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Climatology of Low Latitude Ionosphere : Under Varying Solar Flux During Solar Cycles 23 And 24

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Daytime Low latitude Ionosphere Understanding

Daytime Low latitude ionosphere is known to vary mainly under

(i) Solar flux (Production)
(ii) ExB drifts (Electrodynamics, Transport)
(iii) Meridional winds (Neutral-Ion Interaction)
(iv) Space Weather Events

<u>Not Well Understood</u> -

Large scale asymmetries

e.g.
(i) Latitudinal (Inter-hemispheric) and Longitudinal
(ii) Seasonal (Solstitial/Equinoctial)
(iv) QBO, Solar Cycle Scale and Higher Scales

<u>Not Well Understood</u> -

Short scale Variations

e.g.
(i) Day-to-Day Variations (During Quiet time)
(ii) Storm Time Response (Space weather)
(iii) Effect of waves and Tides (Lower atmospheric)

Quantitative Understanding is hampered due to

Issues with Observations -

? **Limitation of data length (Max. 4-6 years)**
? **Continuity of data from same instrument (Series of Satellites/Change of technology)**
? **Availability of instruments (Commercial availability of receivers)**
? **Sparse spatial resolution (A few groups working in India)**
? **Lack of other simultaneous measurements (like winds, fields, current)**

Issues with Modelling/Numerical Simulations -

? **Empirical models have not fared well over low latitudes**
? **First Principle models do not realistically represent the winds, longitudinal differences (SAMI2, PIM etc)**
? **General Circulation models require to be fine tuned for boundary conditions**

Representative parameter of ionospheric variations = TEC

Due to the fact that it is

1. **The end product of all the Ionospheric Dynamics / Electrodynamics and Structures (Due to Production, Loss and Transport)**
2. **So variations in TEC are resulted as per variation in Latitude, Longitude, Local Time, Season and Solar Activity.**
3. **Best parameter to study the equatorial and low latitude ionospheric variations with high spatial and temporal resolution.**
4. **Available at all time (With high time resolution) –GNSS satellites and radio range**
5. **At all places (Just need to put a GNSS receiver) – Cost Effective**
6. **Covering large range of Latitude-Longitudes (better spatial resolution)**
7. **Global Simultaneous Availability**

Also one shall note that TEC has customarily been studied to understand ionospheric electrodynamics till late 1980s. Hence the past knowledge can be effectively utilized to improve upon.

Global and Indian perspective of TEC Studies

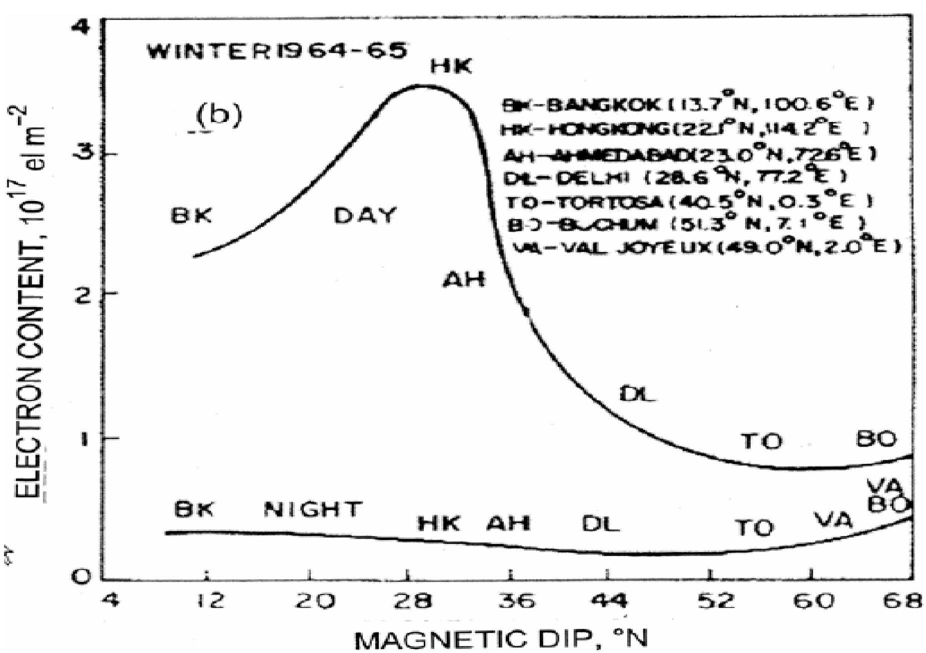
- **Russian Satellite - 1957**

  First determination of total electron content (TEC)of the ionosphere was made from signals radiated by the 'Majak' beacon on Sputnik I in 1957

- **USA Satellite – 1964**

  Explorer 22 (BE-B),Explorer 27 (BE-C) and INTASAT became available in 1964-65

- **Indian Studies**
  - **Satellite beacon studies in India began with signals from COSMOS V in early 1962**
  - **Physical presence of northern crest of the equatorial ionization anomaly was reported for the first time -**

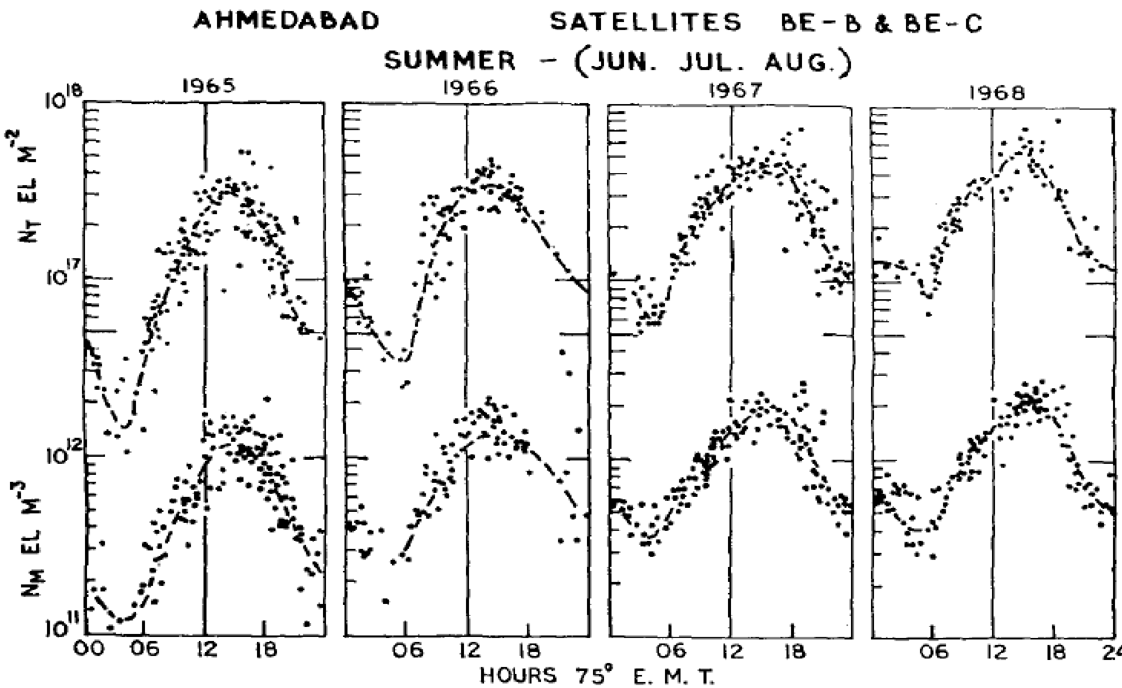


First Results using ionospheric TEC from India

Tyagi and Somayajulu, Radio Science, 1966

Global and Indian perspective of TEC Studies

India - 1964-1969 - solar cycle 20



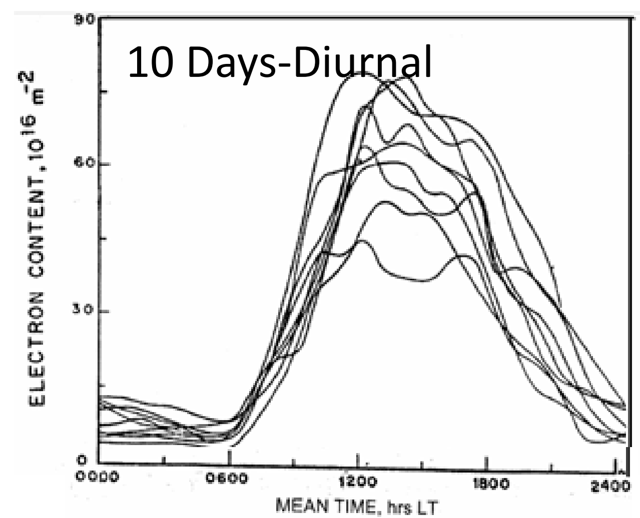
Tyagi and Somayajulu, Radio Science, 1966

Rastogi and Sharma., Planet. Space Sci. 1971

Mean Seasonal variation of diurnal cycle - 4 years

Intelsat -IIF2 (launched in 1967)

Basu et al., Ann. Geophysicae, 1975



Basu et al., Ann.Geophysicae,1975

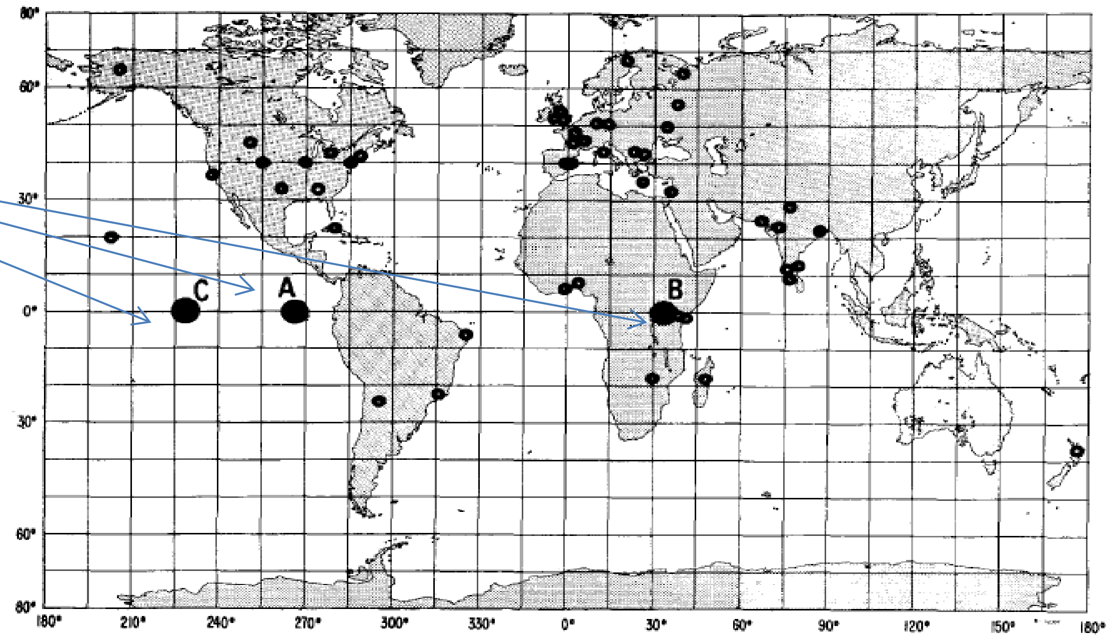
Global and Indian perspective of TEC Studies

The ATS-6 Radio Beacon Experiment - 1974-1979 - USA

- Coordinated measurements of TEC were made with availability of signals from the geo stationary satellite called ATS (application Technology Satellite)

Satellite locations

ATS-6 RADIO BEACON RECEIVER LOCATIONS



A, B and C are the three Satellite Locations

Review of TEC studies before 1979 was given by

Davies, K., Space Science Reviews, 1979.

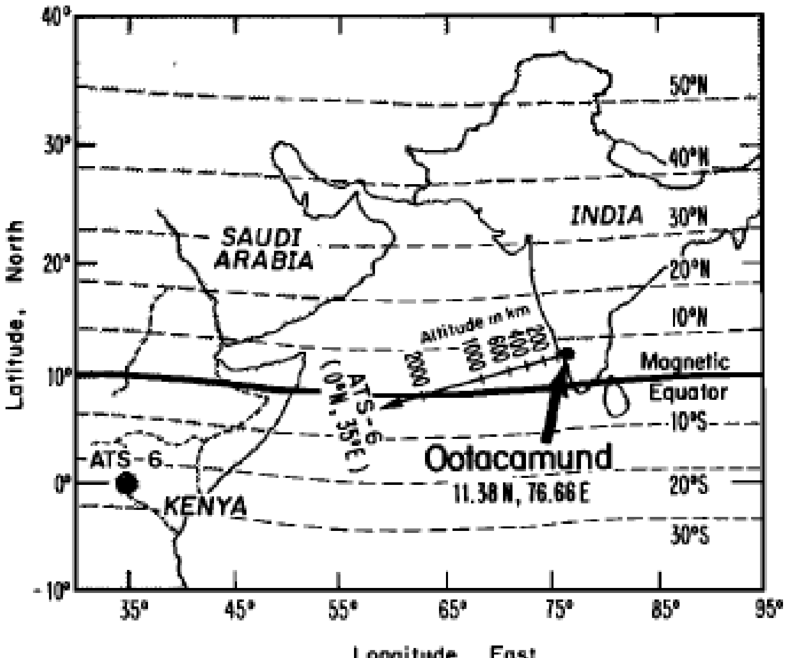
Operational Phase	**Time Interval**	**Location of satellites**
1	June 1974-May 1975	94°W
2	**Aug.1975-Aug.1976**	**35°E**
3	1976-June 1979	140°W

Indian Experiments and Studies – One year

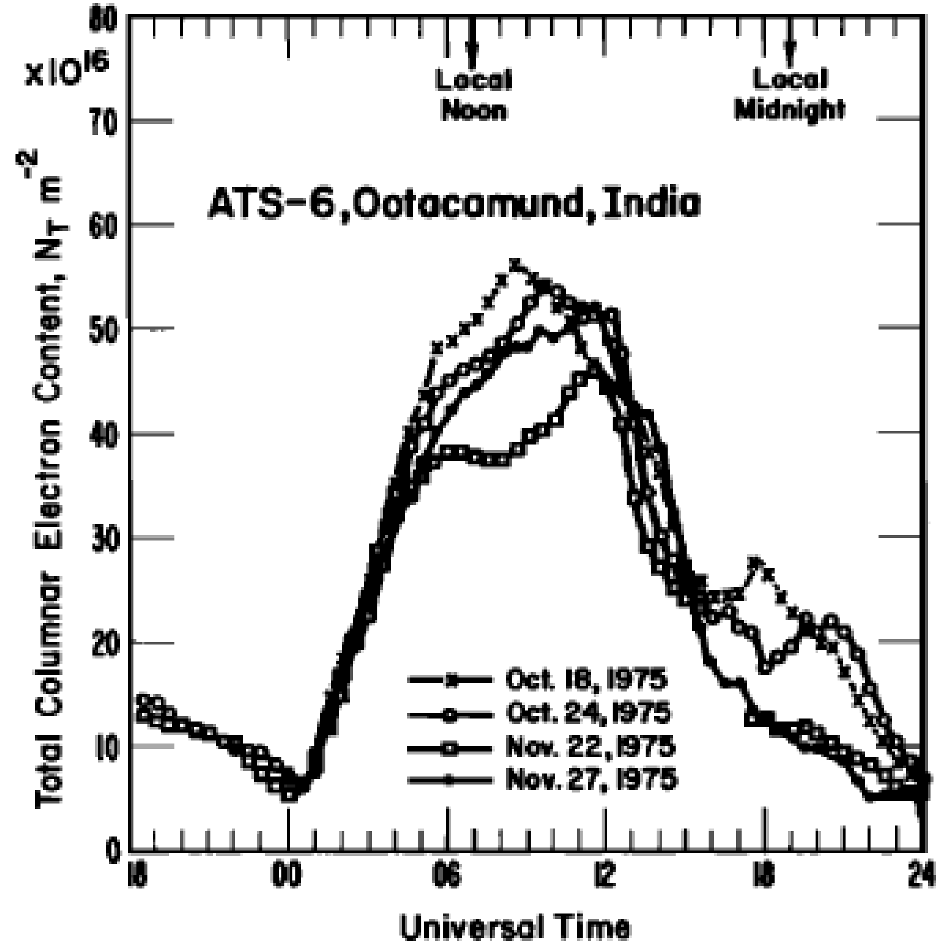
Indian perspective of TEC Studies

ATS-6 Radio Beacon Experiments from India – 1975-76

Davies, K., Donnelly, R. F., Grubb, R. N., Rama Rao, P.V.S., Rastogi, R. G., Deshpande, M. R.,Chandra, H., Vats, H. O., and Sethia, G., *Radio Sci.*. 1979



Ootacamund ray path



Diurnal variations of total electron content

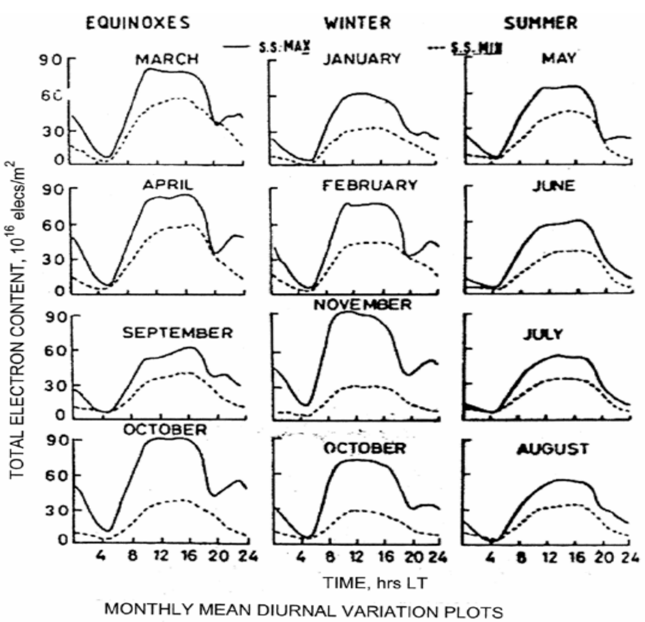
Indian perspective of TEC Studies

1. Indian Work Using ATS-6 in 1976

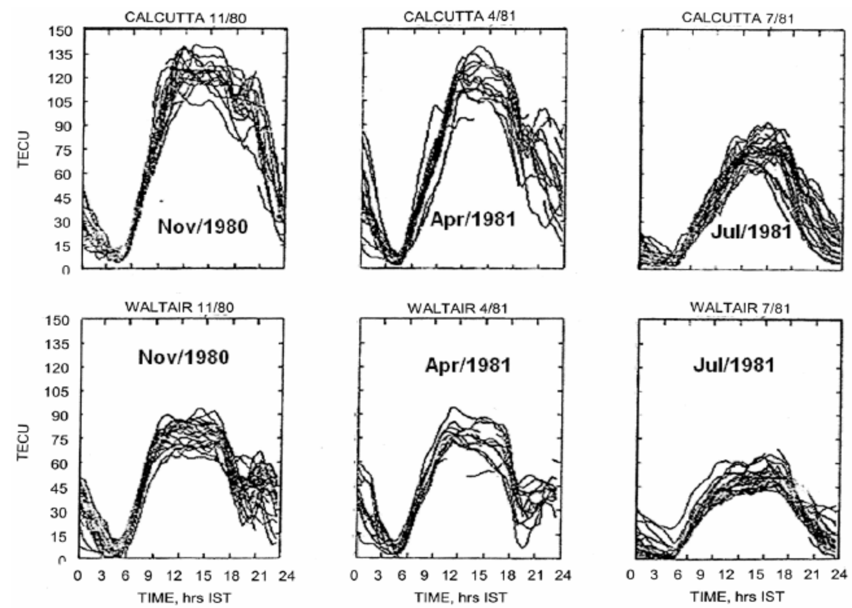
Bhardwaj et al. (1977), Tyagi et al. (1977), Dabas et al. (1984), Bhonsleet al. (1977), Garg et al. (1977) and Klobuchar et al. (1977).

2. Indian Works using ETS II in 1977-

located at 130°E, several studies were carried out in Indian sector (e.g., Rama Rao et al., 1985; 2002, Barbara et al.,1983)



Rama Rao et al.,Proc URSI/IPS Conference, Sydney, Australia,1985



Calcutta 22.6° N

Large spatial gradients 10 TEC/° Lat

Waltair 17.7° N

Rama Rao et al., Proc Iono Eff Symp, Virginia, USA, 2002

Major Results
ATS and other satellites till 1980s

- Gross phenomenology
    - Diurnal (Day and Night time) Variations at changing solar activity and latitude
- Seasonal variations (minimum in summer; equinoctial and winter maxima)
    - Control of sunspot number or F10.7 flux on ionization & Latitudinal gradients in TEC
- Night time enhancement in TEC
    - Relation of F10.7 solar flux with IEC
- Relation of crest of EIA with strength of equatorial electrojet (EEJ)

Global Observations using GPS/GNSS receivers

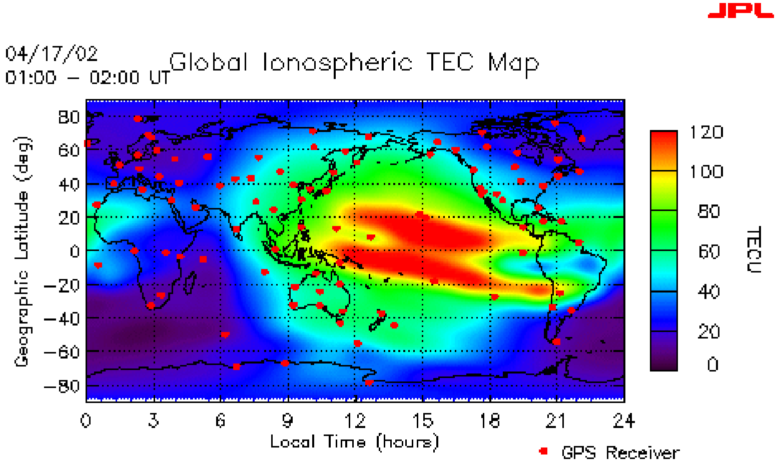
- **Advent of GPS- It was for the first time that**
  - continuous
  - simultaneous
  - calibration free
  - high accuracy observations
  - available to any global researcher

- **International GNSS Service (IGS) – 1990s**

Courtesy - www.igs.org

The International GNSS Service (IGS) gives open access, high-quality GNSS data products since 1994.

Map shows the locations of GPS/GNSS receivers in 2014



Global Ionospheric Maps (GIM) data

Unresolved Issues in
Realistic Representation of low latitude Ionospheric variations

Even with advancement of techniques of observations and simulations none of the physics based ionospheric models completely represent the observed features and variability as obvious from a number of recent studies (e.g. Shim et al., 2012, Borries et al., 2015).

In this background, we are motivated to

- **Enhance the understanding of low latitude TEC over Indian Sector**
- **Ascertain the relative contribution of the major controlling drivers of this part of ionosphere.**

The GIM data which provide continuous VTEC values over the globe is highly useful to begin with.

Data and Method

Global Ionospheric Maps (GIM) data

IGS- 1998 to 2014

- **GIM** – For the first time global TEC maps were generated using GPS TEC observations from IGS data (Manucci et al., 1993, Schaer, 1997, 1998)

- Gridded data = 2.5° latitude x 5° Longitude

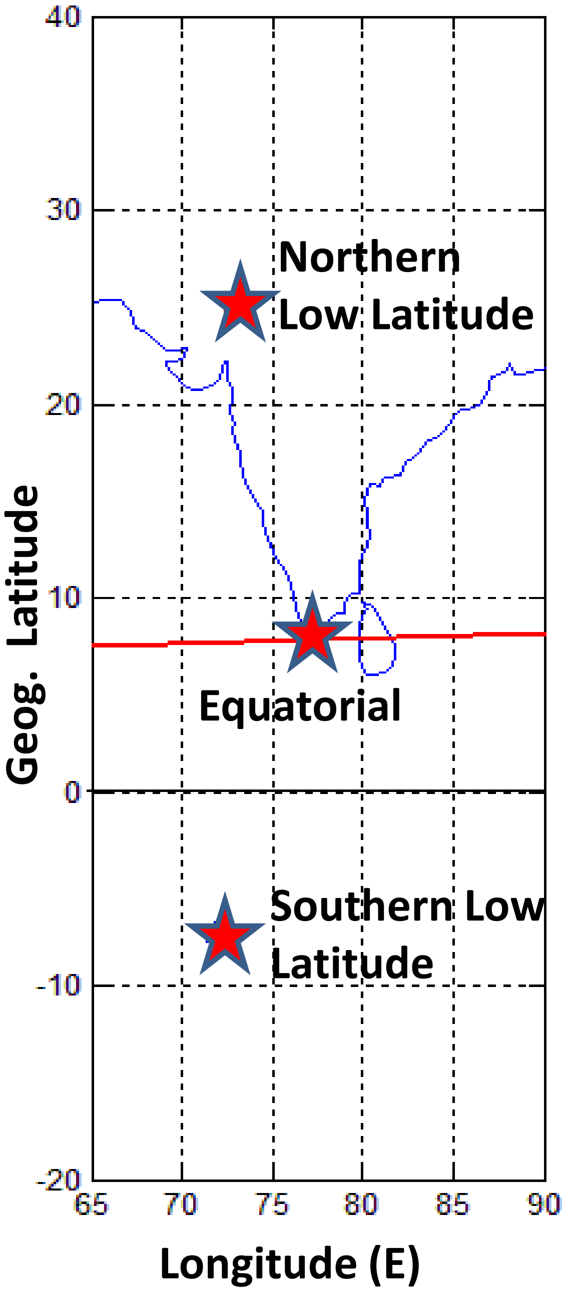
Different Types of GIMs

i. **JPL** –GIM by JPL, USA
ii. **CODE** – GIM - Prepared by University of Bern, Switzerland
iii. **ESA** – GIM By European Space Agency, Europe
iv. **UPC** – GIM by Univ. of Poly. Catalonia, Spain

Studies for Performance Analysis of GIMs

- Orus, 2004, 2008, Jee et al., 2010 - The performance of GIMs has been examined over the years.
- Hernandez-Pajares et al., 2009 - The CODE-GIM has been found to be a reliable source of ionospheric information to the first order after overall validation along other GIMs
- *Petrie et al.*, 2011 - Improvements in accuracy of GIMs

CODE-GIM from Indian Sector 3 Locations



- To represent the characteristics of Equatorial Ionospheric Anomaly (EIA) in Indian sector three locations are selected
  - **Northern hemisphere**
    (Geomag. Lat. 16.08° N, Geog. Long. 73.7 ° E)
  - **Equator**
    (Geomag. Lat. 0.17 ° S, Geog. Long. 76.95° E)
  - **Southern hemisphere**
    (Geomag. Lat. 15.26 ° S, Geog. Long.72.37 ° E)

- Important to note that –

The southern low latitude location is geomagneticaly conjugate to the northern location. Also, the locations have been selected based upon past availability of results from these places.

Results for

IEC=Daytime Max – Nighttime Min.

Duration –

DOY 152, 1998 to DOY 305, 2014

Aim is to obtain Quiet time variations in low latitude TEC

Two data filters -

1. Dst index - **Cut-off value of Dst>-50 nT is adopted to identify quietest days**

2. Solar flares*- **Days with solar flares greater than class M5.5 were excluded**

* It shall be noted that this is the first study to remove the solar flare effects from TEC data to obtain quiet time variations.

PI = Improved weighted Proxy of F10.7 cm solar flux

- Solar EUV irradiance is better represented by (Liu et al., 2006)

  $FUV=(F10.7 + F10.7_A)/2$,

where $F10.7_A$ is 81 day average of daily F10.7 index centered on the day of interest

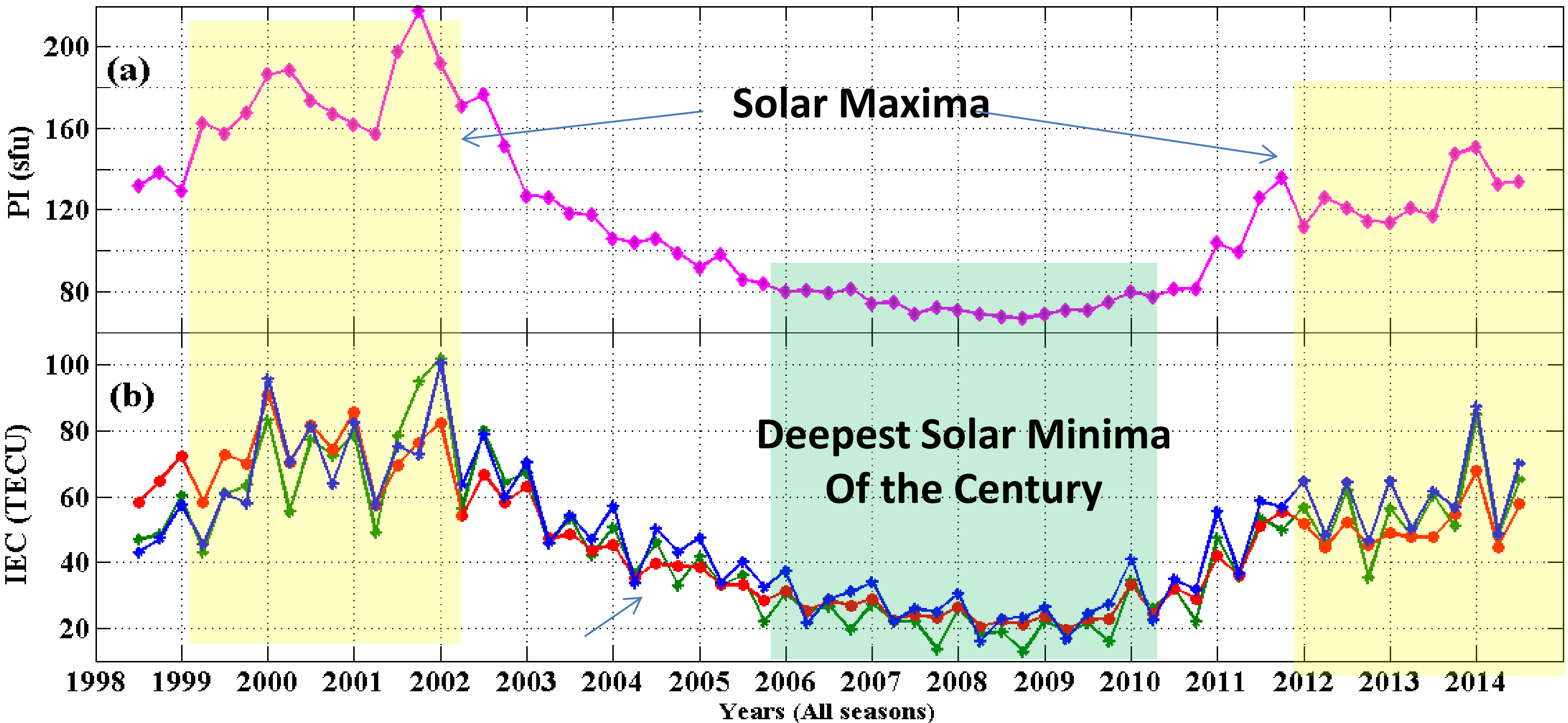
- The improved weighted EUV-proxy is given by

  $\mathbf{PI = 0.4F10.7 + 0.6F10.7_A}$ (by Chen et al.,JGR, 2012)

The Proxy Index (PI) as given by Chen et al. (2012) has been used in present study.

1. Seasonal Mean FUV and IEC (1998- 2014)

Mar. Equinox=FMA; Summer=MJJ; Sept. Equinox=ASO; Winter= NDJ



Total 5957 Quiet days of data

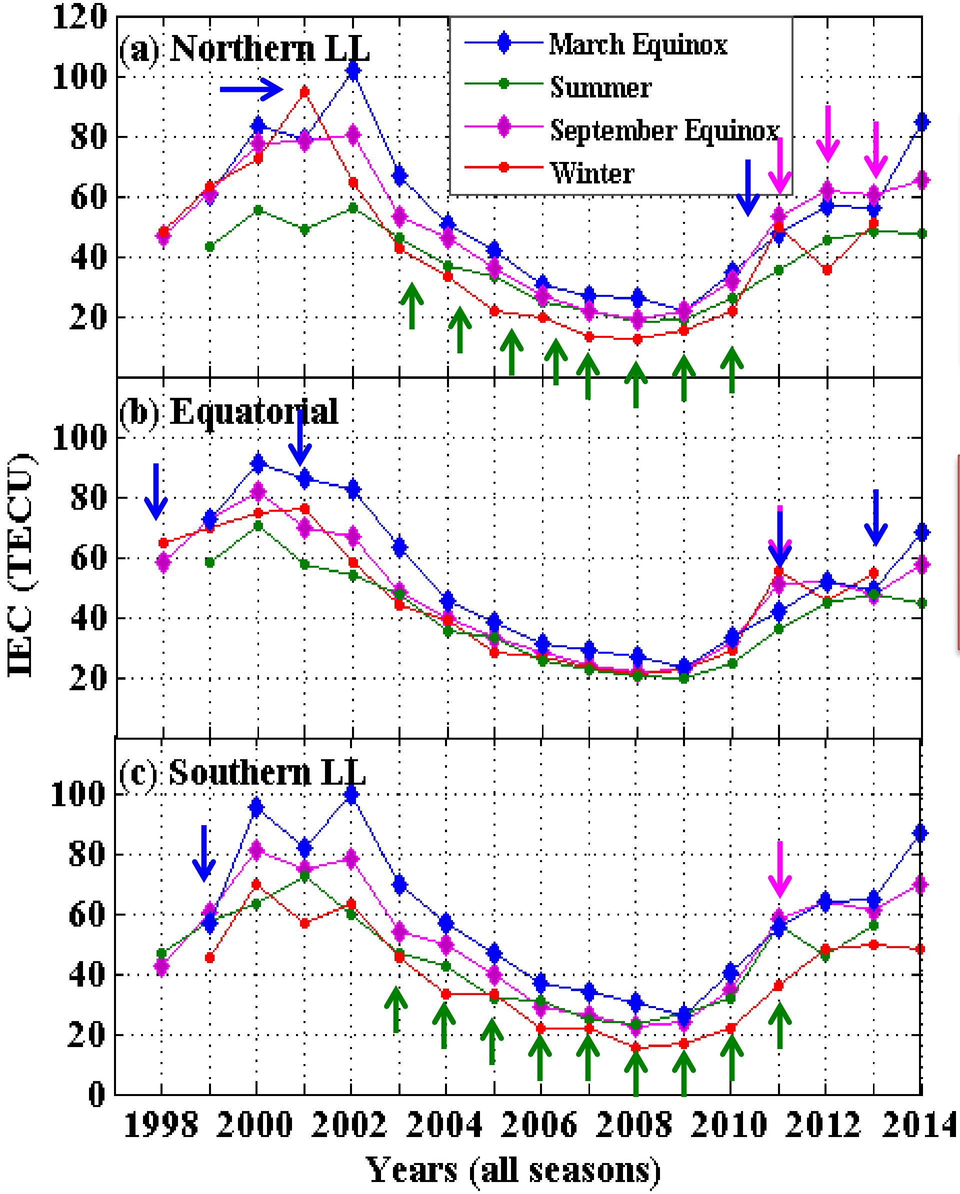
Equinoxes are common but solstices are taken local for each hemisphere

Northern
Equatorial
Southern

We find that -

- **IEC is in tune with Solar FUV - Double peak structure etc.**
- **During maxima of cycle 23 and 24 - Enhanced amplitudes of seasonal variations.**
- **During the deepest Solar minima highly Subdued seasonal variations in IEC.**
- **Clear latitudinal/seasonal difference in IEC against coarser variations in FUV**

2. Split IEC Season-wise during 1998-2014



1. Cases of Winter IEC < Summer IEC

We give the **first report** of the longest absence of winter anomaly from 2003-2010 only seen in low latitude locations(??)

2. Cases of September IEC < March IEC

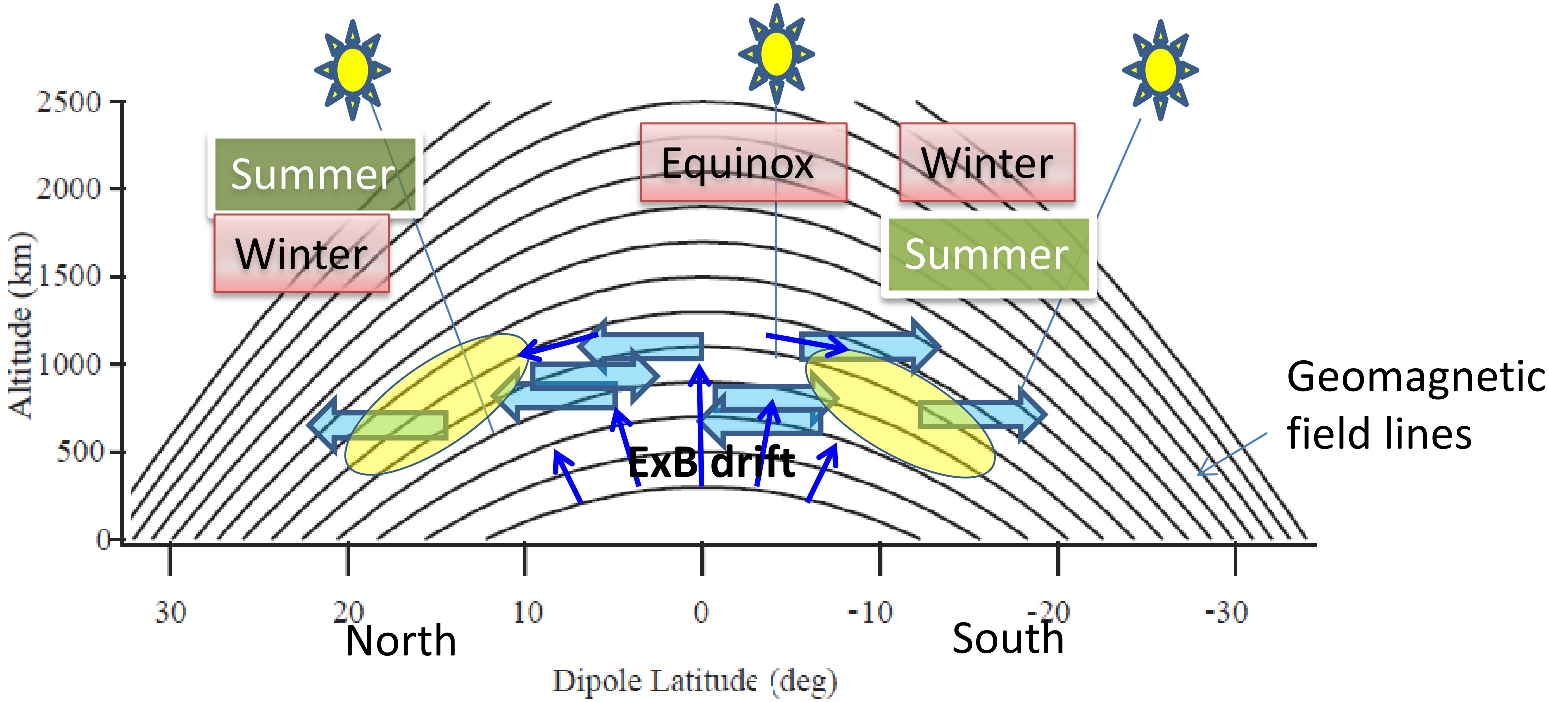
Only during Maxima of Cycle 24 but not during that of cycle 23 (??)

3. Cases of Solstice IEC > Equinox IEC

Only during solar maxima (??)

To bring more clarity and newer results we calculated the anomalies as given in next few slides.

EIA zone
Seasonal Ionospheric Variations



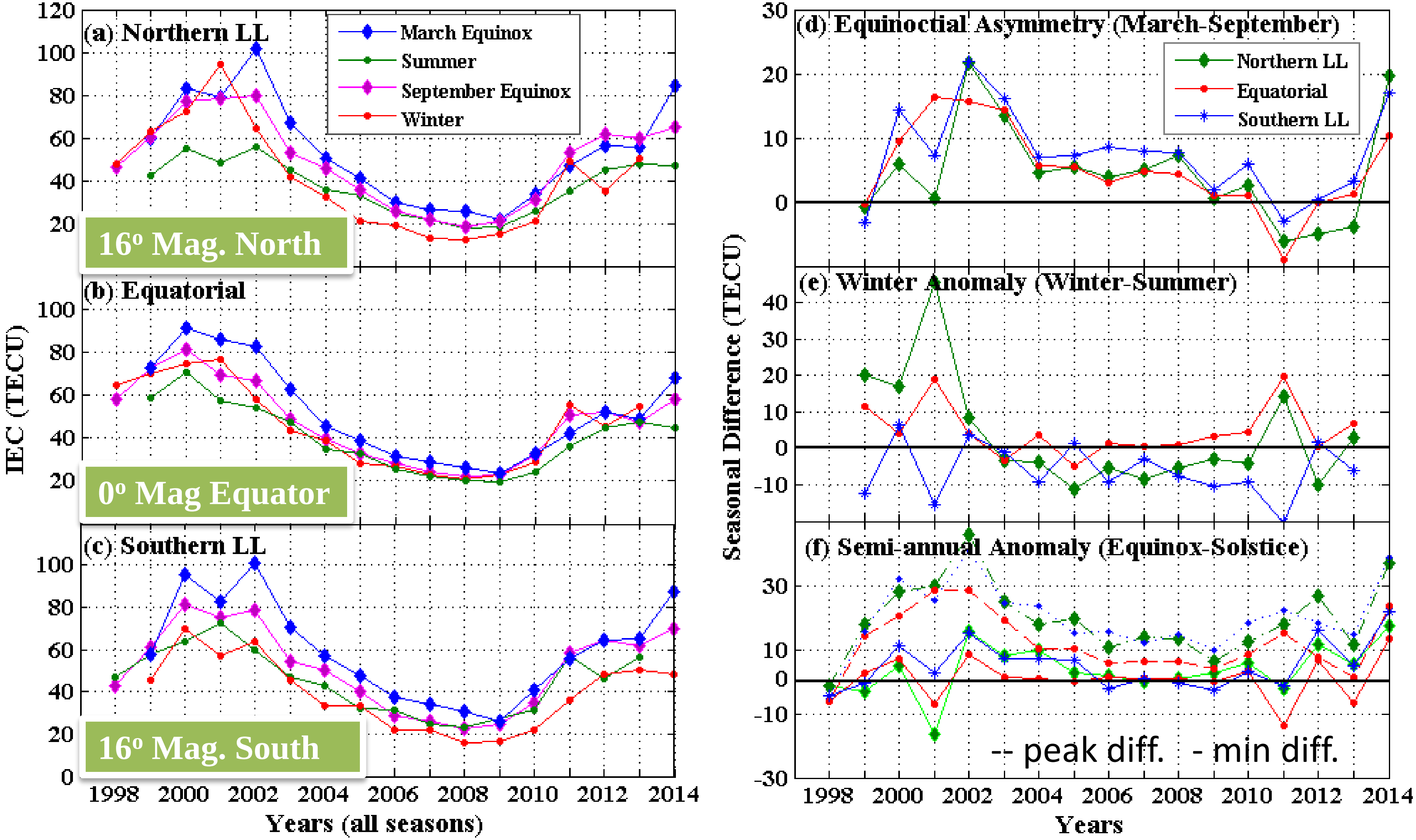
Formation of EIA –

- **Plasma uplift under vertical ExB drift and transport**
- **Electric field (E) show seasonal variations of dynamo origin**

Seasonal Thermospheric circulation pattern

- **Solstices - Trans equatorial from summer to winter hemisphere**
- **Equinoxes - Pole ward**

Seasonal Mean Ionospheric Electron Content (IEC) Assymetries among Equinoxes/Solstices



Lower Atmospheric Forcing like Waves, Tide and coupling with Ionosphere hold the Key to the departures from known mechanisms.

Winter/Summer/Seasonal anomaly:

As per Definition - IEC is higher in winter than in summer

Known and Accepted Mechanism by *[Millward et al., 1996]*

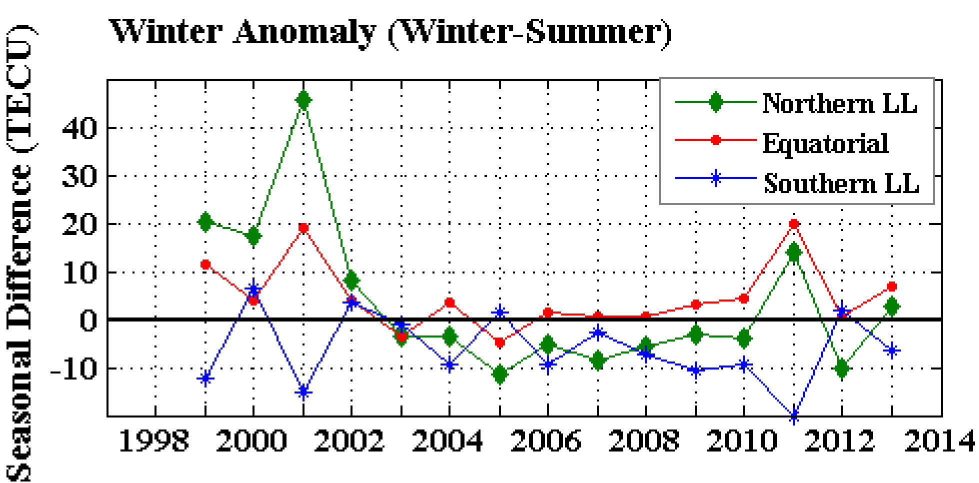
Upwelling (downwelling) in the summer (winter) hemisphere → Upwelling (downwelling) of gases rich in molecular nitrogen → Decrease (increase) in the overall O/N_2 ratio

Zhao et al. [2007] using GIM-TEC data from 1999-2005 found :

- **winter anomaly - prominent in northern hemisphere**
- **mid to mid-high latitudes**
- **moderate to high solar periods.**
- **southern hemisphere was less prone to exhibit the winter anomaly**

Previous studies: *Duncan [1969], Cox and Evans [1970]; Torr and Torr [1973]; Anderson and Matshushita [1974]; Titheridge and Bousanto [1983]; Balan et al. [1995, 1997, 1998]; Rishbeth et al. [2000]. Liu and Chen[2009]; Natali and Meza[2011]; Chen et al., [2012] and Ren et al.,[2011]*

2-11 years of length of data by previous studies



We find using the 17 years data

- **Continuous Absence of winter anomaly during low solar activity**
- **Indicate a changed thermospheric meridional wind pattern**

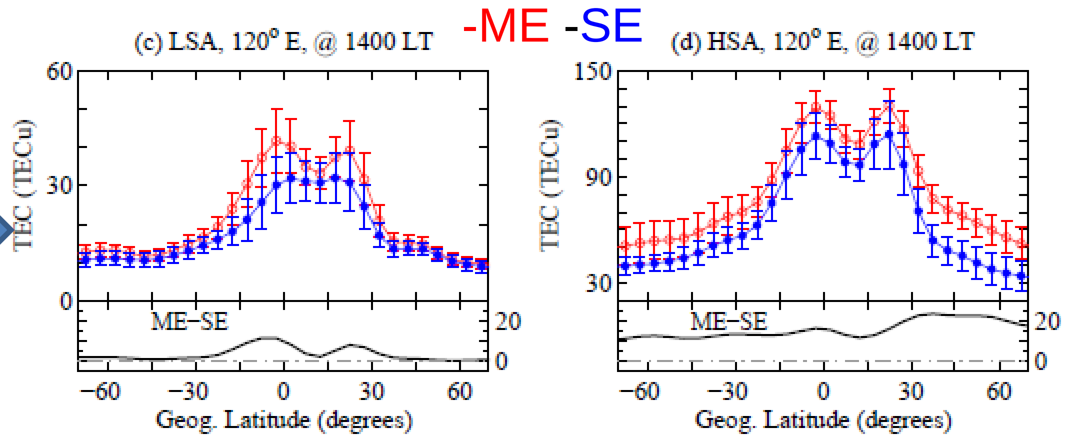
Dashora N. and Suresh S. - JGR (2015)

Equinoctial asymmetry: [Balan et al., 1998]

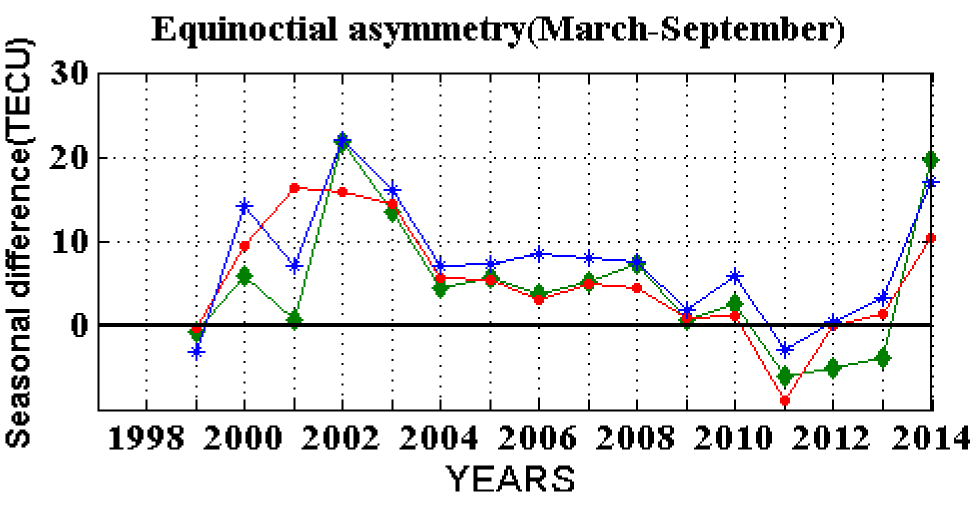
Definition - IEC is higher in March than September Equinox

Thermospheric winds weaker in March than September → Low (high) chemical loss in March (September)

Chen et al. **[2012] using JPL GIM for 1998 to 2009 found**
- **predominantly over all latitudes**
- **Both in low and high solar**
- **peak found near the crests of EIA**



Our study finds
- **Opposite asymmetry in Cycle 24**
- **Less in Southern hemisphere and stronger at Equator**
- **Indicates changed Dynamo region zonal winds and F region meridional winds in cycle 24.**



Dashora N. and Suresh S. - JGR (2015)

Semi annual anomaly [Fuller-Rowell,1998]

Definition -IEC is greater at equinoxes than at solstices

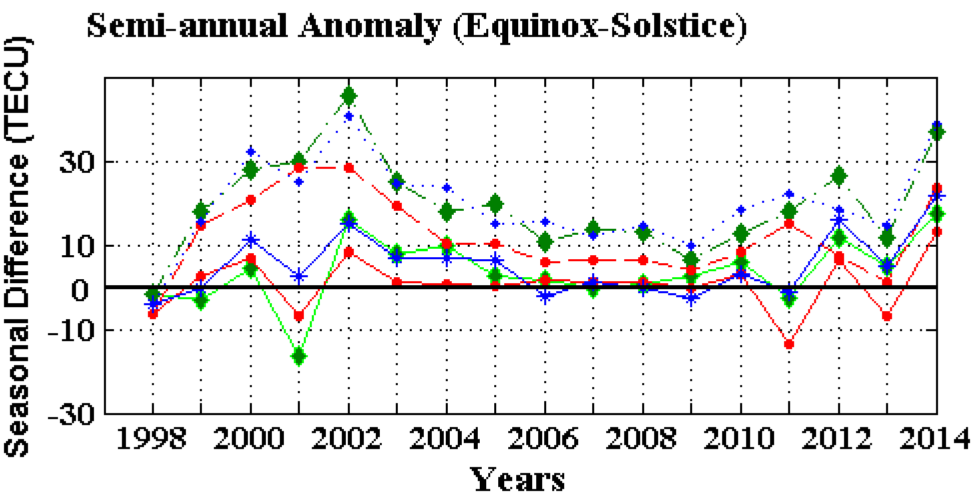
Thermospheric meridional winds weaker Equinoxes than in Solstices → Less (high) mixing equinoxes (solstices)

Zhao et al. [2007] - using JPL GIM from 1999 to 2005 found

- semiannual anomaly exists at all the latitudes during the daytime
- most pronounced in the equatorial anomaly region

- **We find that Less mixing ratios in equinoxes were only possible during solar maxima.**
- **Solar minima brings a dominate change nullifying the difference between seasons.**
- **Clear indication of control residing in lower atmospheric forcing on thermospheric neutral dynamics.**
- **Roles of waves and Tides require quantitative solar cycle dependent understanding**

-- peak diff. - min diff.



Dashora N. and Suresh S. - JGR (2015)

4 Standard definition of high solar activity
Ionospheric Perspective

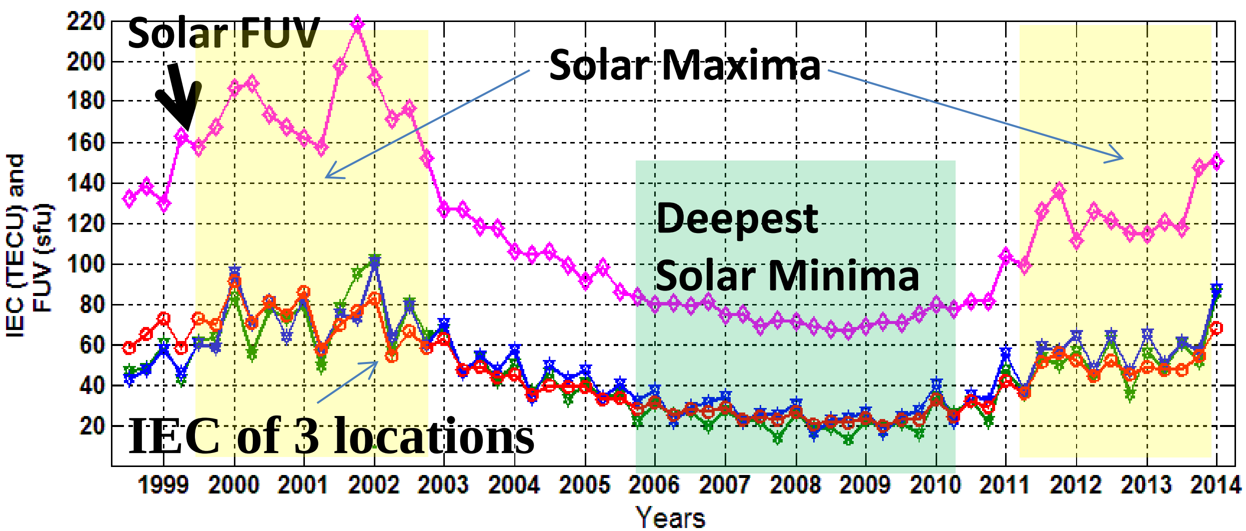
- Arbitrarily definitions using either F10.7 cm flux, Sunspot number etc. made it difficult to compare the results.

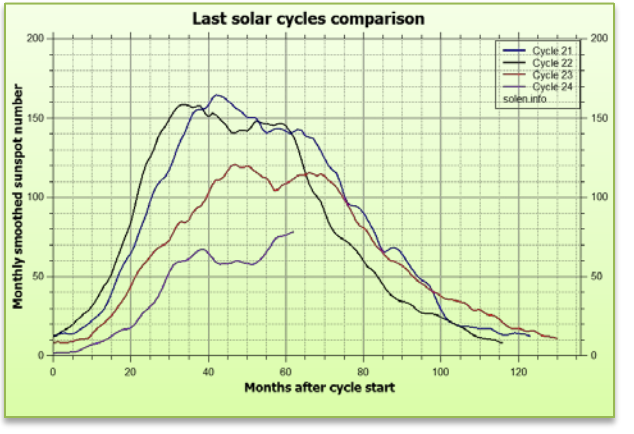
We defined

High solar activity (HSA) =

Interval of a given solar cycle where variations in Solar EUV remained higher than 0.707 times the peak value.

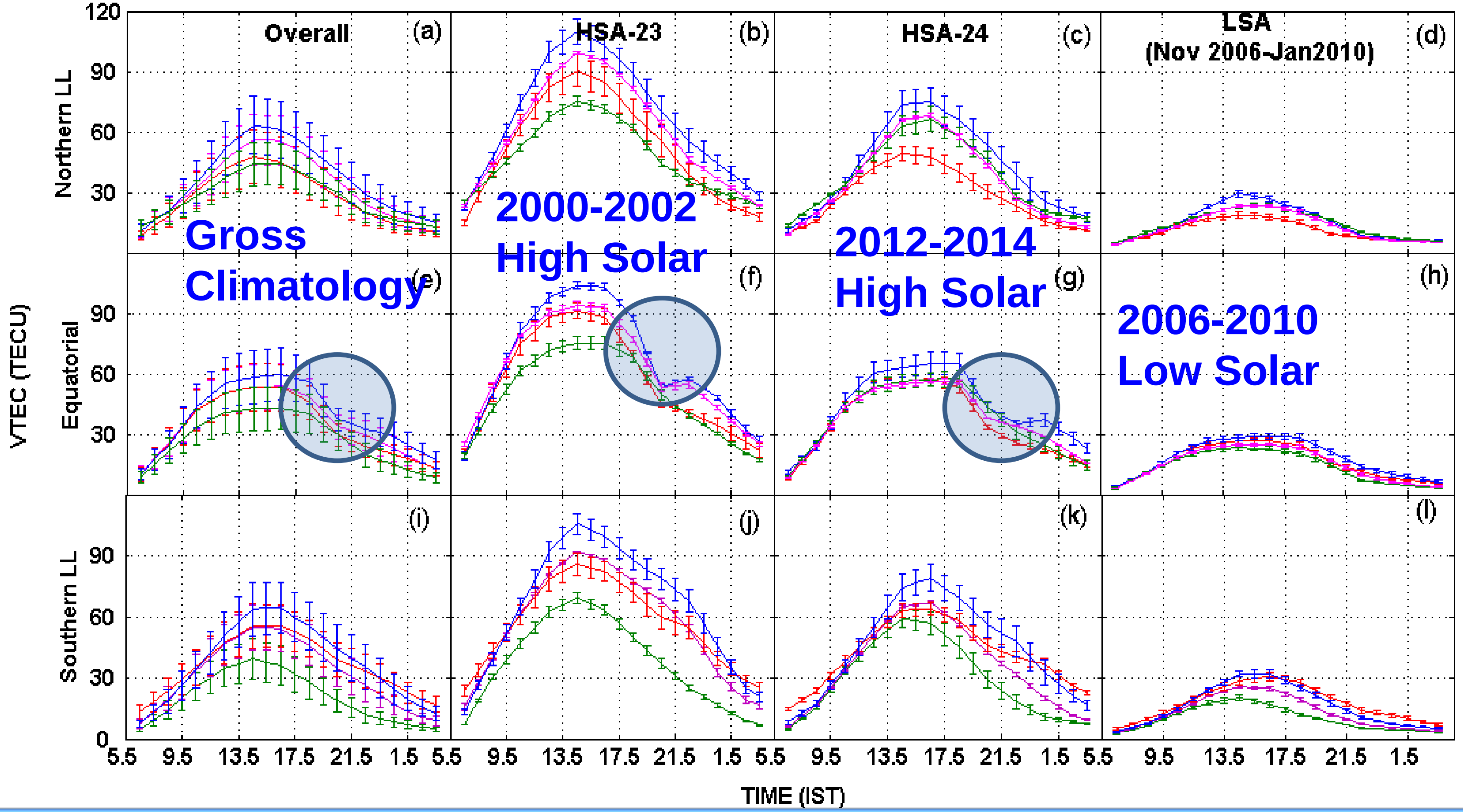
Equal to RMS (root mean square) width of a normal distribution.





Normal/Gaussian distribution

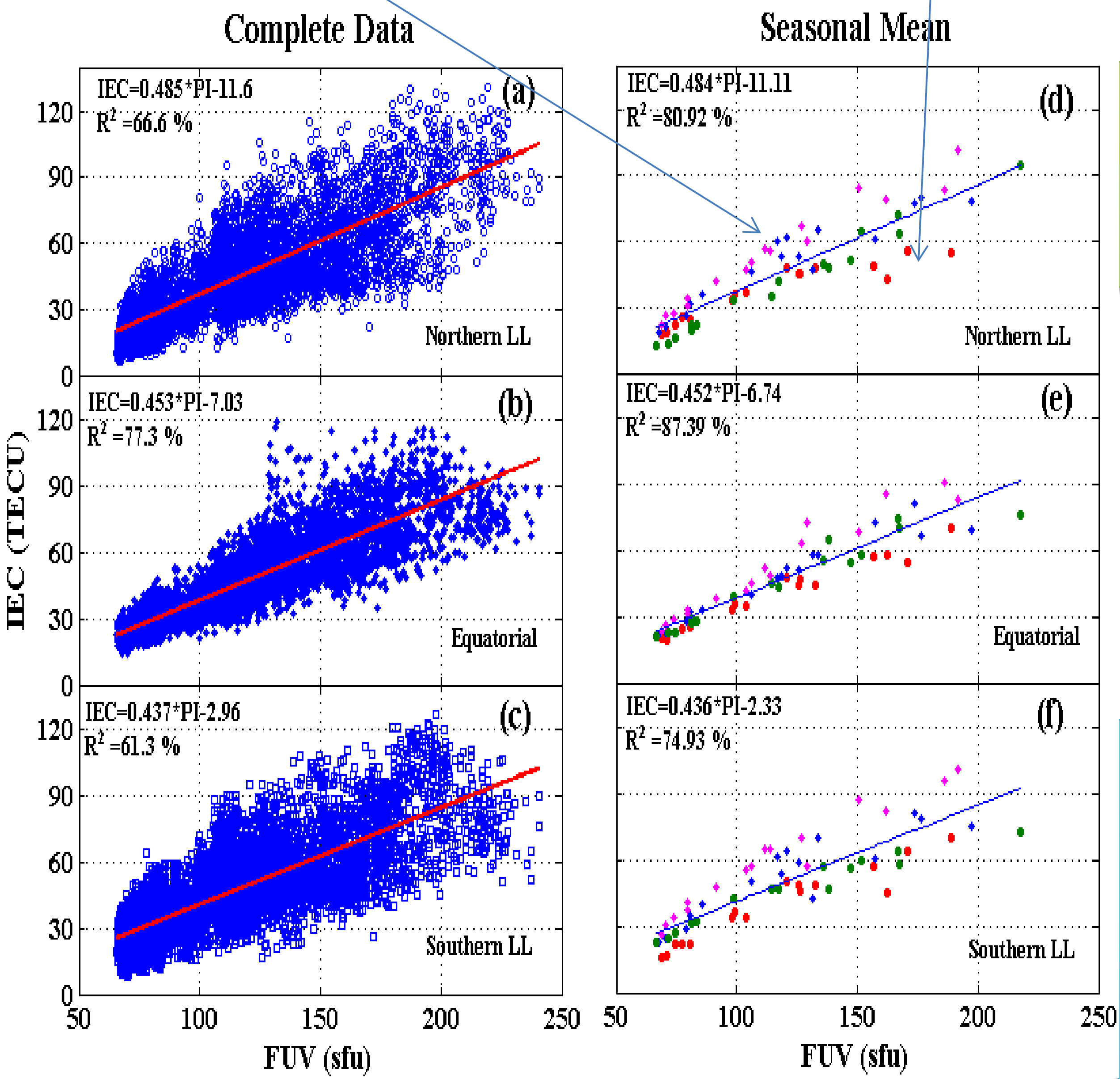
5. Changes in Mean Diurnal Cycle New Classification of Solar Activity



- Effect on diurnal cycle of VTEC with regard to Inter-solar cycle, latitudinal and inter-seasonal differences are very much obvious under the classification scheme.
- Climatology can effectively be used for medium range seasonal TEC forecast for upcoming solar cycles.

6. Linear Correlation (r) : EUV Flux and Electron Content

Equinoxes respond faster than Solstices to Change in solar activity



Different lengths of time series leads to different correlations

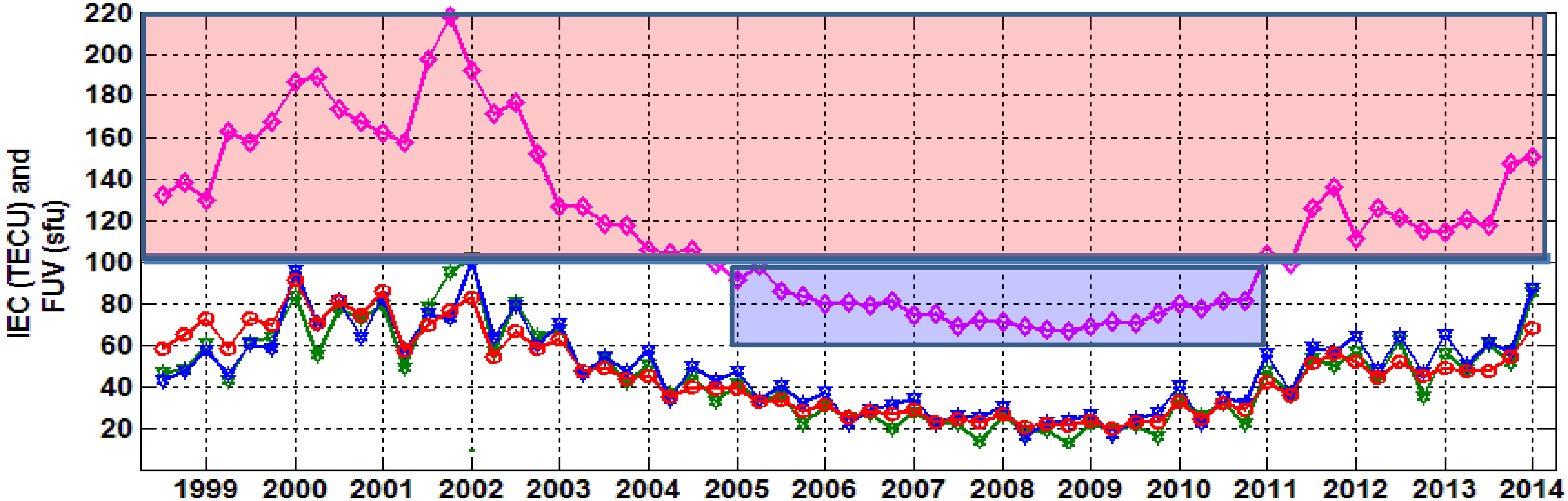
Highest correlation (87%) over equatorial station is opposite to commonly known locations as EIA crests.

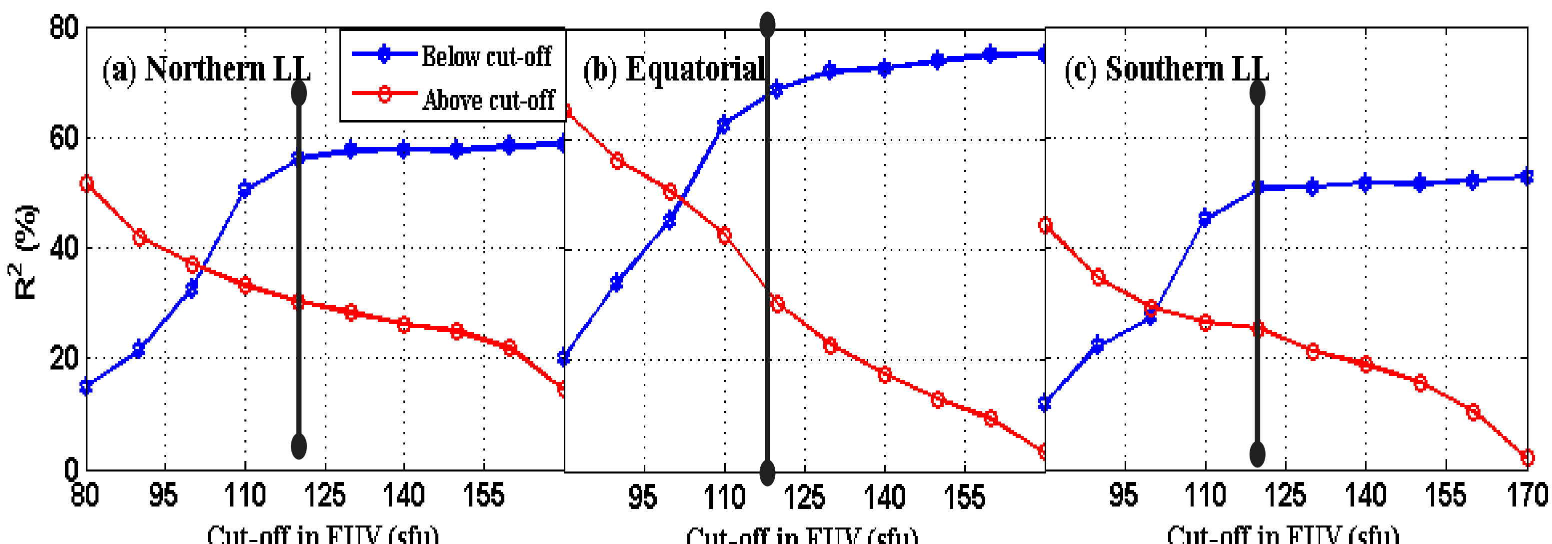
Why Equinoxes respond faster to increasing solar flux than solstices is not clear at present.

7. New Ionospheric Criteria defining solar High activity

Examination and Quantitative Assessment of Correlation between Solar EUV and Ionosphere

Dashora N. and Suresh S. - JGR (2015)

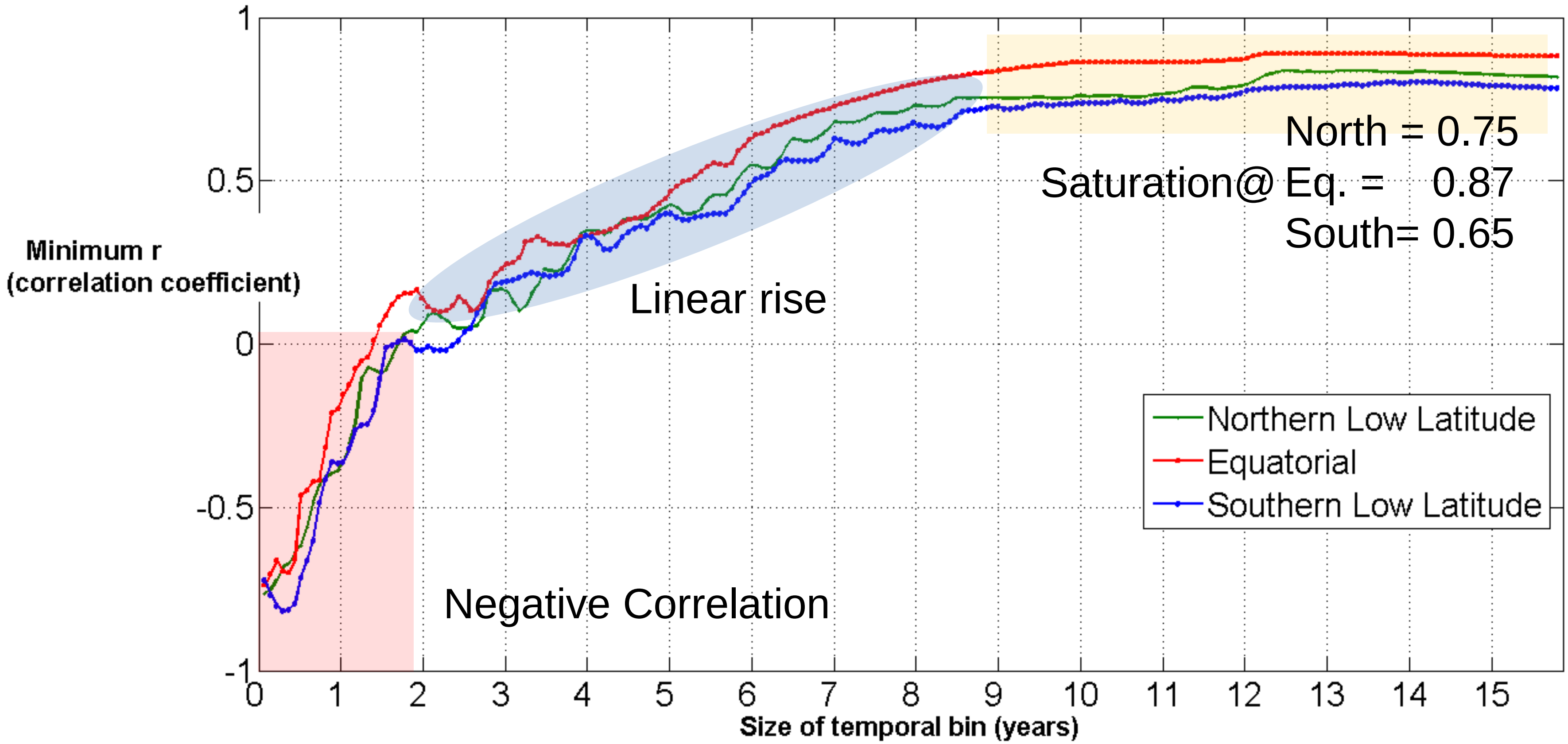




120 sfu =Cut-off and saturation indicates - Peak ionospheric levels =peak solar

8. Minimum Correlation and Length of Time series

Solar EUV and Ionosphere (IEC)

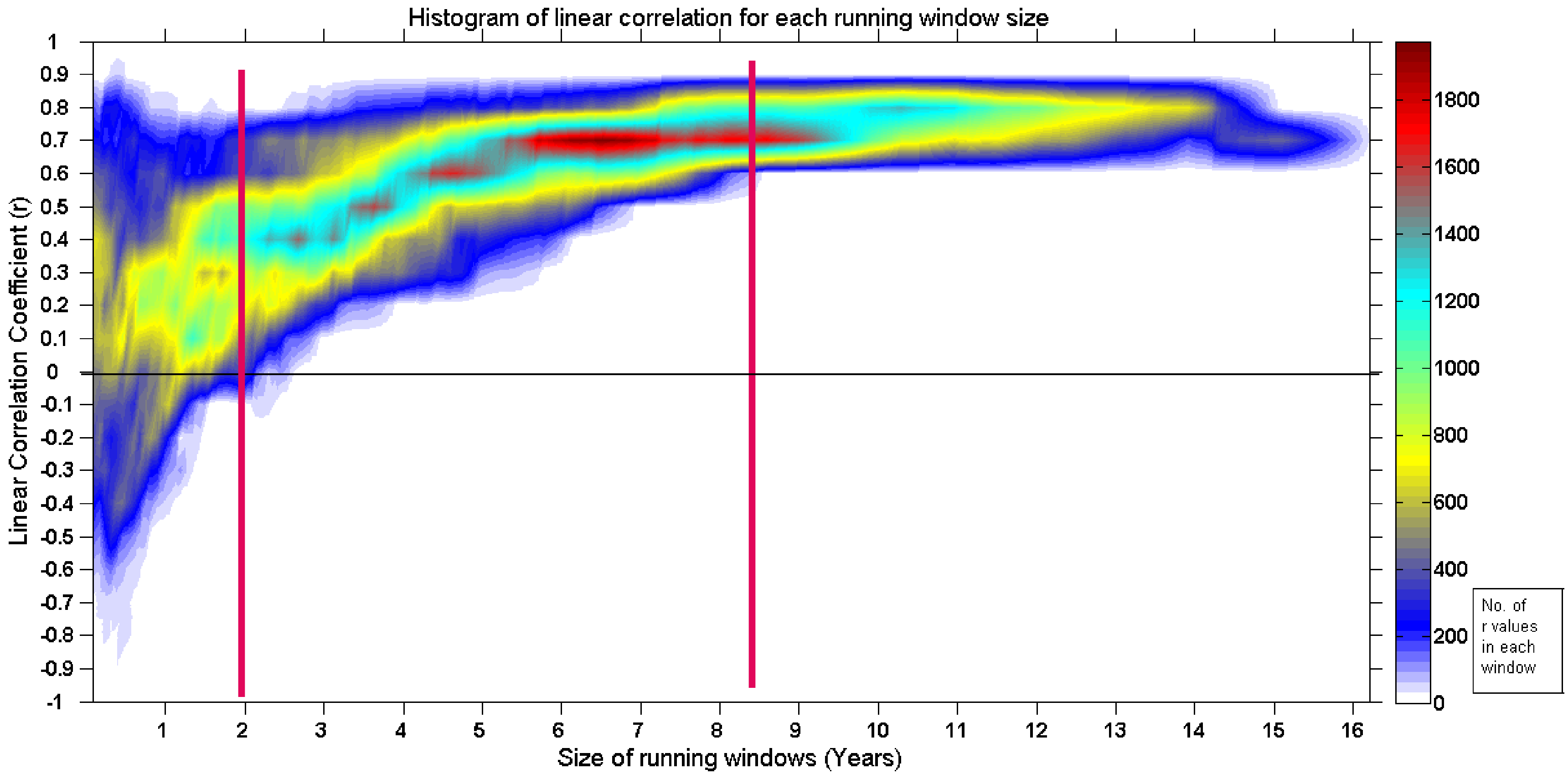


Irrespective of solar activity it is found that -

- Data < 2 years - Negative linear correlation
- Data > 8.5 years - Correlation saturates at a latitude specific value

Suggesting that , a specific length of data in Solar flux v/s TEC is highly required in determining ionospheric climate and role of the Sun

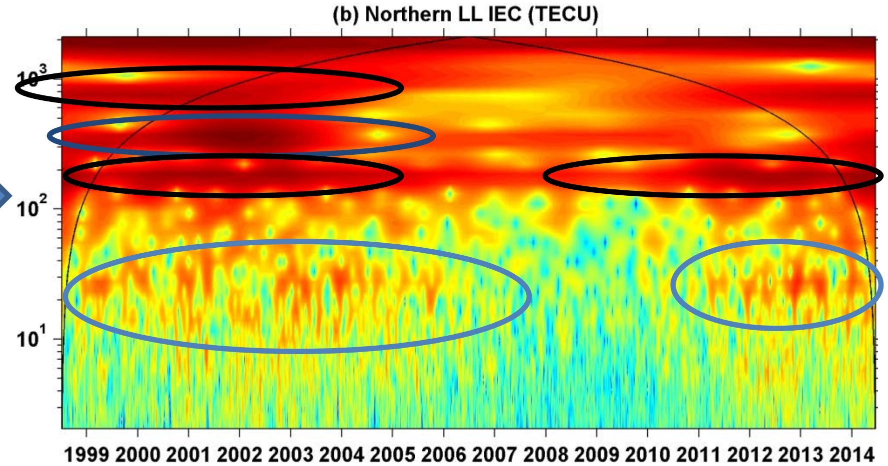
Histogram of Linear Correlation for Each running window

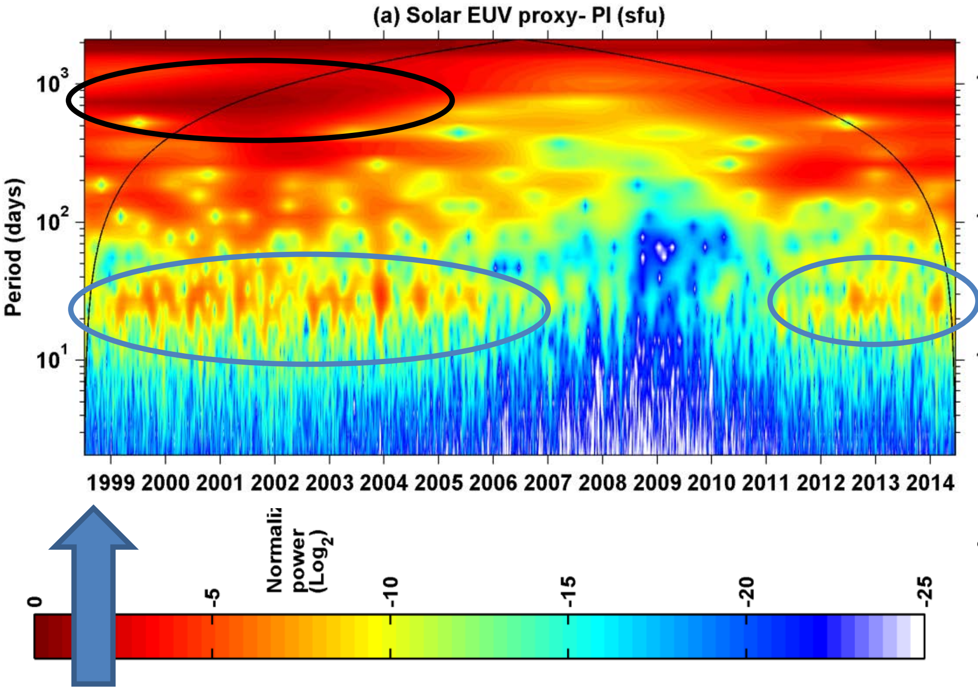


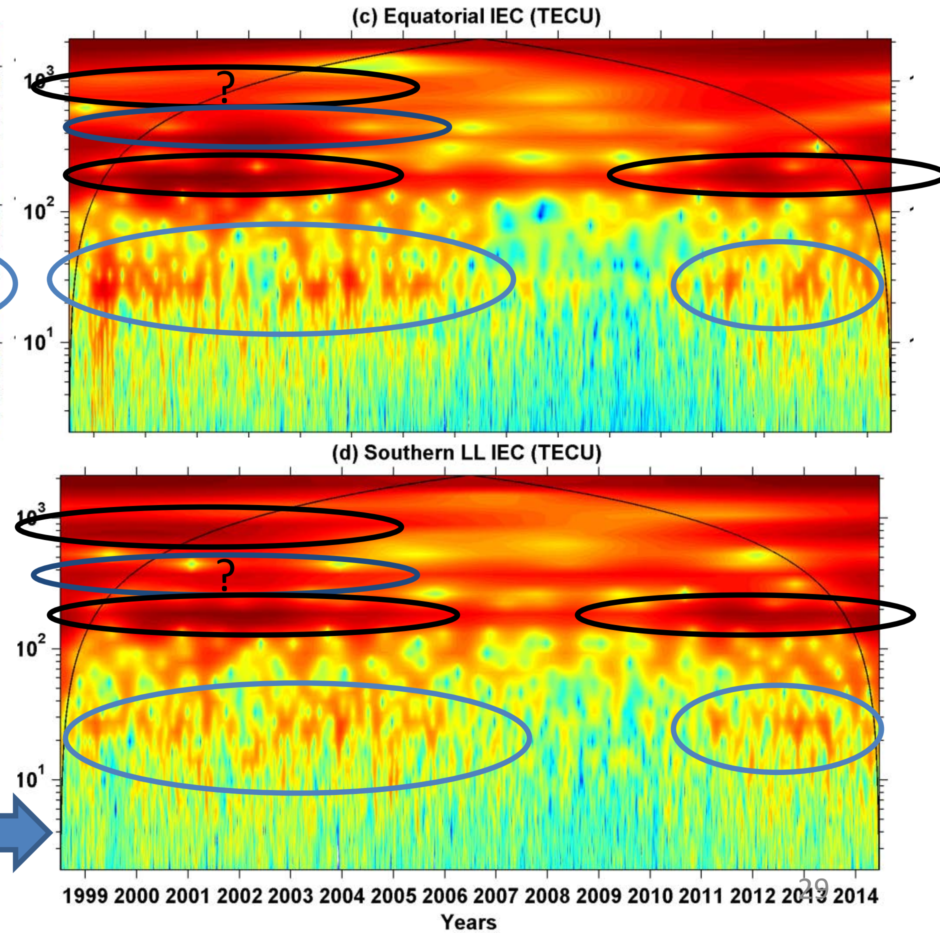
- For every window, the number of r values are represented by the histogram
- Tracing the minimum value of r, we can see that a large number of r values are negative in a window of 2 years (between 600 and 800 values)
- Maximum number of r values are found when window size is chosen to be around 6 years

9. Wavelet Analysis

Wavelet Spectra of Northern low latitude IEC







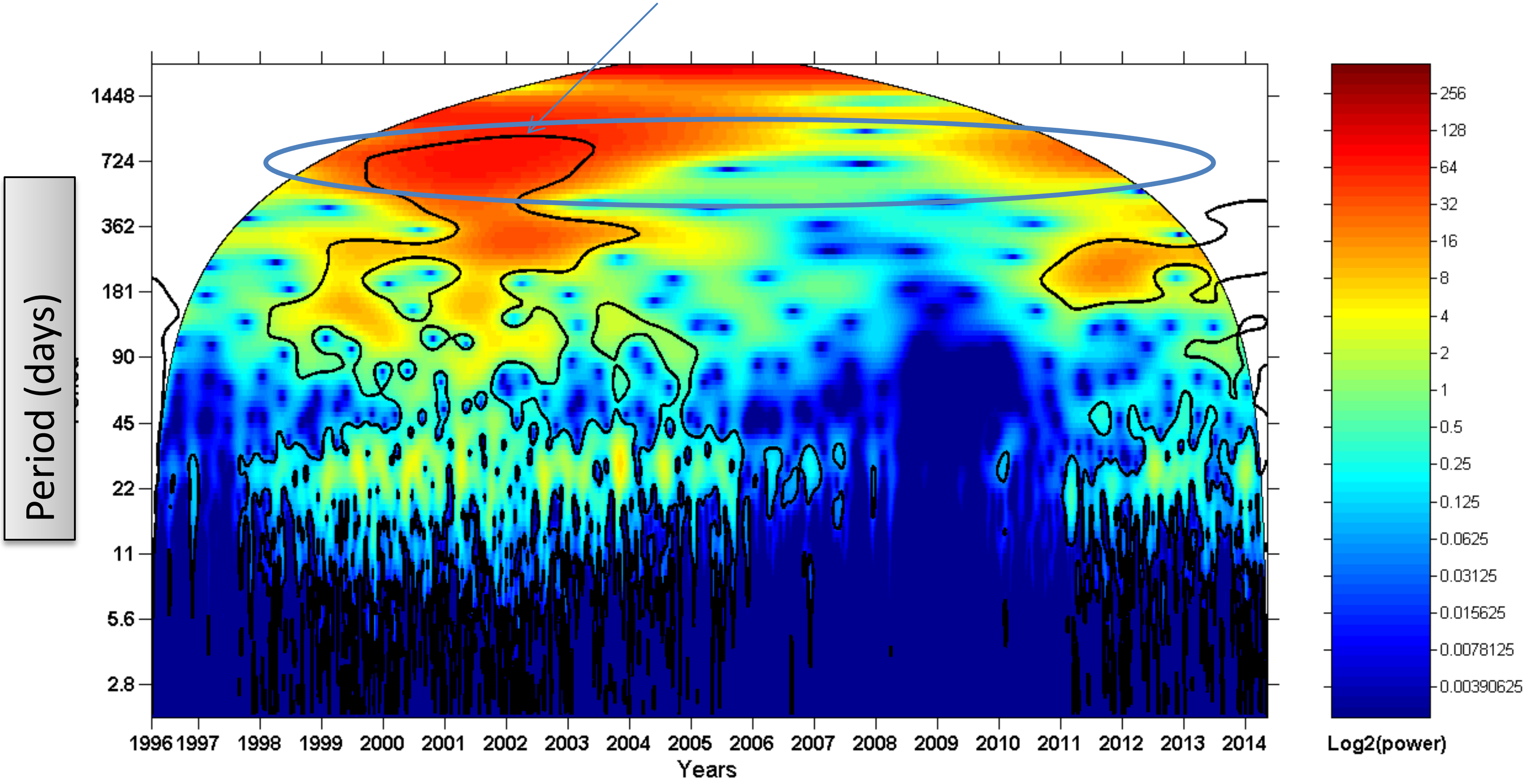
Wavelet Spectra of Solar EUV Flux

Wavelet Spectra of Southern low latitude IEC

10. Confirmation of QBO in Solar

Wavelet Spectra of Solar FUV flux data

- Added extra length to FUV time series = From 1996-2014
- Another software (IDL) with 95% confidence contours



From wavelet analysis we find that

1. **QBO in ionosphere was found to be only during High Solar Phase reported by - Chen et al., 1992; Kane et al., 1995, Kane, 2005**

2. **However, lower atmospheric QBO remains omnipresent with varying phase (Roy and Haigh, 2010 etc.).**

3. **Existence of ionospheric QBO is partly explained by various theories given in Echer (2007), Mansilla et al. (2009) etc.**

Origin of ionospheric QBO has remained a puzzle…. whether
Lower atmospheric OR Solar forcing

4. **Our result - QBO is obvious in Solar EUV and low latitude's IEC only during High Solar but not over equatorial region… which is intriguing.**

5. **Low latitude ionosphere --- governed also by the**
Vertical ExB drift and Meridional winds.
Hence a QBO in both or either of these shall impact the low latitude IEC and would also explain the equatorial absence !!

6. **A physics based model (SAMI 3-D) study has been proposed to ascertain the relative impact of various drivers.**

Summary

[1].For the first time quiet time VTEC and IEC data is filtered to remove the effects of higher than M5.5 class solar flares and geomagnetic storms of Dst<-50nT to obtain long term low latitude seasonal quiet time characteristics.

[2].The southern hemispheric IEC mostly remained higher than northern hemispheric conjugate location in Indian sector. Equinoxes responded faster to change in solar activity than solstices.

[3].Marked difference in nature of equinoctial asymmetry is noted between solar cycle 23 and 24. In fact strong opposite asymmetry during current cycle 24 is seen.

[4]. Winter anomaly has remained subdued (equatorial) and even turned opposite (LL locations) except during extreme high solar activity durations. Deep low September equinox IECs than northern hemispheric winter are noted only during years 2001, 2011 and 2013 and could not be explained by existing mechanism

Summary

[5].A clearer definition of HSA is given by 671 RMS width of PI. The climatology of diurnal cycle in VTEC has shown remarkable differences during HSA-23, HSA-24 and LSA and this can be directly utilized for purpose of data assimilation and improved long term forecast.

[6].Highest contribution of PI in variation of IEC is noted over equatorial region which is a new finding. Minimum positive contribution of PI in variation of IEC requires minimum of 2 years of data and if more than ~8 years of data is used, it saturates. A generalized value of PI of ~120 sfu appropriately demarcates high solar activity above it. Interestingly, PI of ~100 sfu results into equal level of correlation for respective high and low scenarios, irrespective of latitude

[7].Semi-annual and annual oscillations in IEC are substantially stronger in northern hemisphere and weaker over southern location.

[8].Strong signatures of QBO are observed in PI during HSA-23 and HSA-24. The QBO in IEC is noted with equal strength over both the LL location but it is surprisingly subdued over the equatorial location

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Data Sources Thankfully acknowledged -

- ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/
- http://www.spaceweather.gc.ca/solarflux/sx-5-eng.php
- http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html

Thank You Very Much