Report 1
A report on the behaviour of Total Electron Content over candidate sites for SKA location

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1 Introduction

The various proponents who have submitted their proposals for locating the SKA project in their countries have not always used the same methods for deriving the ionospheric TEC values at the chosen sites. While in some cases there are actual GPS measurements close by, in the case of the others, models such as the IRI (International Reference Ionosphere) have been used. In order to be able to compare the sites using similar data bases the International SKA Project Office authorized the authors to look at possible GPS data bases. It was found that the Madrigal data base developed at the MIT Haystack Observatory by Dr.Anthea Coster and her colleagues could be used for such a purpose. (Madrigal is the name of an open source database project of MIT-Haystack) [2]. The MIT Automated Processing of GPS (MAPGPS) has been developed to automate the processing of GPS data into world-wide absolute TEC maps [1]. In this software, all line of site measurements of TEC are converted into zenith (vertical) TEC values. In general the data base contains more than 1000 GPS receivers world-wide. The standard MAPGPS grid size is 1 x 1 deg. over a 5 min. time interval. Currently about 250 days of TEC data are available via the Madrigal database in the years 2000-2005. This is what has been used for our analysis. It is worth noting that the above process is strictly data driven with no underlying models that smooth out real gradients in the TEC [1].

To briefly recapitulate, TEC is the total number of free electrons along the path from a satellite to a ground based GPS receiver. The F2 layer of the ionosphere makes the most contribution to the TEC value. Complete ionospheric height profile models have been derived over the years and can generate average global TEC profiles as shown in Fig-1 [4]. The interesting aspect of the TEC behaviour is that it is maximum at around $+/-15^o$ from the magnetic equator in what are called the 'equatorial anomaly' regions. A typical mid-latitude station has monthly TEC values as shown in Fig-2 [4].

The standard deviation from monthly mean behaviour is $\sim 20-25\,\%$. The short term variation(within a day) of TEC is difficult to predict. However, this is important for radio astronomical data which get corrupted due to such variations. As pointed out by Erickson et al [5], one needs a large grid of GPS receivers around the SKA site to characterize small scale irregularities that contribute to the short term phase shifts.

2 Ionospheric Parameters

Table 1 shows the locations of the four proposed sites. Our aim is to characterize the ionosphere over each of these sites.

The relevant ionospheric parameters which have to be studied in this regard are as follows:-

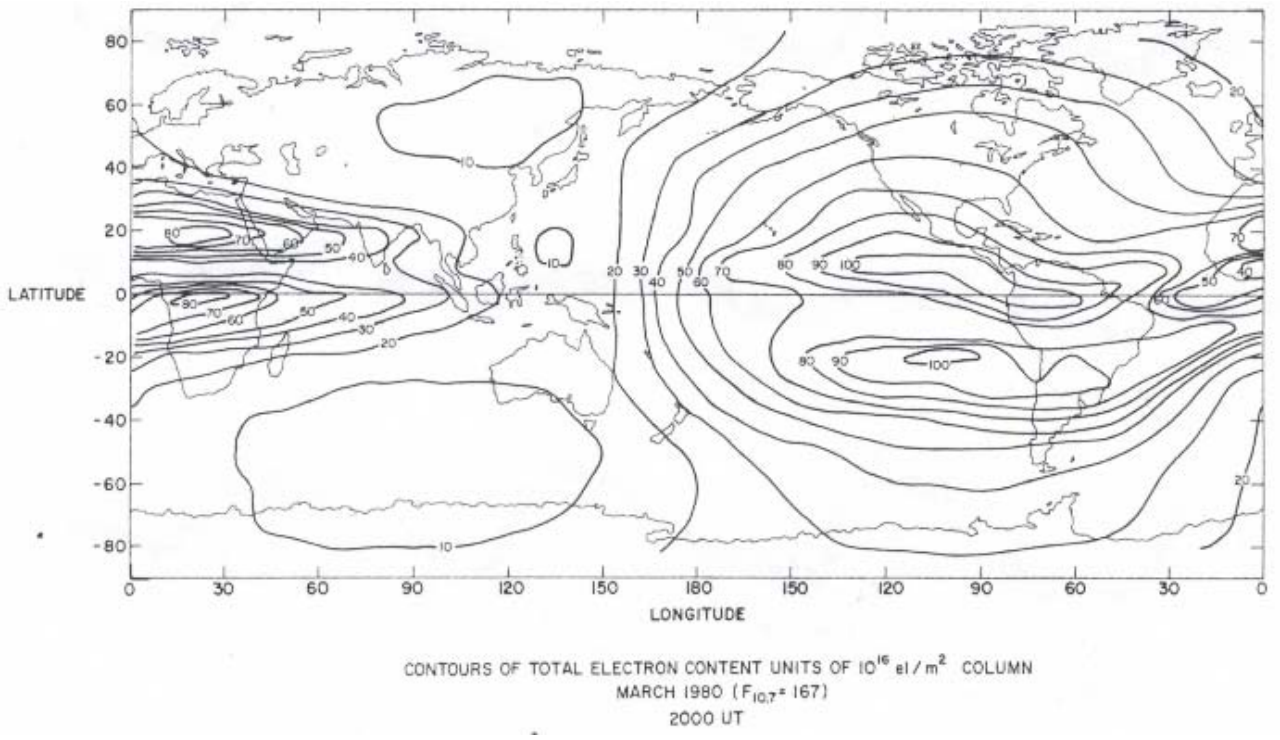


Figure 1: (Contours of vertical TEC in units of 10^{16} el/m^2 for 20:00 UT, March 1980)

1. TEC (Total Electronic Content)
2. Scintillation
3. Spread F and TIDs (Travelling ionoshperic disturbances)
4. Equatorial and South Atlantic Anomalies.

Table 1: Site Locations

Sites	Latitude	Longitude
Argentina	31.5^oS	70.6^oW
Australia	26.6^oS	117.5^oE
China	25.7^oN	106.9^oE
South Africa	30.7^oS	21.4^oE

In this part of the report we will deal with the TEC. The rest of the parameters are dealt with in Part 2 of the report (in pages 43 to 44).

3 Analysis of TEC variation

Vertical TEC values are obtained both from direct measurements of Madrigal Database (World wide GPS Network) and the model IRI data. But for the Madrigal Database, data are not always available in the exact locations, during the time of interest. So while reducing the data and making plots of Vertical TEC for all the sites, we have a chosen a suitable but small region around the sites and averaged the data both spatially and temporally. The need for having the data over a region around the specified site is that the Madrigal database has GPS data over all latitudes (with a resolution of a degree) but not at all longitudes. So depending on how much data are available around the particular site we have chosen a region around those sites upto a maximum of $\sim +/- \ 2^o$ *to* 3^o in longitude. TEC values are expressed in terms of the TEC unit which can be defined as - $1\ TECU = 10^{16}\ electrons\ m^{-2}$.

Initially, just for comparison, in addition to above four sites we also plotted a representative TEC variation for the sites at VLA (USA) and GMRT(India). The Figures of Appendix A shows representative plots for all the six sites for December 16, 2005 and September 21, 2005 (pages 5 to 10), which are typical to solar minimum years. It is clear that the VLA site has the lowest overall TEC value, due to its being a mid-latitude site; the GMRT site, on the other hand, has high TEC values being close to the peak of the equatorial anomaly.

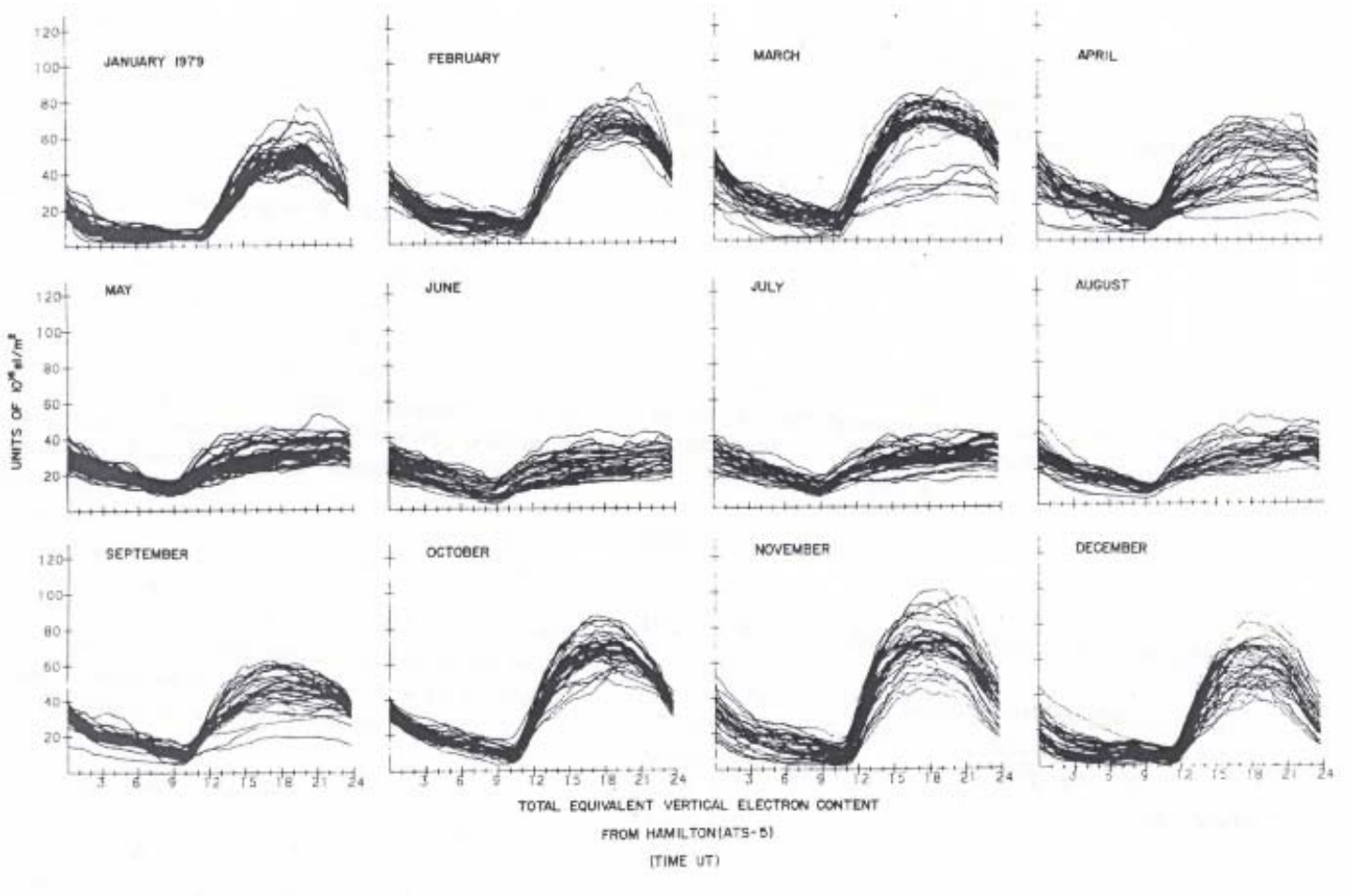


Figure 2: (Monthly overplots of TEC diurnal curves for Hamilton, Mass.,USA for 1979)

In Appendix B (pages 11 to 26) we present the detailed plots of Vertical TEC variation over the four candidate sites at Argentina, Asutralia, China and South Africa in the months of March, June, September and December, as obtained from the Madrigal Database [2]. The plots are made for two years 2001 (solar maxima) and 2005 (solar minima). In each of these plots the different curves represents different days of data available in the respective months (see e.g. page 17 for South Africa June 2001). For some months enough data were not available for the year 2001 or 2005, so we have also included the data from the year 2000 or 2006, respectively to increase the number of plots for those months. The typical Madrigal data are available for every 5 min. But the data which are plotted are smoothed by integrating over every hour.

For the same seasons, another set of plots have been produced, as shown in Appendix C, based on the IRI models for the same sites [3] (pages 27 to 42). The plots represent the variation of TEC in the respective months for two dates (10th and 20th) of each month. IRI data is available for every hour, so no integration over time is done for plotting these data. A comparison of these plots reveals interesting results. Clearly, not all IRI model plots follow the GPS data. In many cases the IRI models significantly underestimate the actual data, while in some others the IRI models are over-estimates compared to the data. Therefore, we believe that using an uniform data base like Madrigal (Appendix B) helps in making

a proper comparison of the TEC values for the various sites.

A careful comparison of the same season's data for all sites reveals that Argentina and China have significantly higher values of TEC as compared to Australia and South Africa, particularly in the solar maximum period. During the solar minimum period, the differences between the sites are not as significant. Between Australia and South Africa the differences in TEC values both during the maximum and minimum are not significant. On a plot by plot comparison, South Africa appears to have a marginally lower TEC value than Australia. As far as radio astronomical observations are concerned, it is the short term variation of TEC which is important. However, if a particular site has significantly higher TEC, in the absence of better understanding of the short term fluctuations it may not be unreasonable to assume that the turbulence which causes short term variation is a small percentage of the measured TEC ($\Delta N_e \alpha N_e$). Hence, we may conclude that the sites which have higher TEC values are likely to be more affected than the sites with lower TEC values. **Viewed from this perspective, since Argentina and China have, in general, higher measured TEC values than Australia and South Africa, the former could be more affected than the latter group**. This aspect needs to be cosidered along with the other parameters given in Part 2 of the report.

Since the plotted vertical TEC values are derived from slant TEC measurements made by the satellites, no effort has been made to get the slant TEC in this report.

Acknowledgement:

The authors wish to thank Dr. Anthea Coster of the MIT-Haystack Observatory for her help in obtaining the madrigal database. Thanks are also due to the international SKA project office for initiating this study. One of us (SA) would like to thank Ms. Shilpa Bhave & other colleagues of NCRA-TIFR for their invaluable help in compiling all the material together.

References

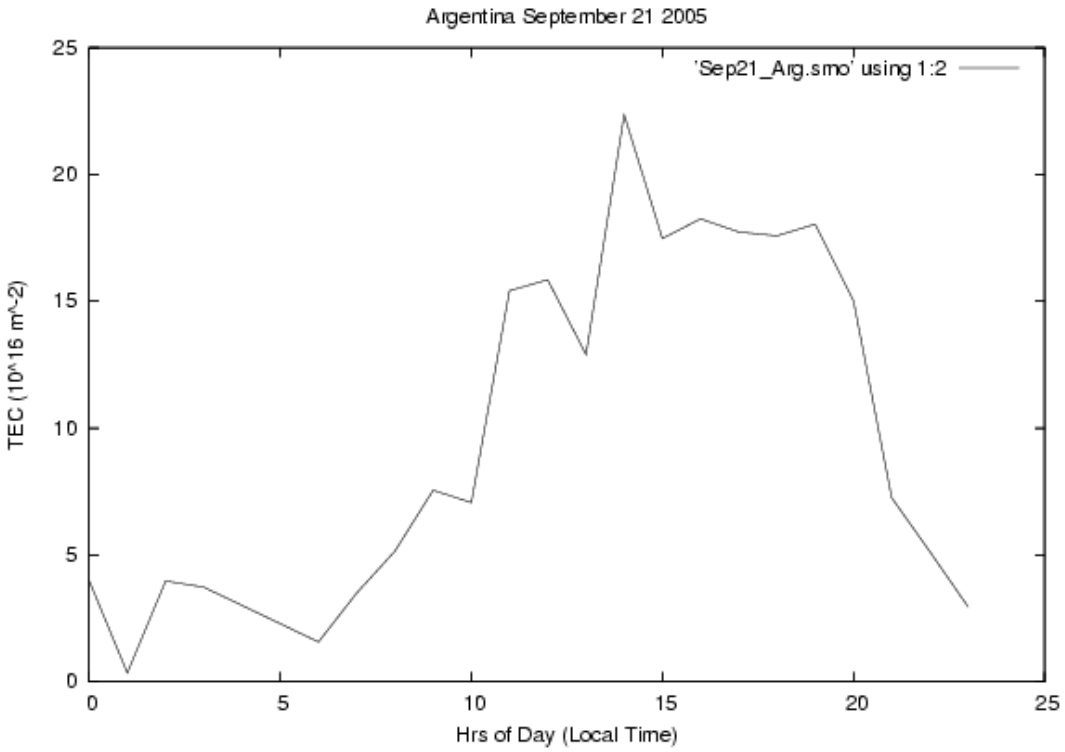
[1] Rideout W. and Coster A., *Automated GPS processing For Global Total Electron Content*, GPS Solutions, 2006.

[2] Madrigal Database, *http://madrigal.haystack.mit.edu/madrigal/index.html*

[3] International Reference Ionosphere, *http://modelweb.gsfc.nasa.gov/models/iri.html*

[4] Jursa A.E. (ed.), *Handbook of Geophysics and Space Environment*, AFGL, USAF(NTIS) 1985, pp 10-90 & 10-91.

[5] Erickson, W.C. et al., *Ionospheric corrections for VLA observations using Local GPS data*, *A&A* v.366, p.1071-1080 (2001).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Hrs of Day (Local Time)
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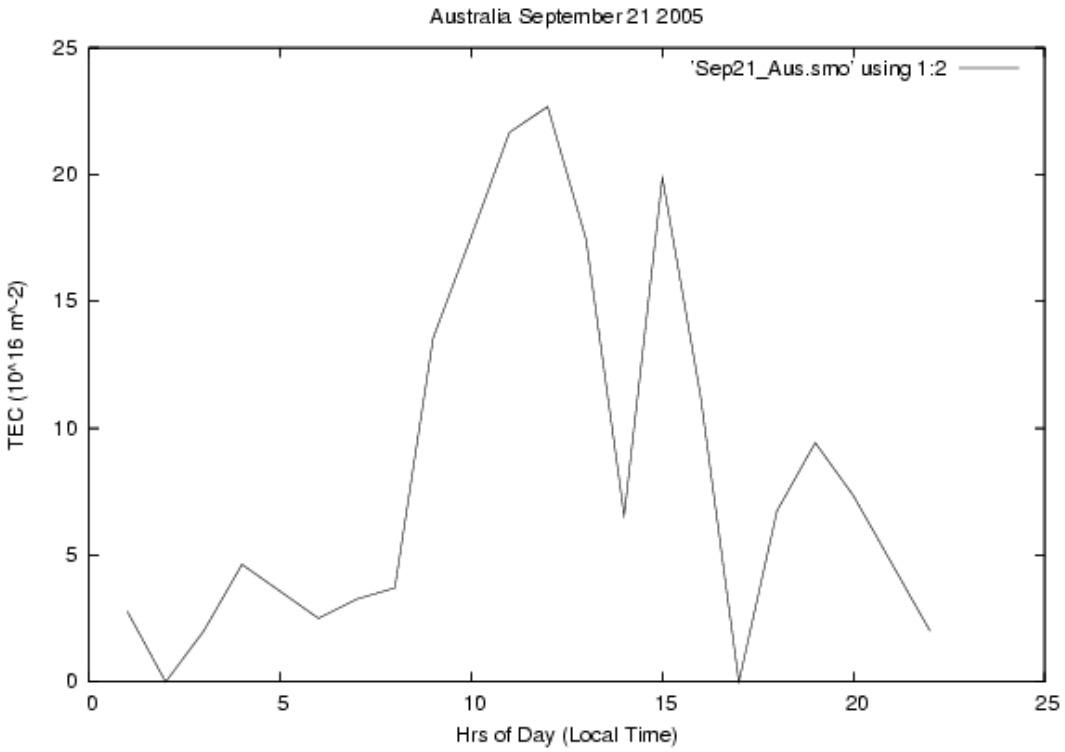
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Hrs of Day (Local Time)
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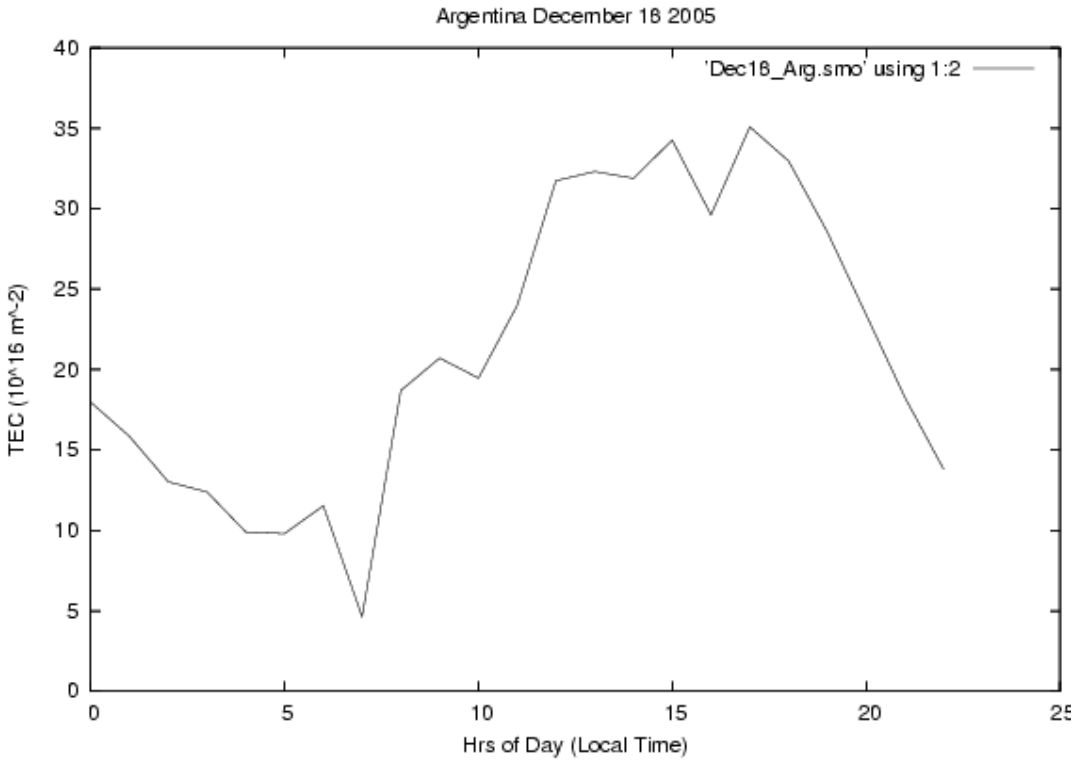
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Hrs of Day (Local Time)
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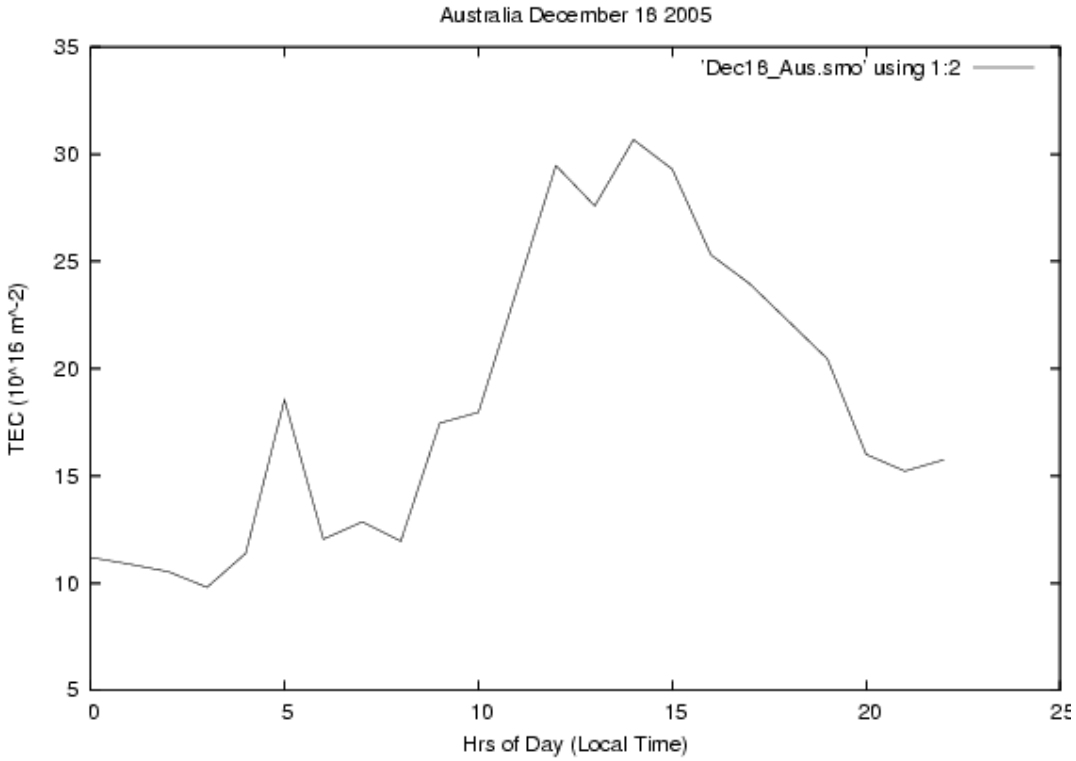
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Hrs of Day (Local Time)
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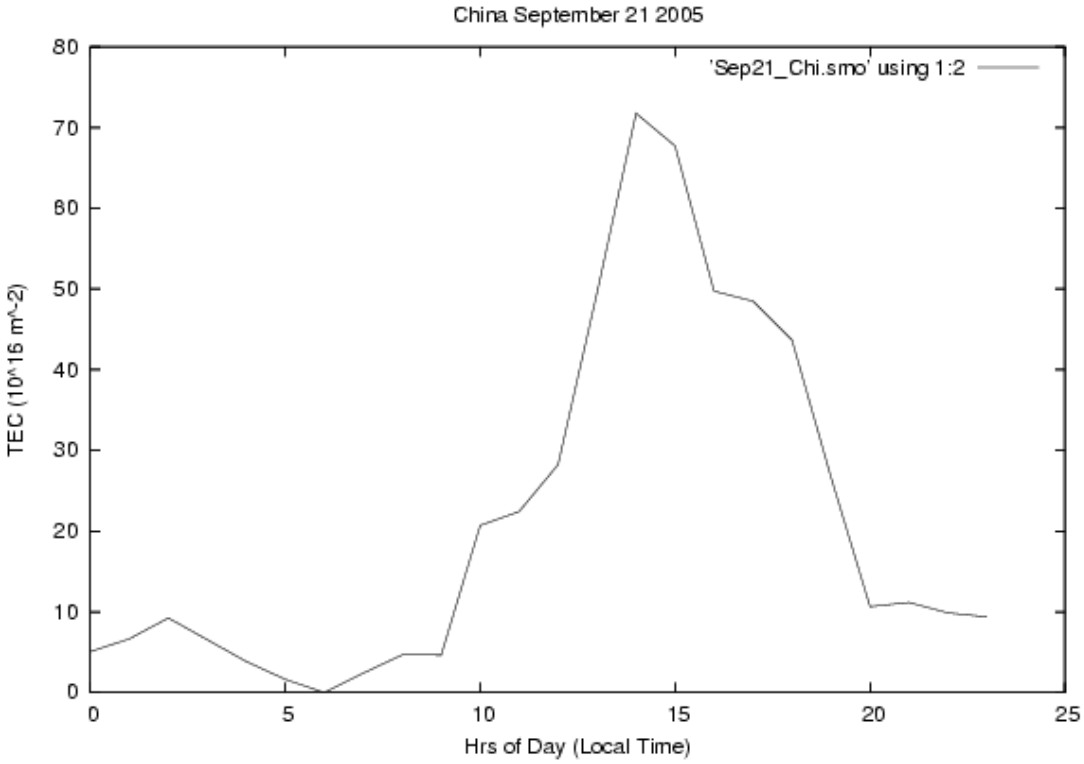
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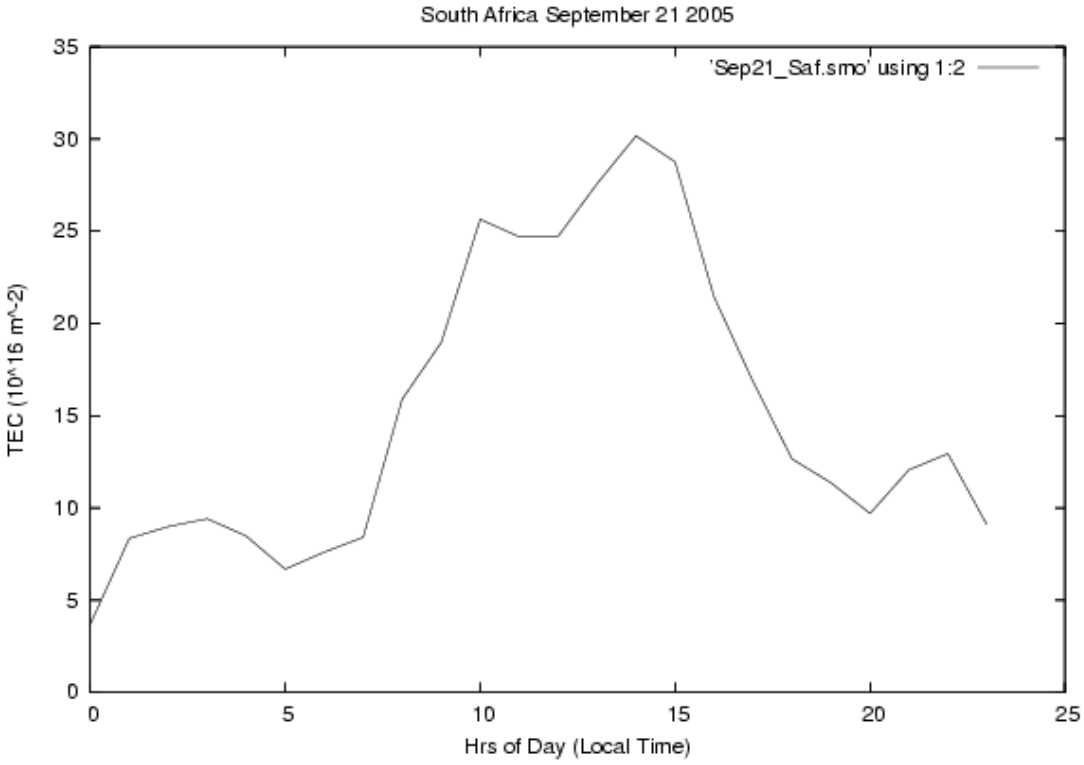
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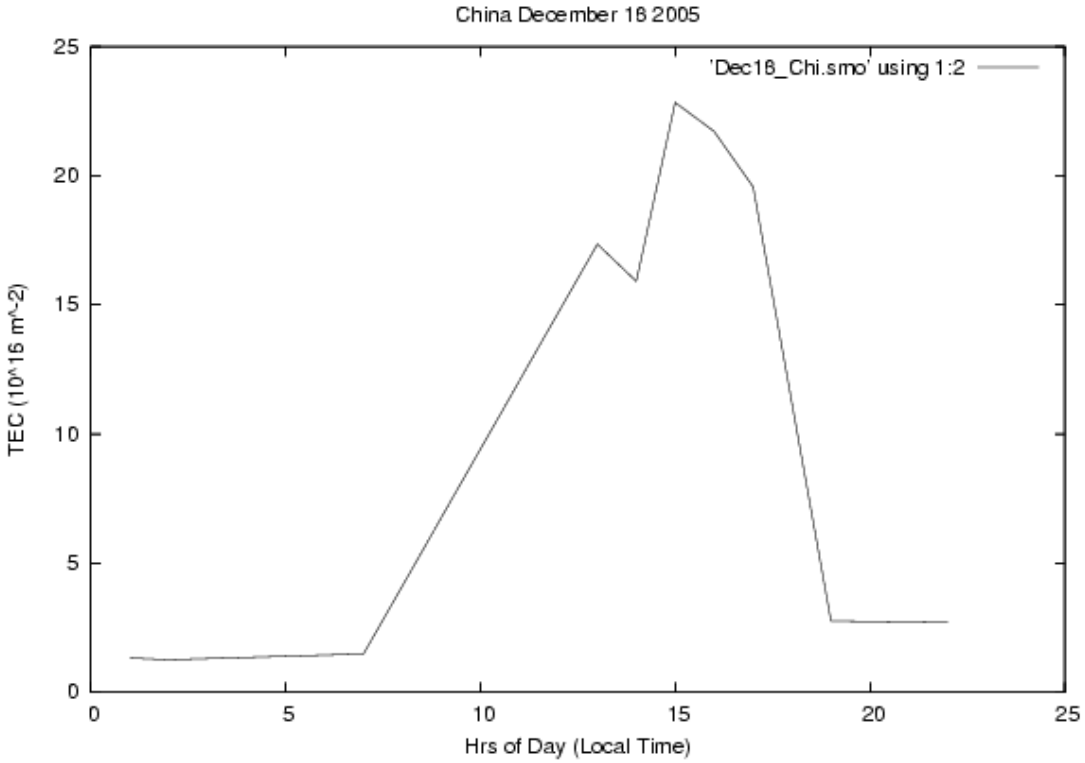
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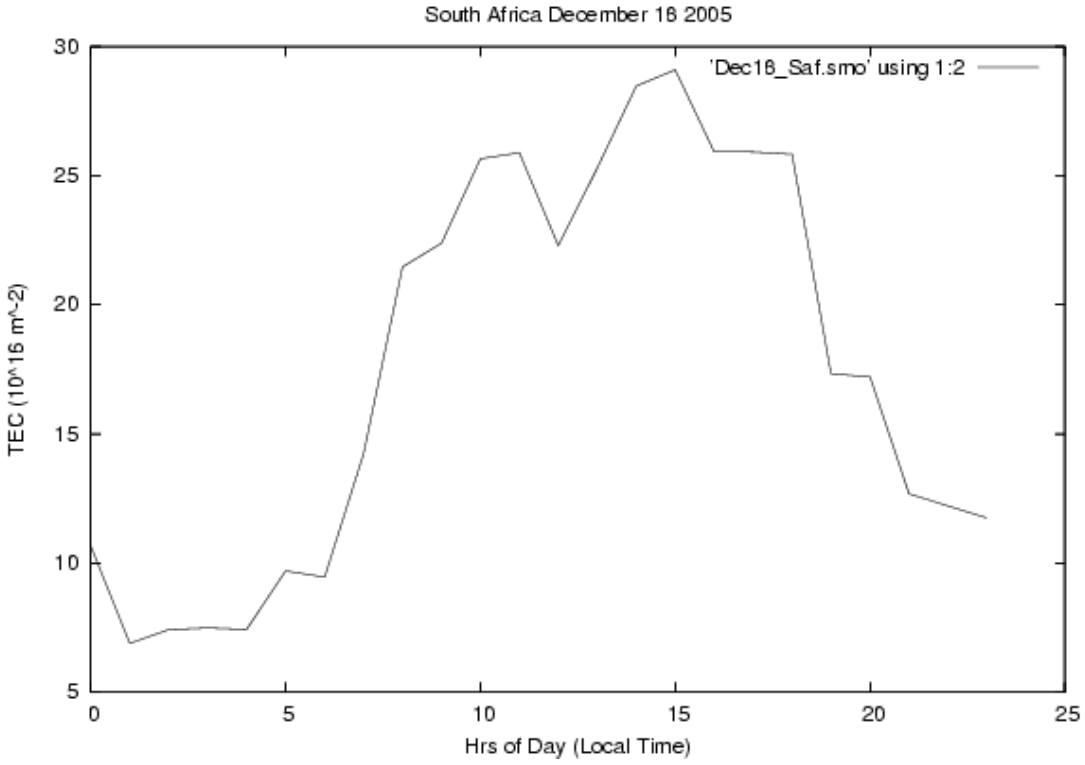
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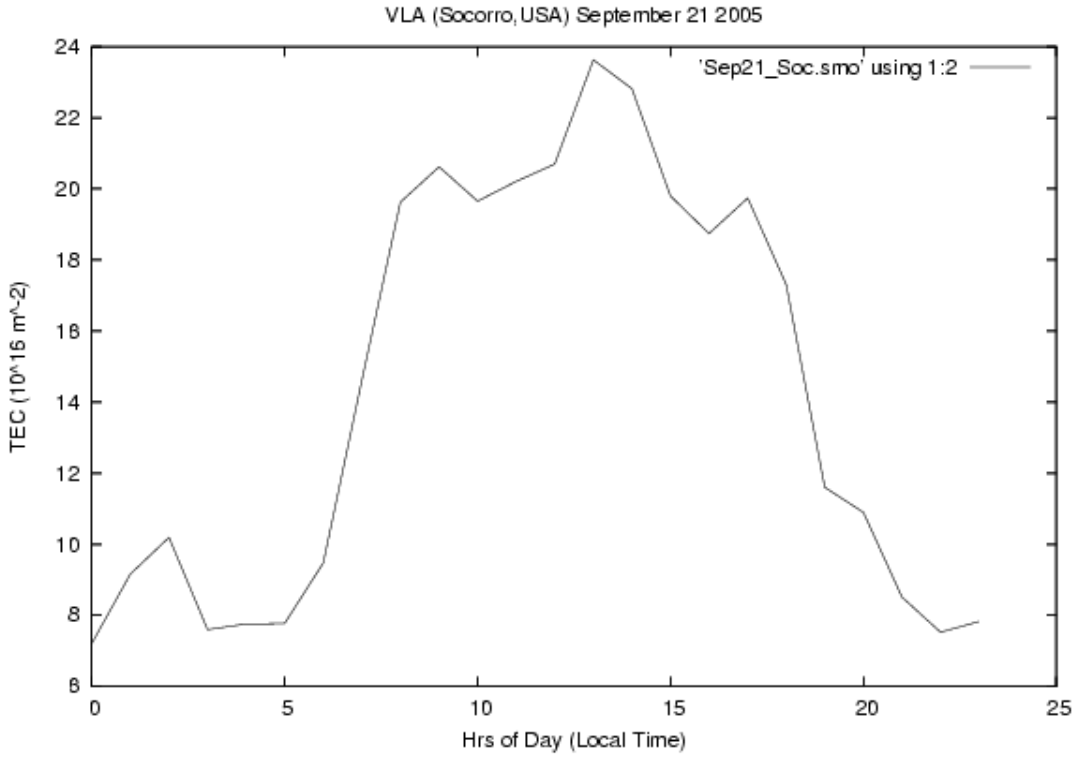
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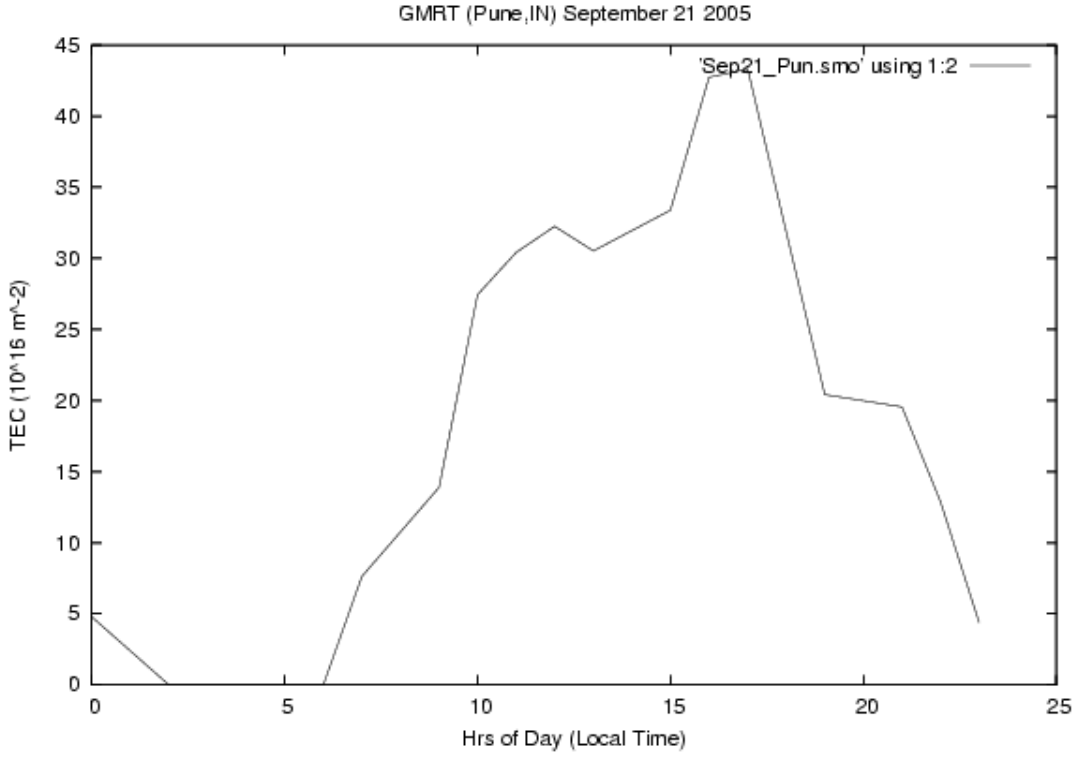
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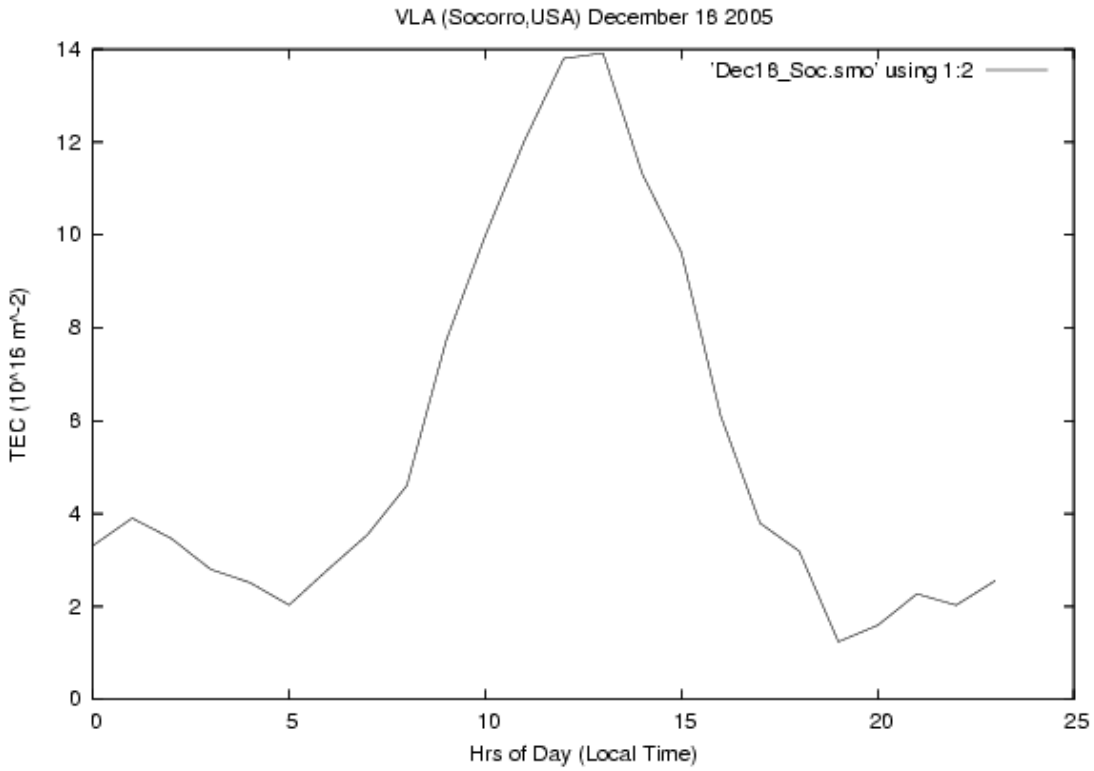
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TEC (10^16 m^-2)
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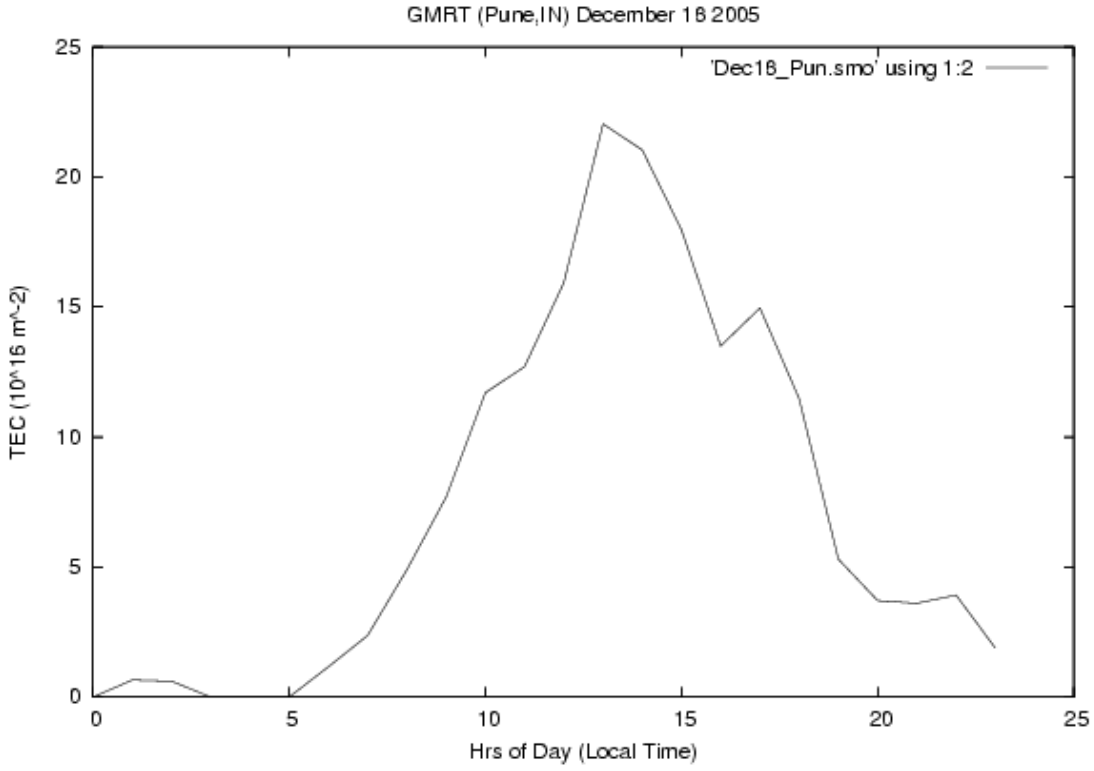
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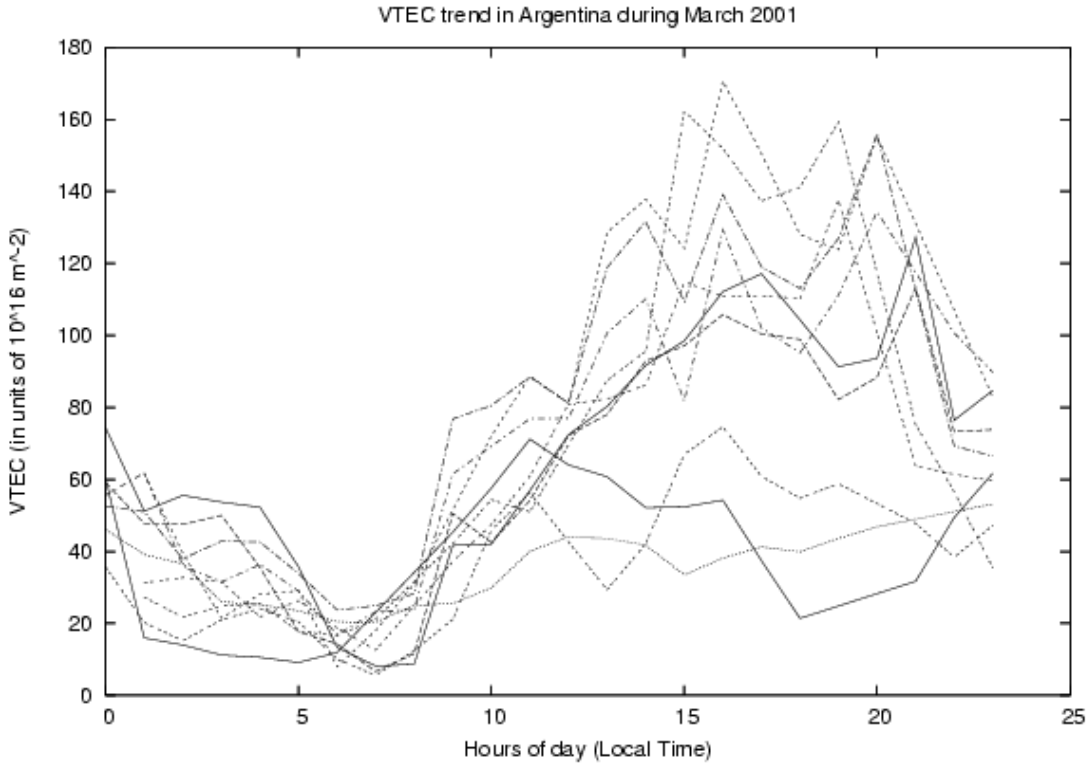
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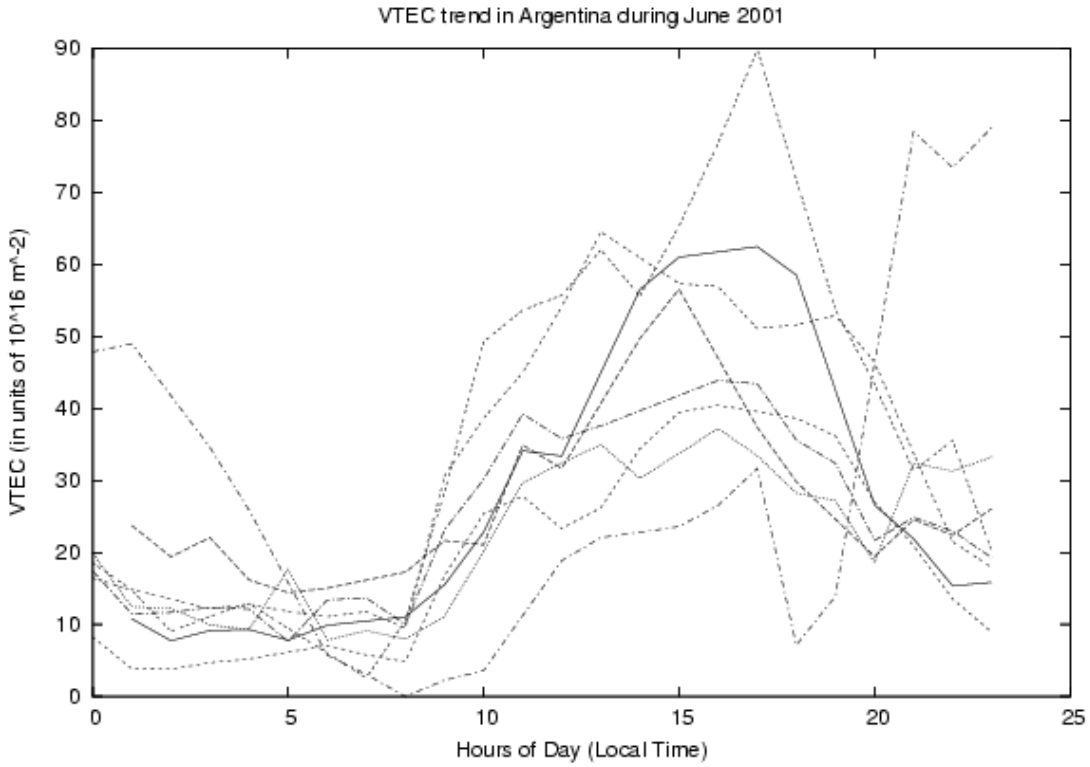
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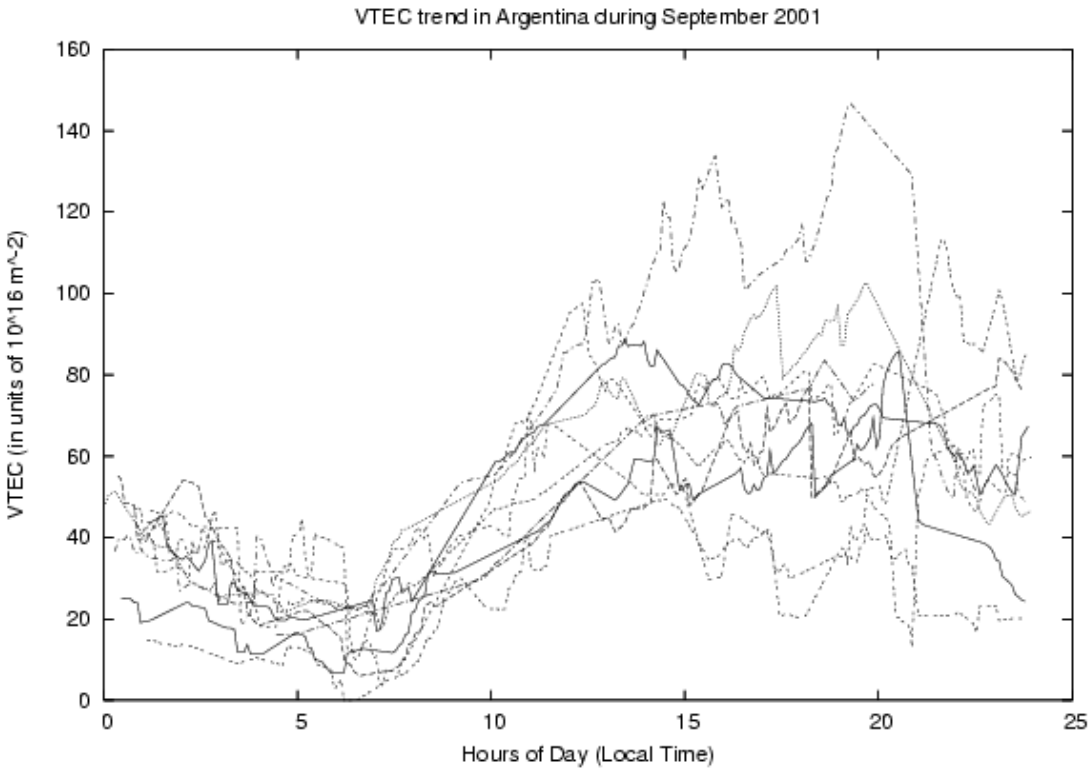
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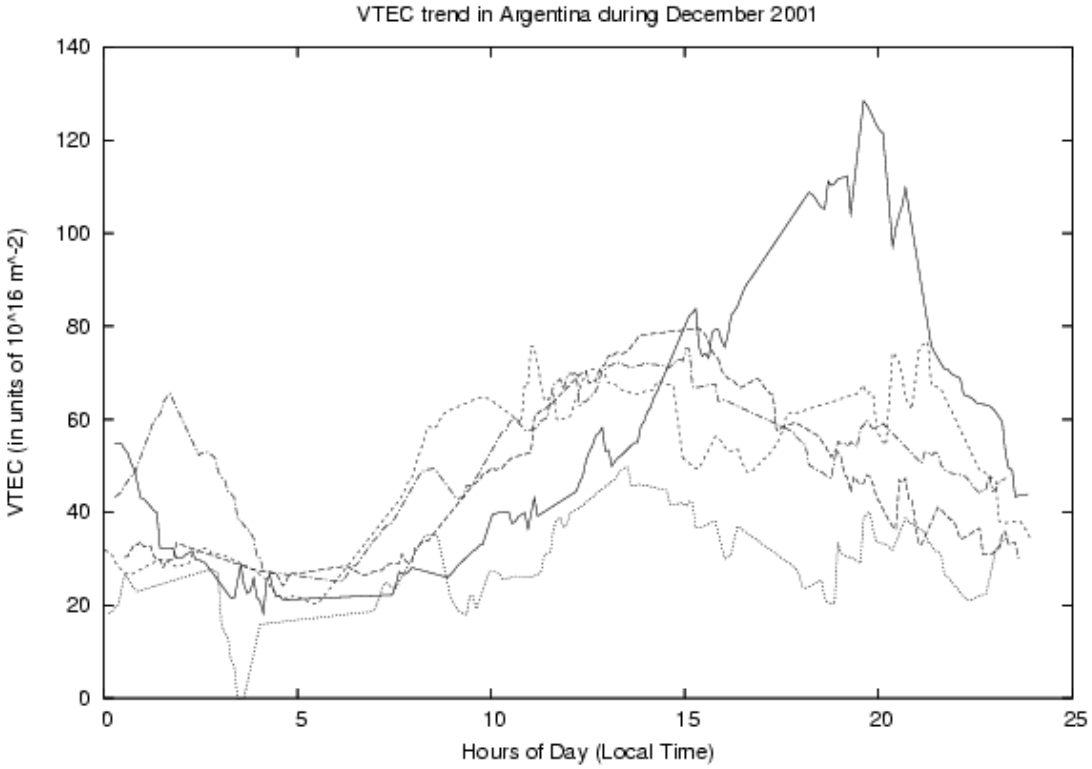
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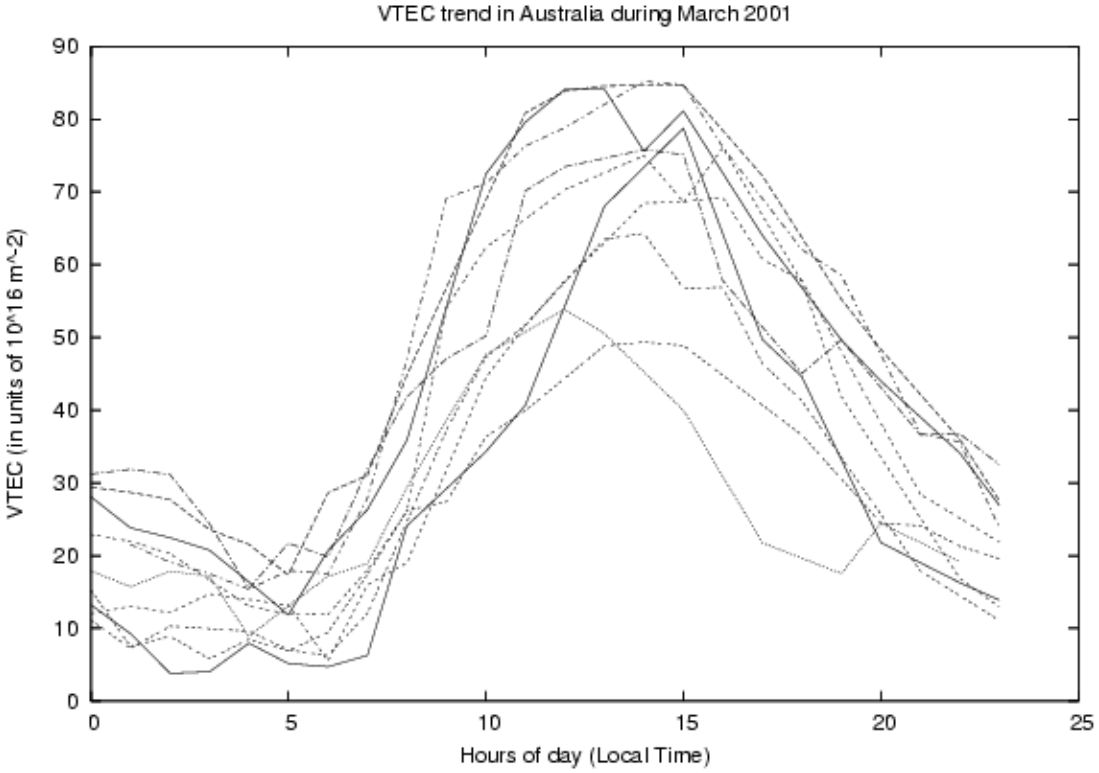
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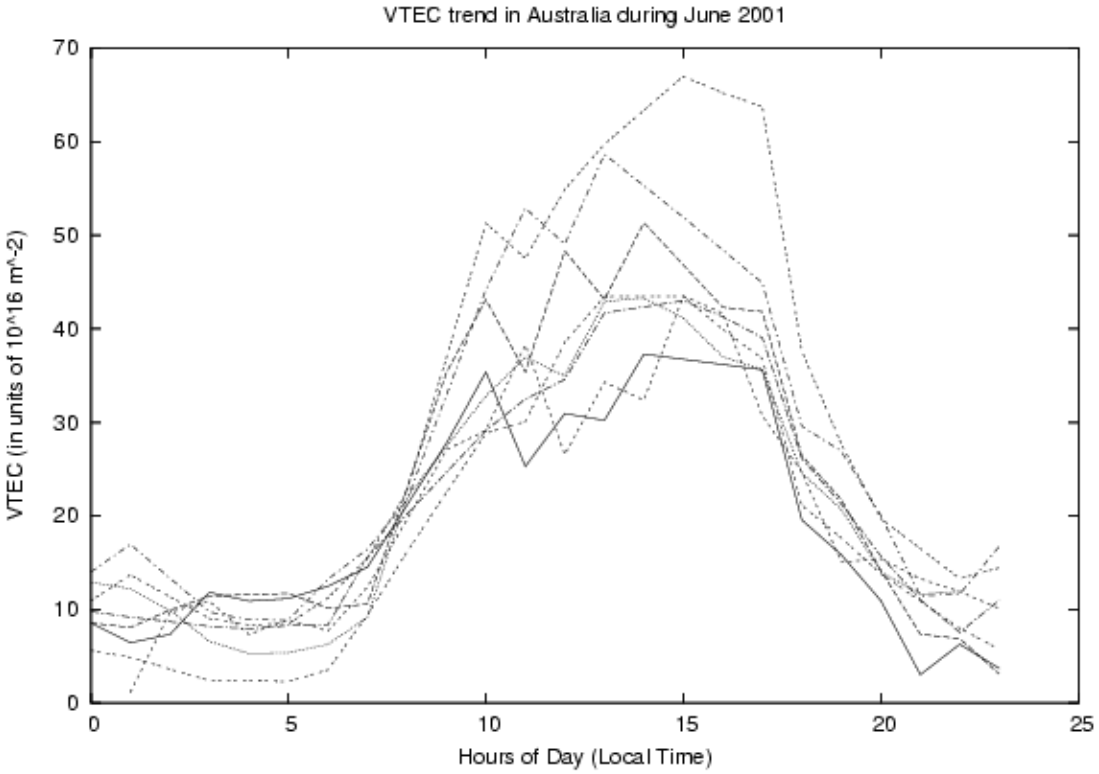
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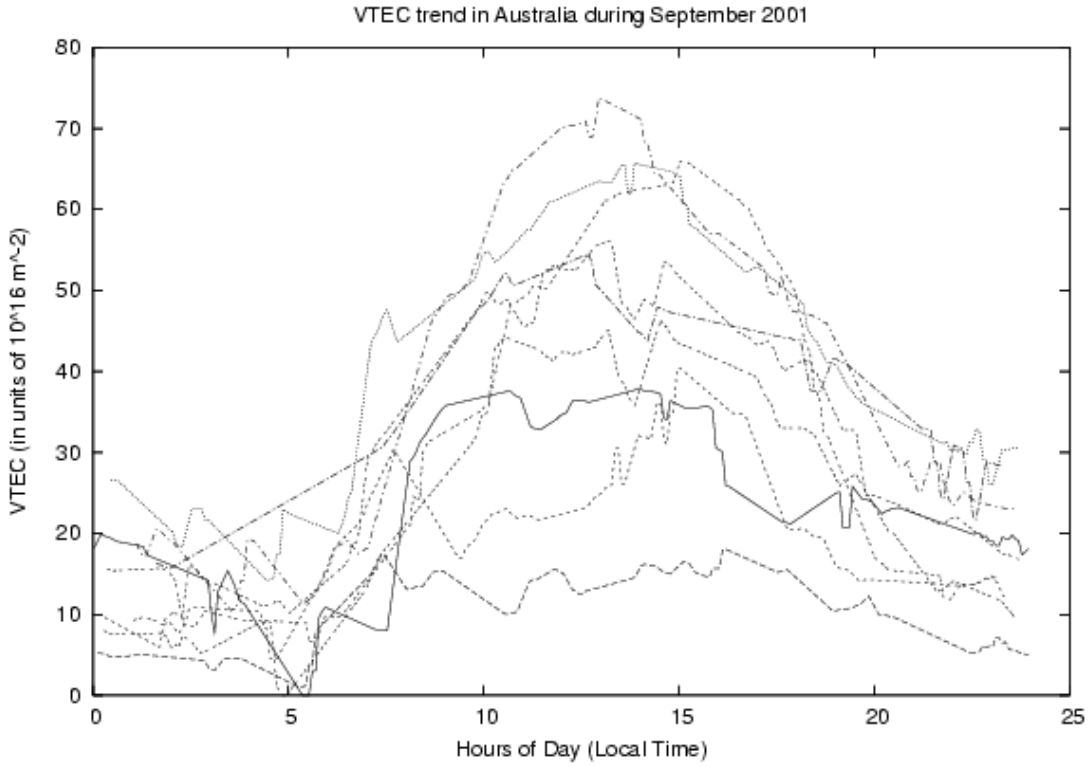
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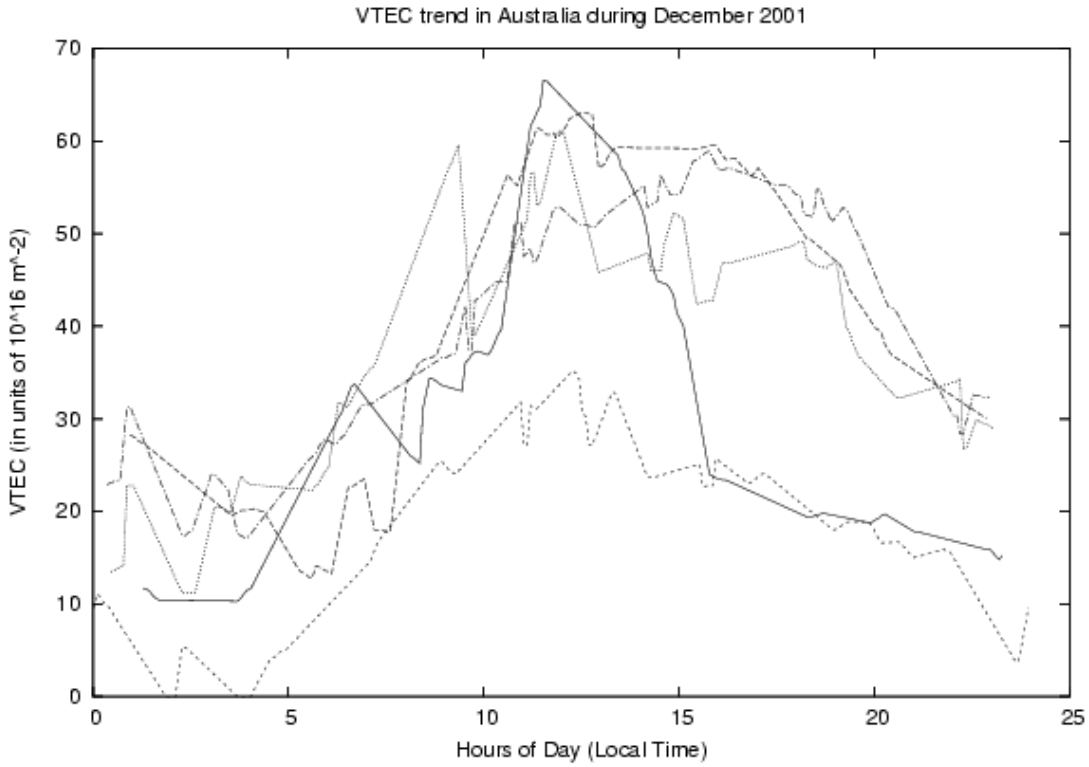
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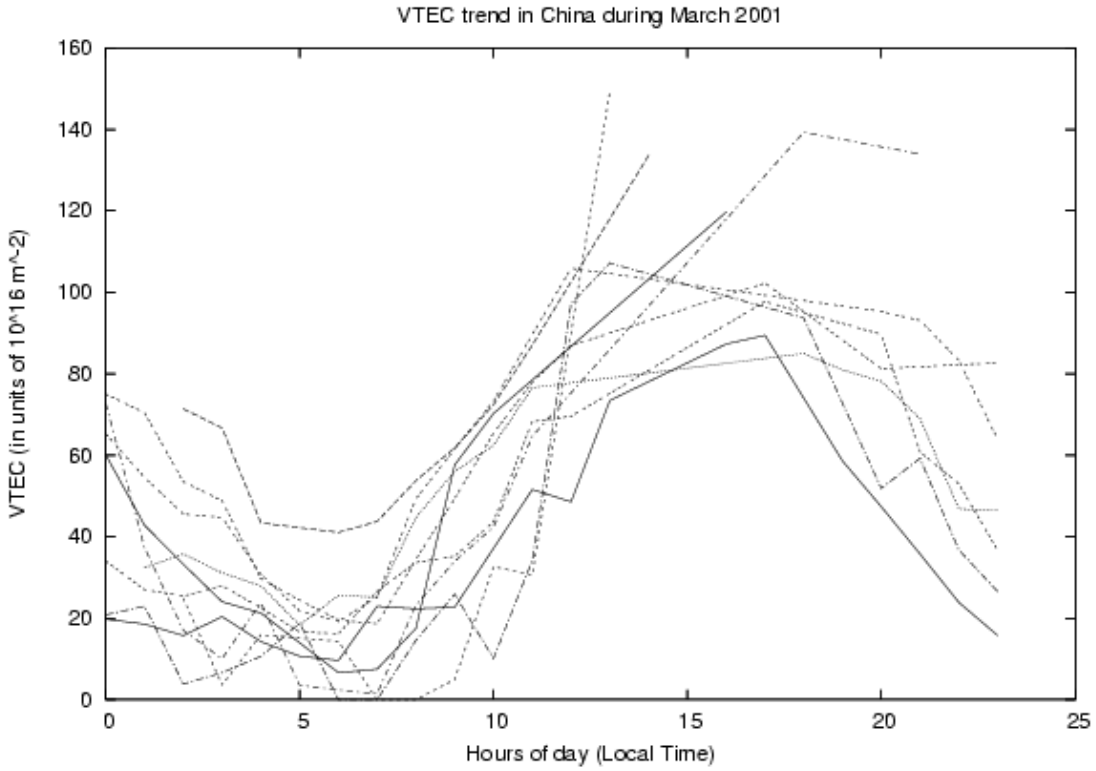
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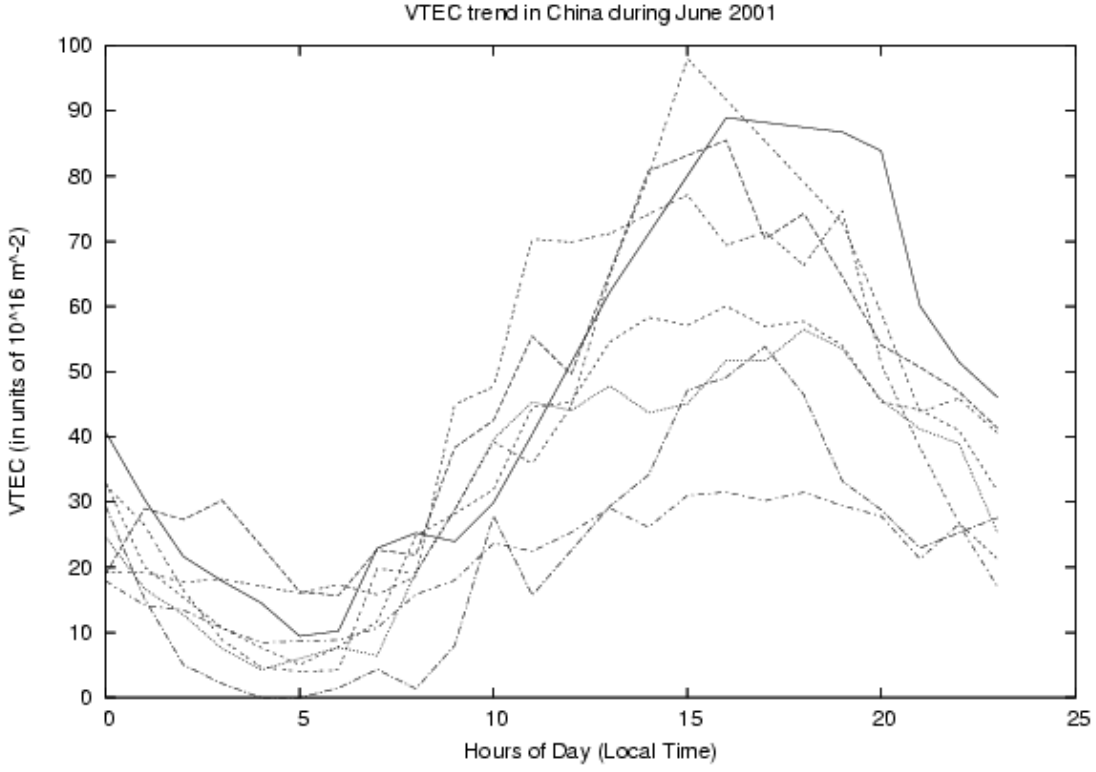
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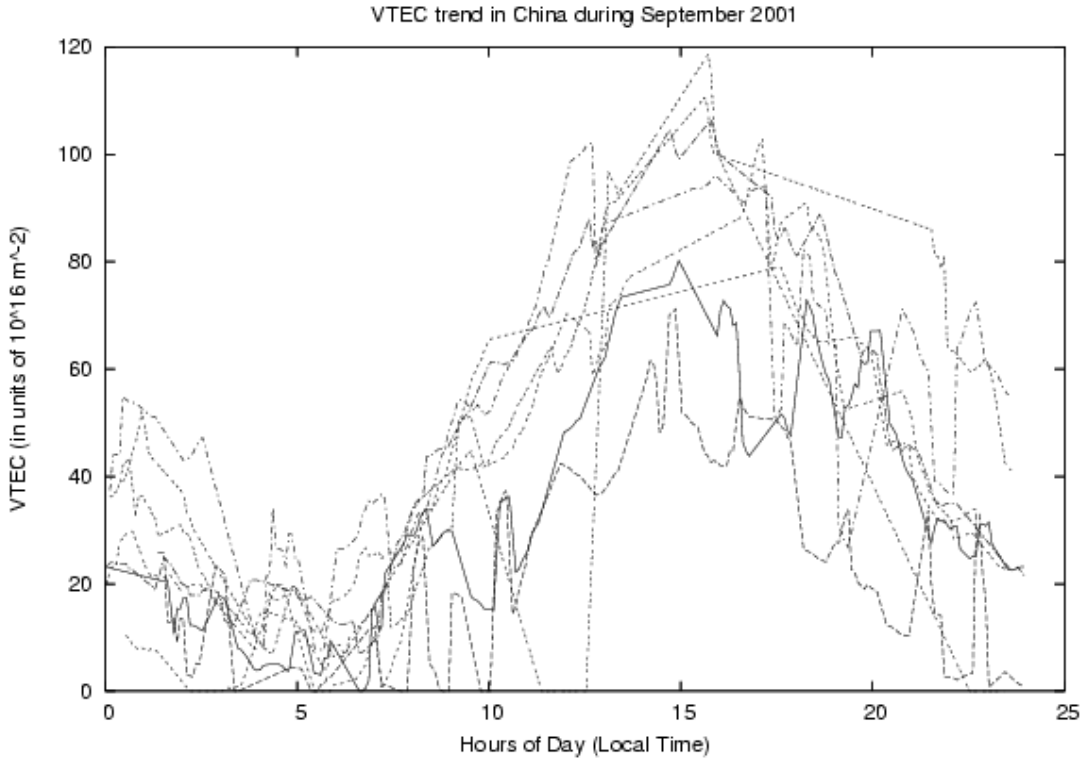
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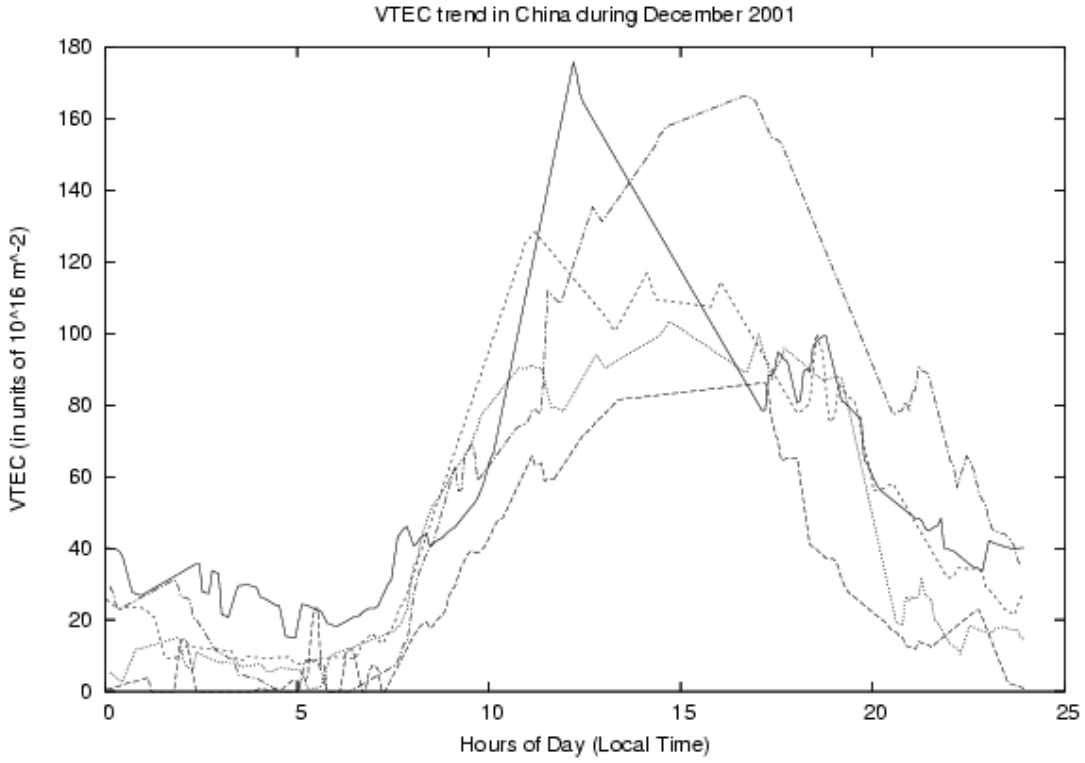
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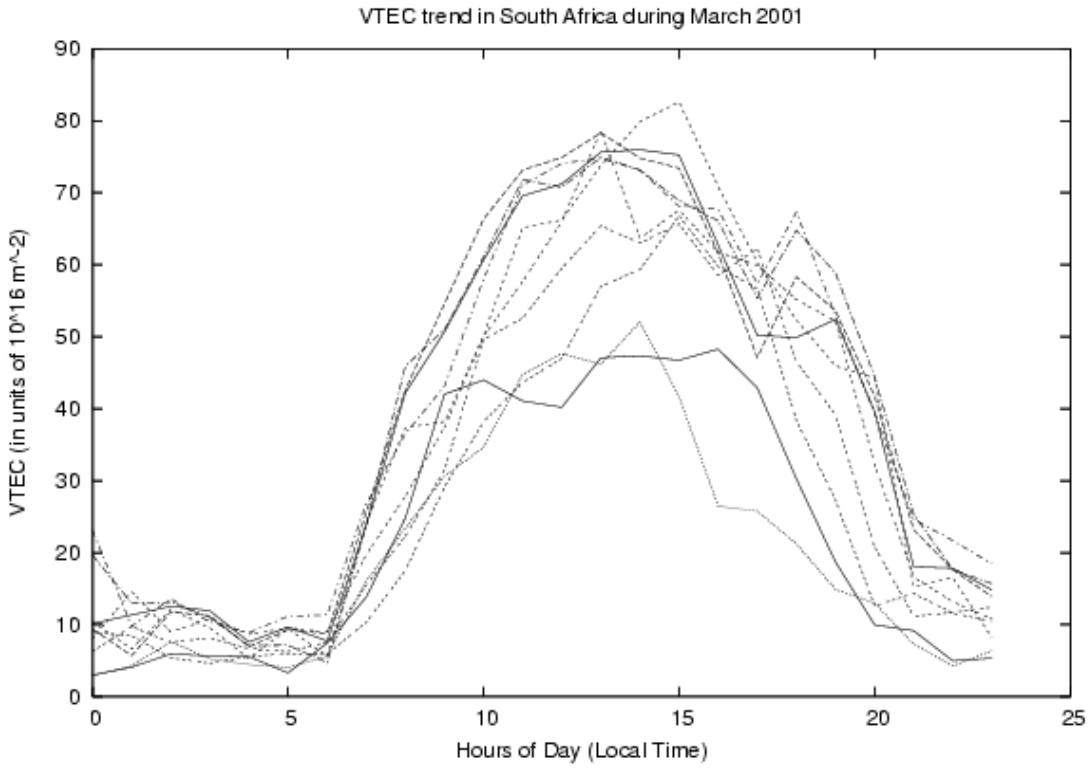
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VTEC (in units of 10^16 m^-2)
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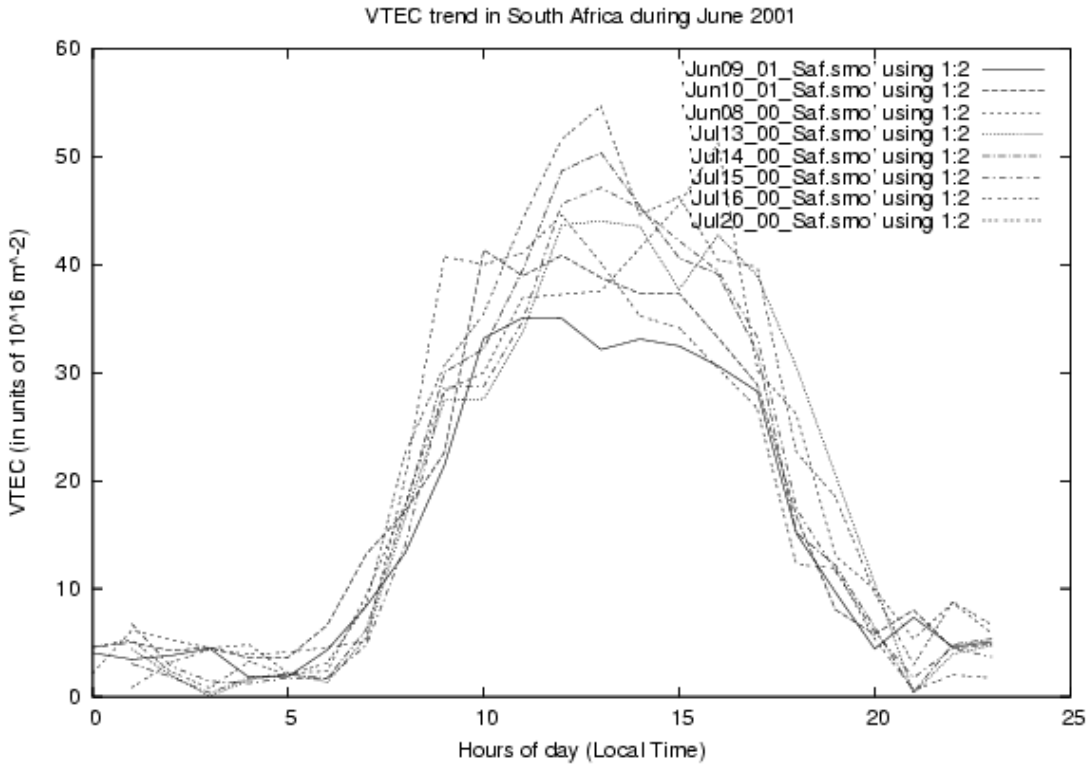
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VTEC (in units of 10^16 m^-2)
Hours of day (Local Time)
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'Jun10_01_Saf.smo' using 1:2
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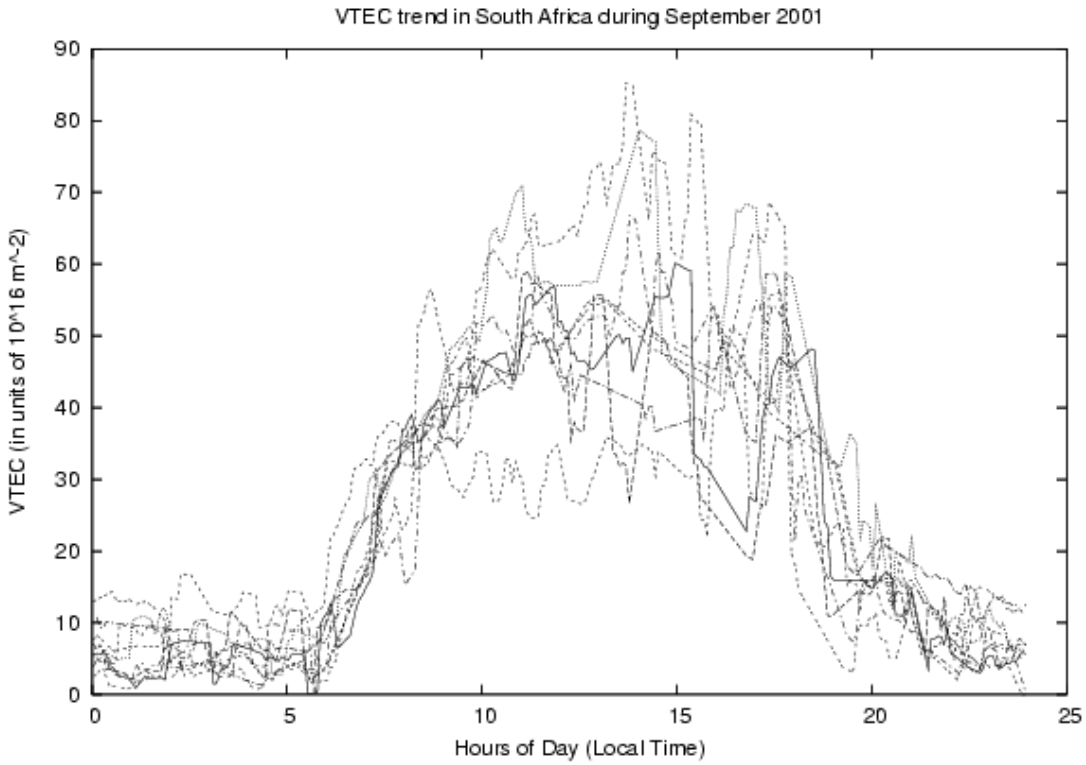
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VTEC (in units of 10^16 m^-2)
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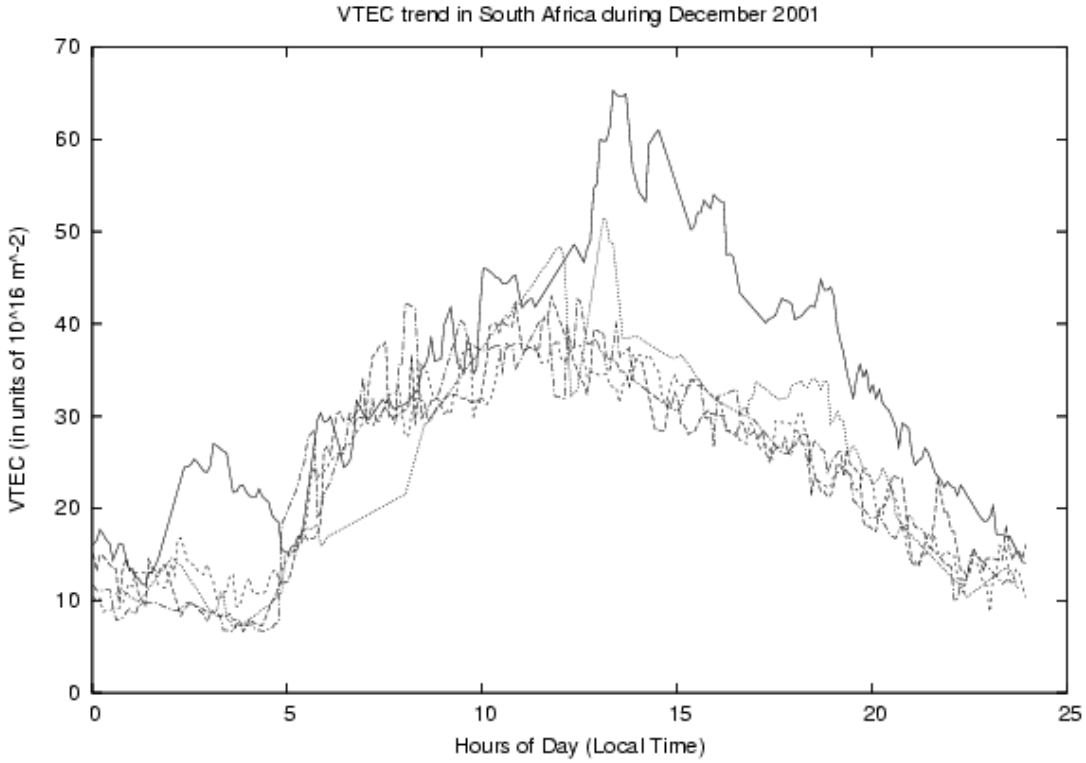
VTEC trend in South Africa during December 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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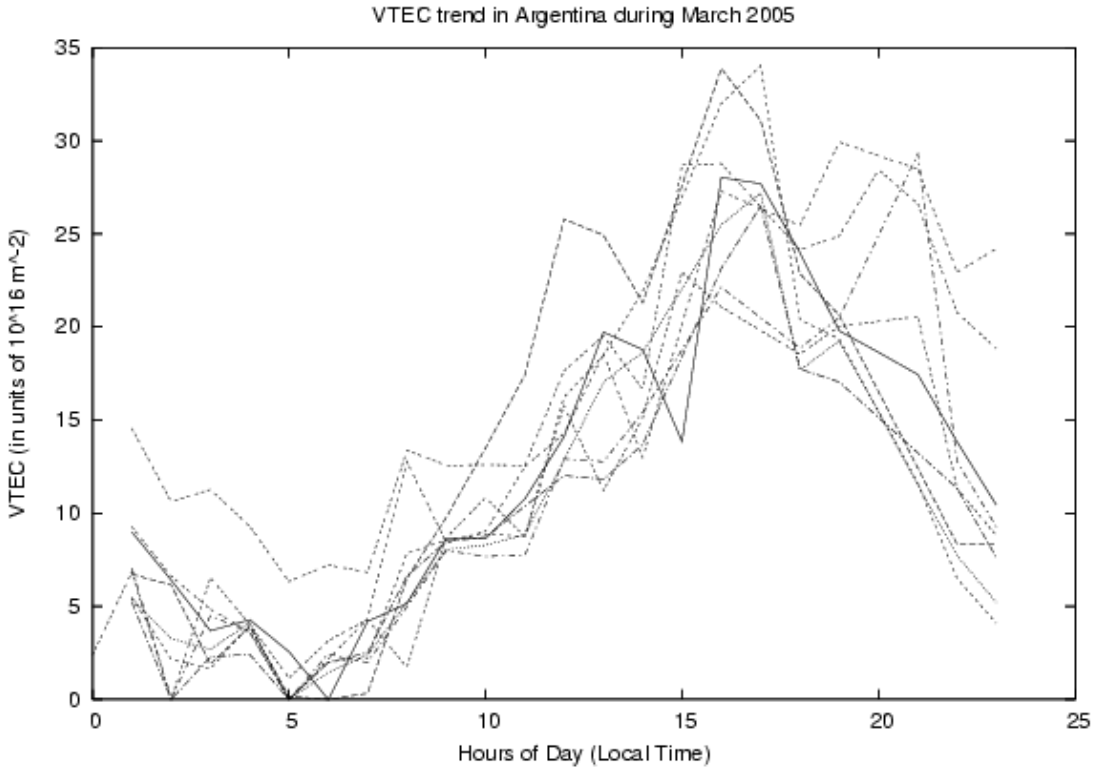
VTEC trend in Argentina during March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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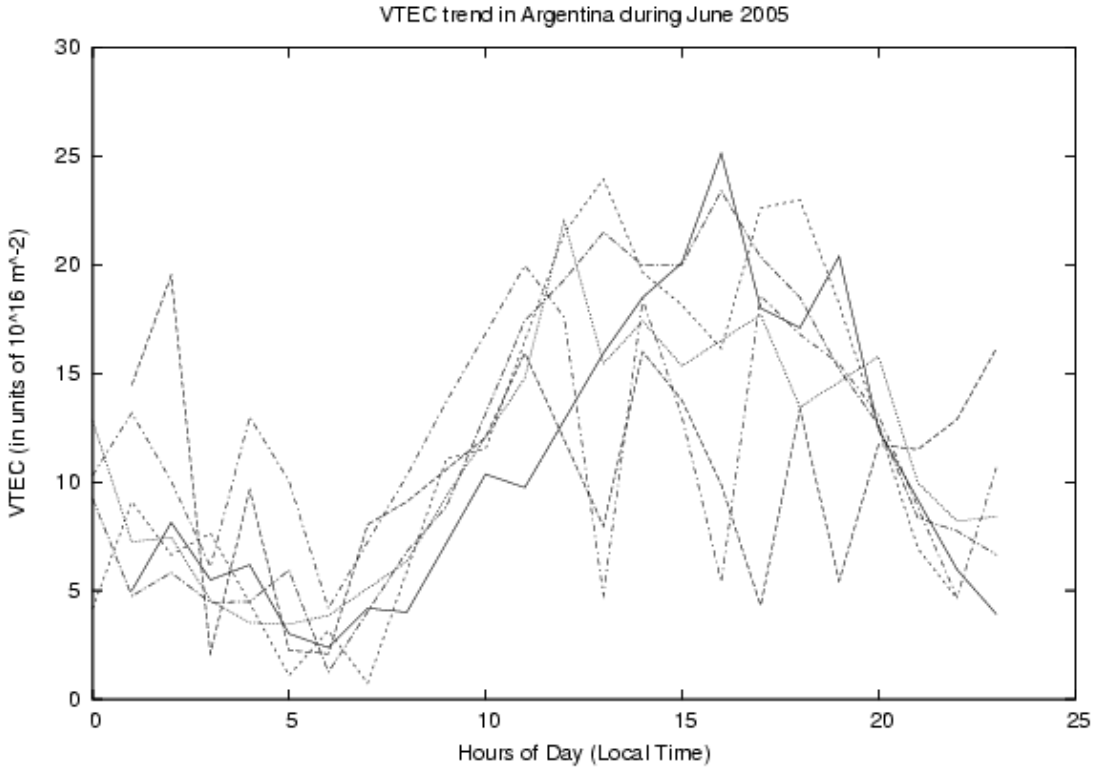
VTEC trend in Argentina during June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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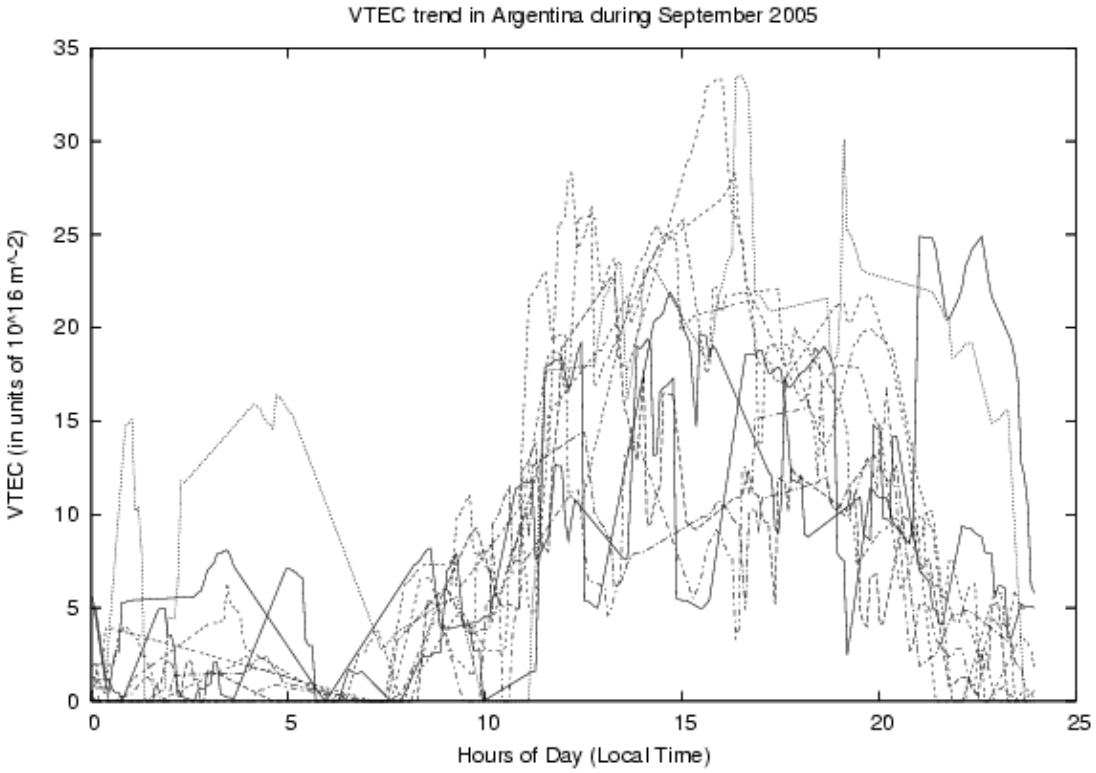
VTEC trend in Argentina during September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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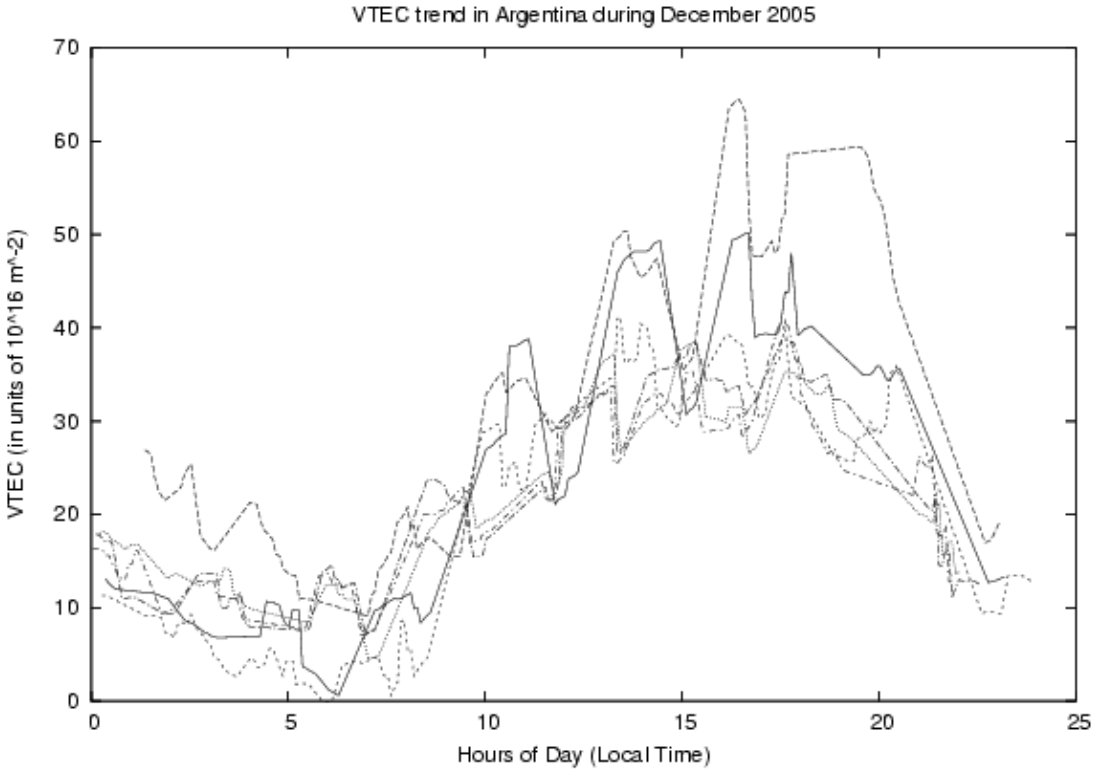
VTEC trend in Argentina during December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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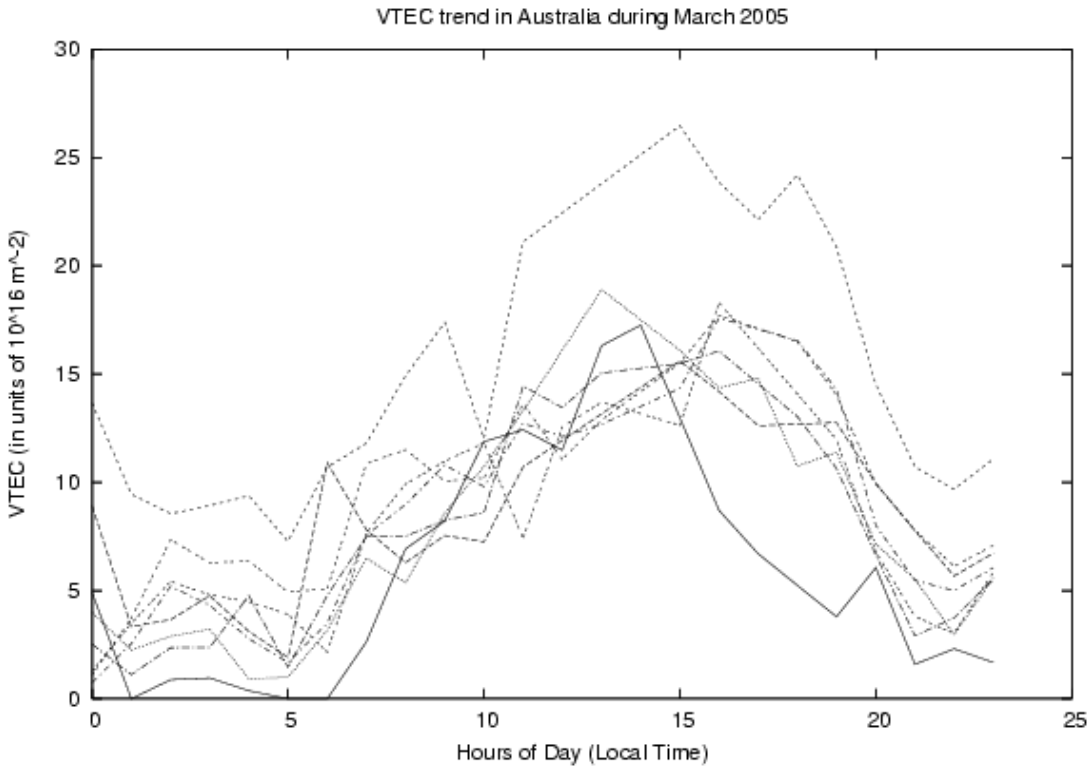
VTEC trend in Australia during March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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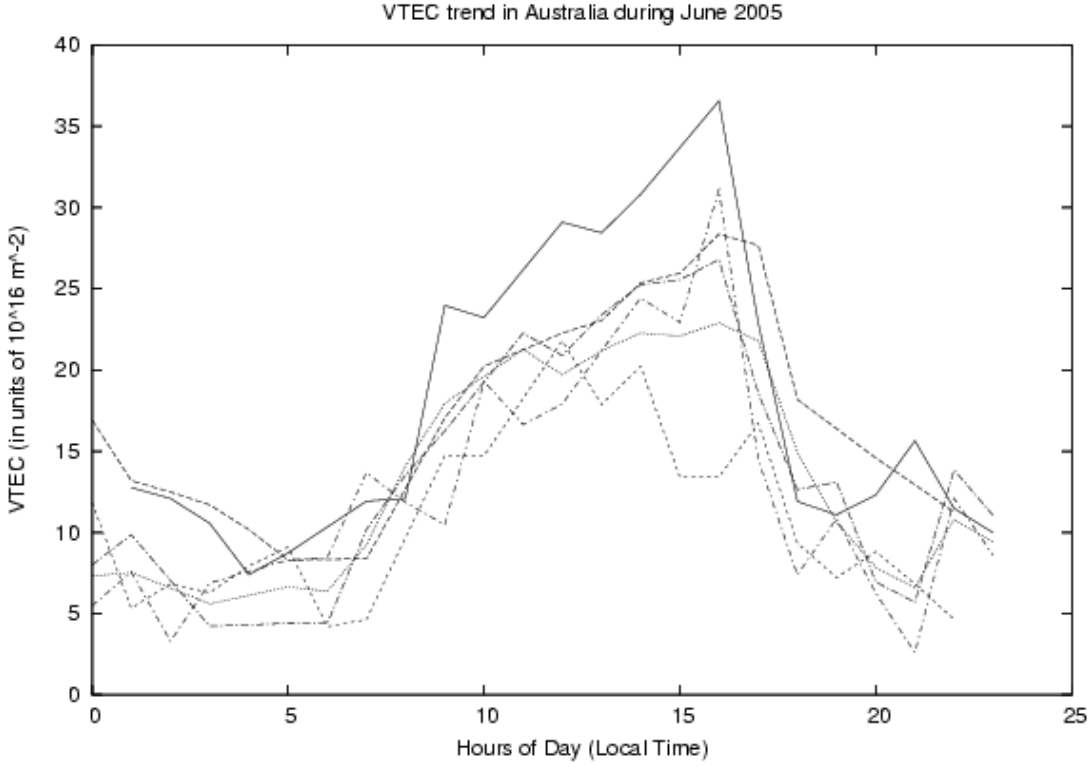
VTEC trend in Australia during June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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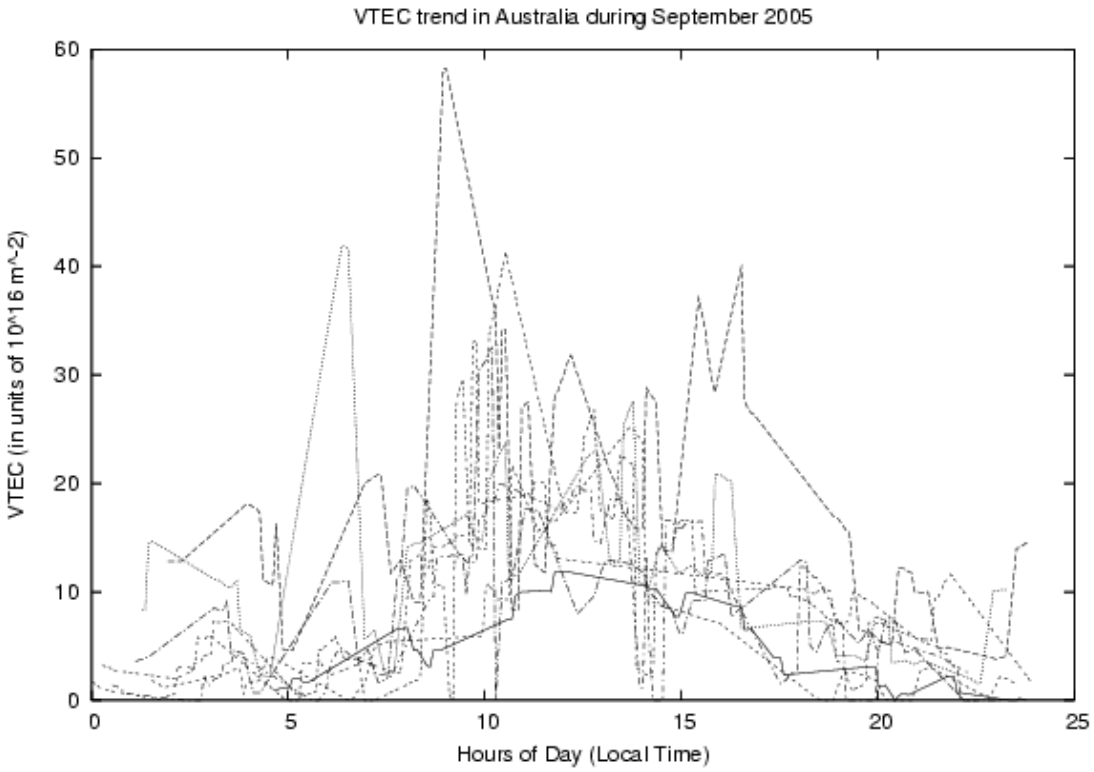
VTEC trend in Australia during September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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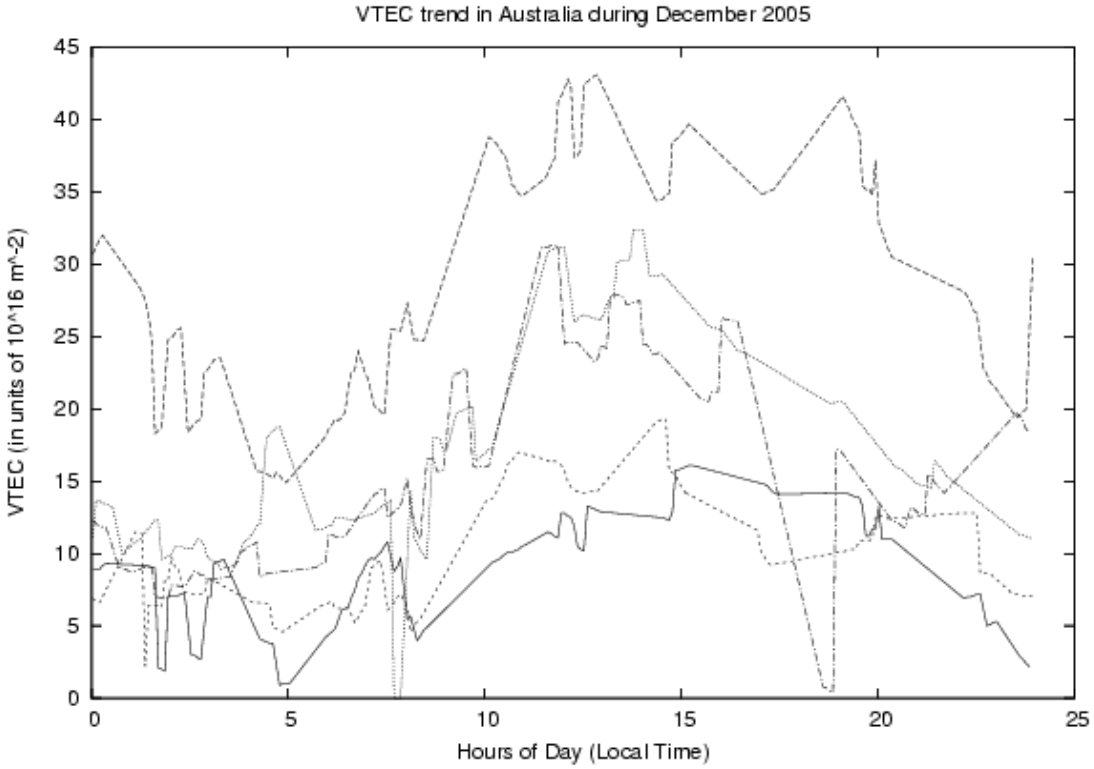
VTEC trend in Australia during December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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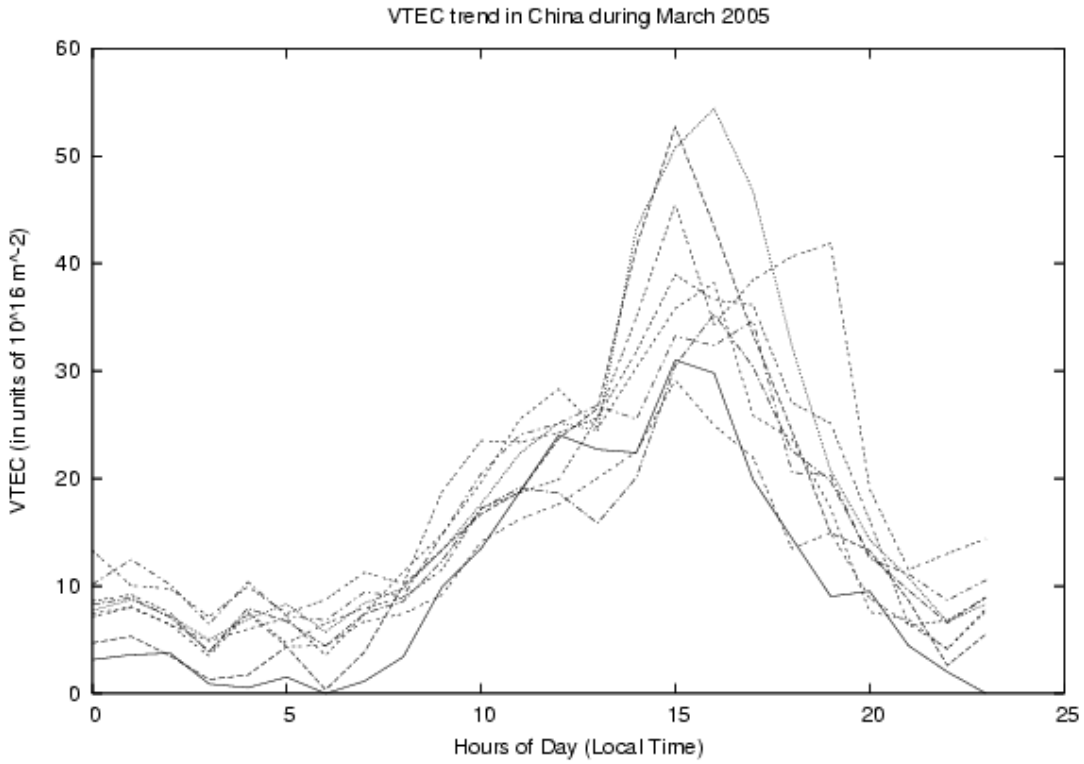
VTEC trend in China during March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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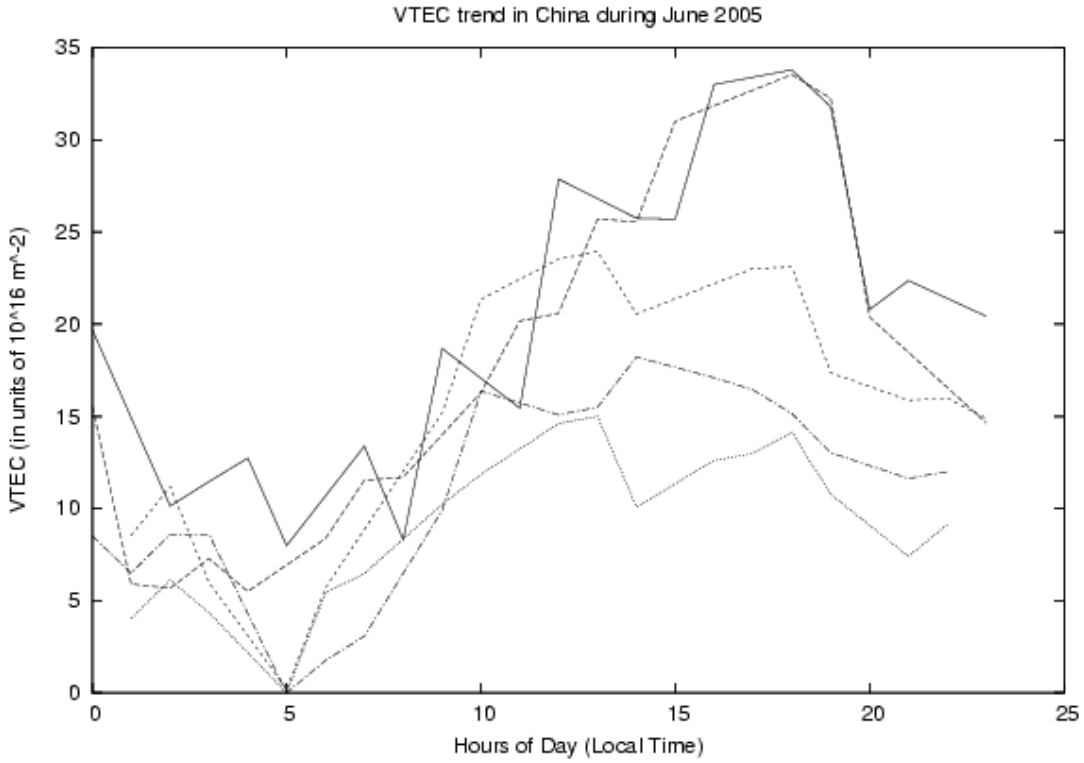
VTEC trend in China during June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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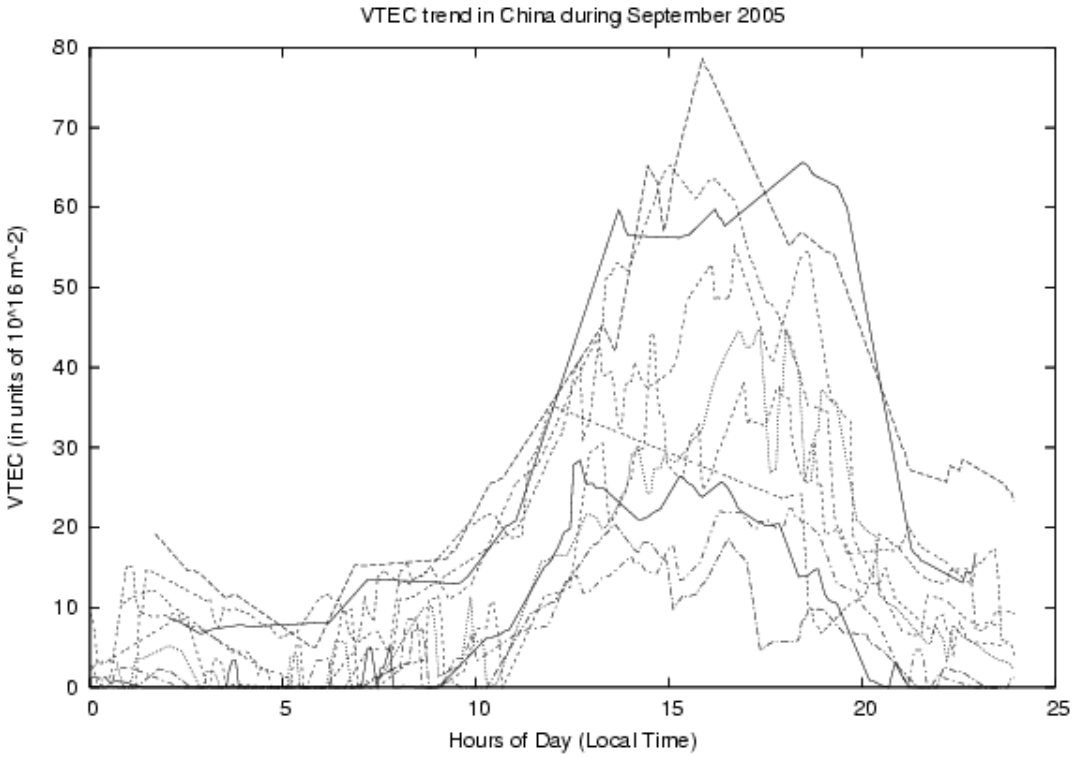
VTEC trend in China during September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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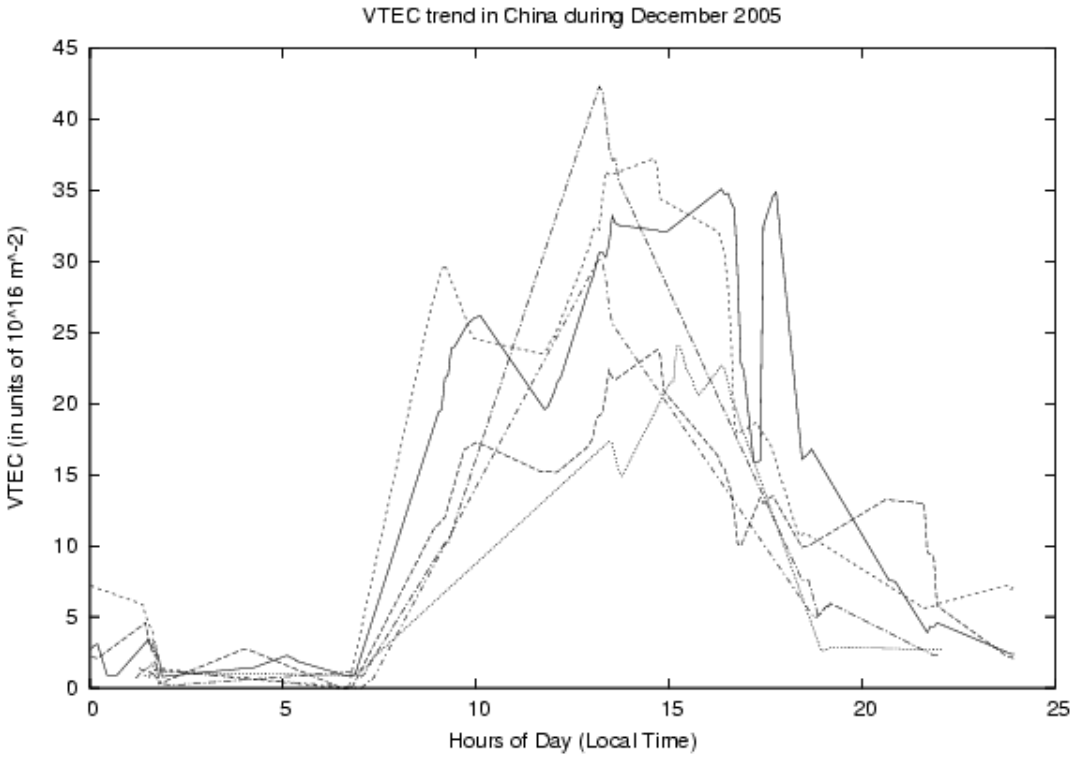
VTEC trend in China during December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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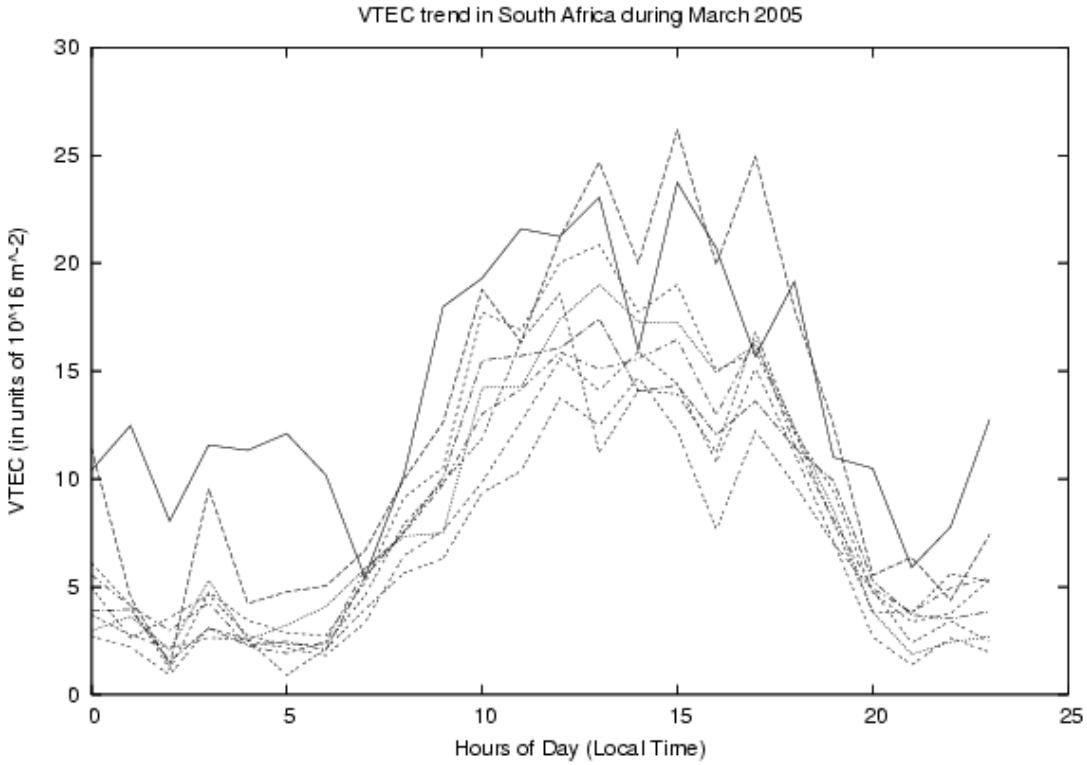
VTEC trend in South Africa during March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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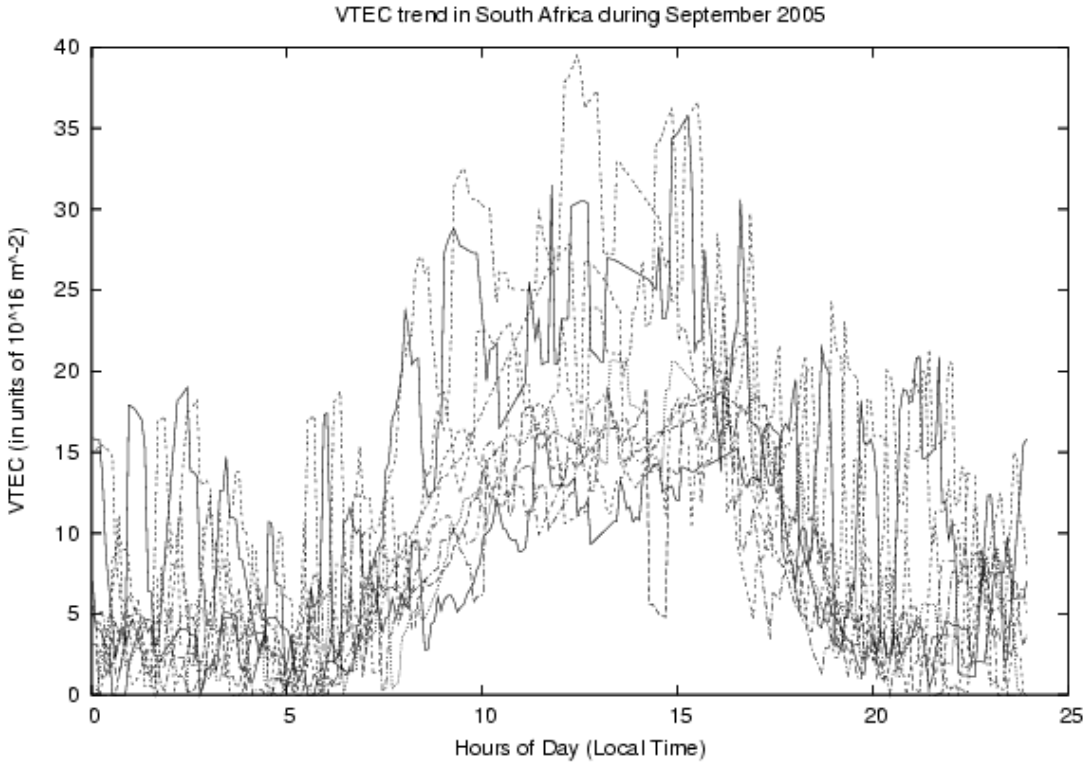
VTEC trend in South Africa during September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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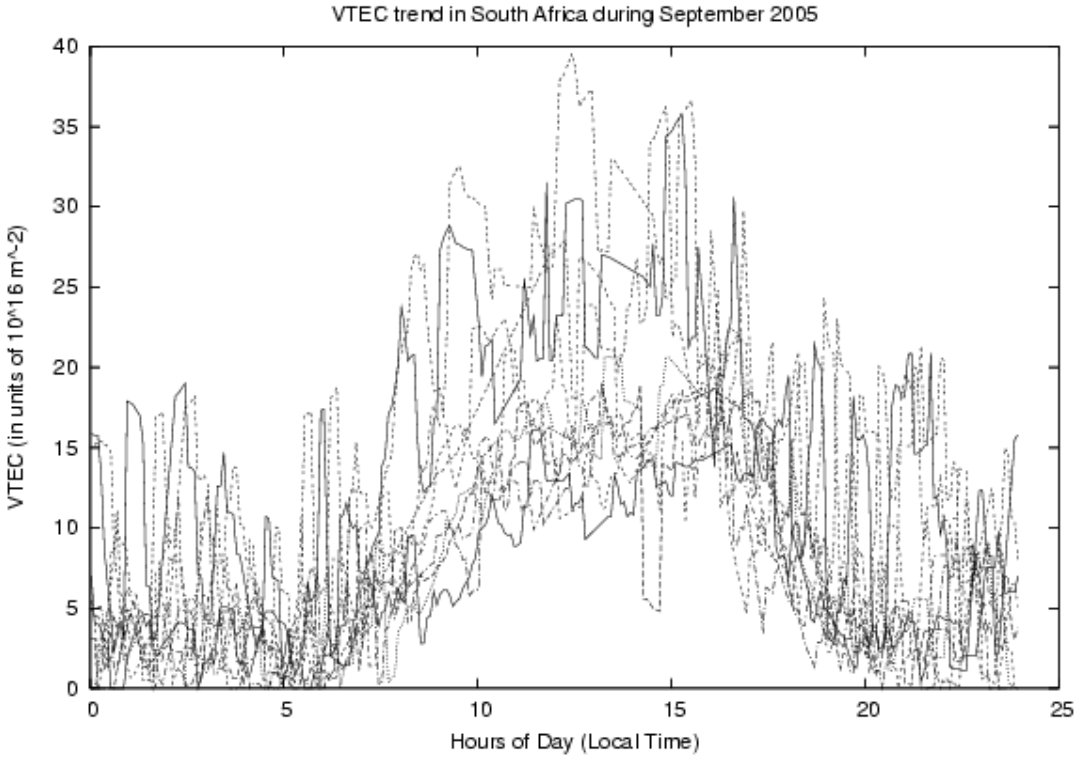
VTEC trend in South Africa during September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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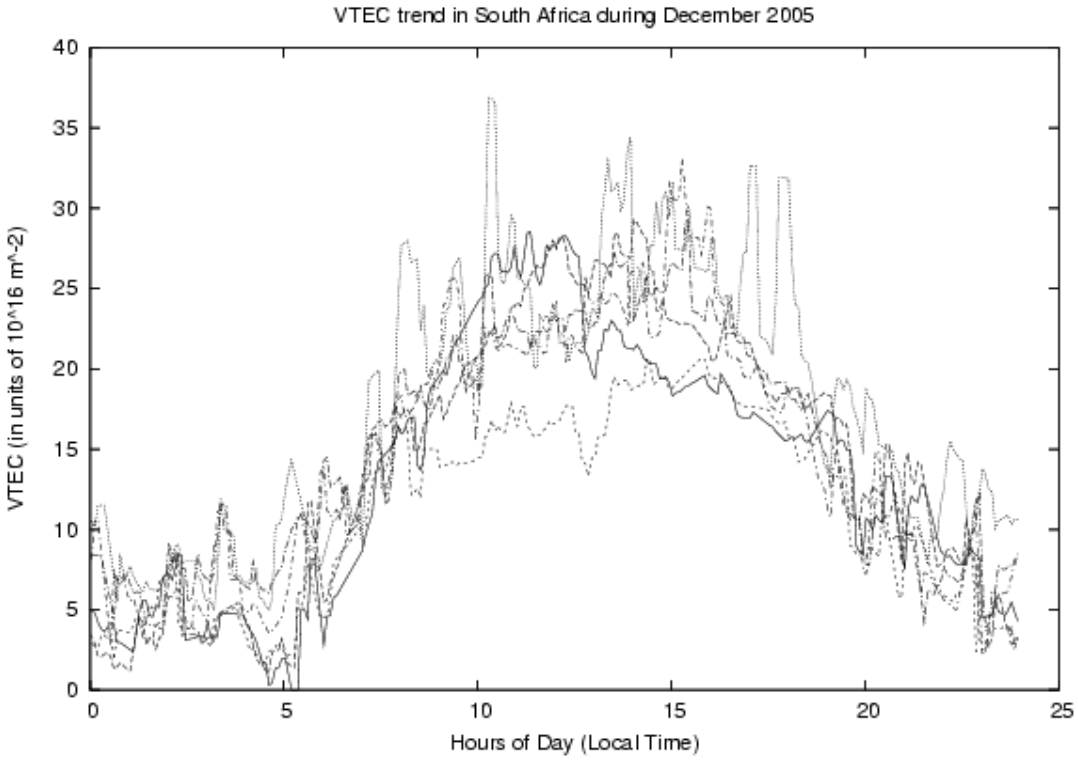
VTEC trend in South Africa during December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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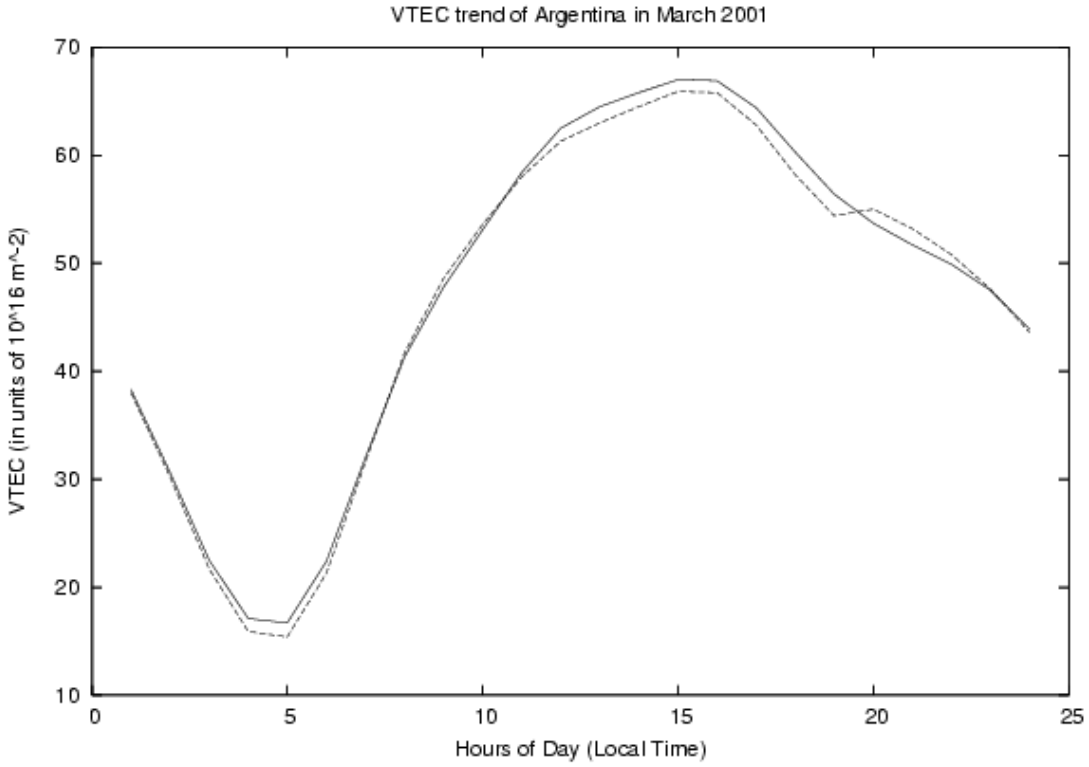
VTEC trend of Argentina in March 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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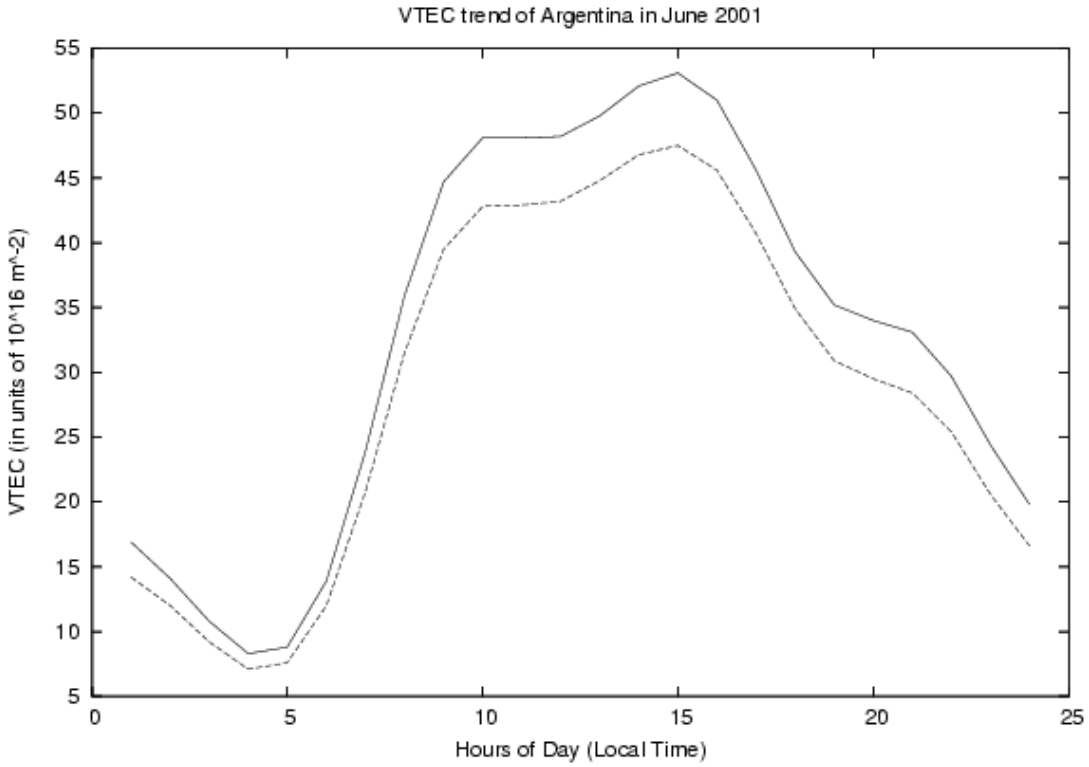
VTEC trend of Argentina in June 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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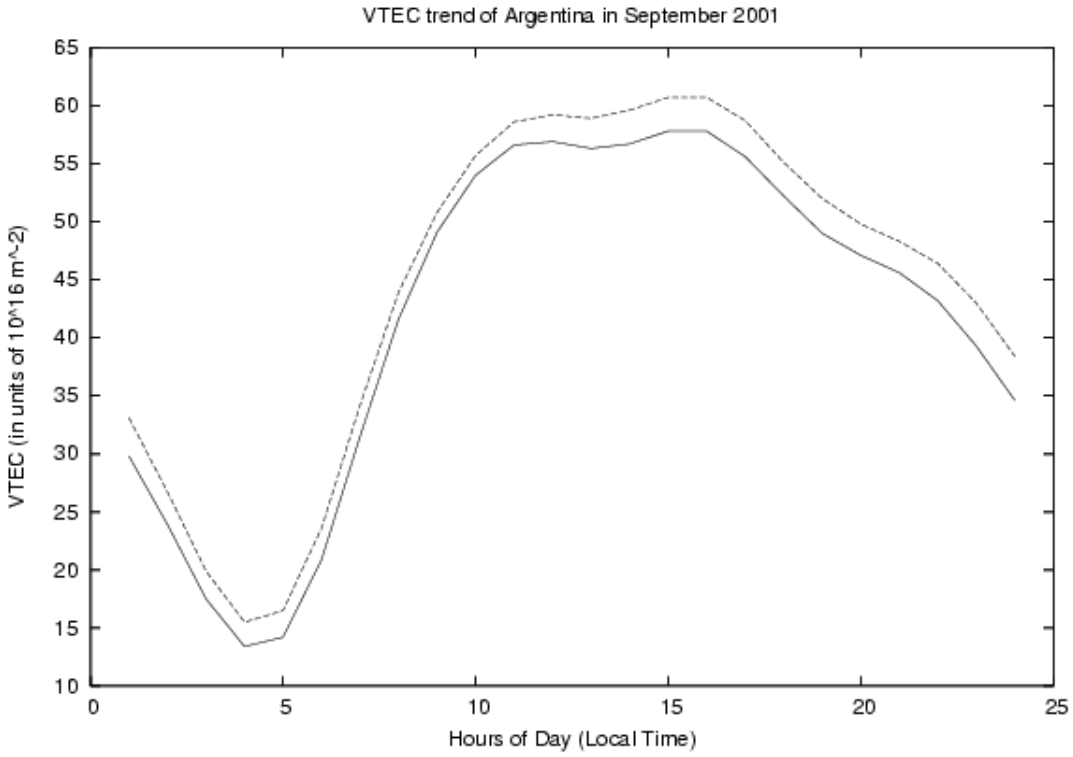
VTEC trend of Argentina in September 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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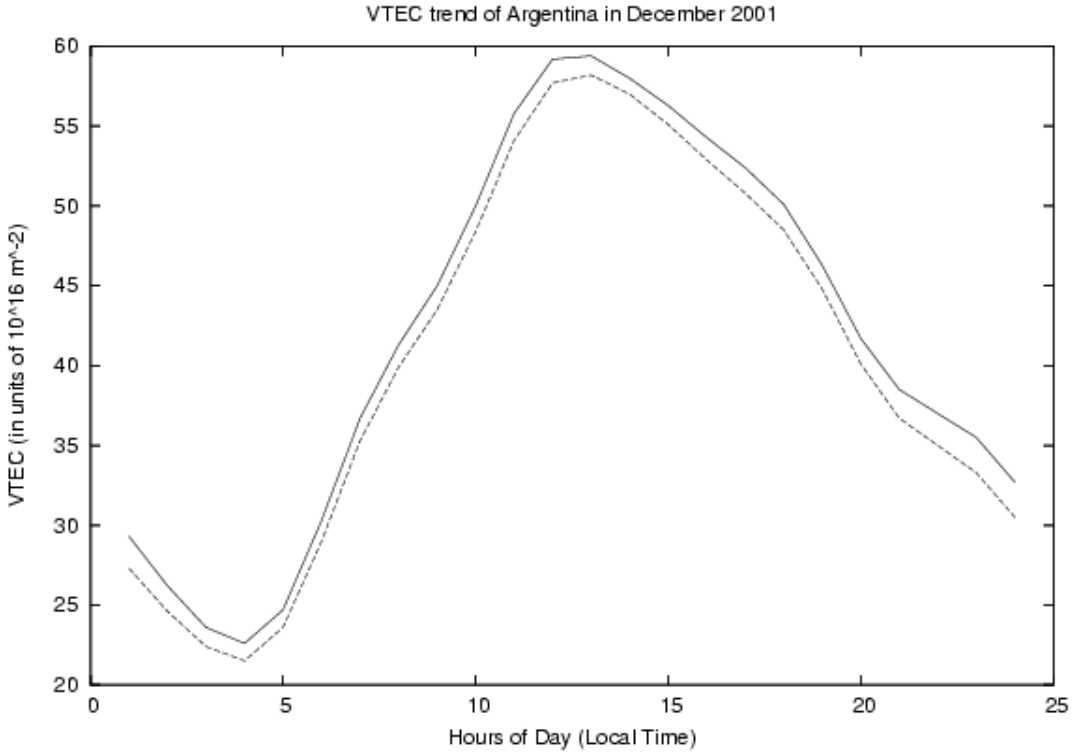
VTEC trend of Argentina in December 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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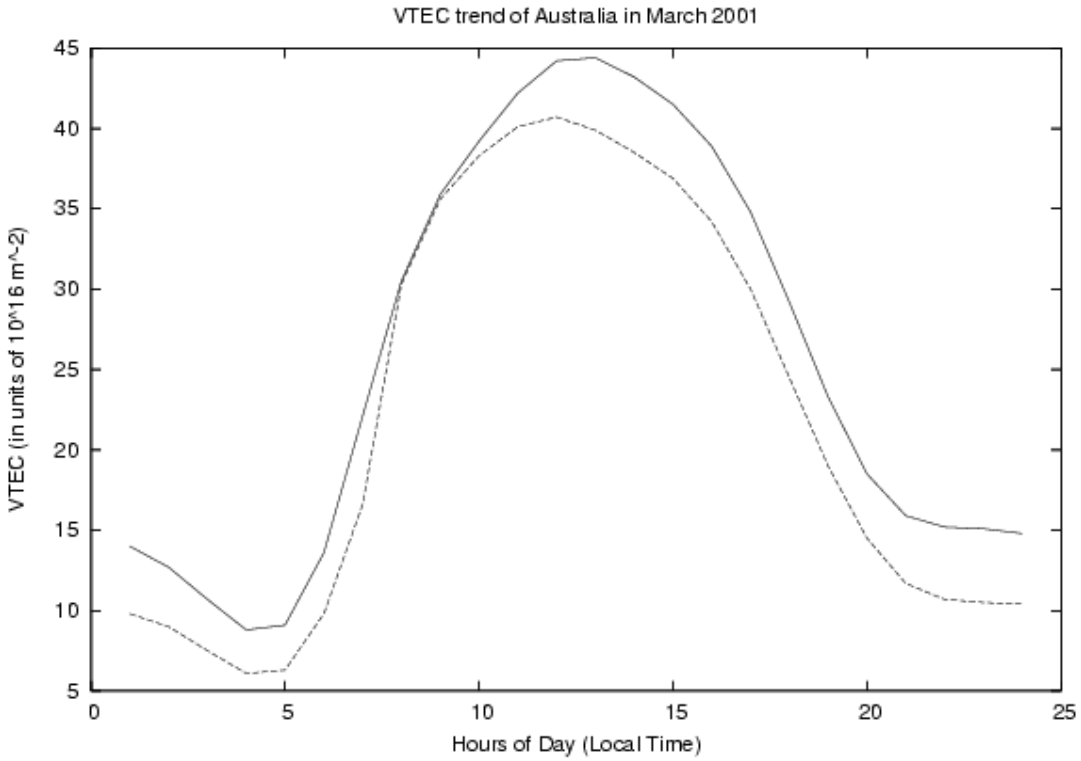
VTEC trend of Australia in March 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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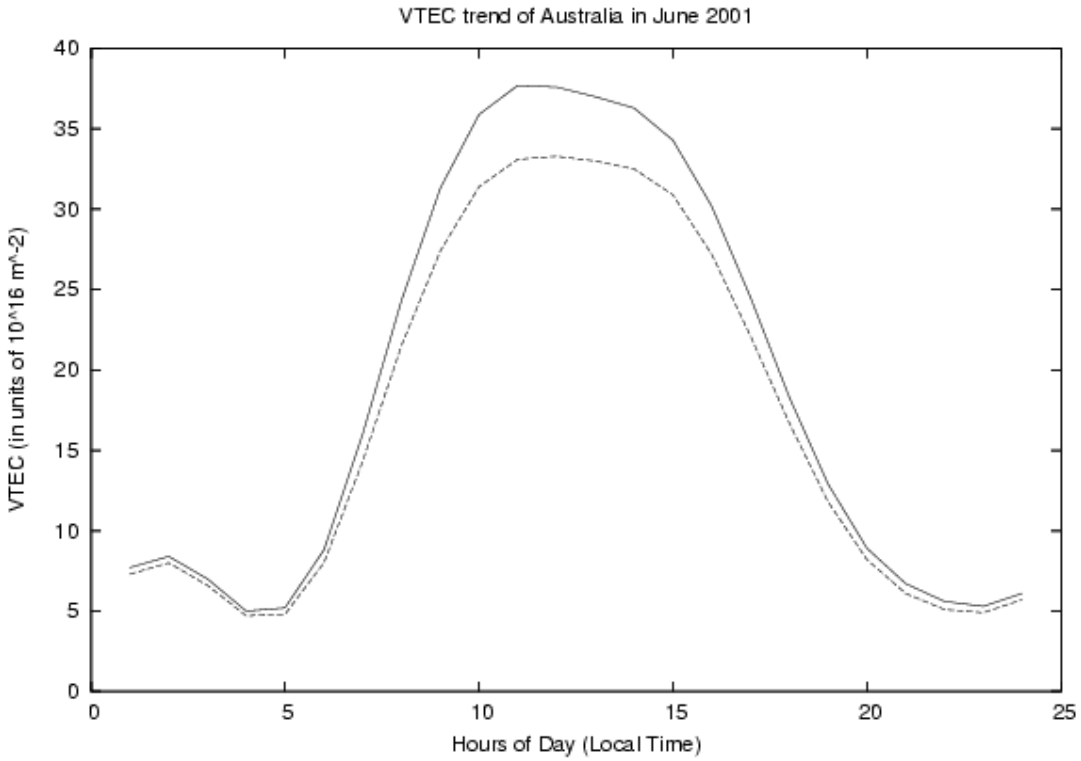
VTEC trend of Australia in June 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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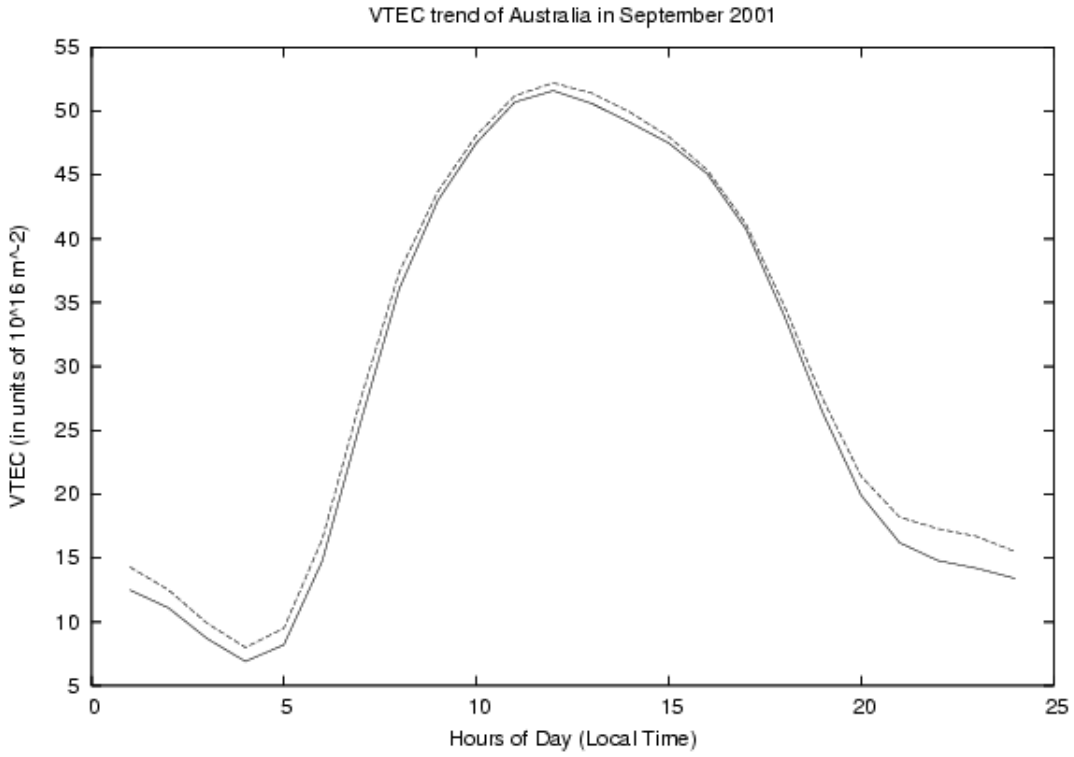
VTEC trend of Australia in September 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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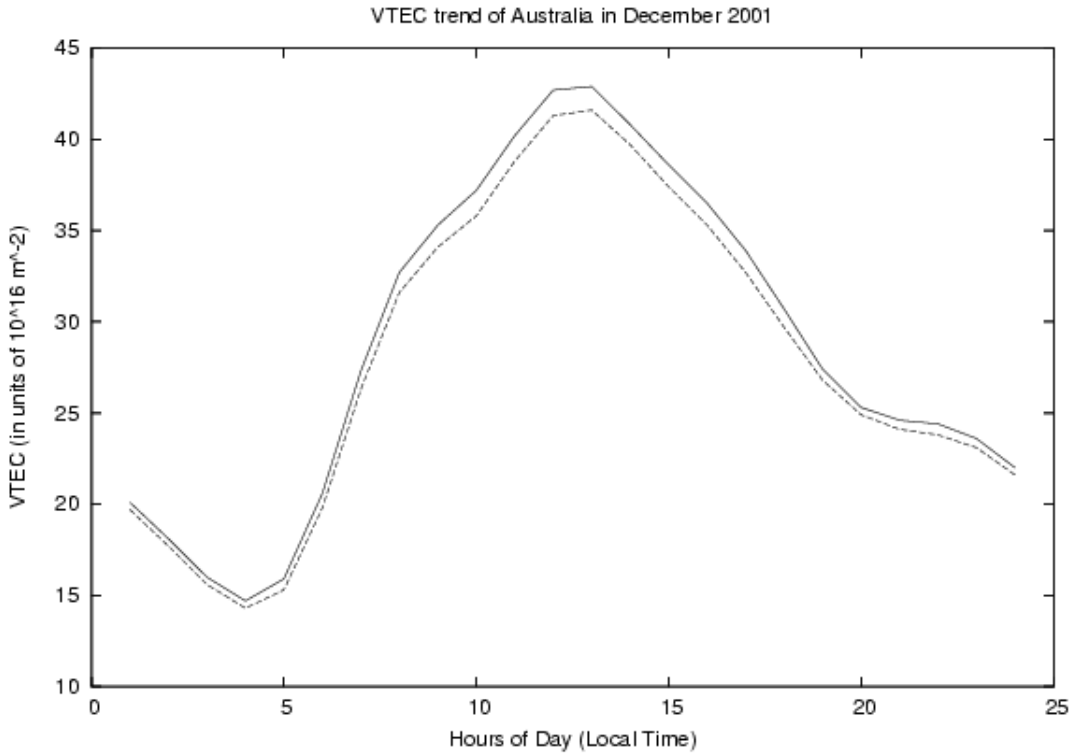
VTEC trend of Australia in December 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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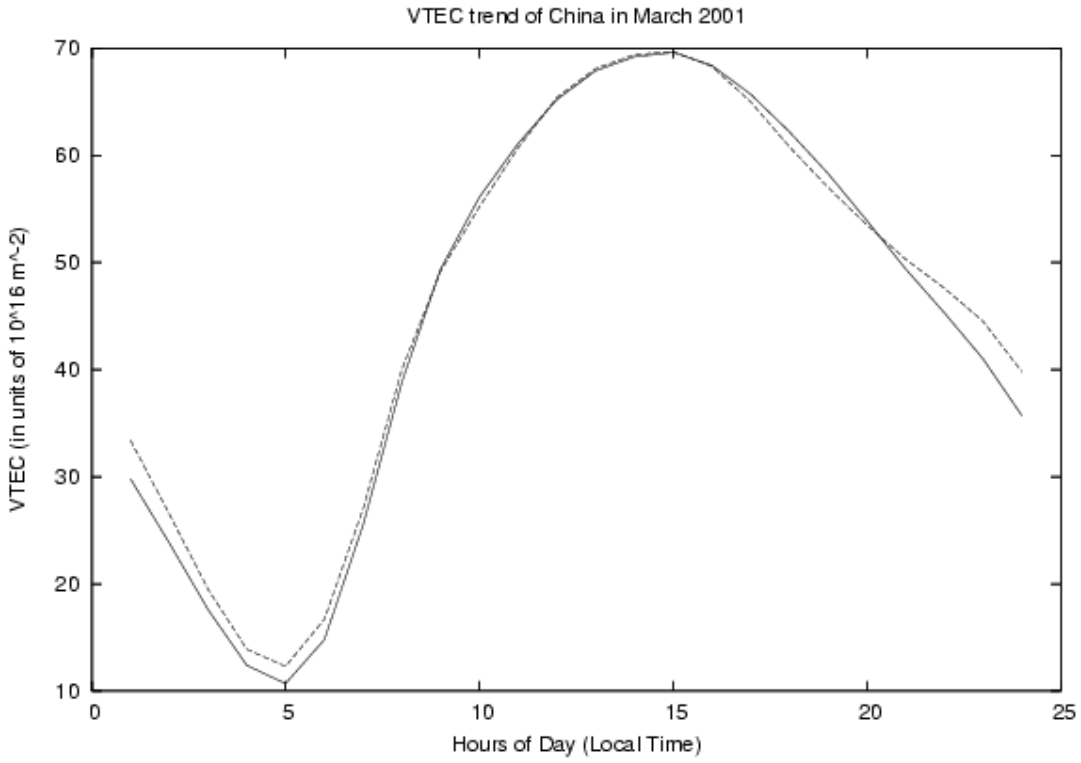
VTEC trend of China in March 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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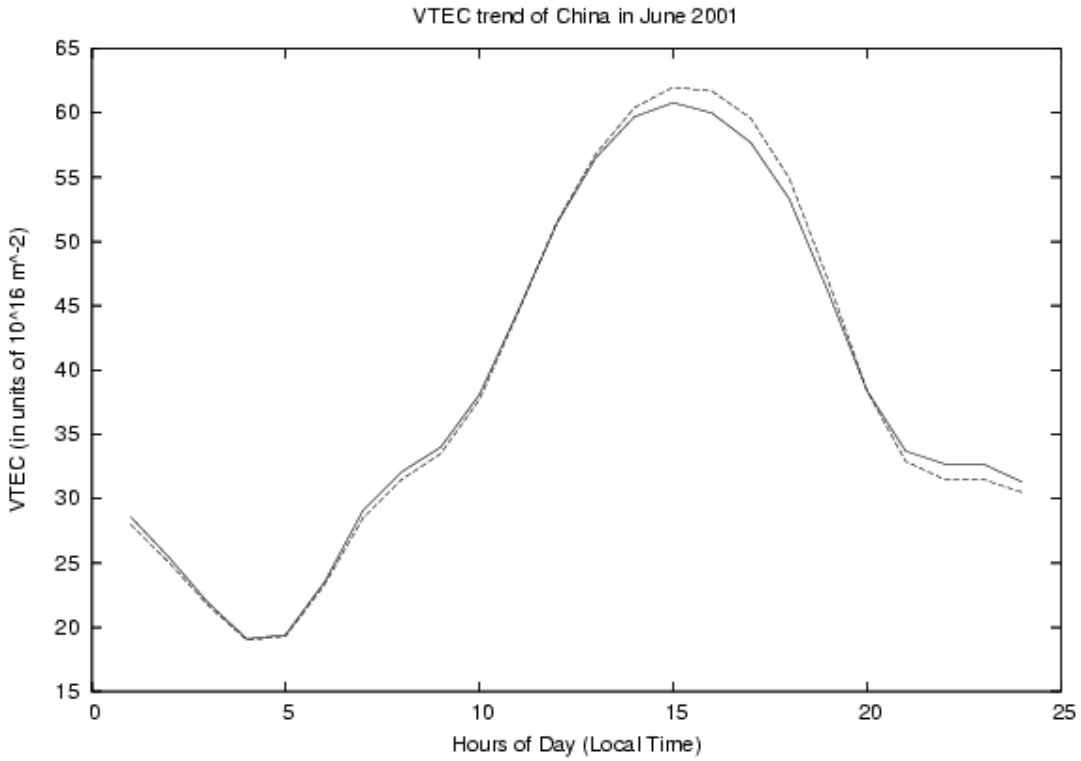
VTEC trend of China in June 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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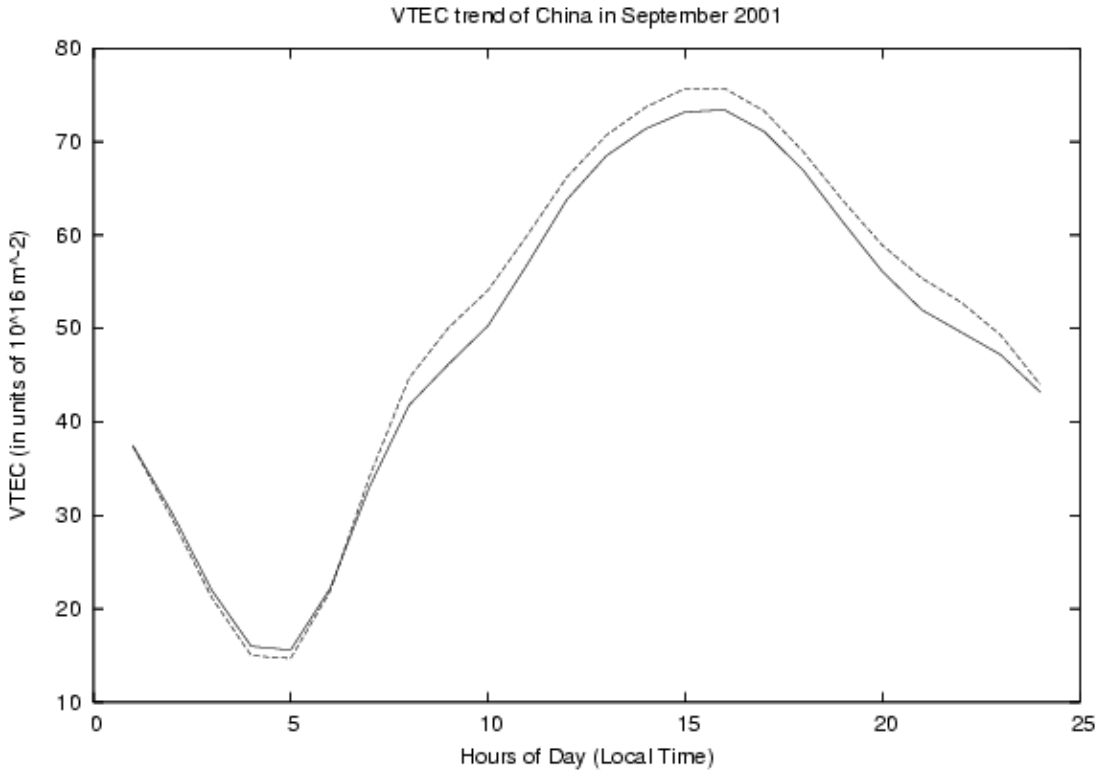
VTEC trend of China in September 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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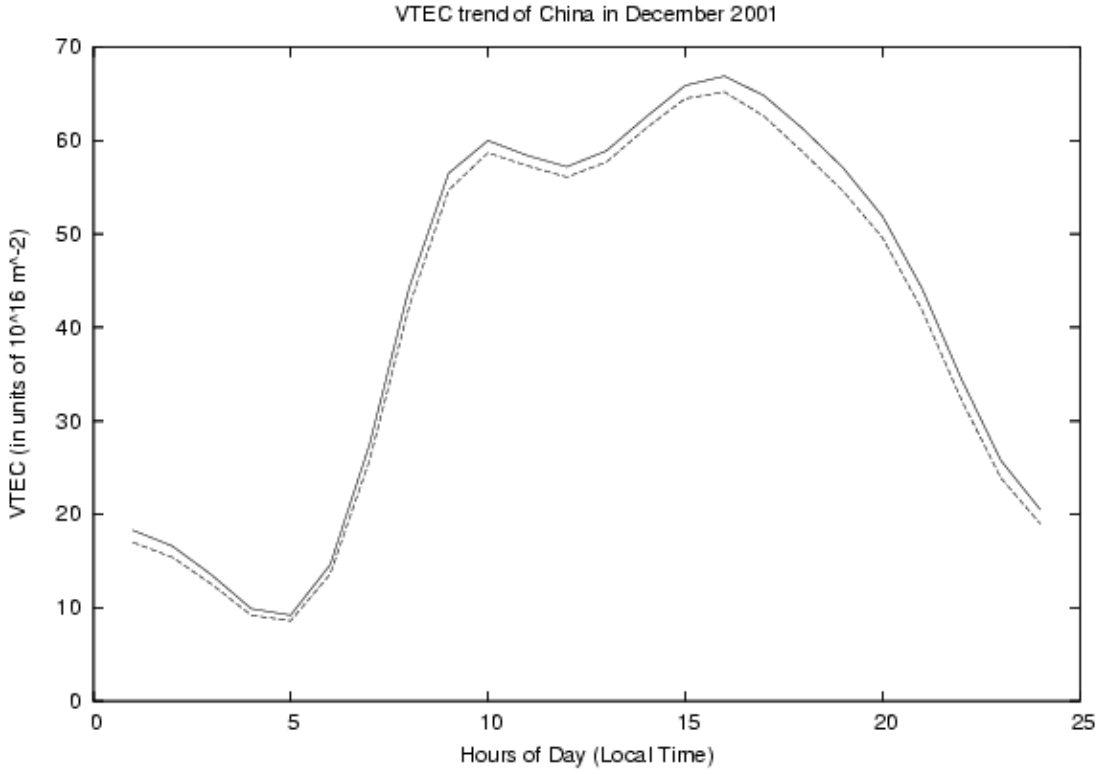
VTEC trend of China in December 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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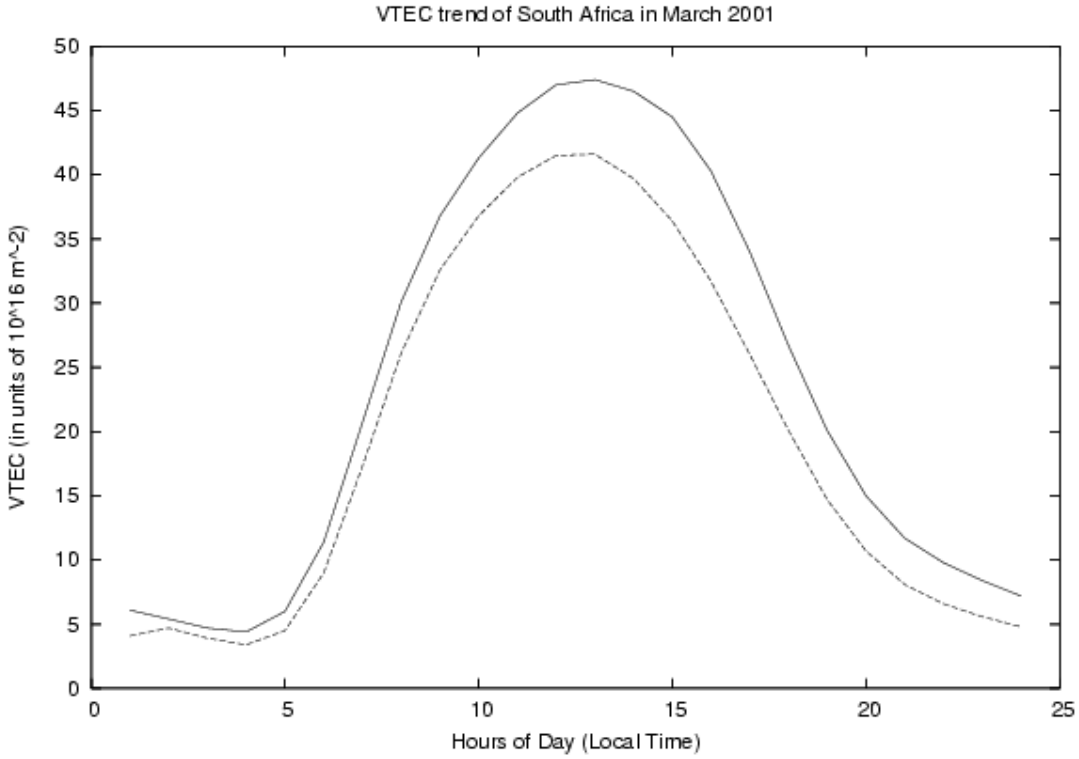
VTEC trend of South Africa in March 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
0
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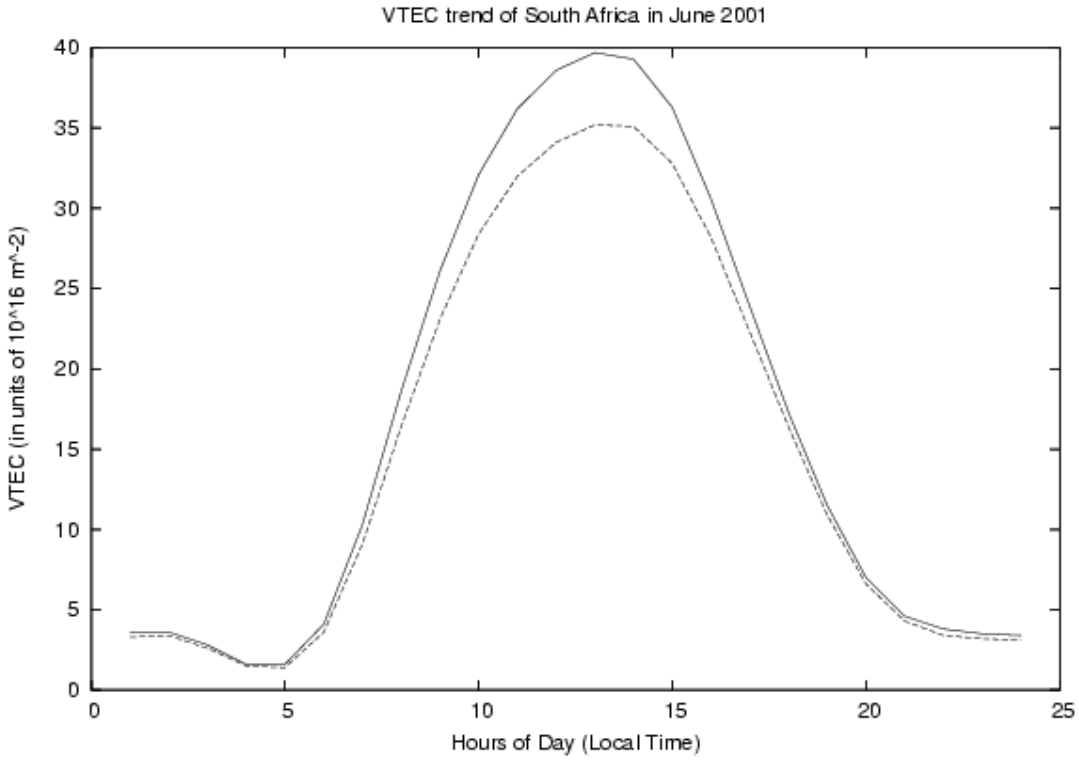
VTEC trend of South Africa in June 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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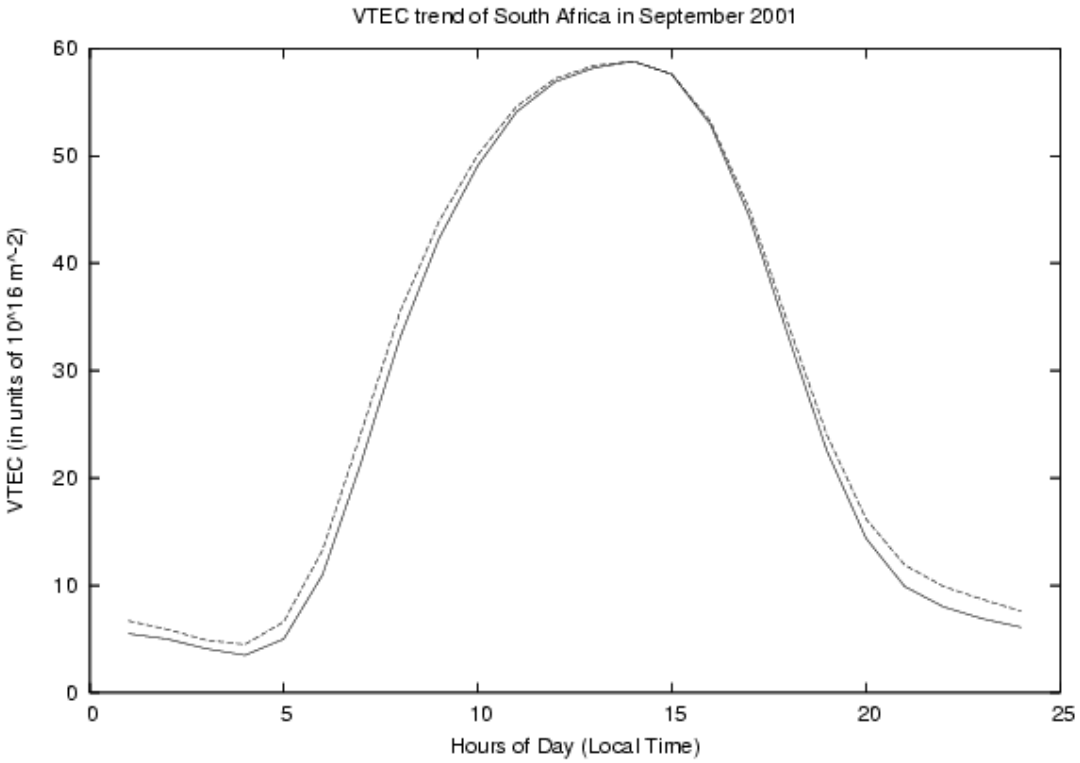
VTEC trend of South Africa in September 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
0
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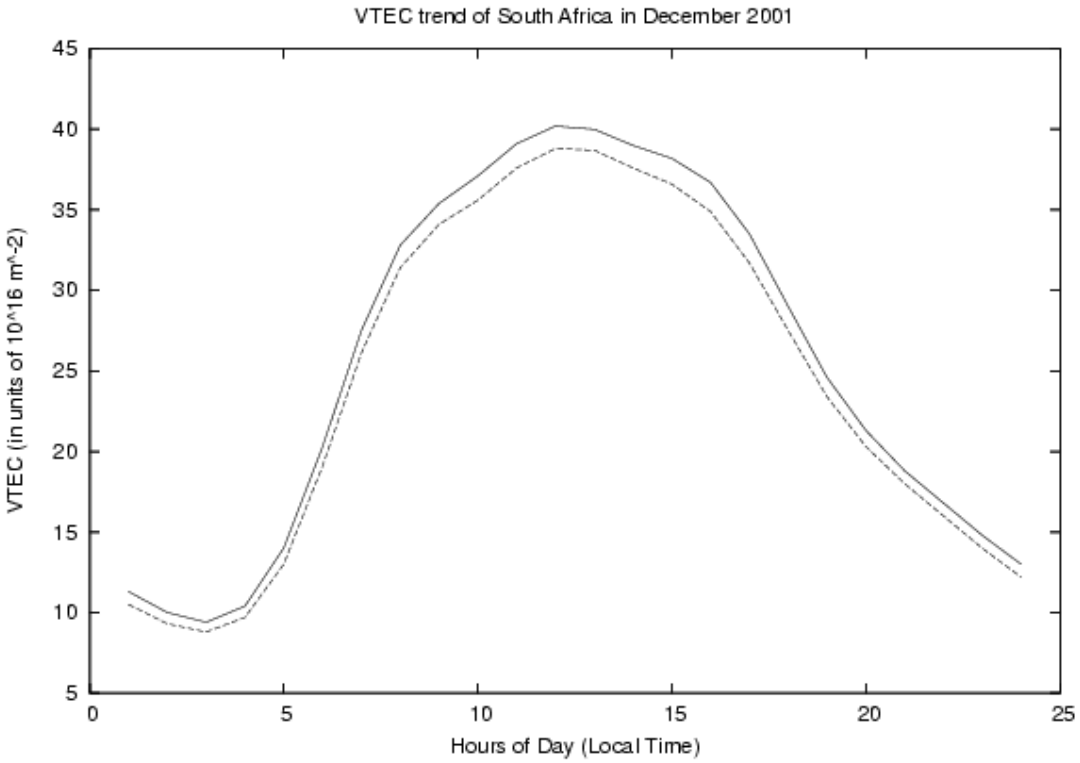
VTEC trend of South Africa in December 2001
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
5
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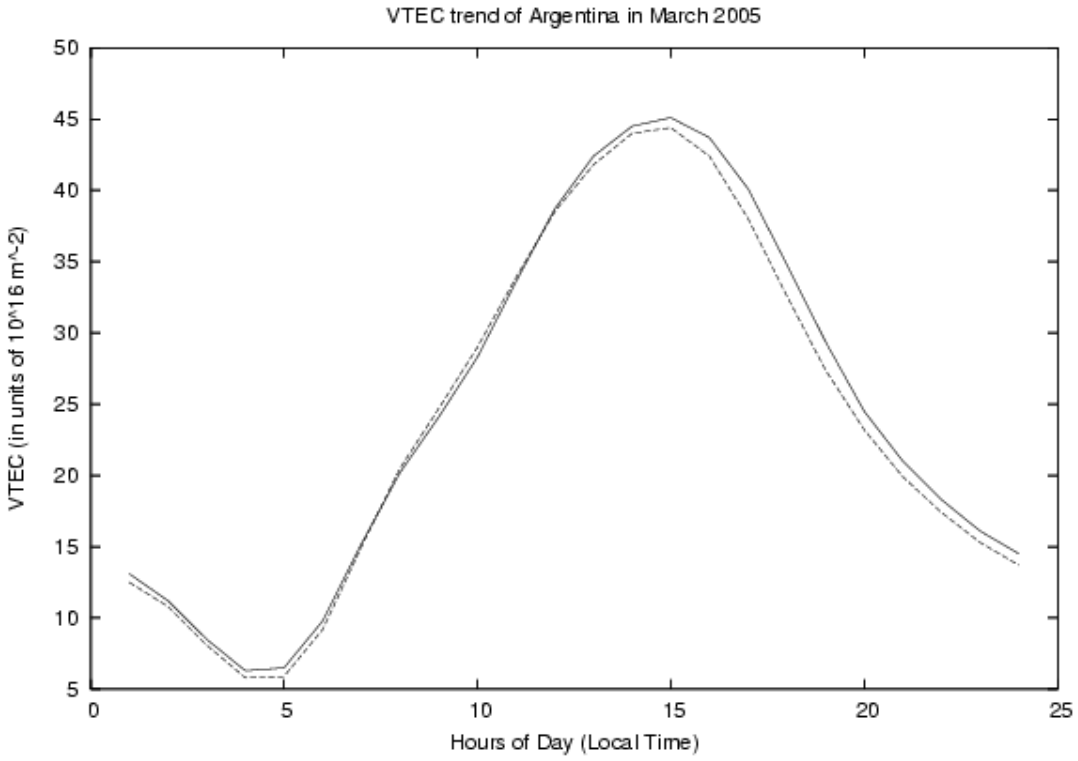
VTEC trend of Argentina in March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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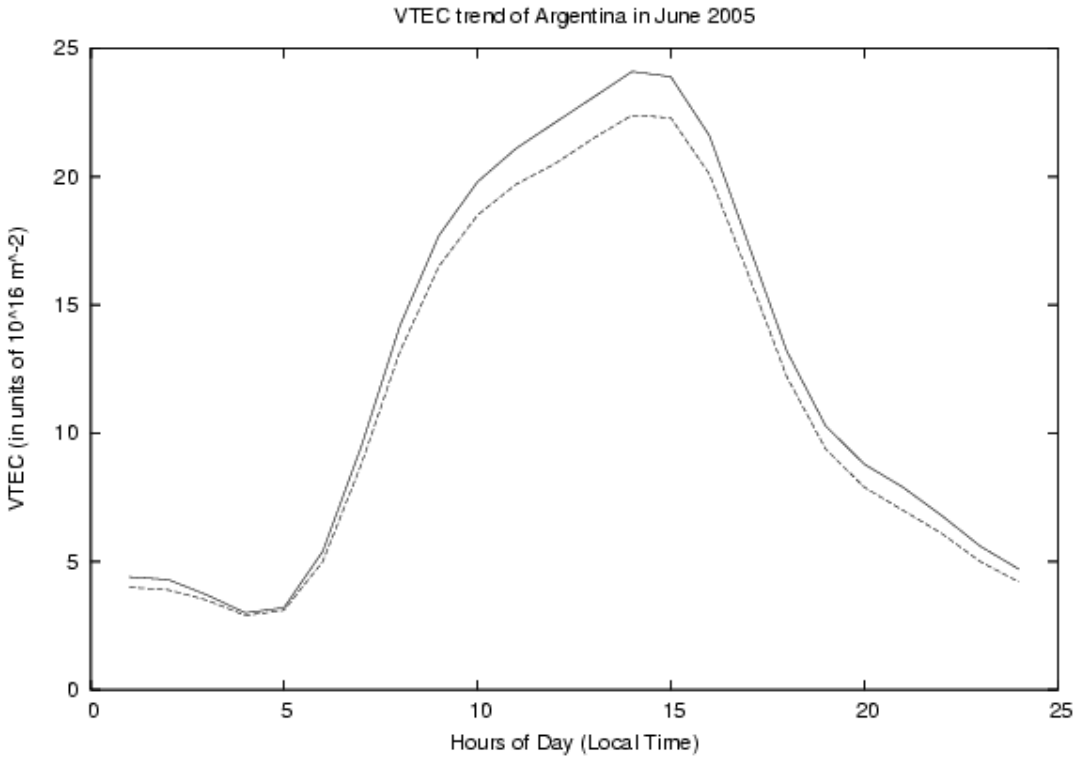
VTEC trend of Argentina in June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
25
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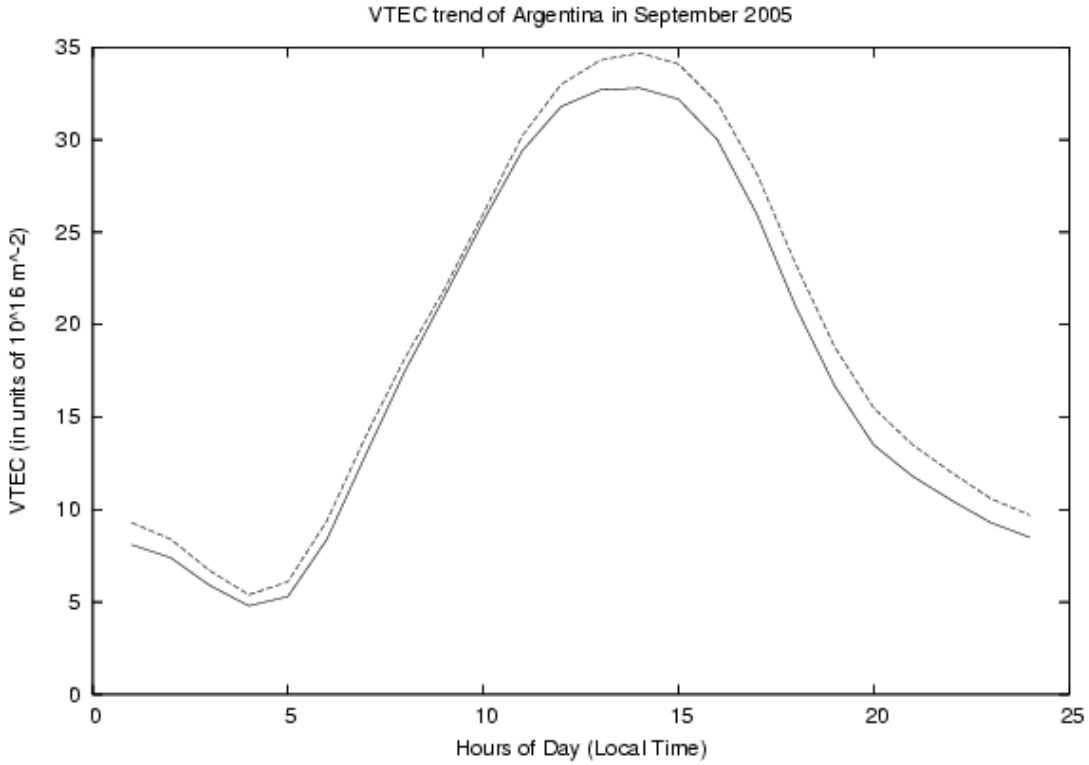
25


VTEC trend of Argentina in September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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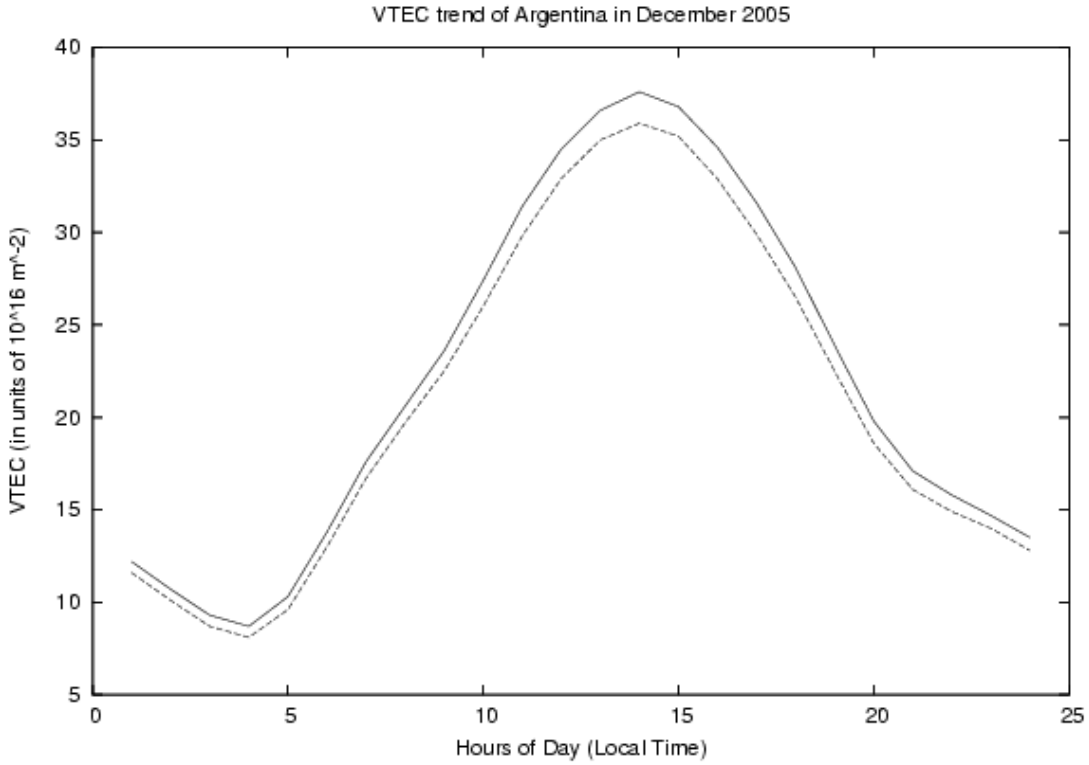
VTEC trend of Argentina in December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
5
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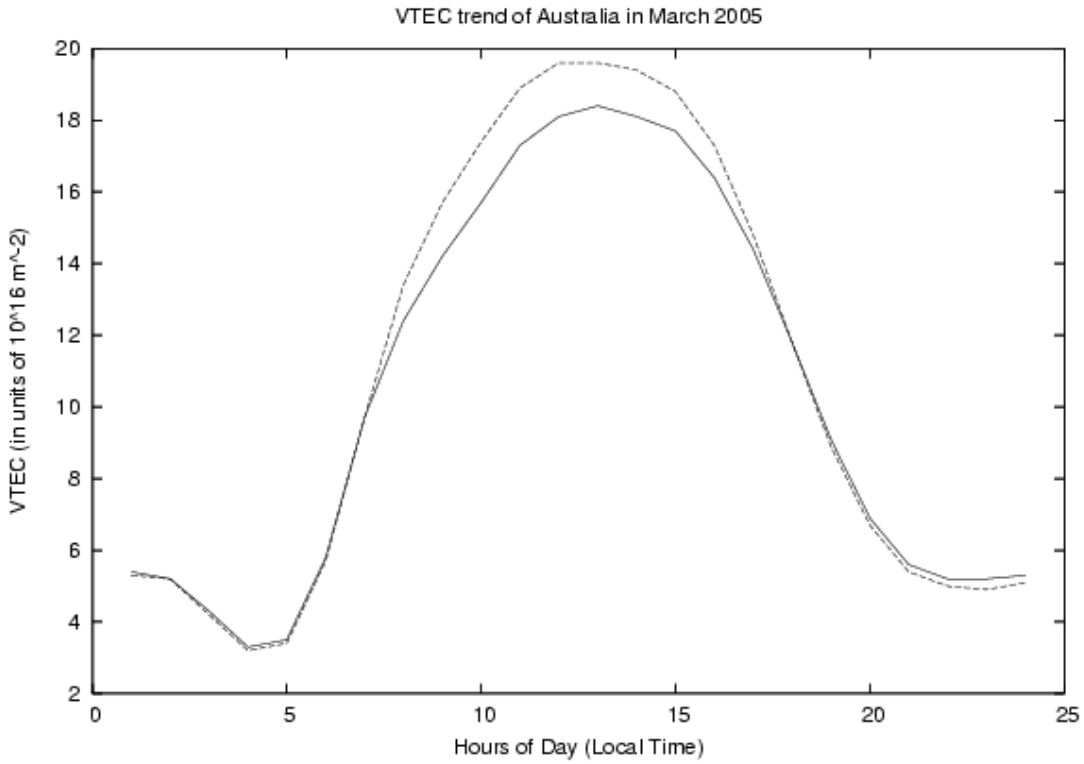
VTEC trend of Australia in March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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18
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2
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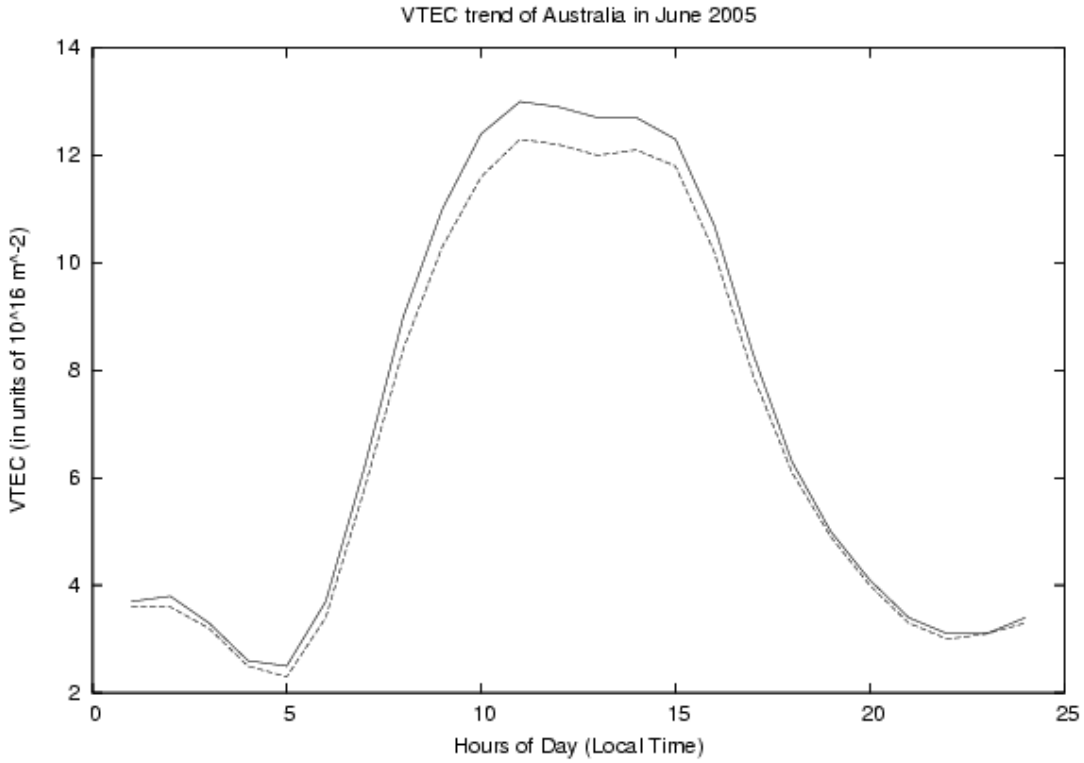
5
10
15
20
25


VTEC trend of Australia in June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
14
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8
6
4
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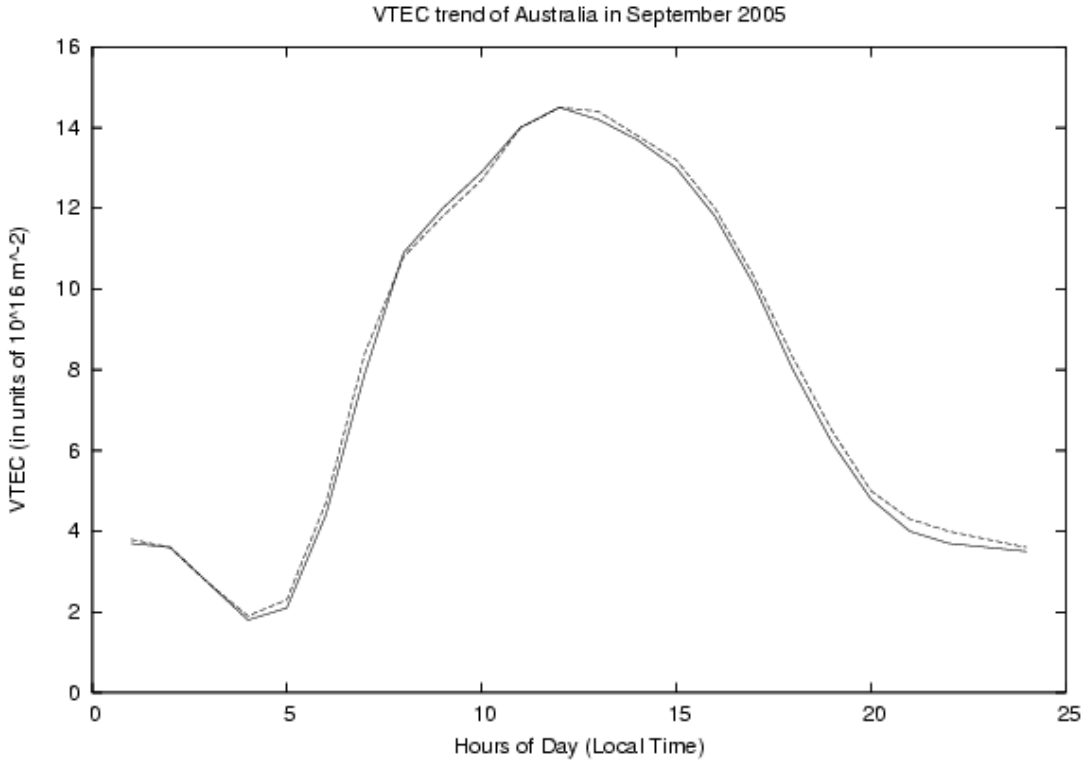
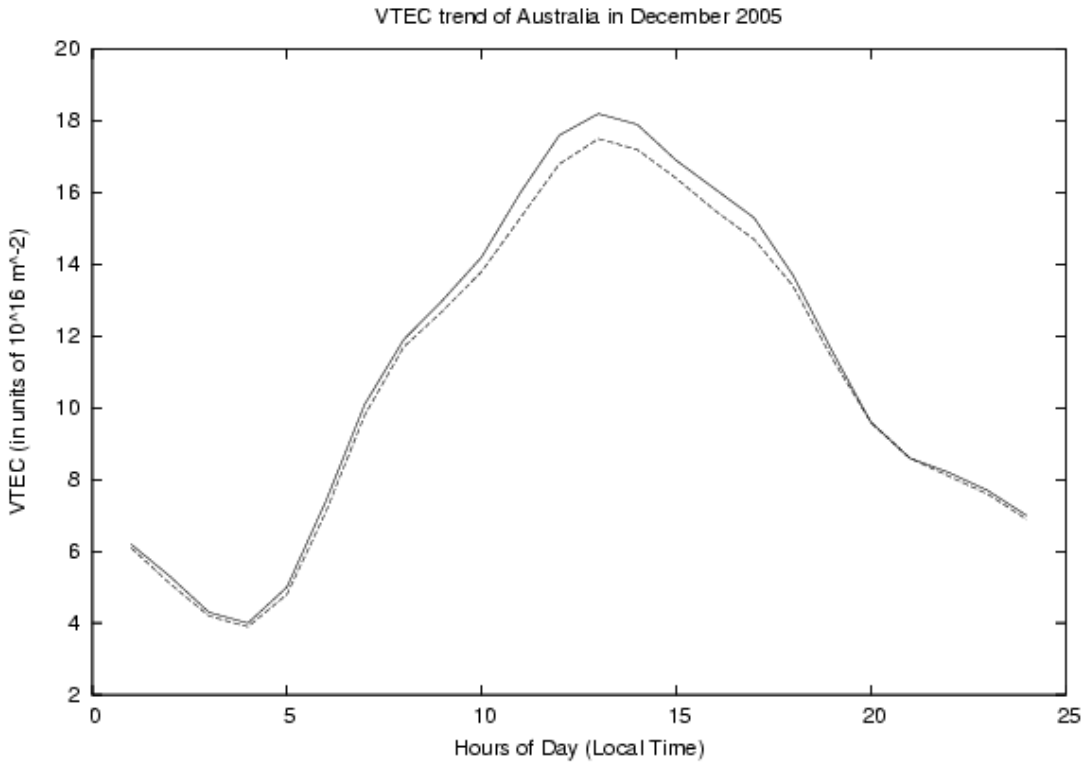

VTEC trend of Australia in September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
0
2
4
6
8
10
12
14
16
0
5
10
15
20
25


VTEC trend of Australia in December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
2
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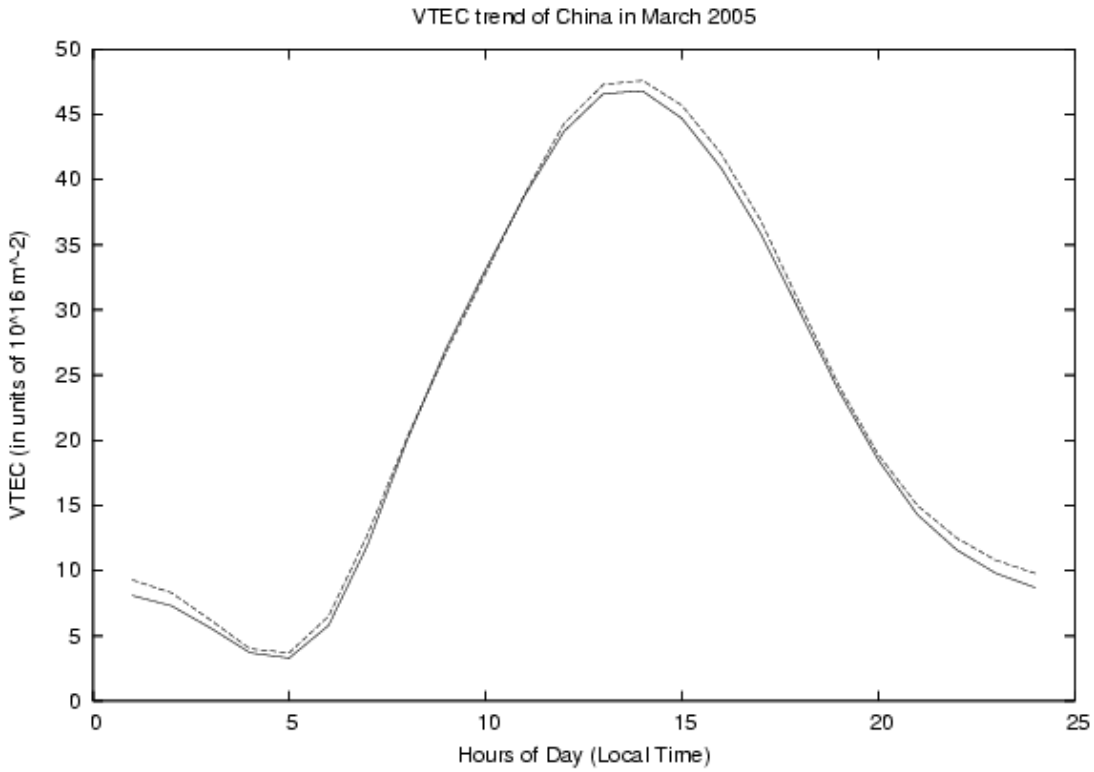
VTEC trend of China in March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
0
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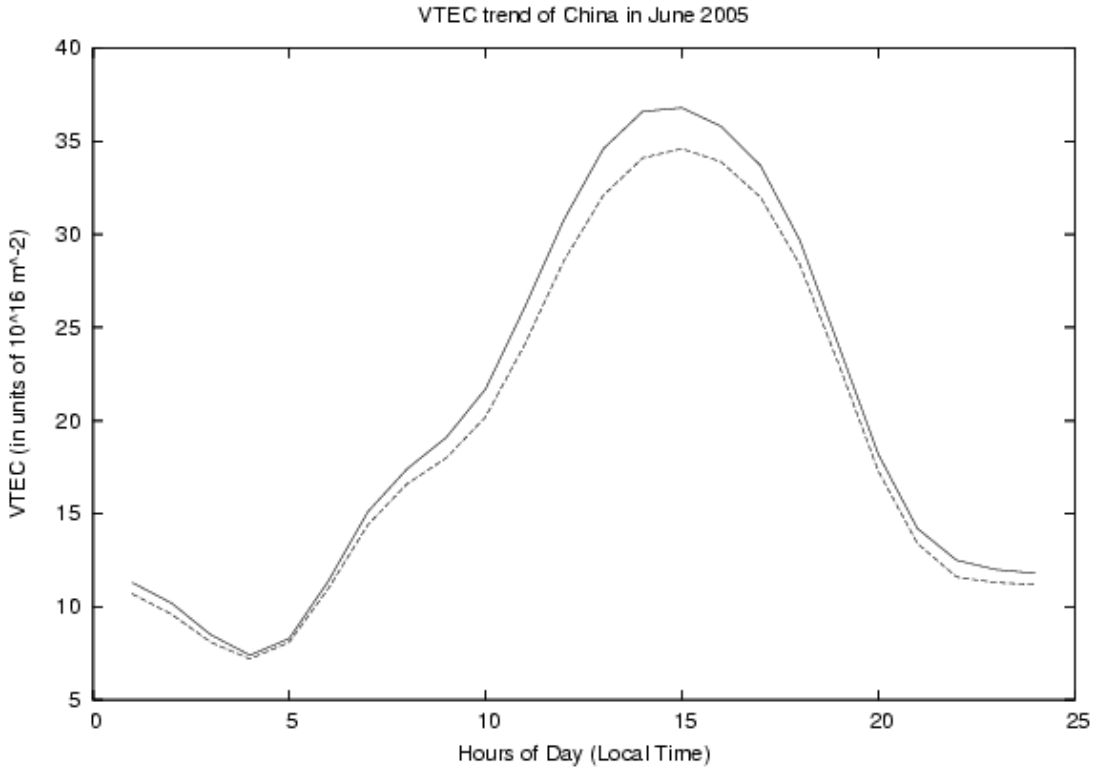
50


VTEC trend of China in June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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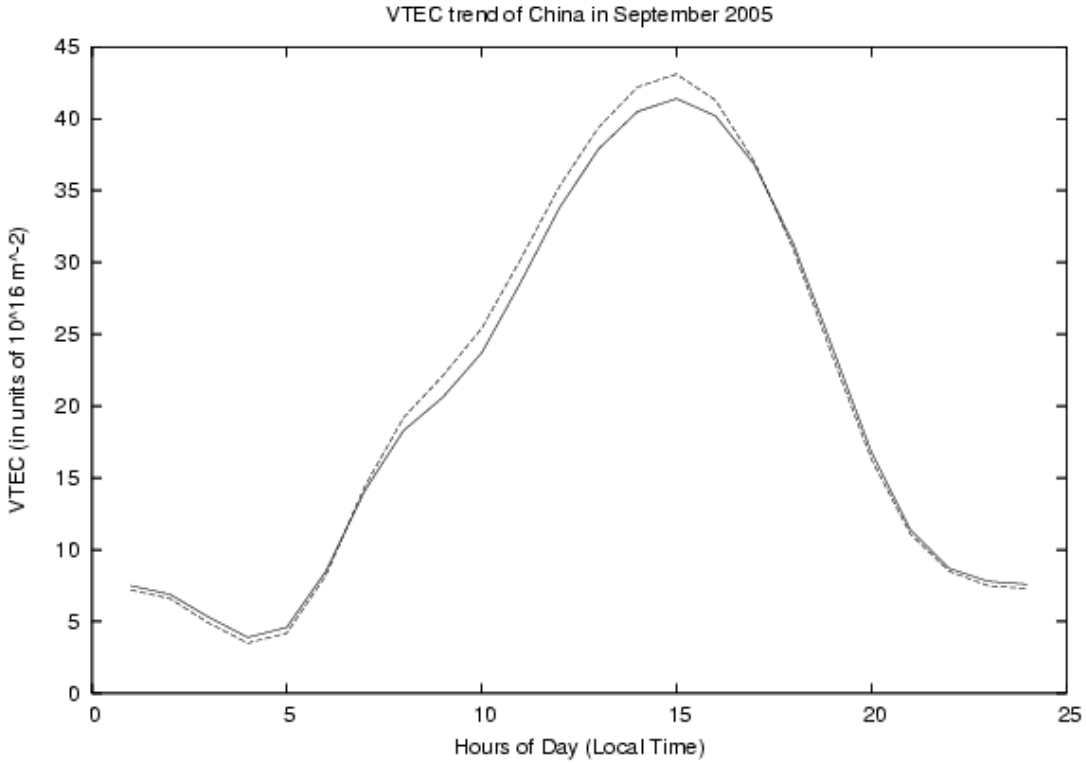
VTEC trend of China in September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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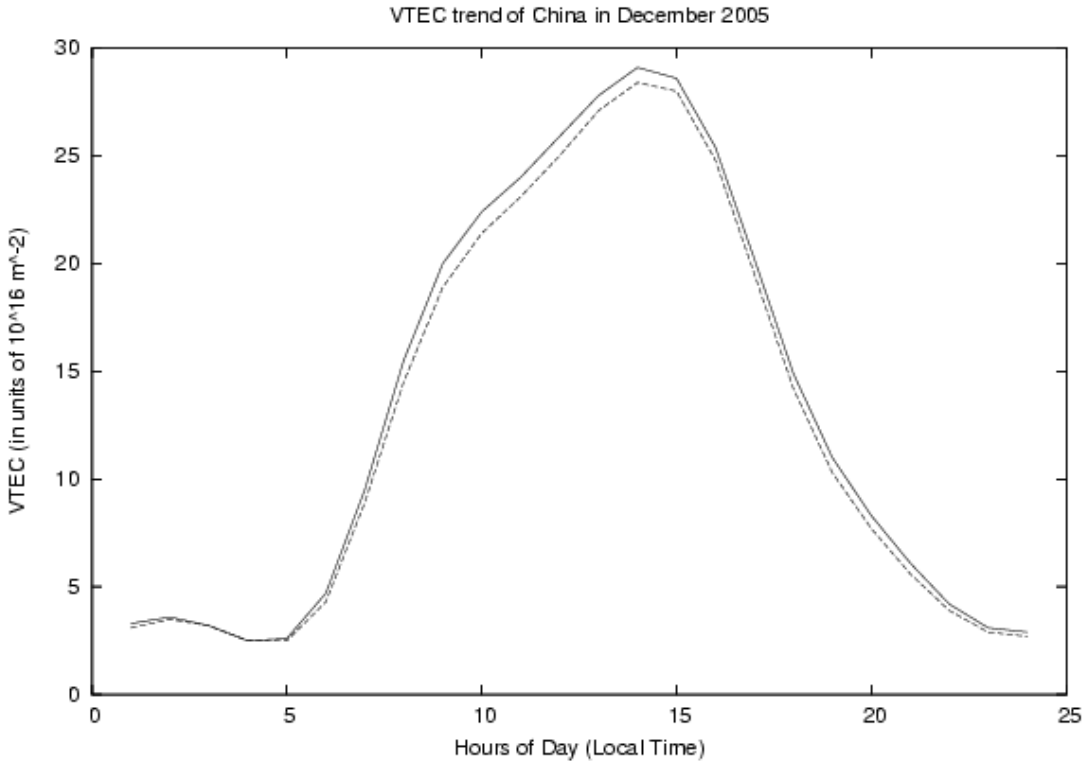
VTEC trend of China in December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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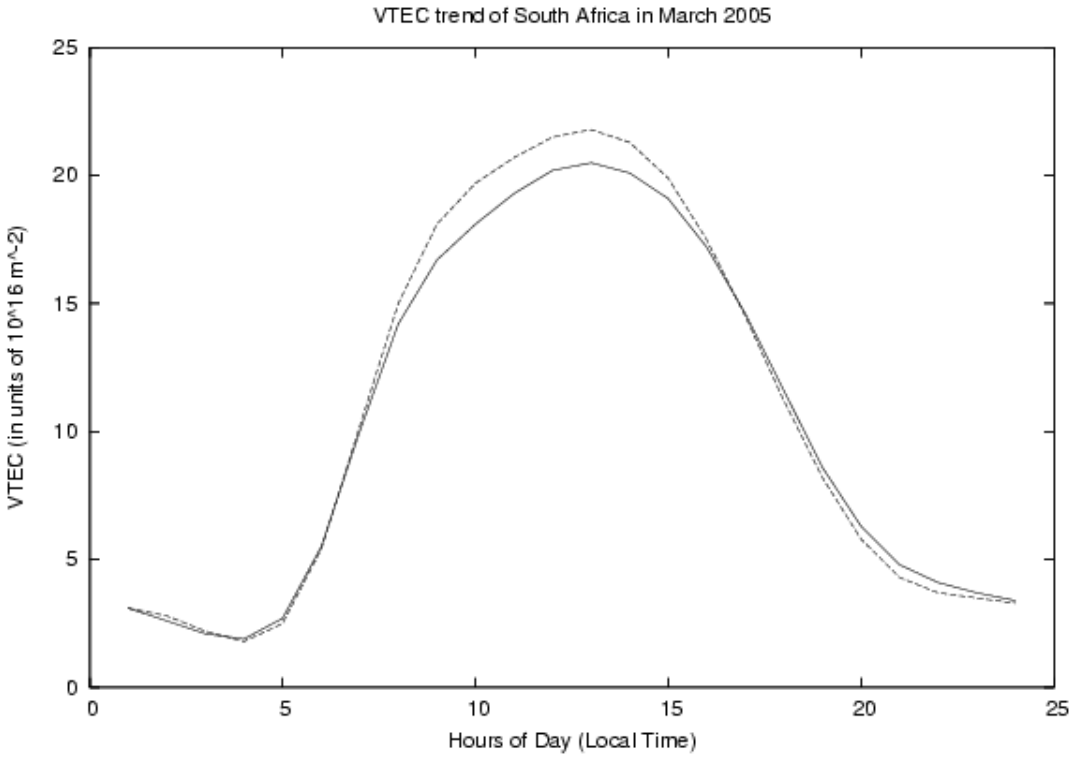
VTEC trend of South Africa in March 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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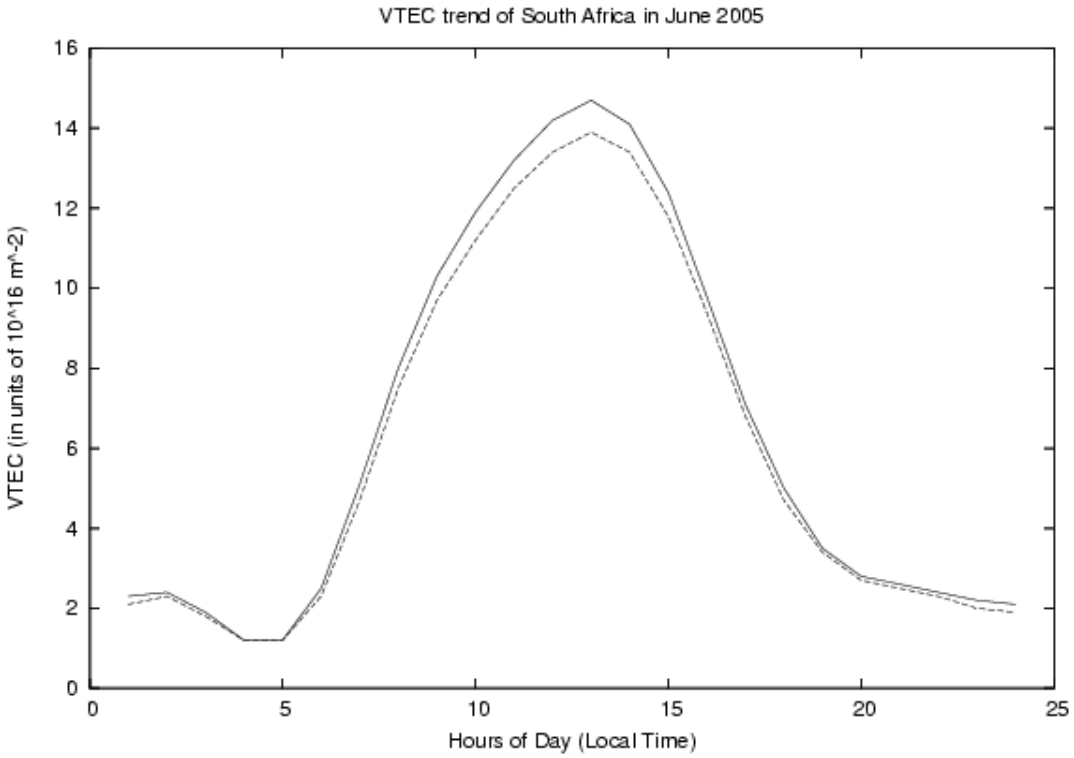
VTEC trend of South Africa in June 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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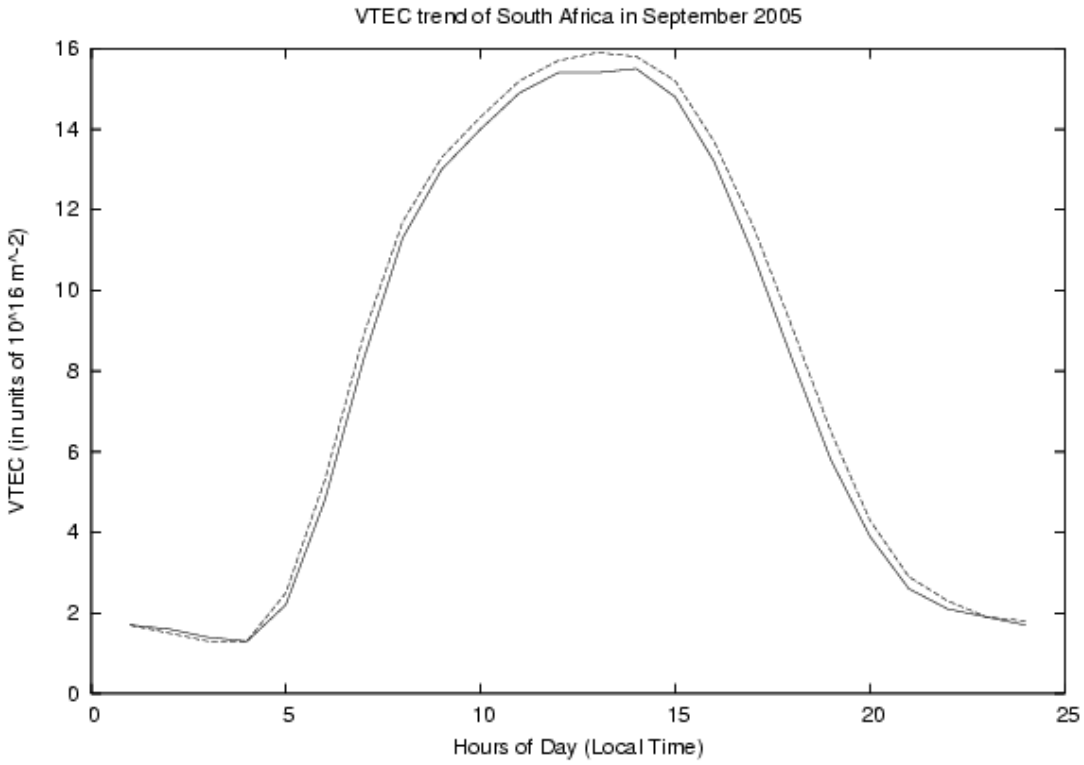
VTEC trend of South Africa in September 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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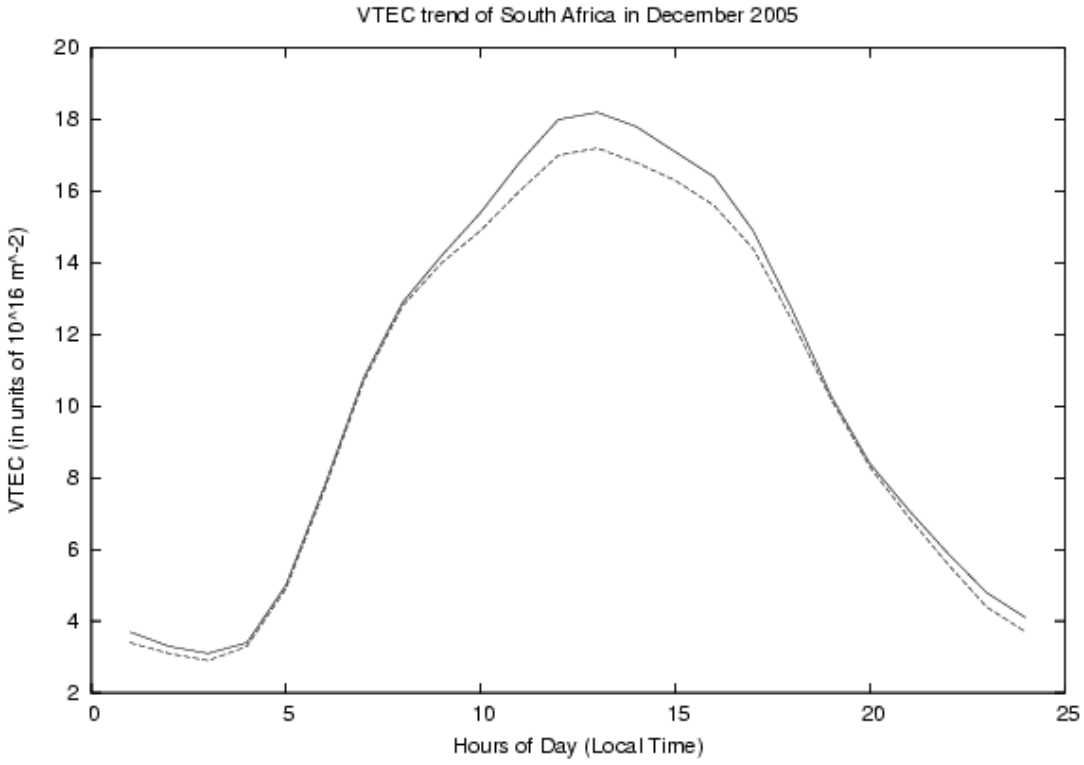
VTEC trend of South Africa in December 2005
VTEC (in units of 10^16 m^-2)
Hours of Day (Local Time)
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Report 2

A report on other ionospheric parameters for the candidate sites for the SKA location and an overall summary.

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National Centre for Radio Astrophysics (NCRA-TIFR), Pune, India

1. Introduction

This report covers the analysis of other ionospheric parameters for all the four sites, which are not covered in the previous report.

2. Scintillation

Sites	S4 Max.	Model Extrapolation
Argentina	$>$ 0.5 (90 %*prob.*)	WBMOD model
Australia	$\sim$ 0.2	WBMOD model
China	$<$ 0.5 (*usually*), stronger during solar activity	No data, but extrapolated from L band data $\sim$ 500 *kms* away
South Africa	$\sim$ 0.25	WBMOD model

3. Spread F and TIDs

Sites	Spread F (% occurence)	Times
Argentina	$\sim$ 30% in Equinox	$22-05$ hrs
Australia	$\sim$ 25% in winter	$23-04$ hrs . 10% at other times
China	$>$ 40% in summer	$23-04$ hrs
South Africa	$\sim$ 30%	$22-04$ hrs

Note :- % occurence is 100 times the number of occasions the parameter was observed divided by the number of times it could have been observed. TIDs are atmospheric acoustic-gravity waves; it is a day time phenomenon and is similar in all the sites.

4. Equatorial Anomaly (EA) and South Atlantic Anomaly (SAA)

Sites	EA	SAA
Argentina	S of South peak	Most affected
Australia	Not present	Not present
China	N of North Peak	Not present
South Africa	South of EA	fringe of SAA

5. Over All Summary of Report 1 and 2

(a) TEC seems to affect China and Argentina more than Australia and SA, based on detailed analysis of GPS measurements over the period 2000-2005.

(b) Scintillation affects Argentina and China most with SA less and Australia least.

(c) Spread F and TIDs affect China most and others less.

(d) EA and SAA affect Argentina most, China (EA) and SA (SAA) next, Australia least.