Interaction between moisture transport and Kelvin waves events over Equatorial Africa through ERA-interim

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Abstract
This study examines the moisture transport variability and its interaction between rainfall and Kelvin wave’s events over Equatorial Africa using 1979–2010 ERA-interim reanalysis data, precipitation from Global Precipitation Climatology Project and outgoing long-wave radiation. Kelvin waves events influenced in Congo basin varies within each rainy season, as the intertropical convergence zone moves through the region. The moisture flux is calculated for the entire tropospheric column (1000–300 hPa) over Central Africa (5°–10°N; 5°–30°E). Analysis of mean monthly fluxes shows a progressive penetration of the flux into Gulf of Guinea (5°S–5°N; 0°–15°E). Mean seasonal values of moisture components across boundaries indicate that the zonal component is the largest contributor to mean moisture over Central Africa, while the meridional component contributes the most over the Gulf of Guinea. Lag correlation between precipitation and moisture is largely dominated over land with a coefficient greater than 0.5, while moisture increases with enhanced phase of Kelvin waves.

Keywords: ERA-interim; moisture flux; Kelvin waves; Central Africa

1. Introduction

Climatology of Central Africa is particularly result from localized convection which is increasing by the passage of intertropical convergence zone (ITCZ). The moisture flux and convergence over Central Africa was first described by Matsuyama et al. (1994). These authors said that during March–April rainy season, vertically integrated vapor is transported westward. From June to July, the moisture flux is divergent over the region. Pokam et al. (2011) analyzed annual cycle of the vertically integrated moisture convergence for the full, lower and upper tropospheric layers. They showed that the full column vertically integrated moisture convergence exhibits a bimodal distribution with maximum during the rainy seasons.

Lélé et al. (2015) evaluated the ocean–land transport of moisture for rainfall in West Africa and showed a pronounced south-west incursion of the flux over West Africa during April–June, while during July–September, the southerly transport weakens, but westerly transport is enhanced. Most studies evaluated the variability of moisture transport and it relationship with precipitation, large-scale or small-scale but the interaction between moisture and equatorials waves like Kelvin waves has not yet been studied and clearly understood in this region. Based on these previous studies, it will be more useful to evaluate the impact of Kelvin waves on moisture variability. The main question is: what would be the impact of Kelvin wave’s events upon the moisture transport over Central Africa?

The aim of this study is to explore the interaction between moisture flux, rainfall and Kelvin waves events at seasonal and annual time scales and evaluate their modification in the climate system over Central Africa. Datasets and methods used in this study are briefly described in Section 2. Section 3 investigates the characteristic of moisture flux field and Kelvin wave’s events over Central Africa, modulation of moisture flux field by Kelvin wave’s events and precipitation and annual cycle of moisture flux convergence associated with Kelvin wave’s activity. Finally, Section 4 summarizes the main results and indicates some prospects for future work.

2. Data and methods

2.1. Data

The study area extends from Eastern Atlantic (5°N–Eq.; 30°–10°W), Gulf of Guinea (5°S–5°N; 0–15°E) and Central Africa (5°S–10°N; 5°–30°E). The topography of Central Africa is always varied, including highlands, mountains and plateaus. Several observational and reanalysis datasets such as outgoing long-wave radiation (OLR) (Grueber and Krueger, 1974; Liebmann and Smith, 1996; Straub and Kiladis, 2002), Global Precipitation Climatology Project and European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis datasets (Simmons et al., 2011) analyzed annual cycle of the vertically integrated vapor is transported westward. From June to July, the moisture flux is divergent over the region. The moisture flux is calculated for the entire tropospheric column (1000–300 hPa) over Central Africa (5°–10°N; 5°–30°E). Analysis of mean monthly fluxes shows a progressive penetration of the flux into Gulf of Guinea (5°S–5°N; 0°–15°E). Mean seasonal values of moisture components across boundaries indicate that the zonal component is the largest contributor to mean moisture over Central Africa, while the meridional component contributes the most over the Gulf of Guinea. Lag correlation between precipitation and moisture is largely dominated over land with a coefficient greater than 0.5, while moisture increases with enhanced phase of Kelvin waves.

This study examines the moisture transport variability and its interaction between rainfall and Kelvin wave’s events over Equatorial Africa using 1979–2010 ERA-interim reanalysis data, precipitation from Global Precipitation Climatology Project and outgoing long-wave radiation. Kelvin waves events influenced in Congo basin varies within each rainy season, as the intertropical convergence zone moves through the region. The moisture flux is calculated for the entire tropospheric column (1000–300 hPa) over Central Africa (5°–10°N; 5°–30°E). Analysis of mean monthly fluxes shows a progressive penetration of the flux into Gulf of Guinea (5°S–5°N; 0°–15°E). Mean seasonal values of moisture components across boundaries indicate that the zonal component is the largest contributor to mean moisture over Central Africa, while the meridional component contributes the most over the Gulf of Guinea. Lag correlation between precipitation and moisture is largely dominated over land with a coefficient greater than 0.5, while moisture increases with enhanced phase of Kelvin waves.

Keywords: ERA-interim; moisture flux; Kelvin waves; Central Africa
2007) are used in this study. Table 1 summarizes the information of observational datasets.

### 2.2. Methods

In this study, Kelvin wave filtering is used for the period of 2.5–20 days, and eastward wavenumber 1–14 (Wheeler and Kiladis, 1999; Wheeler et al., 2000; Kiladis et al., 2009). The filtering is carried out with OLR-National Oceanic and Atmospheric Administration (NOAA) data, field is not separated into symmetric and a dissymmetric components (Straub and Kiladis, 2002). Based on the methodology used by Zebaze et al. (2015), a time series was developed based on a selected regional zone over Central Africa region (5°S−10°N; 5−30°E), selecting all days where the minimum Kelvin-filtered negative OLR anomalies were less than −1.5 standard deviations in magnitude during the 1979–2010 March–June (MAMJ) seasons. The year 1992 appeared to be the weaken Kelvin year event with only 3 events occurred, while 1999 appears as the most active Kelvin year with 12 events appear. These 2 years are used as indicators for possible interaction between Kelvin wave’s events and moisture signatures. The Equations (1) and (2) below represent zonal and meridional flux components:

\[ Q_u = \frac{1}{g} \int_{P_0}^{P_t} u q dP \]  
\[ Q_v = \frac{1}{g} \int_{P_0}^{P_t} v q dP \]  

where, \( u \) and \( v \) are zonal and meridional components of the wind, respectively (their units are m s\(^{-1}\)). The units of \( Q_u \) and \( Q_v \) are kg m\(^{-1}\) s\(^{-1}\). \( g \) is the gravitational acceleration (9.81 m s\(^{-2}\)), \( q \) is specific humidity (g kg\(^{-1}\)), \( P \) is the pressure, \( P_0 \) the surface pressure and \( P_t \) pressure at the top of the atmospheric layer (Rao et al., 1999). The horizontal moisture flux was obtained from \( Q_u \) and \( Q_v \), which provided the vertically integrated meridional and zonal moisture fluxes. In the results, a negative value of divergence is convergence, while positive value is divergence. Moisture flux divergence is calculated using following equation:

\[
\text{MFC} = \frac{1}{g} \left[ \int_{P_0}^{P_t} \left( \frac{\partial u}{\partial x} + u \frac{\partial q}{\partial x} \right) dP \right] + \int_{P_0}^{P_t} \left( \frac{\partial v}{\partial y} + u \frac{\partial q}{\partial y} \right) dP \]

### 3. Results and discussions

#### 3.1. Characteristic of moisture flux field and Kelvin waves events over Central Africa

The propagation regime of the Central Africa integrated horizontal moisture flux during 1979–2010 is illustrated in Figure 1. During March and April (Figures 1(a) and (b)), convection is located over the Gulf of Guinea, between the southern part of the Congo basin and southern part of 10°N. In these northern spring months, moisture field propagated over the East (located over southern part of the region), the large part of the flow is retraced through the Gulf of Guinea. Results showed that vectors flux are small compared to mean value out of the Gulf of Guinea, the moisture transport over this area is very important. Increase in moisture flux over Congo basin region is relatively accompanied the progression of the ITCZ from its southern position near the Guinea coast in December and progresses to around 10°N in April, associated with

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**Table 1. List of observational datasets used in this study.**

| Dataset          | Origin/platform                      | Horizontal resolution | Temporal resolution                  | Vertical levels                  | Selected variables |
|------------------|--------------------------------------|-----------------------|--------------------------------------|----------------------------------|--------------------|
| NOAA/OLR         | Satellite                            | 2.5° x 2.5°           | Daily mean from 1979 to 2010         | Top of atmosphere                | OLR                |
| (ECMWF) ERA-I    | Radiosonde, satellite, model forecast| 0.75° x 0.75°         | 4 times daily (6-hourly) from 1979 to 2010 | 1000–300 hPa                    | Winds, specific humidity |
| GPCP             | GPCP polar satellite precipitation data center emission/observation | 2.5° x 2.5°           | Monthly mean from 1979 to 2010       | Surface                        | Precipitation      |

where, Moisture Flux Convergence (MFC) is moisture flux in the entire tropospheric column (1000–300 hPa). The units of MFC are s\(^{-1}\) g kg\(^{-1}\).

Consider N pairs of observations on two time series \( X_t \) and \( Y_t \) (precipitation and moisture transport). Following Chatfield (2004), the sample cross-covariance function (ccvf) is given by:

\[
c_{XY}(k) = \frac{1}{N} \sum_{n=1}^{N-k} (X_n - \bar{X})(Y_{n+k} - \bar{Y})
\]

\[
[k = 0, 1, \ldots, (N - 1)]
\]

\[
c_{XY}(k) = \frac{1}{N} \sum_{n=1}^{N} (X_n - \bar{X})(Y_{n+k} - \bar{Y})
\]

\[
[k = -1, -2, \ldots, -(N - 1)]
\]

where, \( N \) is the series length, \( X \) and \( Y \) are the sample means, and \( k \) is the lag. The sample lag-correlation function is the ccvf scaled by the variances of the two series:

\[
r_{XY}(k) = \frac{c_{XY}(k)}{\sqrt{c_{XX}(0)c_{YY}(0)}}
\]

where, \( c_{XX}(0) \) and \( c_{YY}(0) \) are the sample variances of \( X_t \) and \( Y_t \).
convection is clearly observed over this part of the region. Congo basin is more associated with convergence during March, May and June (Figures 1(a)–(c)), more convective activity is also denoted in the region. The easterly moisture transport over Central Africa is clearly observed and this propagation is associated with a dipole. The zone of predominance of moisture is no longer compared to the convection which persists over the region. In April (Figure 1(b)), there are clearly an easterly anomaly resulting for the propagation characteristics while westerlies Kelvin waves are observed at that period. Finally, the presence of Kelvin waves can favors formation of moisture which propagated in opposite side. These propagation characteristics were shown by Kamsu et al. (2014). This plot also displays the climatology of moisture flow fields, propagation characteristics and associated convection during July—September (Figures 1(e)–(g)). Moisture field weaken with progression of month and change in the intensity of flow is clearly observed when convection decreases and reaches southern part of the region. The change in direction of moisture is also observed during these months while their intensity is not associated with convective activity. These results are comparable to the previous studies which showed that the Gulf of Guinea region is an important source of moisture for the tropical Africa (Giannini et al., 2003; Lélé et al., 2015).

The mean geographical distribution of the Kelvin-filtered OLR-NOAA variance [averaged over 1979–2010 for MAMJ] shows a peak activity around 2.5°N band over Central Africa. Previous studies suggested that the strongest Kelvin wave’s signatures are observed over 2.5°N (Janicot et al., 2008). The highest variance is also progressed toward the eastern Pacific, Central America and the Atlantic ITCZ. The Kelvin-filtered OLR variance is not symmetric with respect to the equator over this region, consistent with previous analyses of Kelvin wave variance (Straub and Kiladis, 2002). Kelvin wave activity is clearly present over tropical Africa with a peak variance associated with convective activity. The strong convection persists over the region and this convection signature covers almost all the Congo forest. Based on composite methodology, 1980 and 1992 were weak Kelvin year’s event with only 3 events occurred although 1984 and 1999 appear as the most active Kelvin years with 12 events; 1992 and 1999 are used as indicators for possible interaction between Kelvin wave’s events and moisture signatures.

Figure 1. Monthly mean moisture transport (vectors; kg m⁻¹ s⁻¹), moisture flux divergence/convergence (shading; 10⁻⁶ s⁻¹ g kg⁻¹) vertically integrated in layers 1000–300 hPa and NOAA OLR anomalies (green contours; <−5 W m⁻², only the enhanced phase is shown for clarity) for (a) March, (b) April, (c) May, (d) June, (e) July, (f) August, (g) September and (h) October averaged from 1979 to 2010. Boxes indicate Central Africa (5°S–10°N; 5–30°E, red). Gulf of Guinea (5°S–5°N; 0–15°E, black).
3.2. Interaction between moisture flux field, Kelvin waves events and precipitation

During March–May season, moisture flux propagated westward during wet year (Figure 1(d)) and intense Kelvin year (Figure 2(c)). This wettest year is associated with divergence and westward propagating flux. Over Central Africa, these perturbations are centered on the equator and meridional fluxes are low. Enhanced convection occupied more sectors compared to previous season. The vertically integrated horizontal flux is in phase with the easterly wind for low surface pressure showed in previous studies (Nguyen and Duvel, 2008) which immediately associates with the minimum OLR over the Congo basin. This is physically consistent because a maximum in convective activity is associated with stronger convergence. In particular, there is a clear weakening and a latitudinal expansion of the convective anomaly over the region.

High fluxes dominate continental region during June–August, zone of enhanced convection are seen over continental area. The moisture flux propagated northward when it is located over the north part of enhanced convection, the ITCZ displacement and the associated Central Africa rainfall suppression were more pronounced. During the 2007 wet year, the moisture flux transport is located over 10°N. During the years 1992 and 1983, there is a weak convective anomaly over Congo basin. This would be associated with a negative latent heating anomaly (a cooling anomaly) or equivalently a reduction in the total heating and this heating was associated with divergence. The large zone of moisture flux convergence is observed over the ocean. A large area convective activity was observed over Central Africa during intense Kelvin year (1999) and the associated convection extends from Atlantic Ocean to the eastern sector of equatorial Africa. The associated moisture flux propagation characteristic is opposite to the one observed during March–May. Convection occupied large zone during spring while in monsoon, convection is not large. The quasi-dipole is also observed during weak Kelvin year while, divergence is seen during driest and wettest years over the region.

3.3. Annual cycle of moisture flux convergence associated with Kelvin wave’s activity

Figure 3 presents the annual cycle of the atmospheric zonal (Figure 3(b)) and meridional (Figure 3(c)) components of moisture flux in the entire tropospheric column (1000–300hPa) and associated convergence (Figure 3(d)) averaged over 5–25°E through a Hovmöller diagram between 1979 and 2010. The Kelvin wave variability is also presented (Figure 3(a)). The increase in moisture flux convergence is seen over continental region (between 5°S and 5°N), while the moisture flux divergence zone is seen to the south of 5°S and north of 5°N (Figure 3(d)). The northward progression of moisture flux convergence across the Gulf of Guinea coast started in March when ITCZ is centered over equator and progressively migrated trough the north (after 5°N). Two dipoles are observed in zonal flux (Figure 3(b)). The first (Eastward) propagated from December to April and this propagation is clearly associated with dry season. Along the Gulf of Guinea there is some evidence of a convection belt which
increased convergence over the ocean and divergence over land during the spring season. At that time Kelvin waves and associated convection are located over equator forming a convective belt over the region. During June–August season, the field gradually progressed over the continent. The moisture transport clearly denotes south-westerly and north-easterly propagation characteristics. Many phenomena are responsible for the presence of the quasi-dipole observed in moisture flux divergence regime. The belt of convergence over land is accompanied by a large zone of moisture flux divergence over the ocean.
The position of the flux reveals that moisture transport over Central Africa is regulated by an enhanced evaporation coming from tropical Atlantic Ocean at the beginning of Kelvin wave’s active phase which positively interacts with convection over Atlantic. Previous studies (Lélé et al., 2015) showed that Atlantic Ocean is the mayor source of water vapor and the propagated characteristic is mostly progresses from equator to north and south of the continent and this created a bimodal regime over the continental area. But this cannot explain the fact that propagation characteristics suddenly changed with season, this may be related to the presence of Kelvin waves over the region which influenced propagation of dynamic structures which progressed in opposite direction. To explore the precipitation and moisture transport relationship, mean temporal lag-correlation coefficients are calculated with a time lag varying between ±9 months. Positive/negative lag corresponds to moisture changing after/before precipitation.

Figure 4 shows this result. The maximum correlation between precipitation and moisture flux over the Central Africa occurs with a lag between 0 and 2 months and no lag over the ocean. The maximum correlation over the Gulf of Guinea occurs with a positive lag of about 1–2 months (moisture is larger 2 months after precipitation). Correlation between precipitation and moisture is largely dominated over land with a coefficient greater than 0.5. Over the ocean, correlation between precipitation and moisture is lower than correlation over land; this correlation is not significant (lower than 0.3). This result confirms past study which showed that along the coastline and Gulf of Guinea, over land, the precipitation is well correlated to moisture convergence (Bielli and Roca, 2010). Results indicate that over the study area different geographical precipitation regimes are related to different relationships with the moisture flux and the local sources, both in terms of temporal and spatial scales. The scale dependence and the main role of each source indicate that the analysis should be help to clarify the functioning of the moisture control in the climate system.

4. Summary and conclusion

First objective of this study was to understand the moisture transport variability accordingly to wet and dry condition, its interaction with Kelvin wave’s events. The pre-monsoon months (March–May) are characterized by westerly moisture field over the Gulf of Guinea and are associated with intense Kelvin wave’s activity. But relatively weak flow incursion is observed over Gulf of Guinea associated with the northward evolution of the ITCZ. Results also showed that precipitation is strongly correlated with moisture transport over central Africa in monthly time scale while, Kelvin waves which is almost persists in synoptic time scale has no correlation with moisture. In spite of fact that this correlation between Kelvin wave and moisture is too low, the wave creates better conditions for moisture incursion over the region. Lag correlation reveals that the maximum moisture transport occurs 1–2 months after the maximum precipitation occurs over the region. The zonal component of moisture is the largest contributor to mean moisture over Central Africa, while the meridional component contributes the most over the Gulf of Guinea. Wet condition and better precipitation occur over the region. It becomes necessary to quantify the contribution of Kelvin waves to moisture variability in synoptic and interannual time scale. Final point will identify the time scale regime which most contributed for the moisture initiation over Central Africa.

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