The Energetics of African Wave Disturbances as Observed During Phase III of GATE[1,2]

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ABSTRACT

Fields of the meteorological variables in composite wave disturbances constructed for the region from 10°E to 31°W and 1°S to 26°N and for land and ocean subregions are used to diagnose energy transformations in African waves. The composites are based on data contained in the GATE Quick Look Data Set for the period 23 August to 19 September, 1974. The measurements indicate that for the region as a whole the kinetic energy of the waves is maintained almost equally by conversions from zonal kinetic energy and eddy available potential energy. Eddy available potential energy is supplied by the zonal available potential energy at a comparable rate. From the measured conversion rates it is estimated that in the absence of friction the kinetic energy of the waves would double in about 3 days.

Measurements for the subregions show that the conversion from zonal to eddy kinetic energy is stronger over the limited oceanic region considered than over the land, while conversely, the conversion of eddy available potential energy to eddy kinetic energy is stronger over the land than over the ocean. The conversion of zonal to eddy available potential energy differs little between the two regions. From these findings, and budgetary considerations, it is inferred that latent heat release in organized convection plays an important role in the wave growth and maintenance in west Africa but not over the adjacent ocean. This conclusion, however, must be regarded as tentative.

The distributions of the various energy conversion processes in meridional cross section are considered. The conversions of zonal kinetic and available potential energies to their corresponding eddy energies are characterized by concentrated regions of high values closely associated with the mid-tropospheric easterly jet stream. The conversion of eddy available potential energy to eddy kinetic energy exhibits a complex pattern in which the net conversion is a small residual. Consequently this conversion cannot be regarded as being determined with the same high degree of reliability as the other two. However, major features of the pattern can be explained on physical grounds.

1. Introduction

Numerous studies have documented the existence of traveling wave disturbances over west Africa and the adjacent ocean during the season from June to October. The characteristics of the disturbances have been studied extensively with use of conventional synoptic analysis (Carlson, 1969a, b), spectrum analysis (Burpee, 1972) and compositing techniques (Burpee, 1974; Reed *et al.*, 1977). The results of these studies indicate that the disturbances are typically of 2000–2500 km in wavelength, have periods of 3–4 days and propagate westward at speeds of 6–7° longitude day^{-1} (7–9 m s^{-1}). They appear to form over central Africa in the zone of cyclonic wind shear on the south flank of the mid-tropospheric easterly jet stream and they achieve their greatest strength at the level of the jet core (650 mb). Associated temperature perturbations are small, being generally less than 1°C; however, it is well established that the disturbances are cold core below the level of the jet maximum and warm core above. Convective activity and precipitation amounts are greatest in the region just ahead of the wave trough, especially along and south of the disturbance path.

A question of fundamental importance is the origin of the waves. This question has been investigated by Burpee (1972), Pedgley and Krishnamurti (1976) and Rennick (1976), all of whom have found that the necessary condition for the instability of an internal jet, i.e., a reversal in sign of the meridional gradient of *potential* vorticity (Charney and Stern, 1962), was met in the region of formation during periods of observed wave activity. When tested, the necessary condition for barotropic instability (reversal in the meridional gradient of *absolute* vorticity) has also been found to be satisfied.

A related question which has been treated in varying degrees by the foregoing authors (Burpee, Pedgley and

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Krishnamurti, Rennick) is that of the energy sources responsible for the growth and maintenance of the waves. A number of such sources have been identified in earlier studies of tropical wave dynamics. These are 1) the transformation of zonal kinetic energy to eddy kinetic energy (Nitta and Yanai, 1969; Bates, 1970), 2) the generation of eddy available potential energy by latent heat release (Manabe *et al.*, 1970; Nitta, 1970; Wallace, 1971) and 3) mid-latitude forcing by the pressure work interaction (Mak, 1969). In principle a possible additional source of wave energy is the transformation of zonal available potential energy to eddy available potential energy. However, because of the weak temperature gradients that prevail in most tropical regions, this process is generally of little consequence. For the much studied moist disturbances of the western Pacific latent heat release is by far the main source of wave energy (Nitta, 1972).

As yet no attempt has been made to construct a complete energy budget for the African wave directly from observational data. Burpee (1972) has made limited calculations based on observations for five Augusts at a single station (Niamey, 13.5°N, 2.2°E). He found that both the conversions of zonal to eddy kinetic energy and of zonal to eddy available potential energy contributed to the growth of wave energy. The latter, baroclinic process was measured to be the larger of the two. The unusual size, by tropical standards, of this process was attributed to the relatively strong temperature contrast that exists in summer over Africa between the hot, dry air of the Sahara and the cooler air of maritime origin to the south. Burpee did not attempt to measure either the generation of eddy available potential energy by latent heat release or the conversion of eddy available potential energy to eddy kinetic energy.

Pedgley and Krishnamurti (1976) used observational data in conjunction with a two-level, quasi-geostrophic, dry adiabatic model to diagnose the energy exchanges for a special case study. They examined the processes responsible for the growth of disturbance kinetic energy and found the conversion from zonal kinetic energy to be nearly an order of magnitude larger than the conversion from eddy available potential energy in the zone from 7° to 27°N. This result must be accepted with reservations, however, since the uppermost level in their model was 700 mb, while Nitta (1972) indicates that in many tropical disturbances the largest positive contribution to the conversion of eddy available potential energy to eddy kinetic energy comes from the layer between 400 and 200 mb. The use of dry dynamics precluded consideration of the role of latent heat release.

Rennick's (1976) study yielded a complete energy budget. However, the results were obtained from a linearized pseudospectral model applied to idealized mean or climatological states, not from observations of individual states. The principal finding was that the conversion of zonal to eddy available potential energy is about an order of magnitude smaller than the conversion of zonal to eddy kinetic energy. From this she concluded that zonal kinetic energy is the source of the wave energy and that the transport of heat and associated overturning are of minor importance in the wave development. The energetics of moist and dry models were found to differ only slightly, implying that latent heat release is also of little consequence to the wave growth. A crucial test of the reliability of these results is the fidelity with which the model reproduces observed fields of the variables in African waves (e.g., Reed *et al.*, 1977). Although there are some points of agreement, there are also major differences. Under the circumstance it would seem premature to accept the results as fully applicable to the waves that occur in nature.

From the studies conducted to date it is fair to say that a clear picture of the energetics of African waves has not yet emerged. Indeed in some instances the results are contradictory. Thus, there is a need for further studies of the energy processes in the disturbances, particularly studies utilizing extensive observational data and free of modeling assumptions. In the present study we will use composite fields derived in an earlier investigation of wave properties and structure (Reed *et al.*, 1977) to determine various aspects of the energetics of the waves that occurred during a four-week period of the GARP Atlantic Tropical Experiment (GATE). The fields are based on data for the region from 10°E to 31°W and 1°S to 26°N. Computations are carried out for the layer from the surface to 100 mb. Three processes which contribute to the growth of the kinetic and available potential energies of the waves are computed. These are the conversions of zonal kinetic energy and eddy available potential energy to eddy kinetic energy and the conversion of zonal to eddy available potential energy. No attempt is made at this time to measure directly the generation of eddy available potential energy by release of the latent heat of condensation in the disturbances, though some inferences will be made regarding this process from budgetary considerations. Since the computations are carried out for a limited latitude belt, it is possible that energy fluxes and pressure-work interactions at the northern and southern boundaries play a role in the energy balance. However, we have not attempted to evaluate these effects. The results of the previous study (Reed *et al.*, 1977) suggest that the wave fluctuations are confined mainly to the area of study. This fact, coupled with the close association of the disturbances with the mid-tropospheric jet stream over Africa, leads us to believe that the wave energy is derived from internal conversions and not from energy transfers across the boundaries. Since the wave intensity varies only slightly in the longitudinal direction, the net energy transfer across the eastern and western boundaries is almost certainly negligible.

2. The energy equations and computations

The appropriate equations for investigating the growth of wave energy were first derived by Lorenz (1955) and are presented here essentially in the form and with the notation given by Muench (1965). They express the time rate of change of eddy kinetic energy and eddy available potential energy. Thus,

$$\frac{\partial K_E}{\partial t}=C_E+C_K+BK_E+B\Phi_E-D_E, \tag{1}$$

$$\frac{\partial A_E}{\partial t}=C_A-C_E+BA_E+G_E, \tag{2}$$

where K_E is the eddy kinetic energy, A_E the eddy available potential energy, C_E the conversion of eddy available potential energy to eddy kinetic energy, C_K the conversion of zonal kinetic energy to eddy kinetic energy, C_A the conversion of zonal available potential energy to eddy available potential energy and t is time. The expressions for these energies and conversions appear below. The other terms in (1) and (2) are not expressed explicitly since no attempt will be made to evaluate them. These additional terms represent boundary fluxes of energy (BK_E, $B\Phi_E$ and BA_E), the generation (or dissipation) of eddy available potential energy by heat sources and sinks (G_E) and frictional dissipation of eddy kinetic energy (D_E). Note that in the following expressions C_E is positive (gain of eddy kinetic energy at expense of eddy potential energy) when warm air rises and cold air sinks, and that C_K and C_A are positive (increases in eddy energy at the expense of zonal) when the eddy momentum and heat fluxes are down the mean momentum and temperature gradients, respectively:

$$K_E=\frac{1}{g}\int_{100}^{p_s}\frac{\overline{[u'^2+v'^2]}}{2}dp \tag{3}$$

$$A_E=\int_{100}^{p_s}\frac{\overline{[T'^2]}}{2\bar{\sigma}}dp \tag{4}$$

$$C_E=-\frac{1}{g}\int_{100}^{p_s}\frac{R}{p}\overline{[\omega'T']}dp \tag{5}$$

$$C_K=-\frac{1}{g}\int_{100}^{p_s}\overline{[u'v']\frac{\partial[u]}{\partial y}}dp-\frac{1}{g}\int_{100}^{p_s}\overline{[v'^2]\frac{\partial[v]}{\partial y}}dp$$
$$-\frac{1}{g}\int_{100}^{p_s}\overline{[u'\omega']\frac{\partial[u]}{\partial p}}dp-\frac{1}{g}\int_{100}^{p_s}\overline{[v'\omega']\frac{\partial[v]}{\partial p}}dp \tag{6}$$

$$C_A=-\int_{100}^{p_s}\overline{\frac{[v'T']}{\bar{\sigma}}\frac{\partial[T]}{\partial y}}dp-\int_{100}^{p_s}\overline{\frac{[\omega'T']}{\bar{\sigma}}\frac{\partial[T]^*}{\partial p}}dp. \tag{7}$$

Further definitions are as follows:

u zonal wind component, positive to the east
v meridional wind component, positive to the north
p pressure
p_s surface pressure
g acceleration of gravity
T temperature
$\bar{\sigma}$ mean static stability $\{=g(c_p^{-1}\overline{[T]}-pR^{-1}\partial\overline{[T]}/\partial p)\}$
c_p specific heat at constant pressure
R gas constant for dry air
ω vertical $p-$ velocity $[=dp/dt]$
y northward directed coordinate.

In the above expressions $[(\ )]$ represents a zonal average of the quantity $(\ )$ and $\overline{[(\ )]}$ represents a meridional average of the zonal average (area mean). A prime indicates a deviation from a zonal average and an asterisk the deviation of a zonal average from the area mean. Thus,

$$(\ )=[(\ )]+(\ )' \quad\text{and}\quad [(\ )]=\overline{[(\ )]}+(\ )^*.$$

Computations have also been made of the zonal kinetic energy

$$K_Z=\frac{1}{g}\int_{100}^{p_s}\frac{\overline{[u]^2+[v]^2}}{2}dp \tag{8}$$

and zonal available potential energy

$$A_Z=\int_{100}^{p_s}\frac{\overline{T^{*2}}}{2\bar{\sigma}}dp. \tag{9}$$

Since the Hadley circulation is believed to extend well beyond the region of study (see Newell *et al.*, 1972), it is not possible to obtain a meaningful measurement of the conversion of A_Z to K_Z, and thus this conversion is not included in the results.

The expressions under the overbars in the integrands of Eqs. (3)–(7) were evaluated at five latitudes, 4° apart, with the central latitude located at 11–12°N (the average latitude of the disturbance path) and at 50 mb intervals in the vertical. The method of deriving the fields of quantities appearing in the integrands is described in the next section. Horizontal and vertical derivatives appearing in the integrands were determined from cubic splines fitted to the grid-point data. Vertical integration was performed by the trapezoidal rule. Regional averages are simply the means of the integrated values for the five latitudes. They apply, therefore, to the zone from about the equator to just beyond 20°N.

Computations have been carried out for three regions—the whole region from 10°E to 30°W and the so-called land and ocean subregions separated by the 15°W meridian. Because of the small longitudinal

TABLE 1. Number of observations of wind (u, v), temperature (T) and dew point (T_d) at surface and standard pressure levels.

	Ocean			Land			Whole		
	u, v	T	T_d	u, v	T	T_d	u, v	T	T_d
Surface (mb)	3767	3842	—	7660	7581	7159	11427	11423	—
1000	814	1265	1215	160	222	216	9 4	1487	1431
950 (600 m)	527	—	—	1692	—	—	2219	—	—
915 (900 m)	516	—	—	1610	—	—	2126	—	—
850	1401	1369	1310	1833	414	406	3233	1784	1716
790 (2100 m)	461	—	—	1293	—	—	1754	—	—
700	1329	1373	1320	1403	434	421	2730	1808	1740
500	1193	1369	1312	671	430	414	1864	1800	1727
400	1170	1351	1287	581	426	412	1750	1778	1699
300	1147	1305	1205	548	402	395	1684	1708	1601
250	1139	1278	—	538	395	—	1676	1674	—
200	1101	1267	—	504	391	—	1603	1659	—
150	1051	1239	—	478	383	—	1529	1623	—
100	936	1150	—	431	374	—	1367	1525	—

extent of the ocean region, as defined, and because coastal reports are included in the ocean data base, the ocean results are representative of only a narrow coastal strip and cannot be presumed to apply to the tropical Atlantic as a whole or to any large part of it. Similarly, the land results apply only to the African bulge and not to all of tropical Africa.

3. Data

The fields of u, v, T and ω required for calculating the integrands of (3)–(9) were taken from an earlier study of the authors (Reed *et al.*, 1977). In that study we used all surface and upper air data contained in the GATE Quick Look Data Set for the 28-day period from 23 August to 19 September, 1974, and for the area from 10°E to 31°W and 1°S to 26°N to construct composite fields of the meteorological variables in the wave disturbances. Composites were constructed for the whole region defined above and for the land and ocean subregions.

The variables were computed at an array of 56 grid points consisting of eight points in the east–west direction, separated by approximately 3° of longitude, and seven points in the north–south direction, separated by 4° of latitude. Only points for the five innermost latitudes were used in making the energy computations, since the fields tended to become ragged in the outer rows where observations were relatively sparse. The coordinate system is centered on the disturbance center at 700 mb, defined as the point of maximum vorticity. The reader is referred to the earlier paper for more details of the compositing scheme and for illustrations of the various mean and perturbation fields.

The compositing was carried out first for the standard levels given in the Quick Look Data Set (the routine, operational levels). The levels employed and the number of observations available at each level are shown in Table 1. Cubic splines were then used to interpolate the data at 50 mb intervals in the vertical for the purpose of obtaining the greater resolution needed in the energy computations. The interpolated data for the whole region, as initially obtained, were found to have undesirable characteristics at the lower levels. The difficulty was traced to the fact that certain levels were dominated by either land or ocean data in an alternating manner (see Table 1) and that the near-surface wind fields and thermal stratification were substantially different in the two regions. Thus unrealistic fluctuations developed in the vertical. To overcome this problem whole region fields for levels below 700 mb were obtained by averaging the results of the spline interpolations done separately for each subregion. From 700 mb upward this procedure was not necessary, the number of observations being more nearly equal or the regional differences less pronounced. We will hereafter refer to results based on fields obtained from the foregoing procedure as *combined* region results to distinguish them from those obtained totally from interpolation of whole region composites.

The bottom level for the combined region is considered to be 1000 mb, approximately the average of the mean ocean and land surface pressures (1012 and 985 mb, respectively). Surface values of the variables over land were used in obtaining 1000 mb values for the combined region.

4. Results

The main results of the energy computations are presented schematically in Fig. 1. First considering the combined region, we note that the eddy kinetic energy K_E is about twice the eddy available potential energy A_E and that both are about an order of magnitude smaller than the corresponding mean energies (K_Z,A_Z). The eddy kinetic energy is seen to be maintained

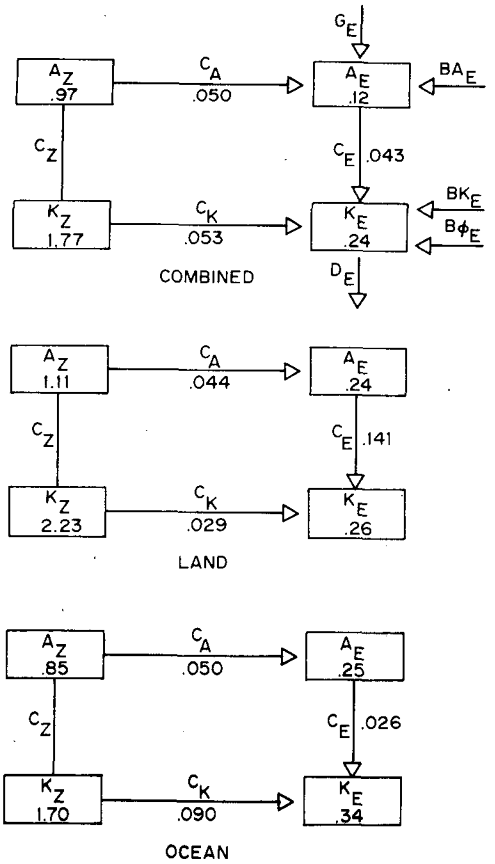

FIG. 1. Partitioned energies (10^5 J m^{-2}) and energy conversion rates (W m^{-2}) for land, ocean and combined regions. Symbols are defined in text.

almost equally by the barotropic conversion C_K and the baroclinic conversion C_E. Division of K_E by the sum of the conversion rates gives a doubling time of 2.9 days for the eddy kinetic energy.

The conversion of zonal to eddy available potential energy C_A proceeds at about the same rate as the other two conversions. Since the change of eddy available potential energy A_E over the period of study is undoubtedly small, it might be concluded from the apparent near equality of C_A and C_E that the generation of eddy available potential energy by latent heat release is also small provided that BA_E in (2) is negligible, as we assume. However, the computation of C_E is subject to considerable uncertainty since the required vertical velocity and temperature fields are difficult to measure accurately. For this reason one must be cautious in drawing inferences about the role of latent heat release from the relative sizes of the two conversions.

The doubling time for total eddy energy, obtained dividing A_E+K_E by C_A+C_K, is 4.0 days.

Also shown in Fig. 1 are the results for the subregions. These indicate some rather striking differences in the energetics of the two regions, the baroclinic conversion C_E being much larger over the land than over the ocean and, conversely, the barotropic conversion C_K being substantially larger over the ocean. The rate of conversion of zonal to eddy available potential energy is about the same for both regions.

Because of the smaller data samples, the aforementioned uncertainty in determining C_E is even larger for the subregions than for the combined region. Therefore, at first sight it might seem that little significance should be attached to the large difference observed in its values for land and ocean. However, there are grounds for believing that the result may be correct, at least qualitatively. First we note that the barotropic conversions, being based on large samples of wind observations of standard accuracy, are almost certainly reliably enough determined for the finding that C_K is larger over the ocean than over land to be accepted. Indeed, this finding can be verified visually when the 700 mb composite wind fields for the two regions (not shown) are compared (Norquist, 1976). Over the ocean the perturbations are larger and the wave axis has a more pronounced tilt, contributing to larger eddy momentum flux. The shear of the mean zonal wind is, if anything, also stronger over the ocean (Norquist, 1976). If C_K is larger over the ocean and frictional dissipation is assumed the same in the two regions, it follows that C_E must be larger over land in order to maintain the eddy kinetic energy balance. Here we are assuming, as well, that the eddy kinetic energy is in essentially a steady state during the period of study and that boundary fluxes are negligible.

If frictional dissipation is stronger over the ocean, the argument fails. However, it seems plausible that the dissipation is greater over land. The surface roughness is larger, tending to produce stronger dissipation in the boundary layer and the internal friction also could be stronger because of the greater depth and vigor of the convection (Reed *et al.*, 1977).

If we now accept the measured energy conversions for the two regions as being at least qualitatively correct, an additional important difference between the energetics of the two regions can be deduced from the eddy available potential energy balances (again under the assumption that the energies are in an approximately steady state and that boundary fluxes are negligible). Over the land region, a substantial generation of eddy available potential energy, presumably by the latent heat of condensation, is required for balance. Over the ocean, the residual is small and negative, suggesting no significant growth of the disturbances due to latent heat release and, if anything, an overall decline in energy due to diabatic processes.

Doubling times for eddy kinetic energy for the land and ocean regions are 1.8 and 3.2 days, respectively. For total eddy energy the corresponding figures are 7.9 and 4.9 days. Burpee (1972) measured a doubling time of about 2 days for total eddy energy based on data for Niamey only. The larger values found here probably

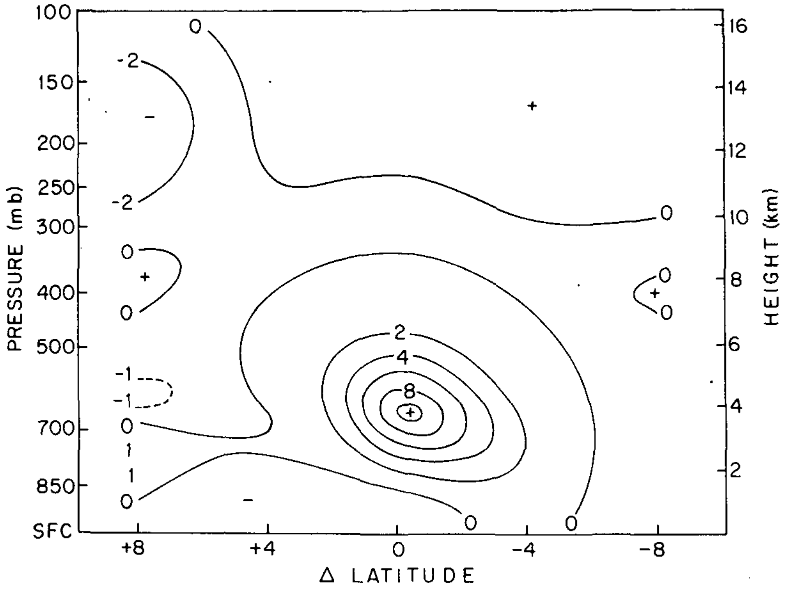

FIG. 2. Meridional distribution of $-[u'v']\partial[u]/\partial y$ for the combined region. Units are 10^{-5} m^2 s^{-3} (or W kg^{-1}).

result from averaging over a broader range of latitudes rather than from real differences in the results.

It is next of some interest to examine the variations with latitude and height of the integrands of the expressions for C_K, C_E and C_A in order to gain insights concerning the energy conversion processes. Fig. 2 depicts the distribution of $-[u'v']\partial[u]/\partial y$, the leading term in the expression for C_K, the conversion of zonal to eddy kinetic energy. The remaining terms in the expression were found to be one or more orders of magnitude smaller and are omitted here (though not in Fig. 1). From the figure it is apparent that the region of maximum conversion, indeed the only region of significant conversion, is located at the height of the mid-tropospheric jet stream just to the south of the zero or reference latitude (~11°N). This result was anticipated in the earlier study (Reed *et al.*, 1977) where it was found that the wind perturbations were strongest at this latitude, and that the wave axis possessed a northeast–southwest inclination, signifying southward transport of easterly momentum. Since the easterly current diminishes rapidly southward in the same region, the flux is downgradient and the conversion of zonal to eddy kinetic energy is readily apparent.

The integrand of the expression for C_E, the conversion of eddy available potential energy to eddy kinetic, is shown in Fig. 3. The pattern is complex, displaying regions of sizeable positive and negative values. The

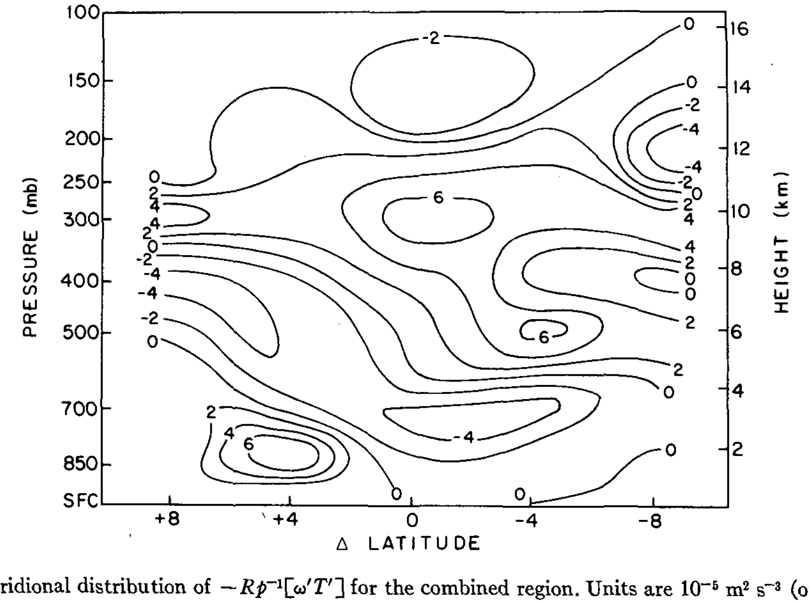

FIG. 3. Meridional distribution of $-Rp^{-1}[\omega'T']$ for the combined region. Units are 10^{-5} m^2 s^{-3} (or W kg^{-1}).

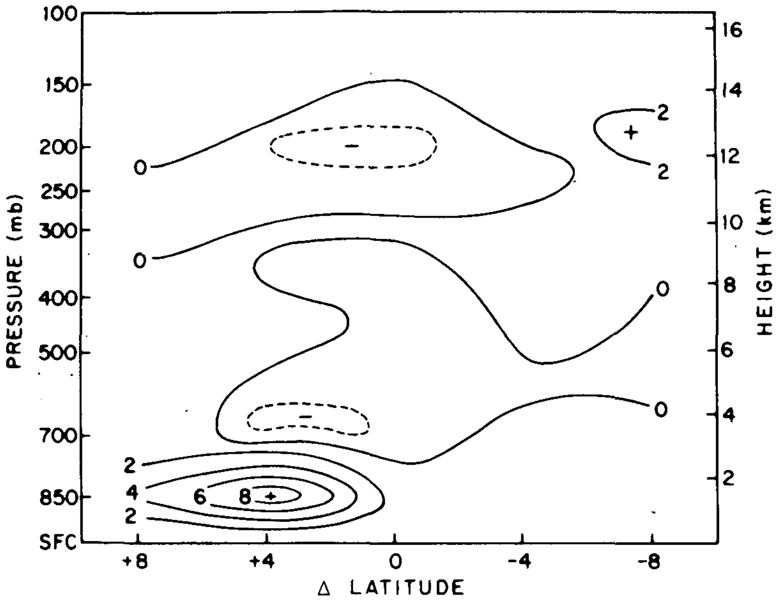

FIG. 4. Meridional distribution of $-g\bar{\sigma}^{-1}[v'T']\partial[T]/\partial y$ for the combined region. Units are 10^{-5} m^2 s^{-3}.

net positive conversion for the region as a whole is not obvious from inspection of the figure, attesting again to the difficulty of determining this conversion accurately. Interpretation of some of the major features of the diagram will now be attempted.

First, we call attention to the region of large positive values centered near 850 mb and Δ latitude $=+4$ (15°N). This is located in the zone of relatively large temperature gradient south of the Sahara. In this same zone it was found in the earlier study (Reed *et al.*, 1977) that northerly (southerly) winds are associated with relatively warm and dry (cool and moist) air and with ascending (descending) motion. We may surmise that the positive conversion seen here is a manifestation of baroclinic overturning of the sort typically observed in middle latitude disturbances.

Next, we take note of the extensive region of negative conversion which is centered near 700 mb south of the reference latitude and which slopes upward to the north. In the southern, lower part of this region, the earlier study shows that relatively cool temperatures are correlated with rising motion despite the advection of relatively warm air from the north. Precipitation amounts are heavy in this region, leading us to suggest that evaporative cooling in convective downdrafts may be responsible for the association of the negative temperature anomalies with the occurrence of large-scale ascending motion. Riehl (1954, pp. 247–249) and others have also suggested evaporation as the cause of the cold cores often observed in tropical disturbances.

The upward slope of the negative region to the north can be explained too by the evaporation hypothesis. According to the results of the earlier study the relative humidity pattern, as seen in meridional section, has a similar upward slope to the north with moist air overlying dry. There is thus evidence that cloud bases, and hence evaporative cooling by precipitation, are elevated in the northern region. Moreover the earlier results indicate that the convective cloud amount, as judged from satellite-derived IR brightness, decreases less rapidly with latitude than the precipitation amount observed at the ground. This behavior is consistent with the occurrence of evaporation aloft.

A third prominent feature of Fig. 3 is the region of positive conversion which at lower latitudes extends from about 600 mb to nearly 200 mb and which is present at all latitudes in the layer surrounding 300 mb. A plausible explanation for this region is the latent heat release in convective updrafts. As mentioned before, this has been found to be a major source of wave energy elsewhere in the tropics (Nitta, 1972), and the fact that the positive conversion is most extensive at the latitudes where precipitation is heaviest supports the explanation in the present instance.

The final diagram of the latitude-height distribution of the energy conversions, in this case

$$-g\bar{\sigma}^{-1}[v'T']\partial[T]/\partial y,$$

the leading term in the conversion of zonal to eddy available potential energy, appears in Fig. 4. A simple pattern is found. Values are everywhere small except in a concentrated region of positive conversion near 850 mb at Δ latitude $=+4$ (15°N). The origin of this maximum is clear from the results of the earlier study. It can be attributed to the correlation of warm temperature anomalies with northerly wind components, and thus with southward directed heat flux in the region of relatively strong temperature gradient to the south of the Sahara. The approximate equality of C_K and C_A is apparent from a comparison of Figs. 2 and 4. It appears that the thermal gradient associated with the mid-tropospheric jet stream provides about the same amount of perturbation energy as the lateral wind shear.

5. Interpretation and conclusions

In the present study we have investigated the energetics of African wave disturbances in the region from 10°E to 30°W and from about the equator to 20°N during a four-week period when the waves were well-organized and relatively uniform in behavior. During this period it was found that for the region as a whole baroclinic and barotropic conversions contributed almost equally to the maintenance of the kinetic energy of the waves. The eddy available potential energy was maintained by a conversion from zonal available potential energy of about the same magnitude as the other conversions. For the combined ocean and land region latent heat release apparently contributed little, if at all, to the maintenance of the eddy energy. However, the latter conclusion is not based on direct measurement and hence must be regarded as tentative. Moreover, it does not apply necessarily to each subregion.

When the land and ocean regions are examined separately quite large differences appear in the character of the energy budgets. These differences are considered to be qualitatively reasonable, even if not quantitatively correct in all respects. Over the land the conversion of eddy available potential energy to eddy kinetic is much larger than over the ocean, and the conversion of zonal to eddy kinetic energy is considerably smaller. Conversions from zonal to eddy available potential energy are about the same in both regions. It is deduced that latent heat release plays a major role in energizing the waves over land. On the other hand, diabatic effects appear to extract wave energy over the ocean. However, the conclusions regarding effects of latent heat release and other diabatic processes must, as stated previously, be regarded as tentative.

The waves under discussion were already moderately well-developed when they entered the area of study; thus our results cannot be applied to the initial stages of wave development. However, from previous findings of Burpee (1972) and Carlson (1969a), it is possible to make some plausible deductions about the energetics of the early stages. A first pertinent finding is that the likely region of origin is between 15° and 30°E, the easternmost region in which the easterly jet is of sufficient strength for the instability criterion to be satisfied. Since the shape of the jet is basically the same in this region as further west, baroclinic and barotropic processes probably contribute about equally to the wave growth. A second finding of importance is that there is little evidence of organized convection in the region of origin. From this we conclude that latent heat release is probably a minor factor in the initial wave growth.

Apparently the wavelength of the disturbance is prescribed by the barotropic instability as in the theoretical studies of Bates (1970) and Rennick (1976). It is perhaps worthy of note that the wavelength of a near-neutral wave in a barotropic atmosphere with sinusoidal jet profile is $4/\sqrt{3}$ or 2.3 times the half-width of the jet (Nitta and Yanai, 1969). Thus a half-width of about 10° of latitude, such as occurs south of the jet axis, corresponds to a wavelength of about 2500 km, approximately the observed length.

In summary, we propose on the basis of the findings of this study, and the above-mentioned results of Burpee and Carlson, that the waves originate over central Africa as a consequence of a joint baroclinic-barotropic instability. In their early stages convection is unorganized, and latent heat release plays little part in the wave development. As they progress westward the convection becomes better organized so that over West Africa the condensation heating becomes a dominant factor in their growth and sustenance. Since the convection is controlled by the wave-induced convergence and vertical motion, wave-CISK (Hayashi, 1970; Lindzen, 1974) can be said to be operative. As noted earlier by Carlson (1969b) the waves characteristically reach their peak intensity in the vicinity of the coast and weaken, at least temporarily, as they cross the central Atlantic. Probably the greater extent of air of relatively high static stability at low levels in the oceanic trade wind regions and the narrowing of the ITCZ contribute to the wave decline. The much reduced baroclinic energy conversion and, by inference, reduced supply of energy by latent heat release in the offshore region may be regarded as possible first signs of the subsequent wave decline.

The foregoing picture is admittedly somewhat speculative since it is based on measurements that are incomplete in some respects and of questionable accuracy in other respects. However, it is in accord with a sufficient number of observational facts to serve as a conceptual framework for further studies of the wave dynamics. Hopefully, more definitive measurements of the energy balance of the waves will be permitted when the final validated data sets become available.

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