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Predicting ionospheric scintillation for users of Global Navigation Satellite System signals

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Equatorial Plasma Bubbles

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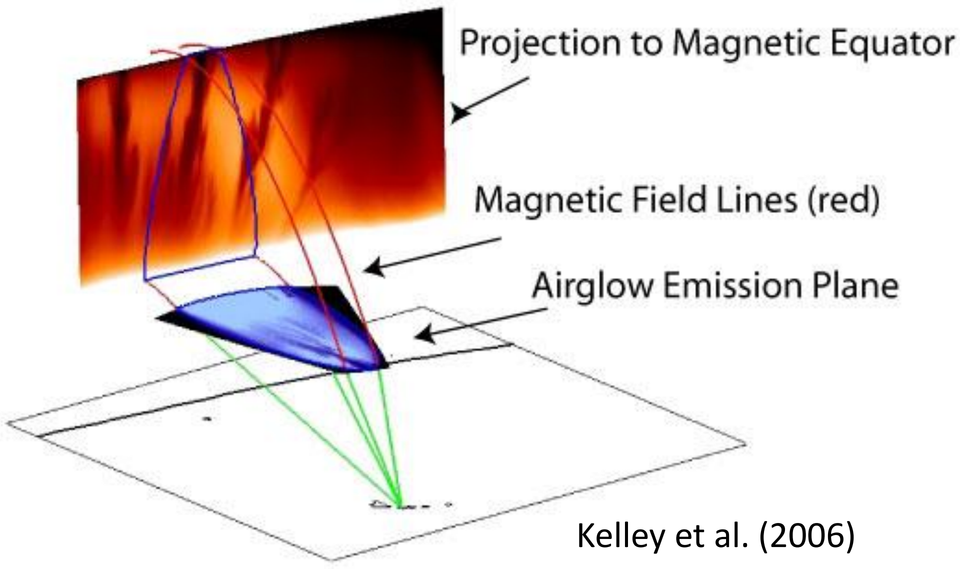
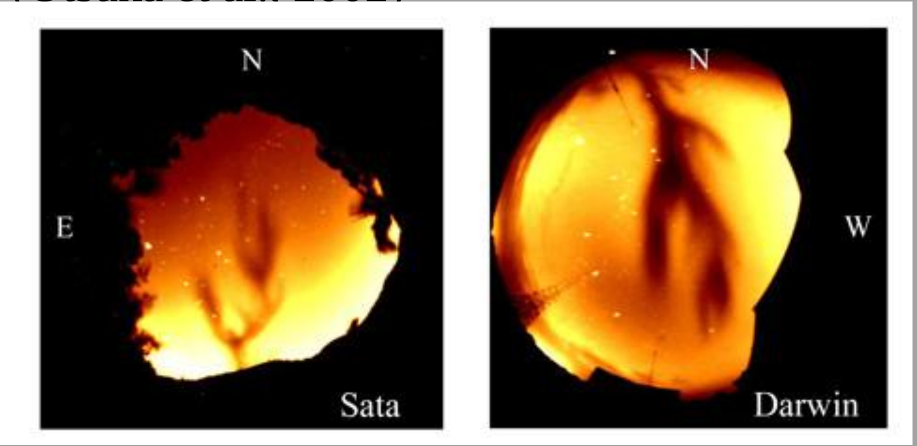
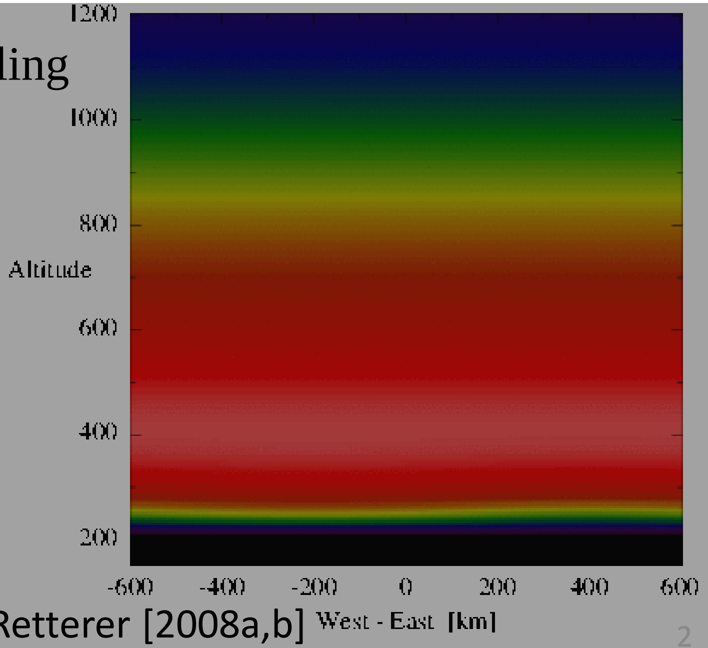


Kelley et al. (2006)

All-sky cameras
(Otsuka et al., 2002)



Modeling



Retterer [2008a,b]

Generalised Rayleigh-Taylor instability:

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(V_p - U_n^P - \frac{g_L}{\nu_{in}^{eff}}\right)\frac{1}{L_n} - R_T$$

(Sultan *et al.*, 1996)

GPS disruptions

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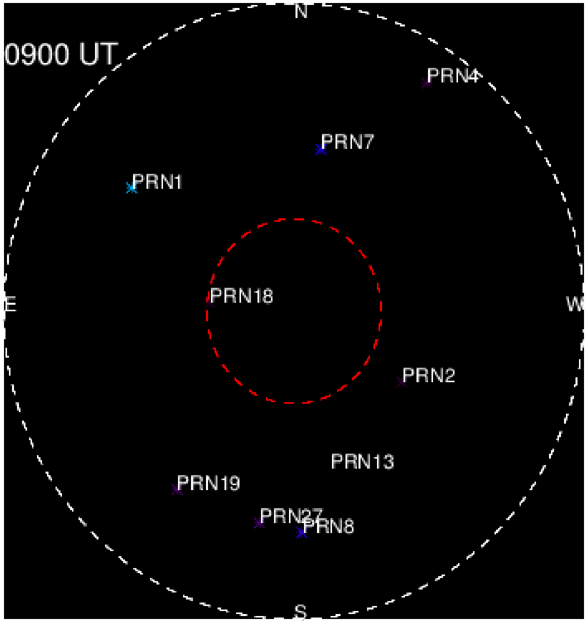
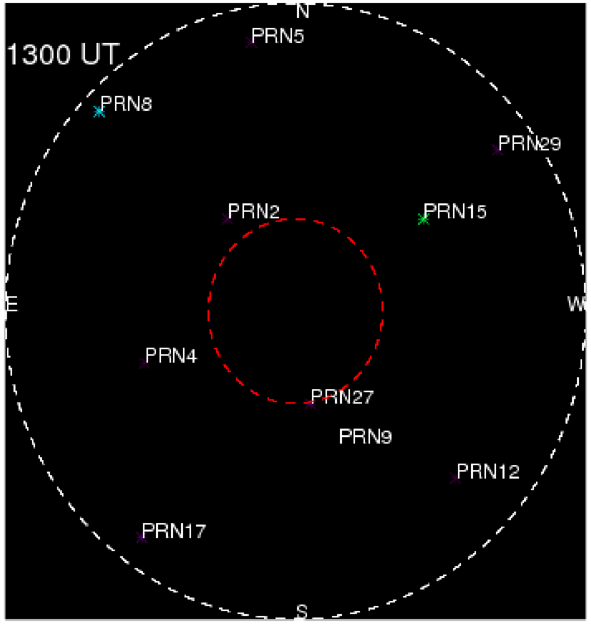
Vanimo PNG, Mar-17-2000

Darwin, Sept-21-2012

View from ground:

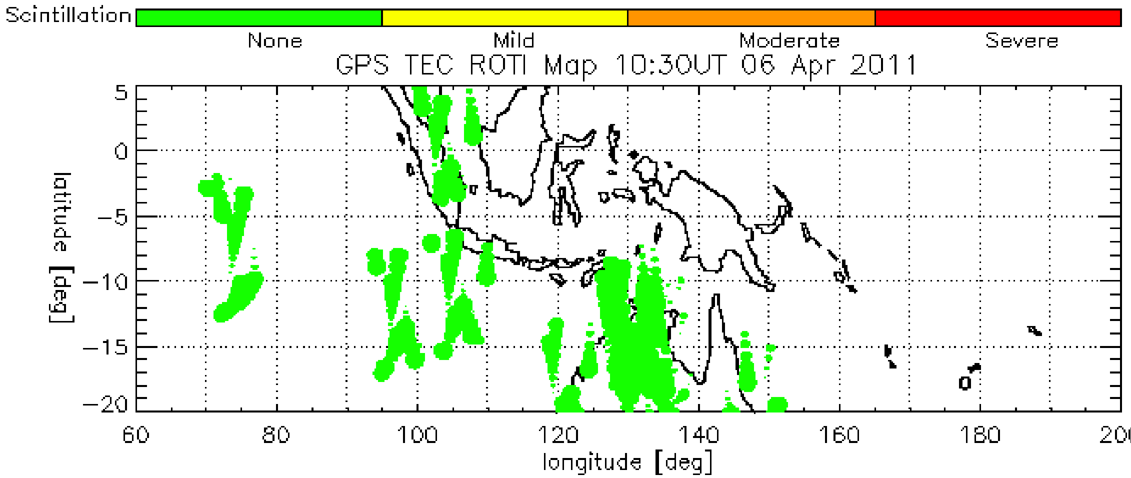


All GPS links affected: 1030 – 1300 UT



All-sky camera data provided by Kazuo Shiokawa

View from sky:
BoM – Space Weather Services



Potential economic vulnerabilities to day-to-day space weather: GNSS

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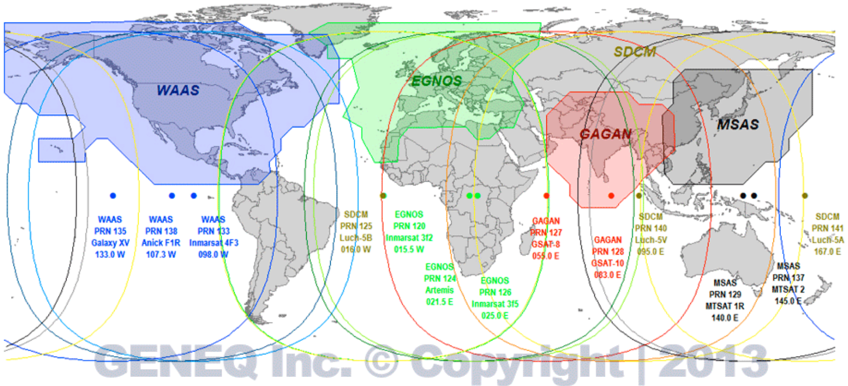
GNSS (Global Navigation Satellite Systems) and satellite communications are being increasingly utilised by various industry sectors. For example;

- Mining
- Aviation
- Agriculture
- Construction
- Military/Defence


GPSat Systems Australia


Credit: SSG Kyle Davis



No study to date has investigated the impact of ionospheric scintillation events on operations in these sectors, and the flow-on impacts on the wider economy.

In the meantime, reliable daily scintillation forecasts are needed around the world…


CRC for Spatial Information

GPS Radio Occultation

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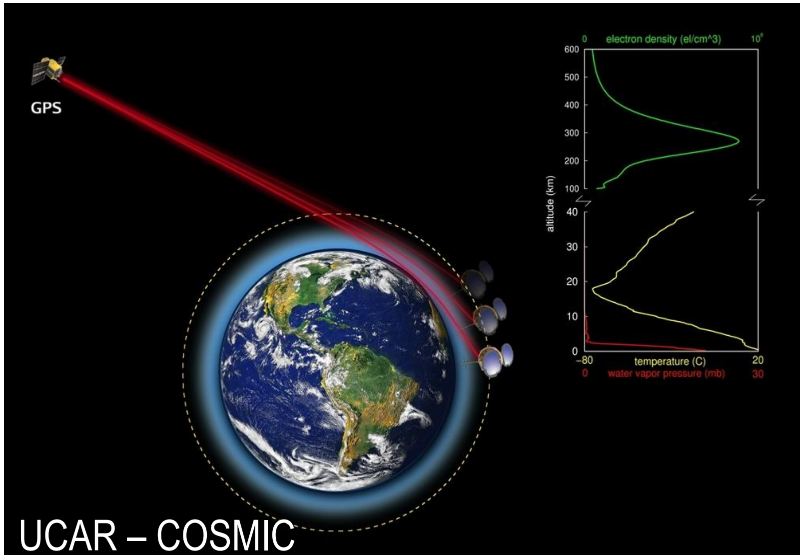
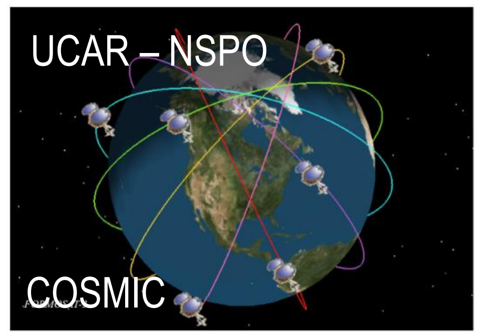
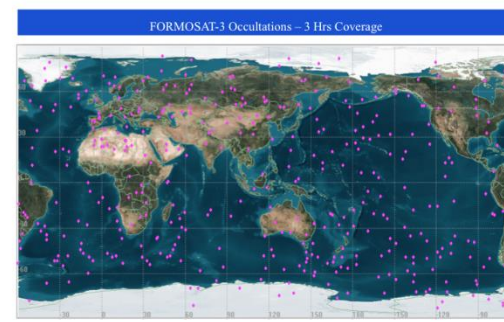
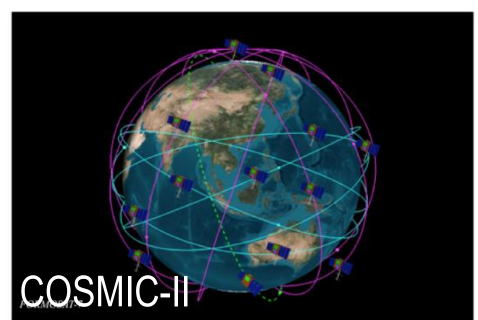
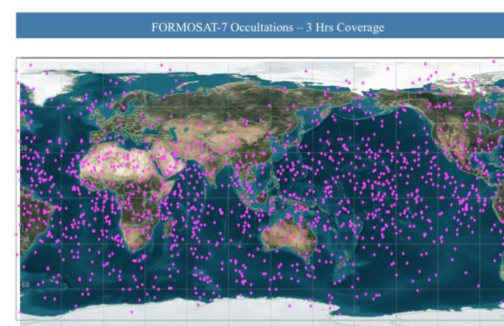


The Low Earth Orbit (LEO) satellites measure the GPS signals that are occulted by the Earth's atmosphere. These occulted signals are used to infer atmospheric properties such as wet temperature (troposphere) and electron density (ionosphere).







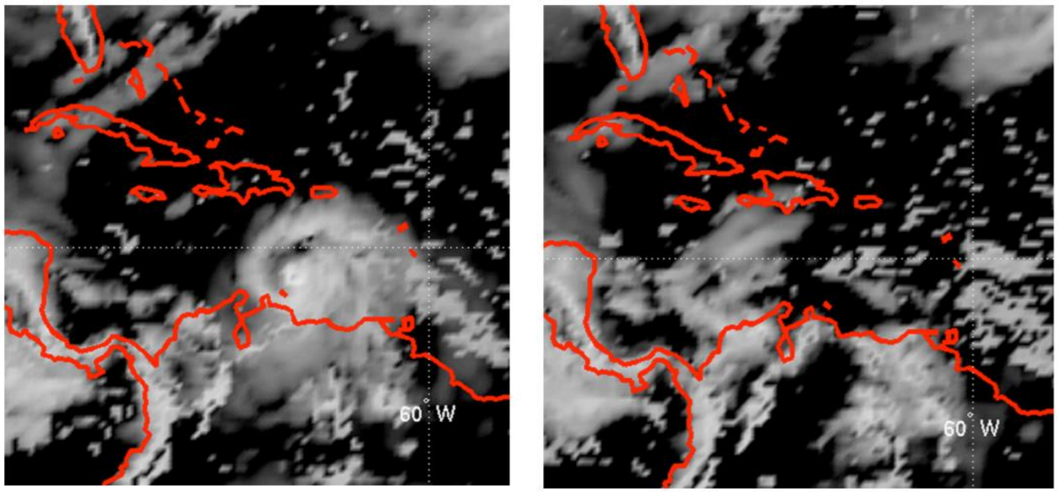


GPS RO data are currently assimilated into weather forecasting facilities around the world (including the Bureau of Meteorology).

Xiong et al. (2016)

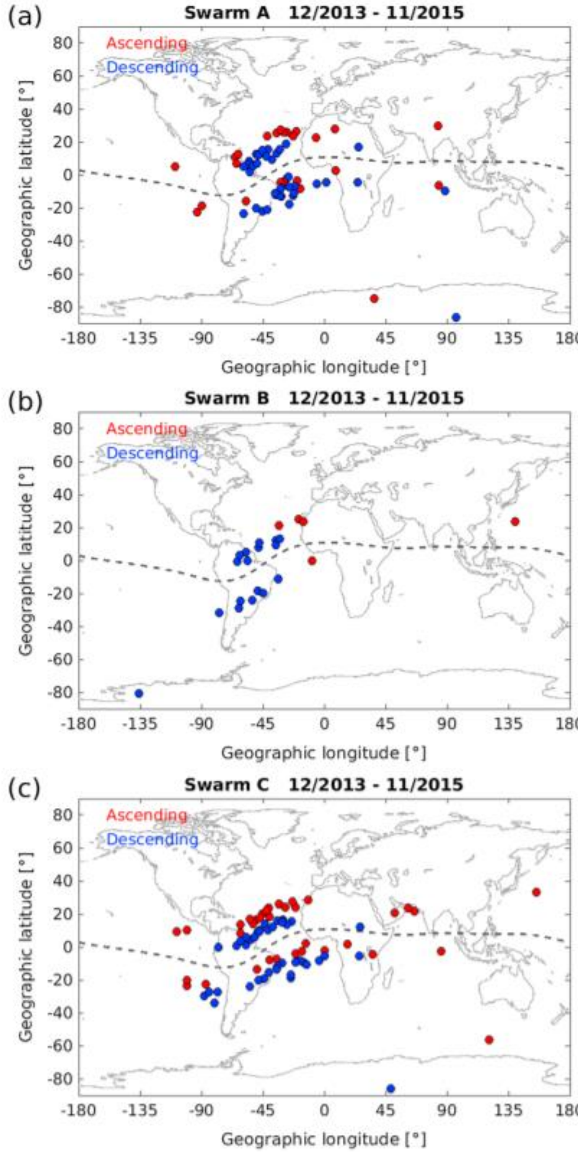
Impact of COSMIC on Hurricane Ernesto (2006) Forecast

With COSMIC — Without COSMIC



Slide from Bill Kuo

Results from Hui Liu, NCAR



GNSS Radio Occultation data is clearly beneficial, but with increased benefit comes increased vulnerability

Scintillation Climatology

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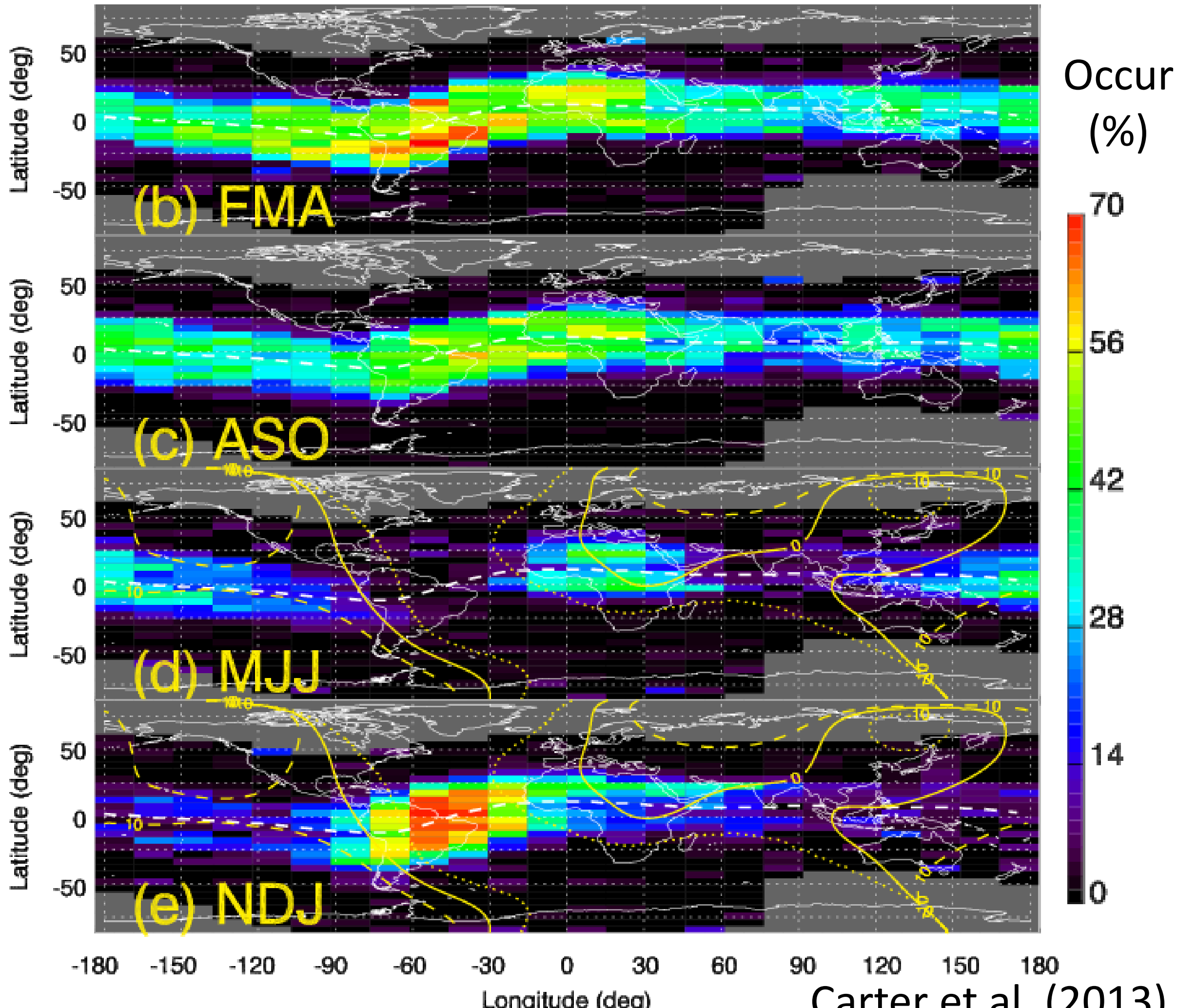
Post-sunset EPBs are most common during the equinoxes across all longitude sectors near the magnetic equator.

The June solstice months have elevated EPB activity in the Pacific and African sectors.

South America and Africa have EPBs during the December solstice months.

Africa gets scintillations all-year-round.



Carter et al. (2013)

Daily variability of EPBs

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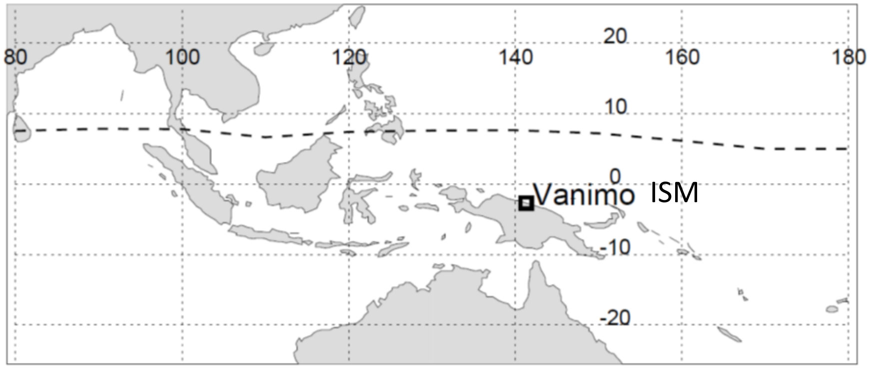

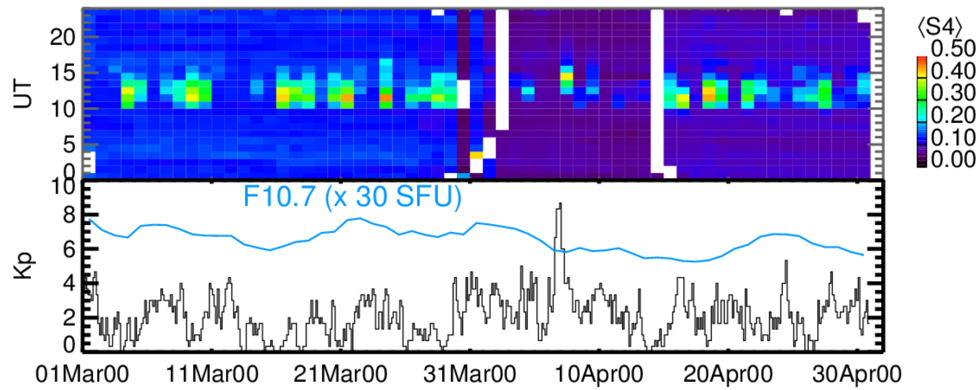

Carter et al., 2014a [JGR]

- Ionosphere - thermosphere observations along the entire flux tube, as required by the Rayleigh-Taylor linear instability growth rate expression, are not possible/feasible

(Sultan, 1996)

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(V_p - U_n^P - \frac{g_L}{\nu_{in}^{eff}}\right)\frac{1}{L_n} - R_T$$

Gravity

Ion-neutral collision frequency

Recombination rate

Unknown

Pederson conductivities

Upward neutral wind

Gradient scale length

Upward plasma drift

Directly measured/known

- Therefore, some form of ionosphere-thermosphere modelling is required…

TIEGCM

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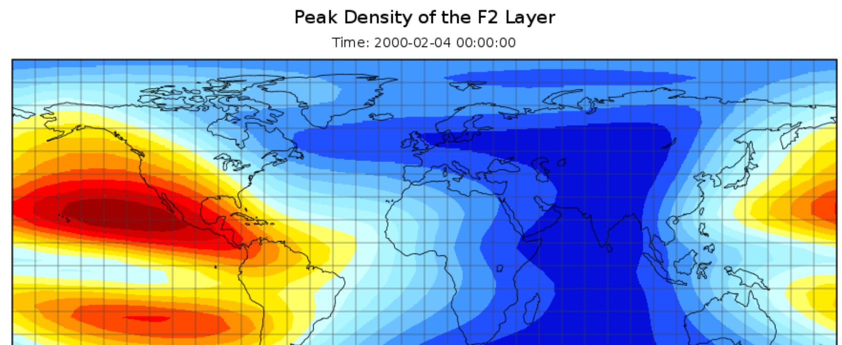
The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) is a time-dependent 3D physics-based (i.e. not empirical) numerical simulation of the Earth's thermosphere and ionosphere.

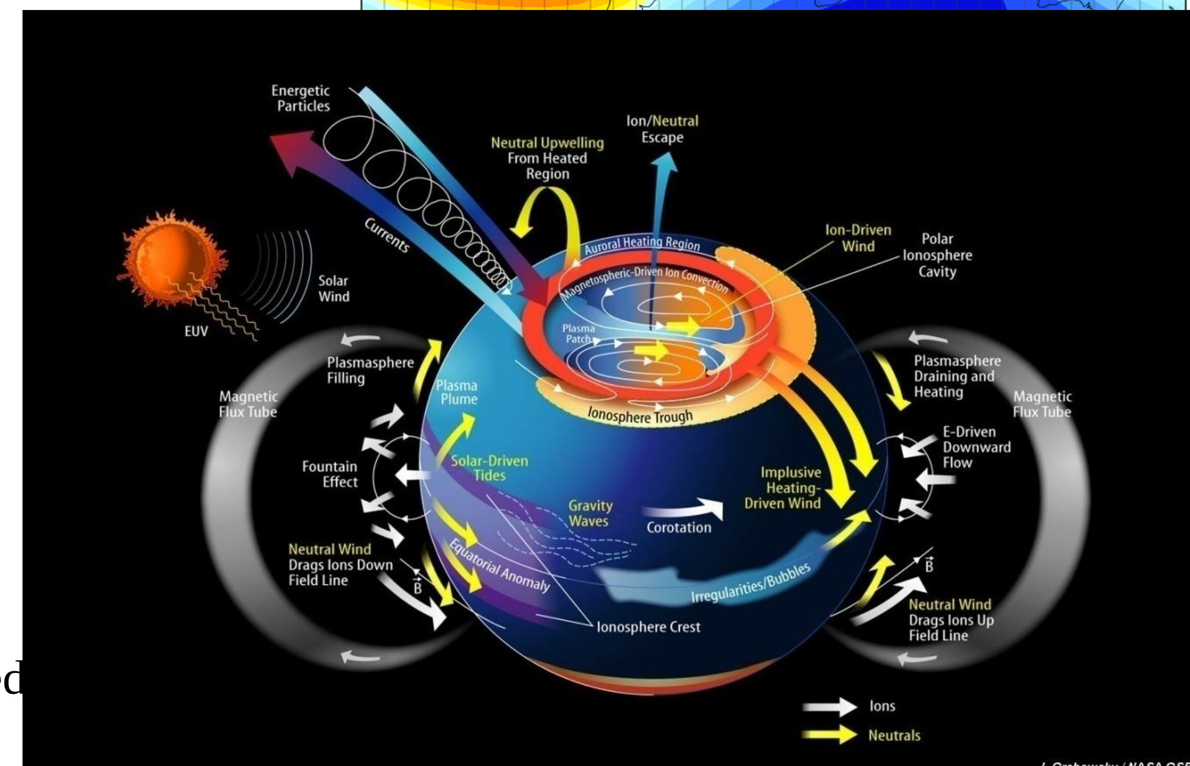


Inputs:

- Solar activity (F10.7 cm flux)
- Geomagnetic activity (Kp index)

Outputs:

- Electron density
- F layer height
- 3D plasma drift
- Thermospheric density
- 3D neutral winds…
- …
- Basically, everything that we need



TIEGCM: EPB variability

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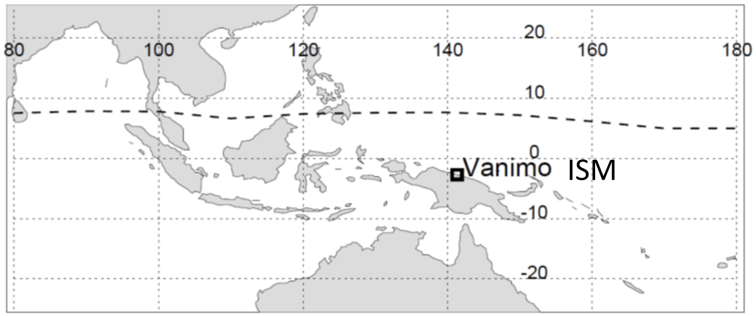
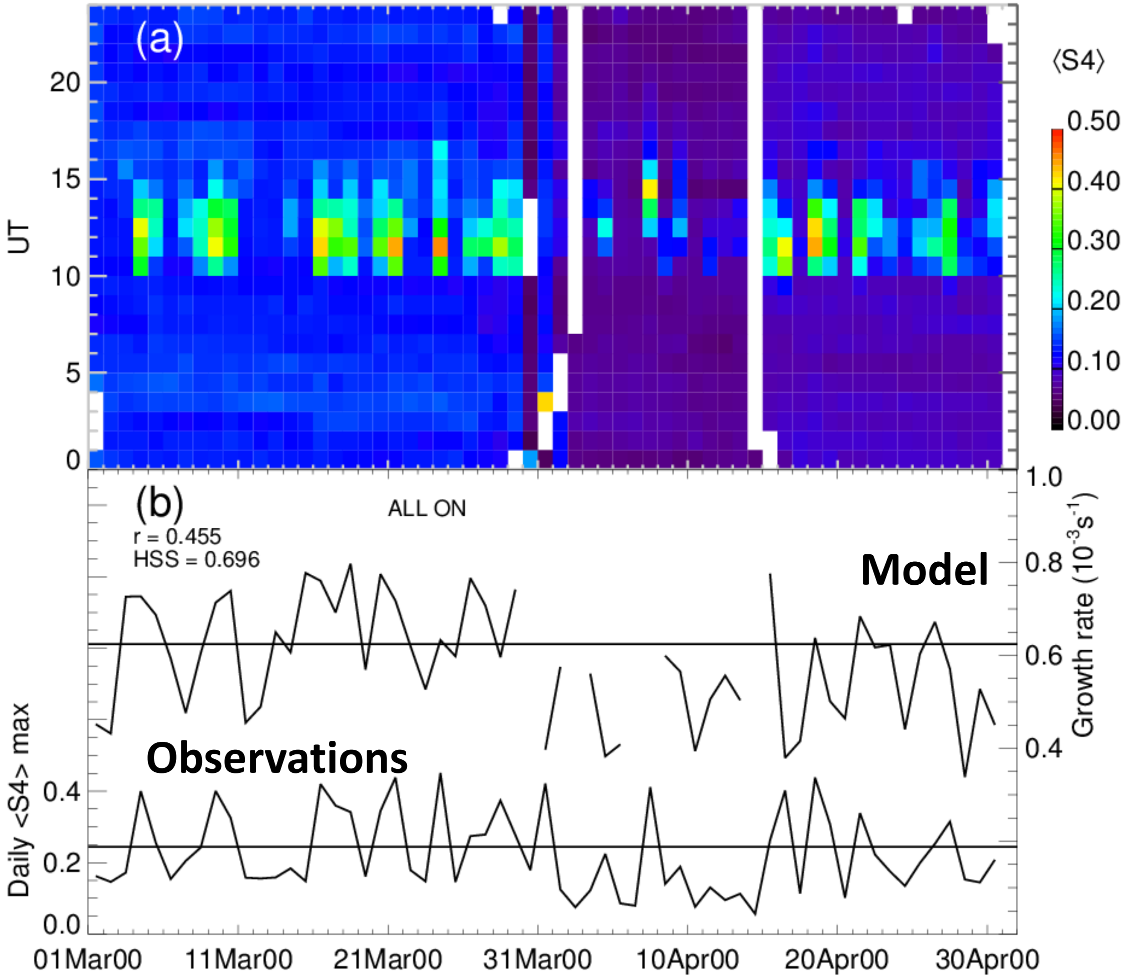


Observed

Modelled

EPBs	Yes	No
Yes	17	3
No	5	31

- Physics-based model was found to imitate the observed daily changes (correct ~86% of days)
- Kp is dominant source of TIEGCM variability during quiet period



Carter et al., 2014a [JGR]

Physical process: EPB suppression

Increased Kp

↓

Intensified plasma convection at high latitudes

↓

Increased Joule heating

↓

Thermospheric wind perturbations propagate towards equator

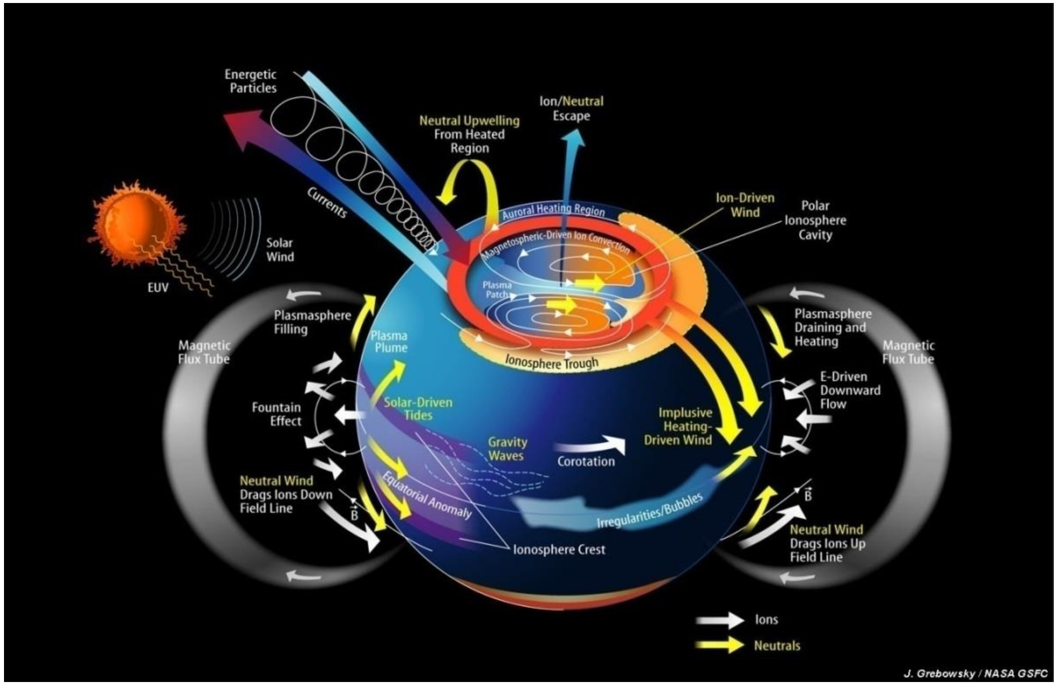
↓

Decrease in zonal wind at equator

↓

Decrease in upward plasma drift (Vp)

→ Decreased R-T growth rate (no EPBs or scintillation)



2015 St Patrick's Day Storm

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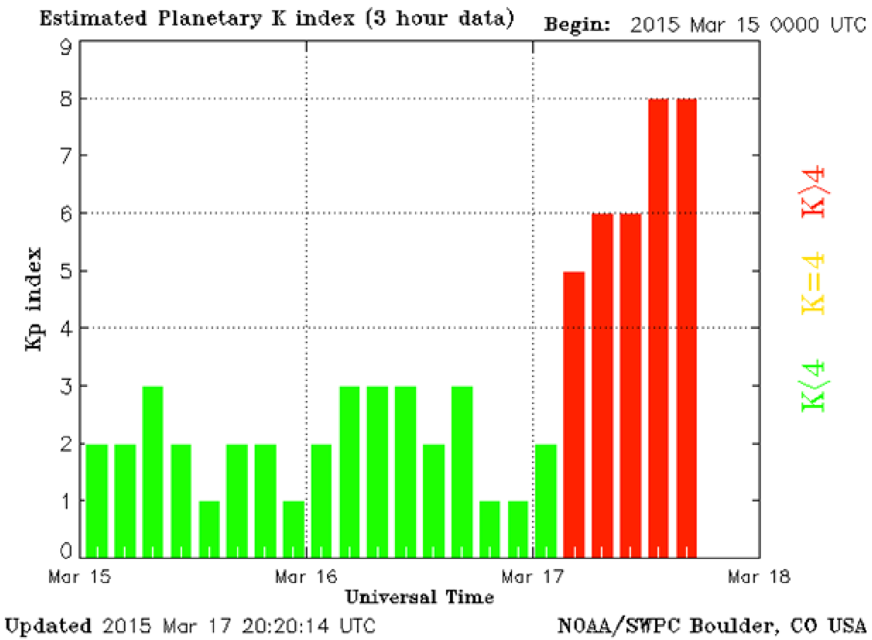
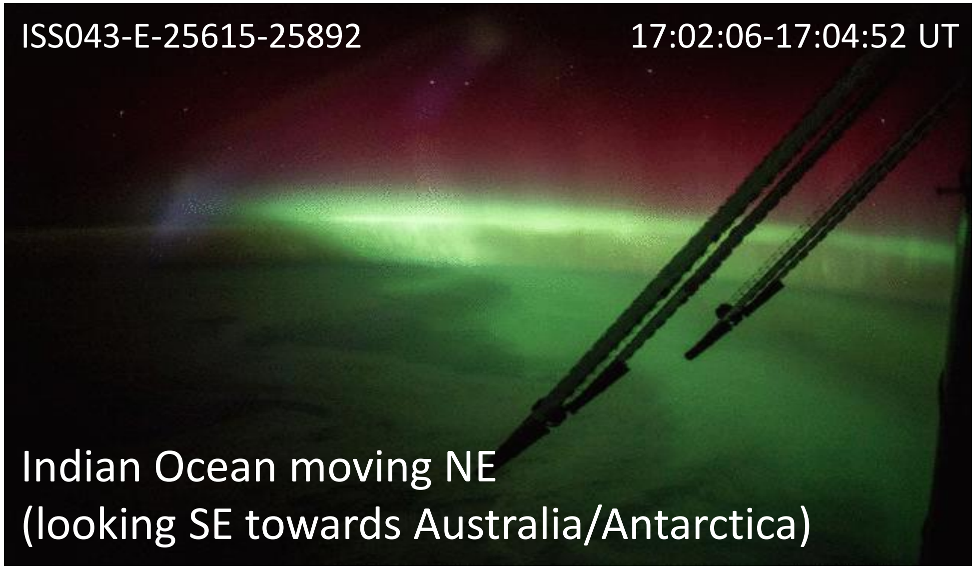
The largest geomagnetic storm of solar cycle 24





GPS scintillation analysis

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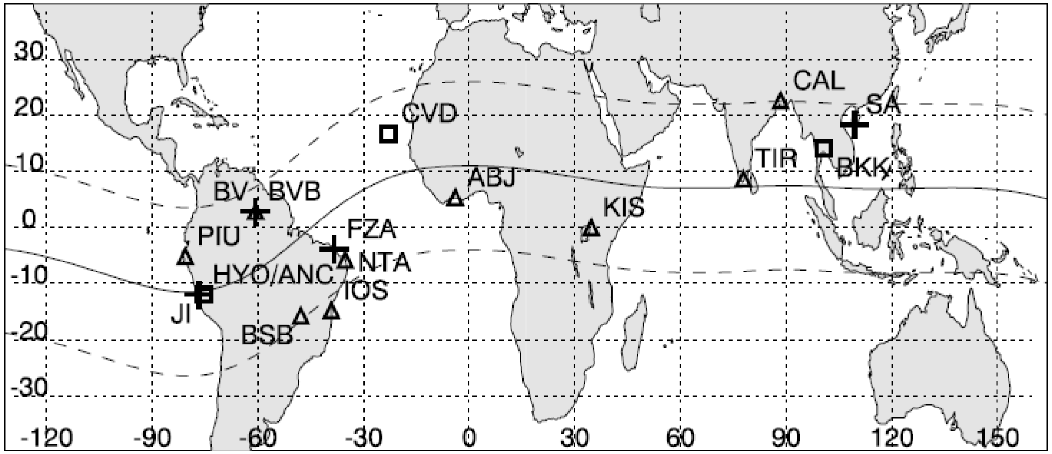
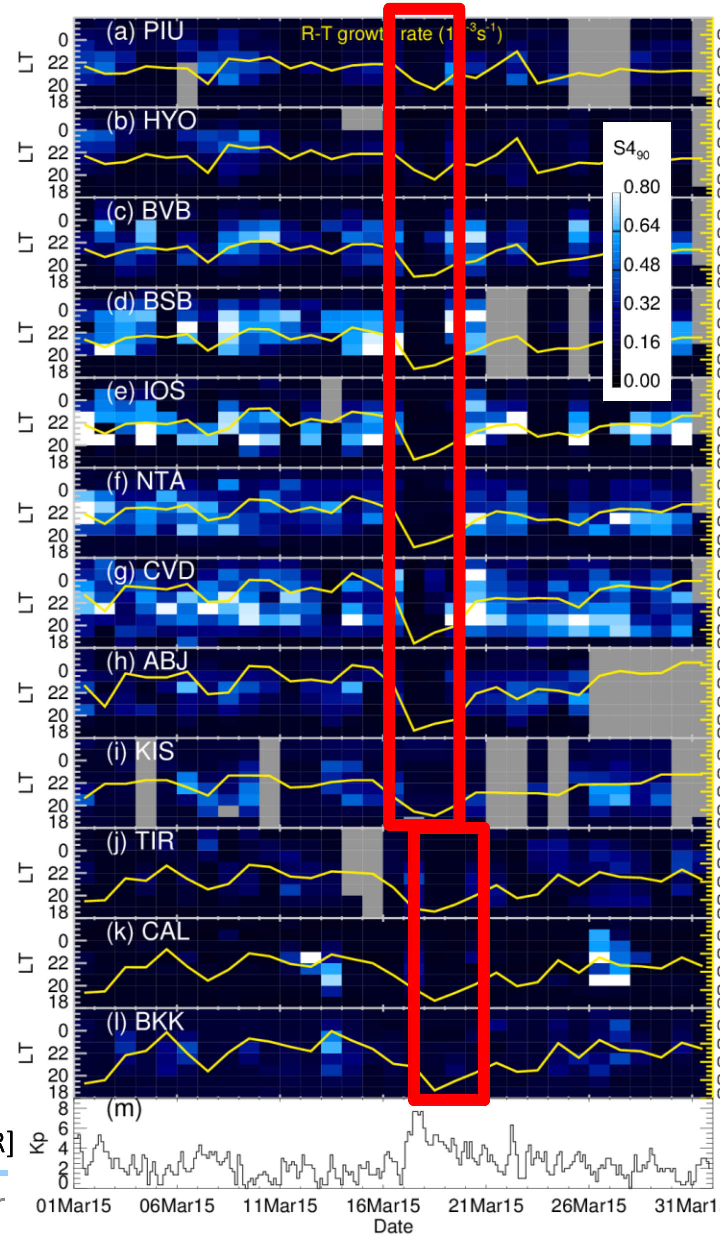


GPS scintillation disappears for 2 days across all stations

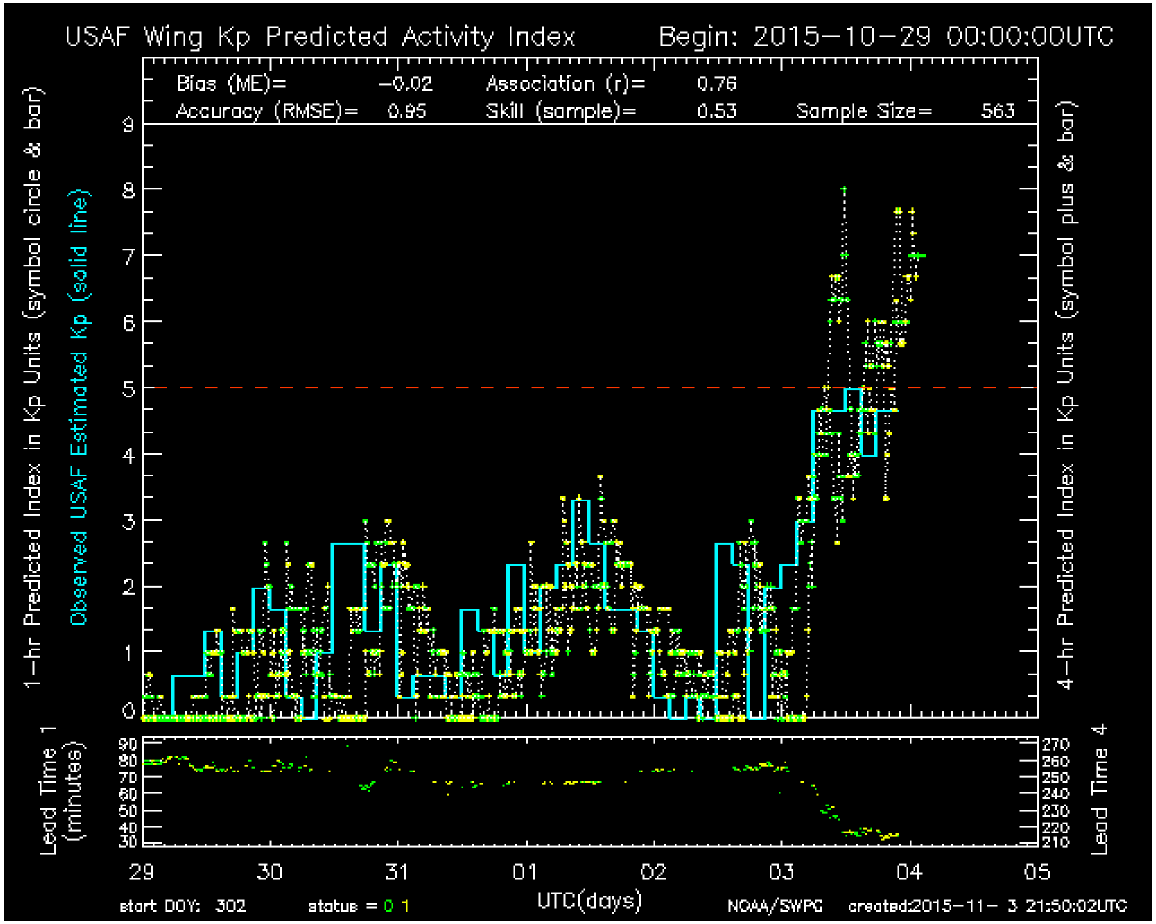
- The EPB suppression is observed a day later for Asian stations

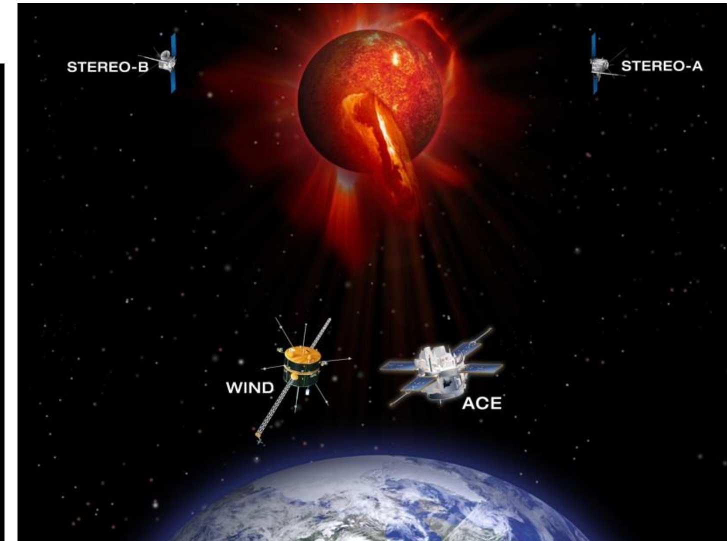
The TIEGCM growth rate drops for all stations, indicating EPB suppression by the storm due to disturbance dynamo electric fields



Carter et al., 2016a [JGR]

Wing Kp Model





- Artificial Neural Network
- Both 1-hour and 4-hour lead-time forecasts

Scintillation prediction trial: Mar-Jul 2014

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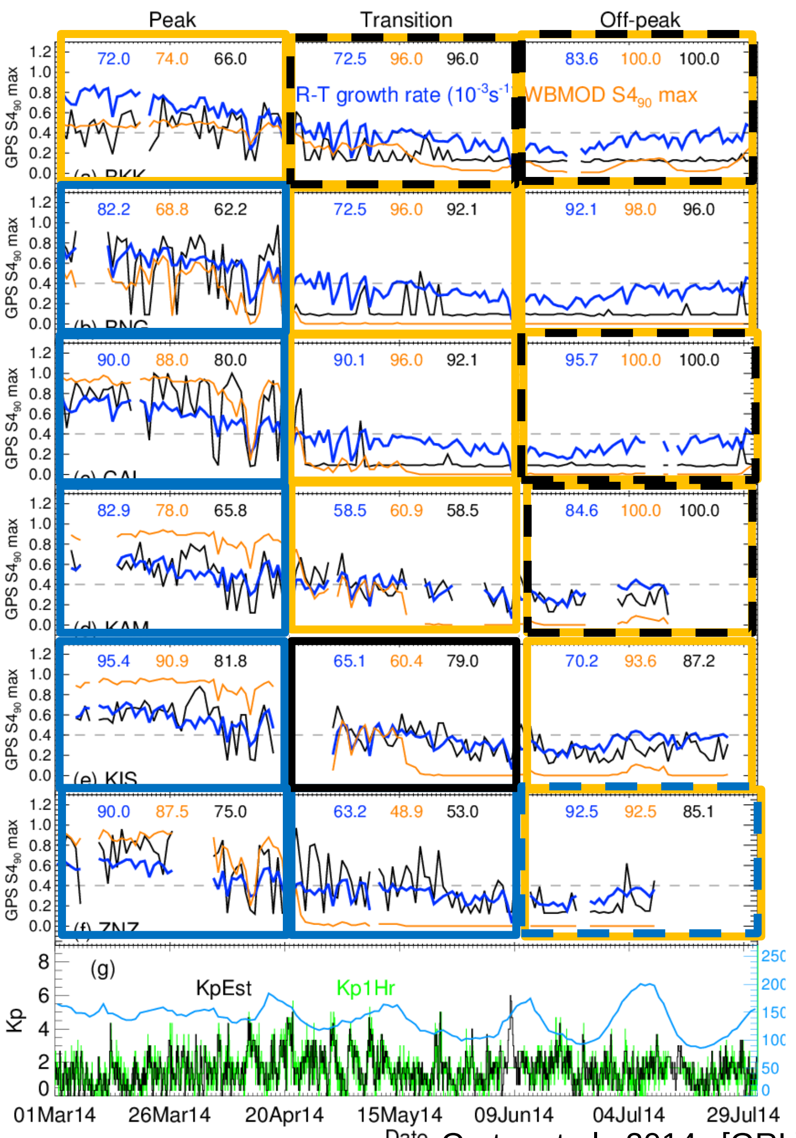
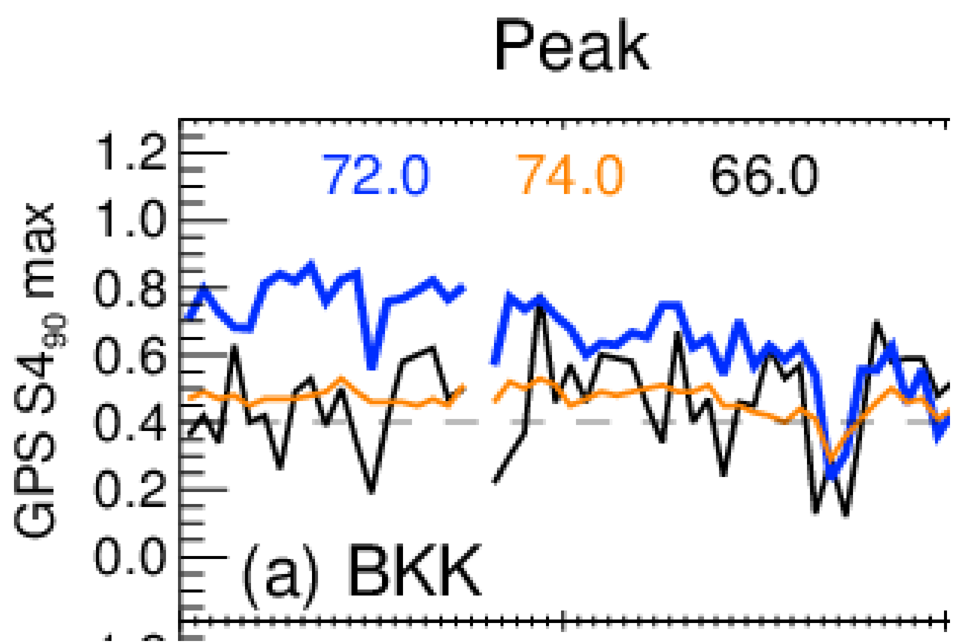


Carter et al., 2014c [GRL]

1-hour Wing Kp predictions:

Our technique generally performs best during peak EPB season, closely followed by US Air Force's WBMOD (up to 95% for KIS)

During transition and off-peak seasons, either WBMOD or "persistence" forecast performs best



Unresolved issues – “DRUIDAE”

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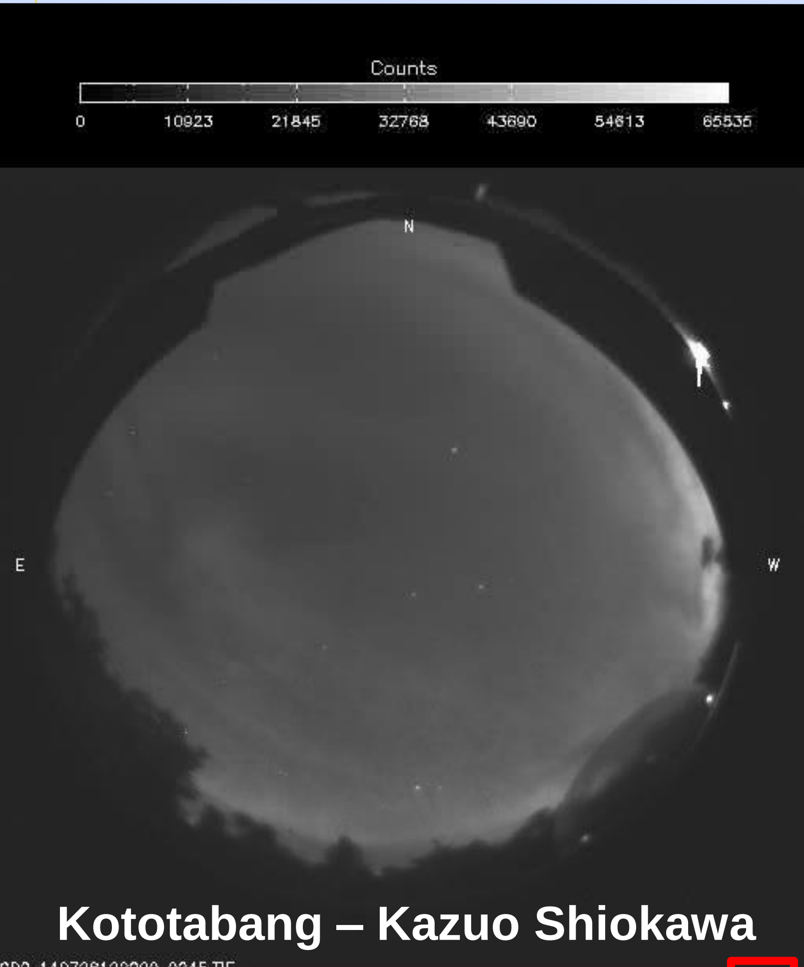
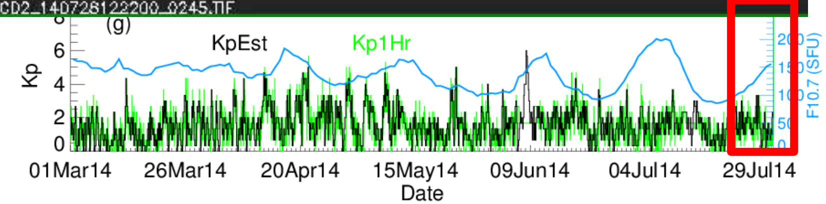
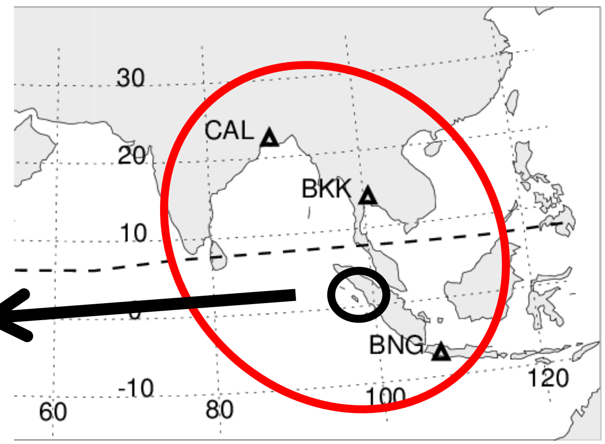
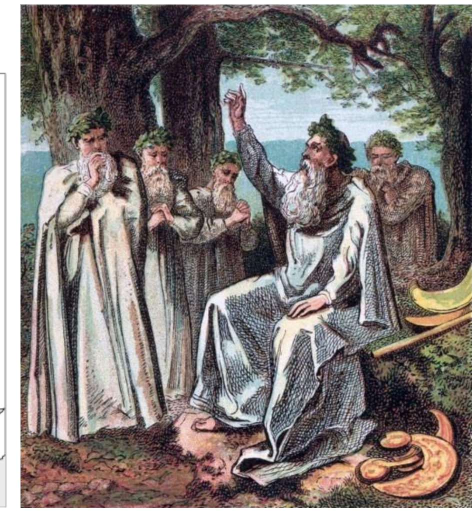
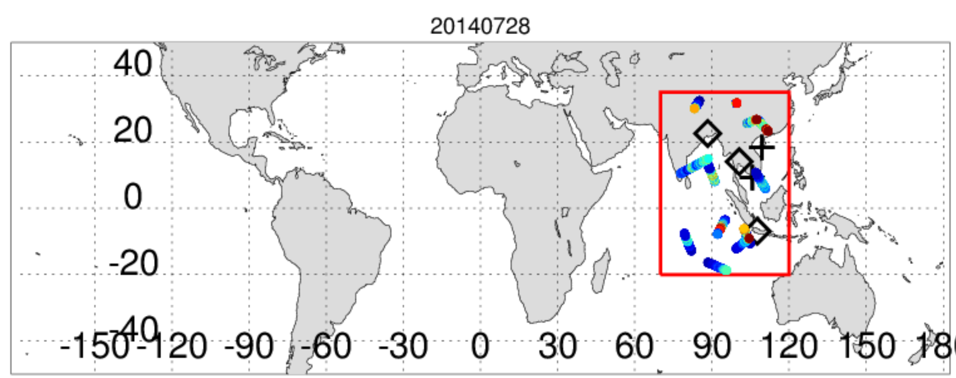




Detrimental, Rapid and Un-seasonal Ionospheric Disturbances Around the Equator **(“DRUIDAE” – Latin for “Druids”)**







Summary and conclusions

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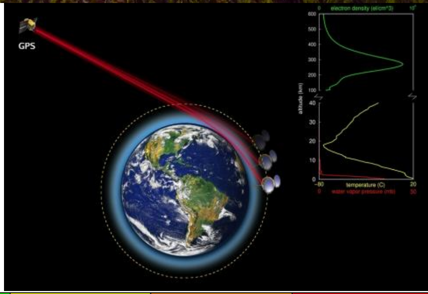
GPS (and more broadly, GNSS) is playing a key role in the development of technological applications that greatly benefit society:

- Positioning, Navigation and Timing (PNT)
- Water vapour and temperature sensing for weather forecasting and climate analyses
- However, with increased benefits comes increased vulnerability to space weather



Predicting Equatorial Plasma Bubbles has been a research focus for many decades (long before GPS):

- The rise in the use of GPS has accelerated our research progress on understanding Equatorial Plasma Bubbles
- The climatology (i.e., seasonal changes) is well understood
- Daily variability is not so well understood (but we're getting there!!!)
- Prediction efforts are ongoing, but we are doing well enough to start to deliver scintillation forecasts for GNSS users
    - An ongoing project between RMIT University and the Bureau of Meteorology aims to do just that.