NMC Climate Analysis Center for providing the data used in this study and Ms. Lisa Davis for her careful editing of the manuscript.

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