An idealized study of African easterly waves. III: More realistic basic states

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SUMMARY

The nature of unstable easterly waves growing on three different easterly jets has been examined. The 'shear-jet' with strongest horizontal mean shear on the equatorward side of the jet is characterized by linearly unstable waves with maximum amplitude equatorward of the jet maximum and are dominated by barotropic energy conversions associated with positive horizontal momentum fluxes. The normal modes of the shear-jet have very little amplitude at the surface.

The 'desert-jet' with lower mean static stability better represents the atmospheric conditions on the poleward side of the jet, and is characterized by linearly unstable waves with maximum amplitude at the surface. The modes have much larger baroclinic energy conversions than those of the shear-jet, although barotropic energy conversions are still larger. About 25% of the value of the barotropic energy conversions is attributable to the vertical Reynolds stress term associated with vertical momentum fluxes.

The 'combined-jet' with both enhanced equatorward horizontal shear and low static stability combined, has also been examined. The linear normal modes associated with this jet are characterized by significant amplitudes at both the jet-level and at the surface. The ratio of barotropic to baroclinic energy conversions is between that associated with the modes growing on the shear- and desert-jets.

The nonlinear behaviour of 3000 km wavelength easterly waves growing on the jets has been examined. All life-cycles are characterized by a transition from initial barotropic energy conversions dominance to baroclinic energy conversions dominance. The nonlinear part of the shear-jet life-cycle is dominated by negative horizontal momentum fluxes on the poleward side of the jet and maximum amplitude at the surface in the region of the temperature gradients. In disagreement with observations only very weak nonlinear positive horizontal momentum fluxes exist on the equatorward side of the jet. The nonlinear desert-jet life-cycle as for the normal mode continues to be characterized by maximum amplitudes at low-levels and becomes dominated by baroclinic energy conversions sooner. The nonlinear combined-jet life-cycle evolves in a similar manner to the desert-jet life-cycle but with more significant jet-level amplitudes.

The synoptic evolution of the relative vorticity in the life-cycles is examined. A single surface relative vorticity maximum, associated with the meridional surface temperature gradient has been identified in all idealized integrations examined, including those with latent heating, in disagreement with observations which indicate two maxima north and south of the jet. At about 850 mb however, two positive vorticity centres do exist; a weak equatorward one associated with the developments at the jet level and a stronger poleward one associated with the low-level temperature gradients.

The shear life-cycle is re-examined with a simple moist parametrization included. Baroclinic energy conversions increase but barotropic energy conversions are almost unaffected by the latent heating and the jet-level structure almost unchanged. The surface vorticity maxima is increased. The relationship between moisture availability and the jet is shown to be important in determining the nature of surface developments and the ascent pattern as well as the magnitude of the baroclinic energy conversions.

It is suggested that differences between observations and the nonlinear equatorward structures identified here, may be reduced with a more accurate representation of diabatic processes.

KEYWORDS: Africa Easterly waves Jet instability

1. INTRODUCTION

There are still many unresolved problems relating to the understanding of observed African easterly waves. Based on several observational studies such as those of Albignat and Reed (1980), Carlson (1969), Reed et al. (1977), Norquist et al. (1977) and Thompson et al. (1979) these include: (1) the observation that at the level of the jet, easterly waves and their associated horizontal momentum fluxes have a larger amplitude on the equatorward side of the jet and (2) the observation that at low-levels, there are two regions of easterly wave activity on each side of the jet with the poleward side dominating.

As shown recently by Thornicroft and Hoskins (1994a, b) (henceforward TH1 and

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TH2) idealized modelling studies can be useful in examining the nature of African easterly waves. TH1 and TH2 examined easterly waves growing on the idealized African easterly jet (AEJ) first constructed by Simmons (1977) and which was based on the Global Atlantic Tropical Experiment (GATE) observations presented by Reed et al. (1977) (henceforward, the Simmons-jet). One of the aims of the present study is to investigate whether the easterly-wave characteristics described above depend on AEJ characteristics not included in the Simmons-jet.

A second aim of this study is to simply consider the nature of easterly waves growing on an AEJ with more realistic characteristics. Also, since the AEJ varies during the season as well as interannually (e.g. Fontaine and Janicot 1992) it is of interest to consider the sensitivity of unstable easterly waves to changes in AEJ structure. Related studies have been performed by Rennick (1981) and more recently by Paradis et al. (1995). Both studies examined the linear instability of different easterly jets on a β-plane. Rennick (1981) considered just symmetric jets and showed that barotropic and baroclinic energy conversions increased with horizontal and vertical wind shear respectively. Paradis et al. (1995) also showed that the linear easterly waves were sensitive to both the horizontal and vertical shears but found less sensitivity to a variation of static stability. The work presented here differs from these studies in that nonlinear characteristics are examined as well as the linear characteristics, the easterly waves are growing on a sphere and because of the extra detail, just three jets are considered rather than 30 as in Rennick (1981) and six as in Paradis et al. (1995).

It is suggested here that the observation that the GATE easterly waves have most of their amplitude on the equatorward side of the AEJ might be related to enhanced horizontal shear on that side of the jet. The observed basic state of Burpee (1972), for example, suggests that this is probably a realistic characteristic of the jet. Indeed, an examination of European Centre for Medium-Range Weather Forecasts (ECMWF) analyses (not shown; see also Paradis et al. 1995), suggests that this is indeed a characteristic of the AEJ. The nature of the easterly waves which grow on the Simmons-jet with increased horizontal shear on the equatorward side (henceforward shear-jet) is therefore examined here.

The Simmons-jet was constructed with a mean static stability based on the mean September temperature sounding for the West African region equatorward of about 14°N (Aspliden and Adefolalu 1976). However, as discussed by Chang (1993), the static stability on the poleward side of the jet in the vicinity of the desert approaches neutrality over the depth of the deep boundary layer which can reach 600 mb. The nature of the easterly waves which grow on the Simmons-jet with decreased static stability (henceforward desert-jet) is therefore examined here.

For completeness, the nature of the easterly waves which grow on a jet with both increased equatorward shear and decreased low-level static stability (henceforward combined-jet) is also examined.

Observations suggest that easterly waves on the equatorward side of the jet are characterized by convective heating (e.g. Burpee 1974 and Duvel 1990). The nature of easterly waves growing on the shear-jet with a simple latent-heating parametrization included is examined. The latent-heat parametrization used is the CISK-type scheme used in TH1 and TH2 and includes a representation of the observed meridional gradients in moisture availability. Since the observed moisture distribution in the tropical north African region varies interannually (e.g. Rowell et al. 1992), some experiments varying the latitudinal extent of the moisture availability are briefly examined.

As in the studies of TH1 and TH2, the numerical model of Hoskins and Simmons (1975) is used. The primitive equations are integrated with 15 σ levels at 0.033, 0.113, 0.216, 0.326, 0.432, 0.524, 0.600, 0.662, 0.714, 0.803, 0.848, 0.894, 0.940, and 0.982.
The horizontal spectral resolution has a triangular truncation at wavenumber 95, giving a resolvable lengthscale (wavelength/2π) of about 67 km.

In section 2 the new basic states are presented. In section 3 the results of a linear study of the jets are examined. In TH2 it was shown that the nonlinear easterly waves had many characteristics which more closely resembled observed easterly waves over land than those of the normal modes. In section 4 the results from nonlinear integrations are therefore examined including some aspects of the synoptic behaviour not presented in TH2. In section 5 nonlinear life cycles using the shear-jet and including a simple latent heating parametrization are examined. Finally, in section 6, a summary with some discussion is presented.

2. Basic states

The mean zonal wind, together with the balanced potential temperature for the shear-jet and desert-jet are presented in Fig. 1. The shear-jet in Fig. 1(a) was constructed in the same manner as the thin jet in TH1 except that the shear was enhanced only on the equatorward side. This results in increasing the equatorward shear from 2.0 × 10^{-5} s^{-1} to 3.2 × 10^{-5} s^{-1}. The latitude of the maximum shear is also changed from 10.6 °N to 13.1 °N. Paradis et al. (1995) in their linear study of easterly waves used a similar value for their enhanced equatorward shear-jet based on ECMWF analyses. The jet with reduced static stability in Fig. 1(b) has the same wind structure as the Simmons-jet but with the mean static stability reduced by changing the mean potential temperature by an amount given by (σ − 0.5) × 5 K. This has the effect of reducing the lower tropospheric static stability by about half, giving a squared Brunt–Väisälä frequency of about 0.7 × 10^{-4} s^{-2}. The surface temperature maximum on the poleward side of the jet is now about 34 °C. Clearly, although in the atmosphere the near neutral layer beneath the jet is restricted to the poleward side of the jet, in this simple study the stability is lowered for all latitudes. Paradis et al. (1995) also examined the linear stability of their basic AEJ with reduced static stability but reduced it nonuniformly in the vertical in an attempt to better represent the mean thermodynamic profile on the equatorward side of the jet. Any comparison with the present study is therefore difficult. Comparison is also difficult since the basic jet used by Paradis et al. (1995) is about 1 km lower and has higher values of vertical shear below the jet and lower values above. Also, the easterly wave structures associated with their enhanced shear and low static-stability jets were not shown.

The Ertel potential vorticity (PV) for the two jets is also included in Fig. 1. Note, that as discussed in TH1, the Charney–Stern necessary conditions for instability are satisfied with PV gradients of different sign on theta surfaces together with the positive meridional temperature gradient at the surface (Charney and Stern 1962). It should be noted however that the PV structure associated with the jets is quantitatively different. The jet with enhanced equatorward shear is narrower and has higher values of PV on the equatorward side than the other jets. The jet with reduced mean static stability has the same shape as that of the Simmons-jet (see TH1) but has lower values everywhere beneath the jet. The PV maximum on the equatorward side is 0.5 PVU, 0.4 PVU and 0.3 PVU for the shear-, Simmons- and desert-jets respectively. The combined-jet (not shown) has a PV maximum of 0.4 PVU, the enhanced cyclonic shear and lower static stability thus compensating each other.

From a knowledge of barotropic and baroclinic instability theories it is possible to deduce the expected sensitivities of unstable waves to the different jets. Simple barotropic instability theory (e.g. Kuo 1949) suggests that the growth rate is proportional to the shear. Also, as the width of the shear zone decreases, so does the most unstable wavenumber.
Therefore, since the shear is only enhanced on the equatorward side of the shear-jet, we would expect unstable waves to be predominantly on that side of the jet, with a higher growth rate and for the most unstable wave to have a shorter wavelength. From simple baroclinic instability theory (e.g. Eady 1949) the most unstable wavelength is proportional to the static stability and growth rate inversely proportional to it. Therefore for the desert-jet with lower static stability than the Simmons-jet we expect unstable waves with a higher growth rate, for the most unstable wave to have a shorter wavelength and baroclinic energy conversions to increase. A similar sensitivity would be expected for a lower jet with stronger vertical shear beneath it.

In the study by Chang (1993), interior PV gradients were constructed to be positive only, in an attempt to isolate the role of the surface temperature gradients on the poleward side of the jet. From the Charney–Stern theorem, this has the effect of removing the possibility of barotropic instability. By assuming that there is an effective lid at 600 mb
the problem was reduced to the Eady problem with zero static stability. The scale of the baroclinically unstable modes identified by Chang (1993) must therefore be determined by the dissipation parameter used as well as the lid height. For the desert-jet and as is suggested here, for observed jets, interior PV gradients of both signs coexist with surface temperature gradients even though the static stability on the poleward side is low. Indeed, the low static stability is likely to enhance vertical coupling between the negative interior PV gradients and the positive surface temperature gradients. Only for very short wavelengths is this coupling likely to be unimportant in which case according to the Charney–Stern theorem there will be no unstable growth. For the scales associated with observed easterly waves it is likely that such vertical coupling will still be significant.

3. **Linear results**

(a) **Growth rate and phase speeds**

The fastest growing mode for each zonal wavenumber, $m$, growing on the jets was found using the same initial value method as in TH1. All integrations converged to within the same accuracy as in TH1 except the $m = 8$ mode associated with the combined-jet, although the relative change in growth rate between one instant and half a day later for this mode was still much less than $10^{-2}$. The growth-rate curves as a function of $m$ and for each basic state including that for the Simmons-jet are shown in Fig. 2. For the shear-jet and the desert-jet, growth rates are generally larger than those for the Simmons-jet with the increases most marked for the larger wavenumbers. The result is that the growth-rate curves are much broader suggesting that the scale of an initial perturbation may be more significant in determining the wavelength than the scale of the most unstable wave. A similar sensitivity was found in the study by Paradis et al. (1995) but less marked than here. The growth rates were also a little larger than in the present study, presumably associated with the stronger vertical shear. The growth rates here are even larger for the combined-jet as may have been anticipated with both enhanced shear increasing the barotropic instability and lower static stability increasing the baroclinic instability.

The phase speeds (not shown) vary in a similar manner to those presented in TH1 for the Simmons-jet, decreasing with increasing wavenumber. The phase speeds for the most unstable wave at zonal wavenumber 10 growing on the Simmons-jet, desert-jet, shear-jet

![Figure 2](image.png)  
**Figure 2.** Growth-rate curves as a function of wavenumber for the most unstable modes which grow on the basic state in TH1 (diamonds), the shear-jet (circles), the desert-jet (squares) and the combined-jet (triangles).
TABLE 1. THE NORMALIZED ENERGY CONVERSIONS CK AND CE FOR THE MOST UNSTABLE m = 10 MODE AND m = 13 MODE FOR THE SIMMONS-JET, SHEAR-JET, DESERT-JET AND COMBINED-JET.

<table>
<thead>
<tr>
<th>JET</th>
<th>m = 10</th>
<th>m = 13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CK</td>
<td>CE</td>
</tr>
<tr>
<td>SIMMONS</td>
<td>0.84</td>
<td>0.16</td>
</tr>
<tr>
<td>SHEAR</td>
<td>0.97</td>
<td>0.03</td>
</tr>
<tr>
<td>DESERT</td>
<td>0.71</td>
<td>0.29</td>
</tr>
<tr>
<td>COMBINED</td>
<td>0.89</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The normalizations used for the Simmons-jet and for m = 10 and 13 are 8.4 and 3.6 × 10^{−2} W m^{−2} respectively. The normalizations used for the shear-jet and for m = 10 and 13 are 5.2 and 6.4 × 10^{−2} W m^{−2} respectively. The normalizations used for the desert-jet and for m = 10 and 13 are 5.9 and 3.1 × 10^{−2} W m^{−2} respectively. The normalizations used for the combined-jet and for m = 10 and 13 are 11.2 and 8.5 × 10^{−2} W m^{−2} respectively. All the modes have been scaled to give a maximum meridional wind of 5 m s^{−1}.

and combined jet are −7.1 degrees per day, −7.0 degrees per day, −6.3 degrees per day and −6.1 degrees per day respectively (7 degrees per day is equivalent to about 9 m s^{−1} at 15°N). The increased shear and decreased static stability are clearly seen to be associated with slower propagating waves.

For comparison with TH1 and TH2 the nature of the most unstable wave at zonal wavenumber 10 will briefly be examined. Since the wavelength of about 3900 km associated with this is quite large in comparison with observations and since the shorter wavelengths are more unstable for the new basic states, the nature of the most unstable wave for m = 13 is also examined. This has an equivalent wavelength of about 3000 km. Indeed for the shear-jet the m = 13 mode is the most unstable with a growth rate of 0.35 day^{−1}.

(b) Energy conversions

The normalized energy conversions indicating the barotropic (CK) and baroclinic (CE) contributions to the growth of eddy kinetic energy (EKE) are presented in Table 1. The effect of enhanced equatorward shear is to increase the relative importance of the CK term in qualitative agreement with Rennick (1981) and Paradis et al. (1995). Indeed CE contributes negligibly and for the m = 13 mode is in fact weakly negative. The m = 13 mode is therefore similar to the dry unstable 3000 km wave found by Kwon (1989) which was dominated by CK and baroclinically damped, although more strongly than here. As discussed in TH1 the baroclinic damping appears to be characteristic of waves which have most of their amplitude concentrated at the jet-level (c.f. Fig. 3(b) below).

The effect of reducing the static stability is to increase the relative importance of the CE term relative to CK although CK still dominates. Note also that the shorter wavelength is more sensitive to the static stability change. It should also be noted that although CK still dominates the energetics for the desert-mode, the contribution to CK from the vertical Reynolds stress term, C_{vert}, increases markedly. The vertical Reynolds stress term, proportional to the vertical momentum flux and vertical wind shear, is often ignored in energetic studies of easterly waves since it is zero by definition using quasi-geostrophic assumptions. For the m = 13 modes which grow on the shear-jet and desert-jet respectively C_{vert} contributes to CK about 3% and 24% respectively implying that for easterly waves associated with the low static stability side of the jet, C_{vert} should not be ignored. The
Figure 3. Zonal-mean eddy kinetic energy for the most unstable $m = 10$ and $m = 13$ modes for the shear-jet (a) and (b), the desert-jet (c) and (d) and the combined-jet (e) and (f). The modes have been scaled to give a maximum meridional wind of 5 m s$^{-1}$. The contour intervals in (a), (b), (c) and (d) are 5.0, 2.0, 1.0, 1.0, 2.0 and 5.0 J kg$^{-1}$ respectively.
contribution from \( C_{\text{vert}} \) would also be expected to increase with increased vertical wind shear.

The energy conversions associated with the most unstable \( m = 10 \) and \( m = 13 \) modes growing on the combined-jet have characteristics somewhat similar to those of the Simmons-jet, the increased CK associated with the enhanced shear apparently balanced by the increased CE associated with the lower static stability. The vertical Reynolds stress, \( C_{\text{vert}} \), accounts for about 8% of CK.

(c) Zonal mean diagnostics

The zonal-mean eddy kinetic energy, EKE, of the most unstable \( m = 10 \) and \( m = 13 \) modes associated with the shear, desert and combined-jets are shown in Fig. 3. Note that for the shear-jet, the modes are concentrated at the jet-level and have little or no surface amplitude. Also note that the maximum amplitude is on the equatorward side of the jet. The nature of the modes associated with the desert-jet are clearly very different, with increased amplitude at the surface around 20 °N in the region of the surface temperature gradients. Indeed the desert-jet \( m = 13 \) mode has only one region of maximum EKE which is located at the surface with much weaker values in the jet region. The contrast between the \( m = 13 \) structures in Figs. 3(b, d) is striking with the shear mode mainly around 12 °N and at the jet level and the desert mode mainly around 20 °N and at the surface.

The modes associated with the combined-jet have their maxima mainly on the equatorward side of the jet although the \( m = 13 \) mode also has a significant secondary surface maximum at the surface near 20 °N. Henceforward for brevity and because they have a wavelength more typically seen to be associated with easterly waves, only the \( m = 13 \) modes are considered.

The horizontal eddy momentum fluxes, vertical eddy heat fluxes and vertical momentum fluxes for the shear-jet and desert-jet \( m = 13 \) modes are presented in Fig. 4. The horizontal eddy momentum fluxes associated with the shear mode are mainly positive on the equatorward side of the jet indicating a mode characterized mainly by a NE–SW tilt. Conversely those associated with the static stability mode are mainly negative on the poleward side of the jet indicating a mode characterized mainly by a NW–SE tilt. The energy conversions presented in Table 1 for this mode indicate that although the mode has its maximum amplitude at the surface it is these horizontal momentum fluxes on the poleward side of the jet that are the main contributor to eddy growth.

The vertical eddy heat fluxes associated with the \( m = 13 \) shear mode have a similar pattern to those fluxes associated with the \( m = 10 \) mode discussed in TH1 with baroclinic damping implied by the jet-level fluxes. This damping, discussed in more detail in TH1, dominates over the baroclinic growth regions further away from the jet resulting in the negative CE seen in Table 1. The vertical eddy heat fluxes associated with the static stability mode in Fig. 4(d) indicate a prominent upward maximum at low-levels consistent with baroclinic growth.

The vertical momentum flux for the shear and desert modes are also included in Fig. 4. The fluxes associated with the shear mode have a quadrupole structure with downward fluxes of easterly momentum on the poleward side of the jet beneath the jet and on the equatorward side above the jet. This pattern of vertical momentum fluxes, also characteristic of the \( m = 10 \) mode in TH1 (not shown) implies growth of EKE on the poleward side of the jet and decay of EKE on the equatorward side. By considering the easterly wave structure, the quadrupole pattern can be understood. With zero zonal-wind perturbation and zero vertical velocity, no vertical momentum fluxes exist at the jet maximum. The ascent region below the jet, at \( \sigma = 0.800 \) for example, has a significant region in phase with the anticyclonic anomaly at that level and hence with westerlies to the north and east-
Figure 4. Zonal-mean eddy diagnostics for the $m = 13$ shear and desert normal modes scaled to give a maximum meridional wind of 5 m s$^{-1}$. (a) and (b) show the zonal-mean horizontal momentum flux $u'v'$ for the shear and desert modes with contour intervals of 2.0 and 1.0 m$^2$ s$^{-1}$ respectively. (c) and (d) show the vertical eddy-heat flux $\omega'T'$ for the shear and desert modes with contour intervals of 0.1 and 0.5 K mb h$^{-1}$ respectively and (e) and (f) show the vertical momentum flux $\omega'u'$ for the shear and desert modes with contour intervals of 0.5 and 0.1 m s$^{-1}$ mb h$^{-1}$ respectively. In each case negative contours are dashed and overbars represent a zonal mean and primes deviations from the zonal mean.
erlies to the south, vertical momentum fluxes of opposite signs exist on each side of the jet. The same is true of the structure above the jet except that there is descent ahead of the positive vorticity anomaly due to the different meridional temperature gradient. The fluxes are therefore opposite to those below the jet thus giving the quadrupole structure seen in Fig. 4(e). With cancellation of terms the net contribution by the vertical momentum flux terms to growth of the shear mode is only 2.9% of CK. In contrast, as shown in Fig. 4(f), the vertical momentum flux associated with the desert-mode is dominated by the flux at low-levels on the poleward side of the jet, and contributes to 24% of CK. Clearly, the nature of the vertical momentum fluxes cannot be ignored in the case of easterly waves growing on the poleward side of the jet with low static stability.

The horizontal eddy momentum fluxes, vertical eddy heat fluxes and vertical momentum fluxes are presented for the $m = 13$ mode associated with the combined-jet in Fig. 5. As may have been expected from the energetics in Table 1, the nature of these

Figure 5. Zonal-mean eddy diagnostics for the $m = 13$ combined normal mode scaled to give a maximum meridional wind of 5 m s$^{-1}$. (a) shows the zonal-mean horizontal momentum flux $u'v'$ with a contour interval of 2 m$^2$ s$^{-2}$. (b) shows the vertical eddy heat flux $\omega'T'$ with a contour interval of 0.2 mb h$^{-1}$ and (c) shows the vertical momentum flux $\omega'\omega'$ with a contour interval of 0.5 ms$^{-1}$ mb h$^{-1}$. In each case negative contours are dashed and overbars represent a zonal mean and primes deviations from the zonal mean.
fluxes has similarities with both those of the shear-jet and desert-jet modes in Fig. 4. Note for example, regarding the horizontal eddy momentum fluxes, that the marked positive fluxes on the equatorward side of the jet around 600 mb have a similar pattern to those in 4(a) whereas the negative fluxes on the poleward side of the jet are more similar to those in 4(b). The vertical heat fluxes associated with the $m = 13$ combined-mode resemble the heat fluxes associated with the $m = 13$ desert-mode consistent with the idea that the low static stability influences the nature of the baroclinic energy conversions. The vertical momentum flux in Fig. 5(c) has the same quadrupole structure as that of the shear-jet mode (c.f. 4(e)) but is dominated by the downward flux of easterly momentum beneath the jet and on the poleward side as with the desert-jet mode (c.f. 4(f)). The $m = 13$ combined-jet mode can therefore be seen to have characteristics of both the shear-jet and desert-jet modes.

4. **Nonlinear results**

(a) **Motivation**

It was shown in TH2 how easterly waves, although initially dominated by CK, become dominated by CE in the nonlinear part of the life-cycle, thus becoming more similar to the observed GATE easterly waves over land (c.f. Norquist et al. 1977). It is therefore clear that in order to obtain a more complete view of the growth of easterly waves on AEJs, nonlinear life-cycles should be examined. Of special interest is to see if the desert $m = 13$ mode, characterized by weak baroclinic damping, has a positive baroclinic signature in the nonlinear part of the life-cycle. Kwon and Mak (1990) suggested that latent heat release was necessary to transform their baroclinically damped normal mode to one which grows baroclinically. The life-cycles presented in this section do not consider moist physics and so any transformation occurs as a result of dry dynamics.

Life-cycles are initiated with a normal mode scaled to give a 1 m s$^{-1}$ maximum amplitude of meridional wind. Only results relating to the $m = 13$ modes are presented.

(b) **Global energetics**

The evolution of the global mean EKE for the $m = 13$ life-cycles associated with the shear, desert and combined-jet life-cycles are presented in Fig. 6(a). As in the $m = 10$ life-cycle presented in TH2, the waves continue to grow up to about day 15 and subsequently decay. Results are presented here only up to day 12. Note that the EKE in the desert life-cycle although initially smaller than that in the shear life-cycle is markedly larger in the nonlinear part of the life-cycle. The EKE associated with the combined-mode grows fastest initially, consistent with the linear stability analysis and reaches a similar amplitude to that in the desert life-cycle.

The global energy conversions for the shear-, desert- and combined-jet life-cycles are shown in Fig. 6(b, c, d). As in TH2, the conversion rate between the basic state and eddy potential energy, CN, is included. Note that despite the shear-jet normal mode having weak negative baroclinic energy conversions, CE soon becomes positive and as in TH2 becomes the dominant energy conversion, the transition from CK dominance to CE dominance taking place around day 8. It appears therefore, that latent heat release is not necessary to transform the baroclinically damped easterly wave here to a baroclinically growing easterly wave. Unlike the easterly wave of Kwon and Mak (1990), dry dynamics is sufficient to explain this transformation.

The global energy conversions associated with the desert-jet life-cycle in Fig. 6(c) indicate that the transition to CE dominance takes place at around day 6 approximately
two days sooner than in the shear-jet life-cycle. This may have been expected, since the difference between CE and CK for the desert-mode was initially much smaller than that of the shear-mode. Note also that CK reaches its maximum around day 9, three days later than in the shear life-cycle. The CE term for the desert-mode also reaches a maximum more than twice that of the CK maximum. Interestingly, the vertical Reynolds stress term continues to contribute about 25% of the total CK during most of the growing part of the desert life-cycle, whereas in the shear life-cycle it contributes only about 7%.

The energy conversions associated with the combined life-cycle in Fig. 6(d) are similarly characterized by CK dominance followed by CE dominance after day 5, as in the desert life-cycle. However, the energy conversions during the early stages of the life-cycle up to about day 4 more closely resemble the conversions in the shear life-cycle than those in the desert life-cycle with CK significantly larger than CE. Also, as in the shear life-cycle CK peaks around day 6. However, unlike the shear life-cycle CE increases rapidly to reach a peak of $66.2 \times 10^{-3}$ W m$^{-2}$ by day 8 comparable to that in the desert-jet life-cycle and much larger than in the shear-jet life-cycle. Associated with this transition to a more baroclinically growing wave is an increased contribution of $C_{\text{vert}}$ to CK. Although initially the contribution is about 8%, the average value over the first 10 days is 18%. Therefore, although the enhanced equatorward shear appears to be important in determining the nature
of the linear part of the life-cycle the low static stability appears to be more important in determining the nature of the nonlinear part of the life-cycle. The life-cycle associated with the combined-jet has characteristics between those of the shear and desert life-cycles with linear similarities with the shear life-cycle and nonlinear similarities with the desert life-cycle. This has been confirmed by examining zonal-mean diagnostics and synoptic fields. Henceforward therefore, for brevity, detailed results are only presented for the shear-jet and desert-jet life-cycles.

The transformation from CK dominance to CE dominance identified in TH2 appears to be a robust result with the different jets and shorter wavelengths, although timings for CE becoming larger and also relative amplitudes of CE and CK may differ. For example, the maximum CE reached in the desert-jet life-cycle is $67.5 \times 10^{-3}$ W m$^{-2}$ compared with $32.3 \times 10^{-3}$ W m$^{-2}$ in the shear-jet life-cycle.

(c) Zonal-mean diagnostics

The nonlinear shear life-cycle is very similar to that of the $m = 10$ life-cycle presented in TH2, with the nonlinear wave characterized by maximum amplitudes poleward of the jet and at the surface. Since, the developments are similar, only the horizontal momentum fluxes are presented in Fig. 7 at days 6 and 10. Although the normal mode is characterized by maximum amplitudes on the equatorward side of the jet and positive horizontal momentum fluxes, a structure which appears to be similar to the GATE observations presented by Reed et al. (1977), it is clearly not maintained in the nonlinear part of the life-cycle. The transition from mainly positive horizontal momentum fluxes equatorward of the jet to mainly negative horizontal momentum fluxes poleward of the jet thus appears to be a robust result, even with enhanced equatorward shear.

The EKE, horizontal eddy momentum fluxes and vertical eddy heat flux are presented for the $m = 13$ desert life-cycle at days 6 and 10 in Fig. 8. The EKE at day 6 and 10 indicate that the normal mode structure is largely maintained with largest amplitudes at the surface in the region of 20°N. Note that even by day 10 there is very little significant amplitude equatorward of 15°N. The horizontal momentum fluxes, initially dominated by negative values on the poleward side of the jet continue to be characterized by this structure. The vertical eddy-heat fluxes also continue to imply positive CE mainly beneath the jet.

Figure 7. Latitude–height section of horizontal momentum flux at day 6 and 10 in the $m = 13$ shear-jet life-cycle. The contour interval is $1.0 \text{ m}^2 \text{s}^{-2}$ and negative contours are dashed.
Figure 8. Latitude–height sections of zonal mean fluxes from the $m = 13$ desert life-cycle. (a) and (b) show the eddy kinetic energy at day 6 and 10 with contour intervals of 2.0 and 5.0 J kg$^{-1}$ respectively. (c) and (d) show the horizontal momentum fluxes at day 6 and 10 with contour intervals of 1.0 and 2.0 m$^2$ s$^{-2}$ respectively and (e) and (f) show the vertical heat flux at day 6 and 10 with contour intervals of 0.1 and 0.2 K mb h$^{-1}$ respectively. Negative contours are dashed.
Thus, whereas in the shear life-cycle and the basic life-cycle in TH2 there is a transition from a wave structure characterized by jet-level amplitudes to surface amplitudes associated with the low-level temperature gradients, the desert life-cycle initially characterized by these low-level amplitudes, remains so. It is interesting to note that all structures dominated by surface amplitudes have negative horizontal momentum fluxes below and on the poleward side of the jet. Although the maximum horizontal momentum fluxes analysed by Albignat and Reed (1980) from GATE data are largest and positive on the equatorward side of the jet at the jet-level, poleward of the jet, negative momentum fluxes exist with increasing amplitude towards the surface consistent with Fig. 8(d).

It should be noted that the negative horizontal momentum fluxes at low levels poleward of the jet contribute positively to the CK term. This is due to the fact that during the nonlinear part of the life-cycle low-level easterlies develop as shown in Fig. 9(a). The low-level easterlies appear to form in the region of the northerly branch of an indirect meridional overturning cell (see Fig. 9(b)) forced by the heat fluxes. Low-level easterlies known as the Harmattan winds are known to exist over northern Africa at about this latitude. The results presented here suggest that these observed winds may have a contribution to them associated with nonlinear easterly wave life-cycles.

The equivalent zonal-mean diagnostics for the combined-jet life-cycle (not shown) are very similar to those of the desert-jet life-cycle except that at day 6 there is still significant amplitude with associated positive horizontal momentum fluxes on the equatorward side of the jet.

(d) Relative vorticity

There are no qualitative differences between the synoptic evolution of the $m = 10$ life-cycle presented in TH2 and that of the $m = 13$ shear life-cycle examined here. However, there are some quantitative differences associated with the nonlinear part of the life-cycle and some synoptic aspects which were not discussed in TH2 which make a brief examination of the relative vorticity structure worthwhile. Figure 10 shows the relative vorticity in the shear-jet life-cycle at day 6 and at day 10 and at $\sigma = 0.60, 0.85$ and 0.98. The relative vorticity at day 6 at $\sigma = 0.60$ indicates a cyclonic region on the equatorward side of the
jet with a predominant NE–SW tilt consistent with the horizontal momentum fluxes in Fig. 7(a). Poleward of the jet, anticyclonic vorticity is more prominent. The prominent cyclonic and anticyclonic regions on the equatorward and poleward side of the jet respectively are a consequence of the sign of the shear on each side of the jet. Between day 6 and day 10 the main cyclonic anomaly strengthens slightly and moves polewards leaving a cyclonic 'tail' behind. The near-surface relative vorticity at $\sigma = 0.98$ shows the vorticity anomalies to be mainly on the poleward side of the surface temperature gradients (c.f.}
Fig. 1(a)) and the cyclones to be slightly equatorward of the anticyclones. Between day 6 and day 10 the pattern changes little although the maximum positive vorticity increases from $1.5 \times 10^{-5} \text{s}^{-1}$ to $3.1 \times 10^{-5} \text{s}^{-1}$. Note also the pronounced NW–SE tilt of the surface wave consistent with the negative momentum fluxes seen in Fig. 7(b).

The relative vorticity at $\sigma = 0.85$ appears to have characteristics between those of the jet-level and low-level patterns. At day 6 there are weak cyclones and anticyclones equatorward and poleward of the jet respectively. However, between day 6 and day 10, a second positive relative-vorticity region develops associated with the surface developments (c.f. Fig. 10(f)). The relative vorticity distribution at day 10 is thus characterized by two cyclonic regions on either side of the jet; a weaker equatorward one associated with development at the jet-level and a stronger poleward one associated with surface developments in the region of the surface temperature gradients. This may be relevant to the observation of two cyclonic centres either side of the jet although at the surface there still exists only one cyclone centre.

The poleward moving jet-level anomaly should not be thought of as evolving separately from the surface anomalies. An eastward tilt with height of the anomalies beneath the jet exists, consistent with baroclinic growth and implying a cooperation between the jet-level and surface. This positive vorticity anomaly is associated with a positive potential-vorticity anomaly and as in the $m = 10$ life-cycle presented in TH2 is advected polewards around the larger-scale anticyclonic region polewards of the jet.

The evolution of the relative vorticity for the desert-jet life-cycle (see Fig. 11) is qualitatively similar to that of the shear life-cycle. The main difference is in the magnitude of the development at the surface associated with the temperature gradients which is larger, and the magnitude of the equatorward jet-level development which is smaller. The more significant surface development is consistent with the fact that the normal mode amplitude there is larger and that surface development does not rely so heavily on downward Rossby wave propagation (see TH2). The low-level maxima at day 6 and 10 are $2.9 \times 10^{-5} \text{s}^{-1}$ and $5.7 \times 10^{-5} \text{s}^{-1}$ respectively, nearly twice the low-level values of the shear life-cycle.

The relative-vorticity evolution in the combined-jet life-cycle (not shown) is similar to that in the desert-jet life-cycle, except that as for the normal mode, larger amplitudes are present at the jet-level. Also, as in the shear-jet life-cycle, the jet-level cyclonic anomaly moves polewards through the latitude of the jet. In the combined-jet life-cycle however, this cyclonic anomaly moves further north, reaching $25^\circ\text{N}$ by day 10.

5. MOIST LIFE-CYCLES

(a) Motivation

Observations suggest that consistent with meridional humidity gradients over tropical north Africa, easterly waves on the equatorward side of the jet have a stronger convective signature than those waves on the poleward side of the jet (e.g. Burpee 1974 and Duvel 1990). Therefore, since the desert-modes are likely to be very dry, only the $m = 13$ shear life-cycle has been repeated with the effects of latent heating included. The moist parametrization used here is the CISK-type scheme used in TH1 and TH2. The energetics and structure changes associated with latent heating included in the waves are examined. Of special interest is to see if latent heating on the equatorward side of the jet can result in a surface vorticity maximum separate from that associated with the surface temperature gradients.

As in TH2 the latitudinal extent of the effect of latent heating is determined by a specific-humidity parameter $q$ which in the first moist life-cycle examined is forced to
Figure 11. Relative vorticity on \( \sigma \)-levels from the \( m = 13 \) desert life-cycle. (a) and (b) show the relative vorticity on \( \sigma = 0.60 \) at days 6 and 10 respectively. (c) and (d) show the relative vorticity on \( \sigma = 0.85 \) at days 6 and 10 respectively. (e) and (f) show the relative vorticity on \( \sigma = 0.98 \) at days 6 and 10 respectively. The contour interval in each section is \( 4 \times 10^{-5} \text{ s}^{-1} \). Negative contours are dashed and the zero is dotted. Lines of constant latitude and longitude are drawn every 10 degrees and the lowest latitude shown is that at the Equator.

decay rapidly north of 15 °N thereby mimicking the observed meridional decrease in convection over tropical north Africa. In this simple study \( q \) is constant equatorward of 15 °N and equal to 14 g kg\(^{-1}\).

The sensitivity to changing the latitudinal extent of the latent heating has also been examined here in four more life-cycles by forcing \( q \) to decay polewards of different latitudes \( \phi_n \), given by 10 °N, 12.5 °N, 17.5 °N and 20 °N. This crudely allows an examination of the effect of moisture availability on the easterly waves which may be expected to vary inter-
or intra-annually. Although it is likely that such variations of moisture availability will be accompanied by shifts in the jet latitude (see e.g. Rowell et al. 1992) this is not explicitly included. The sensitivity to increasing the magnitude of the latent heating has also been examined by repeating the moist life-cycles with a $q$ of 18 g kg$^{-1}$. Since unrealistically, an infinite moisture supply is assumed the life-cycles are only considered up to day 10.

(b) Large-scale view

The EKE evolution (not shown) does not differ greatly from that of the dry life-cycle shown in Fig. 2. This is consistent with the ‘moist’ life-cycles presented in TH2. The most notable difference relating to the energy conversions is that CE becomes larger than CK between day 6 and 7, about a day earlier than for the dry case. Although the maxima reached is slightly weaker than in the dry case it is reached at day 8 instead of day 10. Interestingly CK is almost insensitive to the latent heating. On examining the zonal-mean fluxes (not shown) the moist life-cycle is dominated by vertical heat fluxes around 15 °N. This has the effect of shifting the surface EKE maximum equatorwards relative to that in the dry life-cycle which had maximum vertical heat fluxes around 20 °N.

(c) Relative vorticity

The relative vorticity at day 6 is shown in Fig. 12 for $\sigma = 0.6, 0.85$ and 0.98. Comparing this with Fig. 10 for the dry life-cycle shows that the 600 mb flow is almost unaffected by the latent heating, whereas the low-level relative vorticity maxima is larger and located more equatorward at about 15 °N. The low-level cyclonic region is also more strongly tilted in the NW–SE direction indicating barotropic growth, since easterlies extend to the surface at this time. The relative vorticity at 850 mb has a similar pattern to that at low-levels. At day 10 (not shown), the low-level vorticity continues to be characterized by the 15 °N maxima. No double maxima is seen at 850 mb, the vorticity distribution being dominated by an enhancement of the cyclone associated with the advection of the surface temperature gradients. Even by day 10, the vorticity at $\sigma = 0.60$ is almost totally unaffected by the latent heating.

The low-level vorticity maximum associated with the surface temperature gradients in the dry life-cycle is enhanced and is close to $\phi_n$, the latitudinal limit of the maximum $q$ availability. Thus although the low-level vorticity pattern is dominated by the surface temperature gradients still, the moisture availability in the region of the temperature gradients appears to determine the latitude of the surface maximum. Finally, it should be noted that no low-level vorticity maximum develops, separate from that associated with the surface temperature gradients.

(d) Vertical velocity

A longitude–height cross section of vertical velocity at 15 °N and for day 6 is shown in Fig. 13(a). As in TH2, the vertical velocity pattern loses its dry checkerboard pattern thus appearing to be more realistic compared with the GATE observations, although poleward of the jet where the heating is weak or zero the checkerboard pattern remains. At day 6 the maximum vertical velocity at 15 °N is $-3.4$ mb hr$^{-1}$ compared with $-1.8$ mb hr$^{-1}$ for the $m = 10$ life-cycle in TH2 and $-0.8$ mb hr$^{-1}$ in the dry-shear case. It is interesting to note that although the maximum heating is at about 500 mb, the height of the maximum vertical velocity is around 800 mb indicating the importance of the surface baroclinicity. The vertical velocity at day 6 and at $\sigma = 0.80$, shown in Fig. 13(b) indicates a maximum ascent around 15 °N and west of the jet-level trough (c.f. Fig. 12(a)). The zonal-mean vertical velocity in Fig. 13(c) is characterized by a deep ascending region around 15 °N
with a maximum value of $-0.5 \, \text{mb hr}^{-1}$. This looks similar to that expected of a circulation in the vicinity of the Inter-Tropical Convergence Zone (ITCZ) and indicates that although in a zonal- or time-mean sense, there is mean ascent, it is incorrect to consider this as a zonally-symmetric ascending region (c.f. Fig. 13(b)). This is therefore a reminder that the tropical north African ITCZ should not be thought of as a zonally-symmetric climatic feature but instead as a region where convection is likely to occur, either involved in synoptic waves as here or more intensely in squall-lines (e.g. see Chen and Ogura 1982).
(e) Sensitivity to moisture availability

(i) Energetics. The energetics evolution discussed above and in TH2, characterized by a transition from initially CK dominance to CE dominance is still the main feature of the moist life-cycles with different \( \phi_b \). However, differences exist between the life-cycles regarding the magnitudes of the conversion terms and the time when the transition occurs. To summarize these differences, the energy conversions at day 6 are compared (see Fig. 14). First note that the CK term appears to be quite insensitive to the latitudinal extent of the moisture availability. In contrast, the CE term increases markedly as the moisture is allowed to be more poleward. The CN and the generation of eddy available potential energy (GE) terms also have a similar sensitivity. Figure 14 clearly shows a strong latitudinal relationship between the moisture availability and the jet. For example, for \( \phi_b = 10^\circ \text{N} \) the resulting easterly wave energy conversions are only slightly greater than those of the dry easterly wave, whereas with moisture available in the region of the jet the baroclinic energy conversions increase markedly. Note also that there appears to be a limit to the baroclinic energy conversions with very small sensitivity as the moisture availability extends polewards of the jet.

Clearly, as \( \phi_b \) increases more of the easterly wave benefits from the latent heating and since the easterly wave relies on the jet for its growth the jet region is most sensitive to latitudinal displacements of the moisture availability. The weaker sensitivity of CE to \( \phi_b \)
polewards of the jet latitude is consistent with the fact that it is not just latent heat release that is important for forcing ascent but also the vertical wind shear.

Repeating the experiments with \( q \) increased to 18 g kg\(^{-1}\) reveals the same type of latitudinal sensitivity. With the larger \( q \) however, the energy conversions associated with growth in the jet region (not shown) are much larger, with the CE and GE being particularly sensitive. For example, with the moisture available up to 15 °N, CE at day 6 is larger than CK, and GE larger than CN which is almost insensitive to the different \( q \).

Clearly, the baroclinic energy conversions associated with growing easterly waves are very sensitive to both the latitudinal extent of the moisture availability and also the magnitude of the low-level humidity, whereas the barotropic term, CK, is not.

(ii) Synoptic structure. The synoptic evolution in the moist life-cycles with different moisture availability is qualitatively similar to the \( \phi_h = 15 \) °N life-cycle presented above. For brevity therefore, the quantitative differences are summarized by presenting the magnitudes and latitudinal positions of vertical velocity and relative vorticity maxima (see Table 2). It is clear that although qualitatively the life-cycles are similar there are significant differences in magnitude and position of vorticity and ascent maxima. For example, equatorward of 15 °N the magnitude of the ascent maxima increases with \( \phi_h \). Interestingly, the latitude of the ascent maxima is also dependent on \( \phi_h \). For example, even with \( \phi_h = 10 \) °N the latitude of the ascent maxima is about 7° equatorward of its dry position. As \( \phi_h \) increases, so does the latitude of the ascent maxima, indicating the crucial role of moisture availability. Indeed for \( \phi_h \) up to 15 °N, the latitude of the ascent maxima is close to \( \phi_h \). As noted above, this is consistent with the fact that ascent rate increases with both \( q \) and vertical wind shear. The fact that the ascent maxima and its latitude vary less, poleward of 15 °N is consistent with a weakening of the vertical wind shear there. Thus, with
TABLE 2. VARIATIONS OF MAXIMUM ASCENT RATE AND MAXIMUM VORTICITY WITH $\phi_h$ (SEE TEXT FOR DETAILS).

<table>
<thead>
<tr>
<th>$\phi_h$ (mb hr$^{-1}$)</th>
<th>$\omega_{\text{max}}$</th>
<th>$\zeta_{\text{max}} \sigma = 0.60$ ($\times 10^{-5}$ s$^{-1}$)</th>
<th>$\zeta_{\text{max}} \sigma = 0.98$ ($\times 10^{-5}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRY</td>
<td>-0.9</td>
<td>16.8</td>
<td>2.7</td>
</tr>
<tr>
<td>10.0</td>
<td>-1.0</td>
<td>10.0</td>
<td>2.8</td>
</tr>
<tr>
<td>12.5</td>
<td>-2.1</td>
<td>13.1</td>
<td>2.8</td>
</tr>
<tr>
<td>15.0</td>
<td>-3.6</td>
<td>14.3</td>
<td>2.8</td>
</tr>
<tr>
<td>17.5</td>
<td>-3.7</td>
<td>15.6</td>
<td>2.8</td>
</tr>
<tr>
<td>20.0</td>
<td>-3.5</td>
<td>15.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The maximum ascent rate and its latitude at $\sigma = 0.80$ is shown together with the maximum relative vorticity, $\zeta_{\text{max}}$ at $\sigma = 0.60$ and the maximum relative vorticity at $\sigma = 0.98$ and its latitude.

$q = 14$ g kg$^{-1}$ the latitude of the ascent maxima is restricted to be close to the latitude of the jet maxima. Consistent with this, the observed easterly wave ascent maxima presented by Reed et al. (1977) was at about the jet latitude.

Column 4 in Table 2 shows that the relative vorticity maxima at the jet-level is changed insignificantly by the inclusion of latent-heat release. The relative vorticity at low-levels however varies markedly, except for $\phi_h = 10$°N, which is dominated by the dry structure still, polewards of $\phi_h$. For $\phi_h$ greater than 10°N however the effect of the latent heating is to increase the low-level vorticity maxima and shift it equatorwards relative to the position of the dry maxima. This results in the low-level vorticity maxima being closer to the latitude of the jet maxima. It is therefore clear that the presence of moisture ties the low-level easterly wave development to be closer to the latitude of the jet maxima than it may otherwise be.

The main effect of increasing $q$ to 18 g kg$^{-1}$ is simply to increase the magnitudes of the ascent and vorticity maxima although the maxima at $\sigma = 0.60$ is still unaffected by the heating. For example the ascent maxima for $\phi_h = 15$°N with $q = 18$ g kg$^{-1}$ is $-8.1$ mb hr$^{-1}$ and is at 14.3°N as for the $q = 14$ g kg$^{-1}$ case. Again no surface vorticity maximum separate from that associated with surface temperature gradients was seen in any of the moist life-cycles.

Since increasing the amount and latitudinal extent of the moisture availability has the effect of increasing the surface values of vorticity and since it appears that finite amplitude low-level cyclonic anomalies are important for initiating tropical cyclones (e.g. Emmanuel 1986), this result may be consistent with the observation that during wet years in the Sahel there is a tendency for more intense Atlantic tropical cyclones (e.g. see Landsea and Gray 1992).

6. SUMMARY AND DISCUSSION

Following the idealized studies of African easterly waves by Thornicroft and Hoskins (1994a, b), the nature of unstable waves growing on three different easterly jets has been examined. The jets have observed characteristics which were not represented in the Simmons-jet used in those studies. The shear-jet, with stronger horizontal shear on the equatorward side of the jet was examined to see if the easterly waves which grew on it had predominately stronger momentum fluxes on the equatorward side of the jet, as was observed during GATE (e.g. Albignat and Reed 1980). The desert-jet, with lower mean static stability better represents the atmospheric conditions on the poleward side of the jet. For completeness, a combined-jet with both increased equatorward horizontal shear and decreased static stability has also been examined.
The nature of the unstable waves growing on the shear- and desert-jets are very different. Normal modes growing on the shear-jet are dominated by amplitudes on the equatorward side of the jet and by barotropic energy conversions associated mainly with positive horizontal momentum fluxes as expected. In contrast, normal modes growing on the desert-jet have much larger amplitudes at the surface on the poleward side of the jet and have much larger baroclinic energy conversions associated with low-level heat fluxes, although the barotropic energy conversion term is still largest and mainly associated with negative horizontal momentum fluxes.

Dry nonlinear life-cycles of 3000 km waves growing on the shear- and desert-jets were also examined. In both life-cycles, as in TH2, there is a transition from CK dominance in the linear and early part of the life-cycle to CE dominance in the nonlinear part. It was also found that in the case of the shear-jet life-cycle, although the normal mode is dominated by positive momentum fluxes on the equatorward side of the jet, in the nonlinear part of the life-cycle as in TH2, the negative momentum fluxes on the poleward side dominate thus indicating the robust nature of this result. Although significant negative momentum fluxes have been observed on the poleward side of the jet and below the jet-level, the largest momentum fluxes observed by Albignat and Reed (1980) were observed on the equatorward side of the jet and closer to the jet-level.

The nonlinear desert-jet life-cycle is characterized by earlier dominance of CE and continues to have maximum amplitudes at low-levels on the poleward side of the jet. Even in the nonlinear part of the life-cycle, amplitudes are relatively weak at the jet-level. This therefore appears distinct from the reported observations of easterly waves although since it is predominantly on the poleward side of the jet in the low static stability air of the Sahara, very few observations exist that could have detected it. It is therefore worthy of consideration and future work, although since all the nonlinear life-cycles examined lead to large surface amplitudes on the poleward side of the jet it may be difficult to distinguish the linear desert-mode behaviour from that of nonlinear easterly waves.

The unstable waves associated with the combined-jet have characteristics of the waves growing on both the shear and desert jets. The most unstable 3000 km normal mode has amplitude maxima on the equatorward side of the jet as in the case of the shear-jet and also at the surface as in the case of the desert-jet. Its nonlinear evolution as in all the nonlinear life-cycles examined, is characterized by a transition from CK to CE dominance, maximum nonlinear amplitudes at low-levels in the region of the surface temperature gradients and predominantly negative horizontal momentum fluxes. The structure and nonlinear evolution of the combined-jet life-cycle are similar to that of the desert life-cycle but with larger initial jet-level amplitudes associated with the increased horizontal shear. This life-cycle is suggestive of the fact that even if the normal mode were not dominated by surface amplitudes polewards of the jet, easterly waves still might become strongly influenced by the low static stability below and poleward of the jet in the nonlinear part of its life-cycle. The low static stability, as discussed in section 2 above, would be expected to encourage the baroclinic development of the wave and result in large surface amplitudes. Further study of observed easterly waves is clearly required to examine this.

The relative vorticity structure associated with the shear life-cycle, examined more closely than in TH2, showed clear differences between developments at the jet-level and developments at low-levels. At the jet-level a cyclonic maximum predominantly on the equatorward side of the 600 mb jet initially, moves polewards in the nonlinear part of the life-cycle. At low-levels a cyclonic maximum develops which is associated with the low-level temperature gradients. Inconsistent with the observations presented by Reed et al. (1977) a second weaker equatorward surface maximum is not present. It was shown however that at about 850 mb, two positive relative vorticity centres do exist, a weaker
equatorward one associated with the developments on the cyclonic side of the jet and a stronger poleward one associated with the developments at low-levels. These two types of cyclonic anomaly are probably related to the observations of Carlson (1969) and Reed et al. (1977) although clearly further investigation is required.

It is likely that since the observed equatorward surface cyclone usually has a convective signature unlike the poleward one (see e.g. Duvel 1990), the role of convection needs to be considered to further our understanding of the developments on the equatorward side of the jet. Here however, the presence of simply parametrized latent heating on the equatorward side of the jet did not produce a surface cyclonic region distinct from that associated with the meridional surface temperature gradients. Assuming that the observed equatorward surface cyclone also has jet-level amplitudes as observed during GATE (see e.g. Reed et al. 1977), the absence of such a cyclone in the present study may also be linked to the weakly simulated nonlinear momentum fluxes on the equatorward side of the jet. This in turn may be associated with the simulated poleward moving jet-level cyclonic anomaly.

Thus, although easterly wave developments on the poleward side of the jet may be expected to be well represented by dry dynamics, the same may be less true for the equatorward side. Diabatic processes, such as those associated with convection, radiation and surface fluxes are likely to be important in easterly wave life-cycles (e.g. Krishnamurti and Kanatmitsu 1973). As suggested by Schubert et al. (1991) diabatic heating may also be important in maintaining the mean-meridional PV gradients of the AEJ. This may be expected to help maintain the nonlinear equatorward jet-level easterly wave structure, inhibiting the poleward movement of the jet-level cyclonic anomaly and thereby maintain the positive momentum fluxes.

Other characteristics of the basic state jet not addressed here may also be important in determining the nature of the easterly waves and in particular those developments on the equatorward side of the jet. These include the vertical wind shear and also as commented on by Rennick (1981) the low-level vorticity gradients associated with the monsoon westerlies equatorward of the jet. Rennick (1981) and Paradis et al. (1995) have shown that increased vertical shear is associated with more baroclinic easterly waves as expected. Also, the suggestion of Miller and Lindzen (1992) that the vertical shear may be important in influencing how easterly waves organize rainfall indicates that future studies involving convection should also include an examination of the role of the vertical shear.

The transitions which occur as easterly waves become nonlinear and also as they move from the land to the ocean requires further investigation. In particular, the role of diabatic processes in the easterly wave developments is not well understood and may account for some of the discrepancies identified in this idealized study. Together with a more detailed examination of the role of these diabatic processes, future work should also include an examination of initiation mechanisms and more realistic basic states including both their time and longitudinal variations.

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