Climatology of super-refraction and trapping layers conditions over Central and West Africa

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Abstract
The propagation of radio electric waves emitted from ground-based meteorological instruments is determined through stratification of the atmosphere. In super-refractive cases characterized by strong temperature inversions or strong vertical moisture gradients, the radar beam can be deflected towards the ground (trapping). This phenomenon often results in spurious returned echoes and misinterpretation of radar images such as erroneous precipitation, wind, and temperature detection. In this study, a 5-year Central and West Africa (CWA) climatology of the frequency of super-refractive and trapping-layer base height has been produced using refractivity computations from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses at a 40-km horizontal resolution and 60 levels in the vertical direction. The aim of this climatology is to improve the understanding on how frequent such anomalous propagations conditions are, which is a prerequisite for fully benefiting from radar data information for the multiple purposes of model validation, precipitation analysis, and data assimilation. First, the main climatological features are summarized for the whole CWA: Sahara and inlands seldom experience super-refraction, whereas coastal areas are strongly affected, especially in regions where the temperature inversion and the trade winds are intense lying near the surface. Over land, seasonal averages of super-refraction frequencies reach 80% (40%) over moist areas year-round but remain below 40% (15%) in most other regions. Seasonal statistics exhibit a pronounced diurnal cycle of super-refraction occurrences, with averaged frequencies peaking at 60% in summer late afternoon over the areas located on the Atlantic Ocean border but inlands region are less affected with super-refractive cases by midday.

KEYWORDS
ECMWF operational analyses, super-refraction, trapping layer
1 | INTRODUCTION

Far from being a homogeneous layer, the troposphere is responsible for changes in speed and direction of the radio waves passing through it and therefore responsible for the curvature taken by different trajectories of electromagnetic waves in general (Serdar, 2010; Wang et al., 2018).

These variations are due to a lack of uniformity within the Earth's atmosphere. The atmospheric conditions depend on the altitude: the geographical position (Figure 1) as well as the time (day, night, season, and year) considered. Vertical changes in temperature, humidity, density, and pressure values in the troposphere can have a substantial impact on the propagation of radio waves. The path followed by radio waves during propagation in the atmosphere is determined by the gradient of the refractive index along that path (Bean & Dutton, 1968).

Note that, variations in atmospheric parameters over an area can also be caused by some human activities like land use changes, forest fires, urbanization, transportation of pollutants from a region of intense human activities and other regions (Prasad et al., 2013).

Temperature and humidity variations may modify the refraction gradient and bend the radio signals away from the ground, which will then weaken the signals in the receiver (Adediji & Ajewole, 2010) or, on the contrary, atmospheric conditions can cause a steeper gradient, thus causing signals to bend towards the Earth (Adediji et al., 2019).

Characteristic of refractivity conditions presented in Table 1 have very crucial consequences in navigation systems, communication systems, microwave operations, and many other technological systems that work with electromagnetic wave propagation in the atmosphere.

When certain levels of troposphere are bound above and below by layers that have different refractive indices, they confine and propagate abnormally high proportions of very high frequency (VHF) and ultrahigh frequency (UHF) radiations, leading to anomalous propagations (AP), which may result in the troposphere, as a result the radio transmissions received at very long distances give freak long-distance communications and radar pickup ranges. Then, various effects such as degradation of propagation, transmission fading, altitude errors, decreased (increased) detection ranges, and shortened (extended) radio horizons are also noted (Okoro & Agbo, 2012).

The vertical gradient of the refractive index can be deduced by measuring the refractivity profiles as reported by International Telecommunication Union (ITU-R, 2012). The numerical value of the index refraction vertical gradient depends on the vertical distribution of atmospheric temperature, humidity, and pressure (Bech et al., 2007).

To observe small-scale changes in the vertical distribution of radio refractivity and propagation condition, particularly in the lower atmosphere over a tropical region, spatial resolution is an important factor to be considered (Steiner & Smith, 2002).

Climatological maps of the super-refraction and trapping layers (TLs) over Europe and United States have been set up by Lopez (2009). In similar way, radiosonde data were used to investigate electromagnetic propagation condition over Douala by Lenouo (2014) and over West Africa by Kaissassou, Lenouo, Nzeukou, et al. (2015a). In a more recent paper, Kaissassou et al. (2020) proposed a statistical investigation of ducting conditions in West African stations using high-resolution global positioning system (GPS) radiosonde observations.

Beyond climatological needs, it is crucial to assess how often a given region of the Globe is likely to experience suitable conditions to AP. Despite the difficulties linked to the limitations related with the use of model analyses and limited vertical and horizontal resolutions, such study could be used for data sheet by communication tools developers for the siting of quality instruments. Beyond meteorology used, the results of such work might also be useful in other domains like telecommunications.

**Figure 1** Topographic map of Central and West Africa showing study area

**Table 1** The propagation conditions can be described as follows

| Characteristic | $\frac{dN}{dz}$ (km$^{-1}$) | $\frac{dM}{dz}$ (km$^{-1}$) |
|---------------|-----------------|-----------------|
| Ducting       | $\frac{dN}{dz} < -157$ | $\frac{dM}{dz} \leq 0$ |
| Super-refraction | $-157 \leq \frac{dN}{dz} \leq -79$ | $0 < \frac{dM}{dz} \leq 79$ |
| Normal        | $-79 < \frac{dN}{dz} \leq 0$ | $79 < \frac{dM}{dz} \leq 157$ |
| Sub-refraction | $0 < \frac{dN}{dz}$     | $157 < \frac{dM}{dz}$     |
The purposes of this study are twofold. The first goal of this study is to introduce a 5-year climatology of super-refraction and TLs events over CWA. Data are derived from European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses at roughly 40-km horizontal resolution, which should give valuable information due to a much finer scale over this region (Peng Ji & Yuan, 2020). The second goal is to compute the statistics of the super-refraction and TLs events over CWA, which has important implications for the reliability in the field of telecommunications tools such as weather radar observations in numerical weather prediction and data assimilation. In addition, the results obtained in this study are helpful to the GPS satellite radio occultation community because the occurrence of super-refraction is known to degrade the accuracy of refractivity retrievals obtained from bending-angle measurements.

Section 2 defines the various refraction regimes and explains how super-refraction can be simply identified from temperature, humidity, and pressure profiles. The ECMWF data used in this study are briefly described in Section 3, and some remarks about the computation of ECMWF data used in this study are helpful to the GPS satellite radio occultation community because the occurrence of super-refraction is known to degrade the accuracy of refractivity retrievals obtained from bending-angle measurements.

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### 2 | DEFINITION OF THE RADIO REFRACTIVITY VALUE

Tropospheric refractive index plays an important role in the propagation of radio waves at VHF/UHF bands. For example, radio waves reflections from lower layers cause multipath effect while reflections from higher layers may cause trans-horizon interference (Magaldi et al., 2016; Williams et al., 2002).

Very small variations in the air refractive index \( n \) are responsible for AP. This refractive index value typically decreases with height but may decrease quickly or increase with height if local weather anomalies occur. Since \( n \) is very close to unity (about 1.0003), it is expressed by a quantity called the radio refractivity \( N \), which is related to the refractive index, \( n \) as (derived by Steiner & Smith, 2002):

\[
N = (n - 1) \times 10^6, \tag{1}
\]

\[
N = A(p_0 + B \cdot e/T)/T, \tag{2}
\]

where \( p_0 \) (hPa) is the atmospheric pressure, \( e \) (hPa) is partial water vapour pressure, \( T \) (K) is the absolute temperature; \( A = 77.6 \text{ K/hPa} \) and \( B = 4810 \text{ K} \).

The vapour pressure is also related to the relative humidity \( H \) (%):

\[
e = H \cdot e_s/100, \tag{3}
\]

\( e_s \) is the maximum (or saturated) vapour pressure at the given air temperature \( t \) (°C), and may be obtained from the following equation:

\[
e_s = 6.11 \exp \left( \frac{17.502t}{t+240.97} \right). \tag{4}
\]

Generally \( P \) and \( e \) decrease rapidly with height while \( T \) decreases slowly with height.

The effect of the Earth’s curvature (radius \( R \) [m]) at an altitude \( z \) (m) can be accounted for by considering a modified refractivity \( M \) (e.g., Turton et al., 1988), defined as follows:

\[
M = N + \frac{Z \times 10^6}{R}. \tag{5}
\]

This relationship is valid for all the radio frequencies up to 100 GHz; the error is less than 0.5% (Tamosiunaite et al., 2011).

The radio modified refractivity gradient \( Gr \) \( (\text{km}^{-1}) \) is expressed as follows:

\[
Gr = \frac{M_2 - M_1}{Z_2 - Z_1}. \tag{6}
\]

In practice, the super-refractions that degrade ground-based telecommunication tools such as radars are always located in the lowest 3 km of the troposphere. Thus, refractivity derived from Equation (1) and the minimum vertical gradient over all model layers start from about 6 m height and do not exceed 3000 m height.

### 3 | ECMWF OPERATIONAL ANALYSES

The statistics are done with operational analyses from ECMWF during the period from January 2010 to December 2015. These operational analyses are computed using a 4DVAR data assimilation system, described by Courtier et al. (1994). All data are from the original T511 reduced Gaussian grid, which corresponds to a horizontal resolution of approximately 40 km over the Globe. The periods of 0000, 0600, 1200, and 1800 UTC are the samples for the representation of the diurnal cycle. The humidity and temperature profiles are generated.
from the 60 operational vertical levels (hybrid coordinate). As an example, Figure 2 shows the thickness of each layer of the model up to a height of 10 km. Note that due to horizontal variations in surface pressure and virtual temperature, the actual height of each model level may experience some slight fluctuations between the grid points of the model. For a reliable climatological study, the recent operational configuration T799 L91 was not considered to be suitable within the framework of this study because the running-in period seems very short (Zhang et al., 2019). On the other hand, the configuration T511L60 is capable of taking into account the phenomena of the planetary boundary layer and also of accurately representing the thermodynamic structure of the lower troposphere, as pointed out by von Engeln and Teixeira (2004).

For cases of super-refraction and TLs, which are narrower than the grid spacing of 40 km, will not be correctly taken into account in the mesh of the model. In such situations, the values considered will therefore be underestimated in relation to the actual values. This constraint of resolution is often accentuated in particular for TLs present in regions with strong potential of storm (Lopez & Bauer, 2007). It should also be noted that the statistics recorded in this study display the atmosphere as it appears in the analyses of the model, which can sometimes slightly deviate from the real atmosphere. Nevertheless, data provided from the 40-km model over 5 years are likely to give the best overall three-dimensional representation of the atmosphere available to date.

**FIGURE 2** Model layer thickness as a function of bottom-layer height. Units on both logarithmic axes are in metres. Model levels 40, 50, and 60 are explicitly labelled (Lopez, 2009)

**FIGURE 3** Seasonal mean frequency (%) of super-refractive conditions for winter. The averaging has been performed over analysis times 0000, 0600, 1200, and 1800 UTC. White shading corresponds to regions without super-refraction
RESULTS

4.1 Seasonal and diurnal variation of super-refraction

Maps of the Central and West African seasonal mean frequencies of super-refractive conditions are shown in Figures 3–6. Each figure depicts the diurnal cycle of super-refraction appearance over CWA for winter, spring, summer, and autumn, respectively. In each figure super-refractive conditions statistics at 0000, 0600, 1200, and 1800 UTC respectively are displayed.

Over the whole Central/West Africa, super-refraction frequencies are often low in winter and high summer, with average values in spring and autumn. In each season, over the Sahara desert, super-refraction frequencies are often absent at 1200 UTC, as observed in Figures 3–6. Indeed, the refractivity gradients in the low altitudes decrease during daytime due to tropospheric mixing generated by intensive solar heating associated with the strong convective activity during spring and autumn and also by the scarcity of water vapour and storminess in winter period.

From the beginning of night to early morning, super-refraction is generally maximum due to nocturnal surface cooling and decreased instability, which are more suitable for low-level temperature inversion and increase negative values of vertical gradients of water vapour. Over CWA, super-refractive conditions are more present at 1800 UTC and 0000 UTC compared with daytime. Therefore, during autumn at late afternoon (1800 UTC), northern part of the region, especially, most of Sahara displays low cases of super-refraction (below 30%). For entire year, the Guinea Gulf and the Congo Basin refer to be the Central and West African region with the most occurrence probability of super-refractive conditions, in the same view with the climatology of radar AP over West Africa presented by Kaissassou, Lenouo, Tchawoua, et al. (2015b). The occurrence of night time super-refractive conditions over the Coast could be justified by the cohabitation of increasing stable conditions and low-level water vapour advection from the close ocean. On the other hand, these super-refractive conditions lower in daytime as a consequence of the development turbulence activity at the ground land surface, except in coastal region. Furthermore, Lake Chad Basin and the region up to 20°N seem to be less affected by super-refraction, mainly from early night to early morning in summer. Indeed, the presence of subside dry air (except summer) moving in these Saharan areas combines with the intense heat to make the region virtually free of super-refraction. For instance, during spring at 1800 UTC, over the top of sandy lands and the rocky mountains as shown in Figure 1, super-refractive conditions are often less likely to exist than in valleys and plains (Yang et al., 2020). Over the Sahara, for example, this effect appears very clear. The diurnal cycle is very pronounced over the Atlantic Ocean, with maximum super-refraction occurrences of 100% in some part but with little average seasonal variations in summer. As an illustration, Table 2 compares the spatial averages of super-refraction.
frequencies for each season and time of the day over CWA.

All of these results are in agreement with the statistics of AP conditions in CWA obtained from high-resolution GPS radiosonde observations by Kaissassou et al. (2020).

4.2 | Seasonal and diurnal variation of mean trapping-layer base heights

Diurnal cycle of TL height base (hb) is displayed in Figures 7–10. These figures present the values of mean trapping hb at 0000, 0600, 1200, and 1800 UTC. These
values are generally below 1000 m over the entire study region. Year-around, at 0600 UTC, when sun rises over CWA in the morning, surface heating is not yet intensive and thus turbulence is just beginning, and TL base is below 20 m height. At 1200 UTC, the coastal part of the region is usually affected by TL above 70 m, during the warm season (spring) and especially in some mountainous areas. Over ocean, hb is up to 250 m in all seasons, as a result of the cold sea, surface temperatures

TABLE 2  Spatial mean frequencies of super-refraction presence (%) over Central and West Africa (CWA) at various times of the day and for each season (land only)

|       | 0000 UTC | 0600 UTC | 1200 UTC | 1800 UTC |
|-------|----------|----------|----------|----------|
| Winter| 40.5     | 50.3     | 20.4     | 30.7     |
| Spring| 60.7     | 70.9     | 10.2     | 33.9     |
| Summer| 80.6     | 75.7     | 42.1     | 87.3     |
| Autumn| 40.8     | 50.8     | 15.9     | 30.1     |

FIGURE 7  Mean winter trapping-layer base height (m) over the West Africa for winter at 0000, 0600, 1200, and 1800 UTC. White shading corresponds to super-refraction-free regions

FIGURE 8  As in Figure 7, but for spring
much likely favour the occurrence of temperature inversions near the ground surface. These latter results are of the same view with the study by Lopez (2009), who worked on TL events over Europe and America. TLS with a base up to 3000 m above the ground surface are not taken into account in this work. In addition, top TL base heights are located in regions of deep convection, focusing over the Guinea Gulf and Congo Basin year-round and during the rainy season and over the Sahel in summer.
As mentioned previously, mean TLr base heights depicted in Figures 7–10 are less than 70 m over most of the CWA at night (0000 UTC), and late afternoon (1800 UTC) in all seasons, except regions nearby the Gulf of Guinea where hb exceeds this value. From early morning (0600 UTC) to midday, the TLs’ height began to increase, as well as at midday, higher TL base height values are seen over all coastal domains with hb sometimes reaching 1500 m (Yu et al., 2020).

4.3 Implications of the results

The results carried out from this study proved that the AP conditions have a seasonal variation with larger amount of occurrence during the wet season. However, to discuss the damage of the AP conditions on wave propagation, the losses measured on the same seasons have to be assumed as a function of time. The losses are due in general to the change in atmospheric parameters such as temperature, humidity, and pressure along the radio path. The occurrence of a phenomenon such as super-refraction, which is responsible for the noise in radio receiver signal, is compared with the quality in standard atmosphere. Furthermore, the planning of quality broadcasting services needs a permanent coverage of an area with sufficient and strong signal field and requires the banding of radio services sharing the same frequency. The implication of these results therefore is that for different season percentage occurrences of AP, loss to the signal quality might be noticed. The enhancement of the AP conditions can create interference to distant telecommunication systems. The interference from different distant stations experienced in a locality can thus be sometimes explained in terms of these AP conditions that prevailed in this area. Hence, the super-refraction of radio waves may be responsible for signals often received from distant radio/television stations in West and Central Africa during the dry season.

5 CONCLUSION

Seasonal and diurnal statistics of super-refraction and trapping layers (TLs) over Central and West Africa (CWA) have been done from 2010 to 2015. These statistics have been built by European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses with a resolution of 40 km over 60 levels in the vertical direction. The aim of the current work is to introduce a 5-year climatology of super-refraction and TLs events over CWA, with various applications in telecommunication services such as in numerical weather prediction. Indeed, some electronic materials of observations that supposedly have been quality controlled can sometimes suffer from anomalous propagation damage, in particular when those data are recorded in real time. Despite the difficulties related to model the ability of underestimating the occurrences of TLs in some situations, the results of this work, based on screening favourable situations to super-refraction and TLs, whose procedure has been described in Section 2 would be of great interest for the studied region. This work could also serve for basic understanding of the formation and detection of TLs’ process. Thus, helping the microwave circuit engineer in conceiving quality transmitter and receiver required to achieve the desired coverage gradually as the model’s horizontal and vertical resolutions are enhanced.

ACKNOWLEDGEMENTS

ECMWF team is acknowledged for making the ECMWF operational analyses available. Comments by the anonymous reviewers greatly helped to improve the manuscript.

AUTHOR CONTRIBUTIONS

Samuel Kaissassou: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). Lucie Djiotang: Formal analysis (equal); funding acquisition (equal); methodology (equal); resources (equal); software (equal); visualization (equal). Armand Komkoua: Formal analysis (equal); investigation (equal); project administration (equal); resources (equal); visualization (equal). Brice Ekobo Akoa: Funding acquisition (equal); methodology (equal); validation (equal). Benoit Ndzana: Resources (equal); software (equal); supervision (equal). Romeo Steve Tanessong: Data curation (equal); software (equal); writing – review and editing (equal). Guy Merlin Guenang: Data curation (equal); formal analysis (equal); software (equal). Derbetini Appollinaire Vondou: Data curation (equal); methodology (equal); resources; visualization (equal).

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**How to cite this article:** Kaissassou, S., Djiotang, L., Komkoua, A., Ekobo, B., Ndzana, B., Tanessong, R., Guenang, M., & Vondou, A. (2021). Climatology of super-refraction and trapping layers conditions over Central and West Africa. *Meteorological Applications*, 28(4), e2016. https://doi.org/10.1002/met.2016