Mean State and Wave Disturbances during Phases I, II, and III of GATE Based on ERA-40

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ABSTRACT

Using ECMWF's second-generation reanalysis, ERA-40, the large-scale mean state and synoptic-scale features associated with African easterly wave disturbances (AEWs) are examined over West Africa and the adjacent eastern Atlantic Ocean during the three 21-day observing periods of the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) in 1974 (Phase I, 26 June–16 July; Phase II, 28 July–17 August; Phase III, 30 August–19 September). Results are partitioned into four geographical boxes, in order to highlight differences among the AEW vortices as they propagate westward along two tracks (northern and southern) over West Africa (land) and the adjacent eastern Atlantic Ocean (water). This marks the first time that a detailed diagnosis of the northerly track AEWs has been conducted. Results are also compared to previous GATE studies and a 30-yr climatology is extracted from ERA-40.

In general, the subjectively analyzed wind fields presented in earlier studies compare favorably with the ERA-40 horizontal wind fields. The vertical motion field is one of the parameters that shows the largest differences to previously published results. In the area of the GATE A–B-scale ship array in the eastern Atlantic Ocean, low-level ascent during GATE is twice as large as in the ERA-40 climatology, most likely due to the dense upper-air network that allowed for an exceptionally good analysis of the divergent wind field. The midtropospheric outflow layer found over the ship array is absent in the ERA-40 climatology. Detrimental to the ERA-40 analyses of the upper-level easterly jet over the central Gulf of Guinea and along parts of the Guinea coast, were the assimilation of erroneous aircraft data.

Using a recently developed tracking method of midtropospheric African easterly waves, a complete tracking history of northerly and southerly AEW vortices is presented and discussed for all three phases of GATE. One important result is that the activity of the northern waves at about 20°N was, in contrast to the southern waves at about 9°N, already quite strong during Phase I. At the same time, the low-level monsoonal flow, the heat low, and the upward motion in the northern desert zone were strongest. In contrast, the midtropospheric African easterly jet (AEJ) and the related horizontal shear instabilities were strongest during Phase III. The AEJ is also found at the lowest altitude over land during Phase III and it extends out to the Atlantic Ocean without changing its height and strength. These factors are associated with the well-known peak in the activity of AEWs in the southern wet zone during Phase III. In contrast to earlier findings, no reduction of AEW energy, by lifting of anomalously cool low-level air along the southern moist AEW track, could be observed over land.

1. Introduction

From 15 June to 23 September 1974, the international field program Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) was held over the tropical region encompassing western Africa and the eastern Atlantic Ocean. The scientific objectives of GATE's central program were to examine the interactions between a variety of scales of organized convective systems and the large-scale flow, and to improve numerical models and, thereby, numerical weather prediction (e.g., Kuettner 1974). Four scales of motion were defined for GATE: A, B, C, and D, which range from the synoptic-scale A to the cumulus-cloud–scale D. It is the A scale that is of greatest interest in this paper. That scale's primary scientific objectives were to describe the wave disturbances that propagated from west-
ern Africa to the eastern Atlantic Ocean, as well as to
diagnose the basic or mean state in which they were
embedded, including such features as the ITCZ, jet
streams, and meridional circulations (e.g., Parker 1974).

Several investigators, both prior to and after GATE,
presented analyses of the large A-scale flow features in
the GATE region (e.g., Albignat and Reed 1980; As-
pldien et al. 1976; Burpee 1972, 1974, 1975, 1979; Bur-
pee and Dugdale 1975a; Burpee and Reed 1982; Carlson
1969a,b; Chen and Ogura 1982; Estoque and Douglas
1978; Huang and Vincent 1982; Krishnamurti and Pasch
1982; Miyakoda et al. 1982; Norquist et al. 1977; Pep-
pler and Vincent 1983; Reed et al. 1977; Reynolds 1977;
Sadler 1975; Sadler and Oda 1978, 1979, 1980; Thomp-
son et al. 1979; Vincent 1981). In addition, an excellent
review paper on GATE scientific results was written by
Greenfeld and Fein (1979). The above-cited investiga-
tions were, with the exception of Miyakoda et al.
(1982), based on subjective static analyses of the mean
state and/or the wave disturbances, generally referred
to as African easterly waves (AEWs).

One of the goals of the present paper is to use the
recently available European Centre for Medium-Range
Weather Forecasts (ECMWF) reanalysis dataset, known
as ERA-40, to conduct a comprehensive investigation
of the large-scale circulation patterns (primarily mean
state and wave disturbances) during all three phases of
GATE (Phase I: 26 June–16 July; Phase II: 28 July–17
August; Phase III: 30 August–19 September 1974).
Since the dataset extends back to 1957, another goal
of this paper is to place GATE results in a long-term per-
spective by comparing them to a set of climatological
features, both over West Africa (land) and the adjacent
eastern Atlantic Ocean (water). Relatively few inves-
tigators (e.g., Huang and Vincent 1982; Norquist et al.
1977; Reed et al. 1977; Vincent 1981) compared results
over the African continent to those over the eastern
Atlantic Ocean where a special A–B-scale ship array
was located. Since about 1969 (Carlson 1969b), it has
been established that there are two east–west tracks
along which AEW vortices propagate, one located be-
tween 16° and 20°N and the other located between 7°
and 11°N. Although the existence of AEW disturbances
along the northern track has been noted by several stud-
ies (e.g., Burpee 1974; Reed et al. 1977; Reed et al.
1988a; Duvel 1990; Thomcroft and Hodges 2001; Fink
and Reiner 2003), their kinematic, thermodynamic, and
moisture environments have not been investigated in
depth, especially for the three enhanced observing phas-
es of GATE. Indeed, most GATE studies focused on the
southerly waves during Phase III because these wave
disturbances were more numerous and better organized
during that period (e.g., Burpee 1975; Reed et al. 1977).
Therefore a third goal of this paper is to conduct a
thorough diagnosis of the northerly AEW vortices dur-
ing Phases I, II, and III.

As mentioned earlier, for most studies, AEWs refer
to the barotropically maintained vortices that propagate
westward along about 10°N from central Africa out to
the eastern Atlantic Ocean. Their typical wavelength
is about 2500 km and they travel with characteristic phase
speeds of about 8 m s$^{-1}$, yielding a typical wave period
of 3.5 days (Burpee 1975; Reed et al. 1977). The vor-
ticity associated with these waves is typically strongest
near 600–700 hPa. Avila et al. (2000) found that on
average 61 westward-moving tropical wave disturbanc-
es crossed the West African coastline each year during
the period 1967–96 and propagated across the tropical
Atlantic Ocean. The authors note that for the same pe-
riod, African wave disturbances formed the seedling
circulations for 62% of the Atlantic tropical depressions.
Thus, AEWs are not only relevant for West African
rainfall (cf. Fink and Reiner 2003), but are also impor-
tant to understand the variability of moist convec-
tion over the tropical Atlantic Ocean and of the activity
of the North American hurricane seasons.

A detailed description of the ERA-40 dataset, in-
cluding the data from GATE used for ERA-40 and a
description of our method for tracking AEWs, is given
in section 2. The reexamination of the large-scale mean
state during the three phases of GATE using ERA-40
is discussed in section 3 as the first specific objective
of this paper. In section 4, geographical differences of
the large-scale mean state are examined by partitioning
results into four regional boxes (two over land encom-
passing the northern and southern wave disturbance
tracks found there, and two over water). As a third spe-
cific aim, section 5 presents the large-scale character-
istics associated with AEW activity with special em-
phasis on the role of barotropic and baroclinic insta-
bilites and energy conversions. Section 6 contains a
summary and some concluding remarks. Where appro-
riate, our results will be compared to those from pre-
vious studies, as well as to a 30-yr climatology extracted
from ERA-40.

2. Computational and analysis procedures

a. Description of ERA-40 dataset

ERA-40 belongs to the second-generation reanalysis
benefiting from many improvements and new de-
velopments in the data assimilation scheme, resolution,
dynamics, physics, and formulation of land surface pro-
cesses in the background forecast model. At the time
of this writing, only 30 of the 40 yr of the ERA dataset
were available to compute climatological means. These
years consist of 11 from stream 1 of ERA-40 (1989–
99), 10 from stream 2 (1958–67), and 9 from stream 3
(1973–81). Moreover, the ERA-40 final report series
was not yet available. However, much information about
the ERA-40 project, including preliminary quality as-
sessments, can be obtained from ECMWF’s Web site
(online at http://www.ecmwf.int).

With respect to the quality of ERA-40 fields during
the GATE period, some of the most relevant improve-
ments in the data assimilation technique are 1) the atmospheric model used for ERA-40 has a resolution of T159L60, with 36 (16) model levels below 100 hPa (700 hPa), 2) the three-dimensional variational data assimilation (3DVAR) scheme (Courtier et al. 1998) combined the background forecast and observations to the analysis every hour, 3) both the standard and significant levels in conventional observations (TEMP and PILOT) were assimilated, and 4) temperature and humidity profiles from the Vertical Temperature Profile Radiometer (VTPR) aboard National Oceanic and Atmospheric Administration (NOAA) satellites were derived over ocean from raw satellite radiances at the observed pixel resolution. The ERA-40 parameters used in the present study were transformed from spherical harmonic space onto a $1^\circ \times 1^\circ$ latitude–longitude grid at the 10 standard tropospheric pressure levels up to 100 hPa, plus three additional levels, 925, 775, and 600 hPa. Results for the three observational phases of GATE are based on 4-times daily analyses at 0000, 0600, 1200, and 1800 UTC, whereas the 30-yr climatology was calculated using twice-daily analyses at 0000 and 1200 UTC.

b. Data available for ERA-40 during GATE

One goal of the ERA-40 project is to revitalize diagnostically and modeling work using observations and analyses from past field experiments (cf. Simmons and Gibson 2000). For the West African subcontinent (defined here as the region south of the tropic of Cancer and west of 10°E), the upper-air network consisting of radiosonde, radio, and pilot wind stations was, perhaps, with the exception of the West Monsoon Experiment (WAMEX) in 1979 (cf. Fig. 3 of Peters et al. 1989), never as dense as during GATE (June–September 1974). For the purpose of the present study, one of the major advantages of GATE over WAMEX is the availability of 6-hourly upper-air data from more than 10 research vessels positioned in the eastern Atlantic Ocean east of 30°W.

A good overview of the radiosonde–radiowind network during the three phases of GATE is given in Figs. 5-1, 5-2, and 5-3 of Parker (1975). Over land, radiosondes were usually released twice daily at 0000 and 1200 UTC, except at Praia (Cape Verde Islands), Bamako (Mali), and Dakar (Senegal), where supplemental ascents were made at 0600 and 1800 UTC. At these times, pilot wind observations were carried out at the remaining stations and substantial spatial gaps in the radiosonde network over West Africa were filled by about 23 pilot wind stations performing ascents at 0000, 0600, 1200, and 1800 UTC. Pilot wind data generally do not extend above 700 hPa. Figure 1 in Vincent (1981) conveys a good impression of the land and ocean wind data network during all phases of GATE, and Fig. 12.4 in Burpee and Dugdale (1975b) gives a condensed summary of the functioning of the GATE land upper-air network during Phase III. Other sources of upper-air information during GATE are the Synchronous Meteorological Satellite (SMS-I) cloud drift winds, the VTPR temperature and humidity profiles over water, dropwindsonde profiles from research aircraft over the eastern Atlantic Ocean and flight-level data from both commercial and research aircraft.

In recent years, the availability of conventional upper-air observations over West Africa on the Global Telecommunications System (GTS) declined mainly as a consequence of a further thinning of the already sparse regional network. During GATE, 19 land radiosonde stations were operational; 15 of those reported at least twice daily at 0000 and 1200 UTC. The corresponding numbers reporting to the GTS on rare “optimal coverage” dates in the recent years were 12 and 7, respectively, and the number of pilot stations was decreased by 50% since GATE. In this context, it is interesting to note that denial experiments for the period of the JET2000 experiment (for details of the experimental design and preliminary results, see Thorncroft et al. 2003) in August 2000 revealed that the few available conventional upper-air wind data had the largest positive impact of all types of upper-wind information, including satellite winds, on the analysis of the midtropospheric African easterly jet (AEJ) over West Africa (D. J. Parker, University of Leeds, 2002, personal communication). From the arguments given, the use of ERA-40 during GATE seems to be a promising approach to gain new insights into large- to synoptic-scale processes over West Africa and the adjacent eastern Atlantic Ocean.

c. Tracks of African easterly waves

An important concern in this paper is to reexamine the large-scale features associated with AEWs; therefore, it is necessary to comment on the method used here to identify and track these disturbances. In this context, it seems appropriate to first review some of the previous work on wave identification and tracking.

1) Previous approaches

Among the various approaches to either track individual cyclonic vortices or identify preferential tracks of AEWs, it is possible to distinguish among statistical methods (Burpee 1972; Albignat and Reed 1980; Reed et al. 1988b; Duvel 1990; Lau and Lau 1990; Fyfe 1999; Diedhiou et al. 1999), automatic tracking techniques (Thorncroft and Hodges 2001), and manual methods (Carlson 1969a; Reed et al. 1977; Sadler and Oda 1978, 1979, 1980; Reed et al. 1988a). Most statistical studies used the bandpass-filtered meridional wind (Duvel 1990; Fyfe 1999; Diedhiou et al. 1999) or vorticity variances (Reed et al. 1988b; Lau and Lau 1990) at 700 or 850 hPa. The bandpass filters were generally centered around the typical AEW period of 3–4 days (cf. Burpee 1975) to amplify the AEW signal in the selected variable. In general, these statistical studies display smooth
and longitudinally elongated regions of preferred AEW tracks, and are appropriate for examining the interannual variability in AEW activity (cf. Diedhiou et al. 1999).

The automatic algorithm, described in Thorncroft and Hodges (2001), is an objective procedure that traces closed relative vorticity maxima at 600 and 850 hPa that exceed a threshold value of $0.5 \times 10^{-5}$ s$^{-1}$, have a lifetime of more than 2 days, and propagate zonally over a distance of more than 10$^5$ longitude. Using ECMWF data for the period May–October 1979–98, the algorithm yielded good results over the Atlantic Ocean and the Caribbean. Over West Africa, however, the relation between vorticity maxima and AEWs is not as unambiguous; the vigorous mesoscale convective systems between vorticity maxima and AEWs is not as unambiguous; the vigorous mesoscale convective systems over land are often associated with cyclonic wind shifts in the lower troposphere and Thorncroft and Hodges (2001) note the existence of multicentered AEWs.

Pre-GATE papers and those using the enhanced set of observations taken during GATE almost exclusively employed manual tracking of the wave disturbances. Carlson (1969b) used 2000- and 10 000-ft streamline analyses, together with satellite images, to examine AEWs over western Africa and the eastern Atlantic Ocean during the summer of 1968. From his Fig. 2 and the schematic depiction of an AEW in his Fig. 4, the existence of a pair of vortex centers in the 2000-ft winds, one near 11$^\circ$N and the other near 20$^\circ$N, is evident. The latter finding was one of the earliest documentations of the second, near-surface northerly AEW vortex over Africa. Carlson’s 10 000-ft analyses showed only the southern vortex center, which is associated with the better-known wave track of the southerly AEWs. Burpee (1974) composited surface streamline analyses associated with the wave disturbances over land during the summer seasons of 1968 and 1969. His results revealed two cyclonic vortices, one centered at 18$^\circ$N and the other at 9$^\circ$N. The northern vortex and its east–west axis lie just south of the axis of minimum sea level pressure in the relatively cloud-free, desert zone along the southern fringe of the Sahara, while the axis of the southern system lies close to the latitudinal band of maximum summer precipitation (10$^\circ$N).

Reed et al. (1977) diagnosed the more pronounced wave activity during Phase III and found that the southerly AEWs were best tracked by following the maximum relative vorticity centers at 700 hPa. Their mean latitudes of the waves were 11$^\circ$N over land (15$^\circ$W–10$^\circ$E) and 12$^\circ$N over the eastern Atlantic Ocean (31$^\circ$–15$^\circ$W). The authors also found a separate northerly vortex at 17$^\circ$N in the composited surface wind field and speculated that it merges with those around 11$^\circ$N over the eastern Atlantic Ocean. Finally, Sadler and Oda (1978, 1979, 1980) used surface wind analyses to locate the tracks of southerly AEWs during the 100 days of the entire GATE field program. For Phase III, Sadler and Oda (1980) found the average disturbance paths to be around 10$^\circ$N over land and around 11$^\circ$N over water (for the same longitudes as those used by Reed et al. 1977). Thus, there is good agreement between these two studies.

More recent studies, on the basis of ECMWF data, have confirmed the existence of two tracks straddling the AEJ axis over land. Reed et al. (1988a) considered streamline maps at 850 and 700 hPa, as well as relative vorticity at 850 hPa and Meteosat imagery, to investigate disturbances during August–September 1985. They found two tracks over land, along 10$^\circ$N and 20$^\circ$N, that merged over the eastern Atlantic Ocean. Duvel (1990) used the bandpass-filtered (3–5-day) meridional wind component at 850 hPa, together with Meteosat images, and located two peaks in AEW activity, one along 20$^\circ$N in June–September 1983–85 and another along 7.5$^\circ$N in August–September only. Diedhiou et al. (1999) found two main tracks along 5$^\circ$ and 15$^\circ$N over West Africa in the June–September 1979–95 average.

Finally, it should be stressed that both the merging of the northerly and southerly AEW vortices off the West African coast and the longitudes where the vortices can be first detected remain a controversial issue to date. Thorncroft and Hodges (2001) found few northerly wave tracks at 850 hPa that merged with the 600-hPa tracks over the Atlantic Ocean and proposed the genesis of vortices in the rainy zone at the West African coast around 10$^\circ$N as the source of the Atlantic Ocean disturbances at 850 hPa. Moreover, several of their 600-hPa vorticity maxima could be traced back as far east as the Ethiopian highlands, which is consistent with results from the statistical approach pursued in Albignat and Reed (1980) for Phase III of GATE. The latter authors, however, noted that they could not identify AEWs east of 15$^\circ$E in streamline charts. Based on longitude–time (Hovmoeller) diagrams of 700-hPa relative vorticity, Miyakoda et al. (1982) found that a meridional vortex path at the eastern flank of the quasi-stationary Libyan anticyclone recurves zonally at about 20$^\circ$E. These contentious issues will be addressed in the following section.

2) PRESENT METHOD

The three-step subjective manual tracking method employed in this paper is the same as that used by Fink and Reiner (2003). First, two sets of Hovmoeller diagrams of temporal anomalies of the meridional wind component ($v$) were produced: one at 700 hPa averaged between 7$^\circ$ and 13$^\circ$N, and the other at 850 hPa averaged between 17$^\circ$ and 23$^\circ$N. The two types of Hovmoeller diagrams take into account the existence of northerly and southerly AEWs at different altitudes. From these diagrams, AEW episodes and the approximate longitudinal position of AEW troughs were identified by subjectively interpolating changes of sign in the $v$ component of the wind with a straight line. In a second step, 6-hourly streamline maps of 2–6-day bandpass-filtered wind at 850 hPa were plotted. In most cases, a northerly and southerly center of cyclonic inflow at or close to
the previously identified longitudes could unequivocally be localized in the streamline maps. Maps of 2–6-day bandpass-filtered relative vorticity at 700 hPa were investigated in a third step to diagnose the coordinates of the paired vortex but only in cases of absent closed circulation centers or ambiguity. This multivariate manual identification method was subject to the constraints that the cyclonic center of the AEW was identifiable over more than 2 days and that its wavelength was larger than 1500 km. Advantages of the described method are, among others, the attempt to circumvent the use of the rather noisy relative vorticity fields and the guarantee that through the meticulous analyses of time sequences of bandpass-filtered streamline charts only AEWs will be identified. Disadvantages include the fact that the manual identification method is extremely time consuming; therefore its application is limited to short investigation periods.

Fink and Reiner (2003) used the method described previously to locate and track 81 wave disturbances over Africa and the eastern Atlantic Ocean during the summers of 1998 and 1999. As in some of the previous studies, they found two mean wave tracks over land, a northerly one along 17°N and a southerly one along about 8.5°N. Only 12 of the 81 AEWs were identifiable at one flank of the AEW, corroborating the notion of Pytharoulis and Thorncroft (1999), and Nitta and Takayabu (1985) that the northerly and southerly waves are usually coherent features.

In the present analysis, the wave tracks for each of the three phases of GATE are shown in Fig. 1. All AEWs that existed for at least three analysis times (i.e., 12 h) during the 3-week GATE phases, respectively, were considered. As in many of the previous studies, two distinct tracks are visible, especially over land. The northern and southern tracks of simultaneous twin vortices are depicted in the same color. The only case of a single vortex propagation occurred during Phase I (red northern track in Fig. 1a) and solely during Phase III, a merging of two paired vortices was suggested by the 6-hourly streamline maps (cf. black and light green tracks in Fig. 1c). It is also evident from Fig. 1 that no vortex fulfilled the AEW definition east of 20°E. The mean latitudes of the northern and southern tracks over land and water, averaged for the longitudes already used in Reed et al. (1977), are given in Table 1 for all three phases. Compared to the studies of Reed et al. (1977) and Sadler and Oda (1980), the mean tracks for Phase III are about 2° latitude farther south in the present study. An investigation into the causes of this discrepancy revealed that it can be explained to a large extent by the use of bandpass-filtered wind data that tends to shift the tracks slightly southward (not shown). Finally, it is evident from Fig. 1 that the total number of AEWs per phase does not differ much, but tracks are shorter during Phase II and, especially, during Phase I. Note the well-known increase in the wave activity from the first two phases to the third phase in the ship array over the eastern Atlantic Ocean.

Figure 1 also shows four regions (shaded boxes), two over land and two over water, which were used for the computation of areal averages of several variables. The boxes encompass the typical wave tracks over land and water. Note that the axis of the 700-hPa easterly jet (gray thick line in Fig. 1) separates the northern and southern boxes for each of the three phases. Over land, the northern box includes the relatively cloud-free, east–west-oriented zone of minimum surface pressure near 20°N, whereas the southern box covers the region of maximum June–September rainfall. As will be shown in the next sections, these corresponding two sets of waves differ in terms of their kinematic environment, their energy sources, and the associated shear instabilities.

3. Large-scale mean state

The first objective of this paper is to reexamine the large A-scale mean state because it provides the background for the wave disturbances and other phenomena. Only a few scientists produced results of the mean state based on all three phases of GATE. For example, Reynolds (1977) showed the wind distributions at selected levels, but only for Phase III. Sadler and Oda (1978, 1979, 1980) showed wind fields for each phase, but only at 250 hPa. Similarly, Krishnamurti and Pasch (1982) depicted the flow in the upper troposphere (200 hPa) for each phase. The reference that contains the most appropriate set of mean state results for comparison to the present study is by Vincent (1981); thus, his reference will be cited on occasion.

a. Horizontal distributions

The ERA-40 wind distributions at 925, 700, and 200 hPa for Phase III are shown in Fig. 2. As in all subsequent figures, the locations of the A–B-scale (outer hexagon) and B-scale (inner hexagon) ship arrays are indicated. The same fields, including climatologies, were produced for the other two phases, but are not shown in order to conserve space. Figure 2c illustrates the well-known col area near the surface over the eastern Atlantic Ocean, which is centered near 8°N, 34°W at 925 hPa. Figure 2c also shows that the low-level monsoonal southwesterlies extend to about 20°N over Africa. While the corresponding lines of confluence between the monsoon flow and the Saharan northeasterly trades were only 1°–2° latitude farther north during Phases I and II, the monsoonal southwesterlies were much stronger and deeper in the northern dry zone between 15° and 20°N during the first two phases (not shown). This point will be taken up later. It is important to mention that the monsoonal flow was weaker during GATE (all three phases) in comparison to our climatological maps (not shown). Figure 2b shows that the flow at 700 hPa is predominantly easterly, with an axis...
Fig. 1. Northern and southern AEW tracks and mean positions of the 700-hPa AEJ core axes (gray thick line) for Phases (a) I, (b) II, and (c) III. Tracks of simultaneous twin AEW vortices are displayed in the same color. Track colors are chronologically labeled with roman numerals below each panel. Numbers at the beginning (end) of the tracks denote calendar date of first (last) appearance. Tracks were not truncated to the 3-week observational phases. The gray-shaded boxes represent the regions used for the computation of areal averages of several variables. The approximate location of the A–B-scale ship array over the eastern Atlantic Ocean is indicated by crosses.
TABLE 1. Mean latitudes of the northern and southern AEW vortices over land (15°W–10°E) and water (31°–15°W), averaged over 6-hourly analysis time within each of the three GATE periods.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Northern AEW</th>
<th>Southern AEW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land</td>
<td>Water</td>
</tr>
<tr>
<td>I</td>
<td>19.6°N</td>
<td>16.5°N</td>
</tr>
<tr>
<td>II</td>
<td>19.6°N</td>
<td>18.0°N</td>
</tr>
<tr>
<td>III</td>
<td>17.0°N</td>
<td>16.2°N</td>
</tr>
</tbody>
</table>

of maximum wind speeds corresponding to the AEJ stretching from 13°N, 10°E over land to 16°N, 30°W over water. During all phases of GATE, the AEJ axis was north (south) of its climatological position over ocean (land), that is, the AEJ was more zonally oriented in the 30-yr climatology (not shown). The AEJ pattern was nearly the same in Vincent’s (1981) subjective analysis of GATE Phase III winds.

At 200 hPa, however, there is a distinct discrepancy between the ERA-40 and Vincent’s analysis with regard to the axis of maximum easterly winds. Figure 2a shows a pronounced minimum in the easterlies over the central Gulf of Guinea in the region between 0°–5°N and 0°–8°W, while the axis of maximum easterlies is found over land at about 8°–9°N. In contrast, Fig. 3 in Vincent (1981) displayed the maximum of easterly winds over water just south of the Guinea coast, that is, it stretched across the northern part of the low wind speed region in Fig. 2a. This location is consistent with Sadler and Oda’s (1980, their Fig. 12) 250-hPa analysis for the Phase III mean.

A thorough investigation of the upper-air observations used in the aforementioned ERA-40 “problem area” over the Gulf of Guinea revealed that the ERA-40 analysis system was almost daily fed with erroneous wind data from a commercial aircraft that crossed the central Gulf of Guinea at cruising levels between 35 000 and 37 000 ft (~250 hPa) during all three phases of GATE. Unfortunately, no reference observations were available to the variational quality control to eliminate the wrong data in this area. In this context, the following remarks are important: 1) the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis also seem to suffer from these observations, 2) the ECMWF analysis agrees well with radiosonde and reliable aircraft data outside of the problem area (S. Uppalla and P. Kallberg, ECMWF 2003, personal communication), and 3) the aircraft wind data seem to be reasonable in Sadler and Oda’s (1978, 1979, 1980) daily subjective 1200 UTC analysis, thus, implying that the error was introduced in the digital archiving or

FIG. 2. Streamlines and isotachs in m s⁻¹ (shaded) at (a) 200, (b) 700, and (c) 925 hPa for Phase III. The approximate locations of the A–B-scale (outer hexagon) and B-scale (inner hexagon) ship arrays over the eastern Atlantic Ocean is indicated by bold lines.
processing step. In the remaining discussions, we will draw the reader’s attention to the impact of this analysis error where appropriate.

Because of the importance of relative vorticity at 700 hPa in locating easterly wave activity, the mean vorticity maps at 700 hPa are shown in Fig. 3 for each phase. It is seen that an axis of maximum cyclonic vorticity meanders north–south between latitudes 8° and 12°N in each of the three phases. Note that a rather abrupt latitudinal shift takes place in this axis from 8° to 12°N between 0° and 3°W in each phase that was absent in our climatological maps (not shown). From an inspection of Fig. 2b, it is evident that, during Phase III, this shift is the combined result of the pronounced poleward excursion of the AEJ (cyclonic shear at its equatorward flank) and a transition from cyclonic to anticyclonic curvature over the Guinea coast at these longitudes. The latter circulation pattern was also evident during Phase II (not shown). Figure 3 also shows that the peak values of vorticity occur over land, especially over the Guinean Mountains (∼9°N, 10°W), where cyclonic shear at the equatorward flank of the AEJ and cyclonic inflow into this highly convective area are superimposed on one another (Fig. 2b). A comparison of the patterns and locations of maximum vorticity between Fig. 3 and the corresponding maps in Vincent (1981) reveals very good agreement. The primary differences are that the axes of maximum values in Vincent’s subjective analysis do not meander as much as those in Fig. 3. Also, peak values are smaller in Vincent than in the present analysis.

b. Meridional-height cross sections

The next set of results is meridional-height cross sections of the zonal wind component for each phase along 4°W (Fig. 4) and 24°W (Fig. 5). The choice of these meridians will allow a comparison with Vincent’s (1981) analysis. They represent the flow over land and ocean, respectively. Figure 4 shows that the AEJ is located at 15°N for all three phases of GATE, but at a somewhat higher elevation during Phase I when compared to Phase III. Figure 4 also shows that just north of the Guinea coast (5°N), the depth and strength of the low-level westerly monsoonal flow is greatest during Phases II and III, while in the northern dry zone (15°–20°N), the monsoon flow is strongest and deepest during Phases I and II. Note the unrealistic weak easterly winds in the upper troposphere, from 0°–5°N, during all phases that were introduced into the analysis by the erroneous aircraft data (cf. discussion of Fig. 2a). Figure 5 shows that over water the location of the AEJ is much more variable from phase to phase than it is over land (Fig. 4). In addition, Fig. 5 reveals that the AEJ is, in all three phases, somewhat lower in elevation over water than over land. As expected, the monsoonal flow over water does not penetrate as far northward as it does over land during all three phases.

c. Zonal-height cross sections

In order to examine the behavior of certain variables along the mean paths followed by the AEWs, zonal-height cross sections were analyzed at latitudes 6°, 9°, 12°, 14°, and 20°N for the zonal wind component, relative vorticity, vertical velocity, and relative humidity.
Fig. 4. Meridional cross sections of the zonal wind ($u$) in contour intervals of 2 m s$^{-1}$ along 4°W for Phases (a) I, (b) II, and (c) III. The 0 contour is bold, negative contours (easterly winds) are dashed. Land surface height is indicated by the black solid-filled areas.

Fig. 5. As in Fig. 4 except for 24°W. The approximate maximum north-south extension of the A–B-scale (B scale) ship array is delineated by light (medium) gray shading below the abscissa.
To conserve space, only the cross sections of vertical velocity and relative humidity are shown. Details involving the distributions of zonal wind and vorticity can be seen in Figs. 3, 4, 5, 8, and 9. Since the scale interaction between synoptic-scale AEW activity and vertical velocity, and mesoscale convective activity was one focus of post-GATE research, it is of interest to examine the vertical motion (\(\omega\)) field in this study. Figure 6 illustrates this variable along 9° and 20°N, which are near the mean latitudinal paths over land followed by southern and northern wave disturbances when all three phases are averaged. Figure 6a shows that, during Phase III (only phase shown since wave activity was more organized), upward motion occurs at almost all longitudes along 9°N and has a maximum near the African coast (14°W) and a secondary maximum over the A-B-scale ship array. The level of maximum upward motion is generally between 700 and 600 hPa, especially over land. The peaks in \(\omega\) occur at the same longitudinal positions along 6°N (not shown). At 12°N (also not shown), the ascending motion became much weaker, but still dominated the cross section. At 20°N, it is restricted to land areas (Fig. 6b). The level of maximum upward motion in Fig. 6b is 775 hPa, suggesting a relation to the dry thermal low pressure trough in that region.

During all three phases of GATE, the upward motion over the GATE ship array (cf. Fig. 6a) was much stronger throughout the troposphere than in the climatological means (not shown). It seems reasonable to assume that the cluster of more than a dozen ship upper-air stations in this small portion of the eastern Atlantic Ocean ITCZ led to a much more realistic analysis of the vertical motion field. Along the same line of arguments, one must be cautious with the interpretation of the anomalous upward motion over land during Phase III (both in the moist and dry convection zone, not shown) since it might be related to the unusually dense upper-air network.

The other variable selected for display along zonal-height cross sections is relative humidity (RH). Since it is usually compatible with vertical motion, the same latitudes are used to depict RH, that is, 9° and 20°N (Fig. 7). It is seen that the patterns for RH match very well with those for \(\omega\) and, together, the two variables illustrate that, for the most part, moist air is rising and dry air is sinking. In particular, Fig. 7a shows that, during Phase III, the highest moisture content near the African coast corresponds to the maximum upward motion seen in Fig. 6a. The large values of RH at 100–250 hPa over the A-B-scale ship array are presumably the result of the anomalous upward motion and moistening of these layers in the background model; radiosonde RH observations above 300 hPa were not used to correct the model output. One exception to the aforementioned correlation of RH and \(\omega\) is observed in the 20°N cross section (Fig. 7b). Over land, extremely dry boundary layer air reaches up to 775 hPa. The vertical temperature gradient in the hot desert air is close to the dry-adiabatic lapse rate and, thus, the surface layer is well mixed. As a consequence, RH values increase up to the top of the mixed layer, which is delineated by a striking maximum of RH values at 600 hPa in Fig. 7b. The Saharan mixed layer is advected onto the eastern Atlantic Ocean, where it is undercut by a deepening moist trade wind layer and forms the well-known “Saharan dust” or “Saharan air layer” between 850 and 500 hPa (Greenfield and Fein 1979).

4. Land and water comparisons

The second objective of this paper is to partition the ERA-40 results, described in section 3, into land versus water composites. This will be accomplished for each phase by horizontally averaging a variable at all avail-
The contour interval is 5%. Solid (dashed) contours indicate areas with RH > 50% (<45%).

The next set of profiles shows horizontal divergence. Figures 10b,d reveal that over land the layer of convergence in the lower part of the troposphere is deeper in the southern box than in the northern box during all three phases. The divergence aloft is also stronger in the southern region. These findings will, of course, have a bearing on the vertical motion profiles discussed in the next paragraph. Over water, the three profiles in the northern box all exhibit lower-tropospheric divergence and upper-tropospheric convergence (Fig. 10a), which is a reversal of their counterparts over land (Fig. 10b). This is caused by the large-scale subsidence in the trade wind regime. The southern box over water (Fig. 10c)
Fig. 8. Vertical profiles of the zonal wind \((u)\) in m s\(^{-1}\), horizontally averaged over land (14°W–10°E) and ocean (30°–18°W) for northern (15°–22°N) and southern (5°–12°N) boxes, respectively, for all three phases. The locations of the four boxes are shown in Fig. 1.

shows a divergence profile for Phase III that is different from those in the other two phases. It consists of low-level convergence, midlevel divergence, then another layer of convergence and upper-level divergence above it. A similar pattern was found by Thompson et al. (1979, their Fig. 5) for the A–B-scale ship array in Phase III. They attributed the divergence peaks at 500 and 250 hPa to outflow regions from two distinct groups of convective cloud tops. Phase II, in Fig. 10c, shows the same two divergence peaks as for Phase III, but also a third peak at 775 hPa, which is another level where convective cloud tops often occurred in the GATE region (Thompson et al. 1979). In the 30-yr climatology (not shown), no outflow layer is evident at 500 hPa and the low-level divergence peak is more pronounced and somewhat higher at 700 hPa.

The vertical motion profiles that correspond to the earlier-mentioned divergence profiles are shown in Fig. 11. Since the southern boxes contain the wave disturbances traveling in the ITCZ region, they show a deeper layer of strong upward motion than the northern boxes. The largest peak values of uplift occur during Phase III, both over land and water (Figs. 11c,d). Over water, the double convergence–divergence pattern during Phase III is reflected in the extension of the strong upward motion to the upper troposphere in Fig. 11c. The northern box
over land shows a much lower level of maximum rising motion during all three phases (Fig. 11b) than the two profiles in both southern boxes. Consistent with the earlier-mentioned variations of the low-level monsoon winds in the northern box, the largest value of rising motion occurred during Phase I (Fig. 11b). Finally, Fig. 11a shows in the northern box over water that downward motion exists in all three phases down to the 700- or 850-hPa level. As for the other variables, the Phase III profile for vertical motion in the southern box over the water (Fig. 11c) is in good agreement with that given by Thompson et al. (1979, their Fig. 6). In fact, the peak values in the lower troposphere almost exactly match despite the fact that our average area is much larger than the B-scale area used in Thompson et al. In the B-scale area itself, however, the ERA-40 \( \omega \)-values (cf. Fig. 6a) are 2–3 times greater than those obtained from their subjective analysis.

5. Large-scale features of AEWs

The third objective of this study is to conduct an investigation of the large-scale features associated with AEW activity, including barotropic and baroclinic instability measures, and energy conversions.

a. Instability of the AEJ

First, we investigate some environmental features that indicate barotropic instability associated with the AEJ
and, hence, are related to the initiation and maintenance of AEW disturbances. In their pioneering theoretical work, Charney and Stern (1962) showed that a necessary condition for the barotropic instability of an internal baroclinic jet is a sign reversal of the meridional gradient of potential vorticity (PV) on an isentropic surface. This criterion has been used in several diagnostic studies to identify instabilities associated with the AEJ (e.g., Burpee 1972; Pedgley and Krishnamurti 1976; Rennick 1976; Pytharoulis and Thorncroft 1999). The Charney–Stern instability criterion is also satisfied, if the meridional gradients of PV and the surface temperature gradient have opposite signs (Thorncroft and Hoskins 1994). Moreover Thorncroft (1995) showed that the low static stability in the desert region north of the AEJ increases the interaction between wave disturbances along the jet and the dry baroclinic surface disturbances to its north.

Based on this previous theoretical and diagnostic work, we produced maps of the meridional-PV gradient on isentropic surfaces (Fig. 12), as well as meridional-height cross sections of PV, the zonal wind ($u$), and the potential temperature ($\theta$) (Fig. 13) to examine the instabilities (barotropic and baroclinic) associated with the northern waves north of the AEJ and the southern waves to the south of it. This approach is similar to that used by Pytharoulis and Thorncroft (1999), who investigated both types of waves over Africa and the eastern Atlantic Ocean during the summer of 1995.

The isentropic surface chosen to create the maps of meridional PV gradients shown in Fig. 12 is the $\theta = 315$ K surface, which is generally located near the 700-
hPa level south of the AEJ (i.e., where the southern waves are propagating). It was also used by Pytharoulis and Thorncroft (1999) to identify unstable regions and to assess the growth rate of a disturbance. As expected, the jet axis is collocated with the zone of largest negative meridional gradients of PV (i.e., largest instability) in all three phases (cf. Figs. 1 and 12). Over the continent, the instability is weakest in Phase I for areas west of 5°E, whereas in Phases II and III the degree of instability is comparable. A striking difference between Phases II and III is observed over the eastern Atlantic Ocean; instabilities are quite low during Phase II, but substantially higher during Phase III. Presumably, the resulting weak activity of the southerly barotropically maintained AEW vortices over the eastern Atlantic Ocean (cf. Fig. 1) during Phase II has contributed to suppressed convection over the A–B-scale ship array (not shown). In summary, the meridional gradients of PV near the AEJ axis were strongest and most uniformly developed in the zonal direction over both land and ocean during Phase III. They were also somewhat stronger than normal (not shown).

Figure 13 shows cross sections of PV, u, and θ as a function of latitude, averaged from 14°W–10°E (land) and 30°–18°W (water) for each phase. We also produced the same set of cross sections for GATE climatologies and anomalies for each phase (not shown). First, as noted earlier, and expected, it is seen that the midtropospheric jet core lies in a region of negative meridional PV gradients. Second, and also stated previously, these
gradients are strongest during Phases II and III over land (Figs. 13d,f). The low barotropic instability over water during Phase II is clearly evident from the almost horizontal PV contours south of the AEJ core (Fig. 13c). Third, Fig. 13 gives an impression of phase-to-phase and land–ocean differences in the low-level $\theta$ fields. Over land, the highest surface temperatures and strongest meridional gradients are observed during Phases I and II. This is visible in Figs. 13b,d through the intersection of the 310-K isentrop with the 1000-hPa level.
at about 20°N. This is not observed during Phase III (Fig. 13f). The northern wave mean tracks over land during each phase of GATE were 19.6°, 19.6°, and 17.0°N, respectively (Table 1). The right-hand side of

Fig. 13 reveals that these latitudes correspond to the transition zone between positive meridional temperature gradients to the south and the desert region to the north, where the atmosphere is nearly neutrally stratified from
the surface to 600 hPa. Over the ocean, the meridional gradient of $\theta$ is near 0 during all phases (Figs. 13a,c,e).

b. Energetics

Finally, we turn our attention to the large-scale barotropic and baroclinic energy conversions, which represent the environments of the southern and northern wave disturbances. Three typical conversions are examined: CA, which expresses the meridional flux of sensible heat down the temperature gradient and acts to increase the eddy available potential energy; CE, which expresses the vertical flux of sensible heat and, when thermally direct, converts eddy available potential energy to eddy kinetic energy; and CK, which is based on the meridional flux of zonal momentum down the zonal wind gradient and increases the eddy kinetic energy at the expense of the zonal kinetic energy. While CA and CE are generally referred to as baroclinic conversion terms, CK is a barotropic conversion term. The corresponding equations used in the present study are as follows:

$$CA = -\frac{1}{\sigma} vT \frac{\partial T}{\partial y}, \quad (1)$$

$$CE = -\frac{R}{\rho} \omega T \frac{\partial T}{\partial y}, \quad (2)$$

$$CK = -\frac{u}{\sigma} u' \frac{\partial \theta}{\partial y}, \quad (3)$$

where the primes denote 2–6-day bandpass-filtered values and the overbars represent means over each of the individual phases. Note that, in agreement with Norquist et al. (1977), only the leading terms of CA and CK were computed and are given in (1) and (3). The bandpass filtering of the input variables in (1)–(3) in the typical frequency band of AEWs was applied to extract energy conversions associated with the waves. As for the stability parameters discussed earlier, maps of the three conversion terms were produced and examined at selected levels for each phase of GATE, but are not shown. Instead, the focus will be on meridional-height cross sections of these terms. After examining several cross sections, we decided that the most meaningful ones were for CE (Fig. 14) and CK (Fig. 15), both averaged over land and water.

Figures 14b,d,f show that maximum positive values of CE over land occur near or just equatorward of 20°N, in the 850–700-hPa layer during all three phases. This is primarily due to the strong rising hot air west of the trough of the northern AEWs (cf. Duvel 1990, his Fig. 14), a process that enhances their eddy kinetic energy. Note that the largest conversions are observed in Phase I (Fig. 14b) when the heat low and the associated monsoonal flow were the strongest of all phases. In this context, it is interesting to note that the second-largest conversions over land are observed during Phase III (Fig. 14f), when the intensity of the heat low and the meridional gradients of $\theta$ were lowest. Presumably, this is related to strong near-surface fluctuations of vertical motion and temperature in response to the strongest activity of southern waves during Phase III. Recall that, according to Thorncroft (1995), a strong interaction between PV anomalies on the jet and surface temperature anomalies at the ground can occur in regions of low static stability. With respect to the long-term means, CE over the heat low was stronger during Phase I, weaker during Phase II, and about average during Phase III (not shown).

As evident in the left-hand side of Fig. 14, the conversion to eddy kinetic energy by the northern waves extends out to the ocean. There, however, maximum conversions occur at a somewhat lower level (850 hPa) and at a more southerly latitude (17.5°N), reflecting the influence of cool water temperatures and the more southerly location of the monsoon trough (Fig. 2c). Also note that secondary maxima occur in each phase over land and water in the mid- to upper troposphere between about 6° and 10°N, most likely associated with the modulation of the latent heat release in deep convective clouds by the southern waves.

One of the most important findings of the AEW energetics, presented in this study, is the missing reduction of wave energy (negative values of CE) below the previously mentioned secondary CE maxima over land during all three phases. In the classical study on AEW energetics during Phase III by Norquist et al. (1977), the authors found that wave energy is reduced in the lower troposphere and related this observation to the lifting of evaporatively cooled air. In the present study, negative CE values are only visible around 8°N in the oceanic ITCZ with a maximum at about 775 hPa (Fig. 14, left). It is interesting to note that, although Norquist et al. (1977) presented combined land–water energetics, more oceanic upper-air observations went into their analysis. On the other hand, Miyakoda et al. (1982) presented a CE cross section for Phase III based on unfiltered data, which shows negative values in the lower troposphere for the land area between 15°W–30°E. The present results, however, were also seen in the unfiltered energetics (not shown). Moreover, only very small areas of positive covariances of vertical velocity ($\omega$) and temperature (corresponding to negative CE values) can be found over West Africa in the 850-hPa maps presented by Reed et al. (1988b, their Fig. 5a), and by Pytharoulis and Thorncroft (1999, their Fig. 13a). Both studies used operational ECMWF analyses. The discrepancy in the low-level CE term over land between the ECMWF (re-)analyses and the studies of Norquist et al. (1977) and Miyakoda et al. (1982) are, by definition, related to subtle differences in the $\omega$ and temperature analyses over land. Plausible explanations of the missing low-level wave energy destruction in the ECMWF datasets over land are that the rising motion ahead of the trough is associated with warmer northerly flow down to the rainy zone at 10°N and/or the
Fig. 14. Meridional cross sections of the conversions term CE (conversion of eddy available potential energy to eddy kinetic energy) in contour intervals of $2 \times 10^{-5}$ W kg$^{-1}$. (a)–(f) The same as in Fig. 13.

synoptic-scale ascent in the same wave phase is less often associated with rainfall and, thus, evaporational cooling at low levels.

The results for the barotropic conversion term CK (Fig. 15, left) show that over water there is a conversion of zonal kinetic to eddy kinetic energy in the vicinity of the southern wave tracks during all phases, with maxima centered at about 10°N and 600–700 hPa. The most
Fig. 15. Meridional cross sections of the conversion term CK (conversion of zonal kinetic energy to eddy kinetic energy) in contour intervals of $10^{-5}$ W kg$^{-1}$. (a)–(f) The same as in Fig. 13.

significant conversion, by far, occurs in Phase III, in conjunction with the most organized and intense wave activity. The CK term was also stronger than normal (not shown). The right-hand side in Fig. 15 shows that maxima of CK are found at the same locations over land. Even though the values are still strongest in Phase III (Fig. 15f), CK is generally much weaker over the continent, a result already noted in Norquist et al. (1977). In the 30-yr ERA-40 climatology for the Phase III period, however, CK peak values over land and water
were about equal (not shown), indicating enhanced activity of the southern AEWs over the eastern Atlantic Ocean. Our results for CK during Phase III (if Figs. 15e and 15f are combined, not shown) compare very favorably to those given by Thompson et al. (1979, their Fig. 2) for their combined land–water cross sections. This confirms that the subjective analyses of the wind fields used in the latter study were of excellent quality.

6. Summary and conclusions

ECMWF has recently completed its second-generation reanalysis ERA-40. Within the scope of this project were major efforts to incorporate data from past field programs into the reanalyses. In the case of the West African Tropics, where the network of conventional upper-air observations is comparably sparse, the enhanced observations taken during GATE formed a unique opportunity to use ERA-40 to study synoptic-scale processes over land. Moreover, the ERA-40 fields over the adjacent eastern Atlantic Ocean benefited from surface and upper-air data from an experimental ship network that was enhanced in the ITCZ area between 5°–12°N and 27°–20°W. In the present study, ERA-40 was used in a comprehensive investigation of the mean state and large-scale features associated with AEWs during all three phases of the GATE experiment. Results were compared between land (West Africa) and the adjacent eastern Atlantic Ocean (water), as well as to previous studies and a 30-yr climatology extracted from ERA-40.

In general, the subjectively analyzed wind fields presented in earlier studies (e.g., Vincent 1981; Thompson et al. 1979) compare favorably with the ERA-40 horizontal wind fields during all phases of GATE. Surprisingly, the upper-level easterly jet over the central Gulf of Guinea and the adjacent Guinea coast region was found to be incorrectly analyzed in ERA-40. By inspection of the daily 250-hPa streamline and isotach charts in Sadler and Oda (1978, 1979, 1980), it became apparent that the acceptance of some erroneously archived commercial aircraft data by the ERA-40 assimilation scheme damaged the 400–200-hPa wind field over the Gulf of Guinea. No reference observations were available in this region to eliminate the erroneous data. Due to the resulting changes in the geopotential height field, the upper-level easterly jet was analyzed to be in a wrong position, that is, north instead of south of the Guinea coast. NCEP–NCAR reanalyses also suffered from this erroneous data and future reanalyses of the GATE period should try to use the original aircraft data, since the dynamics of the upper-level easterly jet are important for West African rainfall (cf. Newell and Kidson 1984).

As expected, the vertical pressure velocity, \( \omega_v \), is one of the variables showing the largest differences to previously published work. In the region of the A–B-scale ship array, reanalyzed \( \omega_v \) values in the lower troposphere were more than twice as large as in the ERA-40 climatology and in the subjective analysis presented for the B-scale ship array by Thompson et al. (1979). This is most likely due to the fact that the dense upper-air network in the two nested ship hexagons and the advance in data assimilation techniques allowed for a much better analysis of the divergent wind component in ERA-40. In this context, it is interesting to note that the existence of three tropospheric divergence maxima at 800, 500, and 250 hPa, found in Thompson et al. (1979), is corroborated in the reanalysis during Phases II and III. Thompson et al. argued that the multiple divergence layers owe their existence to the outflow levels of three main cloud populations observed in the GATE ship array. Provided that these cloud populations are a climatological feature, ERA-40 fails to capture the midlevel outflow layer in most other years. This may partly be related to that fact that the assimilation of satellite cloud motion winds, and the shallow and deep convective parameterization schemes in the background model favor two outflow layers in the lower and upper troposphere.

In the aftermath of the GATE experiment, many studies contributed to a deeper understanding of the midtropospheric wave disturbances (AEWs) that traveled westward over West Africa and the eastern Atlantic Ocean south of the midlevel jet (AEJ) in the zone of maximum seasonal rainfall (e.g., Burpee 1975; Reed et al. 1977; Norquist et al. 1977). Although the existence of northerly AEW vortices has been noted by the two former authors, their properties and their kinematic, thermodynamic, and moisture environments during GATE have not been investigated thus far. In the present paper, therefore, another focus was on the diagnosis of the northerly AEW vortices. Using the multistep manual AEW tracking method described in Fink and Reiner (2003), a complete tracking history of northerly and southerly vortices was presented for all three phases of GATE. No vortex fulfilled the AEW definition east of 20°E. Albignat and Reed (1980) were also unable to find a consistent wave propagation in streamline charts east of 15°E during Phase III. With the exception of one case, a northerly vortex was always accompanied by a southerly vortex, and vice versa, at least during part of their lifetimes. The respective latitudinal belts of propagation over land were found to be within 8°–11°N and 17°–19°N, respectively. Only two of the 18 paired AEW vortices merged near the west coast of Africa. This is in agreement with the results presented in Nitta and Takayabu (1985) for the 1979 First GARP Global Experiment (FGGE) period, and Thornicroft and Hodges (2001) for their tracks in the rainy seasons of 1994 and 1995.

One important result of the present study is that the activity of the northern waves over land was, in contrast to the southern AEWs, already quite strong during Phase I, both in terms of their frequency and related baroclinic conversions (CE) from eddy potential to the kinetic energy. In fact, CE values were by far the largest in the
925–600-hPa layer at about 20°N during the first observational phase. This strong wave activity was accompanied by the strongest low-level monsoonal flow, intensity of the heat low, and upward motion in the northern zone. It must be stressed, however, that the heat low was only slightly weaker in Phase II, but CE values were the weakest of all phases indicating much smaller wave amplitudes. The second-largest baroclinic conversions in the northern zone were found during Phase III. At this time, the monsoon circulation and the low-level horizontal temperature gradients in the north were the weakest. Certainly, the investigation of wave growth in the north and its relation to the wave activity in the south deserves further study.

Barotropic instability, as measured by the negative meridional gradients of PV on the 315-K isentropic surface, was largest just south of the AEJ core during Phase III. During this phase, the AEJ core was strongest and at its lowest altitude over land compared to the other two phases. Moreover, it extended out to the eastern Atlantic Ocean at about the same height and strength. At the same time, the height of the monsoon layer was largest north of the Guinea coast. All these factors are consistent with the well-known peak in AEW activity in the southern wet zone that occurred during Phase III. The question “Do intraseasonal height variations in the AEJ core and/or in the jet’s vertical distance from the monsoon layer in the southern moist zone play a role for wave organization?” is an avenue for future research. One of the few papers that addresses this subject is the modeling study of Miller and Lindzen (1992).

Finally, the present study suggests that further insight into other dynamic aspects of the West African monsoon may be achieved with the use of ERA-40 during GATE. One example is the poorly studied diurnal cycle in the monsoonal flow. The near-surface zonal wind in the northern belt peaks at 0600 and 1800 UTC (not shown), in agreement with findings discussed in Farquharson (1939) and Dolman et al. (1997). Another example is the investigation of the 6–9-day waves, one of which has been described in Diedhiou et al. (1999) during Phase I of GATE; their Fig. 10 shows a westward-moving 700-hPa vortex north of the Guinea coast between 5 and 12 July 1974. In addition, the dense radiosonde and pilot wind network in the southern moist zone may enable studies of poorly known vortices or disturbances in the low-level monsoonal westsoutherlies. Unfortunately, the activation of upper-air stations at the extremely wet southwest coast of West Africa, stretching from Cape Palmas to Cape Skiring, during GATE failed, probably leaving the monsoon dynamics in this region as one of the least well-known of the Tropics.

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REFERENCES


Reedolds, R., 1977: Large-scale (A-scale) mean features of the GATE atmosphere during Phase III of GATE. Met Office 20 Tech. Note No. II/105, Bracknell, Berkshire, United Kingdom, 14 pp.


