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ORIGINAL PAPER

The Study of Atmospheric Stability Using Radio Refractivity Profiles Over a Tropical Climate in Nigeria

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Abstract: The variations of meteorological parameters have significant effects on radio wave signals propagating through the troposphere. Proper planning of radio communication links can be achieved by continuous studying of the atmosphere using refractivity profiles to provide baseline data that could be used to mitigate satellite communication outage before the onset of severe adverse hydrometeor environment. The stability of the atmosphere based on ten (10) years (2009–2018) reanalysis data of atmospheric parameters (temperature, atmospheric pressure, and relative humidity) obtained from the European Center for Medium-range Weather Forecast (ECMWF) at 1000 hPa, 975 hPa, 950 hPa, 925 hPa, 900 hPa, 800 hPa, 700 hPa, 500 hPa, 400 hPa, 300 hPa, 200 hPa, and 100 hPa to estimate the Atmospheric Stability Indices (ASI) and the Refractivity of the Lifted Index (LIR) has been analysed. The trend in the variation LIR and Lifted Index (LI) shows that when LI is negative, LIR is more negative, which implies that the atmosphere is more unstable. Results also show that positive LI indicates negative LIR, which implies that the atmosphere is more stable. However, some cases occurred when a significant amount of water vapour accumulates at 500 hPa pressure level; in such case, positive LI indicates negative LIR which implies that the atmosphere is not stable. The results will serve as a database to checkmate the occurrence of severe weather conditions in the study area

Keywords: Radio refractivity profile; LI; Stability of the atmosphere; LIR; water vapour; Tropical climate

1. Introduction

The dynamic of the atmosphere continually call for an accurate prediction and has always been the concern of atmospheric scientists and meteorologist. Over the years, the impact of severe weather has caused more havoc on humans and their environment. This includes, but is not limited to structures like buildings, agricultural outputs, and human lives. The destructive impact of severe weather, most especially the loss of lives and properties, is projecting a warning to all [1].

For centuries, humans have utilized certain physical characteristics of the atmosphere as keys to forecasting. As technology has improved, the study of the atmosphere has become more complex. The scientists have established the importance not only of surface data but also of data obtained from a higher altitude. Several satellites and weather balloons have also been utilized for gathering, yielding satellite and radiosonde data. The data collected includes temperature, relative humidity, wind velocity, wind speed, and Geopotential heights at some pressure levels throughout the atmosphere [2]. Basic concepts that help explain the atmosphere have been developed from these data. Computers have also given scientists the ability to use tremendous quantities of acquired data in primitive equation models, deriving future weather situations and displaying them as maps. Analysis of maps generated by the computer is then used to help form general forecasts. Just as important as computer-generated map analysis, the weather forecaster often uses the knowledge gained from the experiences of forecasting in a particular region to analyse and interpret the situation. Thus, the duties of a weather forecaster have developed into a complex scientific profession. The time involved in making a proper analysis and forecast takes numerous hours of analysis and years of experience. Researchers have begun to look for ways to shorten the forecast time and provide experience without losing a great deal of accuracy.

In the early 1950s, simple concepts in terms of the forecast were developed by scientists based on a wide

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range of the atmospheric parameters relating to the incident of thunderstorms [3]. To understand the atmospheric parameters, some concepts about the thunderstorms' formation were required. Amongst such information are the vertical and horizontal motions and the unstable trend experienced by the way of thermodynamic stratification. The importance of vertical motion is brought about by the fact that upward movement, and the related adiabatic cooling is the most common way to bring an air parcel to saturation. Horizontal convergence and divergence patterns at different levels relate to vertical motion. For example, if there is upper-level divergence and low-level convergence acting on a certain column of air, vertical motions are generated. However, obtaining the actual atmospheric parameters continues to serve as the major challenge for predicting atmospheric phenomena [3].

Researchers can therefore categorize atmospheric conditions based on indices generated from what they observed, and it may either relate them to the possibility of thunderstorm occurrence or associated severe weather for a given period in a particular location. Some of the advantages of developing these equations are speed, uniqueness to a specific area, and simplicity. Based on the aforementioned factors amongst others, the stability of a specific sectional area of the atmosphere can therefore be determined by the equation. A stable atmosphere can determine the wind profile and the possible disturbance in the atmospheric boundary layer (ABL) [4, 5]. An unstable atmosphere may be as a result of turbulence due to the positive vertical heat flux that is either generated from the stability of the ground or water surface being warmer than the air above [6, 7]. There are many techniques and parameters for describing the occurrence of atmospheric stability. Amongst such is the lapse rate, which describes the static stability peradventure the vertical profile of the temperature parameter is available.

In this paper, we aim at three objectives. The first is to use the formulation deduced by [8] for simulating atmospheric stability based on radio refractivity profiles. Secondly, analyzing the diurnal and seasonal influence of refractivity lifted index and lifted index over Akure, Nigeria at different pressure levels, and thirdly, estimating the Spatio-temporal variation of LIR at four synopsis hours of the day.

2. Materials and Methods

2.1. Materials

Average monthly temperature and relative humidity data for 12 different atmospheric pressure levels (1000, 975, 950, 925, 900, 800, 700, 400,300, 200, and 100 hPa) which spanned between 2009 and 2018 were downloaded from the European Center for Medium-range Weather Forecast (ECMWF) over Akure, Southwestern part of Nigeria. The data were downloaded for four synopsis hours of the day in 6 h intervals (00 h, 06 h, 12 h, and 18 h local time).

2.2. Method of Analysis of Refractivity Lifted Index (LI)

Basically, vertical temperature profile-based LI at a pressure level of 500-hpa is usually linked with the temperature of an air parcel lifted (APL) [7]. If we consider a constraint such that APL does not combine with the surrounding commencing from the surface to a higher pressure range. Then, the pressure associated with the lifting condensation level (LCL_p) can be represented as [8]:

$$\mathrm{LCL_p} = \frac{\mathrm{SP(PT/ST)}^{3.5}}{1000} \tag{1}$$

where the surface temperature in K is the ST, PT denotes the surface pressure level in hPa and the temperature of the parcel in K is denoted as PT.

The PT at LCL_p is represented according to [8] as follows:

$$\mathrm{PT} = ((1/(1/\mathrm{SDPd} - 56) + \log(\mathrm{ST/SDPd})/800) + 56 \tag{2}$$

where SDPd is the surface dew point in K. Reaching the LCL_p level, APL temperature changes based on the dry adiabatic lapse rate (DALR). On vertical profiling, the DALR value remains constant with a value of about 9.8 K km^{-1}. However, at a level higher than LCL_p, APL temperature of an air parcel changes based on moist adiabatic lapse rate (MOALR), and can be represented by

$$\mathrm{MOALR} = \xi_d \frac{\left[1 + \frac{\mathrm{WV_S Lh_v}}{\mathrm{Ra_d T}}\right]}{\left[1 + \frac{\mathrm{W_{VS} Lh_v^2} v}{\mathrm{C_p R_{WV} T^2}}\right]} \tag{3}$$

where ξ_d represents the DALR given (about 9.8 K km^{-1}), Lh_v is the latent heat of vapourization (2.25×10^6 J kg^{-1}), wv_s = the mixing ratio of the saturation water vapor (kg/kg) at a given temperature T (K), Ra_d = gas constant for dry air (287.0 J K^{-1} kg^{-1}), Rw_V = gas constant for water vapour (461.51 J K^{-1} kg^{-1}), and C_P = specific heat for dry air at constant pressure (1004 J K^{-1} kg^{-1}).

Further details on achieving stability are available in [8] and not re-iterated here due to the paucity of space.

Also, inferring stability through parcel refractivity (PR) can be achieved by comparing PR with the environmental refractivity (ER) over some pressure ranges. This method may not be easily achievable because of the differences between PR and ER based on the precise nature of the parcel with the environment. A comparison between the 'dry' terms of PR with that of the ER can be carried out [9]. The resultant atmospheric refractivity gives

$$N = Q_1 \frac{P}{T} + Q_2 \frac{e}{T} \quad (4)$$

where Q_1 = 77 0.6 KhPa^{-1} and Q_2 = 373,000.0 KhPa^{-1}, The atmospheric pressure measures in hPa is represented by P, T represents the absolute temperature in Kelvin and e is the water vapor partial pressure in hPa.

The first and the second terms in Eq. (4) denote the dry and wet terms, respectively. Hence, at 500 hPa, the index can be referred to as a lifted index based on refractivity (LIR) measures in N units to symbolise the atmospheric stability.

$$\text{LIR} = -(N_e - N_{\text{exp,dry}}) \quad (5)$$

N_e is referred to as environment refractivity at 500 hPa, $N_{\text{exp,dry}}$ is the estimated parcel of the dry section of refractivity at 500 pressure level in hPa. Substituting Eq. (4) into (5), we have

$$\text{LIR} = \left[Q_1 \frac{500}{T_e} + Q_2 \frac{e}{T_e^2} - Q1 \frac{500}{T_p} \right] \quad (6)$$

T_e is the denotes temperature of the environment, T_p is the parcel temperature at 500 hPa pressure level and e is the water vapor partial pressure in the environment at 500 hPa pressure level. Hence,

Table 1 Lifted index values [7]

LI values	Implication
> 0	Stable but weak
0 to −3	Marginally unstable
−3 to −6	Moderately unstable
−6 to −9	Very unstable
< -9	Extremely unstable

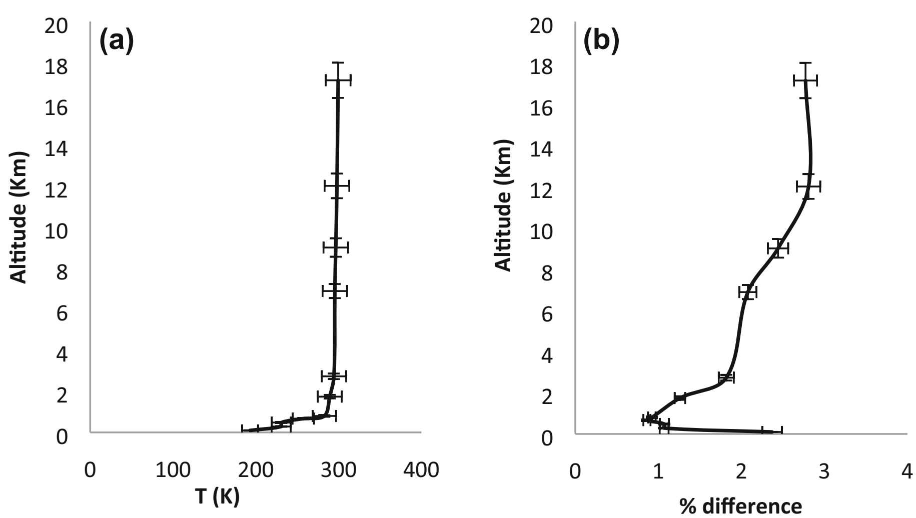

Fig. 1 Atmospheric profiles for **a** The temperature with error bars and **b** percentage difference errors based on standard deviation

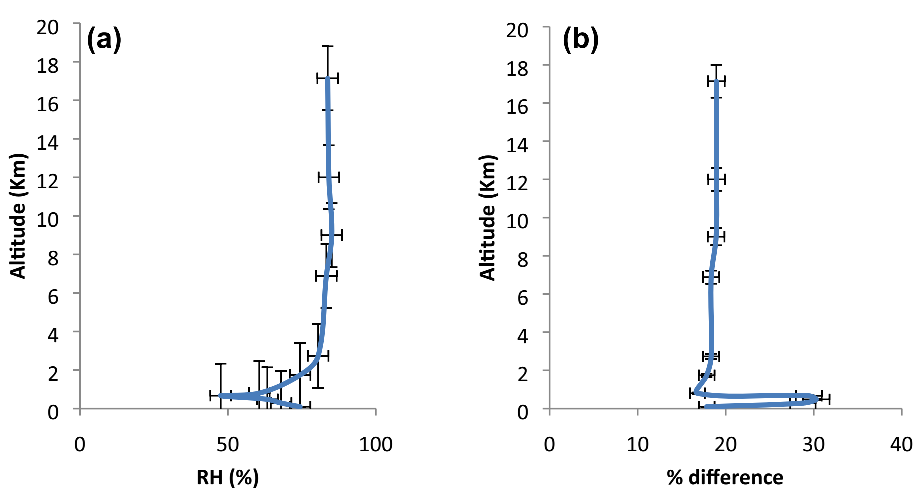

Fig. 2 Atmospheric profiles for **a** the relative humidity with error bars and **b** percentage difference errors based on standard deviation

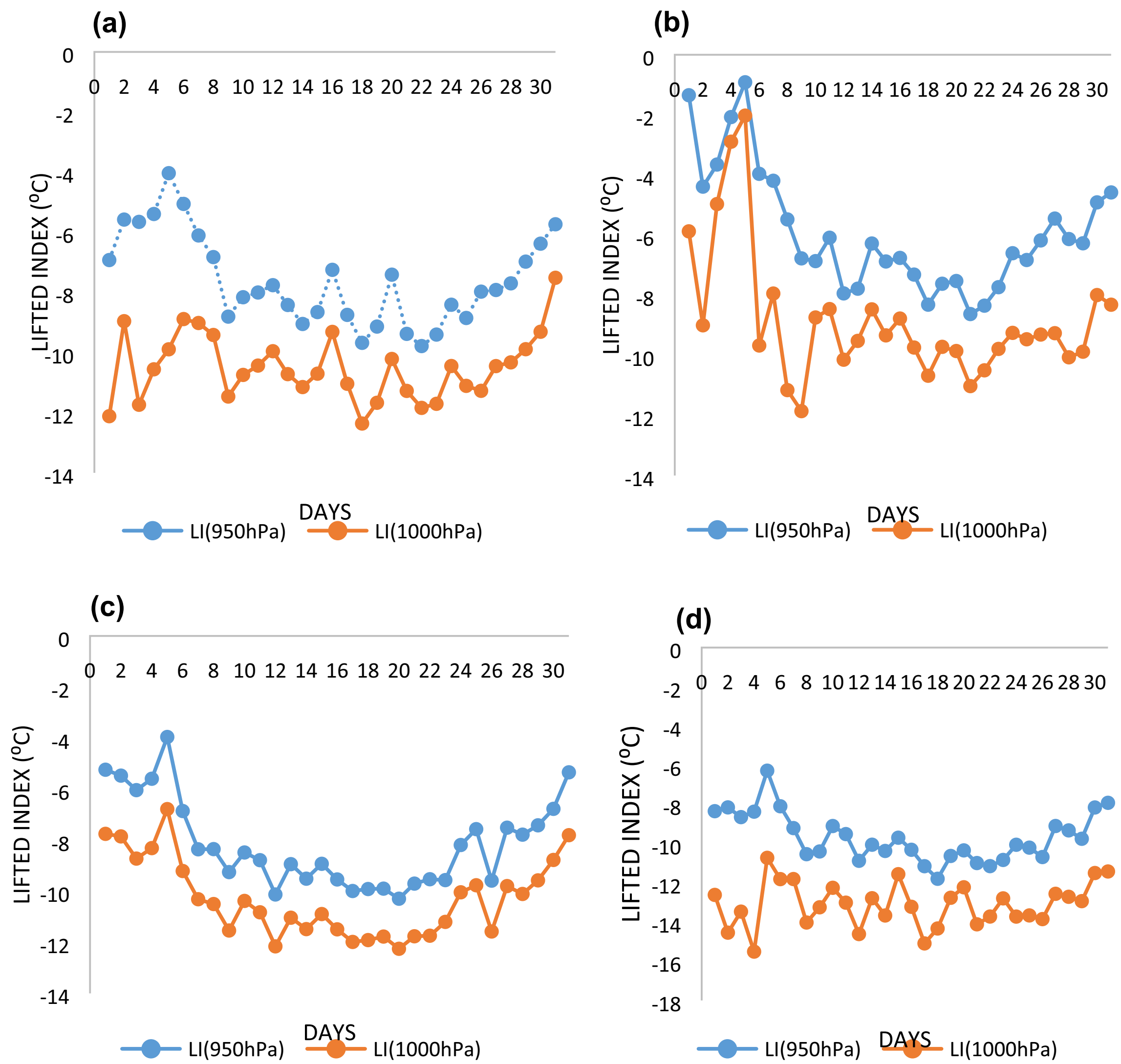

Fig. 3 Variation of the LI during dry month at 950 hPa and 1000 hPa for **a** 0 h, **b** 6 h, **c** 12 h, and **d** 18 h local time

$$\mathrm{LIR} = \left[Q_1 \frac{500(T_\mathrm{p} - T_\mathrm{e})}{T_\mathrm{p} T_\mathrm{e}} + Q_2 \frac{e}{T_\mathrm{e}^2} \right] \tag{7}$$

Equation (7) can be written in terms of traditional lifted index as

$$\mathrm{LIR} = Q_1 \frac{500\mathrm{LI}}{T_\mathrm{p} T_\mathrm{e}} - Q_2 \frac{e}{T_\mathrm{e}^2} \tag{8}$$

LI is the traditional temperature based lifted index $(T_\mathrm{p} - T_\mathrm{e})$.

Hence,

$$\mathrm{LIR} = Q_1 \frac{\mathrm{PLI}}{T_\mathrm{p} T_\mathrm{e}} - Q_2 \frac{e}{T_\mathrm{e}^2} \tag{9}$$

Estimation based on the above index is achievable if and only if the refractivity profile and other atmospheric parameters like the temperature in K, the mixing ratio of the water vapour at the surface level, and pressure in hPa and are known. The implication of the formulation is that LIR is negative when LI (temperature) is negative. Although, if a considerable amount of water vapour is found at a pressure level of 500 hPa, in such condition, when LI is positive, LIR can also be negative [8]. A typical standard value of LI is presented in Table 1.

3. Results and Discussion

3.1. Uncertainty in Atmospheric Thermodynamic Profiles

Uncertainty cannot be ruled out when dealing with physical quantity obtained through measurement, and hence, it is appropriate to quantify the quality of the data so that a high

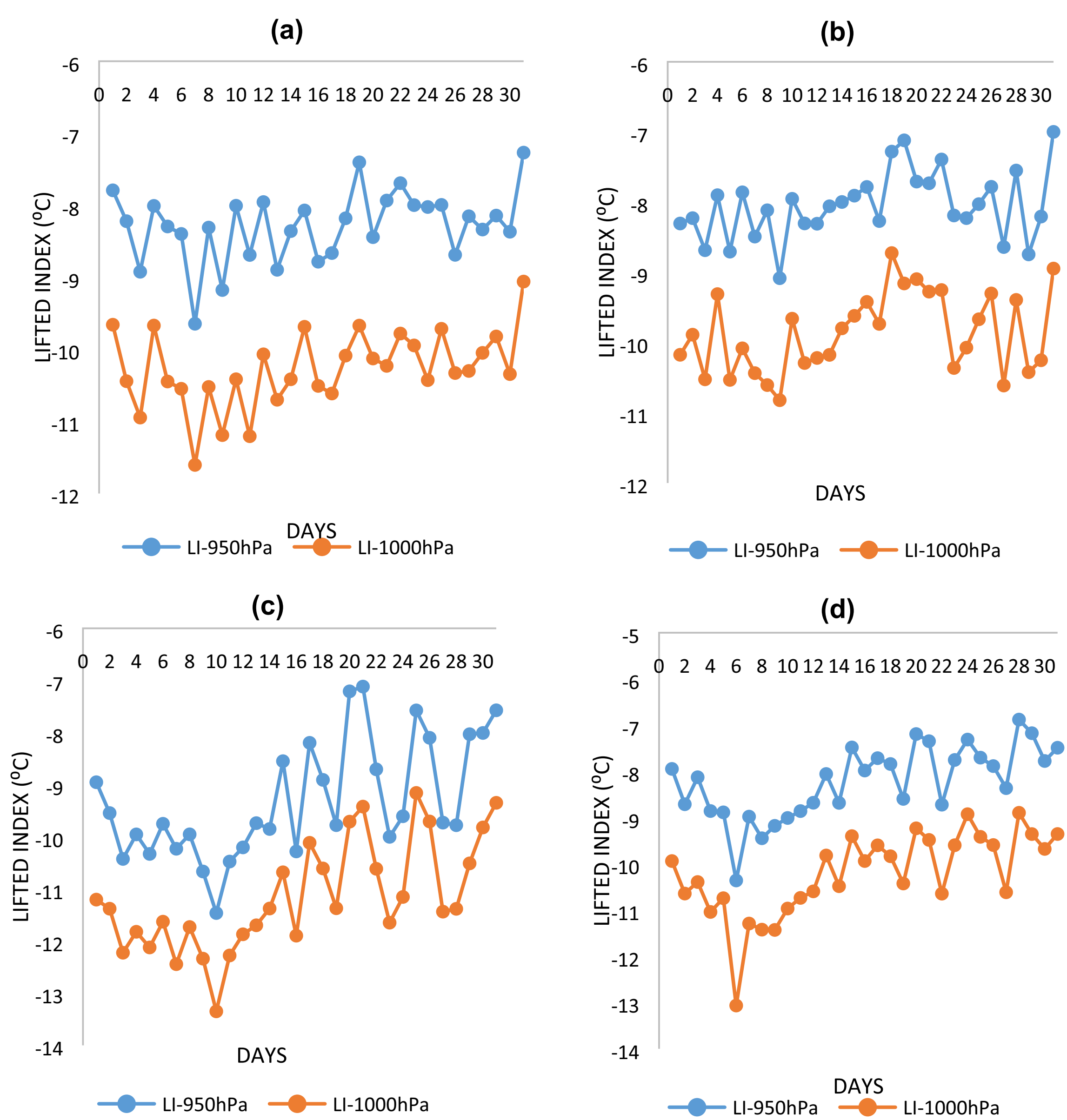

Fig. 4 Variation of the LI during wet month at 950 hPa and 1000 hPa for **a** 0 h, **b** 6 h, **c** 12 h, and **d** 18 h local time

degree of confidence can be ascertained about the product [10]. Uncertainties in some products have been checked using an inbuilt algorithm associated with the instrument. The products used in this work have been reprocessed (re-analyzed data) with the uncertainty incorporated with the data. However, we have performed some level of uncertainty in the present work.

Figures 1 and 2 show a typical uncertainty in the atmospheric parameters temperature and relative humidity, respectively, which is used in the study of the atmospheric stability index by radio profiling. A low standard deviation is recorded in the temperature profile, which indicates that the data points tend to be very close to the mean [10]. In the RH profiles, the standard deviation is high and it indicates that the data points are spread out over a large range of values. Generally, the results on the uncertainty in the data used show that it was well within about a percent.

3.2. Variation of the Lifted Index (LI) at Different Hours of the Day

LI can simply be defined as the difference between the environmental temperatures, T_e and parcel temperature T_p at a specific pressure level at the troposphere [8]. Whenever LI takes a positive value then, the atmosphere over the specified height considered is stable and when the value is negative; then, the atmosphere is regarded as unstable. The larger the negative number, the more unstable the

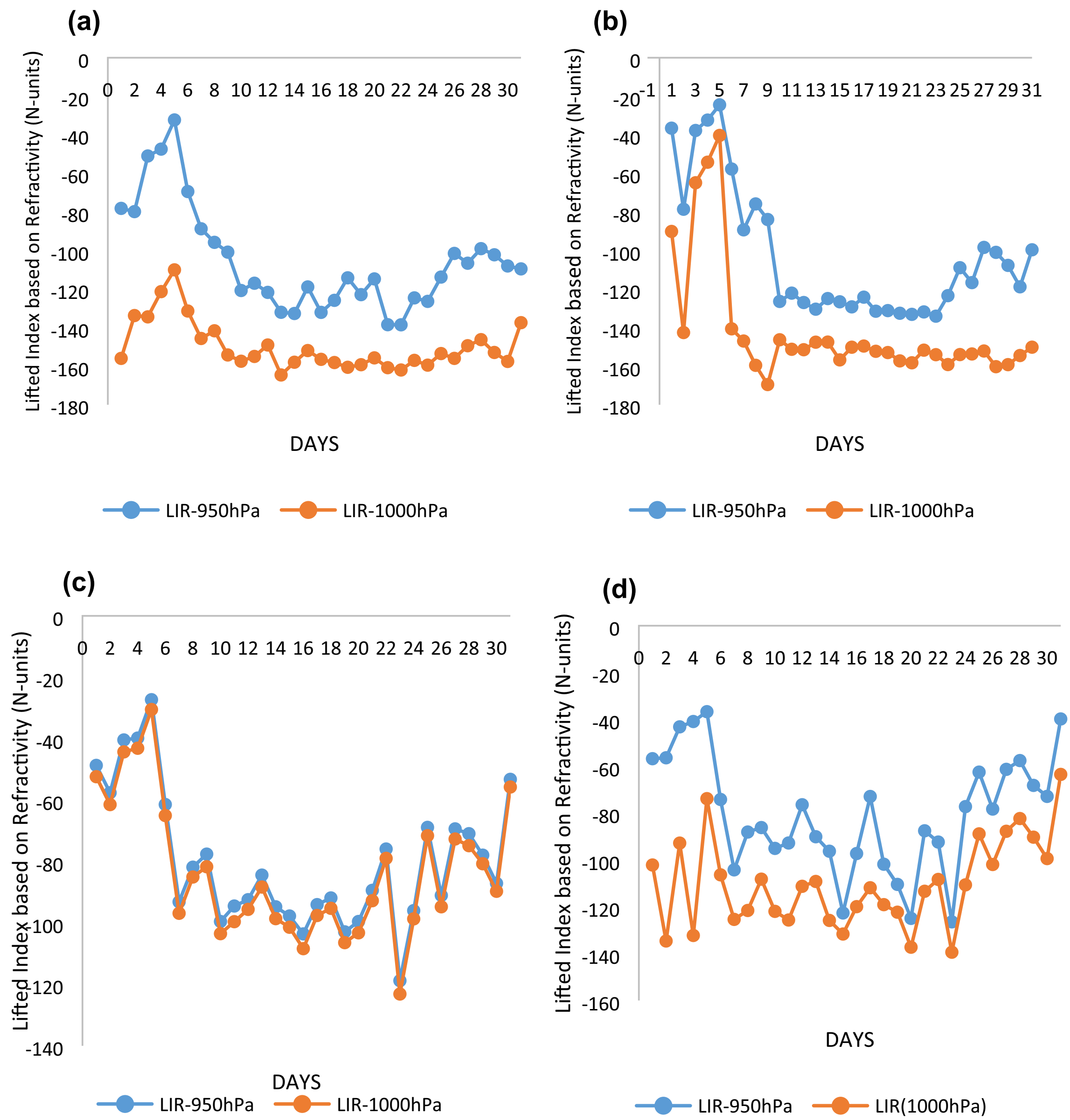

Fig. 5 Variation of LIR at 950 and 1000 hPa during the dry season month for **a** 0 h, **b** 6 h, **c** 12 h, and **d** 18 h local time

atmosphere. The more negative the value, the greater the possibility of thunderstorms occurrence. A positive value suggests stability, no further lifting above 500 hPa, no further cloud development, and little chance of thunderstorm formation [7].

According to [11], the lifted index calculated for a parcel originating from 950 hPa is as good an indicator of atmospheric instability as the lifted index calculated from a parcel origination at 1000 hPa. For the purpose of this study, January is taken to be the driest month whilst July is taken as the wettest month.

Figure 3a–d shows the trend in Lifted Index (LI) variation in the dry month at 950 and 1000 hPa for 0 h, 6 h, 12 h, and 18 h local time, respectively. At 950 hPa, the value of LI for most of the day in the dry month at 950 hPa is above the threshold of -9, this indicates less action for convective activities, which infer that the atmosphere in those days is marginally stable.

The LI values as shown in Fig. 3a-d are mostly above -9, at 950 hPa which implies that the atmosphere is usually stable during the dry season, whilst at 1000 hPa large negative values are recorded which implies instability.

Figure 4a–d shows the trend in LI variation for the wet season month. At 950 hPa, the LI values vary between values greater than -9 shows potential for less convective activities. The values of LI at 1000 hPa pressure level for most of the day in July are less than the threshold of -9 which infer that the atmosphere is largely unstable. The

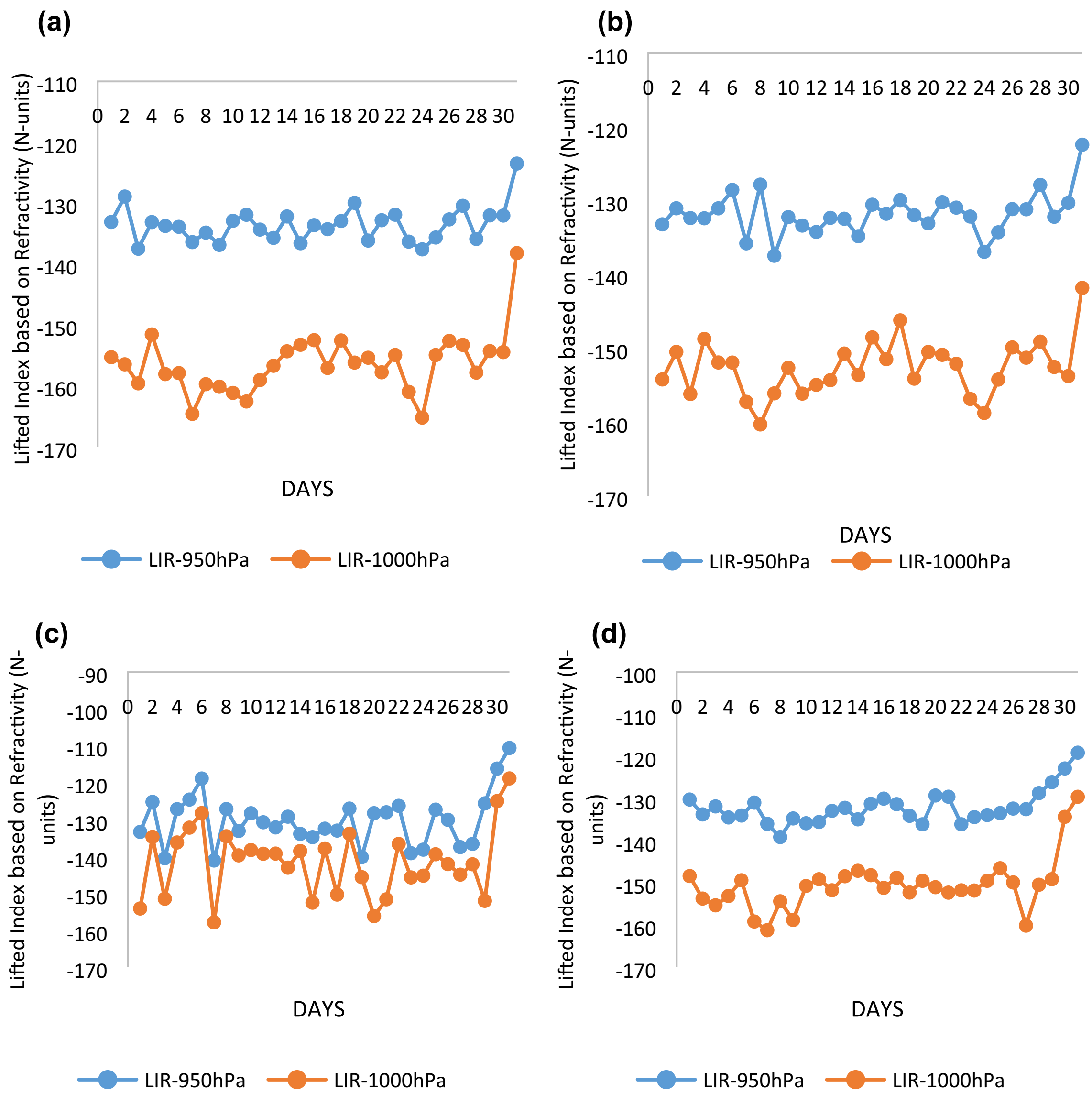

Fig. 6 Variation of LIR at 950 and 1000 hPa during the wet season month for **a** 0 h, **b** 6 h, **c** 12 h, **d** 18 h local time

value of LI at 950 hPa at the 0 h, 6 h, and 18 h local time as shown in Fig. 4a and b is above the threshold of -9 and below -9 at 1000 hPa. This implies that the atmosphere under such conditions is said to be more stable at 950 hPa and very unstable at 1000 hPa. At the 12 h, as shown in Fig. 4c, the atmosphere is largely unstable at 1000 hPa, and has a range of values that falls below −9 at 950 hPa.

3.3. Variation of Lifted Index Based on Refractivity at Different Hours of the Day

Figure 5a–d shows the variation of the lifted index based on refractivity (LIR) during the dry months at 950 hPa and 1000 hPa. The lifted index based on refractivity at 950 hPa is higher than at 1000 hPa. This is due to low water vapour content at 950 hPa and variations of atmospheric parameters, except in Fig. 5c which denotes the 12 h where the lifted index based on refractivity is high at both pressure levels.

Figure 6a–d shows the variation of the LIR during the wet months at 950 hPa and 1000 hPa. The lifted index based on refractivity at 950 hPa is shown to be higher than that at 1000 hPa. This is due to low water vapour content at 950 hPa and variations of other atmospheric parameters.

3.4. Seasonal Variation of LI With LIR

Figure 7a–d shows the seasonal variation of LI and LIR at 950 hPa for 0 h, 6 h, 12 h, and 18 h, respectively. The trend in the variation shows that when LI is negative, LIR

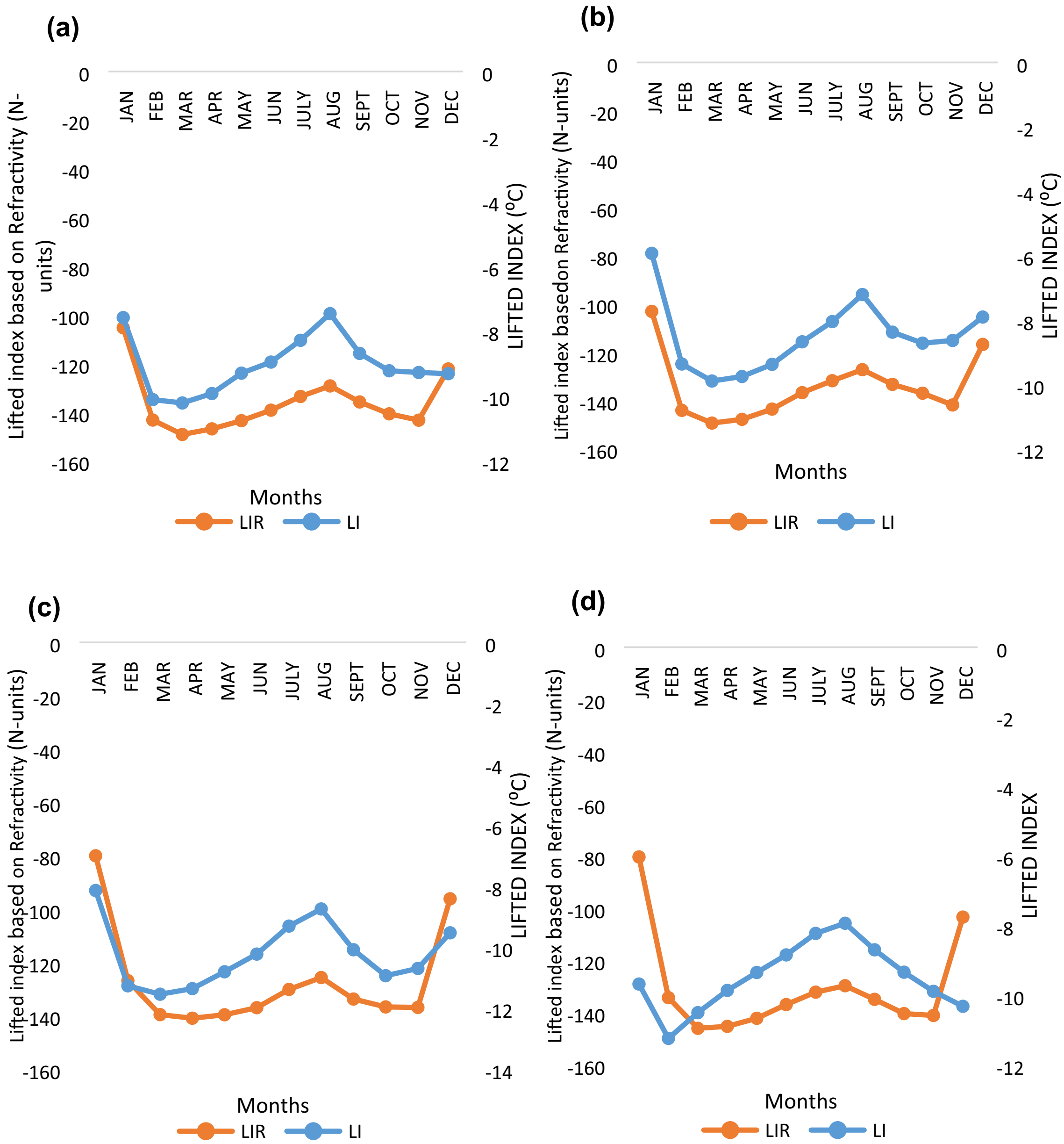

Fig. 7 Variation of LI with LIR at 950 hPa for **a** 0 h, **b** 6 h, **c** 12 h, and **d** 18 h local time

is more negative, and when LI is positive, LIR is less negative.

3.5. Vertical Profile of LIR at Different Hours of the Day

Figure 8a–d reveals the Spatio-temporal variation of the lifted index based on refractivity at 0 h, 6 h, 12 h, and 18 h local time, respectively. The result reveals that the lifted index based on refractivity increases with height up to about 9 km and decreases gradually at higher altitude. This occurs when warm air parcel compresses and starts sinking from 100 hPa downward. The parcel temperature at this level is relatively higher than that of the environmental temperature at a pressure level of 500 hPa, and the water vapour pressure at this level is relatively low when compared to other levels.

3.6. Variation of Radio Refractivity Profiles (RRP) and LIR

The radio refractivity profiles (RRP) were considered from the surface (1000 hPa) level up to 100 hPa. Figures 9, 10, 11 and 12 present the Spatio-temporal variability of the RRP and atmospheric stability index using radio refractivity profiles [12]. The variability observed in the radio

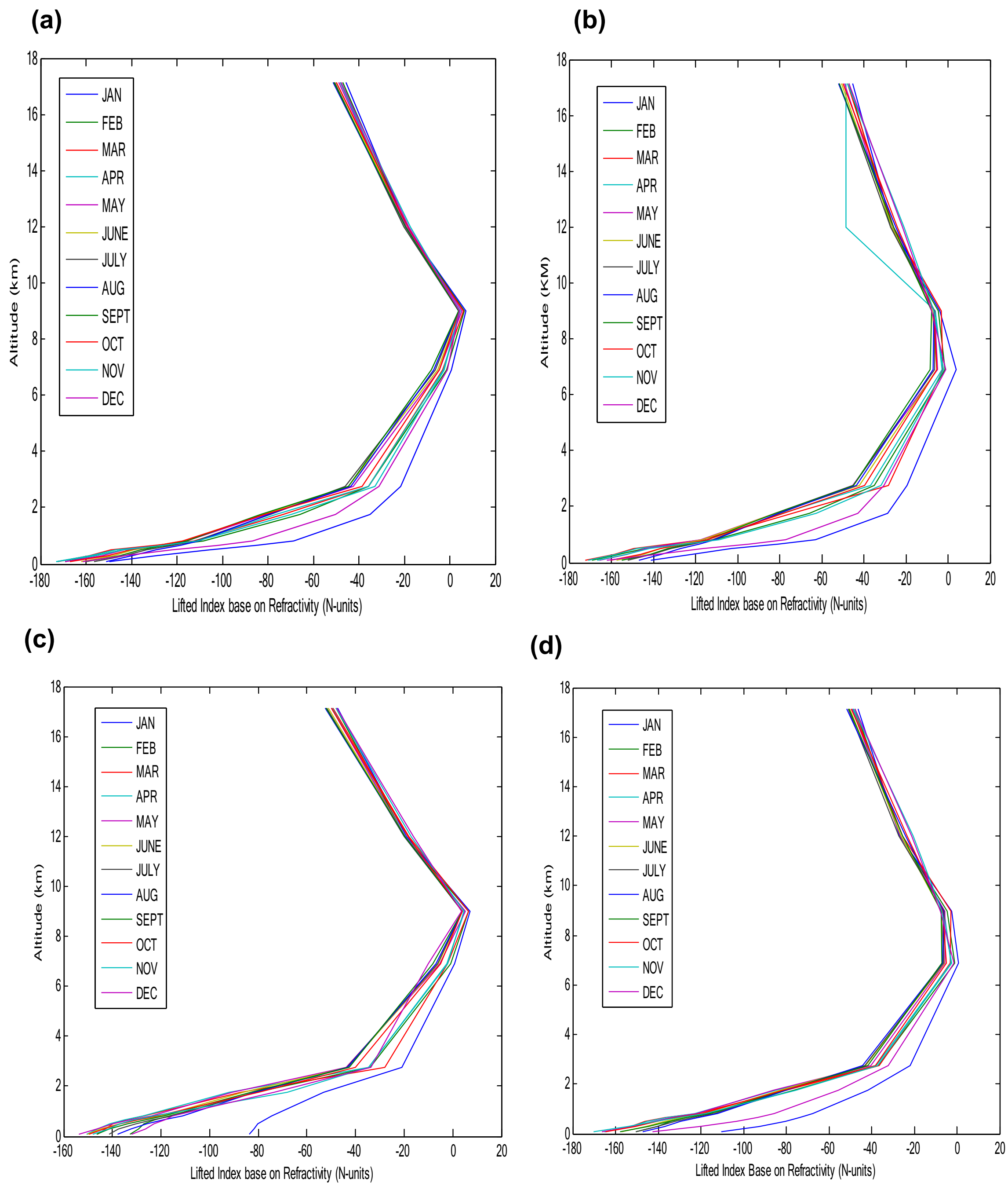

Fig. 8 Spatio-temporal variation of Lifted Index based on Refractivity at **a** 0 h, **b** 6 h, **c** 12 h, and **d** 18 h local time

refractivity profiles is attributed to the varying values of atmospheric parameters which include temperature, pressure, and relative humidity in the tropical savannah climate [13]. On the other hand, the observed variability in the LIR is associated with atmospheric stability and moisture parameters [14]. Hence, LIR combines information about the water vapour in the environment with atmospheric stability from the planetary boundary layer where the parcel is assumed to originate up to 100 hPa. The onset of the LIR anvil coincides with the onset of the West Africa Moonson (WAM) around March. The LIR anvil is representative of increased moisture and deep convection. The active phase of the WAM over Akure attained peak values between May and July.

In Figs. 10, 11 and 12 refractivity profiles ranged around 350 N-unit to 50 N-unit from 1000 to 100 hPa, with a corresponding value of −150 N-unit to 0 N-unit from 1000

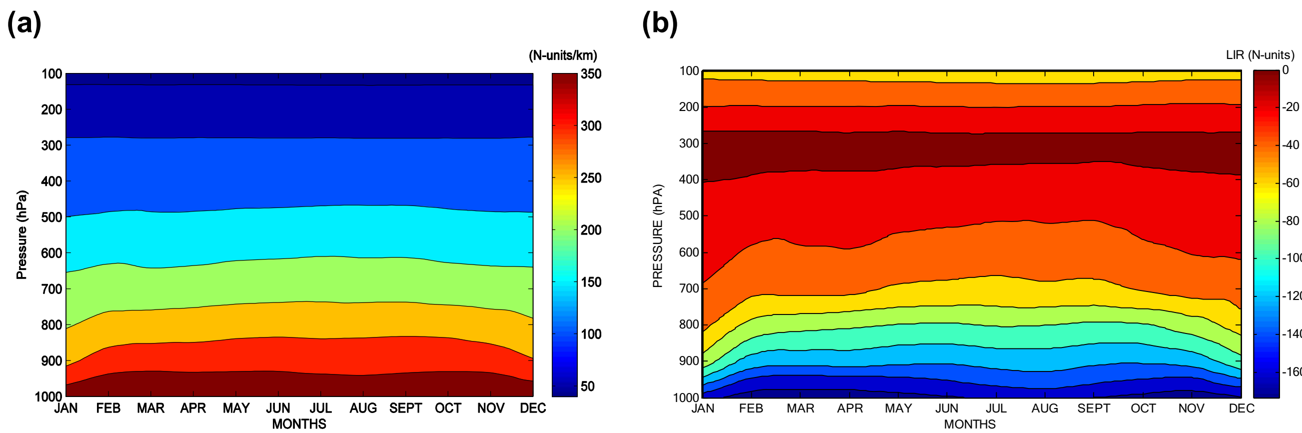

Fig. 9 Spatio-temporal variability at 0 h local time for **a** radio refractivity and **b** LIR

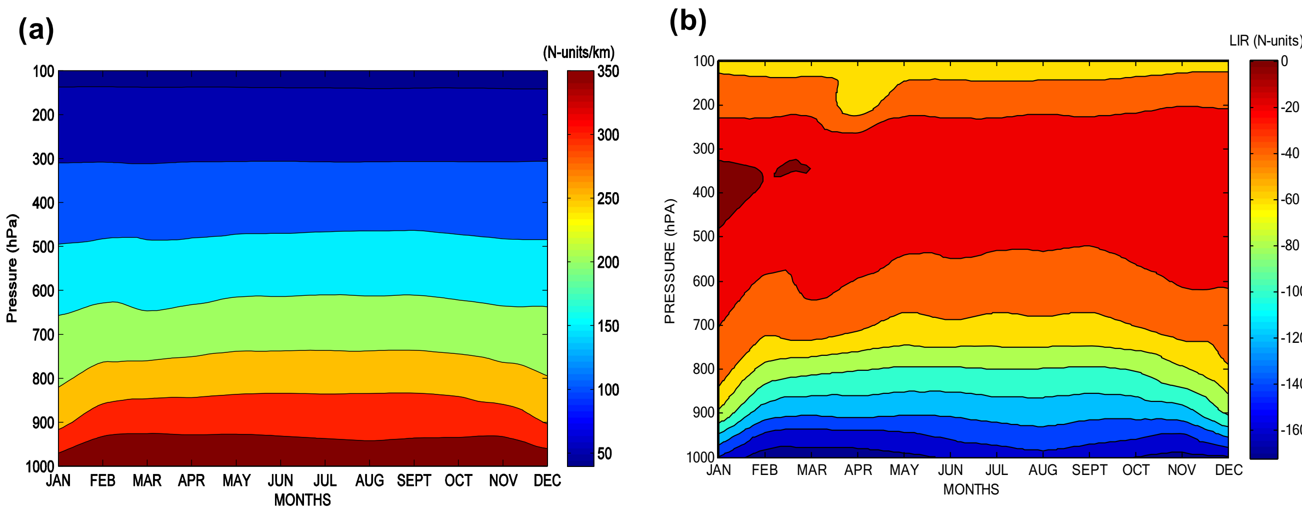

Fig. 10 Spatio-temporal variability at 06 h local time for **a** radio refractivity and **b** LIR

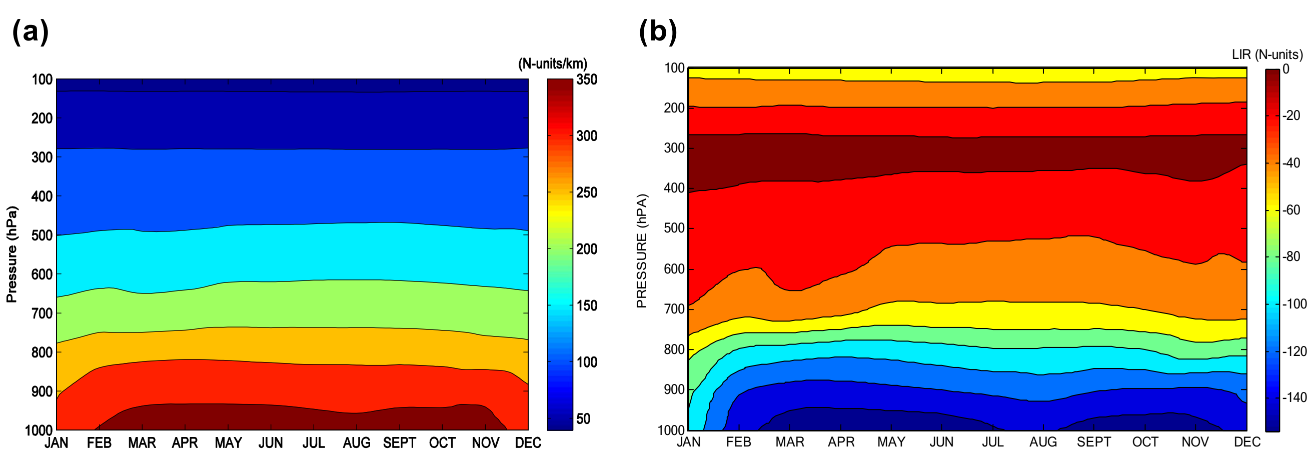

Fig. 11 Spatio-temporal variability at 12 h local time for **a** radio refractivity and **b** LIR

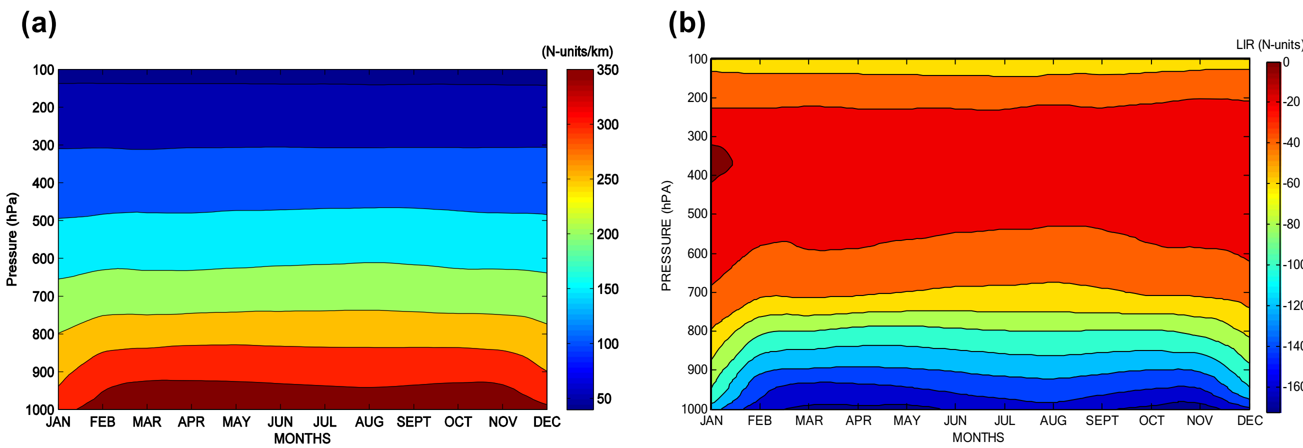

Fig. 12 Spatio-temporal variability at 18 h local time for **a** radio refractivity and **b** LIR

to 100 hPa for LIR. In Fig. 10, for example, a characteristic wide LIR anvil was observed from 700 to 200 hPa.

In Fig. 11, the refractivity profiles range between 350 N-unit and 50 N-unit from 1000 to 100 hPa, with a corresponding range of −140 N-unit to 0 N-unit from 1000 to 100 hPa for LIR.

4. Conclusion

The LI at 950 hPa conforms with the work of Sharma et al. (2009), which indicates that LI estimated for a parcel originating from 950 hPa is a good indicator of atmospheric instability. The following conclusion can therefore be inferred from this work:

- The values of the Lifted index obtained for the dry season are mostly above the threshold of -9 which infers that the atmosphere during the dry season is mostly stable, and radio signal will travel in their propagation path smoothly without loss of signals unlike when the atmosphere is unstable, which can cause scintillation and attenuation of signals
- The trend in the variation of the LIR and LI shows that when LI is negative, LIR is more negative, and when LI is positive, LIR tends to be less negative except in cases when a considerable amount of water vapour is observed at 500 hPa pressure level, in such condition, when LI is positive, LIR can also be negative
- The Refractivity Lifted Index increases with height up to about 9 km and started decreasing at higher altitudes. This occurs when warm air parcel compresses and starts sinking from 100 hPa downward.

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