Regional modelling and forecasting using GNSS techniques.

Z.Bouya, M. Francis, M. Terkildsen

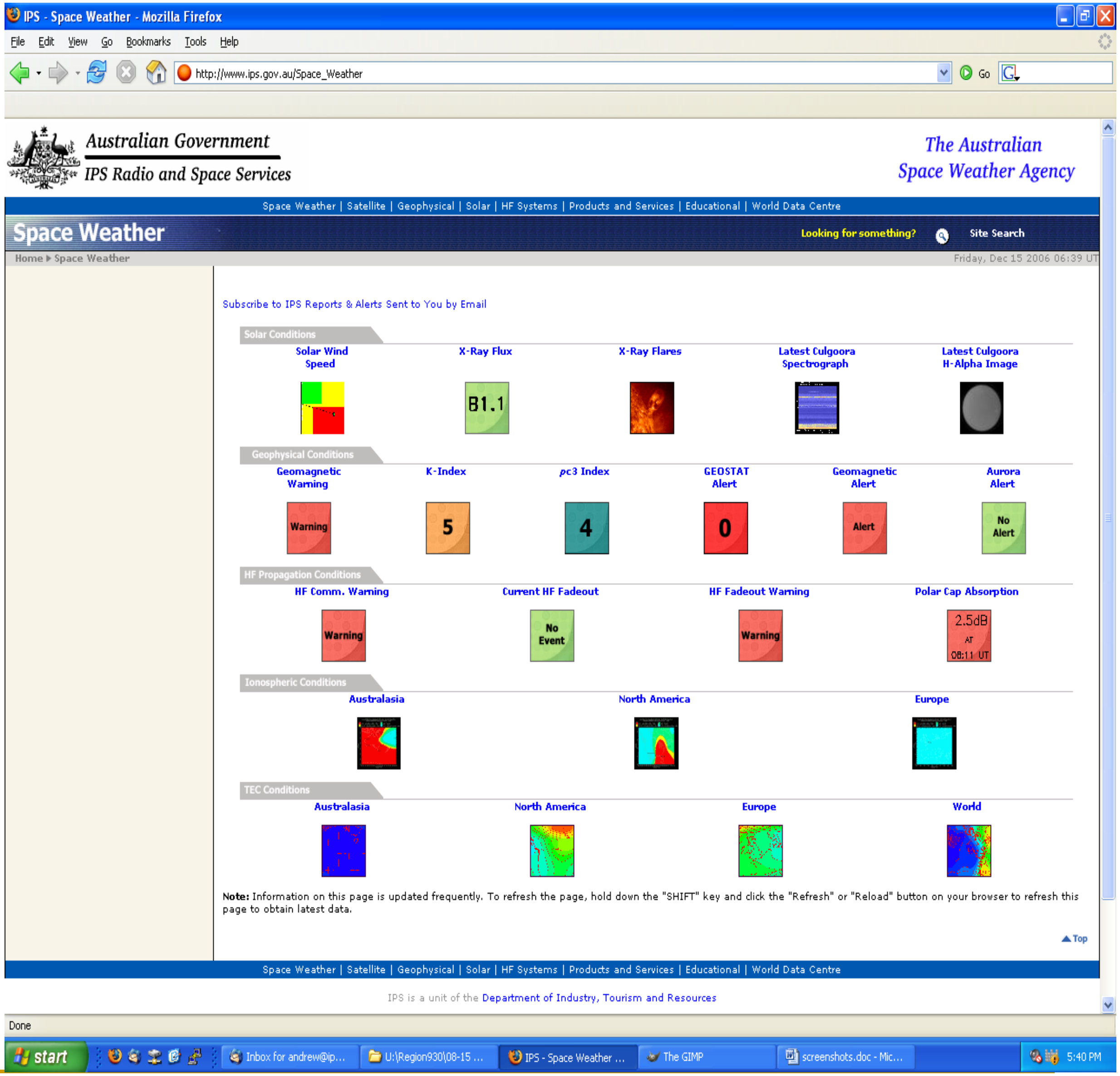
Australian Bureau of Meteorology, IPS Space Weather Services.

Products

-Flare Forecast

-Flare Alert

-Coronal Mass Ejection (CME) Warning
(Automated Type II, III Detection)
-Geomagnetic Storm Warning
-Geomagnetic Storm Sudden commencement (SSC) and Sudden Impulse (SI) Alert
-Geomagnetic Storm Alert
-Geomagnetically Induced Currents (GICs) in Pipelines
-Polar Cap Absorption (PCA) Alert -HF COMMS Warning
-HF radio 'Short Wave Fadeout' (SWF) Alert
-Total Electron Content (TEC) Ionospheric Modelling
-Scintillation alert



Data for the Services: Space Weather monitoring network (IPS_attached.xls)

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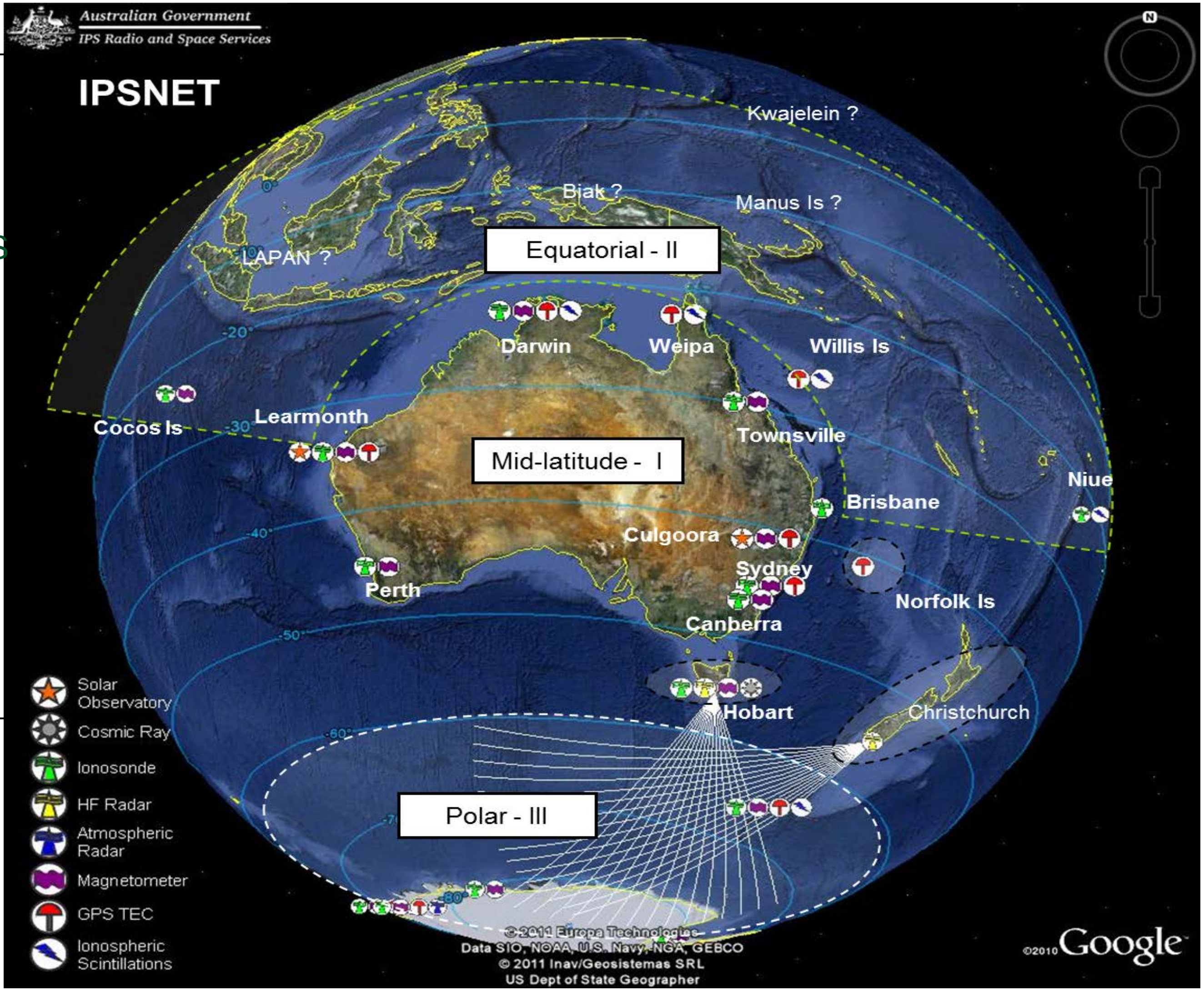
3rd party sensors

Magnetometers
- U. Newcastle
- ICSWSE-MAGDAS
- Geoscience Aust

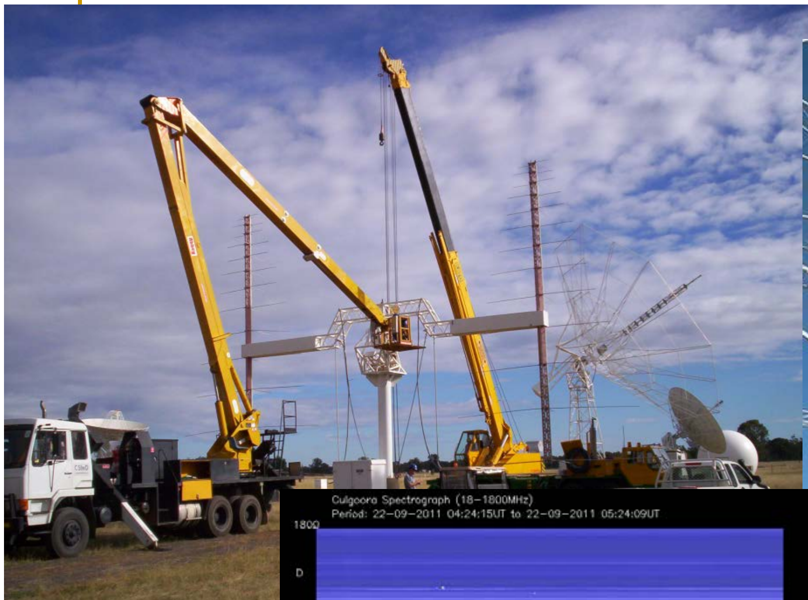
GPS
- Geoscience Aust

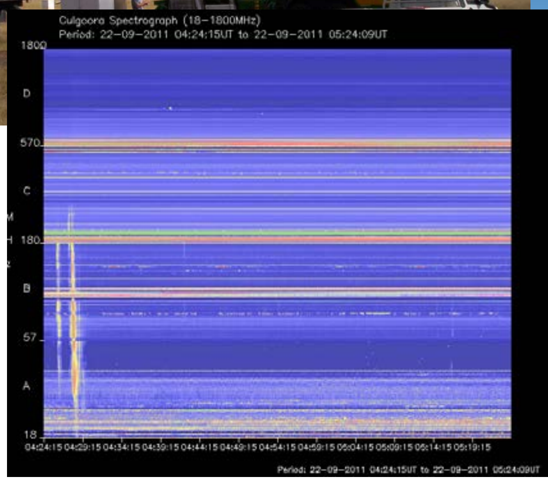
Solar
- USAF Learmonth

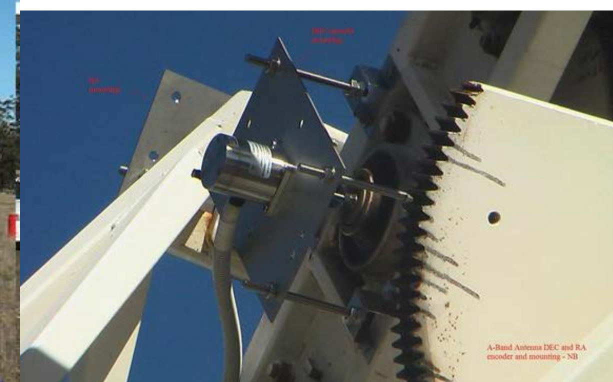
Antarctica
- AAD



Solar Radio Spectrograph







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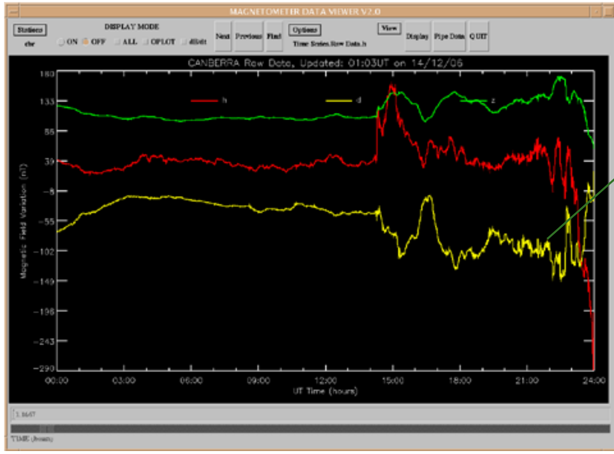
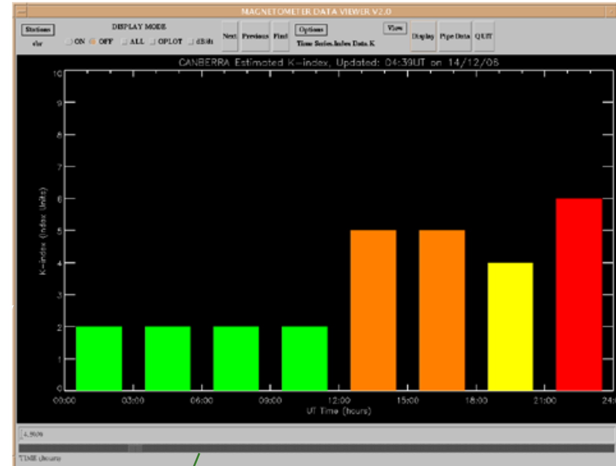
Geomagnetic



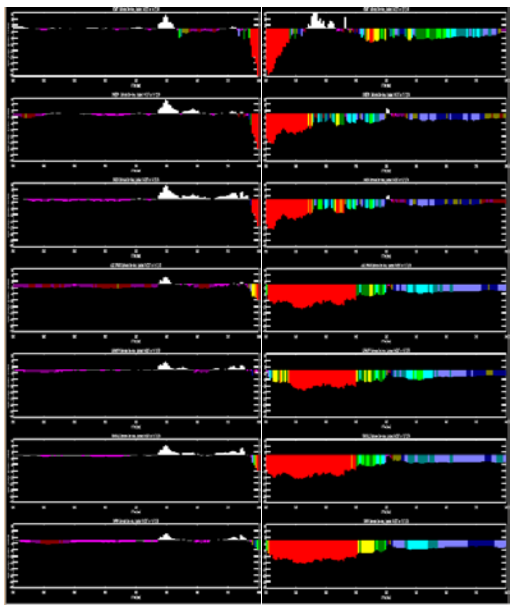
Raw data

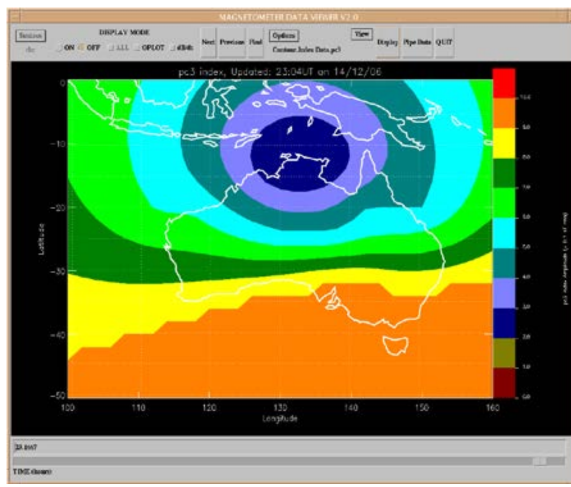
processing

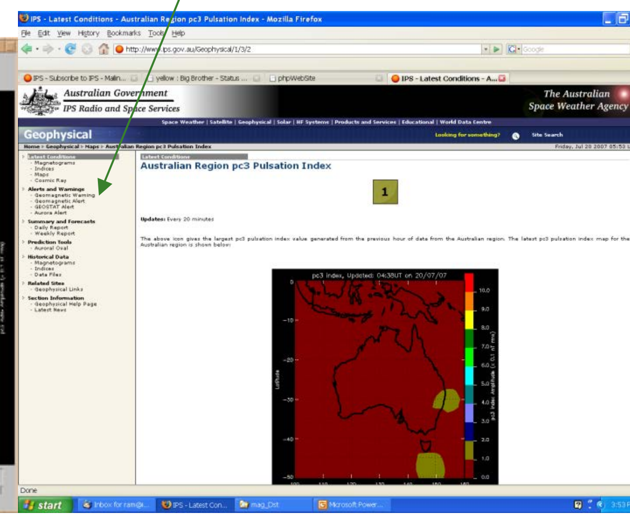


Indices – K, A

Maps of K

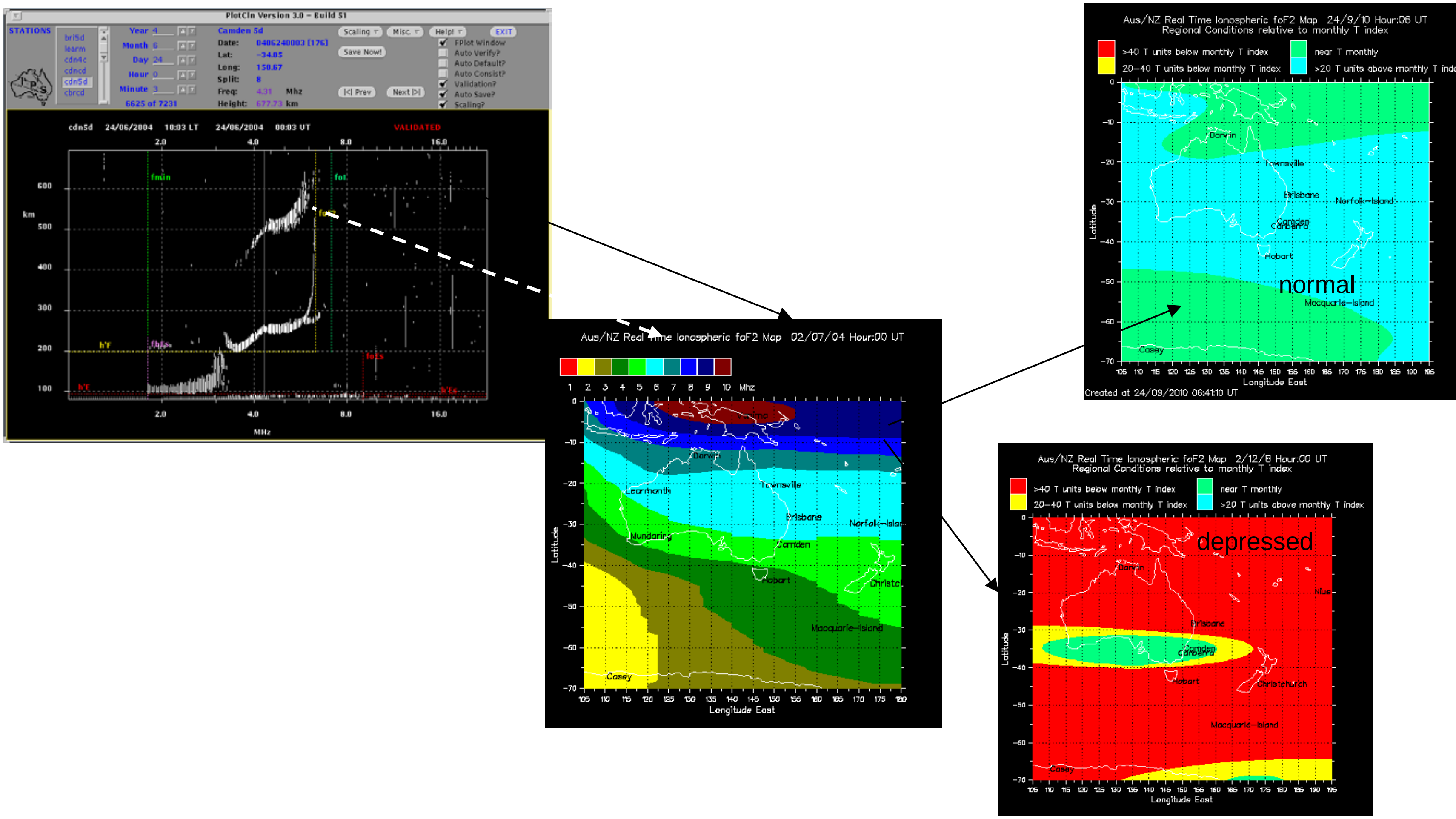






Dst storm index

HF radio communications



SUBJ: IPS HF RADIO COMMUNICATIONS WARNING 10/21 ISSUED AT 23/2354Z OCTOBER 2010 BY THE AUSTRALIAN SPACE FORECAST CENTRE. DEGRADED HF PROPAGATION CONDITIONS EXPECTED FOR 24 OCTOBER 2010

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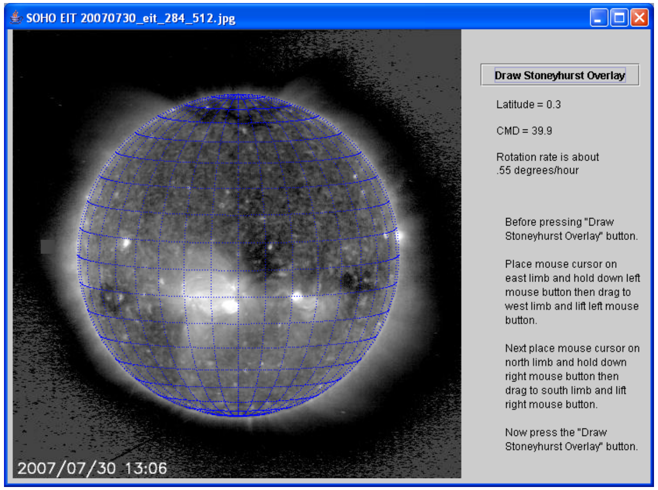
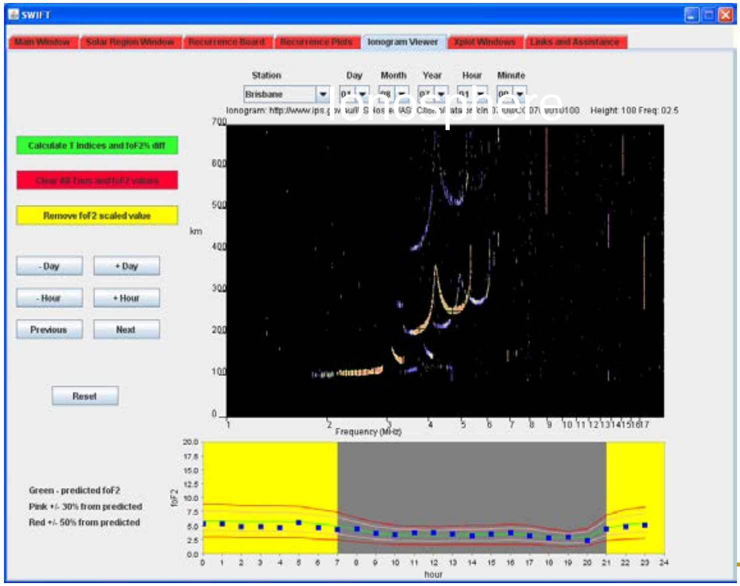
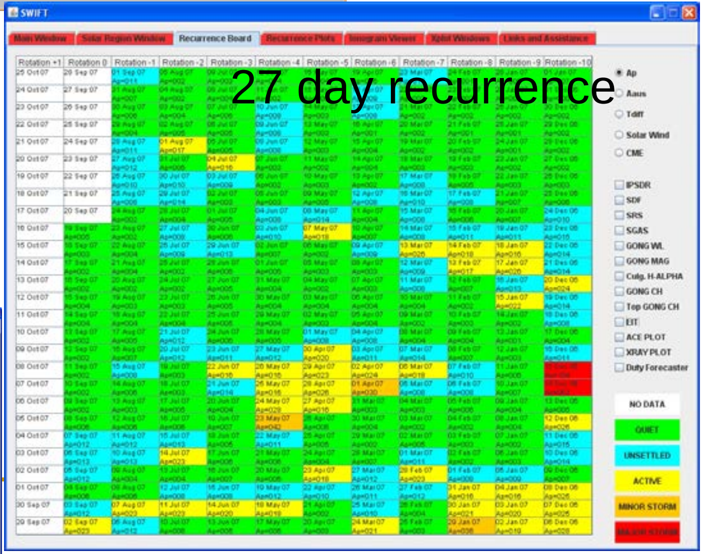
Australian Space Forecast Centre (ASFC)

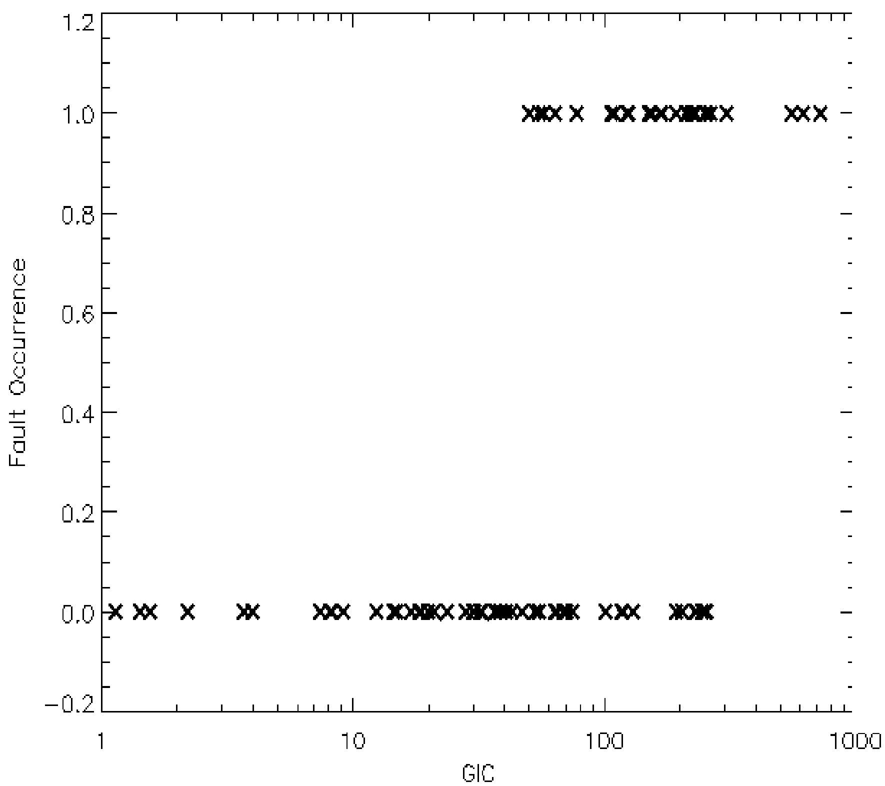


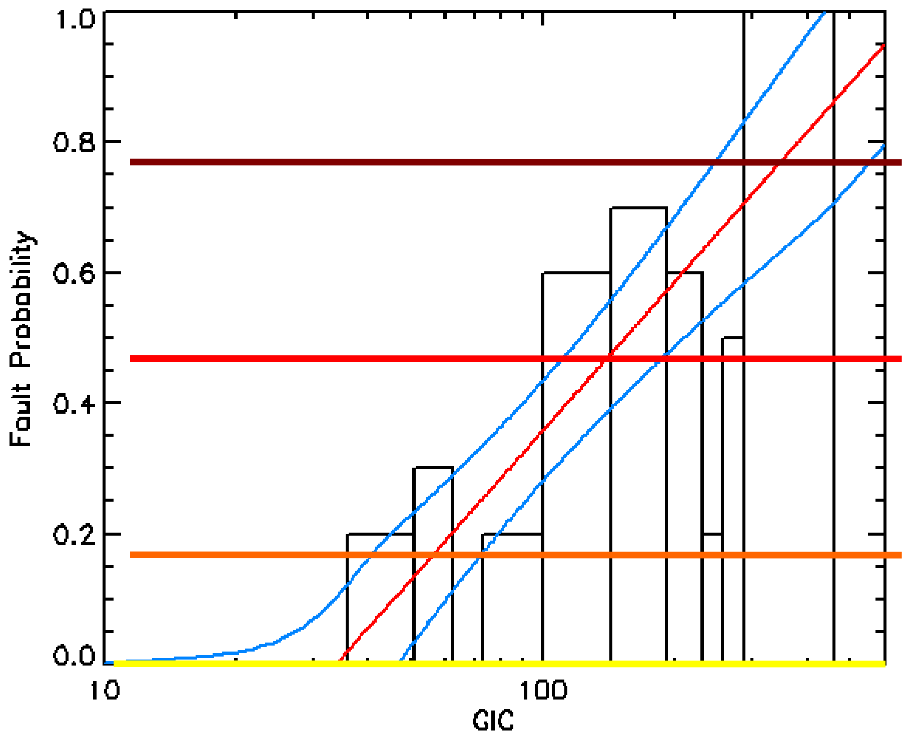




Geomagnetically Induced Currents (GICs) in Pipelines

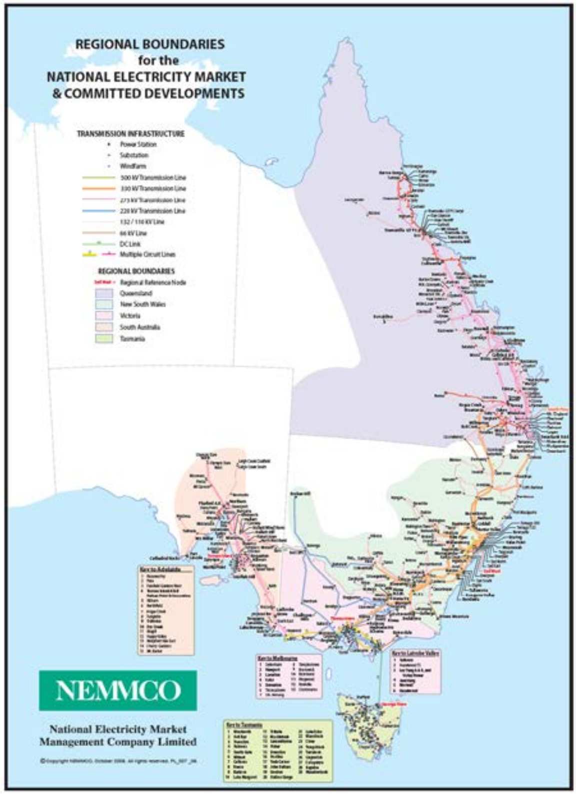
Threat Level Model from Global network observations

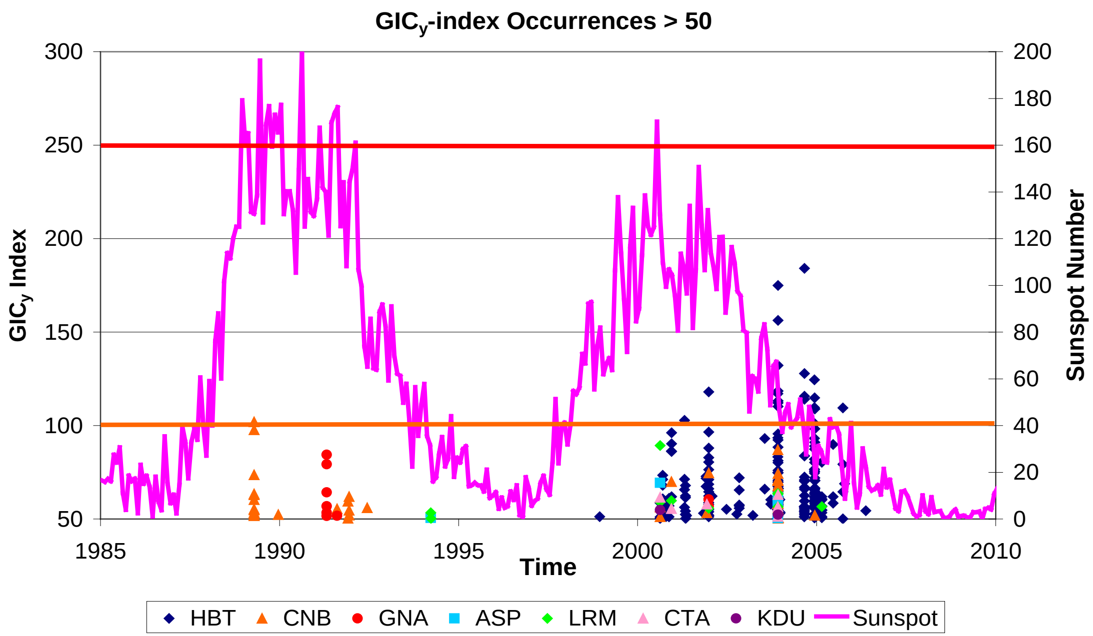




[Marshall, Smith, Francis, Waters and Sciffer, Space Weather, 2011]

Geomagnetically Induced Currents (GICs) in Power Networks





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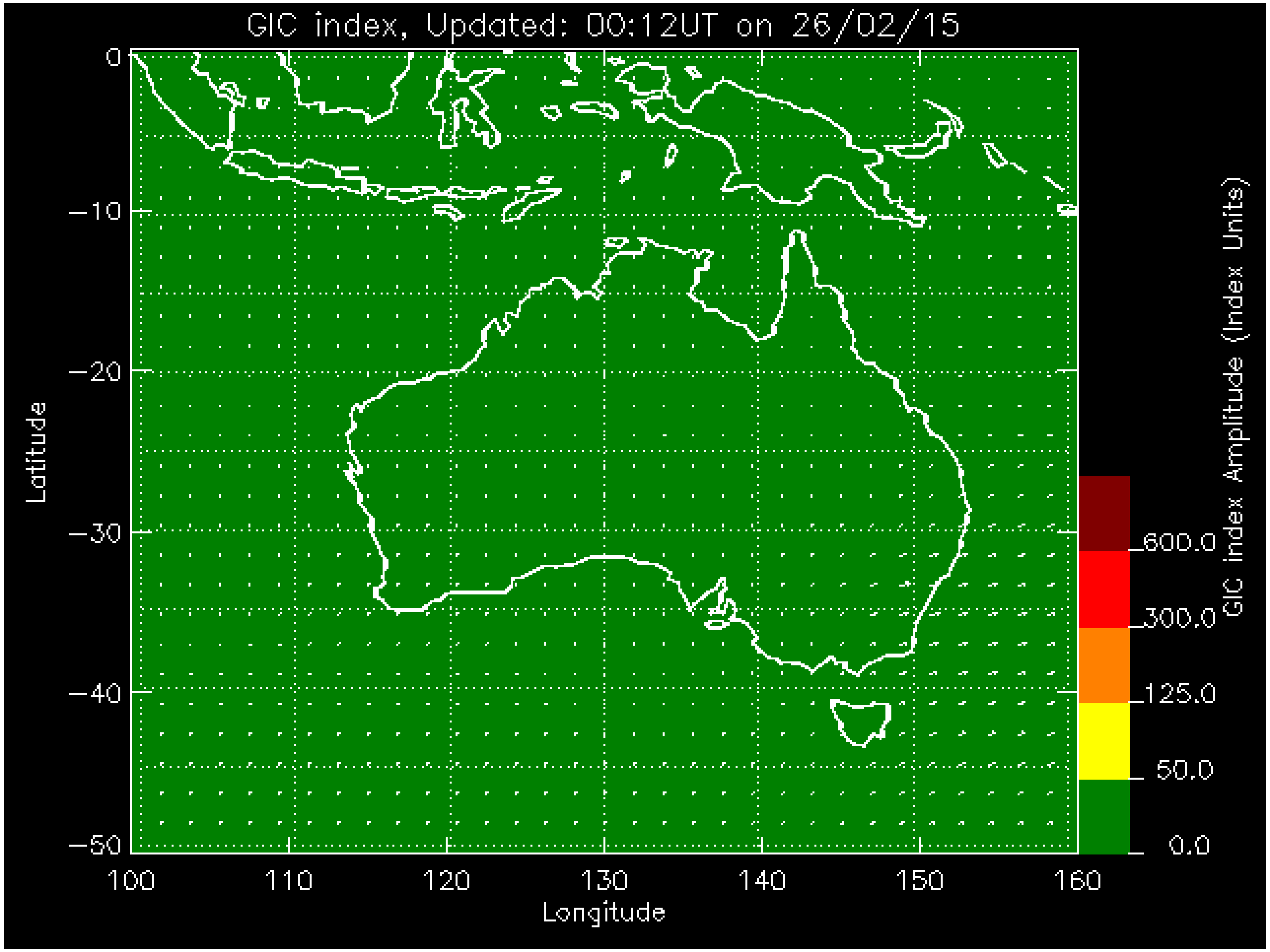
Australian Region Estimated GIC-Index



Extreme Space Weather (ESW) Model

-Most space weather impacts in Australian region associated with extreme events

-Event-based analysis

-Requirements:

LATENCY

-'Long range' warning (> 12 hours) □Based on solar data only

-'Short range' alert (~ 1 hour) □Based on solar data + ACE

ACCURACY

-Long range: Optimise to minimise missed events

-Short range: Optimise for forecast accuracy

SIMPLICITY

-Design for active use in space weather forecast environment

ESW Model Events

Associated CME

Event- based analysis

≥M1 X-ray flare specifies solar disturbance event

Solar wind shock

IMF Bz south event

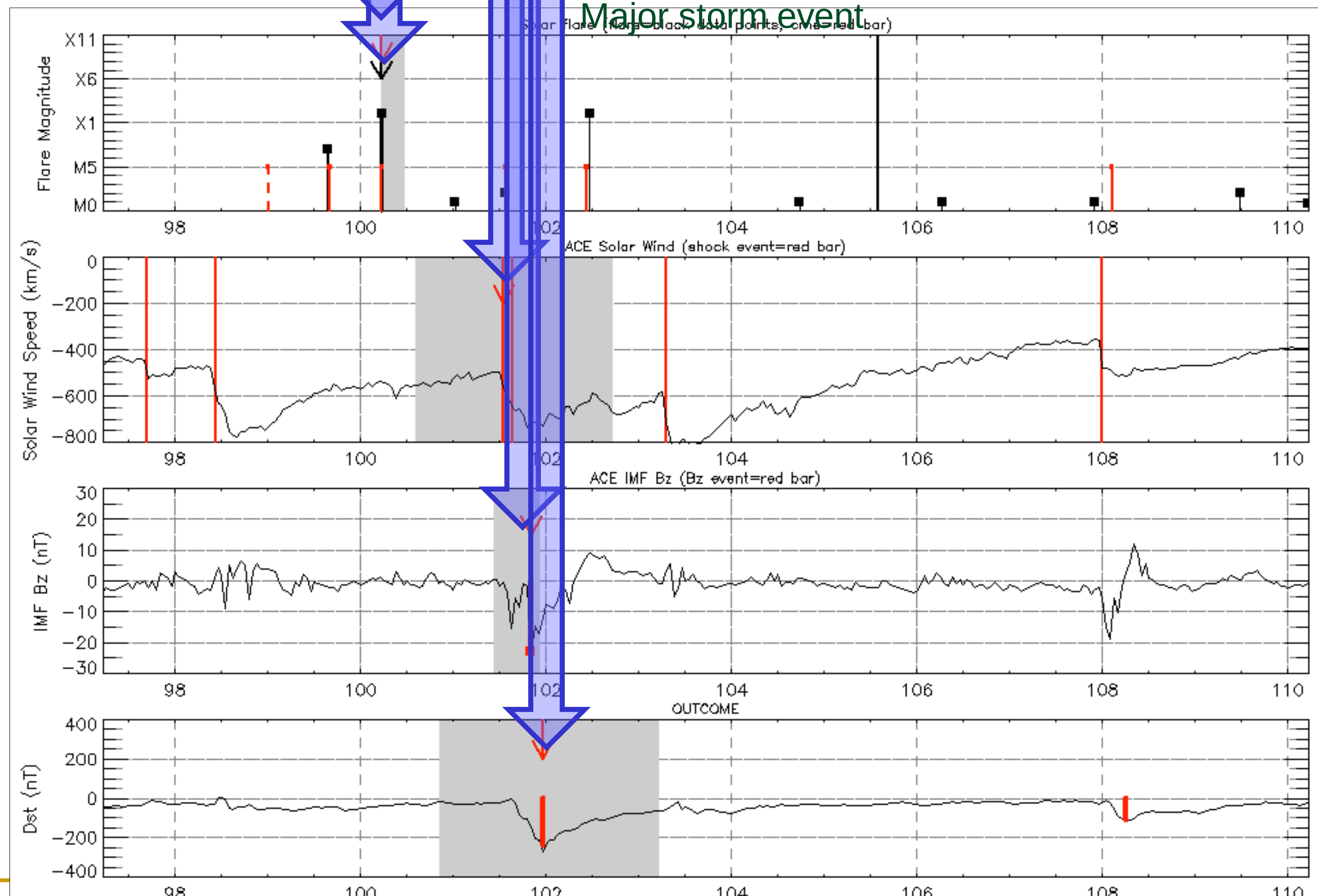
Major storm event

Flares / CMEs

solar wind (shocks)

IMF (Bz events)

Dst (storm events)



day of year

ESW Model Parameters

Model covariates (the ‘input data’)

X-RAY FLARE

- **Solar flare magnitude**
- **Solar flare duration**

LOCATION OF SOLAR ACTIVE REGION

- **Latitude of solar active region**
- **Longitude of solar active region**

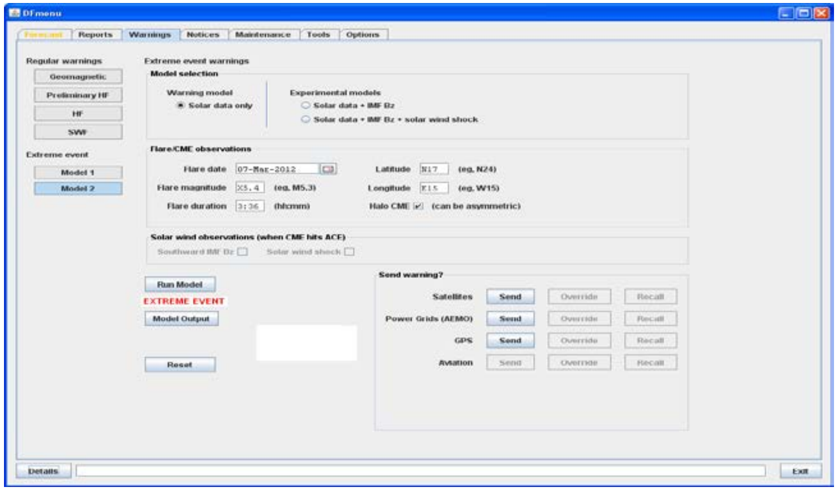
CME CHARACTERISTICS

- **Presence of Halo CME (CME width)**
- **CME speed**

SOLAR CYCLE
–Solar Cycle Phase

SOLAR WIND / IMF
– IMF Bz
– Solar wind shock

ESW Model Implementation



Regional Ionospheric specification and forecasting.

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Objectives:

Develop an Australian Regional Ionospheric modeling capability
-Develop/add value products and services for ionospheric specification and forecasting

IPS products and services are based on:

-Regional ionospheric TEC modeling

-Real time updating of the regional model: Kalman Filter

-Scintillation

-Ionospheric short time forecast

-Australian regional Disturbance /Activity Index

Regional ionospheric modeling: Spherical Cap Harmonic Analysis (SCHA)

Spherical Harmonic Analysis (SHA)

$$f(\theta,\lambda) = \sum_{k=0}^{K\max}\sum_{m=0}^{K} P_k^m(\cos(\theta)\left[g_k^m \cos(m\lambda) + h_k^m \sin(m\lambda)\right]$$

(Haines,1985) ***k*** $\Rightarrow$ ***n*** $_k$***(m)***

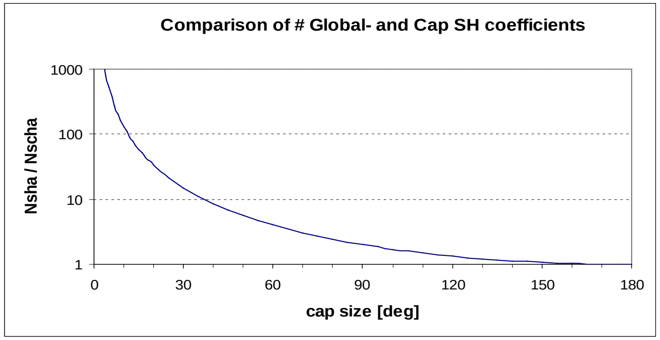
-Mathematical formalism:
Extension of the global SHA.

-Difference between SCHA global SHA:
Basis functions

-Wavelength /Resolution
Shorter in SCHA

- **Model coefficients**
for the same resolution, far less coefficients are used in SCHA

(De Santis et al.,1999)



$$N_{SCHA} = \sin^2\left(\frac{\theta_0}{2}\right) N_{SHA}$$

Mathematical formalism

Objective: Create harmonic expansion, using basis functions satisfying the boundary conditions at edge of cap. $\Rightarrow$ solving Boundary Value Problem (BVP)

Laplace equation in spherical coordinates:

$$\Delta = \left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial}{\partial\theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2}{\partial\phi^2}$$

Laplace equation can always be separated into three ordinary equations:

$$\frac{d}{dr}\left[r^2 \frac{dR(r)}{dr}\right] = kR(r),$$

$$\frac{1}{\sin(\theta)}\frac{d}{d\theta}\left(\sin(\theta)\frac{d\Theta}{d\theta}\right) - \frac{m^2}{\sin^2(\theta)}\Theta = -\lambda\Theta,$$

$$\frac{d^2\Phi}{d\varphi^2} + m^2\Phi = 0.$$

The solution to these differential equations is reduced to solving the eigenvalue/eignfunction problem of equations under boundary conditions.

SCH model for mapping the Australian Regional TEC

$$VTEC(\theta_c,\lambda_c)=\sum_{k=0}^{K\max}\sum_{m=0}^{K}P_{nk(m)}^{m}(\cos(\theta_c))\left[g_k^m\cos(m\lambda_c)\quad+h_k^m\sin(m\lambda_c)\right]$$

d=AX

***n k*(*m*)** : Non integer degree ($\theta_0 \neq \pi$)

Basis functions (geometry matrix)

$0 \leq \lambda \leq 2\pi$:Natural $\Rightarrow$ eigenfunctions/ eigenvalue: Trigonometric/ integer.

$0 \leq \theta \leq \theta_0$: Not natural $\Rightarrow$ eigenfunctions/eigenvalue: Legendre functions/real.

g_k^m, h_k^m :(m**odel coefficients, N=(Kmax +1)2)**

K_{max}: Maximum degree

Haines (1988)

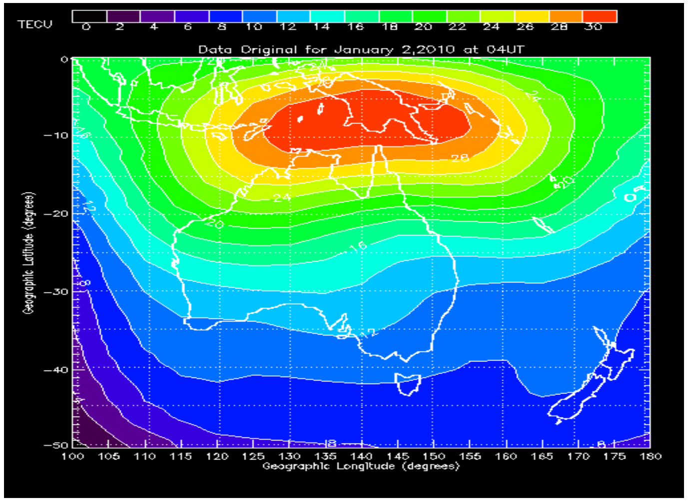
$$K_{\max}=\frac{2\theta_0}{\pi}\left(\frac{2\pi}{\lambda_{\min}}+0.5\right)-0.5$$

The cap and kmax determine the minimum wavelength of the model

$$d^{pr}=G^{pr}X$$

SCHA model for the Australian Regional TEC:

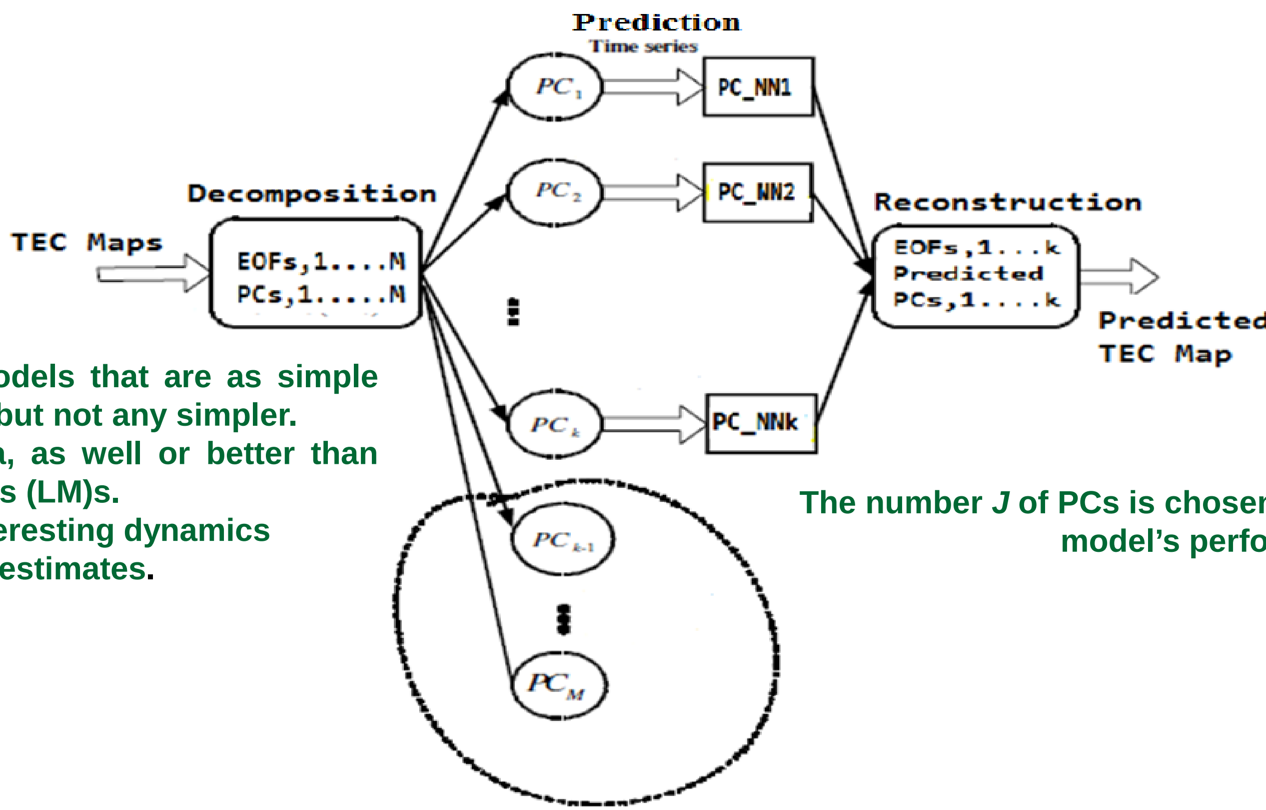
Benefits?
- -Improved spatial resolution.
- -Manageable number of coefficients / processing requirements.
- -Overcome uneven data distribution.
- - Scaling of cap size (“cap zooming”).



Regional TEC map on 02/01/2010 at 04:00UT

Modeling approach: Combined use of the Principal Component Analysis (PCA) and artificial Neural Network (NN)

Motivation for NN in forecasting – Nonlinearity!



-We want models that are as simple as possible, but not any simpler.
-Fit the data, as well or better than Linear Models (LM)s.
-Capture interesting dynamics
-Good noise estimates.

The number *J* of PCs is chosen so as to optimize the model's performance.

PC_NN method for TEC Prediction: M PCs extracted, for each PC a NN model trained and next value of each PC predicted, finally predicted PCs and EOFs combined for the prediction of the main Map.

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Modelling approach : Eignmode Decomposition

-Database :z(t,x) Matrix of N Regional TEC maps at P : locations $x = (\theta_i, \varphi_j)$ **, P=IXJ** spatial grids

-Spatial structures: $E_j(\theta,\varphi)$ Eigenvectors (Basis Function) (generated directly by themselves)
(ranged in descending order according to the proportion of variance explained)

-Their time evolution :

$$A_j(t) = z'^T(t,\theta,\varphi)E_j(\theta,\varphi)$$

(uncorrelated and carrying information about the variation of TEC along E_j)

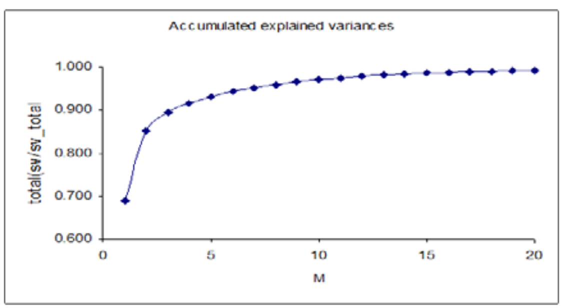
The largest components: Capture the slow-varying trends
-Seasonal variation and the solar dependence of the background TEC over Australia

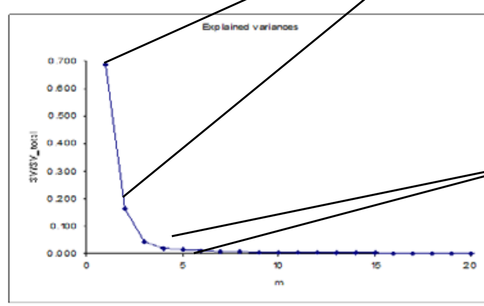
-Lower component: short-term variation
-The meteorology of the regional TEC perturbation

Near-cyclic nature: Predictable "comletely".

Improve the understanding and prediction of the irregular part.

-With decreasing variance PCs explain increasingly complex features





Irregular structures/ ionospheric weather.

Unpredictale "Totally".

Explained variance and the accumulated explained variance for the TEC .

Modelling approach : Main Spatial and Temporal Variations:

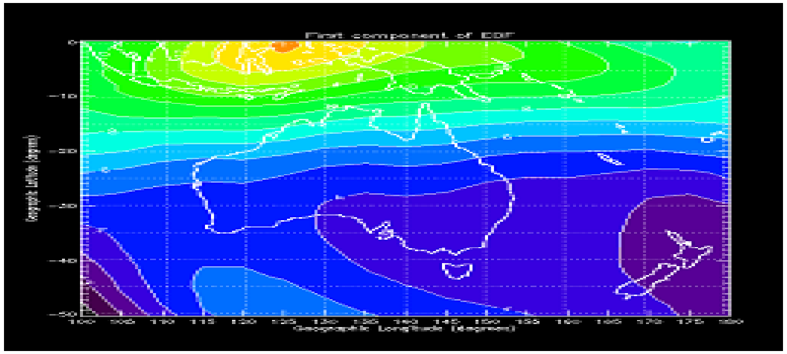
-The largest components

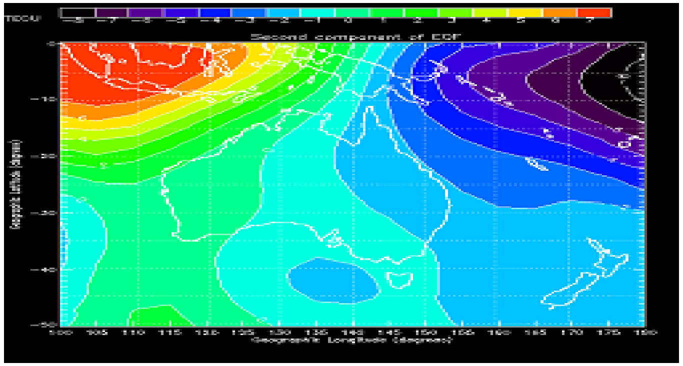
Significance: 69.7%

A1E1 mainly controls the intensity of the Ionospheric electron concentration.

Significance: 16.3%

A2E2 : the correction of the main trend.



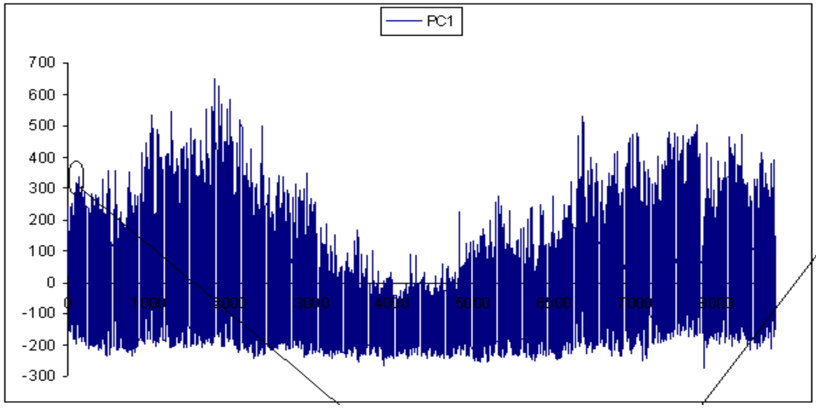


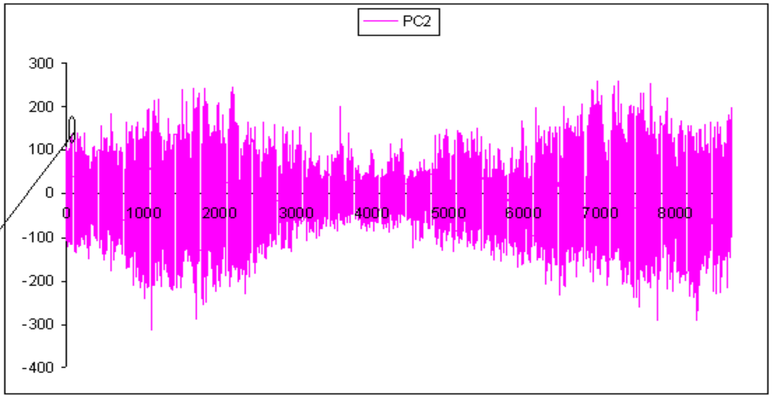
First two EOFs of the TEC for the year 2010, function of longitude and latitude

A1: Semiannual : 2 maxima

(March/April and September/October).

A2: Annual variation

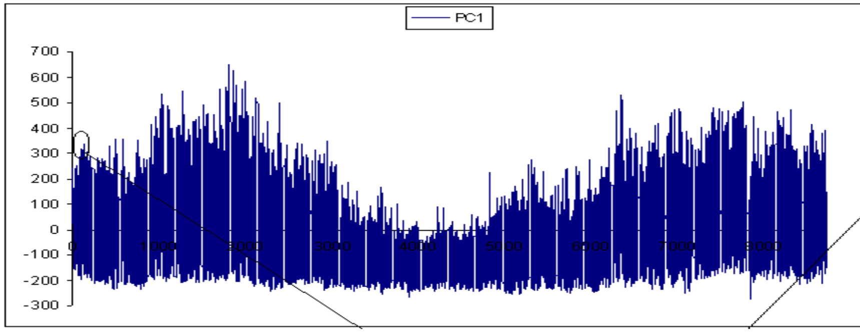


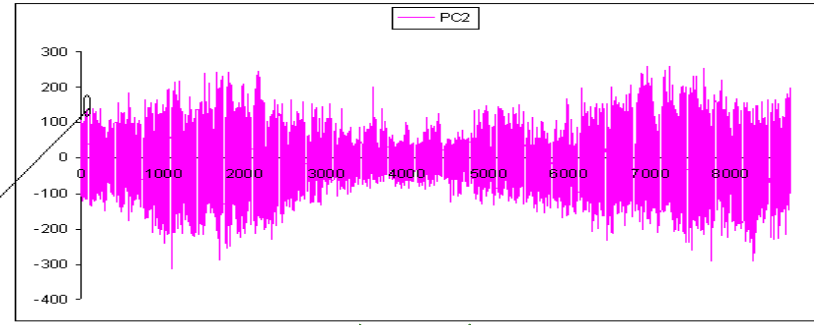


Time series of the first 2 EOFs coefficients shown above (*A1*, *A2*) (blue, pink) for the year 2010.

Forecasting approach: *Three ionospheric time varying characteristics*
Stage 1: 1 day ahead prediction

Eigenvalue decomposition of A1(UT,d): (first layer decomposition coefficient)



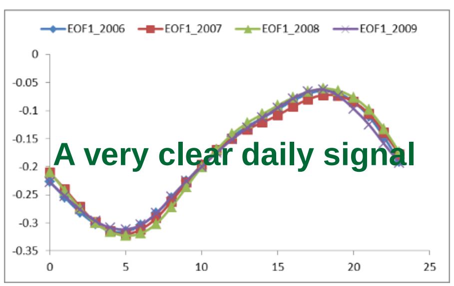


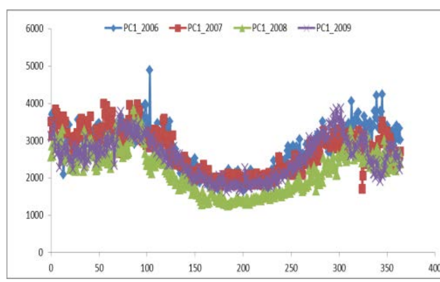
$$A_k(UT,d) = \sum_{j}^{N} F_k^j(UT)\, PC_k^j(d)$$

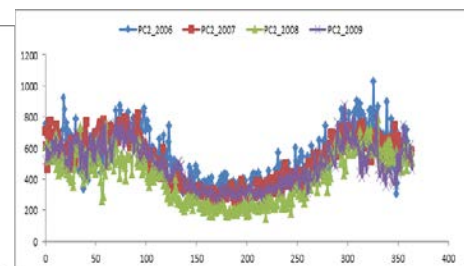
EOF coefficient: (Seasonal, solar cycle)

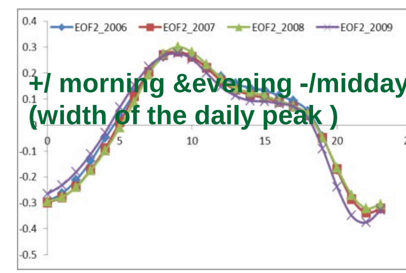
(Base function) $F_1^1(UT)$

$F_2^1(UT)$









The signal has the same shape and magnitude for all the 4 years

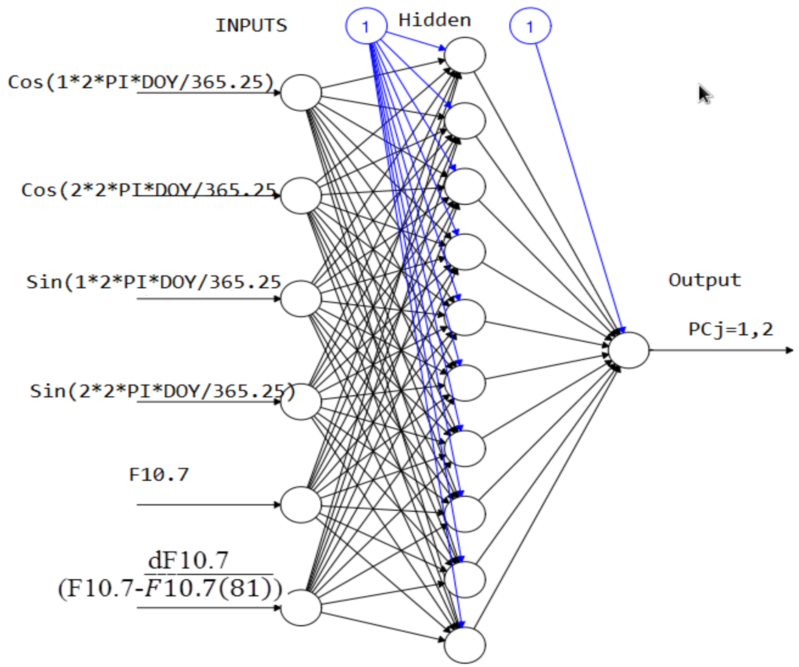
How the daily signal varies through the year.

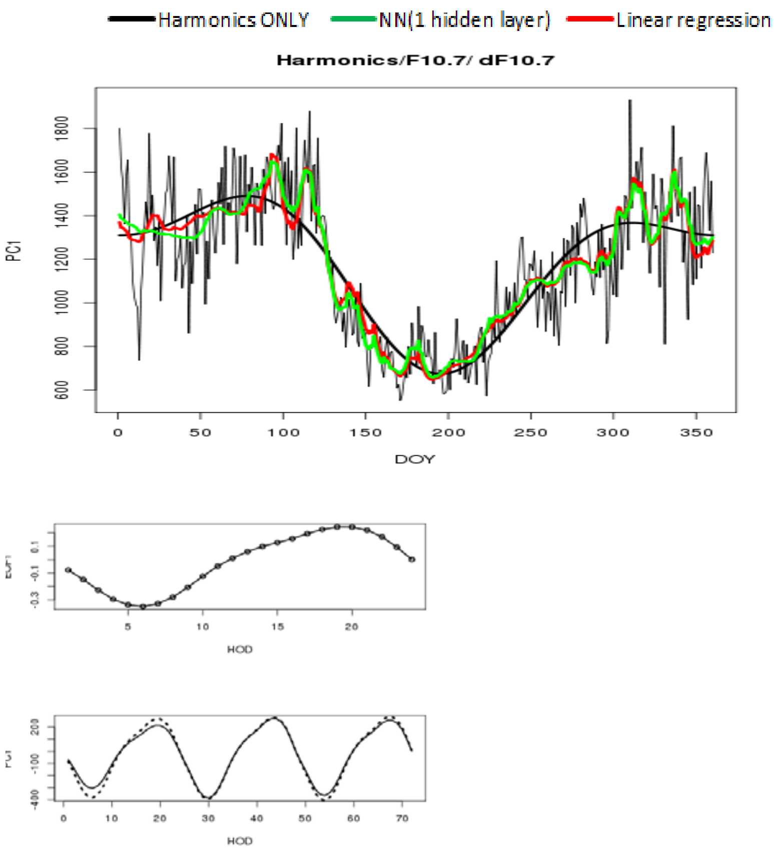
The signal has the same shape and magnitude for all the 4 years

Model construction: Modeling PCj=1,2

Harmonic functions representing: Seasonal (annual and semi annual)
Solar activity : F10.7 (10.7-cm solar radio flux in units of W m-2Hz-1)

-A bottom-up strategy: Starting point is a Linear Model
-Non linear components are added (*only if necessary*)
(Justify additional efforts necessary for a nonlinear model compared to a linear one)





Including geomagnetic indices as input to the neural network was investigated and it was found that the performance was not improved.

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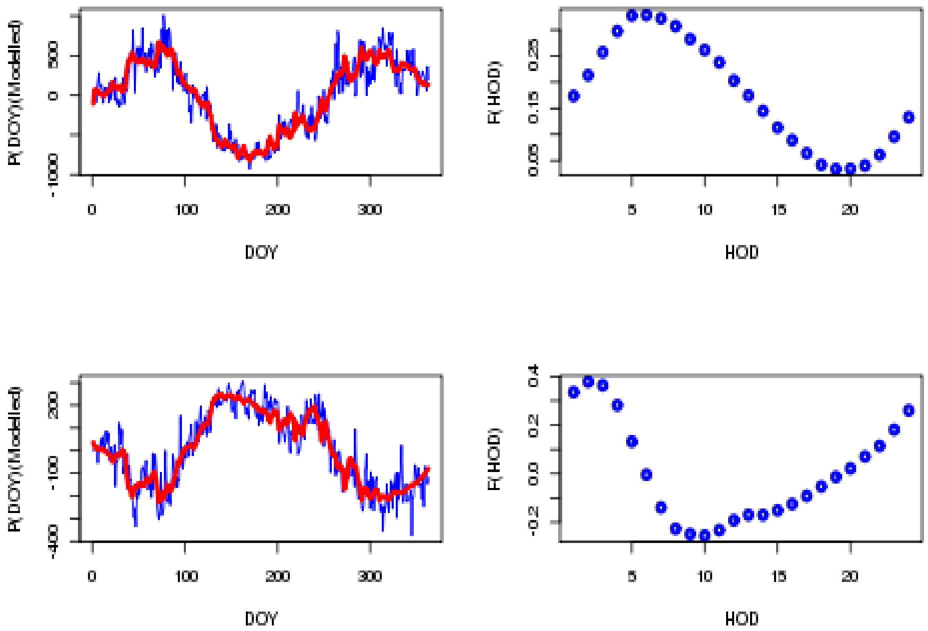
The tree time varying characteristic of the ionosphere. (daily, yearly and solar cycle)

-Low frequency: Easy to predict (harmonics modulated by the solar activity)

Harmonic functions representing: Seasonal (annual and semi annual)
Solar activity : F10.7 (10.7-cm solar radio flux in units of W m-2Hz-1)

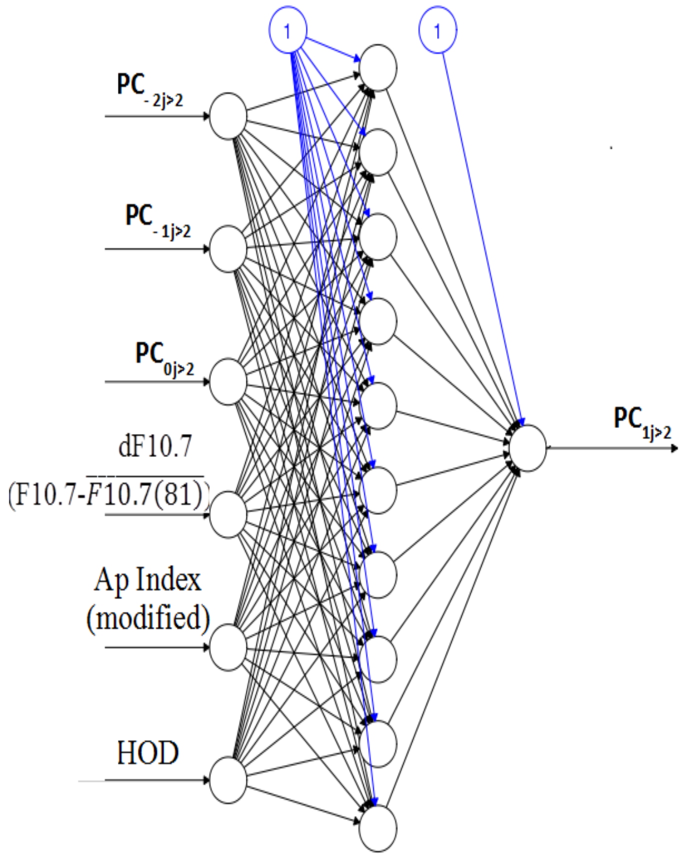


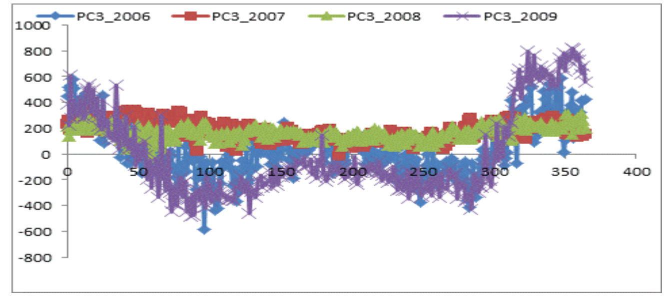
EOF (dashed blue line) and Coefficient of second layer decomposition (P(d)) (solid blue line) and corresponding predictions calculated by the model (solid red line).

Model construction: Stage2: Short term forecast (1hour ahead prediction) (under development)

The proposed model predicts (outputs) the TEC at a certain time from the Geomagnetic avtivity and its history and the history of the TEC.

Nonlinear adjustment





Higher order components: PCj>2
-Present mainly short-term variation and noise
-Less correlated with the primary variation in TEC.

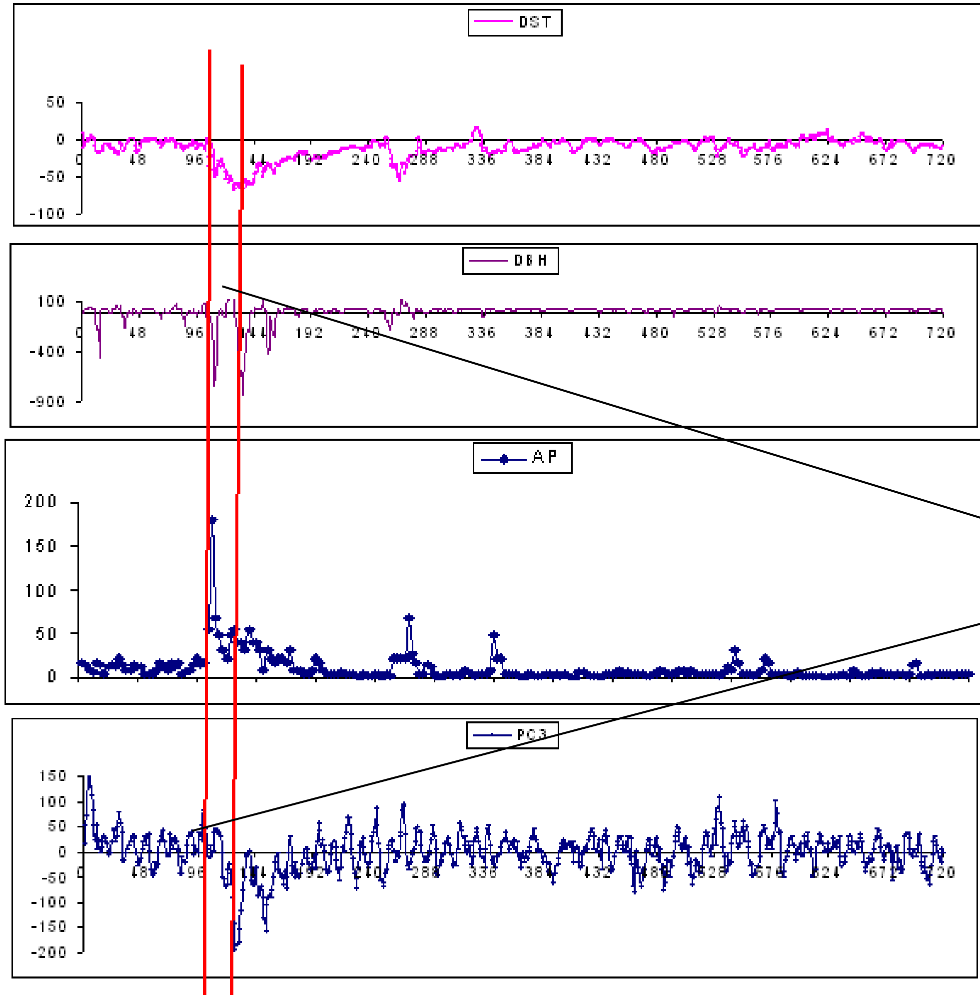
-**The complexity of the nonlinear part of the models is increased step- by- step, only if contribute significantly to the performance of the models.**

The number *J* of PCs is chosen so as to optimize the model's performance.

The aim of such a procedure is to keep the models as simple as possible.

NN Improved linear models rather that pure non linear models.

Space Weather Indices and TEC variations: April 2010



Comparison of daily Dst index (a), change in the geomagnetic field’s horizontal component at Canberra (b), Ap index (c) and TEC perturbation (d) over the Australian region (April 2010).

Most influential factors

Factors	F10.7	dF10.7	AP	Dst
Correlation	0.23	0.38	0.51	0.43

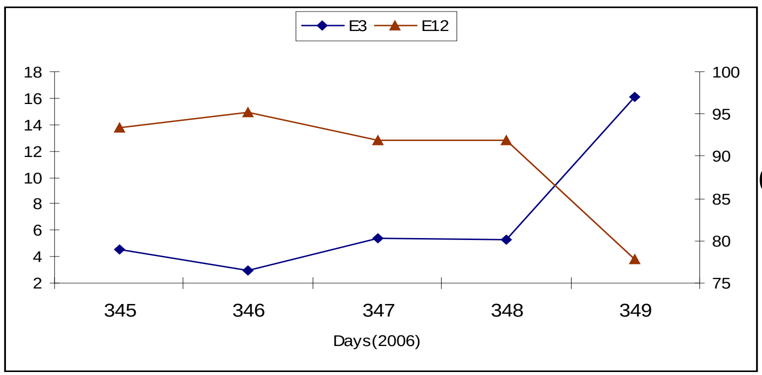
-Delayed perturbation acros the region

-Potential for predictionbased on earlier space weather observations

Application of the approach (test cases): December 2006 Geomagnetic Storm

Probable CME observed by SOHO satellite

Probable CME (UTC)	Class
13 Dec 02:40	X3.4
13 Dec 14:23	C2.2
13 Dec 18:25	C1.7
14 Dec 12:10	C1.0
14 Dec 16:49	C1.2
14 Dec 22:15	X1.5



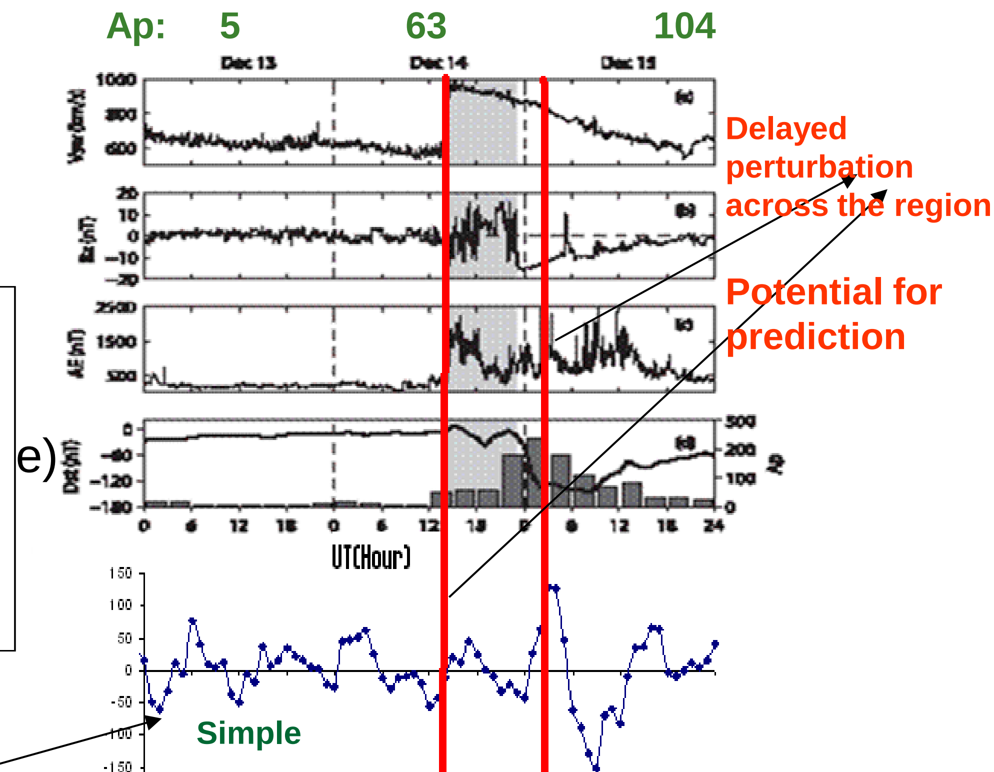
Development of the storm:

-Solar flares and Sunspots associated with large CMEs

-Change in Dst index (SSCs)

-Severity of the disturbed geomagnetic conditions (Ap Index)

- Rapid direction changes in the IMF Bz component and the Solar Wind .



(a) Solar wind speed, (b) interplanetary magnetic field Bz, (c) AE index, (d) Ap and Dst index and (e) ionospheric perturbation on 13–15 December 2006. The patches indicate the initial phase of this storm.

Storm dynamics:

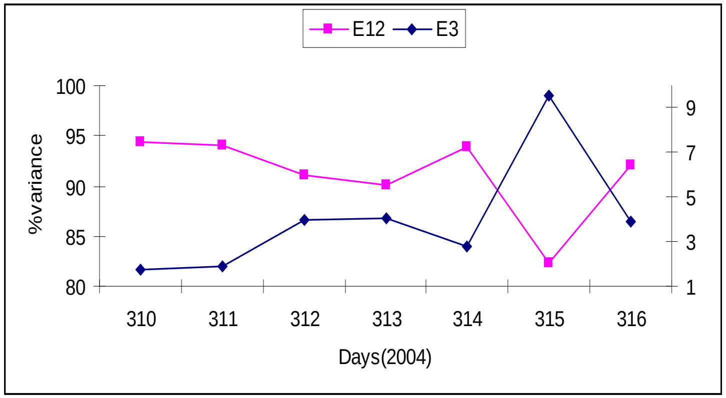
-Three interrelated causal mechanisms: mechanical, electrical and chemical.

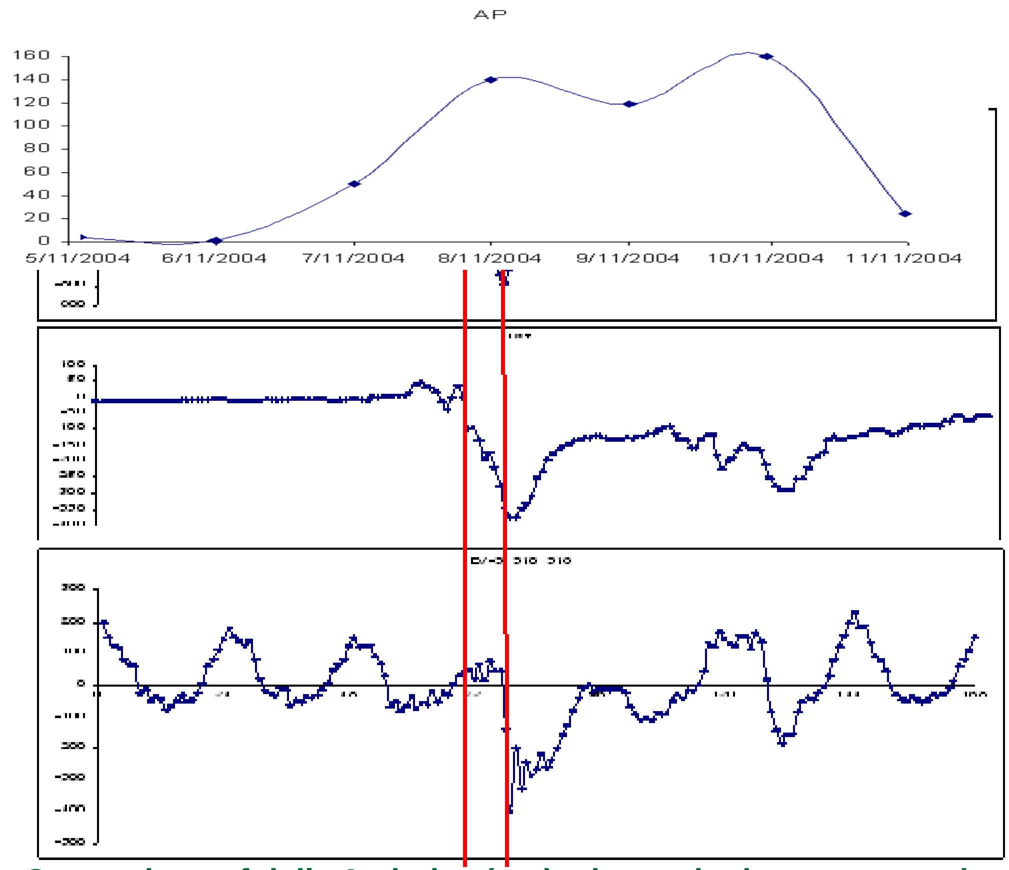
-Competition among electric fields as well as thermospheric dynamics and composition changes.

Complex (Incomplete knowledge)

Application of the approach (test cases): November 2004 Geomagnetic Storm

5-11 November 2004





Comparison of daily Ap index (top), change in the geomagnetic field's horizontal component at Canberra (middle) and TEC perturbation (bottom) over the Australian region.

-The largest components(PC1 and PC2)
- -Capture the slow-varying trends
- - Primarily deterministic

-Lower component (PC3)
- - short-term variation

The main contributions are:

-The developed SCHA methodology for mapping TEC is the first of its kind for the Australian region and may be adapted for application in other regions and for other ionospheric parameters.

-We can widen its applicability from regional to local
-By including harmonics with higher spatial index to investigate shorter wavelength features

-The NN approach for the multicomponents modelling /prediction.

-Reducing the dimension of the prediction problem and the associated processing overhead.
-Gap Filling in Geophysical data.

Fact Sheet for Needs-Seeds Matching

Name of Organization:	Australian Bureau of Meteorology , Space Weather Services.	
SEEDS	Data& Instrument	See attached
	Other	Training Cources
NEEDS	Data& Instrument	High rate, near real time GPS and ISM data from PNG/Indonesia and South East Asia. Ionosonde data from PNG and Indonesia . Oblique ionospheric sounding (OIS).
	Model	Regional scintillation forecast model.
WANTS	Data &Instrument	Plasma bubles observations