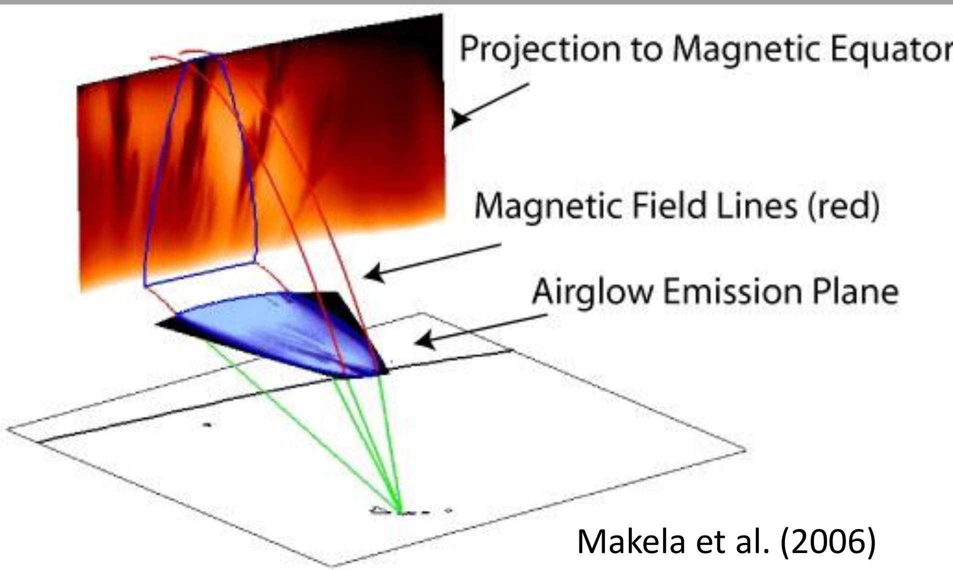
On the predictability of Equatorial Plasma Bubbles for Global Navigation Satellite System users

Brett A. Carter[1], J. Currie[1], M. Terkildsen[2], Keith Groves[(3)], and Ron Caton[(4)]

1. SPACE Research Centre, RMIT University, Australia
2. Space Weather Services, Bureau of Meteorology, Australia
3. Institute for Scientific Research, Boston College, USA
4. Space Vehicles Directorate, Air Force Research Laboratory, USA

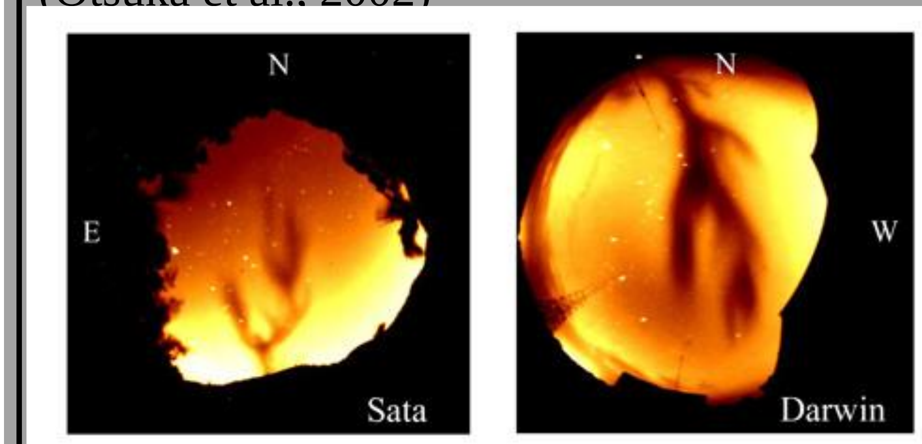
Equatorial Plasma Bubbles

RMIT UNIVERSITY
SPACE Research Centre

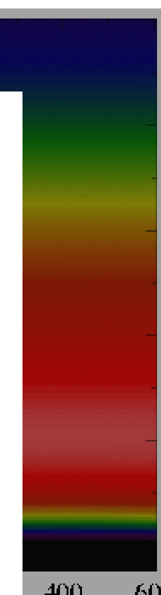


Makela et al. (2006)

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



Modeling



Retterer [2008a,b]

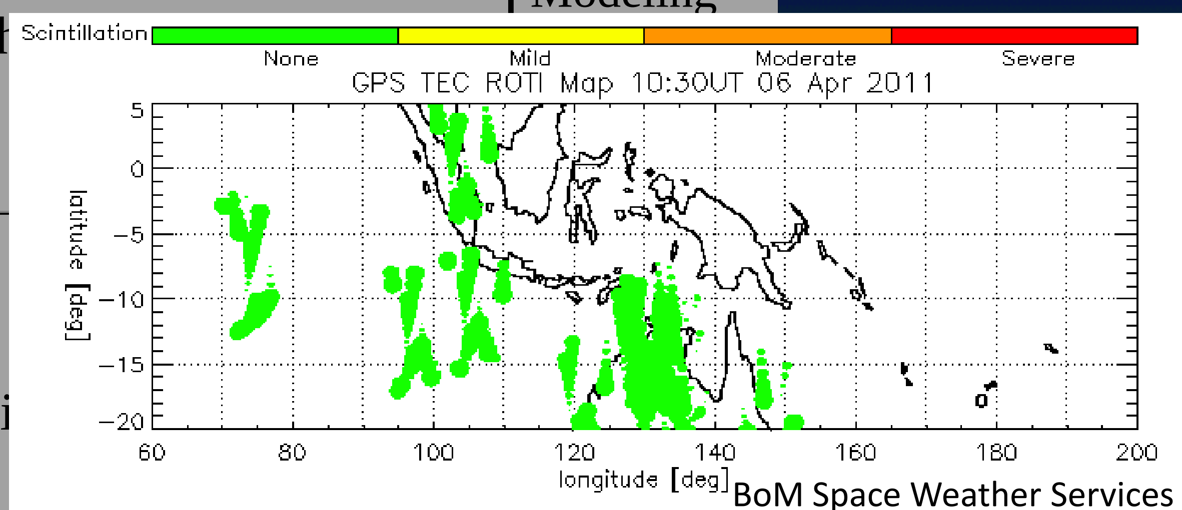
Generalised Rayleigh

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(V_p - \right.$$

(Sultan *et al.*, 1996)

Detected using ampli

Scintillation index



BoM Space Weather Services

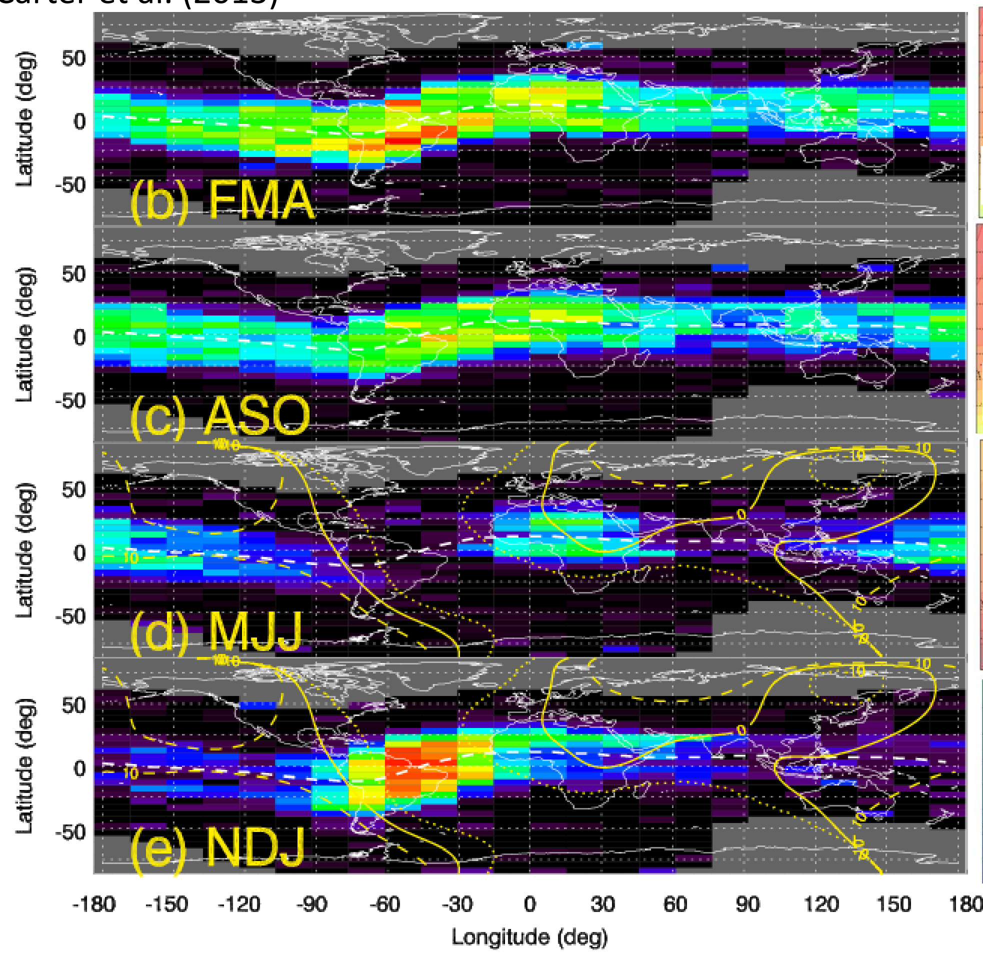
EPB Occurrence Climatology

RMIT UNIVERSITY

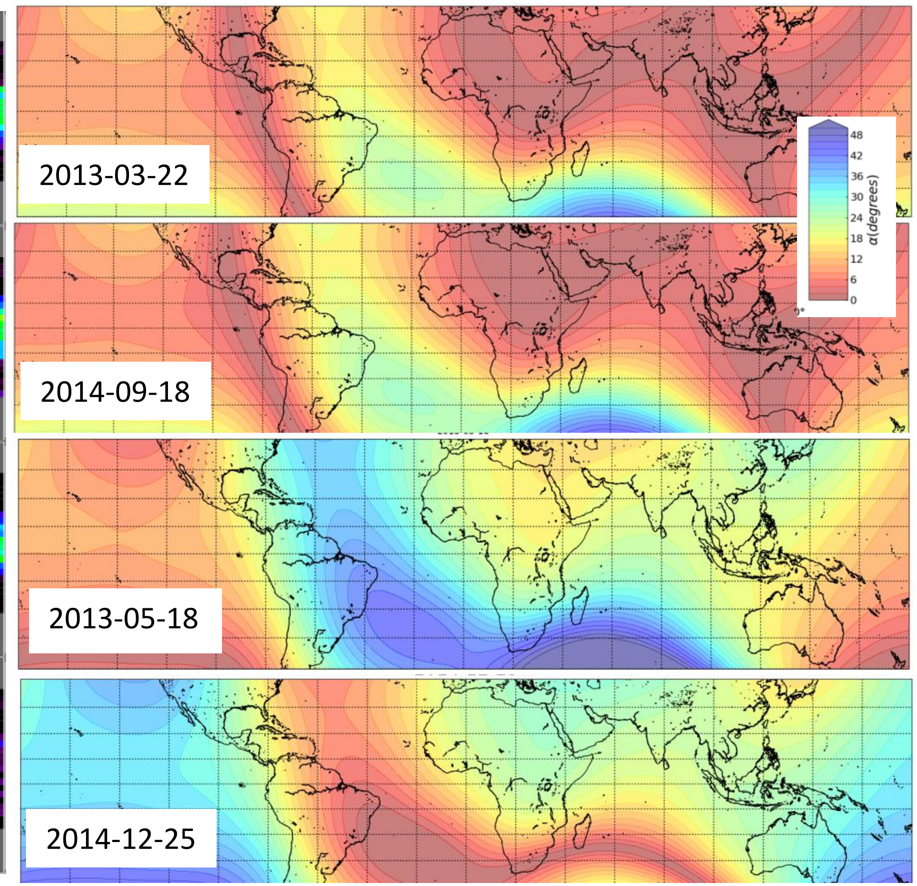
SPACE Research Centre

Carter et al. (2013)

GPS RO data



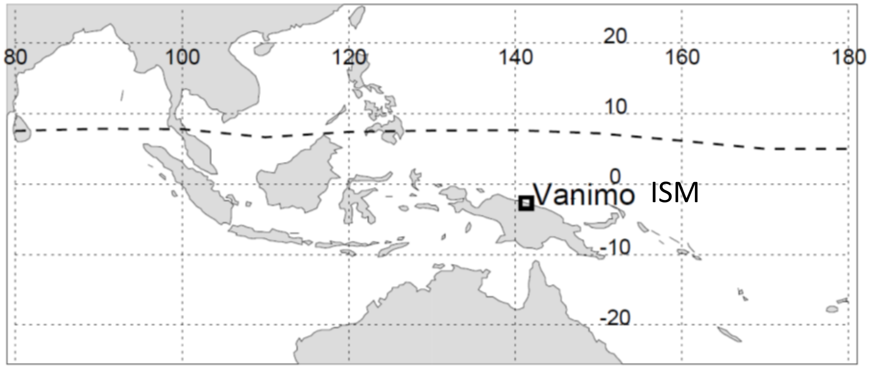
"Alpha" maps

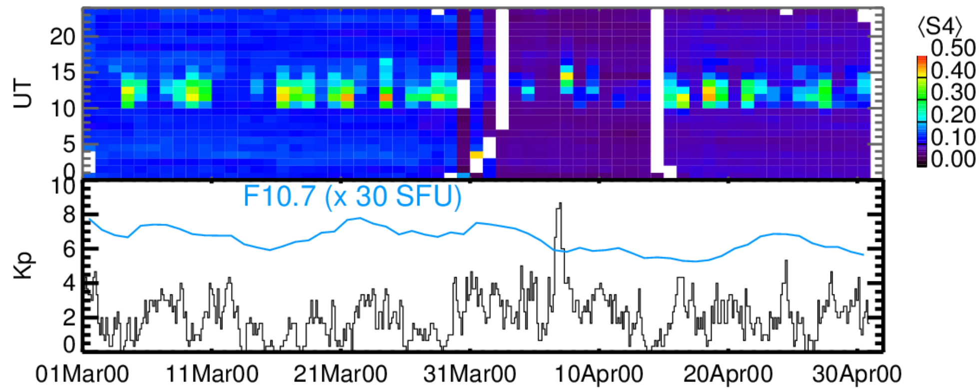


Climatology is largely uncontrolled by the longitudinal E-region conductivity gradient, which controls the strength of the PRE (Abdu et al., 1981; Tsunoda, 1985)

Daily variability of EPBs

RMIT UNIVERSITY
SPACE Research Centre





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

Pederson conductivities

Upward neutral wind

Gradient scale length

Upward plasma drift

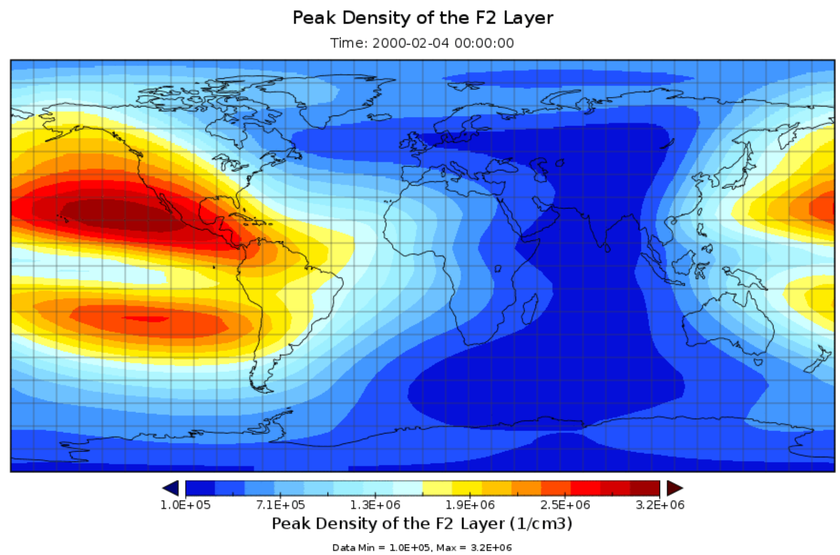
Unknown

Directly measured/known

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

TIEGCM

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.

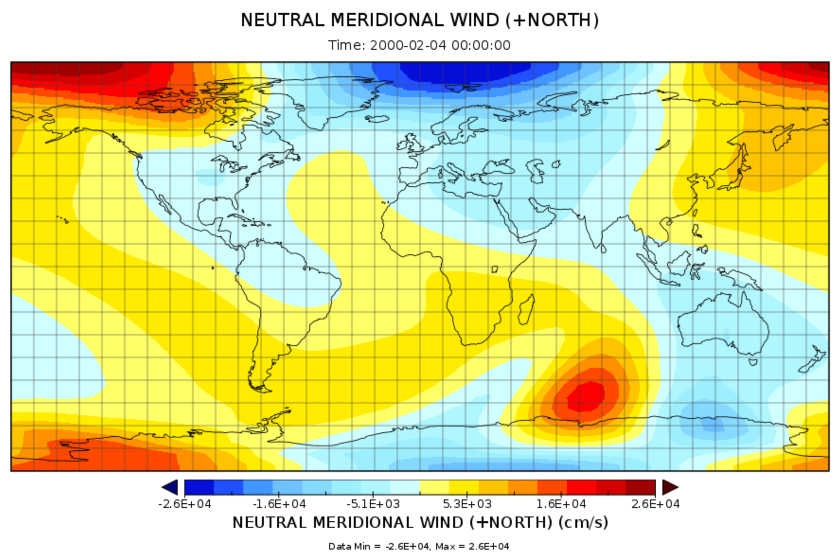


Inputs:

- 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

- Daily maximum average S4 shows good correlation with TIEGCM growth rate

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

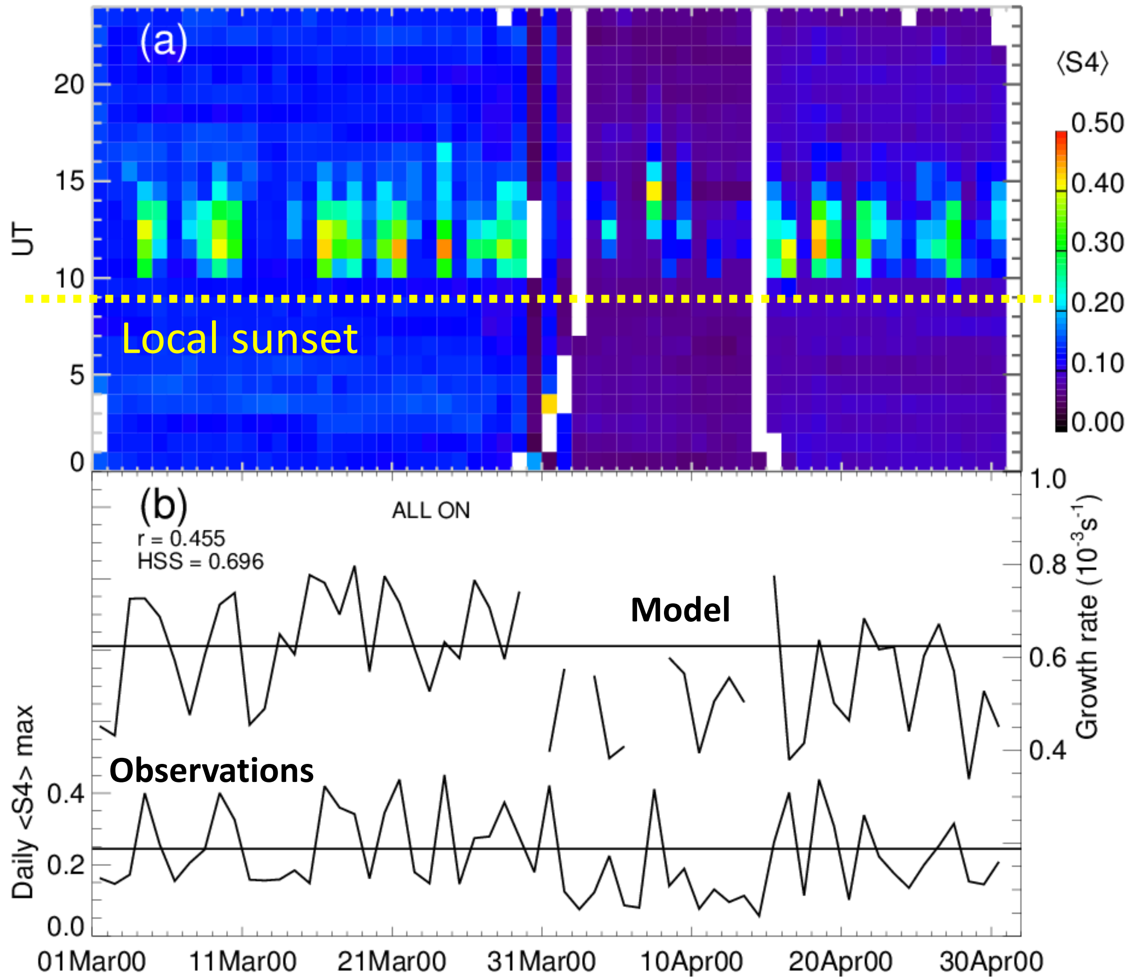
- EPB modelling vs observations:

Observed

Modelled

EPBs	No	Yes
Yes	3	17
No	31	5

- Heidke skill score = 0.696
- Accuracy (17+31)/56 = 85.7%



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

↓

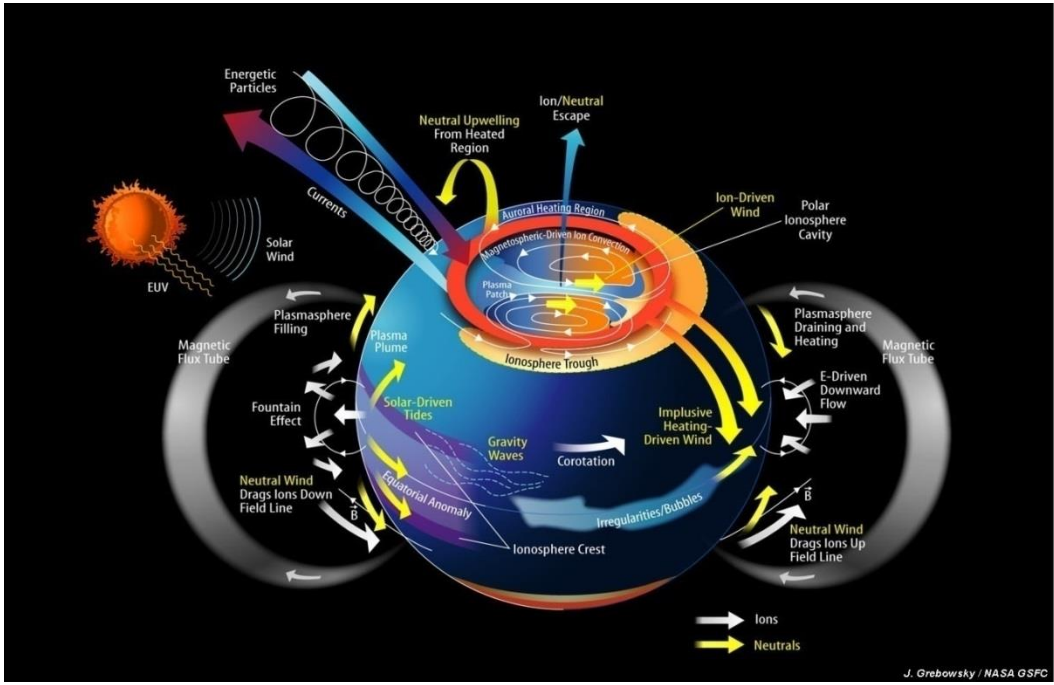
Decrease in zonal wind at equator

↓

Decrease in upward plasma drift (Vp)

↓

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

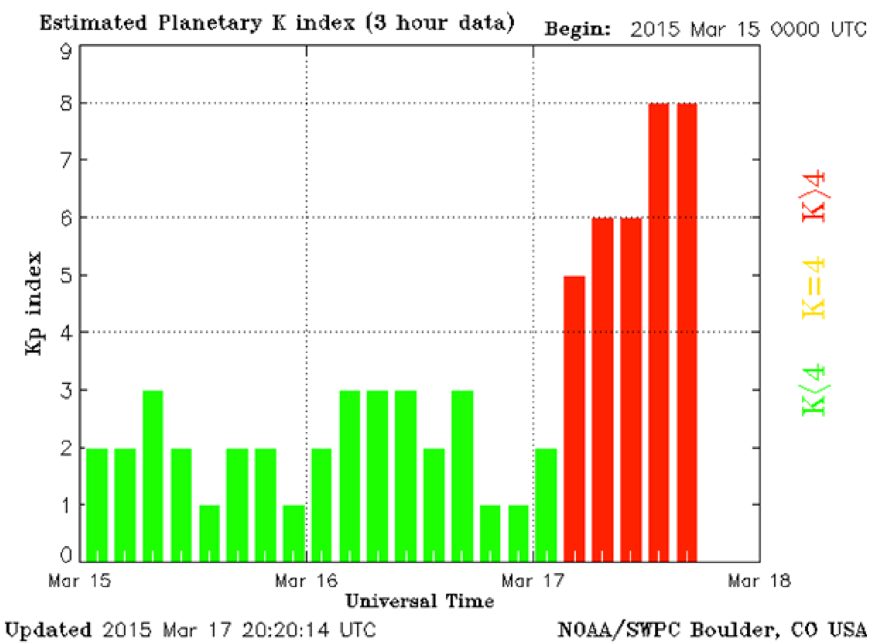


Physics that is **not** captured:
(1) Penetration electric fields
(2) Lower atmospheric forcing
(3) Small-scale effects (e.g., seeding)

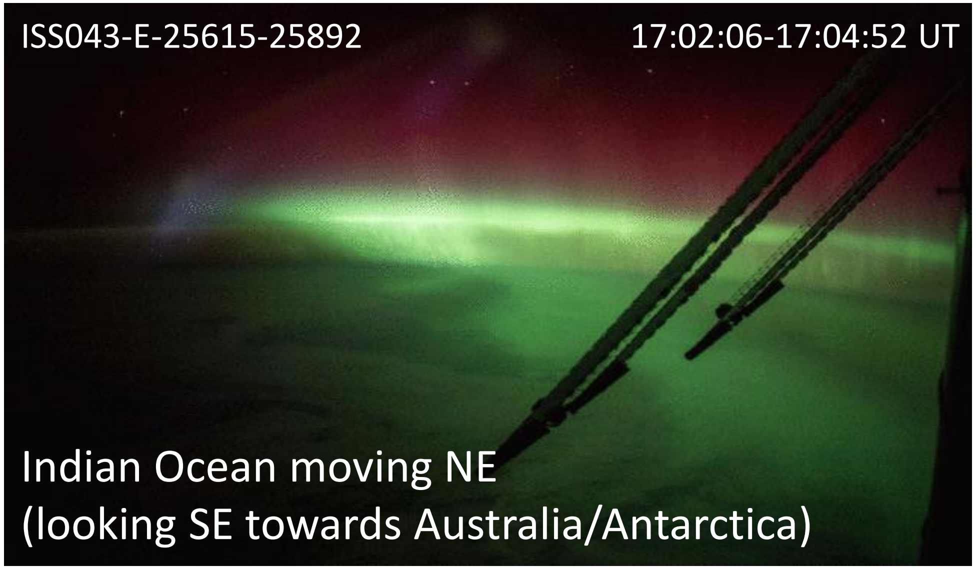
Carter et al., 2014a [JGR], 2014b, 2014c [GRL]

2015 St Patrick's Day Storm

The geomagnetic storm that occurred on March 17-18 2015 was one of the largest storms in the last 10-15 years.



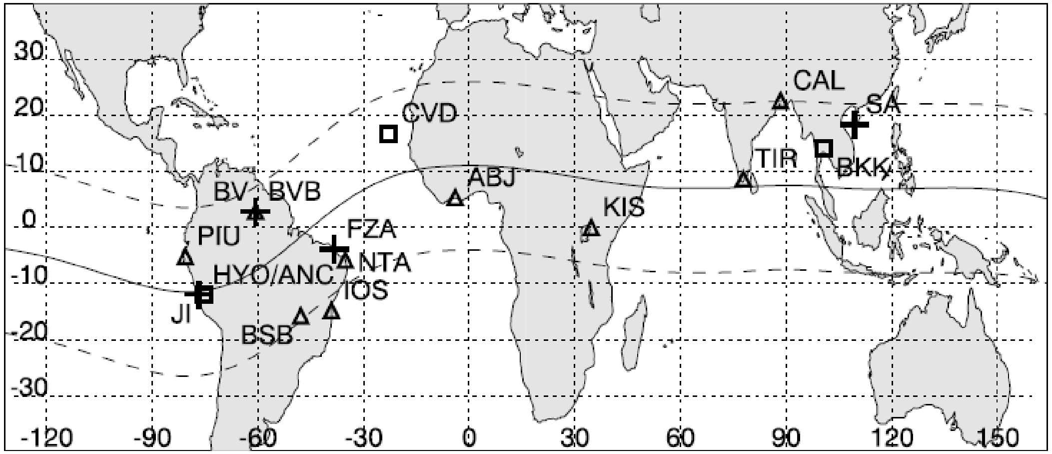
Uluru, Australia (MLAT~35°S)



2015 St Patrick's Day Geomagnetic storm

RMIT UNIVERSITY

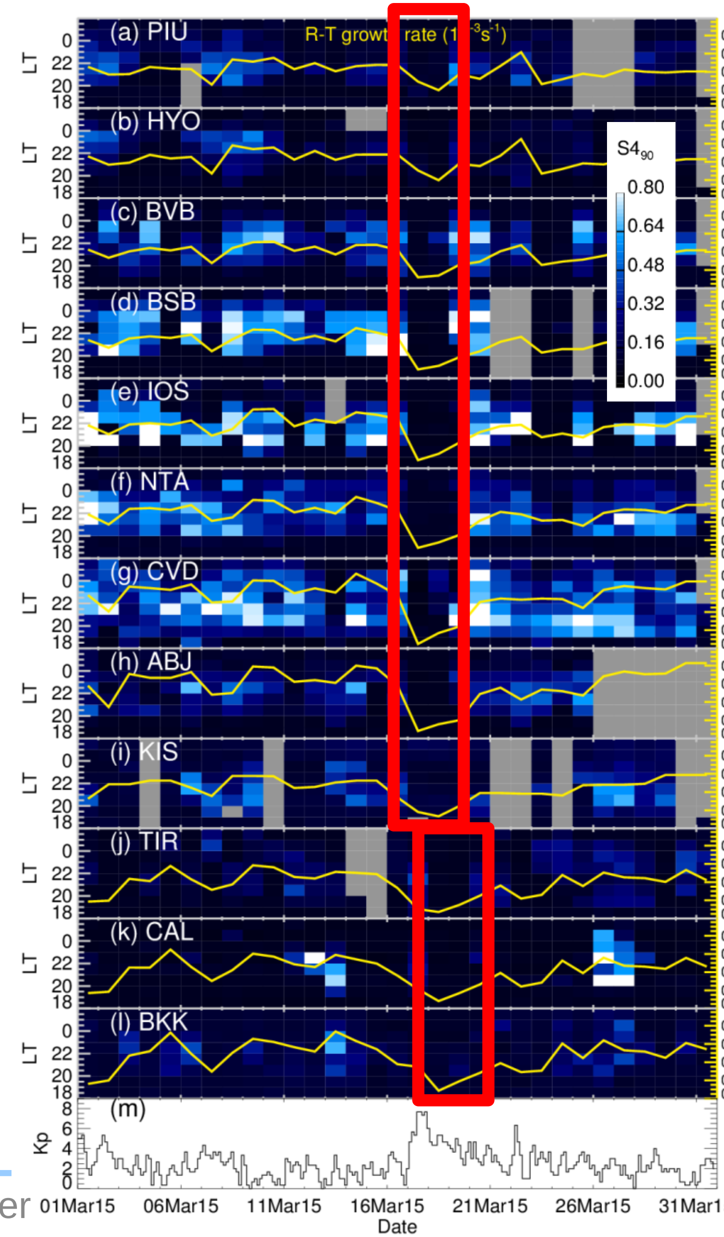
SPACE Research Centre



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

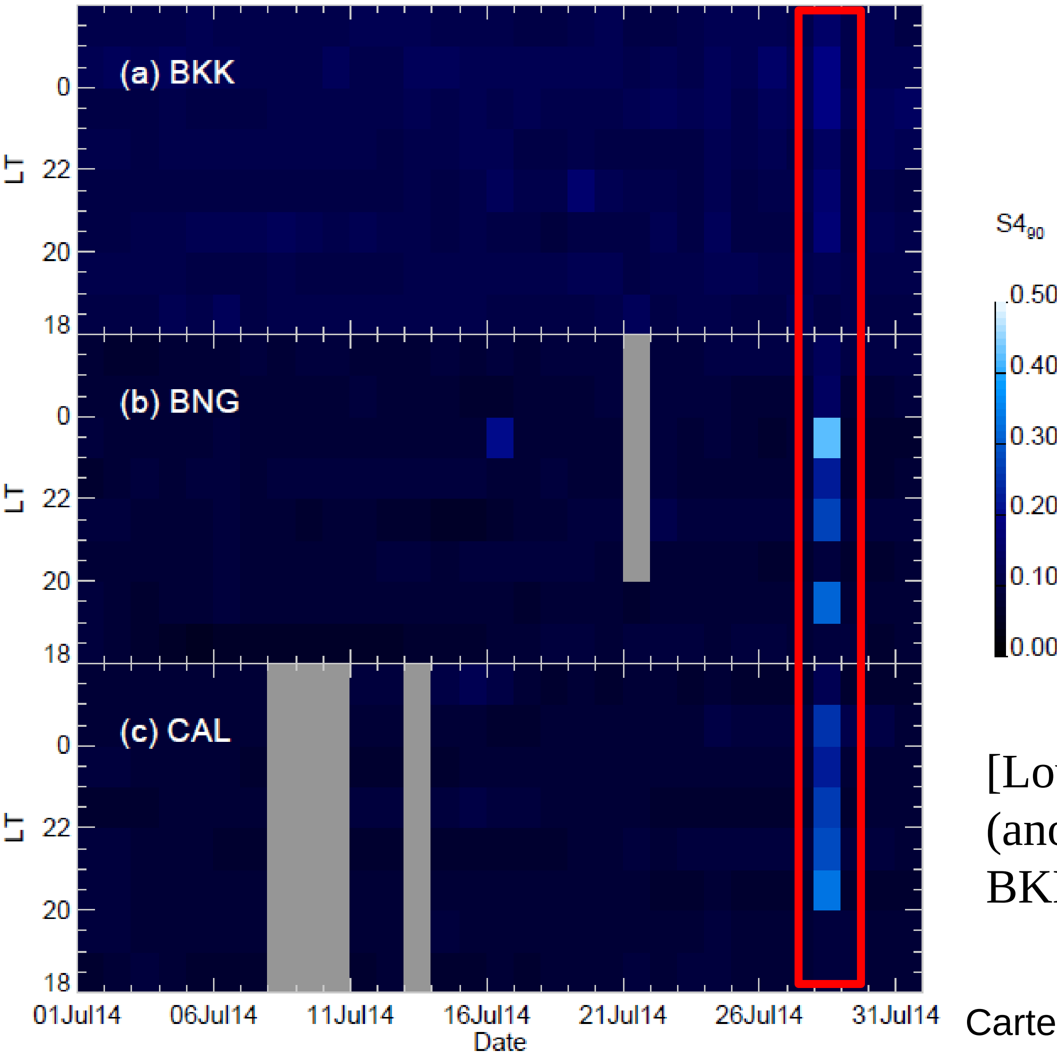


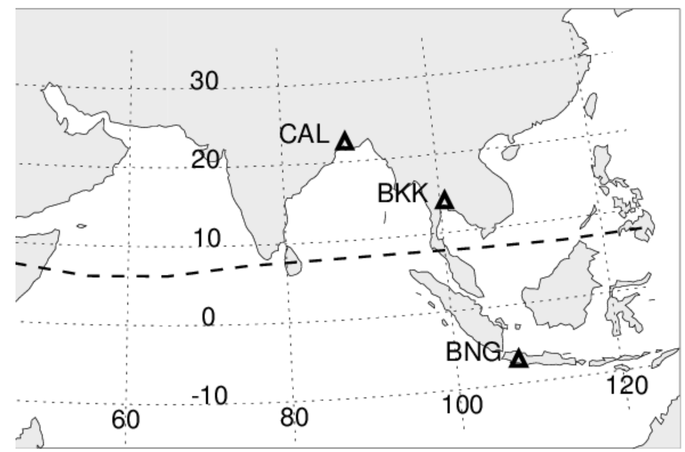
Carter et al. (JGR, 2016)

Unresolved issues – Unseasonal EPB events

RMIT UNIVERSITY
SPACE Research Centre

A significant scintillation event in Southeast Asia on July 28th



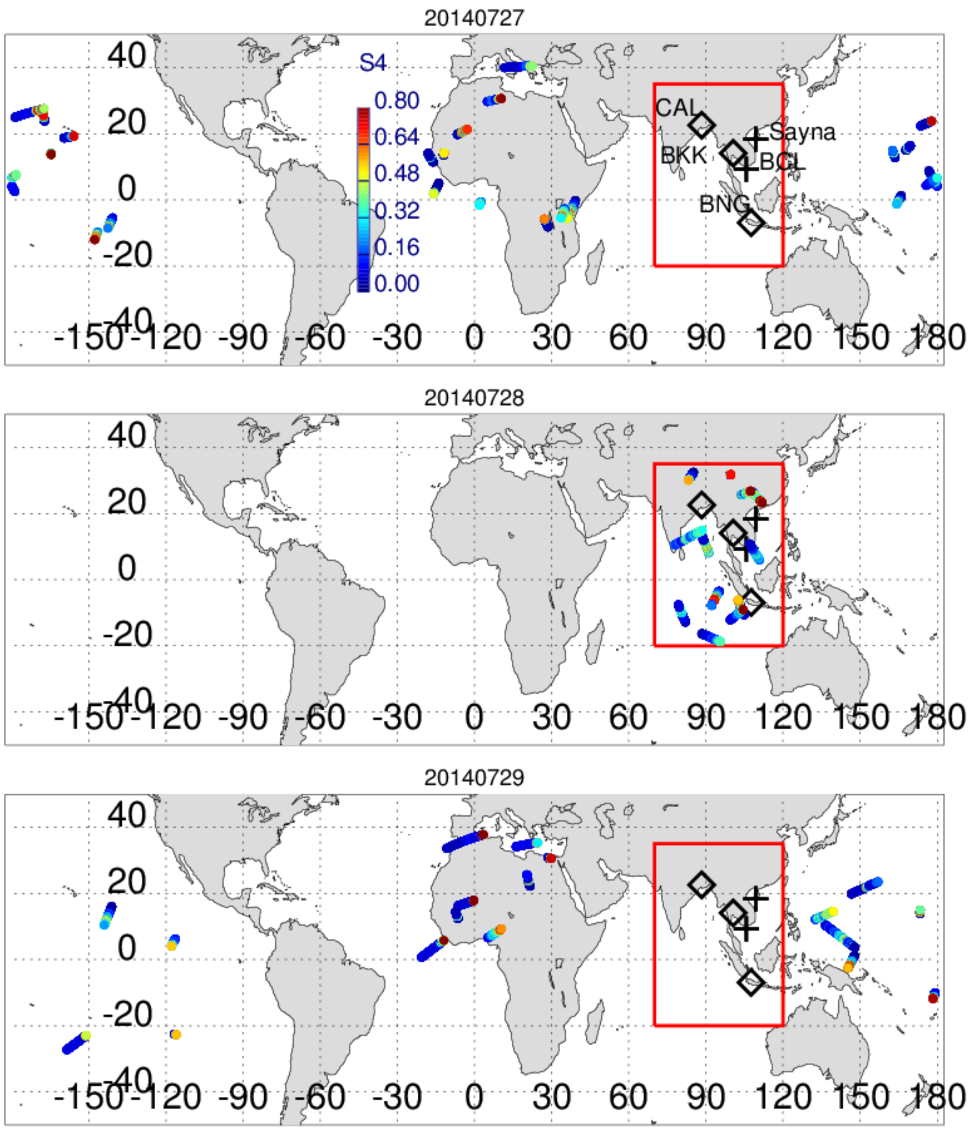


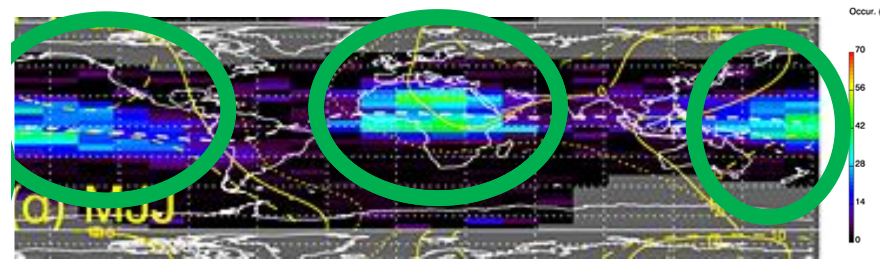
[Low electron density at the magnetic equator (anomaly trough) is the reason S4 was low for BKK]

Carter et al. (PEPS , 2018)

GPS RO observations

RMIT UNIVERSITY
SPACE Research Centre





Carter et al. (2013)

- RO events with S4max9sec > 0.3 during 19-24 LT are shown
- On July 27 (and days prior, not shown), the appearance of scintillations is consistent with climatology during June solstice
- On July 28, scintillations **only** appear over Southeast Asia (red box)
- On July 29, scintillation event locations once again match climatology

Carter et al. (PEPS, 2018)

Application Usability Levels

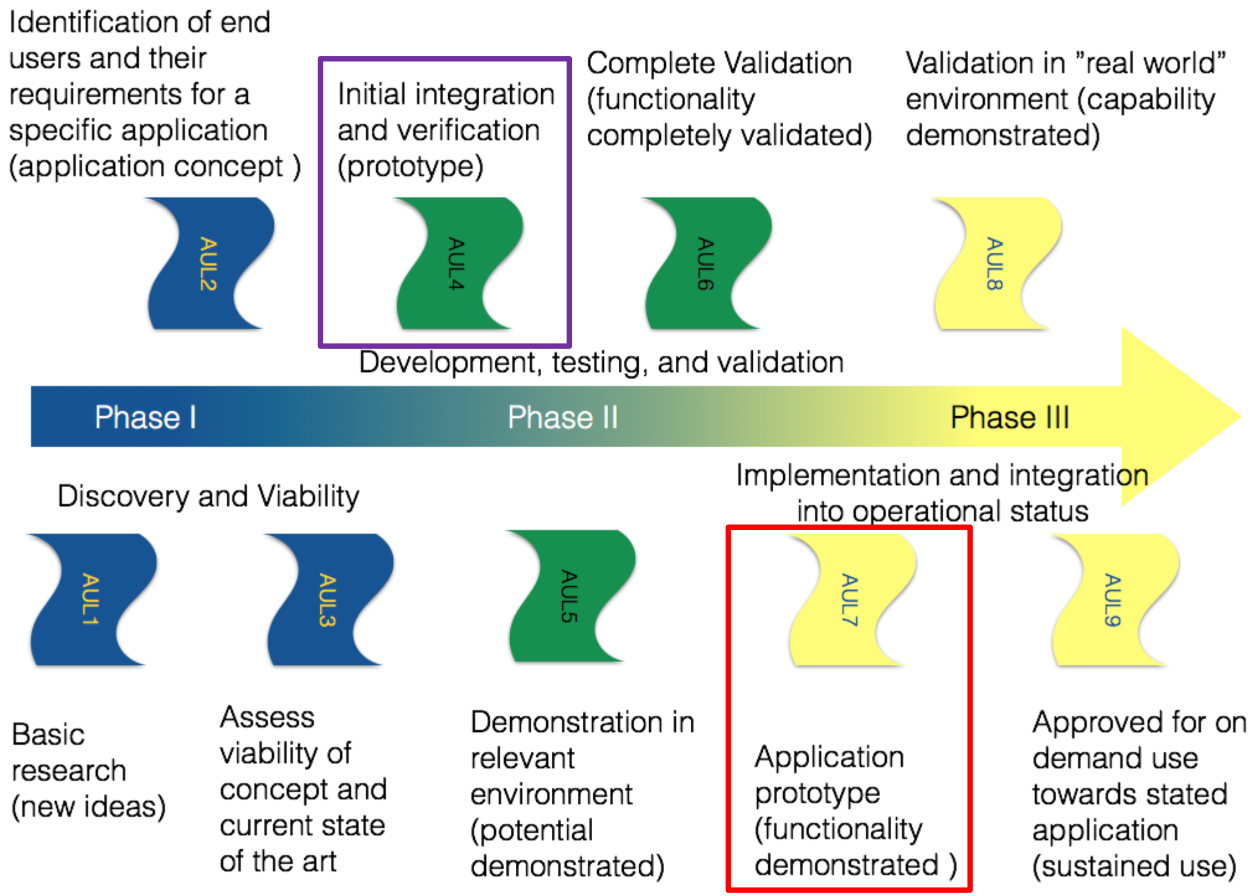
RMIT UNIVERSITY
SPACE Research Centre

Assessment of Understanding and Quantifying Progress team

Purpose: Connecting fundamental research to applications

Our scintillation prediction technique used as example

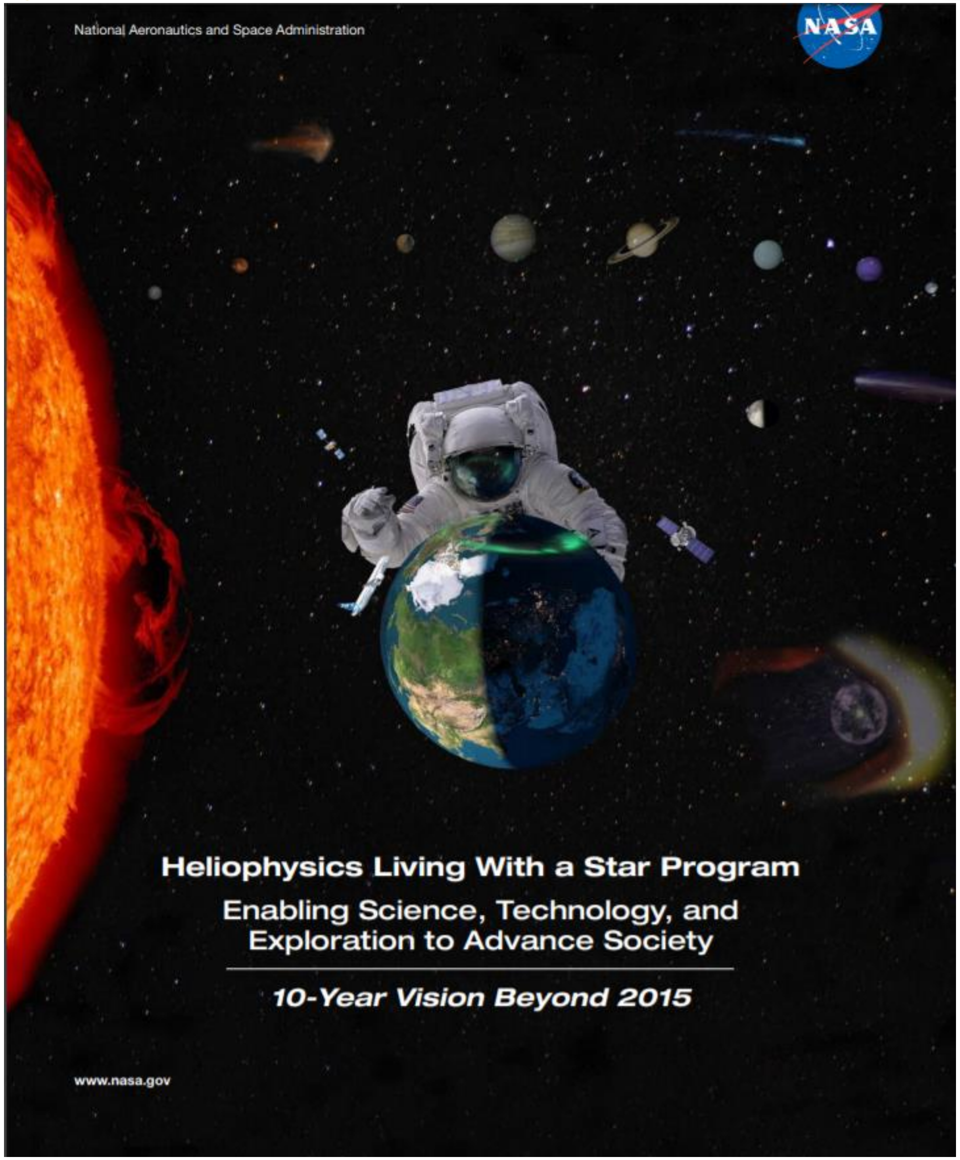
AUL 7 reached, but need to double back and review “verification” at AUL 4.



Halford et al. (JSWSC, accepted 12 June, 2019)

Assessment metrics

RMIT UNIVERSITY
SPACE Research Centre



Strategic Science Area (SSA)-5

SSA-5: Ionospheric Irregularities and Scintillation

Understanding and mitigating the effects of ionospheric irregularities on radio communication and navigation.

Metrics and Assessment

Establishing quantitative benchmarks (skill scores) for success in these areas should be considered part of the SST. Metrics should be developed based on specific impact domain requirements. Assessment should go beyond case studies and model runs and should establish rigorous statistical quantification of limits of predictability and demonstrate improved prediction capability resulting from the proposed innovations.

https://lwstrt.gsfc.nasa.gov/images/pdf/LWS_10YrVision_Oct2015_Final.pdf

Performance Metrics

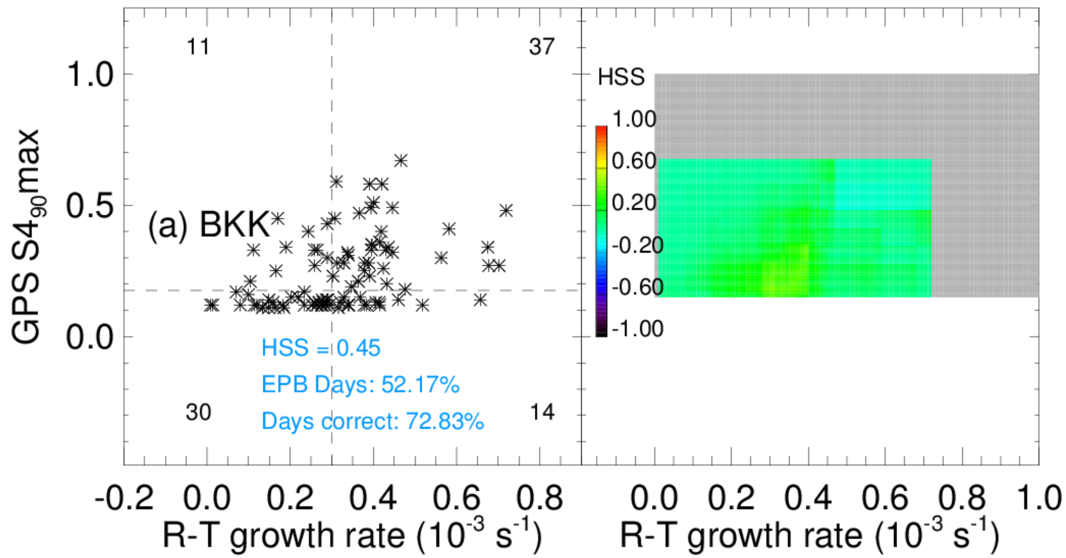
RMIT UNIVERSITY
SPACE Research Centre

What does success look like?

What skill score(s) can we use to measure it?

- Reward "skill" in capturing variability
- Insensitivity to "hedging"
- Applicable to variable datasets/time periods
- Uses an appropriate "baseline" for comparison
- Complement symmetry (i.e., switch focus of "yes" and "no")

	Modelled: No	Modelled: Yes
Observed: Yes	None/small	Some number
Observed: No	Another number	None/small



Contender skill scores

RMIT UNIVERSITY
SPACE Research Centre

- **Heidke Skill Score** (HSS)

HSS=(Correct – E_{random})/(Total – E_{random})

- **Brier Skill Score** (BSS)

BSS = 1 – ($P_{forecast}$/$P_{climatology}$)

- **Peirce Skill Score** (True Skill Statistic)

PSS= hit rate –false alarm rate

Can have confidence interval assigned (e.g., 95% confidence)

- **Odds Ratio Skill Score** (ORSS)

OR = (hits*correct negatives)/(false positives*false negatives)

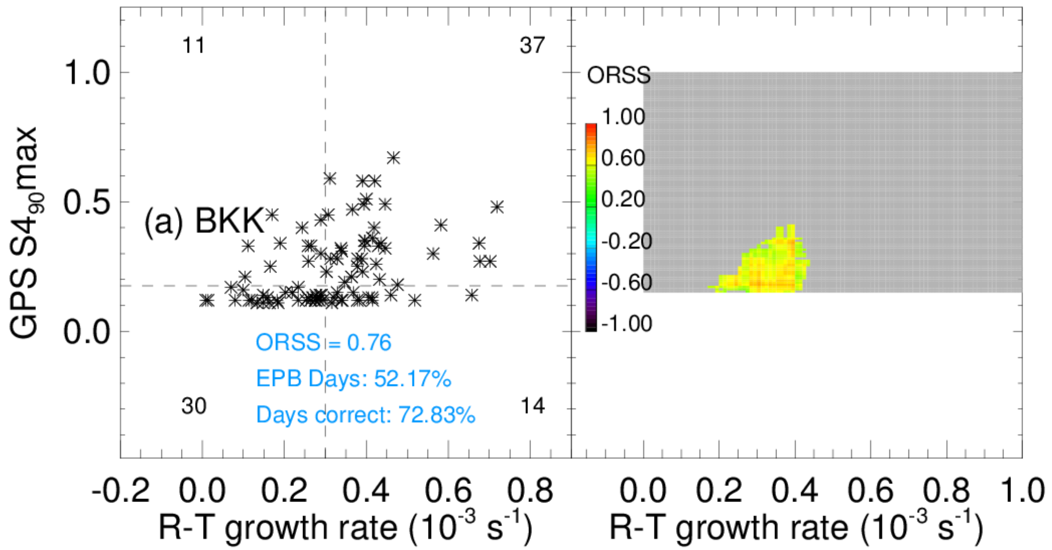
ORSS = (OR-1)/(OR+1)

Can also have confidence interval assigned

Stephenson (2000) *Use of the "Odds" Ratio for Diagnosing Forecast Skill*

Modelled

Observed	No	Yes
Yes	None/small	Some number
No	Another number	None/small

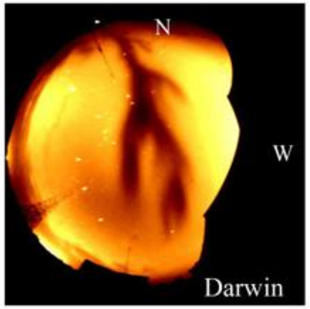


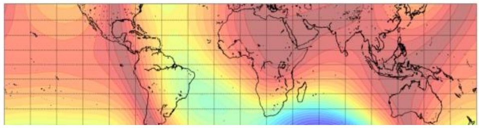
Summary and conclusions

SPACE Research Centre

Climatology of Equatorial Plasma Bubble events is well understood, but predicting daily variability in EPB occurrence is still a significant challenge

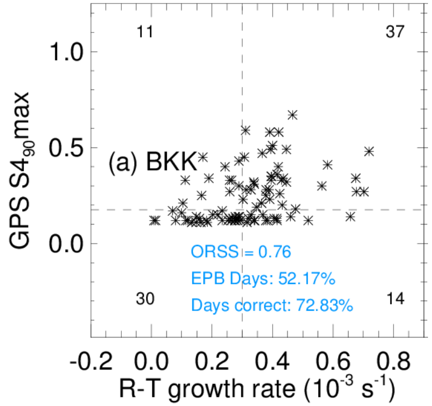
- Some recent success in modelling EPB suppression days using TIEGCM
    - Minor geomagnetic variations appear to influence daily variability during peak EPB seasons
    - Large geomagnetic storms, such as the 2015 St Patrick's Day storm, are capable of preventing GPS scintillation events for a couple of days





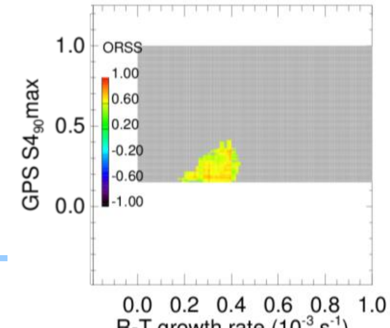
Which assessment metrics we should, and should not, use in our modelling and forecasting attempts?

- The Odds Ratio Skill Score (ORSS) and the Peirce Skill Score (TSS) appear to be the best measures of skill for comparison; e.g.,
    - 95% confidence levels can be applied, so that comparisons (and thresholds) are *significant*
    - Work on this is continuing, and will be used to identify gaps in understanding that impact our ability to accurately forecast scintillation events



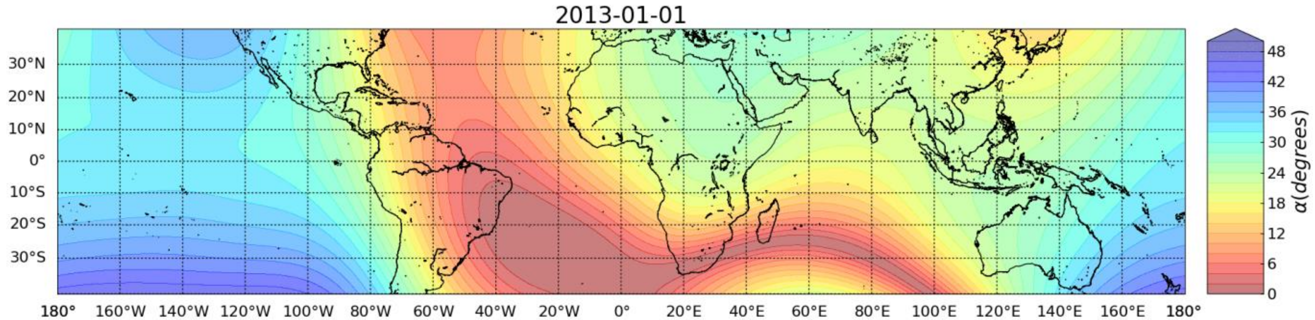
What next?

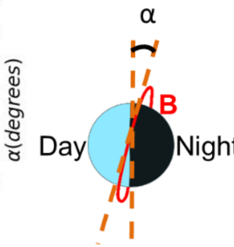
- Not all of the physics is captured by the TIEGCM – e.g., forcing from lower atmosphere – <u>development of WACCM-X/GAIA/WAM-IPE creates exciting opportunities for EPB/scintillation forecasting</u>



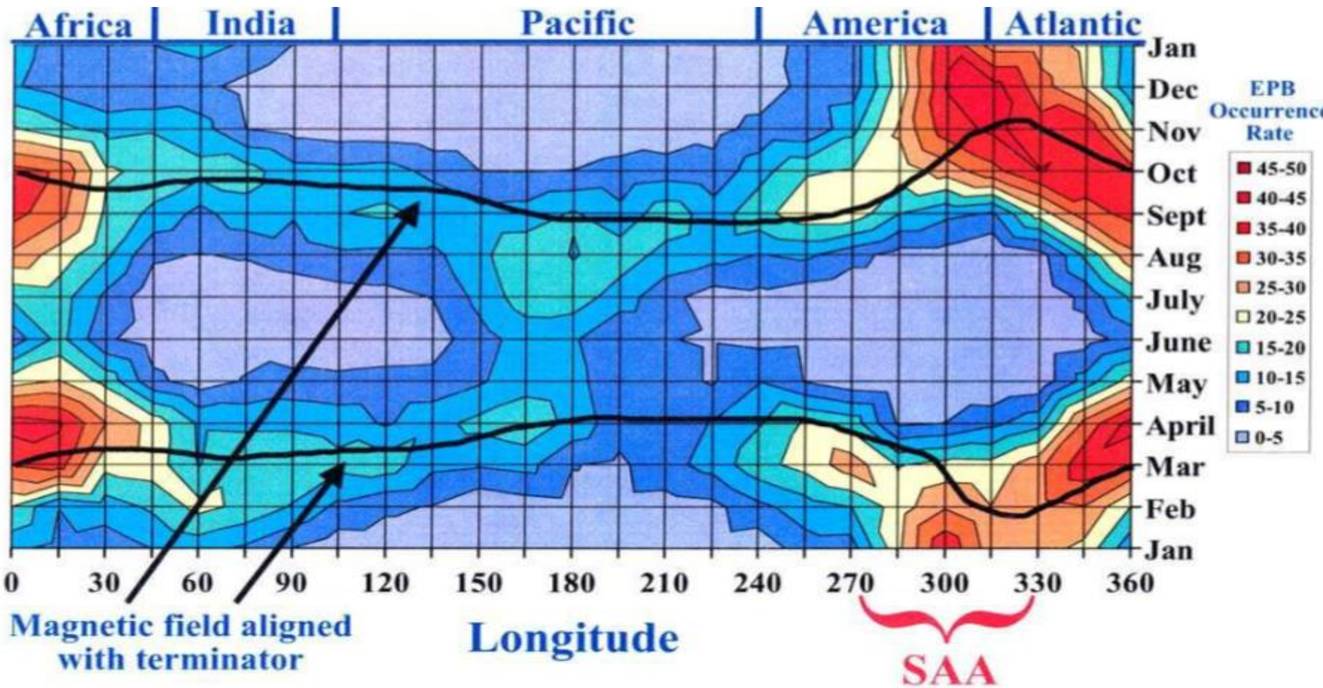
Extra slides

EPB Occurrence Climatology





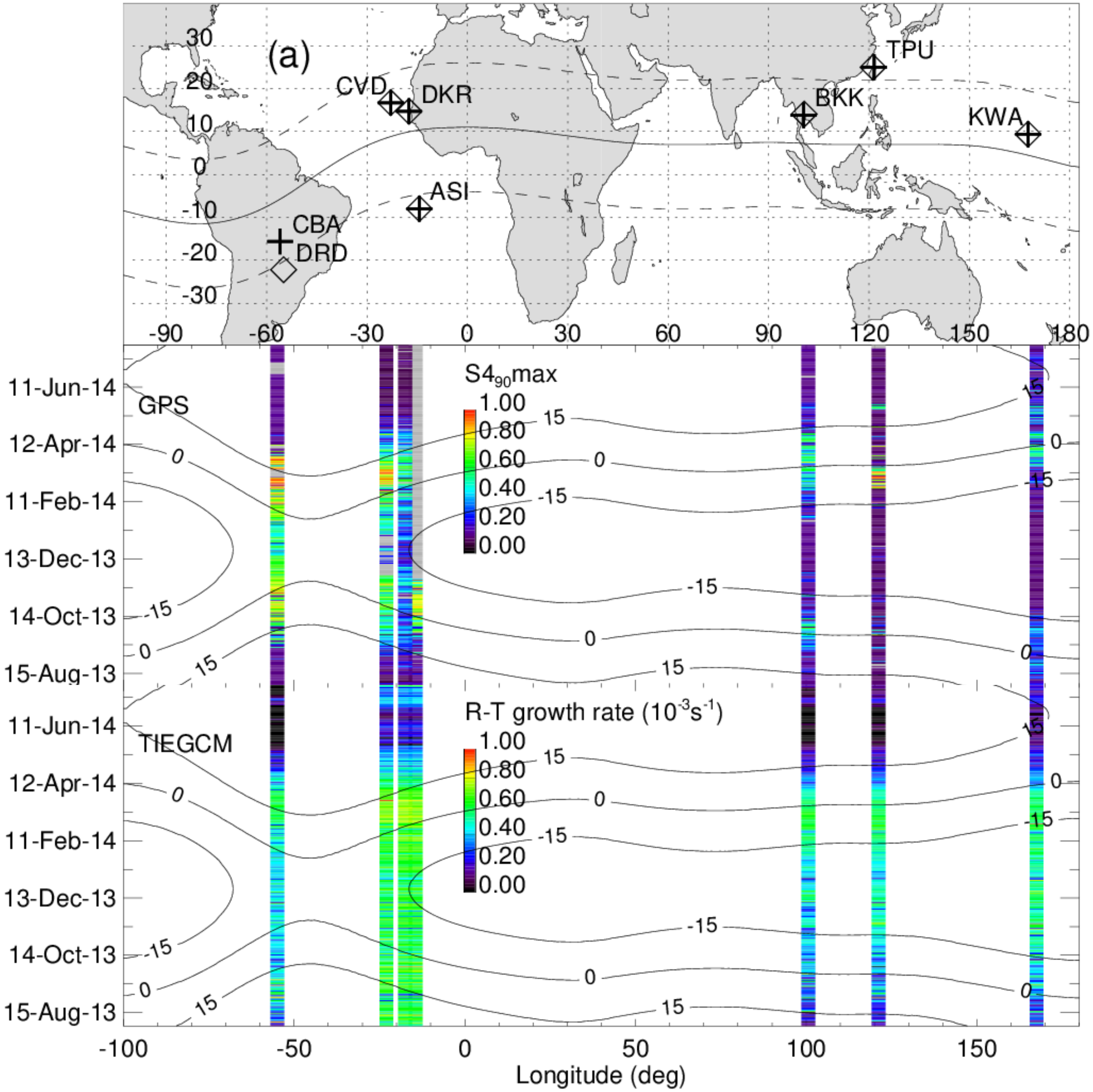
DMSP data (Burke et al., 2004)



Climatology is largely uncontrolled by the longitudinal E-region conductivity gradient, which controls the strength of the upward plasma drift after sunset (Abdu et al., 1981; Tsunoda, 1985)

Dataset: GPS and UHF scintillation

RMIT UNIVERSITY
SPACE Research Centre

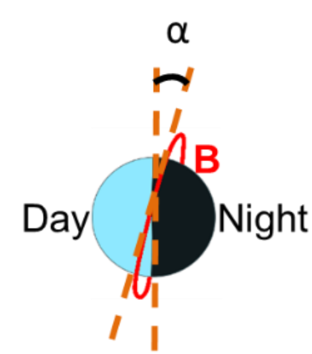


Period: 1 August, 2013 – 25 July, 2014

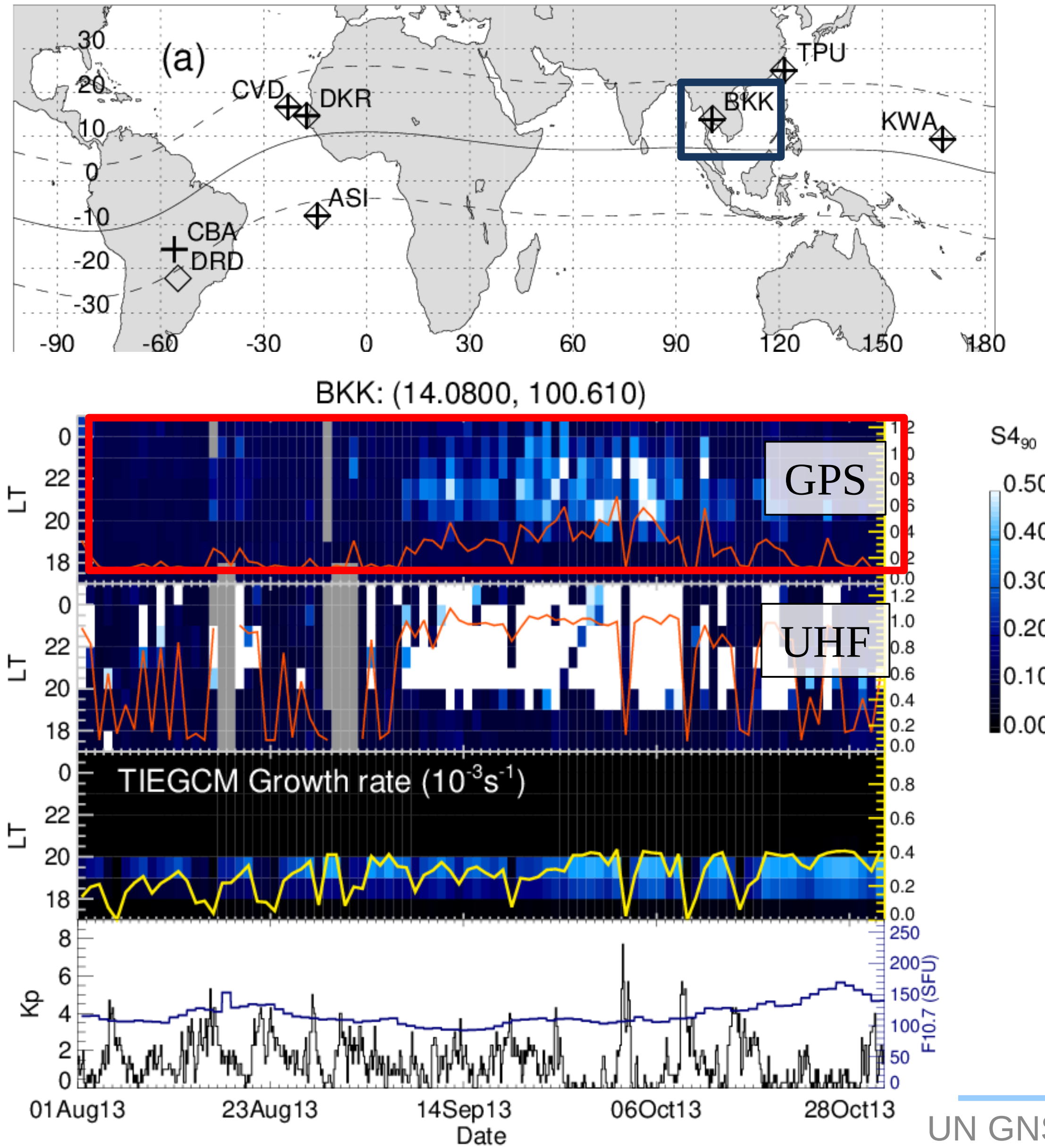
Data: SCINDA GPS (cross) and UHF (diamond), 90th percentile of S4 index (hourly)

Model: TIEGCM v2.0, R-T growth rate calculated for station magnetic meridian

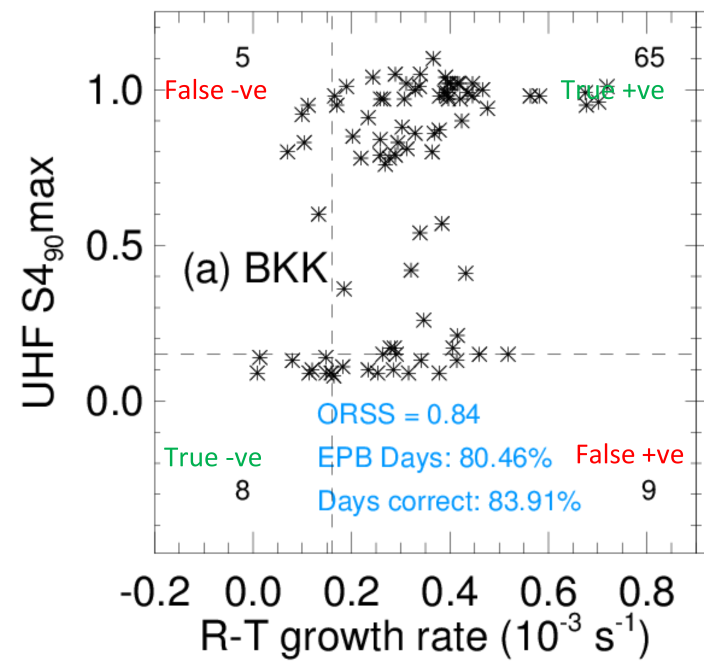
Evaluation: Comparison against constant "yes" forecast during EPB season



BKK: 2013 September Equinox

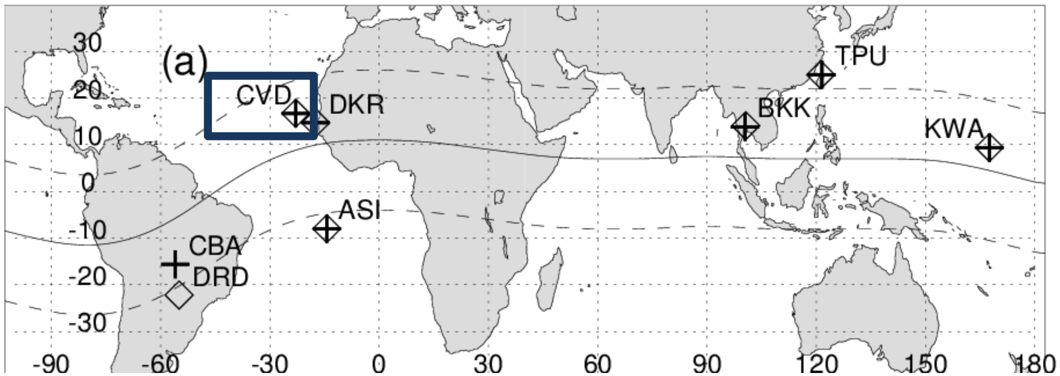


- Difference between EPB day and non-EPB days is clearer in UHF data (not surprising)
- TIEGCM is capturing quite a few non-EPB days (storms late Sep/early Oct)
- “Prediction” success better than constant “yes” forecast

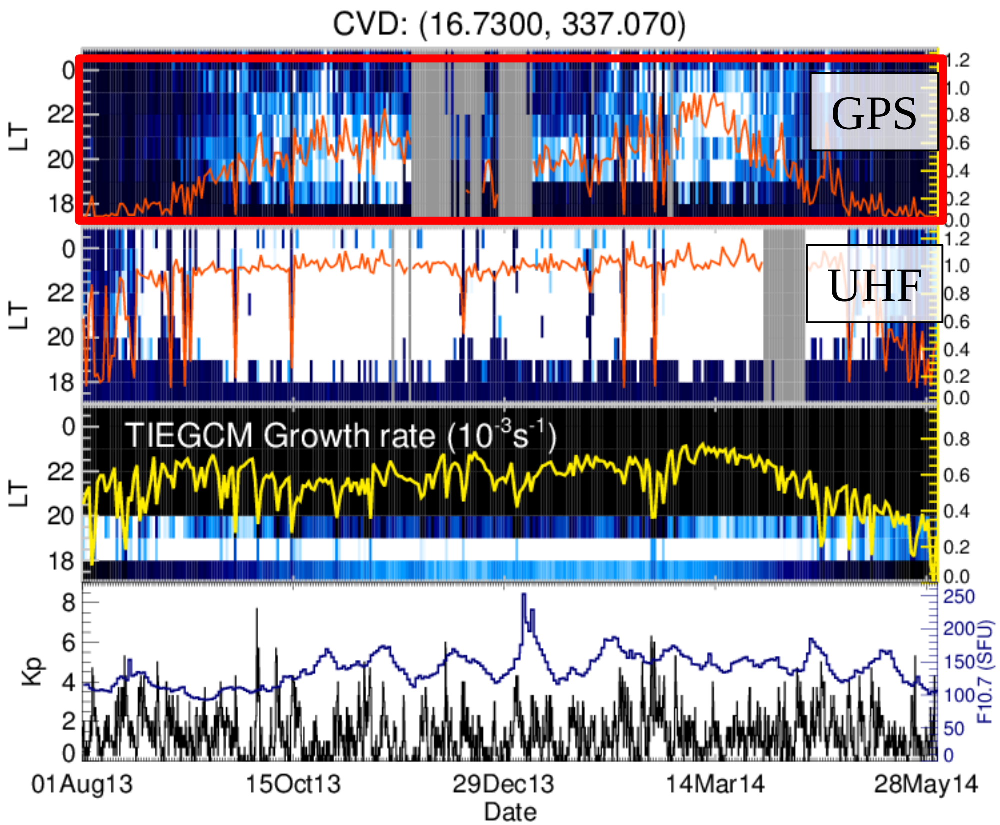


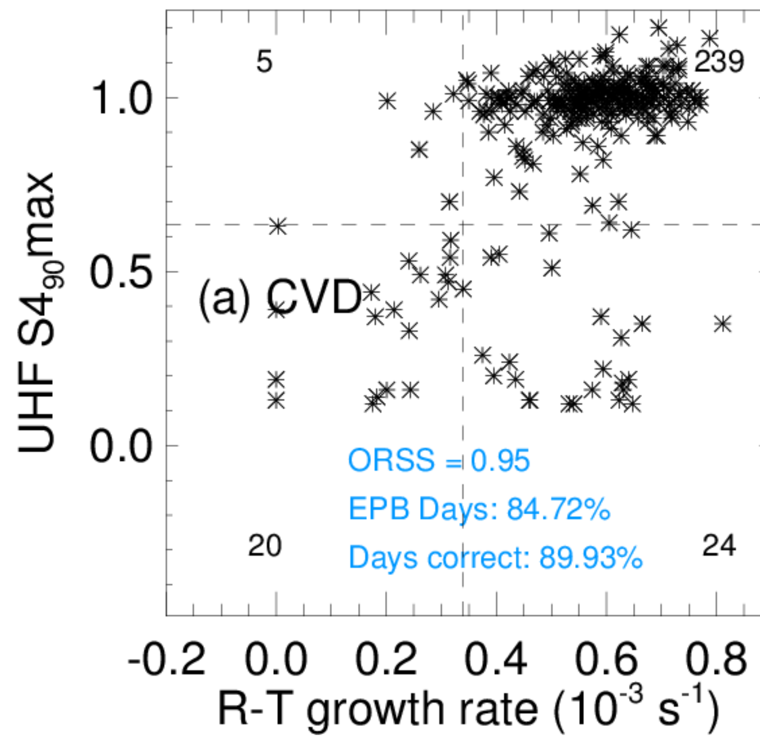
CVD: Aug 2013 – May 2014

RMIT UNIVERSITY
SPACE Research Centre



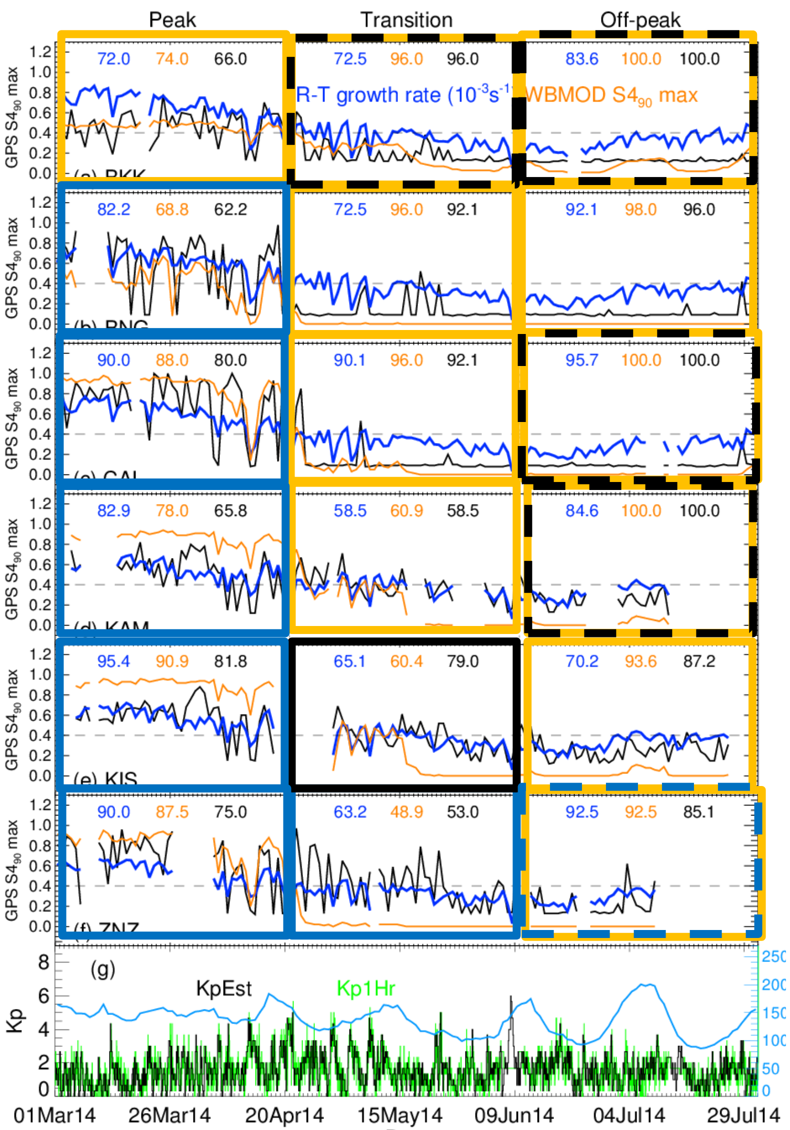
- 10-month EPB season for CVD
- TIEGCM is capturing some non-EPB days
- TIEGCM R-T growth forecast better than "yes" forecast





Scintillation prediction trial: Mar-Jul 2014

RMIT UNIVERSITY
SPACE Research Centre

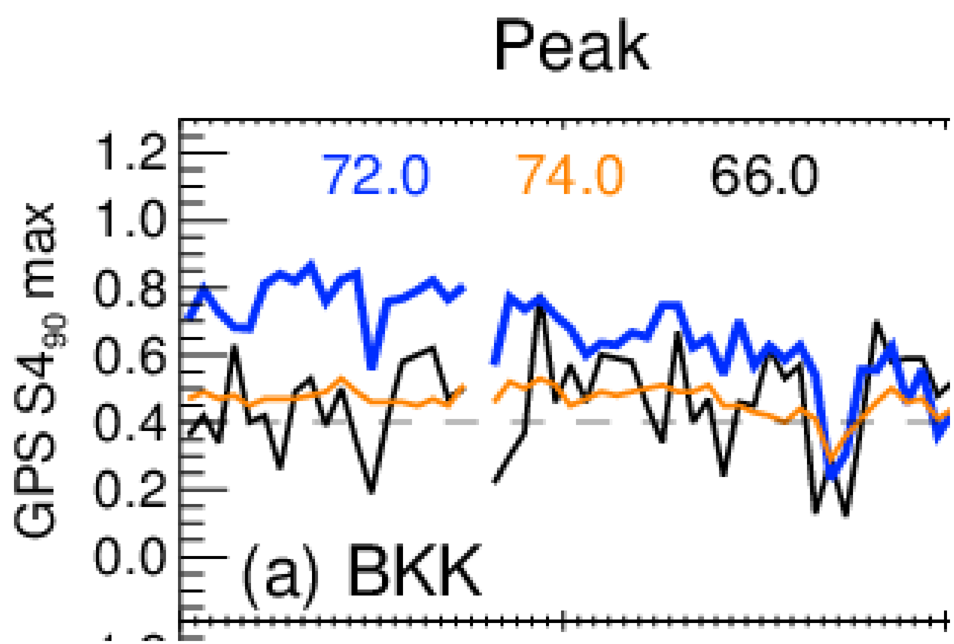


Carter et al., 2014c [GRL]

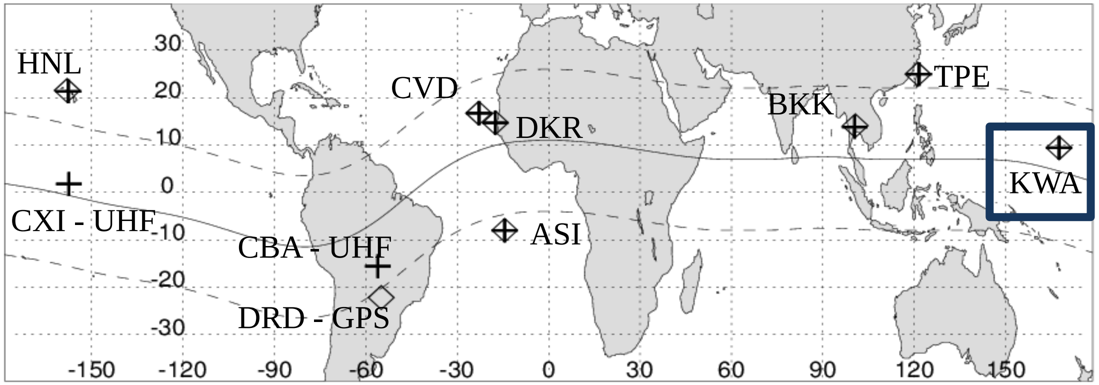
1-hour Wing Kp predictions:

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

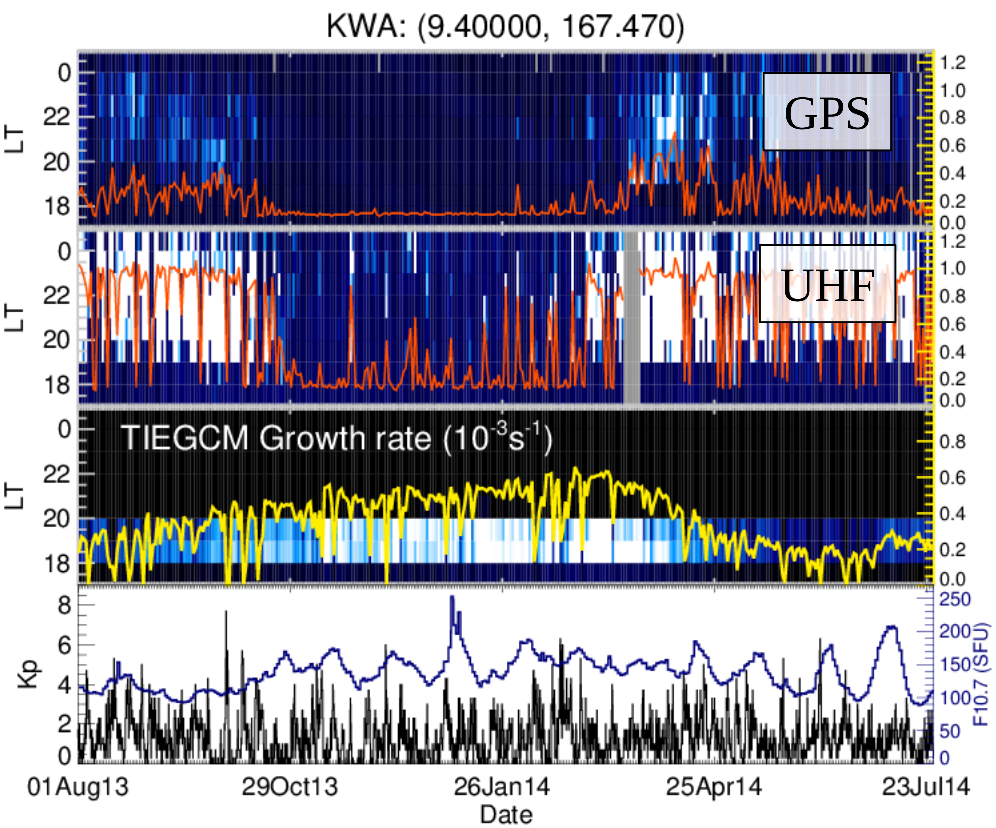
During transition and off-peak seasons, either WBMOD or "persistence" forecast performs best

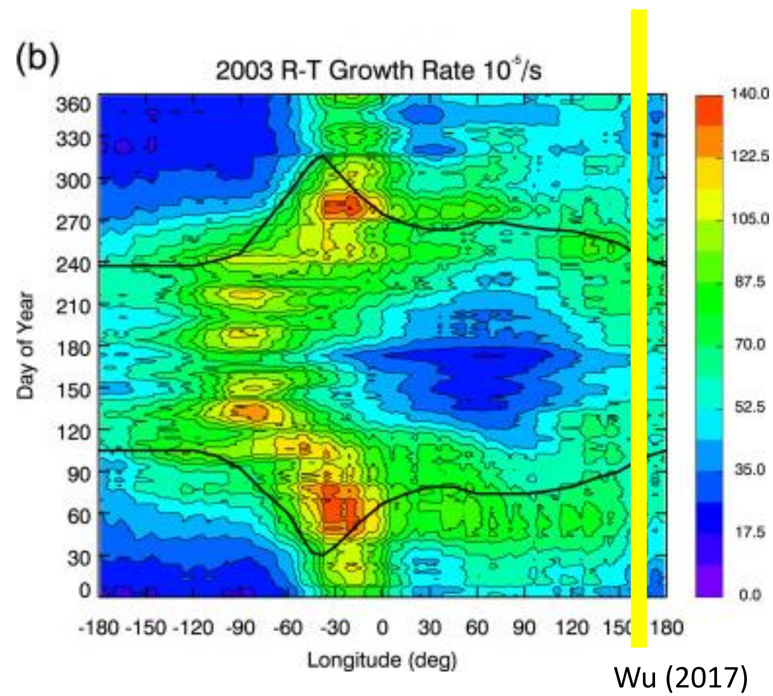


KWA: Aug 2013 – Jul 2014



- Observed EPB climatology matches expectations, but R-T climatology does not; maximum during Dec solstice/Mar equinox
- Our TIEGCM v2 results also in contrast to Wu (2017)'s results
- The exact reason is still not fully understood…



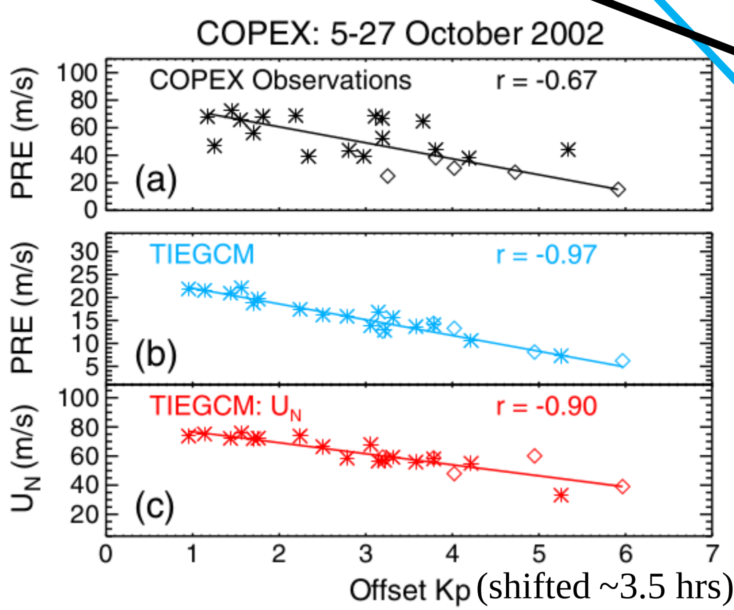


TIEGCM: EPB variability

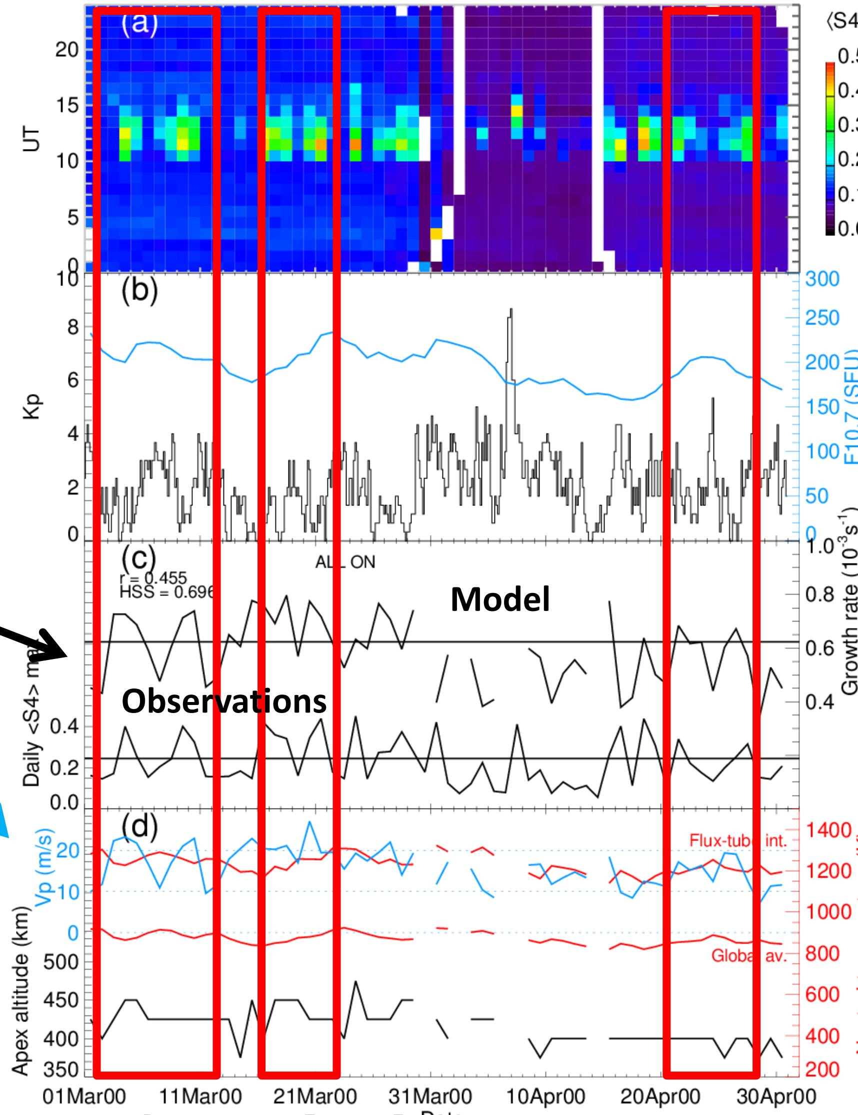
RMIT UNIVERSITY
SPACE Research Centre

- Increases in Kp coincide with decreases in the upward plasma drift (Vp)

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



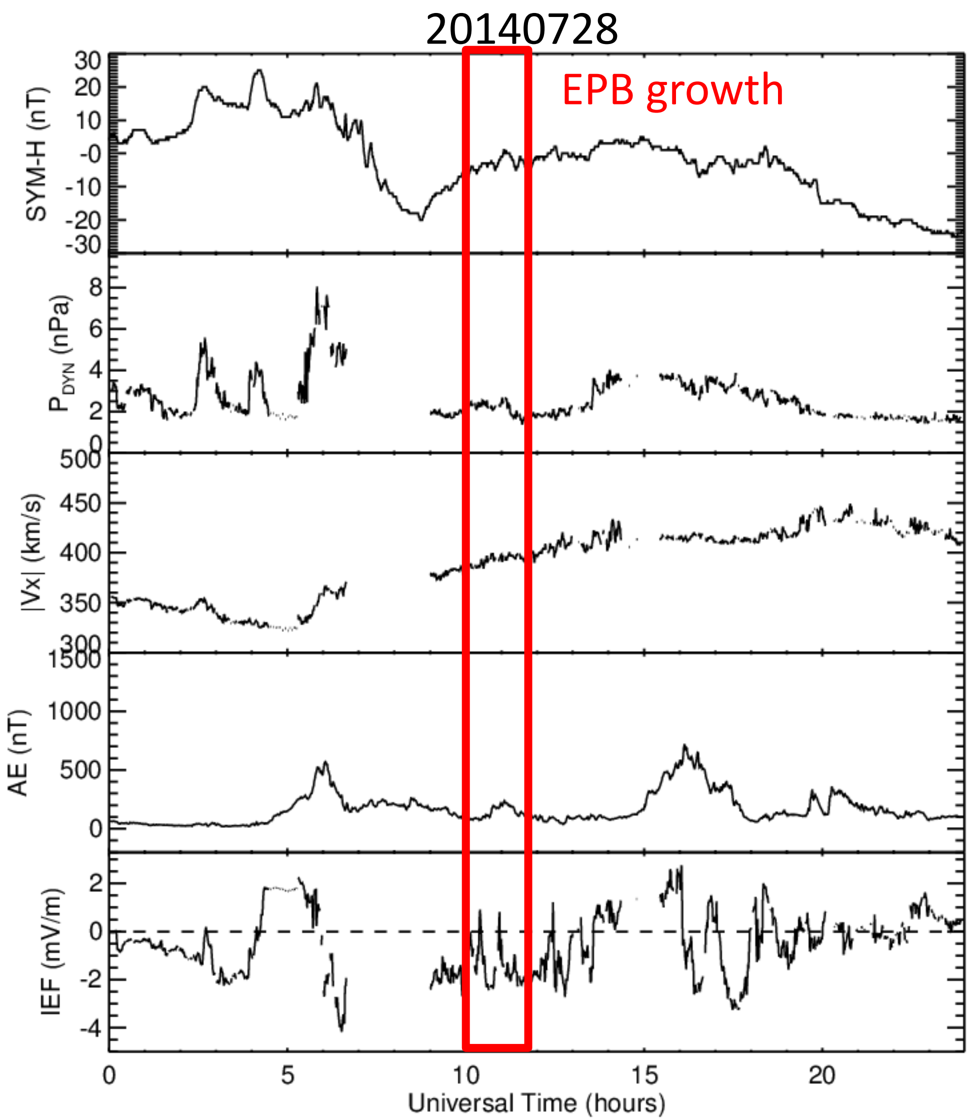
Carter et al., 2014b [GRL]



Carter et al., 2014a [JGR]

Geomagnetic activity

RMIT UNIVERSITY
SPACE Research Centre



Carter et al. (submitted, PEPS, 2017)

- Analysis of geomagnetic activity shows the presence of a co-rotating interaction region on July 28
- Negative IEF (northward IMF) during EPB growth period shows that an under-shielding electric field was not present
- When present, over-shielding and disturbance dynamo electric fields both suppress EPB growth, not encourage it (e.g., Abdu, 2012)
- **Conclusion:** Geomagnetic activity is not related to the enhanced upward plasma drift (and EPB activity) observed over Southeast Asia

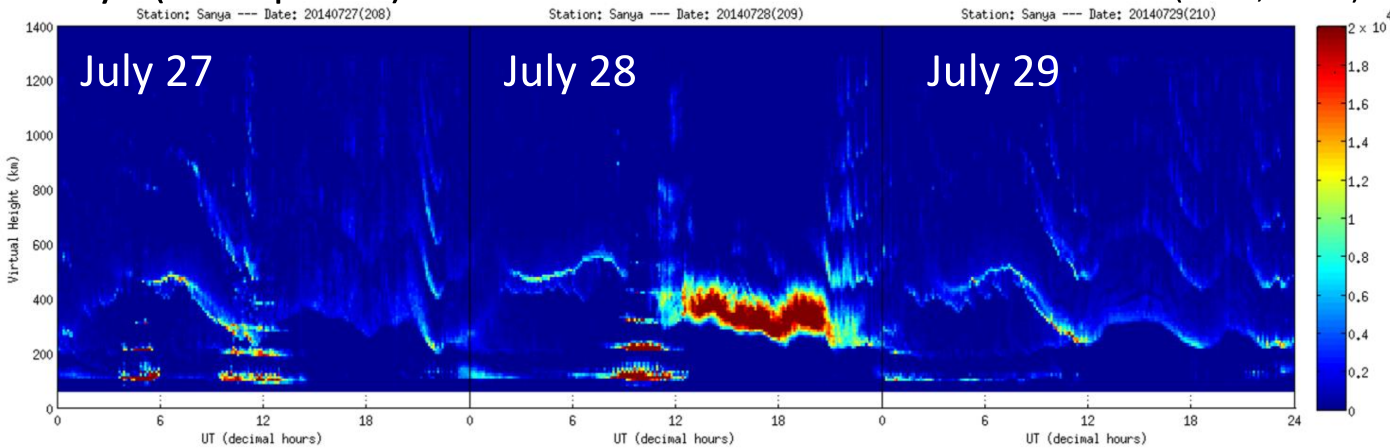
So, forcing from below…?

Ionosonde observations

RMIT UNIVERSITY
SPACE Research Centre

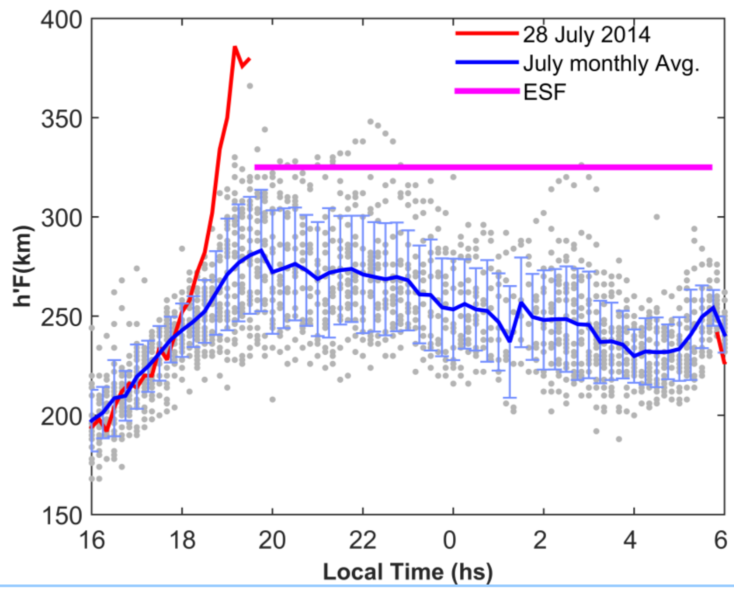
Sanya (off-equator)

Carter et al. (PEPS, 2018)



EPBs confirmed by Spread F observed by Sanya on July 28

BCL (equatorial)

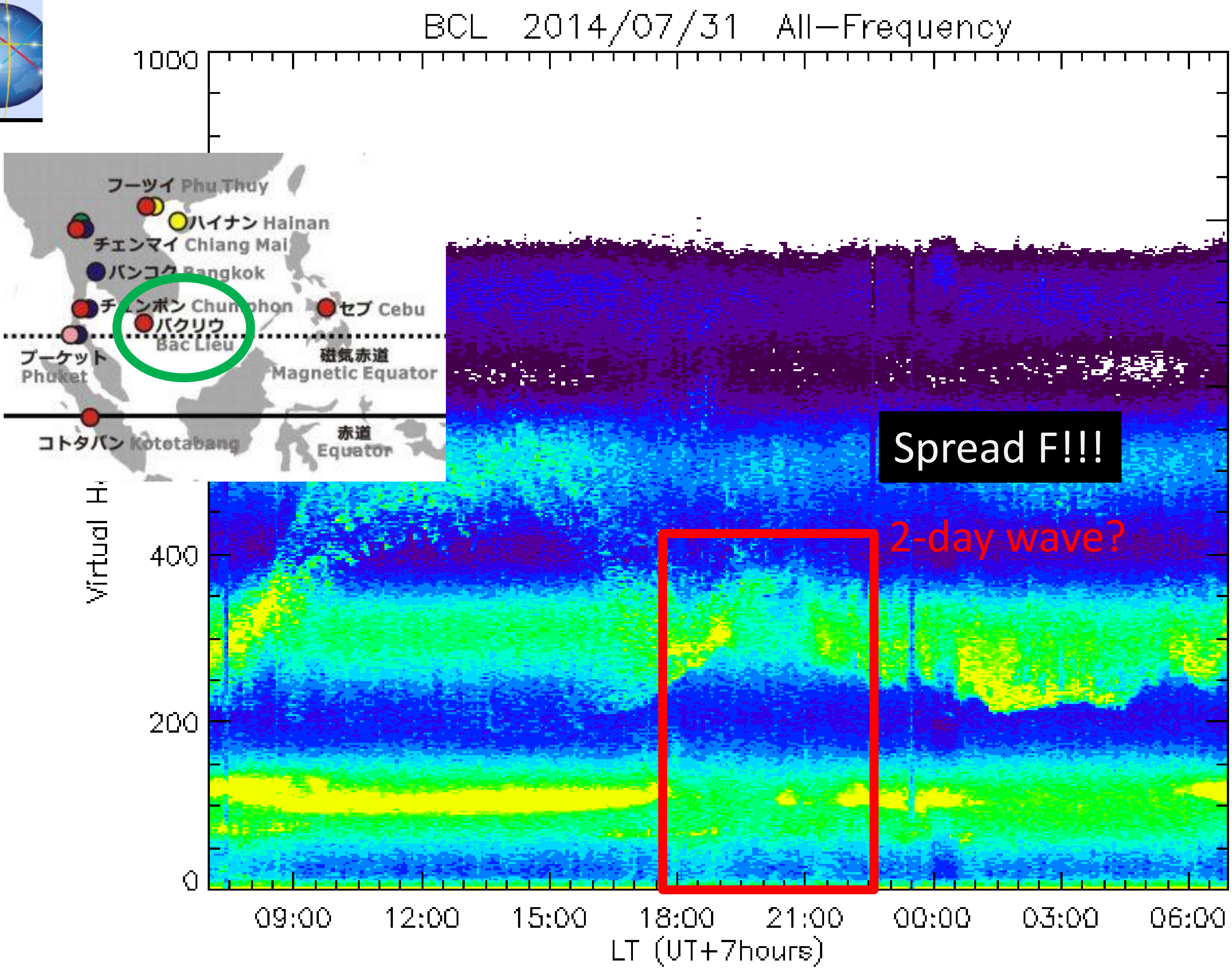


h'F data from BCL station reveals that upward plasma drift was significantly higher on July 28 compared to the rest of July (31.6 m/s vs. 6.4 m/s)

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

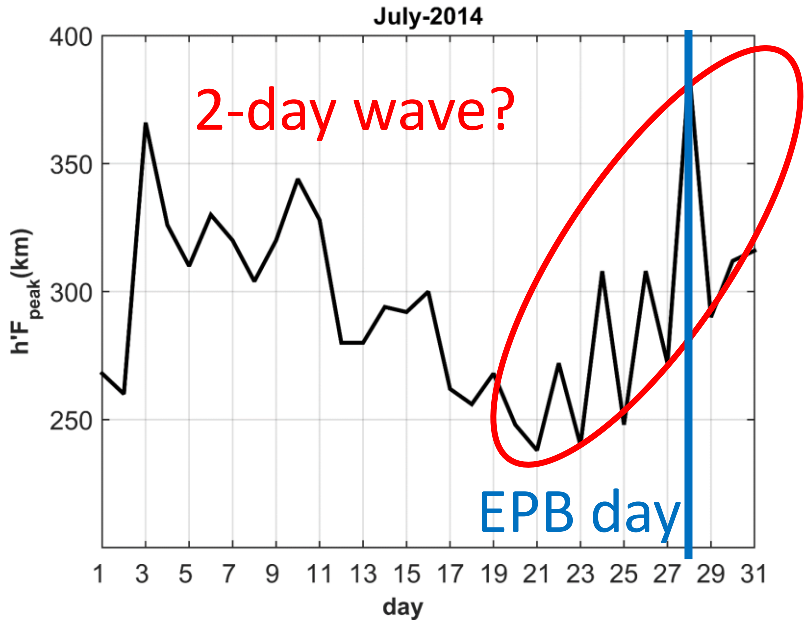
Question: Why?

We don't know for sure, but planetary waves are thought to be involved



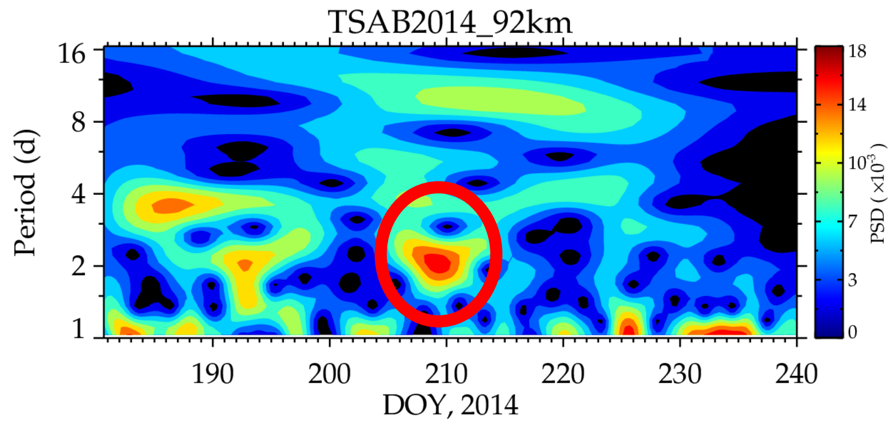
BCL 2014/07/31 All-Frequency
1000
400
200
0
Virtual H
09:00
12:00
15:00
18:00
21:00
00:00
03:00
06:00
LT (UT+7hours)
Spread F!!!
2-day wave?
フーツイ Phu Thuy
ハイナン Hainan
チェンマイ Chiang Mai
バンコク Bangkok
チュンポン Chumphon
セブ Cebu
バクリウ
Bac Lieu
プーケット
Phuket
磁気赤道
Magnetic Equator
コトタバン Kototabang
赤道
Equator

Forcing from below?



Ajith et al. (submitted, PEPS, 2017)

- Increase in h'F from 21-28 July
- Apparent 2-day wave evident during increase



Contact: Takahashi-sensei <hisao.takahashi@inpe.br>

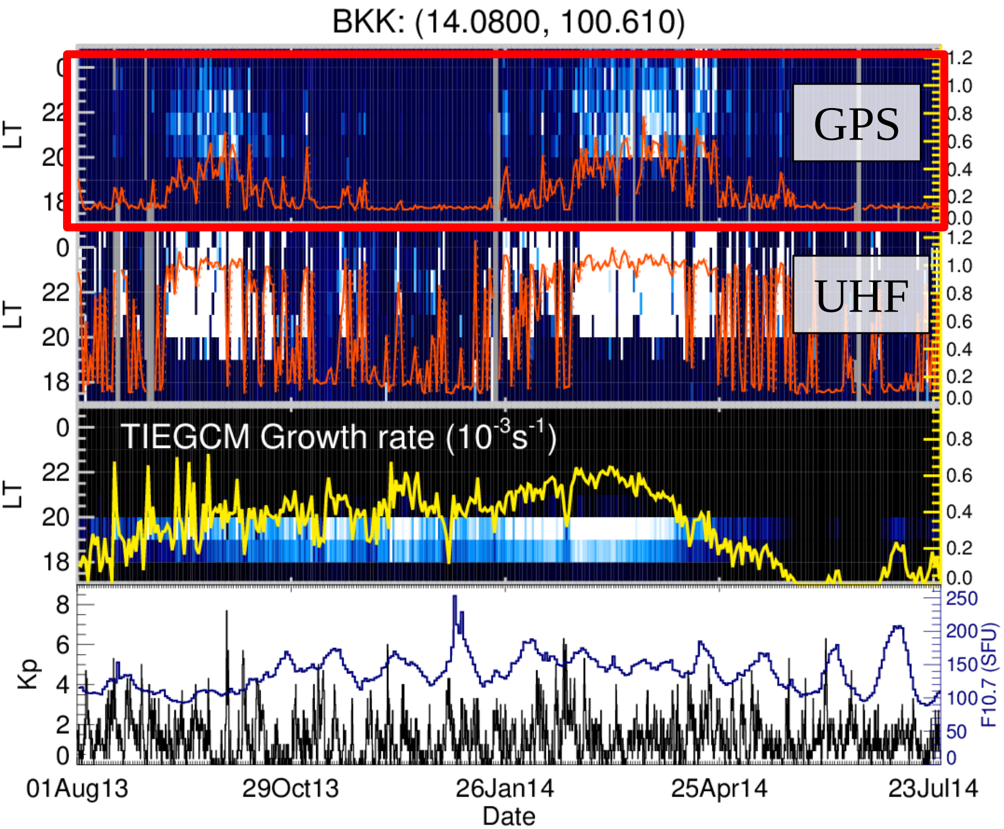
- Mesospheric temperature data from TIMED/SABER shows a strong 2-day wave centered on July 28 (day 209)

Conclusion: Unseasonal EPB event in Southeast Asia appears to be linked with a 2-day Planetary Wave (an "Ultrafast Kelvin wave") from the lower atmosphere

First (??) clear example of an EPB event caused by the lower atmosphere

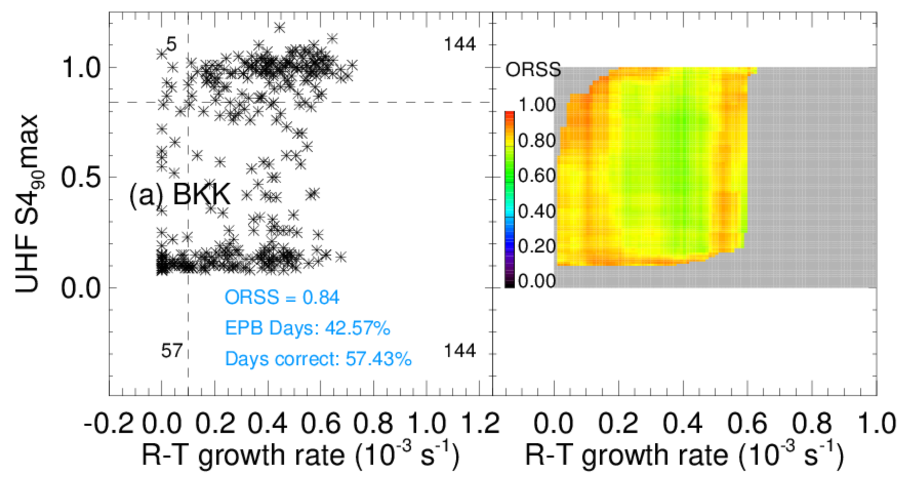
BKK: August 2013 – July 2014

RMIT UNIVERSITY
SPACE Research Centre

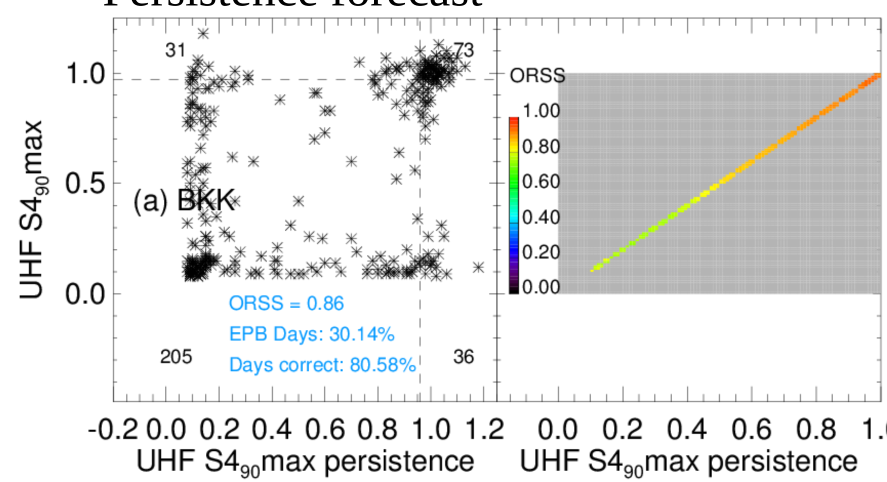


- Across all EPB seasons, persistence achieves the highest ORSS values – although the optimized thresholds are quite high

TIEGCM R-T growth rate



Persistence forecast

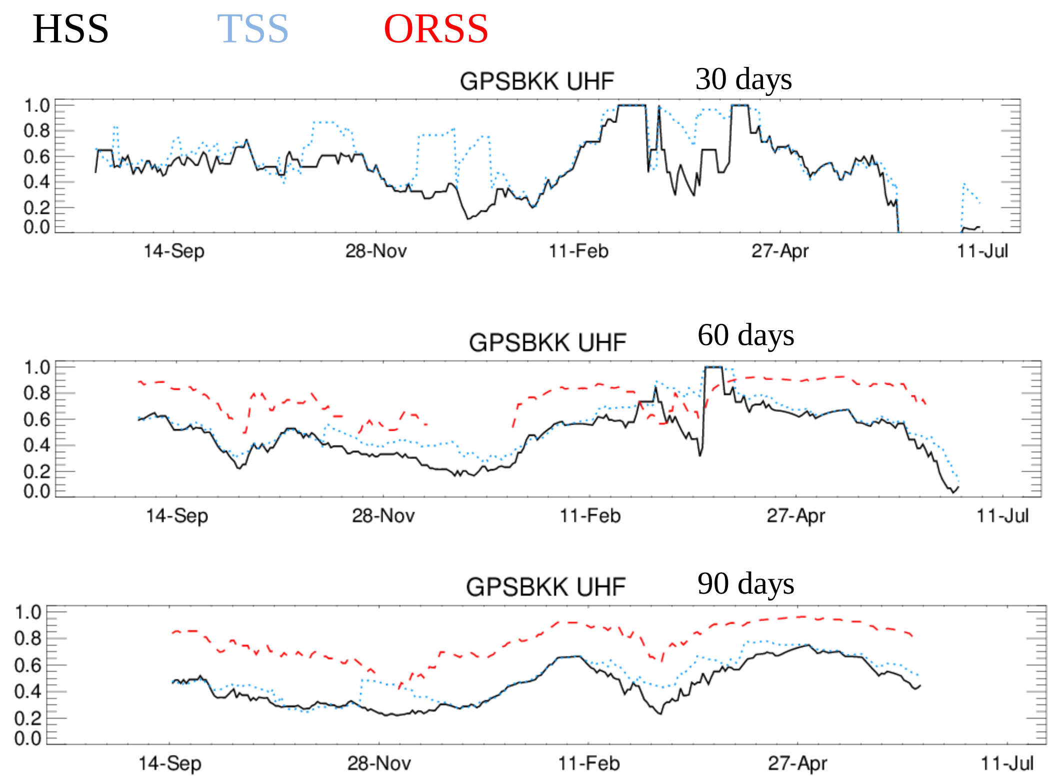


Sensitivity to dataset size

RMIT UNIVERSITY
SPACE Research Centre

What does success look like?

- Reward "skill" in capturing variability
- Insensitivity to "hedging"
- Applicable to variable datasets/time periods
- Uses an appropriate "baseline" for comparison
- Complement symmetry (i.e., switch focus of "yes" and "no")



- The larger the dataset, the more stable the skill scores
- All skill scores vary throughout the seasons, but ORSS varies the least
- Lack of ORSS points indicates insignificant statistics – i.e., 30 days of data is not enough for forecast-observation comparison