Climatology of convective available potential energy (CAPE) in ERA-Interim reanalysis over West Africa

Cyrille Meukaleuni, André Lenouo* and David Monkam

Department of Physics, Faculty of Science, University of Douala, Cameroon

Abstract

Seasonal study of convective available potential energy (CAPE) is done using 6-h ERA-Interim data over West Africa during 35 years (1979–2014). Climatology of CAPE presented in terms of seasonal means, variances and trends shows large values toward 12°–16°N with maxima during summer, according to higher relative humidity due to the arrival of monsoon in West Africa. Spectral analysis in the zone 10°–20°N/20°W–30°E, centered on the latitudes of maxima of CAPE trends at 12°–16°N toward inter-tropical convergence zone (ITCZ) mean position in summer, shows significant power in the 3–5 day within the regions of tropical deep convection in connection with African easterly waves.

Keywords: CAPE; West Africa; ITCZ; ERA-Interim; trends

1. Introduction

Convection plays a crucial role in the terrestrial climate with the formation of the clouds such as the cumulonimbus. The cumulus and other cumulonimbus are conditioned by the general circulation of the atmospheric air (orientation and force of the wind on ground) and the mode of precipitation (Lenouo et al., 2010). The human activities are directly influenced by their effects: cloud cover, downpours, storm, gust of wind, etc. In order to better understand and envisage the episodes of convection’s effects, international program as African Monsoon Multidisciplinary Analyses (AMMA) organized a series of measurements on the ground to study the atmospheric stability over West Africa.

The convective available potential energy (CAPE) has become an instability index widely used in the past few decades to evaluate the convective potential of the atmosphere. It is calculated by means of an integral of a vertical profile of cloud buoyancy and has been used for different kinds of studies. For example, CAPE was the appropriate parameter to analyze the conditional instability in the tropical atmosphere (Williams and Renno, 1993) for studies on tropical ‘Hot Towers’ (Williams et al., 1992) and for other research projects on atmospheric convection (Renno and Ingersoll, 1996). The importance of the CAPE in all these projects has led to a more precise way of calculating their values, and to certain approximations and corrections that may be included in the general formula. Later research into the CAPE also inquired into the possible relationships between this and other parameters that characterize atmospheric conditions (Blanchard, 1998; Monkam, 2002). Brooks et al. (2003, 2007) presented global CAPE climatology derived from 7 years using National Centre for Atmospheric Research (NCAR)/National Centres for Environmental Prediction (NCEP) reanalysis. For the United States and Europe, many researches have been done, sometimes through the use of several coupled atmosphere and ocean models (Trapp et al., 2007; Riemann-Campe et al., 2009, 2010) or by using 30 year climatology of CAPE and Convective Inhibition (CIN; Romero et al., 2007) based on ERA-40 from the European Centre for Medium-Range Weather Forecast (ECMWF). Riemann-Campe et al. (2010) also provided a global climatology of CAPE and CIN and their relation to convective precipitation, using 1979–2001 ERA-40 reanalyses data and 1979–2009ECHAM5/MPI-OM model and analyzed both parameters in terms of trends and how they change in a warmer climate. Such statistical analyses which can characterize the climatology of a region, specifically the West Africa region that has a large zone of deep convection deserve to be done.

Therefore, we propose to complete the CAPE analyses from the West Africa climatology based on 35 years (1979–2014) of ERA-Interim data, to provide seasonal ensemble means, a trend analysis and its link to African easterly waves (AEWs). The outline of the article, is as follows: the data and methods of analysis are presented in the Section 2. In Section 3, we present the result of the climatology of CAPE, trends and relationship with AEW. Section 4 presents conclusions and the outlook on future research on higher order statistics.

2. Data and methods

In this document, we have calculated the different variables by using the 0.75° grid ERA-Interim data firstly because of its high quality even if differences sometimes occur due to the varying density of observations (as in the southern hemisphere, and over oceans), and
secondly because it is the most recent reanalysis from the ECMWF started in 1979. By taking into account the satellite observations, the quality and quantity of data have improved considerably (Uppala et al., 2005), even if the change in the measurement system leads to an artificial warming trend in the global mean temperature of the lower troposphere (Bengtsson et al., 2004). The differences between observed and ERA-Interim temperature trends were also pointed out by Simmons et al. (2004). However, ERA-Interim data yield the general trend signal with an improving performance after 1979. Thus, trends in CAPE can be analyzed for the whole period of time and additionally before and after 1979.

CAPE is calculated between the level of free convection (LFC) and the Level of Neutral Buoyancy (LNB) as measures of the bottom and top of the cloud, respectively. As the effect of moisture on buoyancy is taken into account, the virtual temperature $T_v$ is used and the CAPE is given by $R_d$ gas constant for dry air (287.05 J kg$^{-1}$ K$^{-1}$):

$$\text{CAPE} = \int_{\text{LFC}}^{\text{LNB}} R_d \left( T_v - T_e \right) d\ln(P) \quad (1)$$

where $P$, $T_v$, $T_e$, LNB and LFC are, respectively, the pressure, the virtual temperature of the air parcel, the virtual temperature of the environment of the air parcel, the LNB and the LFC.

The air parcel rises dry adiabatically from the surface to the lifting condensation level (LCL). Above the LCL, the parcel raises pseudo adiabatically which means that any condensates will immediately fall out of the parcel as rain (Riemann-Campe et al., 2009). Between cloud bottom and cloud top the parcel rises freely as the temperature of the parcel is higher than the temperature of its environment. The pseudo equivalent potential temperature $\theta_{ep}$ is used to calculate the temperature of the rising parcel (Emanuel, 1994).

$$\theta_{ep} = T \left( \frac{P_{\text{se}}}{P} \right)^{0.2854(1-0.28r)} \times \exp \left[ r(1+0.81r) \left( \frac{3376}{T_{\text{LCL}}} - 2.54 \right) \right] \quad (2)$$

with the mixing ratio $r$ of dry to moist air and the temperature $T_{\text{LCL}}$, of the parcel at the LCL, where the ascent of the air parcel changes from dry adiabatic to pseudo adiabatic and $P_{\text{se}}$ is the pressure at the sea surface (1000 hPa). The expression of the saturation temperature $T_{\text{LCL}}$ can be approximated by (Bolton, 1980):

$$T_{\text{LCL}} = \frac{2840}{3.5 \log T - \log E - 4.805} + 55 \quad (3)$$

with the vapor pressure $E$.

Local seasonal trends in CAPE are analyzed by the Mann–Kendall trend test which is a robust trend estimator applicable for any theoretical distribution. As noted by Wilks (2011), investigating the possible trend through time of the central tendency of a data series is of interest in the context of a changing underlying climate, among other settings. The usual parametric approach to this kind of question is through regression analysis with a time index as the predictor, and the associated test for the null hypothesis that a regression slope is zero. This particular test is used here, as CAPE is not normally distributed in general. The trend in CAPE is calculated on a seasonal mean basis. Only positive CAPE values are considered in the calculation. Grid points with less than two positive CAPE values per season are neglected. The Mann–Kendall score indicates a given trend being positive or negative, which is supplemented by a two sided $p$-value to provide the probability of a detected trend (Riemann-Campe et al., 2009). Trends are only included in the analysis if their probability exceeds the 95% significance level. The magnitude of a given trend is estimated by linear regression, although the error is rarely normally distributed in CAPE.

The wavelet analysis method is applied here to identify the dominant synoptic oscillation modes and to isolate the synoptic oscillation components. In this work, it is used on daily CAPE time series over West Africa for the period 1979–2009 in order to evaluate the seasonality of the variance of the synoptic time scale and of the related AEW signal. Previous studies have shown that dominant modes of monsoon synoptic variability are characterized by strong and reproducible 3–5 day oscillations (Sultan and Janicot, 2003). Hence, CAPE spectra are calculated on each individual June–September period using wavelet analysis method. A red noise background spectrum is computed from the formula of Gilman et al. (1963). The 95% confidence limits about this red noise spectrum are determined using $F$-statistic (Wilks, 2011).

3. Results and discussions

3.1. Means and variability

The global distribution of seasonally averaged CAPE (Figure 1) follows basically the distribution of the wind at 850 hPa over West Africa. CAPE generally increases from Sahara which is the arid zone with values of about 500 J kg$^{-1}$ to the equator where they can reach 2000 J kg$^{-1}$. CAPE minima are observed in regions of cold water upwelling and where currents are colder than the ambient ocean temperatures, and in arid regions. CAPE also moves with the inter-tropical convergence zone (ITCZ) as show in Figure 1. However, the northward evolution of monsoon around 10$^\circ$N during the months of April–May–June (AMJ, Figure 1(b)) to about 15$^\circ$N in July–August–September (JAS, Figure 1(c)) before decrease southward at October–November–December (OND, Figure 1(d)) suggested that good correlation can exist between CAPE and the seasonal migration of the West Africa monsoon where sufficient moisture are available. The location and intensity of convective systems occurring during JAS are more frequently north of the ITCZ. This suggests the possible influence of AEW versus CAPE in their development during
AMJ and JAS. In other way, the maximum CAPE over Congo basin or in Guinea coast can be viewed as the development of Kelvin wave versus CAPE during JFM and OND.

Interannual variance of the seasonal CAPE means varied from 500 to about $6.5 \times 10^7$ (J kg$^{-1}$)$^2$, with mean values around $1.3 \times 10^5$ (J kg$^{-1}$)$^2$ (Figure 2). The zone of maximum variance corresponds to those of the seasonally averaged mean. In general, larger values are observed in summer (AMJ, Figure 2(b) and JAS, Figure 2(c)) according to higher relative humidity due to the arrival of the monsoon over West Africa. In the dry season (JFM), high variance is present around the Congo basin and the Benin coast where relative humidity is 80 and 65%, respectively, and in OND (Figure 2(c)) around the Guinean coast where the relative humidity remains around 65%.

3.2. Trends

CAPE trend magnitudes are displayed (Figure 3) at the level of significance exceeding 95%. Trends are shown for the full 35 years time series (1979–2014). Calculated trends before 1979 might correspond to changes in measurements instead of changes in climate (Bengtsson et al., 2004). Significant trends in CAPE occur in most parts of the West Africa except in dry region. Regions with a positive trend outnumber the regions of negative trends considerably with magnitudes varying in the time periods considered. Trend magnitudes range from about $-800$ J kg$^{-1}$ to about $1000$ J kg$^{-1}$ per decade during 1979–2014. The largest increase in CAPE of about 1600 J kg$^{-1}$ per decade occurs in the Congo basin during JFM (Figure 1(a)) and around the AEW axis (15°N) in the south of Chad and at the borders of Mali and Senegal during JAS (Figure 1(c)). The change of sign yields in a net decrease by 200–600 J kg$^{-1}$ per decade from the dry period (OND and JFM) to the wet season (AMJ and JAS) in the band of latitudes 10°–20°N can be due to the migration of the ITCZ which is also linked to the southward decrease of CAPE during the two periods.

3.3. Link with AEW

Figure 4 shows the relationship between CAPE and AEW through spectral analysis of CAPE during the
Wavelet analysis is a common tool for decomposing a time series into a time-frequency space and detecting time-frequency variations. The wavelet transform allows the treatment of a signal as a wavelet function called a mother wavelet (here the Morlet wavelet is used; Sultan and Janicot, 2003; Mohr and Thorncroft, 2006). We have tested different mother wavelets and the results look similar. Because the wavelet transform is a band pass filter with a known response function (the wavelet function), it is also a powerful filtering technique. The wavelet analysis method is used here to identify the dominant synoptic oscillation modes and to isolate the synoptic oscillation components. The mean seasonal cycle and interannual variability were removed before computing the spectrum. At the right (Figure 4), the wavelet significance with the red noise background spectrum and the 95% confidence level are shown.

Spectral analysis using high resolution data shows significant power in the 3–5-day band period over tropical West and Central Africa in the box 10°–20°N and 20°W–30°E, where CAPE is high as shown in Figure 1. Within the regions of tropical deep convection, the 3–5-day time scale variance accounts for about 25–35% of the total variance. The 3–5-day convective variance has similar amplitudes from east to west in the band 10°–20°N, while dynamic measures of AEW activity show stronger amplitudes in the west. Weak AEW activity in the east is consistent with initial wave development there. AEWs are initiated by the convection triggered on the western sides of the Darfur Mountains (western Sudan) and Ethiopia. The subsequent development and growth of AEWs are associated with stronger coherence with convection there (Mohr and Thorncroft, 2006).

4. Summary and conclusions

By using the ERA-Interim data, with a 0.75° grid over West Africa, it was found that CAPE minima are observed in arid regions over West Africa and move with the ITCZ. The evolution of the monsoon around 10°N during the months of AMJ to about 15°N in JAS prior to a southward decrease in OND suggests good correlation between CAPE and the seasonal migration of West Africa monsoon where sufficient moisture are available. Larger values of CAPE variance are observed
in the summer according to higher relative humidity due to the arrival of the monsoon in the continent. We found that significant trends in CAPE occur in most parts of the West Africa except in dry region. Trend magnitudes range from about $-800$ J kg$^{-1}$ to $1000$ J kg$^{-1}$ per decade during 1979–2014. The largest increase in CAPE of about $1600$ J kg$^{-1}$ per decade occurs in the Congo basin during JFM and around the AEW axis ($15^\circ$N) in the south of Chad and at the borders of Mali and Senegal during JAS. The change of sign yields decrease from
200 to 600 J kg$^{-1}$ per decade between the dry period (OND and JFM) and the wet season (AMJ and JAS) in the band of latitudes 10$^\circ$–20$^\circ$N. Spectral analysis using high resolution data shows significant power in the 3–5-day range in the box 10$^\circ$–20$^\circ$N and 20$^\circ$W–30$^\circ$E, where CAPE is high. Within the regions of tropical deep convection in the band of latitude 10$^\circ$–20$^\circ$N, the 3–5-day time scale variance accounts for about 25–35% of the total variance. The 3–5-day convective variance has similar amplitudes from east to west of this band, while dynamic measures of AEW activity show stronger amplitudes in the west.

Similar intra-seasonal CAPE fluctuations occur also over the Congo basin, especially during the dry season (OND and JFM). This point must be investigated further. Another point would be to quantify the contribution of such intra-seasonal variability to the interannual variability. It will be also interesting to investigate the links with atmospheric modes of this zone since Kamsu-Tamo et al. (2014) showed that corresponding regressed deseasonalized atmospheric fields highlight an eastward propagation of patterns consistent with convectively coupled equatorial Kelvin wave dynamics.

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