SEMIANNUAL VARIATION OF IONOSPHERIC CHAOTICITY AND DYNAMICAL COMPLEXITY OVER THE EQUATORIAL IONIZATION ANOMALY REGION

B. O. Ogunsua[1], A. B. Rabiu[1,2] I. A. Fuwape[1] and G. K. Seemala[3]

[1] {Space Physics Laboratory, Department of Physics, Federal University of Technology, Akure, Ondo State, Nigeria}

[2]{Centre for Atmospheric Research, National Space research and Development Agency, Anyigba, Kogi State Nigeria}

[3]{Indian Institute of Geomagnetism, Panvel, Navi Mumbai, India}

Correspondence to: B. O. Ogunsua (iobogunsua@futa.edu.ng)

The Ionosphere

- The upper region of the atmosphere with sufficient proportion of electron that can affect propagation of radio waves
- It ranges from 50 km to about 1000km
- It is stratified into four Layers D,E,F1 andF2
- Formed mainly as a result of Photoionization (Mostly from EUV to Hard X-rays) and particle precipitation from the sun.

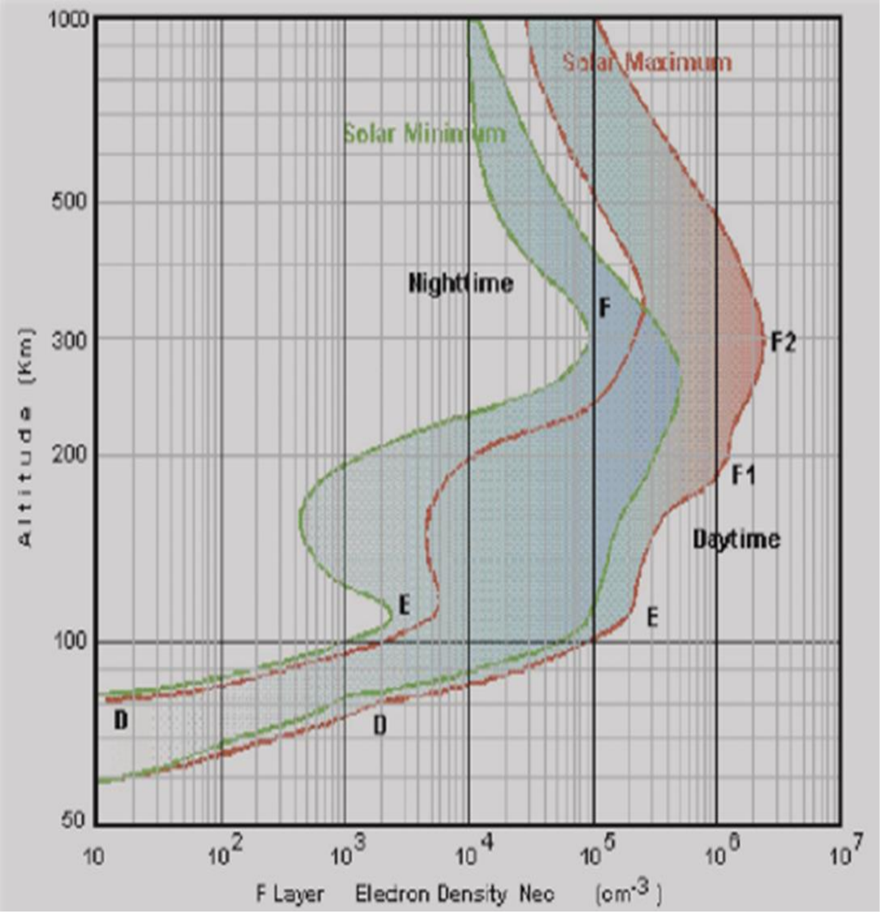

Fig. 1 The ionosphere and its layers (after Radicella 2013)

Equatorial ionization anomaly (EIA)

- Occurs within ±15° the low latitude region
- ExB drift transports the F-region plasma over the magnetic equator upward to the height of about 700 km.
- This results in the fountain effect where the loss in momentum of the electrons causes the electron to diffuse along the field lines due to gravity and pressure gradients to either side of the equator to form two crests. (Yeh et al., 2001)
- EIA results from fountain effect with reduced F-region ionization density at the magnetic equator.

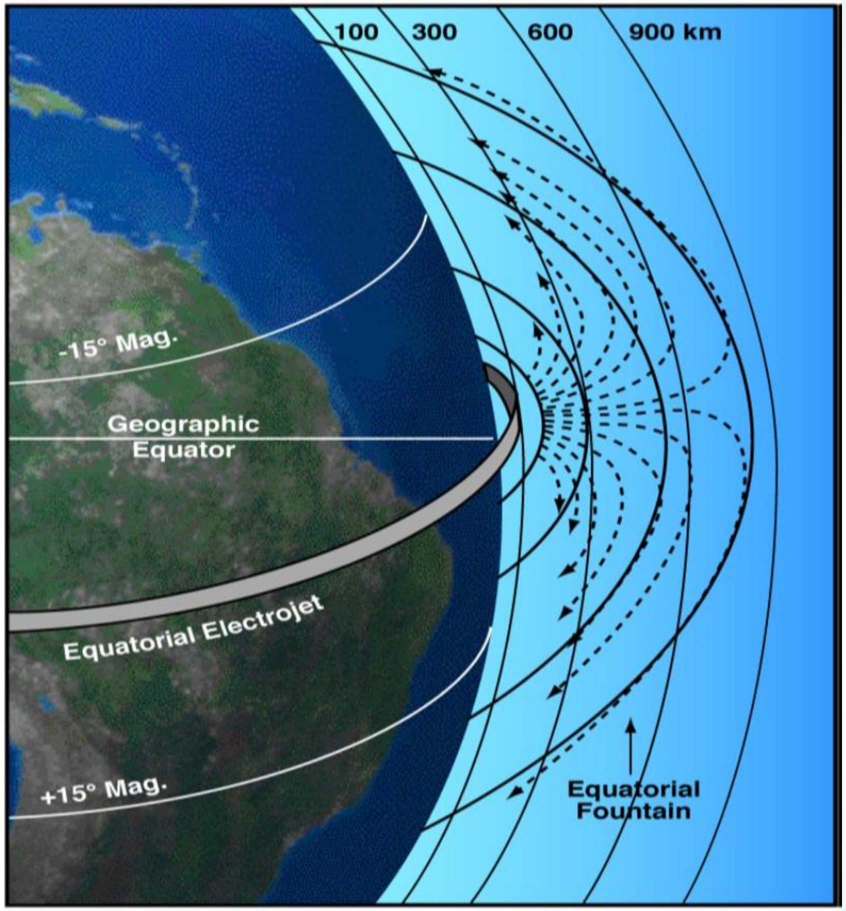

Fig.2: A representation of the EIA with arrows showing the fountain effect (After Radicella 2013).

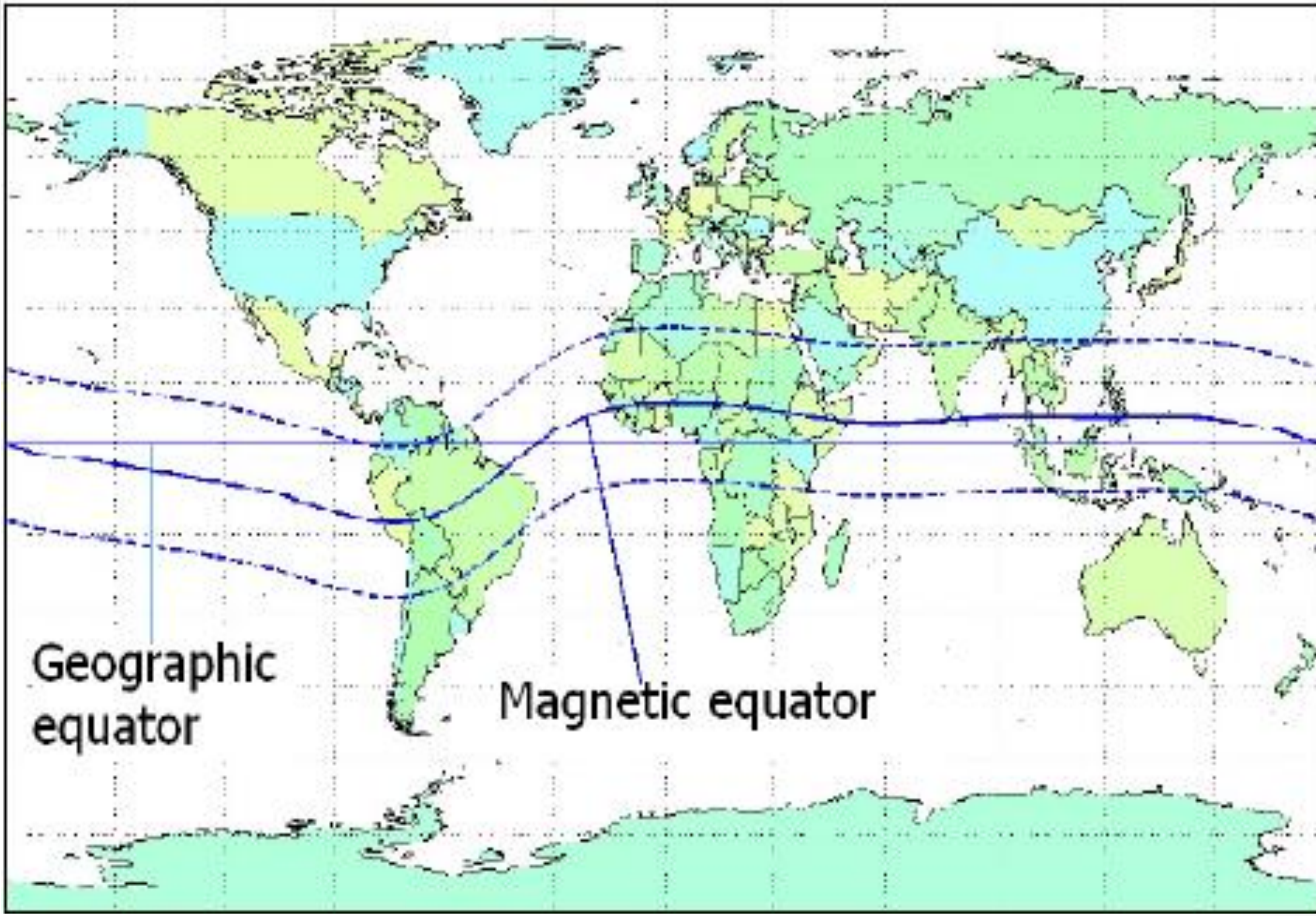

Fig. 3 : The map showing the equatorial anomaly region

(Called from Rabiu 2011 presentation) MAGDAS school Litho-Space Weather Redeemers University Lagos.

THE NEED TO STUDY CHAOS AND DYNAMICAL IN THE IONOSPHERE

- The need to characterize the ionosphere using various techniques.

- Characterizing the ionosphere is of utmost interests due to numerous complexities associated with the region (Rabiu et.al., 2007)

THE NEED

- Many factors responsible for these complexities include:
  - Local time variation of the neutral winds, ionization processes, production-recombination rates, photoionization processes; particle precipitation; plasma diffusion; gravity waves; other electro-dynamic processes etc (Unnikrishnan 2010; Ogunsua et al, 2014).

CHAOS AND CHAOTICITY QUANTIFIERS

- Chaos is an aperiodic long-term behaviour in a deterministic system that exhibits sensitive dependence on initial conditions.

- Chaos is the irregular behaviour of dynamical systems arising from a strictly deterministic time evolution without any source of external stochasticity but with sensitivity to initial conditions.

- Chaos can be quantified using the following:

  i. *Lyapunov Exponent*

  ii. *Correlation Dimension*

  iii. *Entropy measures*

  iv. *Implementation of Surrogate Data Test*

DYNAMICAL COMPLEXITY

- Too complex to define
- Dynamical complexity is the great number of possible interconnections between parts of an evolving system
- Can be seen as a measure of evolving static complexity
- Use of Information Theory and entropy measures
- Entropy measures includes: Tsallis entropy, Shannon entropy, Renyi entropy, Hurst exponents etc.

EXISITENCE OF CHAOS IN THE IONOSPHERE

- Existence of low dimension chaos in ionospheric density fluctuation by Bhattacharyya (1990), using amplitude and phase scintillation data. Wernik and Yeh(1994) obtained similar result using scintillation data and numerical modeling of scintillation at high latitude

- Existence of low dimensional chaos was reported in a set of TEC data obtained by Faraday Rotation Technique measured at a high latitude station; (Kumar et al.,2004)

- The presence of chaos was reported from the study of GPS TEC fluctuations at mid latitude (Unnikrishan et al., 2006). After which he got similar result for the equatorial region in 2010. Similarly Ogunsua et al., (2014)

- Balasis et al., (2008; 2009) worked on the dynamical complexity of the magnetosphere using Tsallis entropy and other entropy measures.

SEMIANNUAL VARIATION IN THE UPPER ATMOSPHERE

- The existence of semiannual variation in upper atmosphere has been described by various scientists.
- Earlier suggested by Russell and Mc-Pherron, 1973 are a result of the semi annual variation of the southward component of the solar wind magnetic field an phenomenon now referred to as Russell Mc-Pherron Effect.

- Rabiu 2004 revealed Semiannual variation of Geomagnetic activity Ak Index and its response to solar activity
- Yamazaki and Yumoto (2012) also found that the Sq Current system also undergoes semiannual Variations Keeping its two-vortex pattern.

- Cliver et al. (2002) and Savagard (2002) pointed out that the semiannual variations could be as a result of the equinoctical hypothesis.

- In this work, the study of variation of chaoticity combined with the dynamical complexity using Tsallis entropy has been employed to reveal the semiannual variations in the ionosphere.

DATA
And
METHODOLOGY

DATA

- Receiver Independent Exchange(RINEX) format files were obtained from two stations selected from the network of augmented GPS Satellite System receiver stations as shown in table 1.

- RINEX files are unreadable data format which were converted to readable format to obtain the total electron content (TEC) data.

- TEC (Measured in TECU) is a measure of total number of free electrons in a column of a unit cross-sectional area along the path of the electromagnetic wave between the satellite and the receiver. The STEC was determined.

$$TEC = \int_{rec}^{sat} n_e(l)\,dl \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

- Where $n_e(l)$ is the variable electron density along the signal path from the satellite to the receiver (Misra and Enge, 2012).

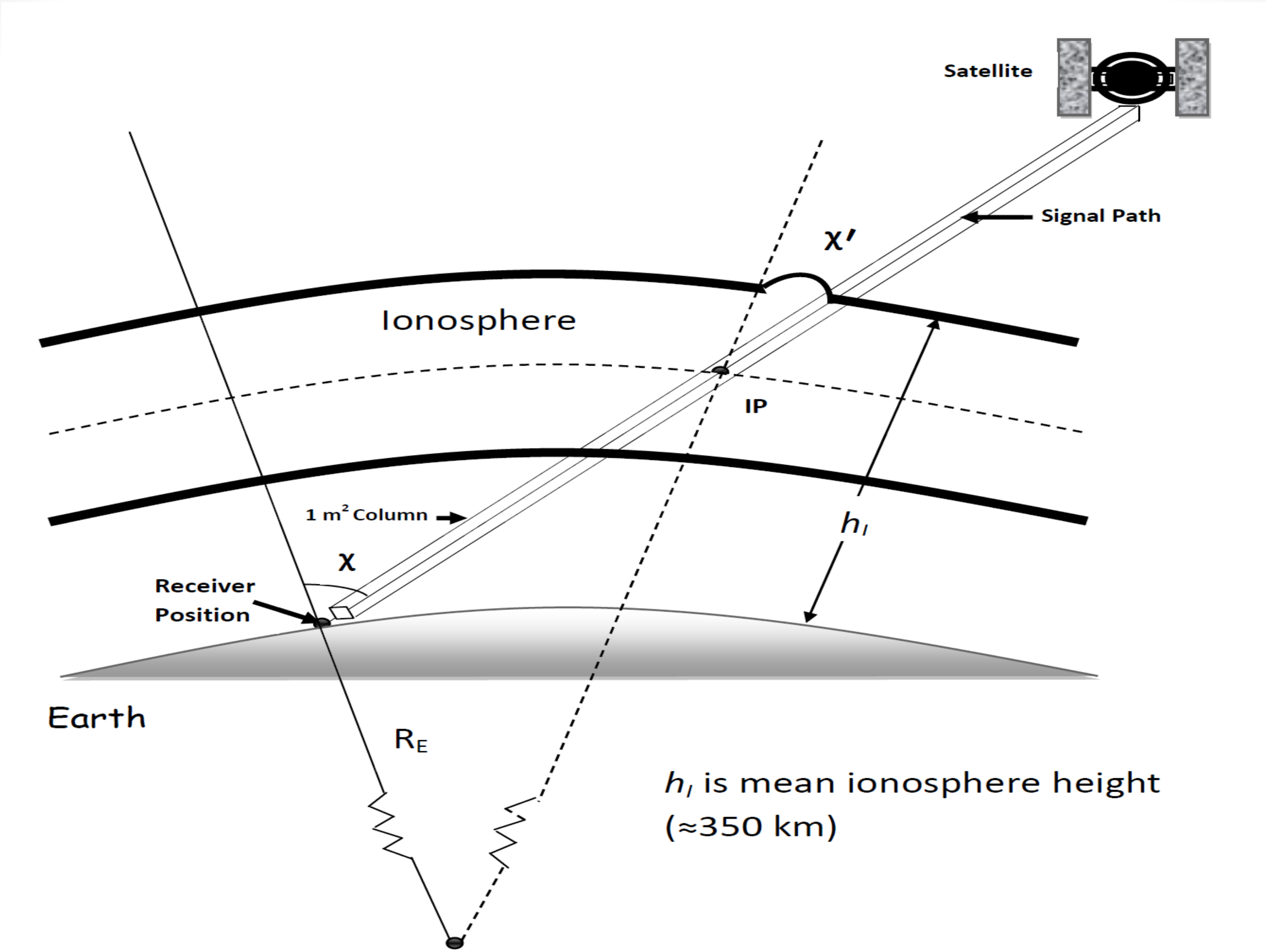

Fig.4: A Schematic representation of the GPS TEC measuring system signal path, from the path of the satellite to the receiver.

Table 1 List of selected stations and their coordinates

Station Name	Station Code	Latitude	Longitude	Dip Latitudes
Addis Ababa	adis	9^{o} 27’N	38^{o} 44’E	3.62˚N
Enugu	unec	6^{o} 26’N	7^{o} 30’E	-3.21˚N

METHODOLOGY

- The vertical Total Electron Content (VTEC) is obtained from STEC using the thin shell model assuming the height of 350km

where ;

$$VTEC = STEC \times \cos[\arcsin(R_e \cos\theta / R_e + h_{\max})] ......(2)$$

$\boldsymbol{R_e} = 6378\boldsymbol{km},\ \boldsymbol{h}_{\max} = 350\boldsymbol{km},$

$\boldsymbol{\theta} =$ Elevation angle at the ground station

Data analysis

Time series and phase space

- The TEC time series data were plotted to study the dynamics an Example is shown in fig 1.

- To reduce the influence of the diurnal variations of data , epoch data analysis were carried out as follows.

Time series and Phase space

- The diurnal variation reduced time series is given by

$$T_i = t_i - a_j \text{..} (3)$$

- t_i is the observed time series
- a_j represents the diurnal variation
- Where $i = 1,2,3........$

$$\boldsymbol{J} = \mathrm{mod}(\boldsymbol{i},1440), \boldsymbol{if}\ \mathrm{mod}(\boldsymbol{j},1440) \neq 0$$

$$\boldsymbol{J} = 1440, \qquad \boldsymbol{if}\ \mathrm{mod}(\boldsymbol{j},1440) = 0$$

- This method gives the detrended time series T_i of the TEC data.
- Fig. 2 shows the detrended time series

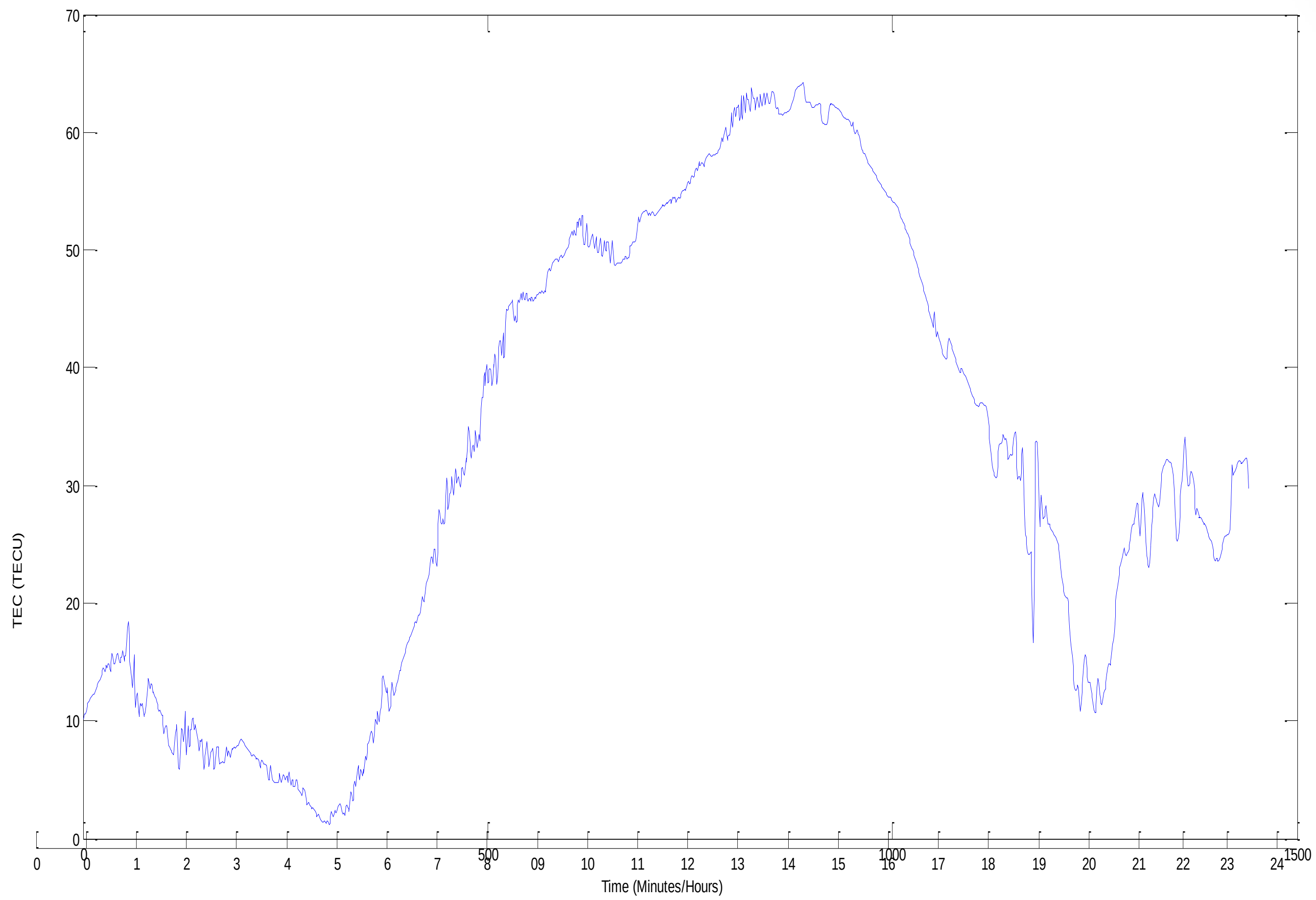

Fig.6 : A typical TEC time series plot for TEC taken from UNILAG station

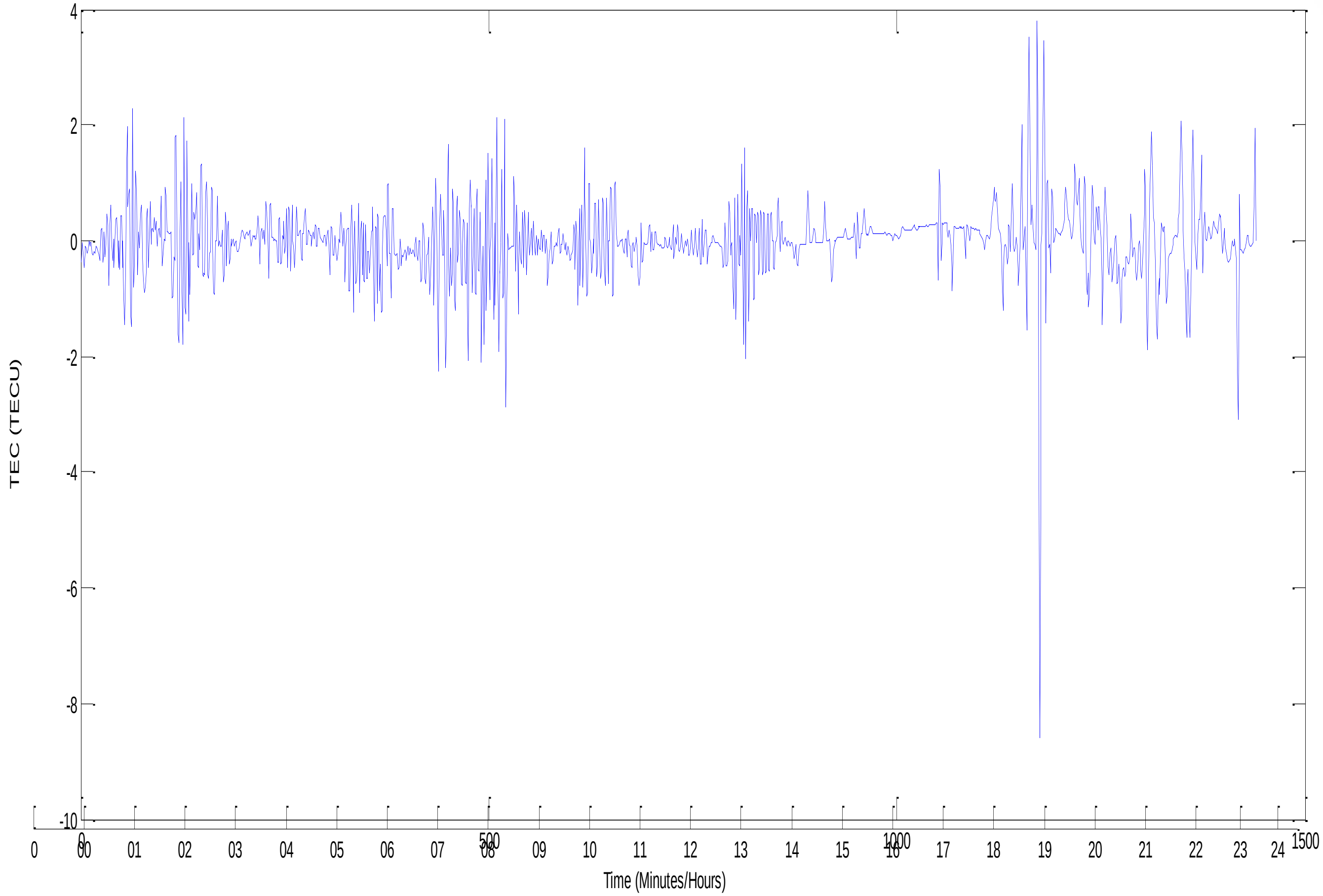

Fig. 7: Detrended TEC time series plot obtained from the TEC shown in fig. 1.

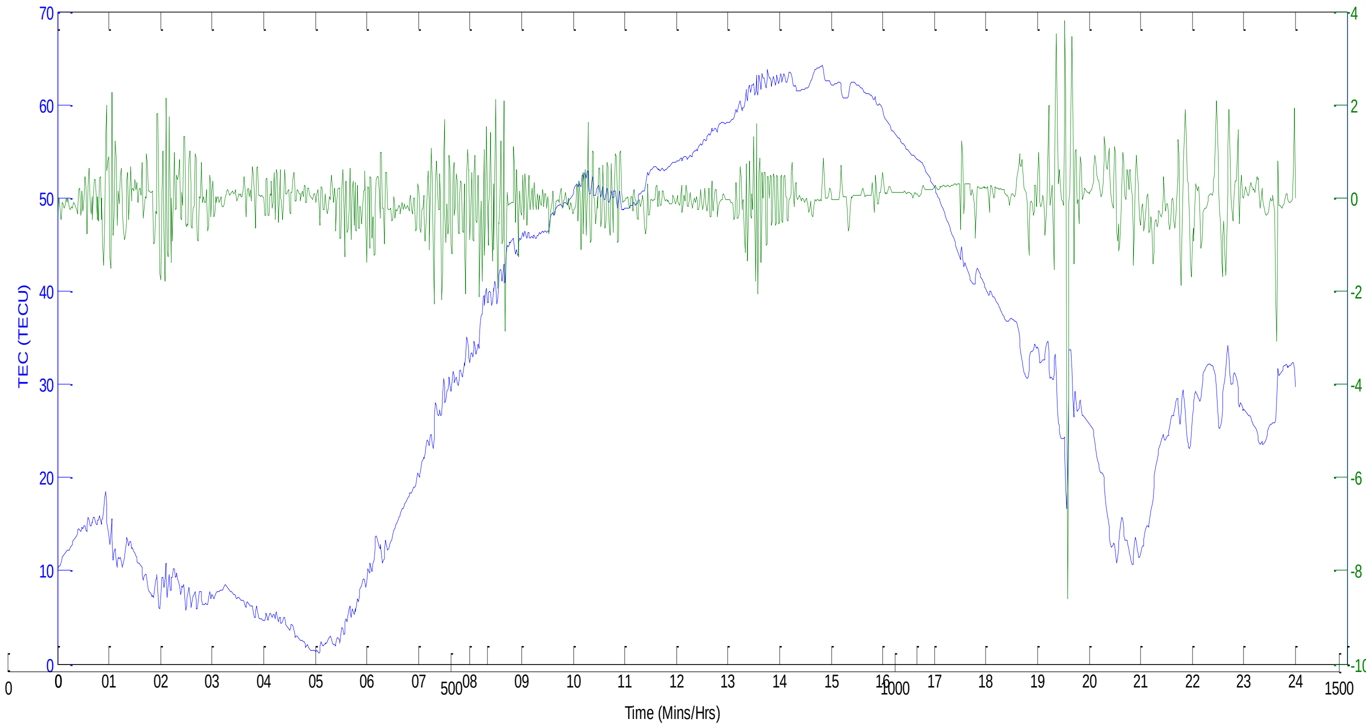

Fig. 8: Original and detrended TEC time series plot obtained from t he TEC shown .

DATA ANALYSIS

- The detrending filter will transfer the non linear TEC variabilities/fluctuations by minimizing diurnal variations

- Detrended TEC from various stations were subjected to analysis to obtain the following :
    1. Mutual information
    2. False nearest neighbours
    3. Delay coordinates and Embedding Dimension
    4. Lyapunov Exponents
    5. Correlation Dimension
    6. Tsallis Entropy

Phase Space Reconstruction

- Time delay (τ) is essential (Fraser and Swinney, 1986; Kennel et al, 1992)
- Corresponding time delay to Minimum mutual information value can be considered as reasonable time delay.
- Likewise, the minimal embedding dimension, which corresponds to the minimum number of false nearest neighbours can be found out and treated as the optimum value of m.
- Based on embedding theorem, a multidimensional state space will be reconstructed as follows:

$$Y_n = (S_{n-(m-1)\tau}, S_{n-(m-2)\tau}, \ldots, S_{n-\tau}, S_n) \ldots\ldots(4)$$

where Yn are vectors.

- The reconstructed phase space of the detrended TEC time series showing the trajectory of the dynamical system (fig11) .

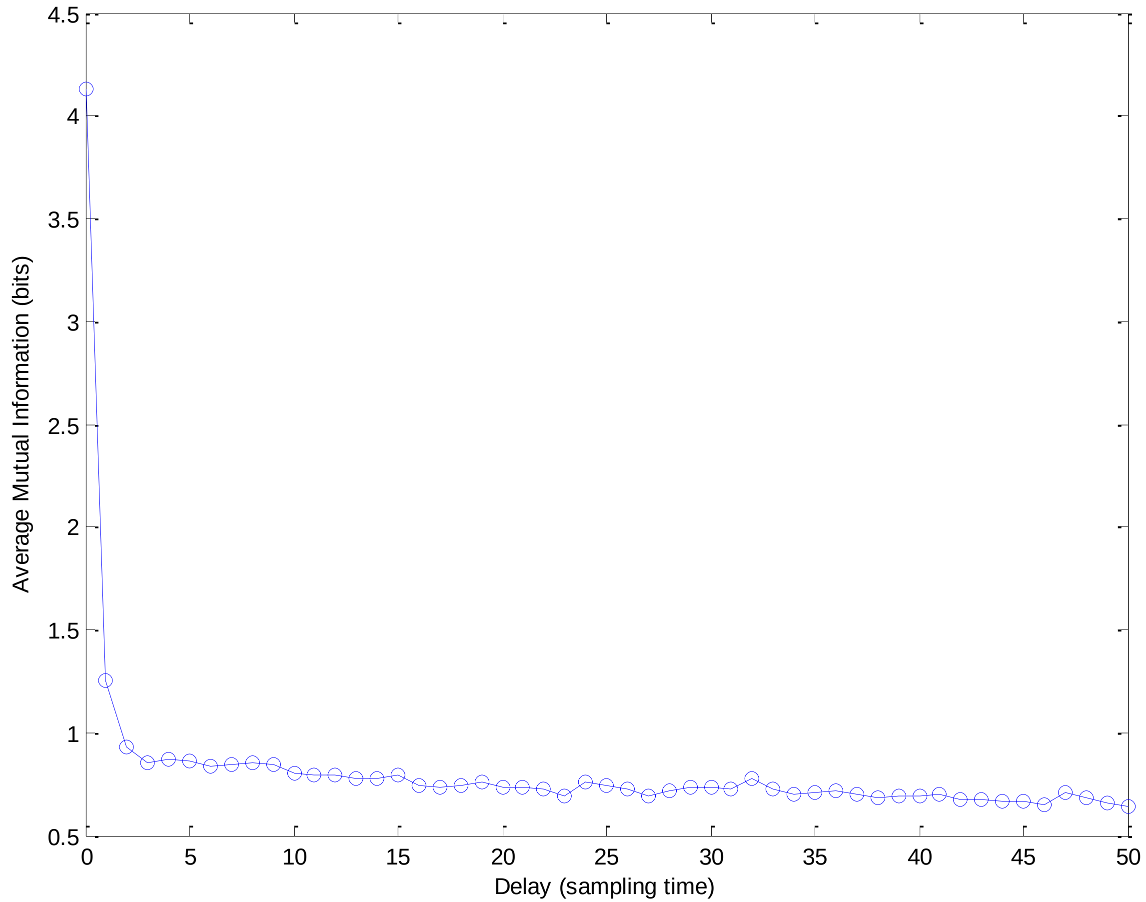

Fig. 9: Average Mutual information against time delay

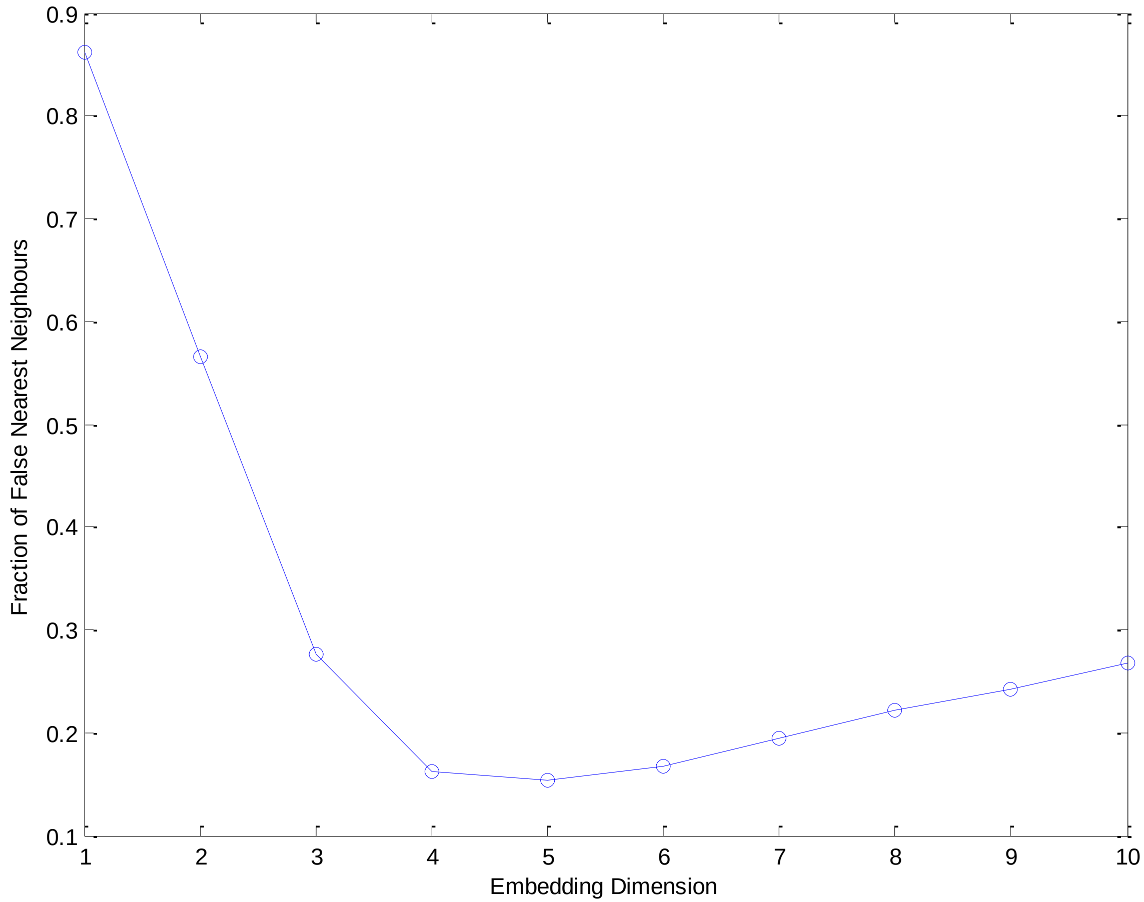

Fig. 10: Fraction of False nearest neighbours against Embedding Dimension

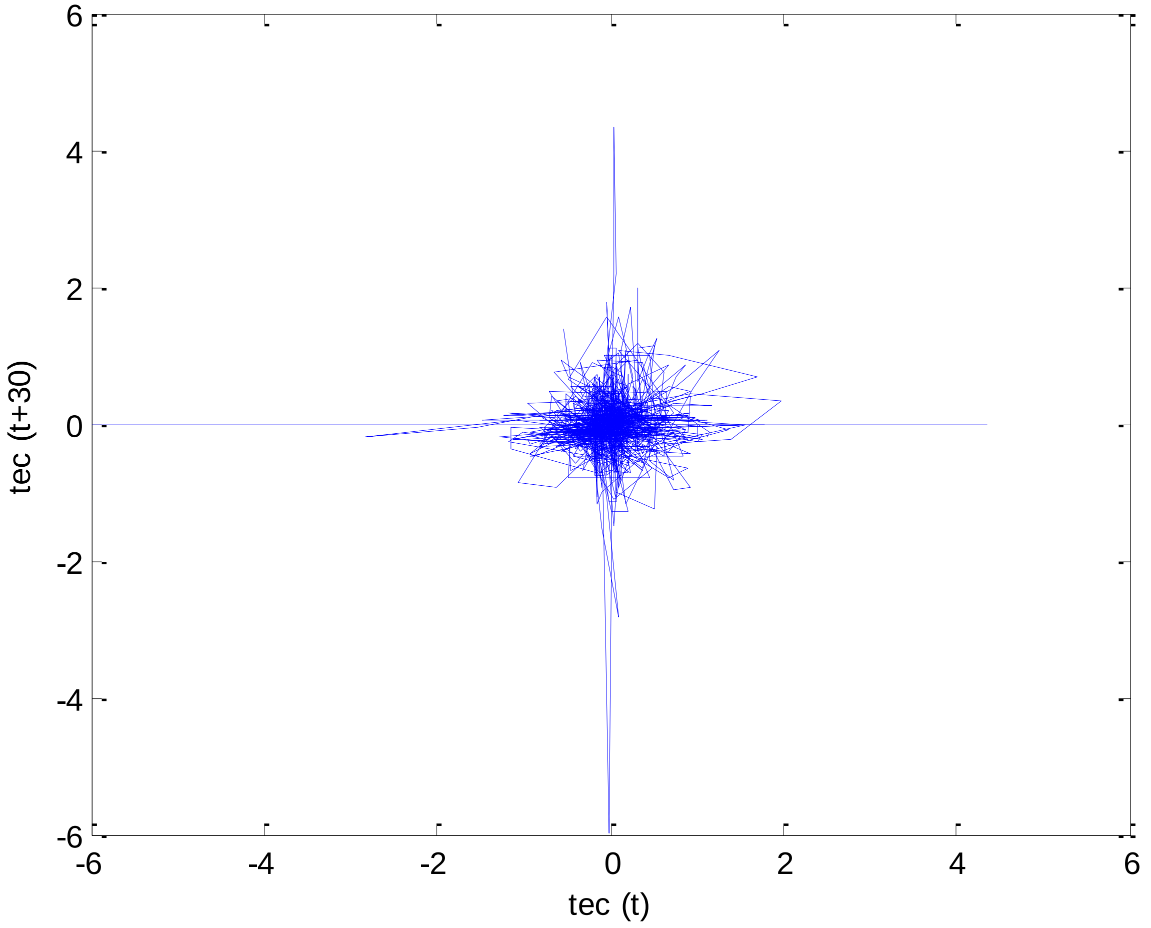

Fig. 11 : The Phase space Trajectory for the detrended TEC measured at Lagos.

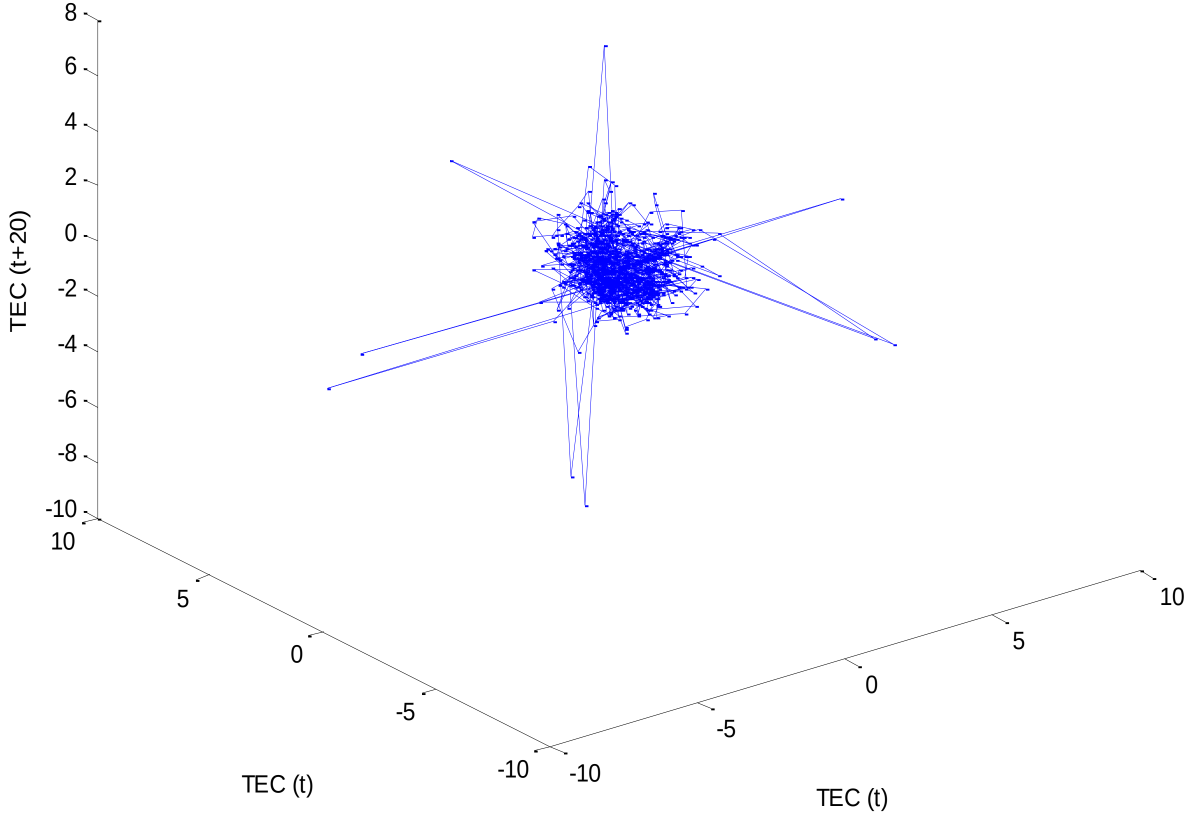

Fig. 12 Plot of delay representation for the detrended time series of TEC in three dimension with m=4 and tau = 30 fig

LYAPUNOV EXPONENT

- One of the most prominent evidences of chaotic behaviour of a dissipative deterministic system is <u>the existence of a positive Lyapunov exponent.</u>

- The average rate of divergence can be estimated by the first Lyapunov Exponent ($\lambda 1$) (Wolf et al 1984, Roseintein et al 1993)

$$\lambda_1 \equiv \lim_{r \to \infty} \frac{1}{t} \ln\left(\frac{\Delta x(t)}{\Delta x(0)}\right)$$

$$= \lim_{r \to \infty} \frac{1}{t} \sum_{i=1}^{l} \ln\left(\frac{\Delta x(t_i)}{\Delta x(t_i - 1)}\right) \ldots\ldots\ldots (5)$$

- Lyapunov exponent for TEC time series measured at the chosen stations were computed for the entire year using the method above and observations were also made for both five most quiet and five most disturbed days of each month using the IQD and IDD data from Geoscience Australia.

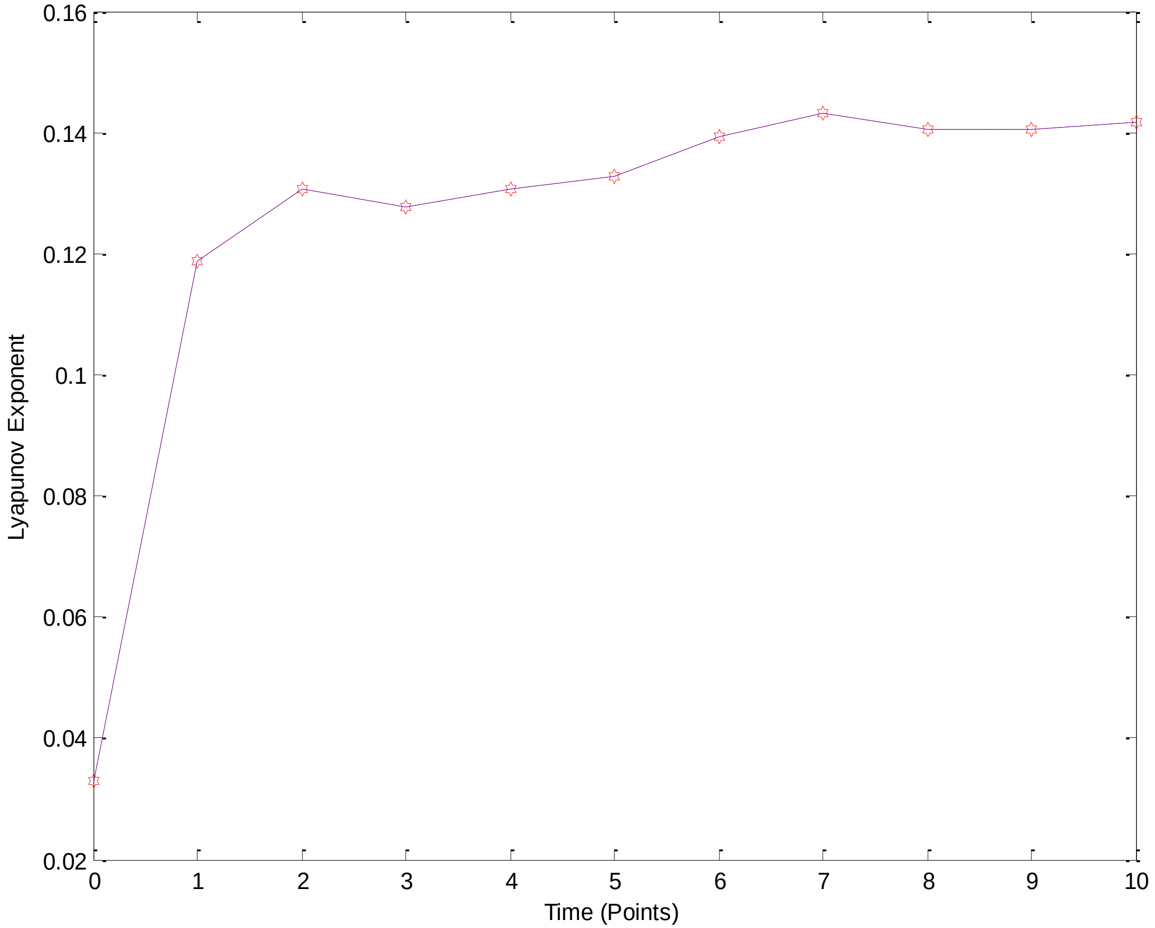

Fig. 13 Lyapunov Exponent computed and its evolution, computed as the state space trajectory scanned with tau=30, m=5 for detrended time series measured at Lagos with Largest Lyapunov Exponent equal to 0.1432

CORRELATION DIMENSION

- Another significant quantifier to be used in this study is the Correlation Dimension, D defined as;

$$D = \lim_{r \to o} \frac{\ln C(r)}{\ln(r)} \text{................}(6)$$

- Where $C(r)$ is the Correlation sum for radius r, where $C(r) \sim r^d$ for $r \to 0$.
- This method will be used to compute the correlation dimension for the detrended TEC time series.
- From Grassberger and Procaccta, 1983.

Correlation Dimension

- The correlation sum $C(r)$ is given as;

$$C(r) = \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} \Theta(r - \|y_i - y_j\|) \text{........}(7)$$

- Where Θ is the Heaviside step function, with $\Theta(H) = 0$ if $H \leq 0$ and $\Theta(H) = 1$ for $H > 0$

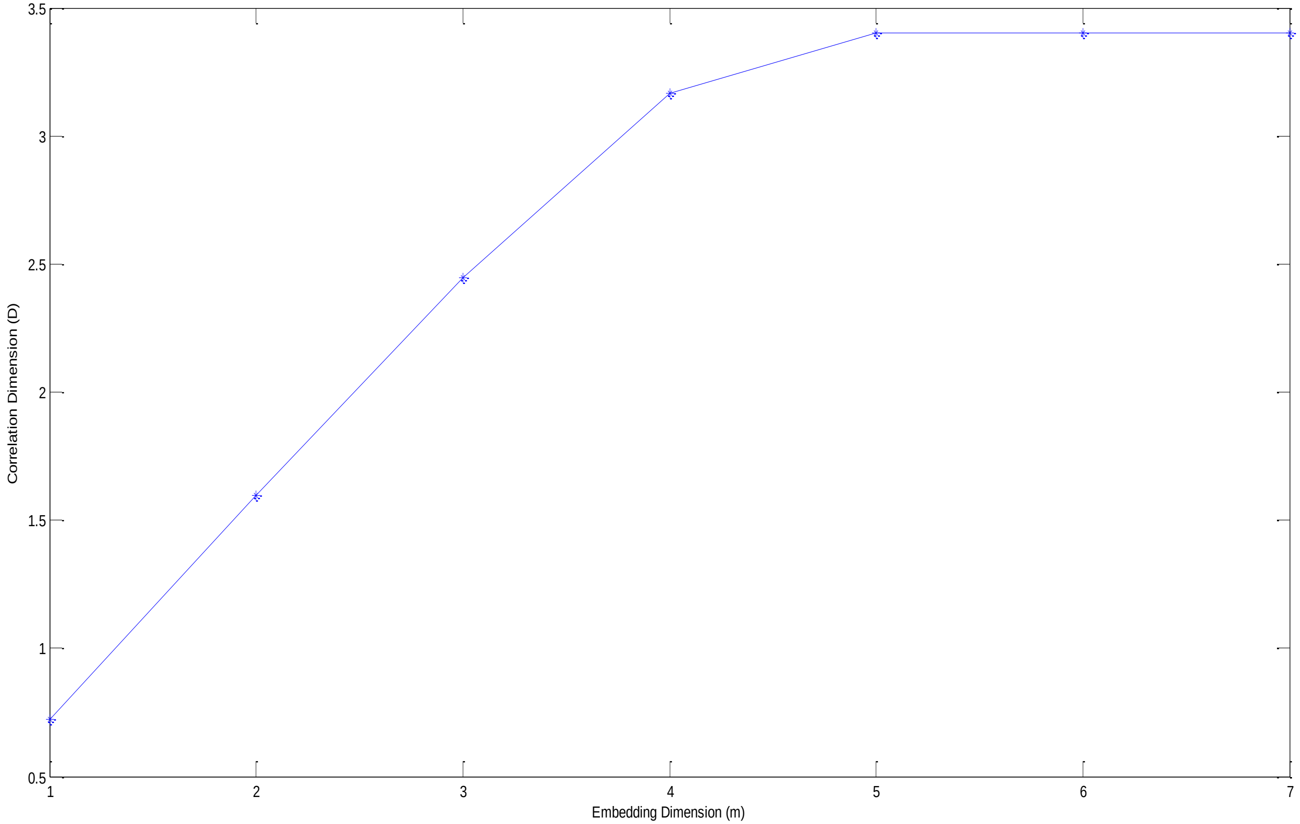

Fig. 27a: Correlation dimension for the quietest day of October 2011 for TEC measure at Lagos which saturates at $\tau = 35$ and $m \geq 5$.

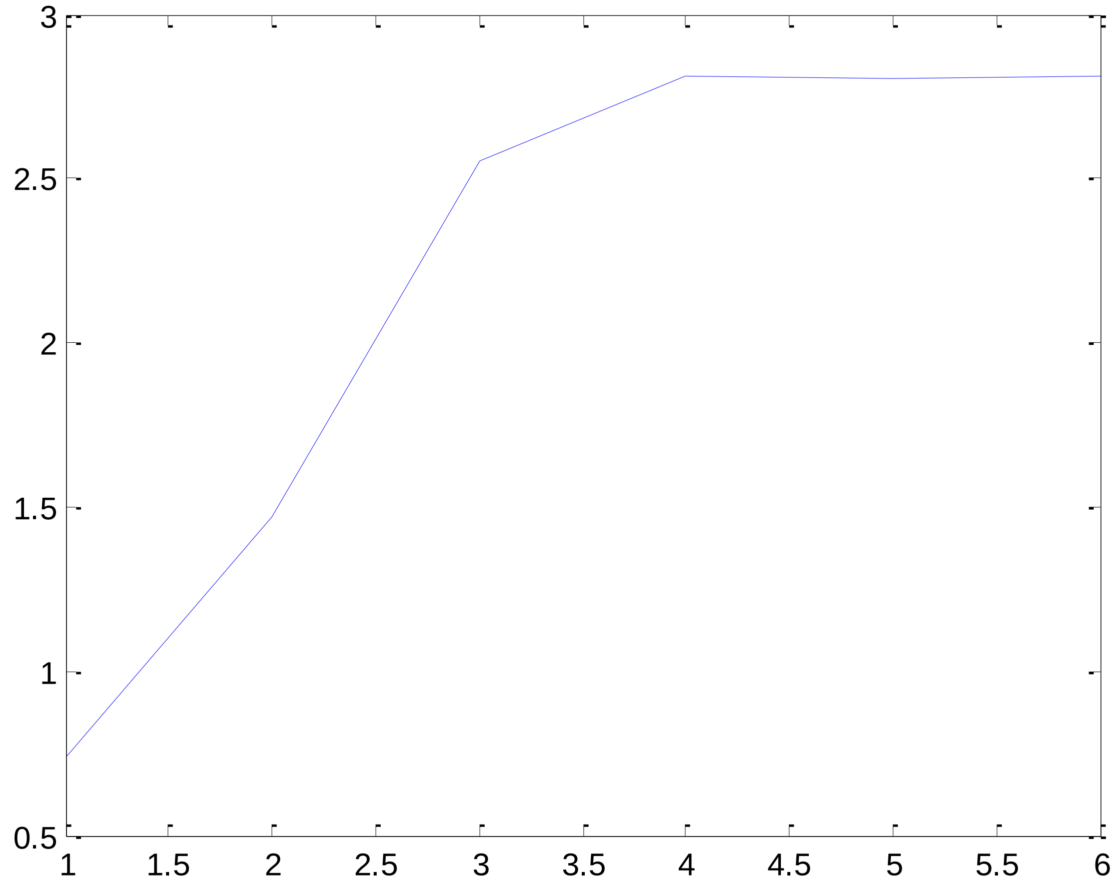

Fig. 27b.: Correlation dimension for the most disturbed day of October 2011 for TEC measure at Lagos which saturates at $\tau = 30$ and $m \geq 4$

Tsallis Entropy

- Tsallis entropy is an entropy measure from Non extensive Statistical mechanics introduced by Tsallis (1988)

- It can be used to study determinism in dynamical system

$$S_q = k\frac{1}{q-1}(1-\sum_{i=1}^{w} p_i^q)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

- Where p_i are probabilities, associated with the microscopic configurations, W is their total number, K is Boltzmann's constant and q is a real number the determines extensivity. (Tsallis 1998 a; b, 1999; Balasis et al., 2008; 2009)

- $\boldsymbol{S_q}$. was computed for the entire year and observations were made for the five quietest and five most disturbed days of each month to understand the dynamical complexity of the ionosphere.

Implementation of Surrogate Data

- In this present study the improved algorithm of Schreiber and Schmitz(1996) will be used to generate surrogate data for each detrended TEC data.

- In this case the generated surrogate data is to mimic the original time series` in terms of the autocorrelation and probability density function.
- The geometrical and dynamical characteristics of the measured and surrogate data will be compared.

- The significance of difference (SD) of characteristic can be defined as:

$$S = \frac{\alpha - \alpha_{original}}{\sigma} \quad \text{.........................(8)}$$

- If the SD for all the quantifiers is greater than 2 the null hypothesis that the time series is a linear stochastic process can be rejected, a confidence greater than 95%.

Trend filtering

- ✓ The moving average trend filtering method was engaged for the smoothing of the Chaoticity and dynamical complexity data produced for the entire year to clearly show to trend pattern

- ✓ The simple moving average method has a limitation of truncating the data to zero for the first few values

- ✓ An improvement on the simple moving average method is the Savitzky-Goley method which is a generalized form of moving average that engages polynomial fitting of the values.

RESULTS

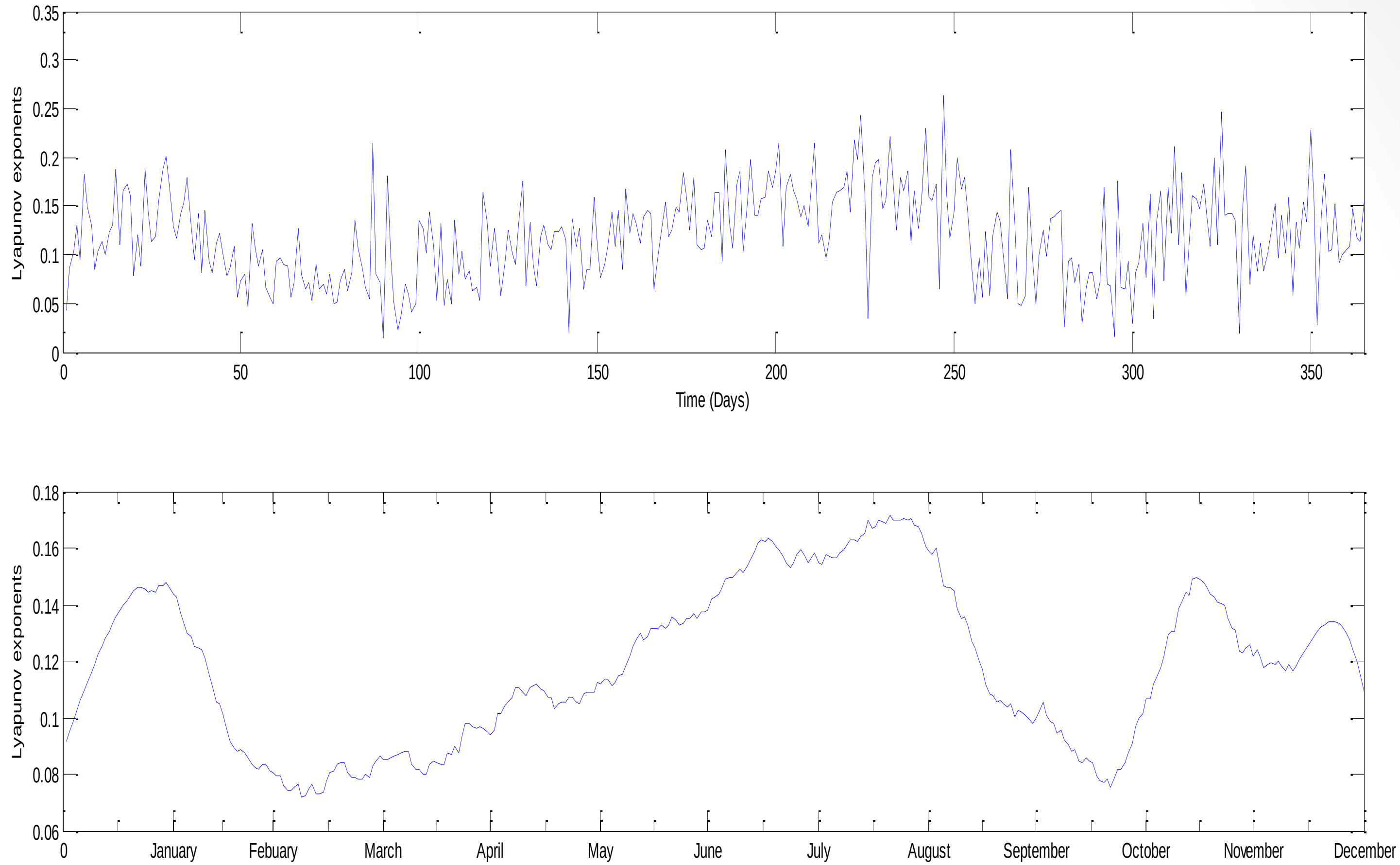

Fig. 16d: Plot of daily variation of Lyapunov exponents for TEC measured at the Enugu station for the year 2011 showing the Original data (Upper Panel) and the smoothed Plot of daily variation of Lyapunov exponents for TEC measured at the Enugu station for the year 2011 (Lower panel).

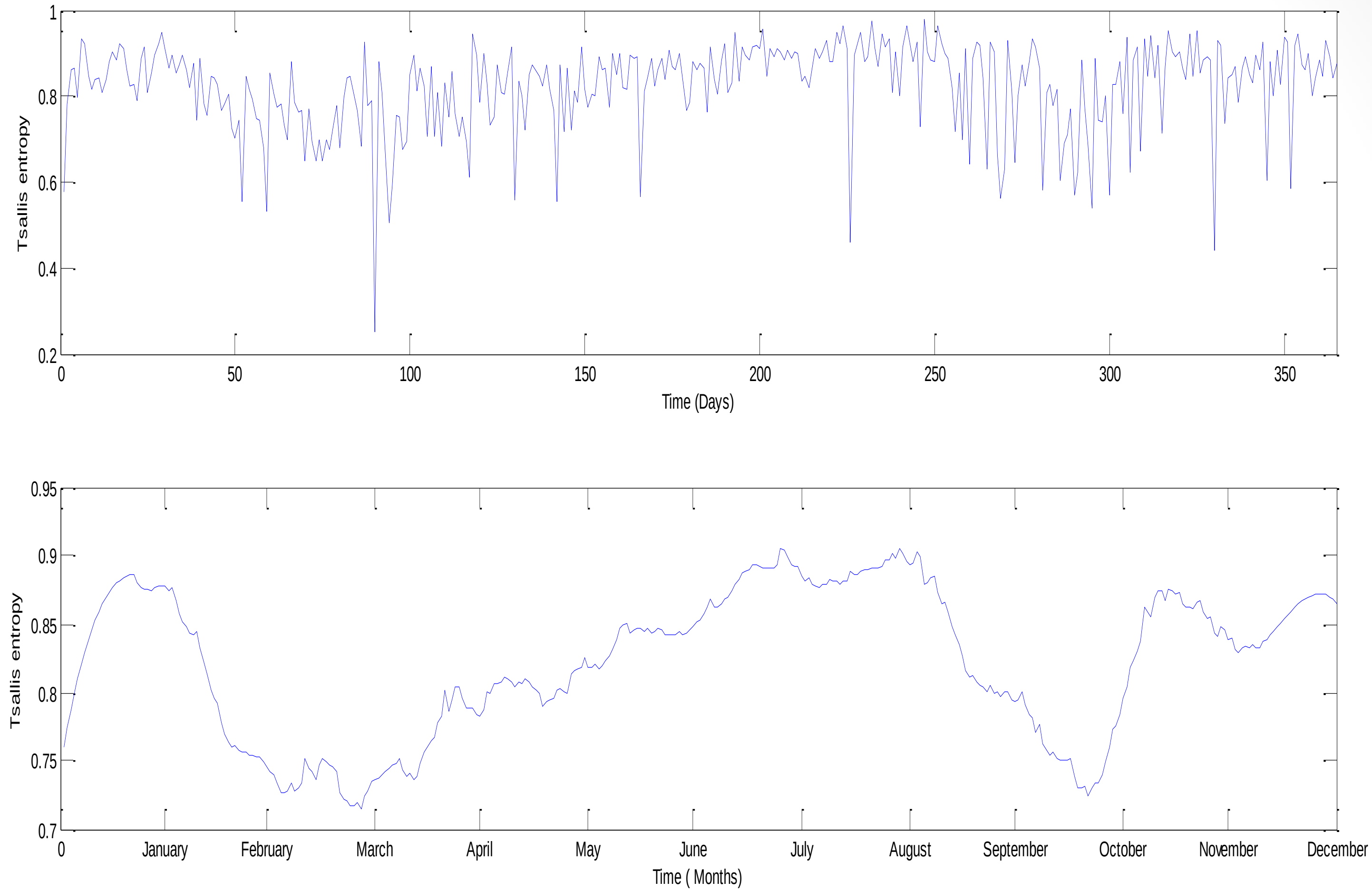

Fig. 17b: Plot of daily variation of Tsallis entropy for TEC measured at the Enugu station for the year 2011 showing the Original data (Upper Panel) and the smoothed Plot of daily variation of Lyapunov exponents for TEC measured at the Enugu station for the year 2011 (Lower panel).

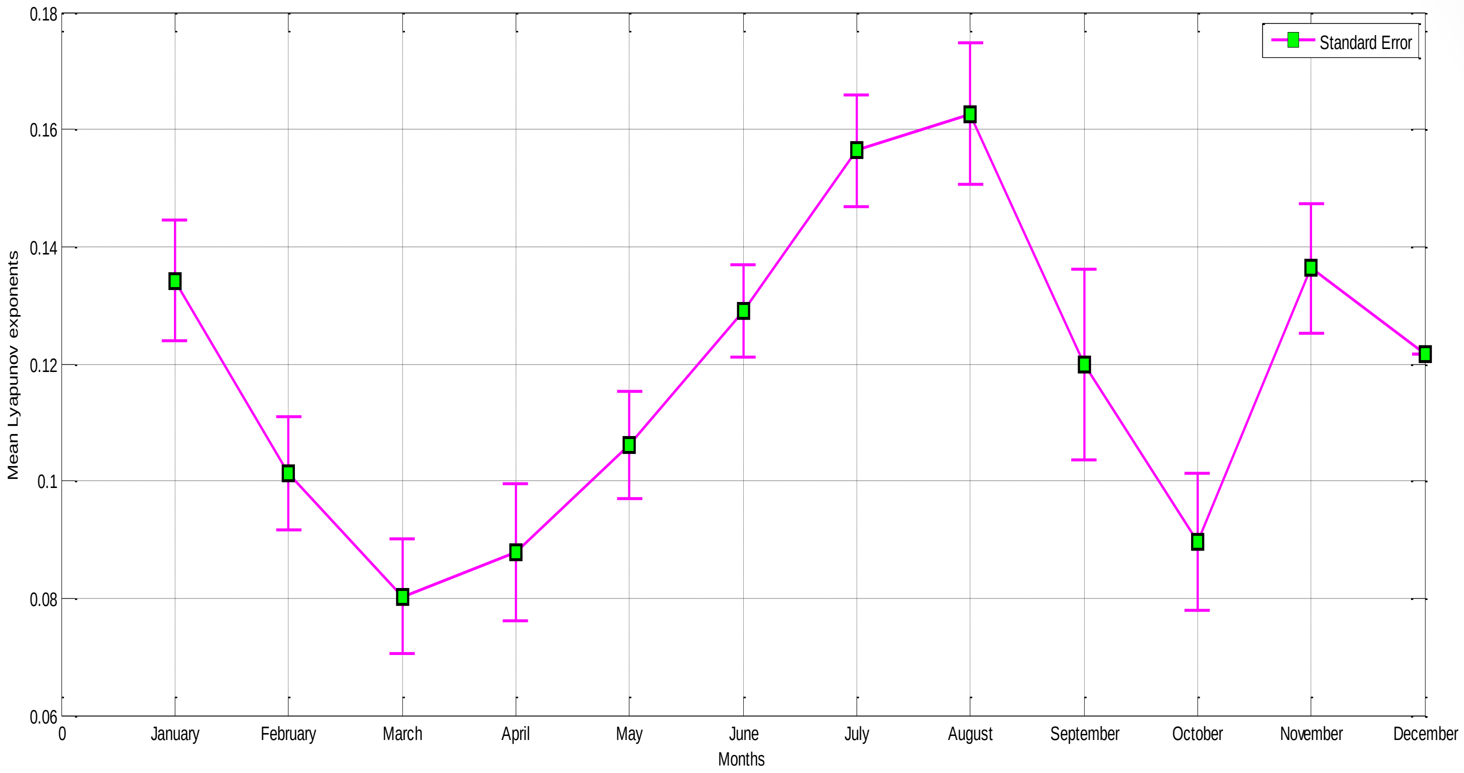

Fig . 20: The graph of monthly averages of the daily values of Lyapunov exponents with standard error for TEC measured at Enugu station for 2011.

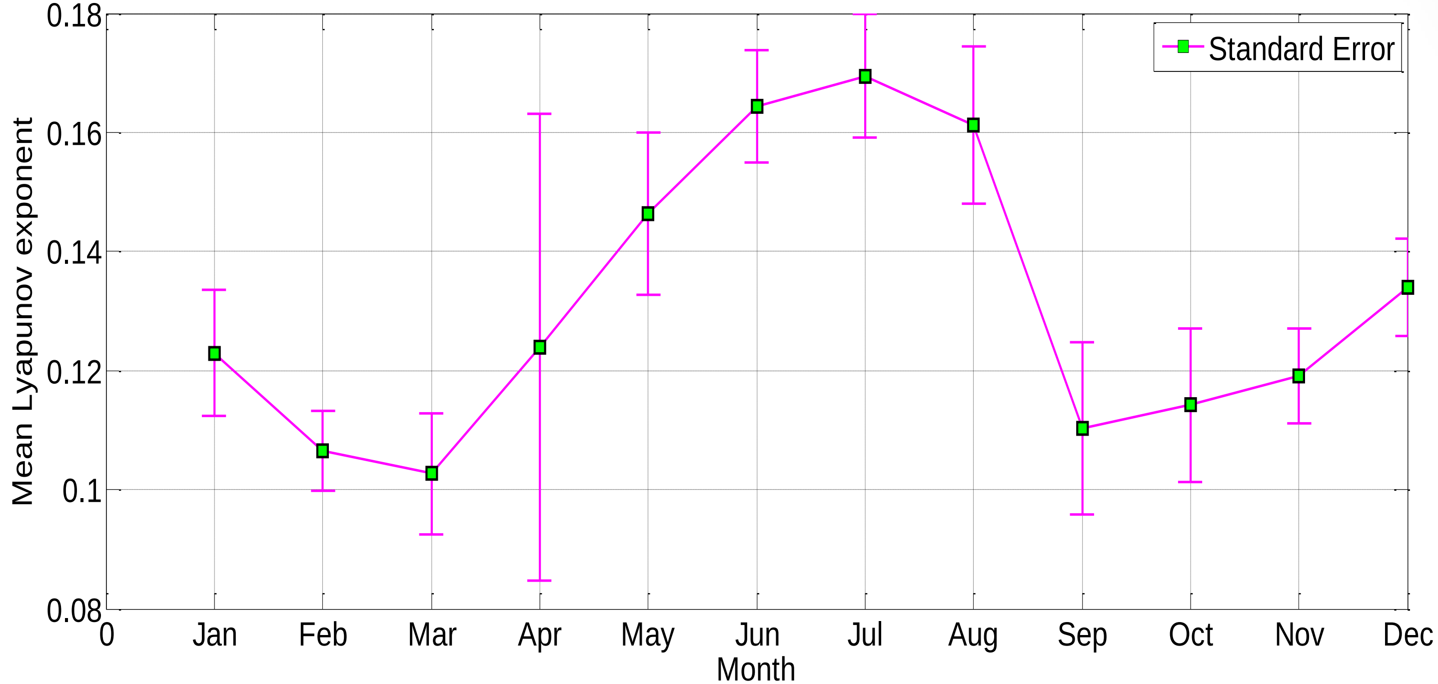

Fig . 20c: The graph of monthly averages of the daily values of Lyapunov exponents with standard error for TEC measured at Addis Ababba station for 2011

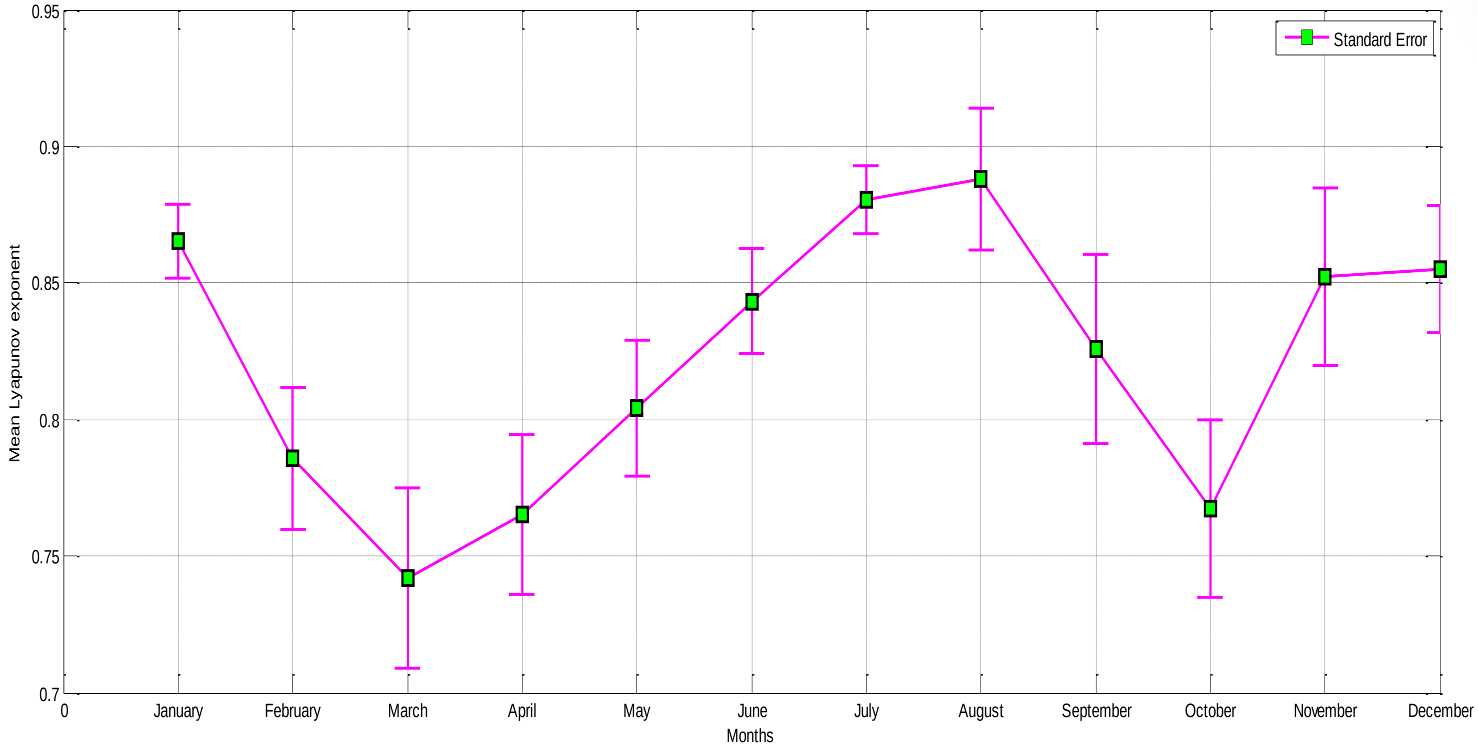

Fig. 21: The graph of monthly averages of the daily values of Tsallis entropy with standard error for TEC measured at Addis Ababa station for 2011.

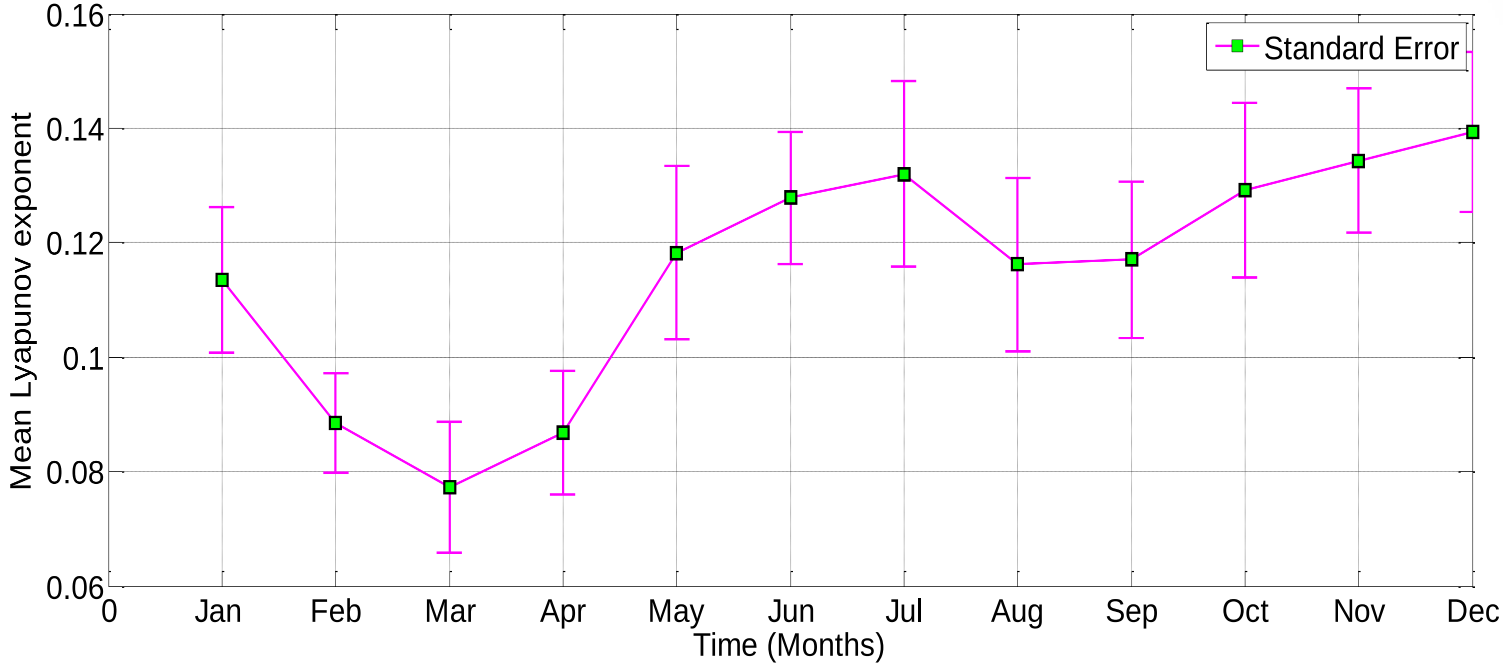

Fig . 20b: The graph of monthly averages of the daily values of Lyapunov exponents with standard error for TEC measured at Addis Ababa station for 2012

Results contd.

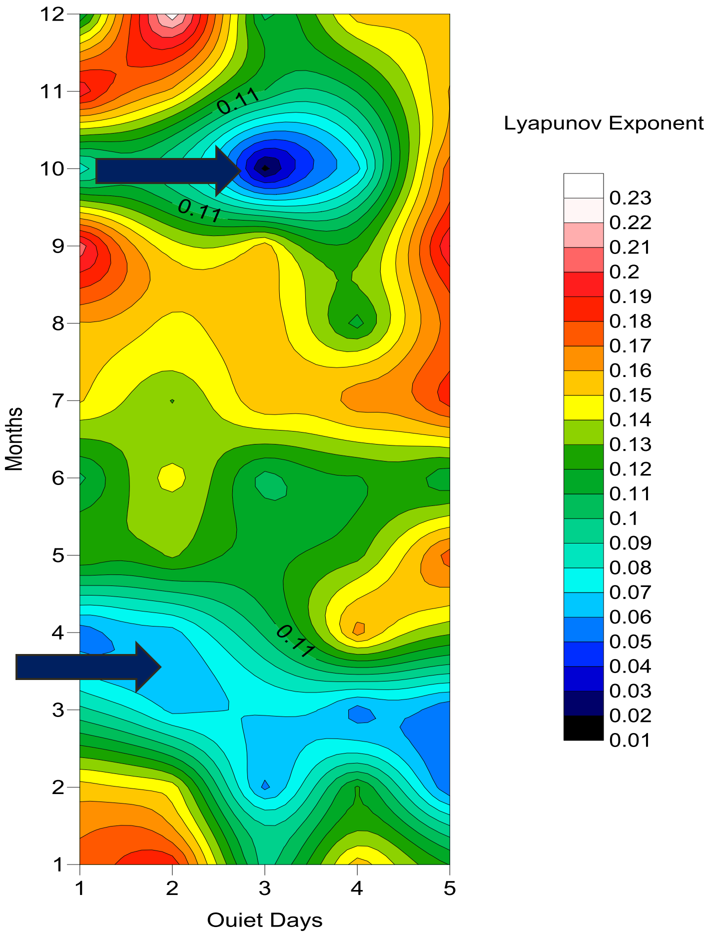

Fig.24a (i) Contour Plot of Lyapunov Exponent at Enugu station for quiet days of Enugu 2011

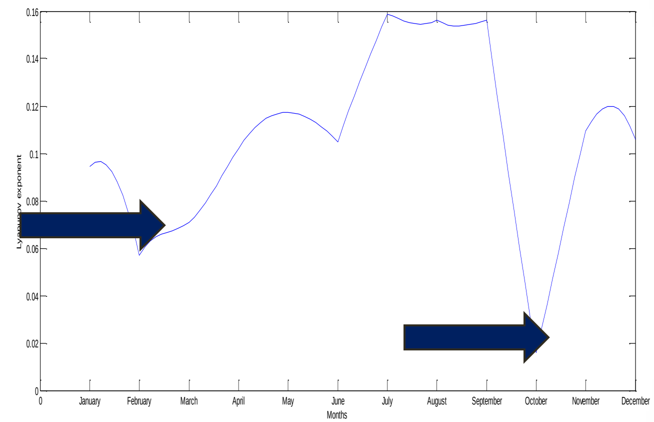

Fig. 24a (ii) A slice of Lyapunov exponent for quiet day 3 for the entire year

Results contd.

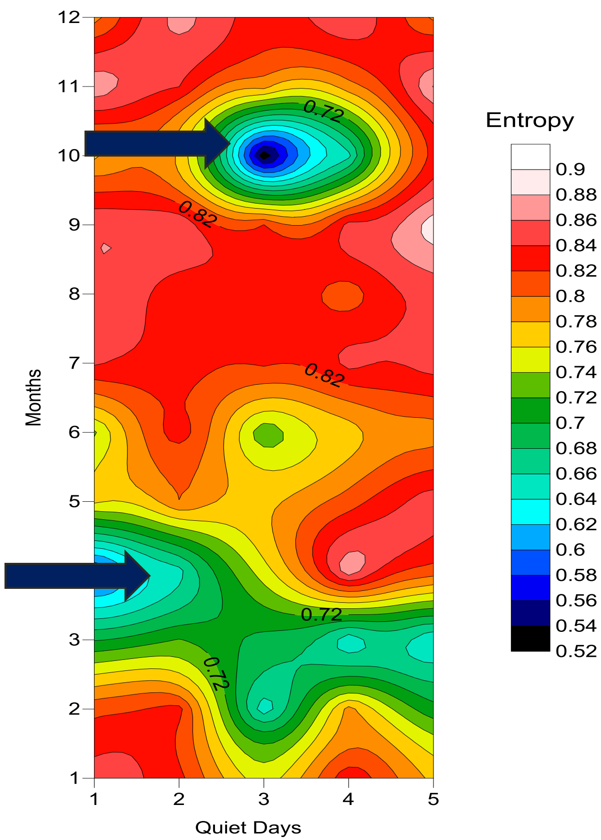

Fig.24b (i) Contour Plot of Tsallis entropy at Enugu station for quiet days of Enugu 2011

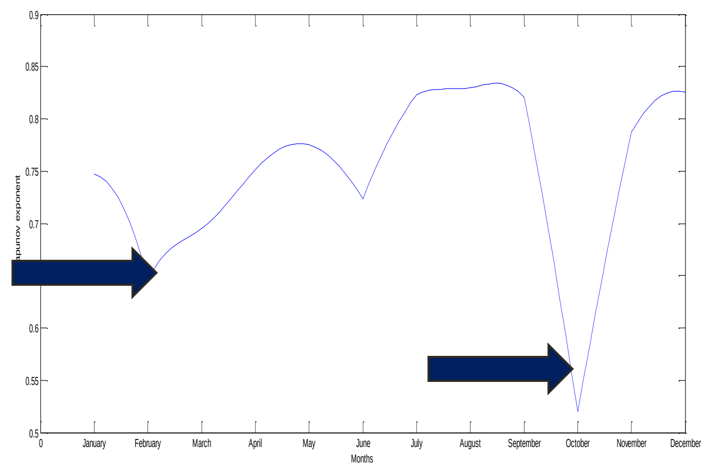

Fig. 24b (ii) A slice of Tsallis entropy for quiet day 3 for the entire year

Results and Discussion

- The phase space reconstruction for the stations shows a clustered trajectory which can also indicate chaos.

- The computations reveal positive values for largest Lyapunov exponent (LLE) all stations which gives the evidence of deterministic chaos.

- The values of correlation dimension computed ranges from 2.8 to 3.5 with the lowest values recorded at the storm period of October 2011.

- The surrogate data test shows a significance of difference greater than 2 for all the quantifiers with values of Lyapunov exponent at 0.1383 for original data and for surrogate 0.4091 $\pm$ 0.0684.

- Agrees with results from previous works that show that there is a reasonable presence of chaos in the ionosphere, (Bhattacharyya et al., 1990; Wernik and Yeh,1994, Kumar et al.,2004; Unnikrishnan et al., 2006; Unnikrishnan, 2010; Ogunsua et al., 2014).

Discussion Continues

- The lower dimension during the equinoxes compared to solstices may be due to the effect of a stochastic drivers like strong solar wind and solar flares.

- The internal dynamics must have been suppressed by the external influence, a phenomenon that might be responsible for low chaos during storm and during equinoxes. (Unnikrishnan 2010, Ogunsua et al., 2014)

- The day to day signifies a sporadic transient variation of chaoticity and dynamical complexity which may be due to both the external and internal influence.

Results And Discussion

- The day to day annual variation shows a reverse wavelike variation pattern for all stations with troughs at the equinoctical months.

- The reverse wave form can be likened to a semiannual variation as a result of various external influence as presented by Russel and McPherron (1973), Rabiu (1994) Cliver et al., (2001,2002) Svagaard et al., (2000, 2002), and Yamazaki and Yumotto (2012).

- Might be mainly due to equinoctical hypotheses. (Cliver et al., 2001, 2002; Lyatsky et al., 2001and Svagaard et al., 2000, 2002)

- This signifies a Phase transition from higher of chaoticity and dynamical complexity during the solstice months to lower values during the equinoxes.

CONCLUSION

- As a result this research work reveals that:
- There is a significant presence of chaos in the low latitude ionosphere with inconsistent daily values due to the inconsistencies of the internal dynamics of the ionosphere.
- There is an interplay between stochasticity and determinism
- There is a seasonal signature in the computed values of chaoticity and dynamical complexity
- The lower values for chaoticity and dynamical complexity of the ionosphere during equinoxes may be due to higher energy input during this periods.

Conclusion

- The higher influx of solar wind results in the modification of the ionospheric system as a result of the induced self reorganization phenomenon during storm and also at equinoxes.

- This self reorganization Phenomenon results in Phase transition from higher value of chaoticity during quiet period to lower value of chaoticity during storm

- The wavelike pattern is consistent and is a reverse form of semiannual variation
- Most likely due to equinoctical hypothesis

THANK YOU FOR LISTENING