

# Statistical models of night-time equatorial F region plasma irregularities based on Swarm geomagnetic and plasma density data

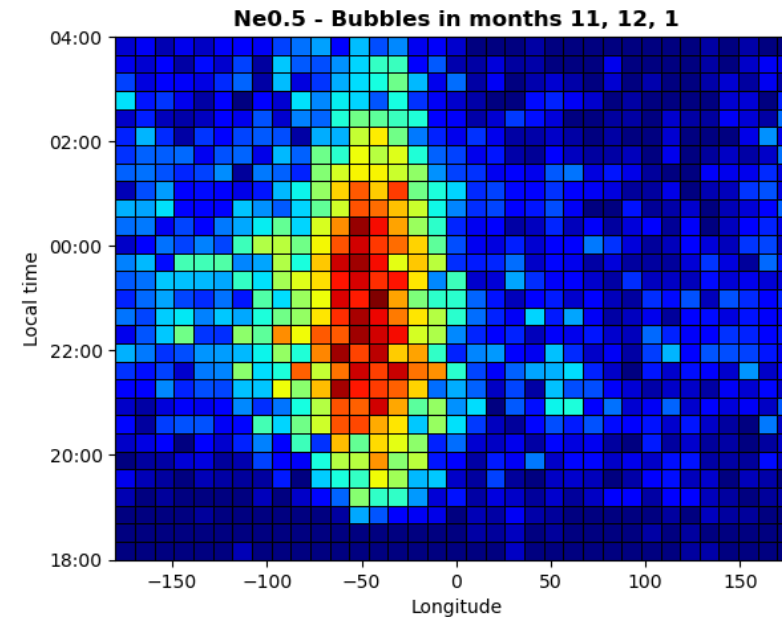
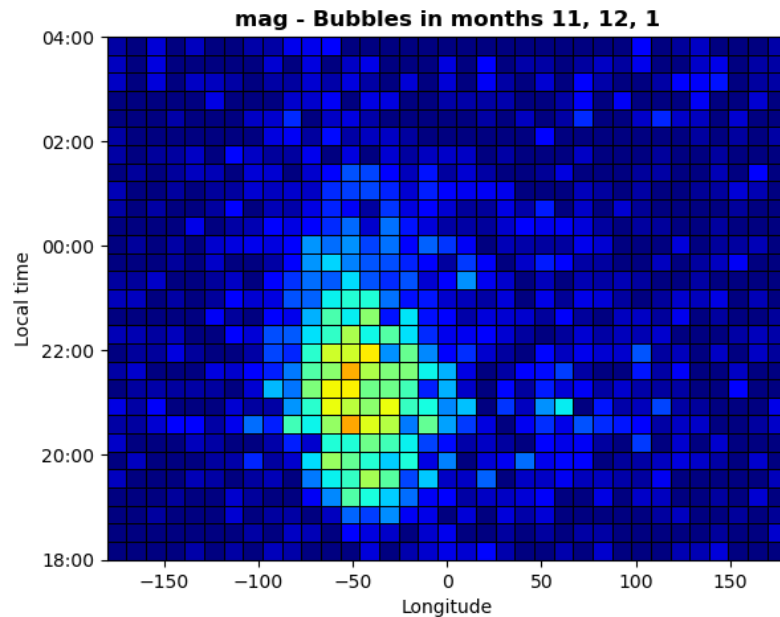
Claudia Stolle<sup>1</sup>, Morteza Feizbakhsh<sup>2,1</sup>, Suman K. Das<sup>1</sup>, Yosuke Yamazaki<sup>1</sup>, T. A. Siddiqui<sup>3</sup>, Lucas Schreiter<sup>4</sup>

<sup>1</sup> Leibniz Institute of Atmospheric Physics (IAP) at the University of Rostock

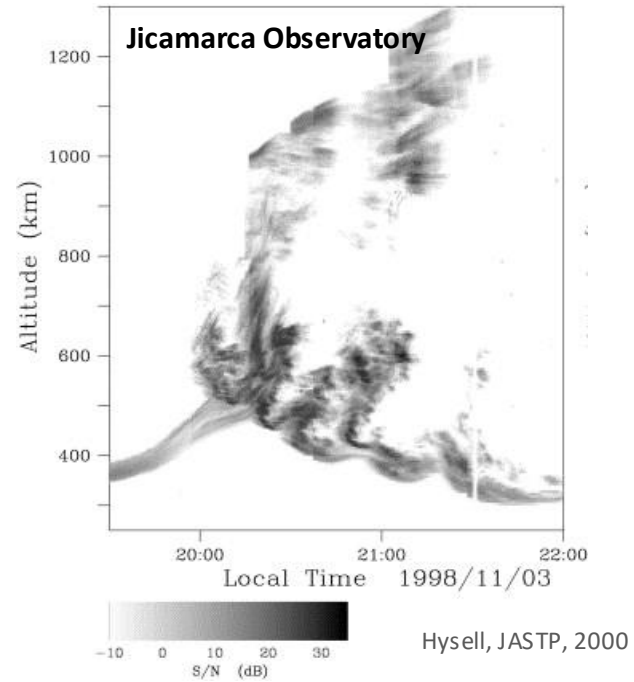
<sup>2</sup> University of Rostock, Faculty of Mechanical Engineering and Marine Technologies

<sup>3</sup> Robert Koch Institute, Climate and Societal Analytics, Center for Artificial Intelligence in Public Health Research

<sup>4</sup> DGFI-TU München

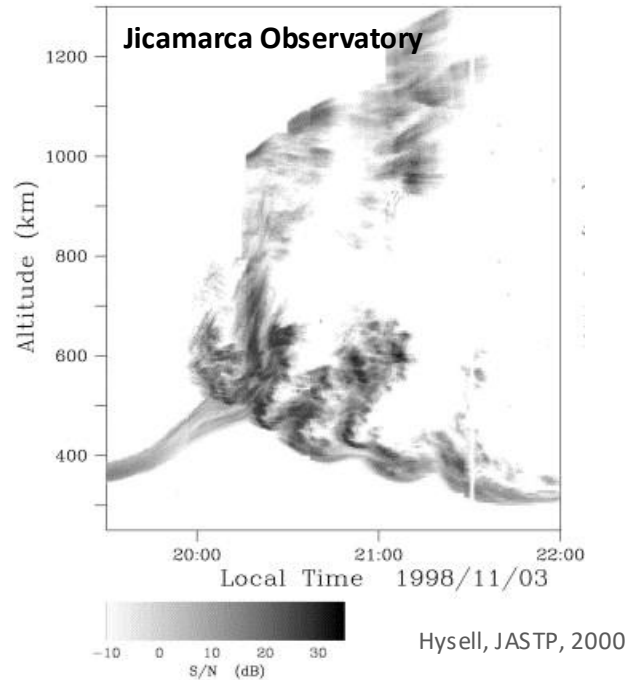


# Equatorial plasma irregularities

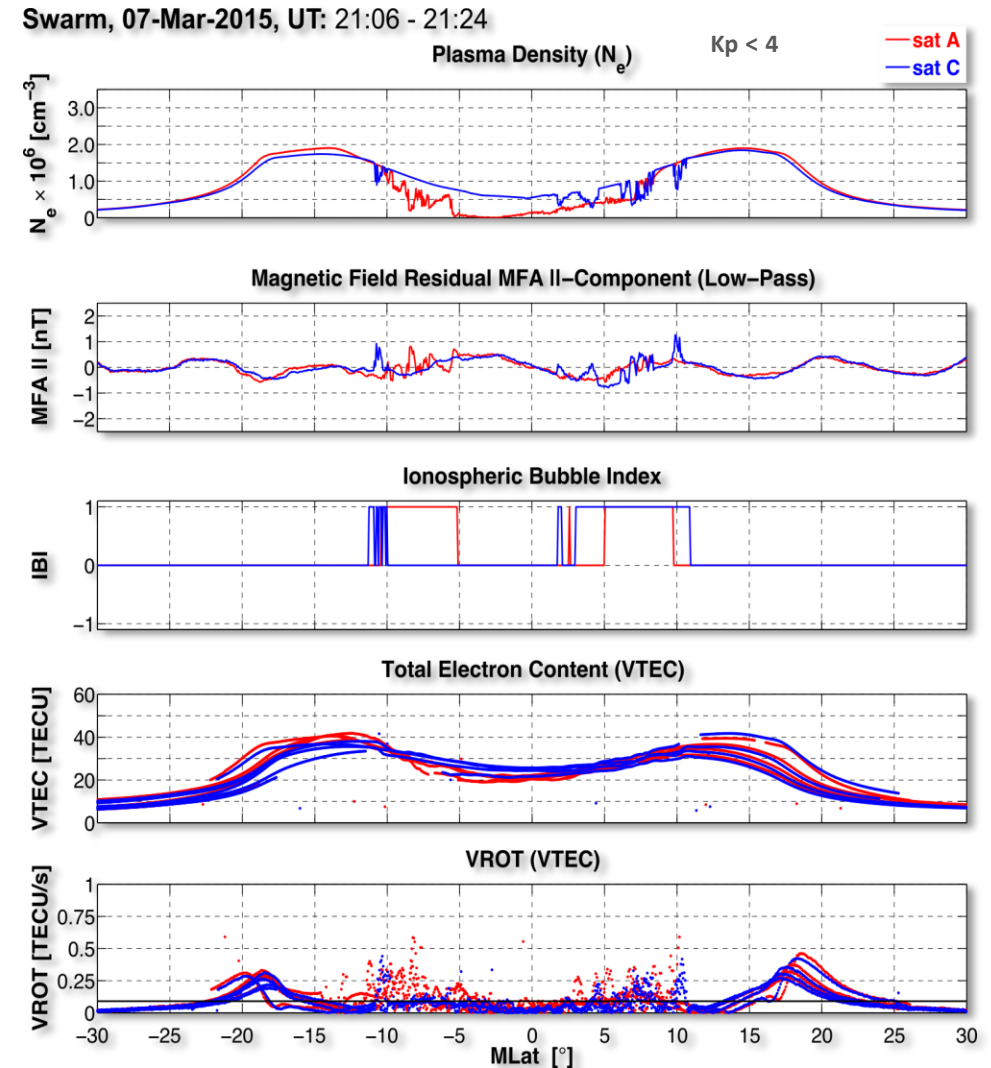


- Major event (“convective storm”) in space physics

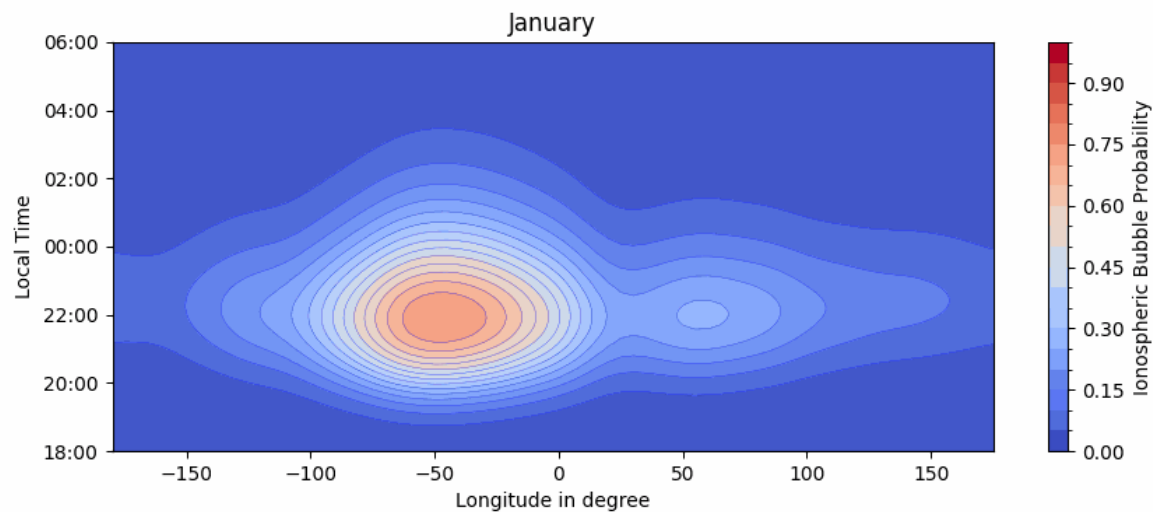
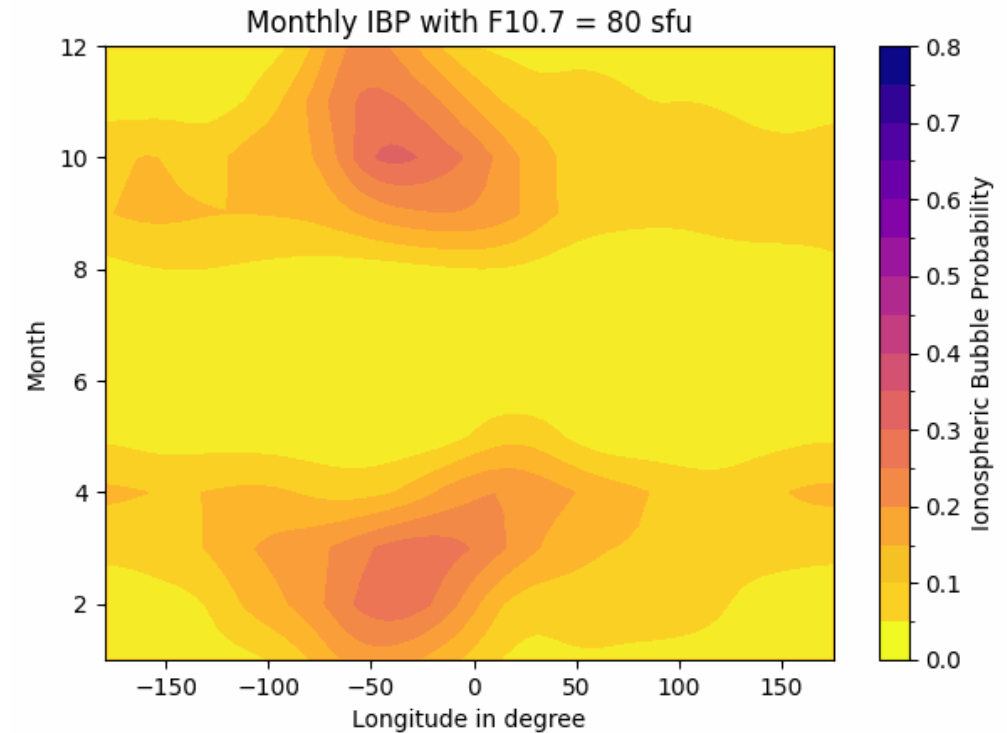
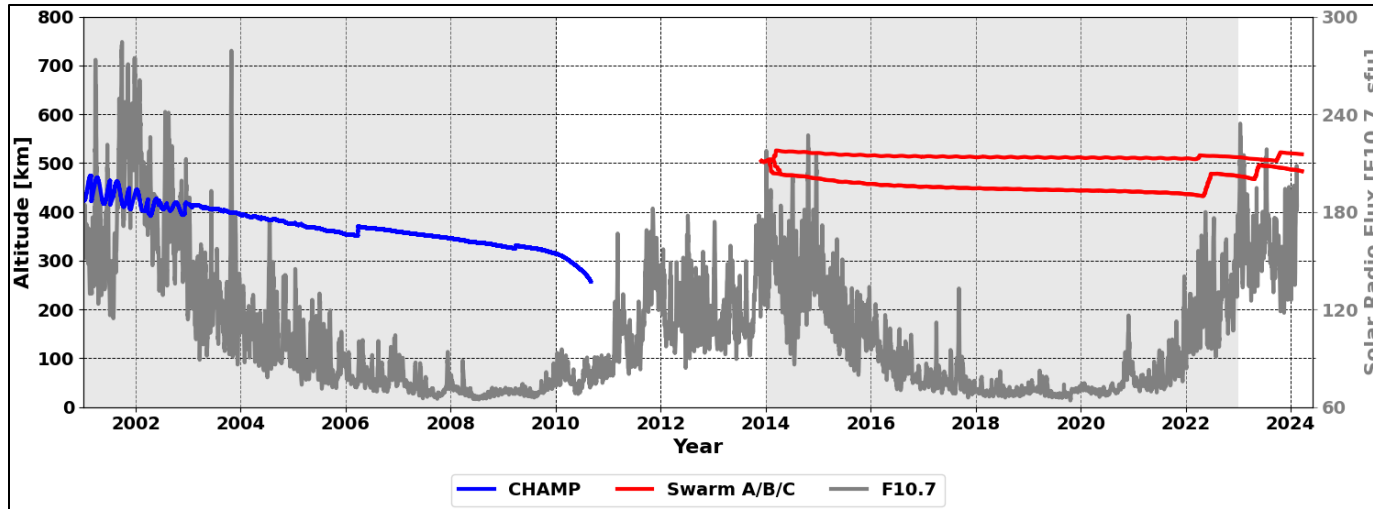
# Equatorial plasma irregularities



- Major event (“convective storm”) in space physics
- In situ visibility in multi-instrument **Swarm** LEO satellites
  - Depletions in e-density
  - Diamagnetic effects in B-field (IBI)
  - Disturbance / Loss of GNSS signals

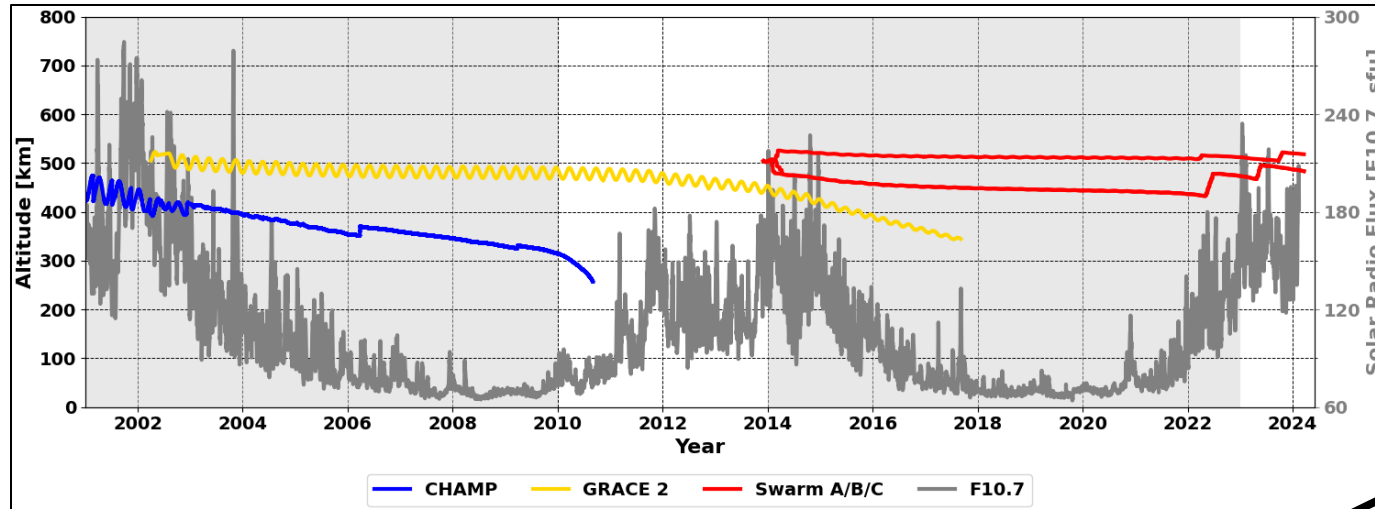


# Statistical model of occurrence of irregularities



- Based on 9 years of CHAMP and 11 years of Swarm magnetic data (IBI) – **parameter estimation**
- Estimate of probability (0-1) for a given local time, longitude, day of year and F10.7 solar flux
- Stolle et al., *Space Weather*, 2024.
- <https://igit.iap-kborn.de/ibp/ibp-model>
- <https://ccmc.gsfc.nasa.gov/models/IBP~1.3/>

# Statistical model of occurrence of irregularities: validation

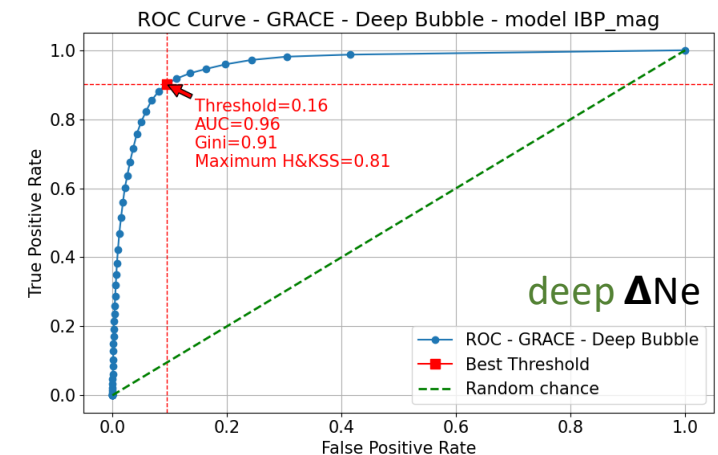
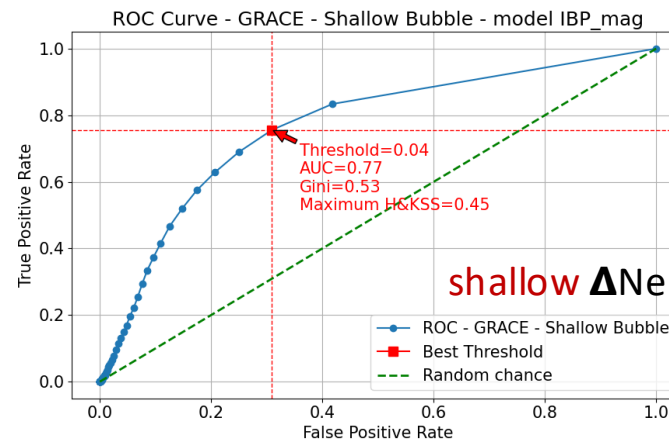
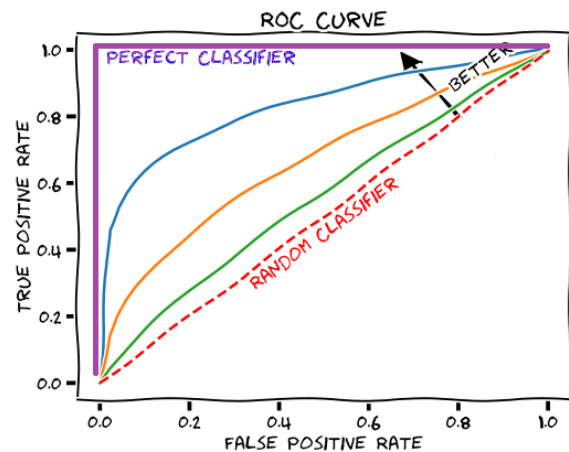


**GRACE Ne:** 2002 – 2017,  $\pm 20^\circ$ mlat, 18-04LT,  
F10.7 > 80, Hp30 < 3

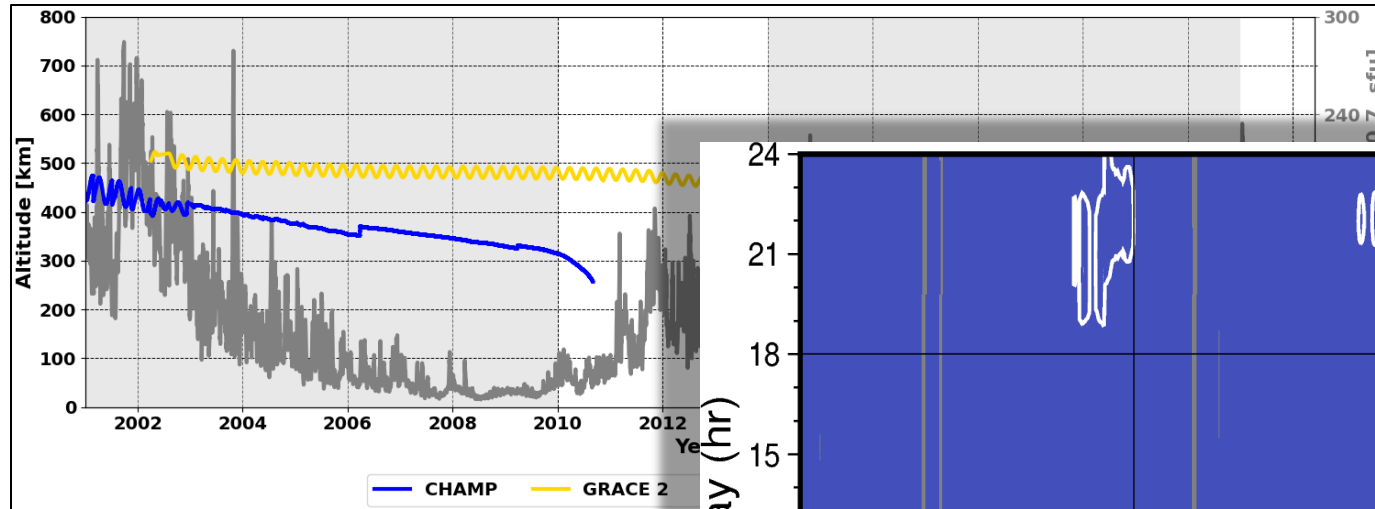
A forecast for a binary event by a probabilistic model is better the larger the area,  $A$ , under the *ROC* curve is:  
(ROC: Receiver Operating Characteristic)

**GC** =  $2A - 1$       **Good:** GC= **1**      **Bad:** GC= **0**

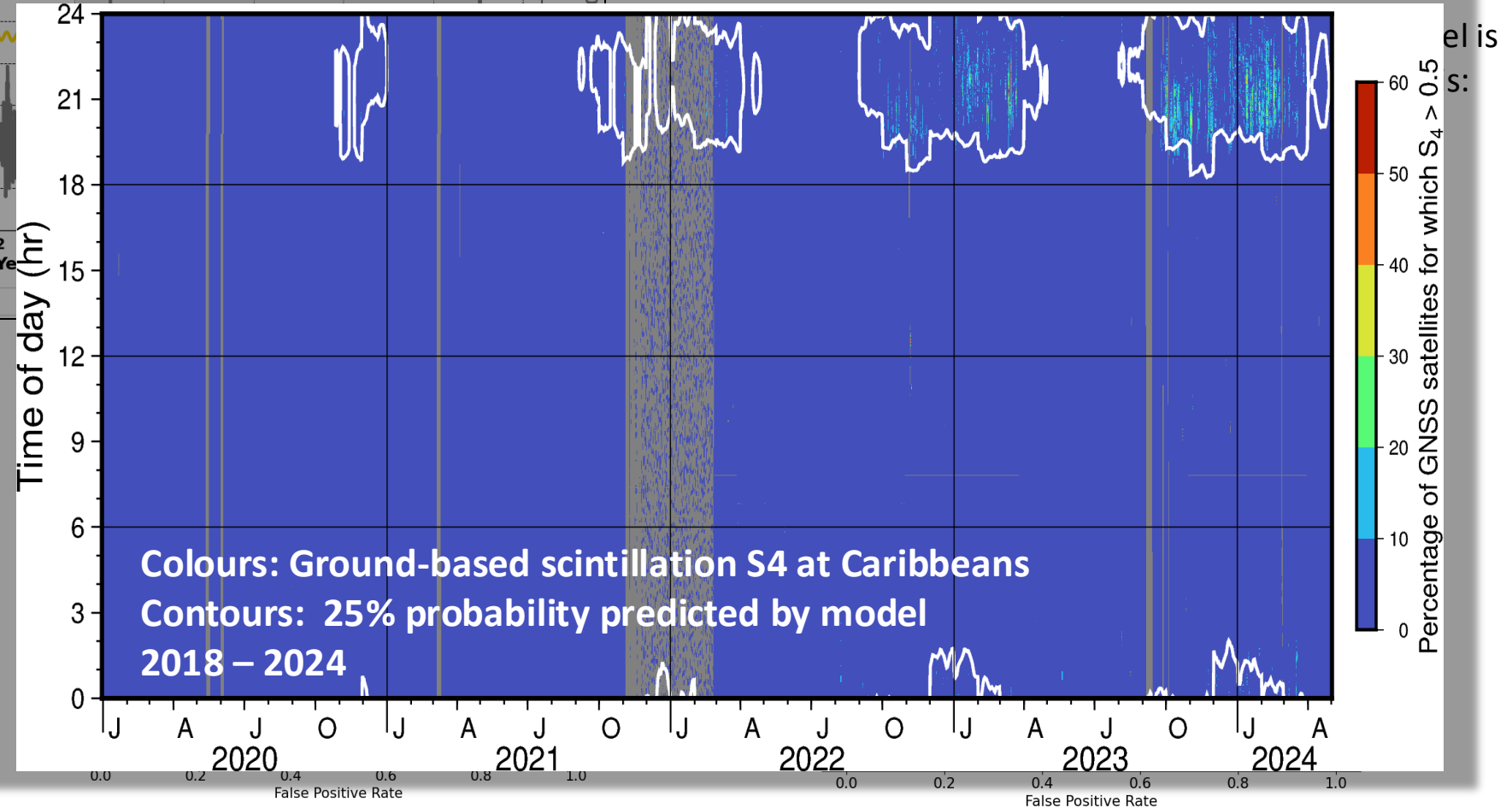
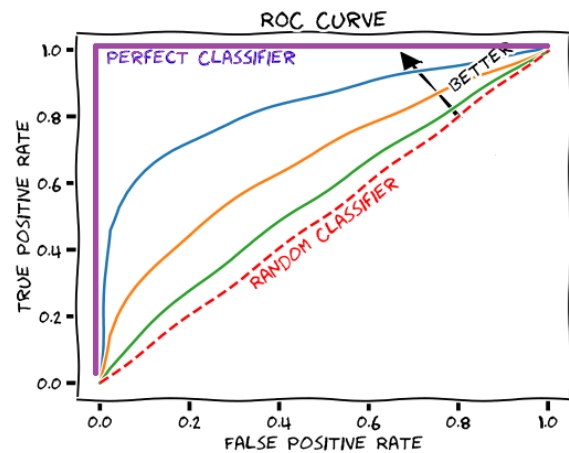
GC ( $\Delta \text{Ne} < 2 \cdot 10^5 \text{cm}^{-3}$ ) = **0.53**, Threshold = **4%**  
GC ( $\Delta \text{Ne} > 2 \cdot 10^5 \text{cm}^{-3}$ ) = **0.91**, Threshold = **16%**



# Statistical model of occurrence of irregularities: validation



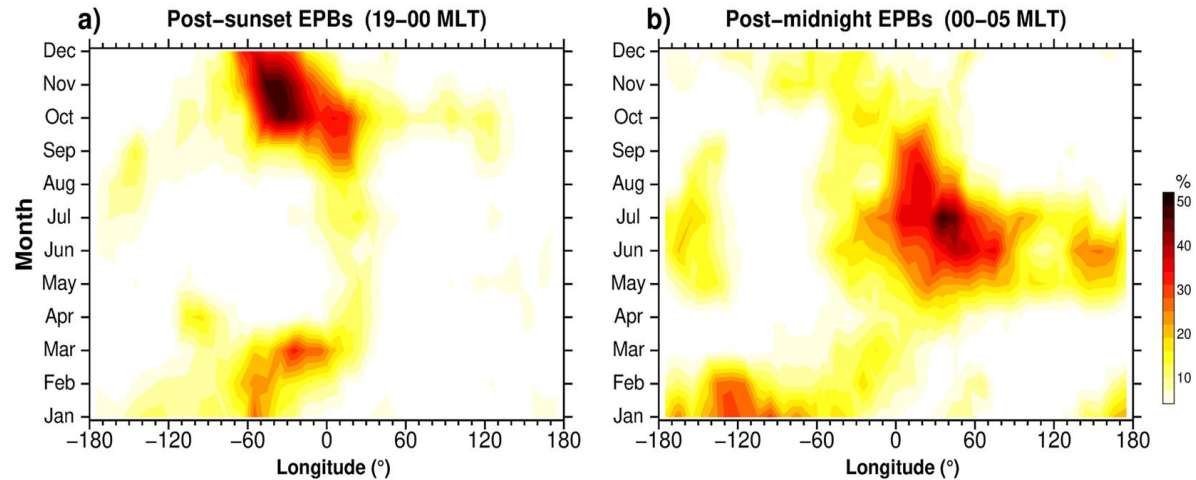
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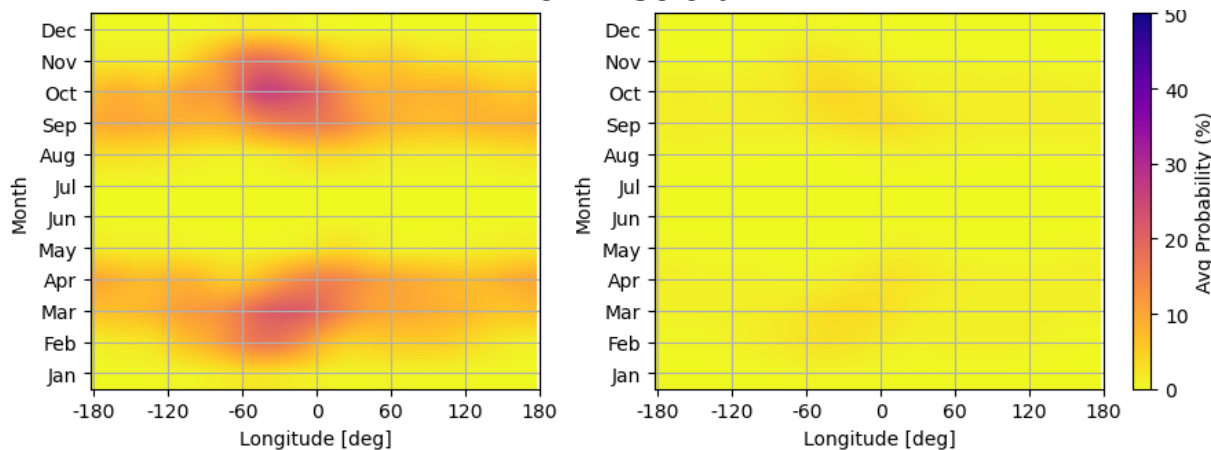
# Post-midnight irregularities

Zakharenkova et al., *Space Weather*, 2023; **COSMIC-2**  
year 2021, F10.7 = 75 sfu ,  $\Delta N_e > 0.6 \cdot 10^5 \text{cm}^{-3}$



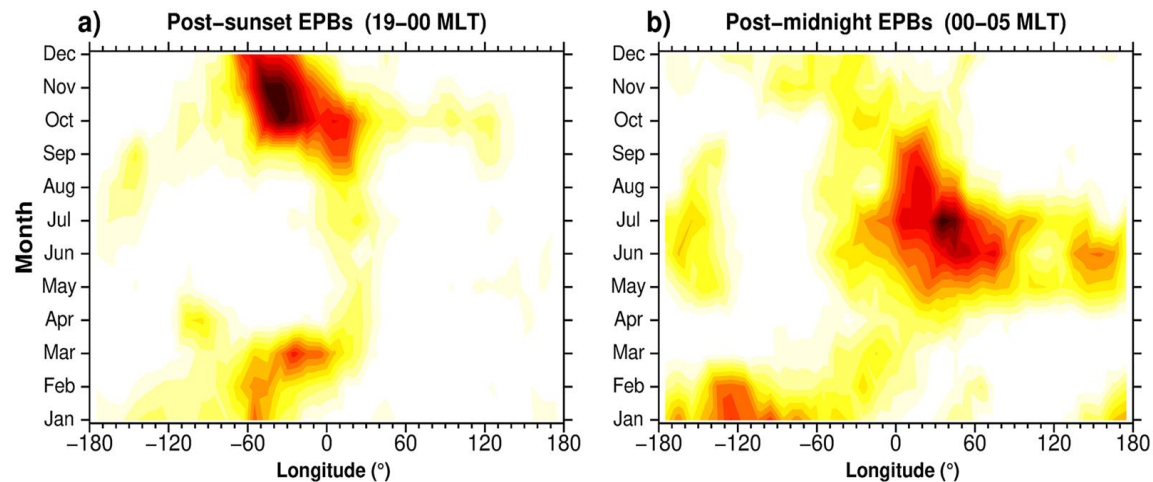
Pre-midnight **Swarm/CHAMP** statistical model (IBI) Post-midnight

F10.7 = 80 sfu

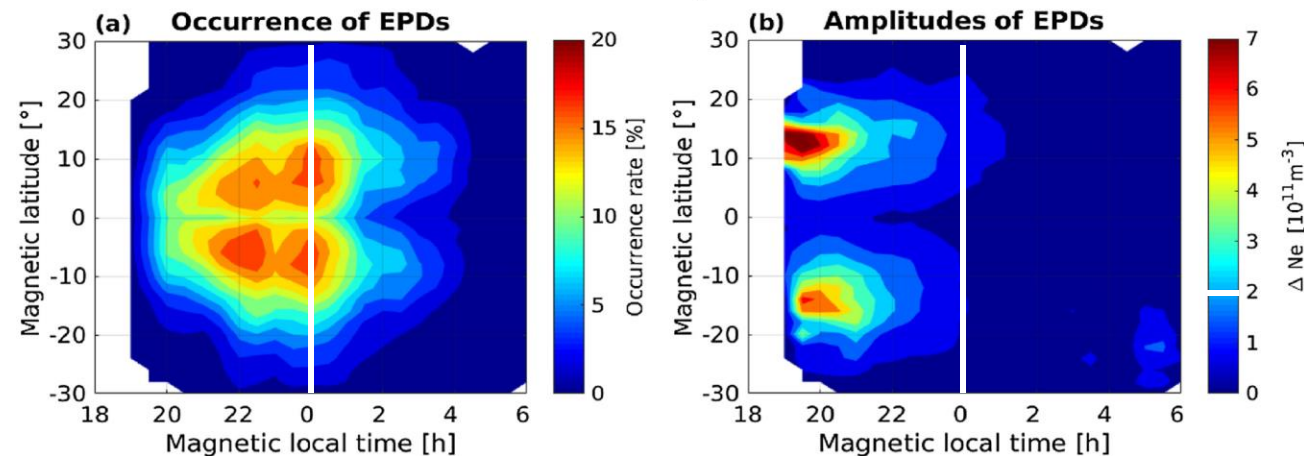


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Zakharenkova et al., *Space Weather*, 2023; **COSMIC-2**  
year 2021,  $F_{10.7} = 75$  sfu,  $\Delta N_e > 0.6 \cdot 10^5 \text{cm}^{-3}$

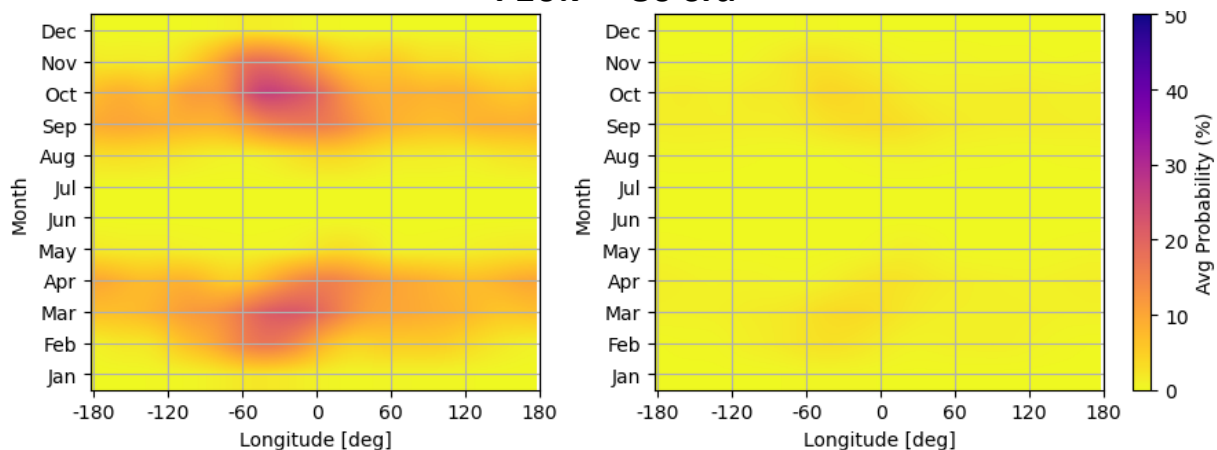


Wan et al., *JGR*, 2018; **Swarm A**,  
2013–2017,  $K_p < 3$ ,  $\Delta N_e > 0.5 \cdot 10^5 \text{cm}^{-3}$



Pre-midnight **Swarm/CHAMP** statistical model (IBI) Post-midnight

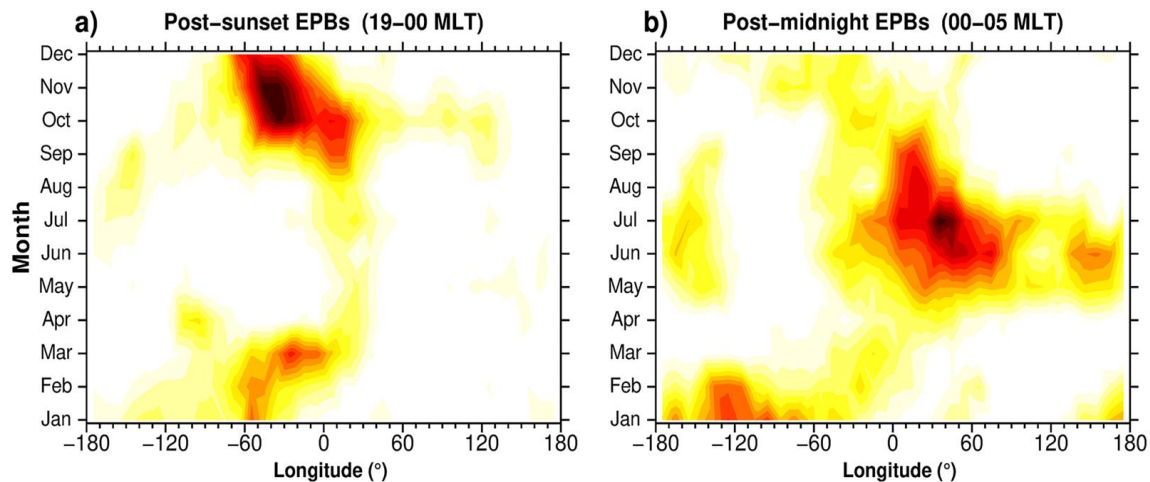
$F_{10.7} = 80$  sfu



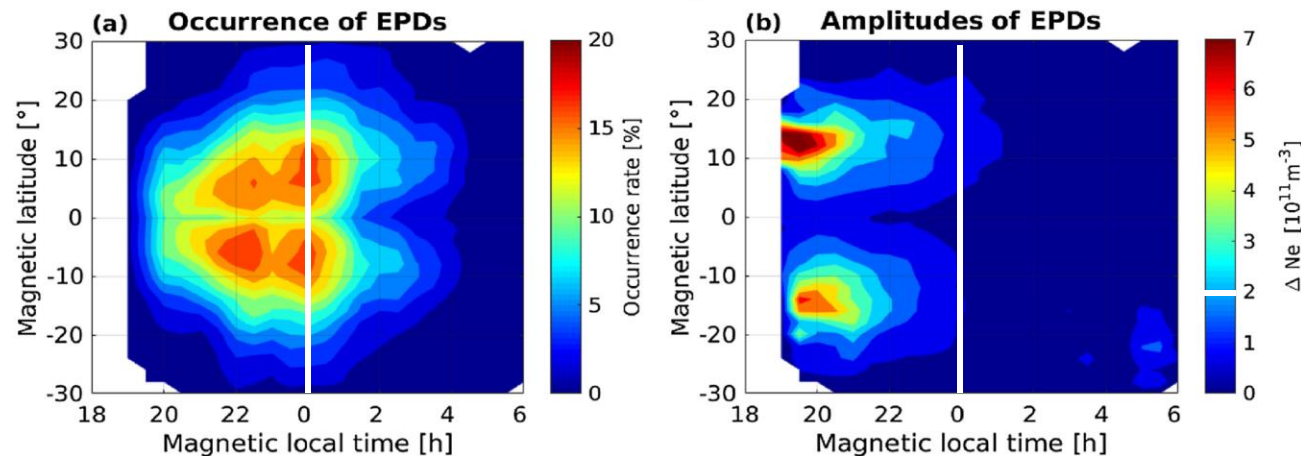


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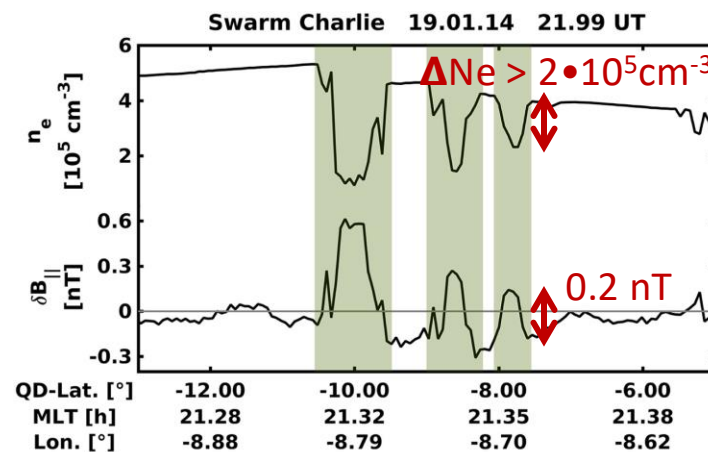
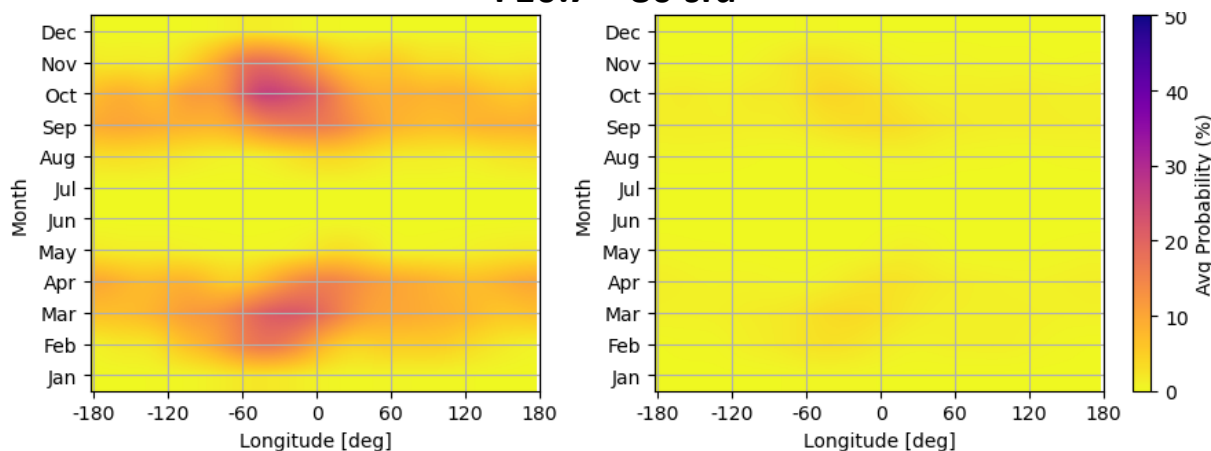


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Pre-midnight **Swarm/CHAMP** statistical model (IBI) Post-midnight

$F10.7 = 80$  sfu



- The statistical model is sensitive to depletions of  $\Delta N_e > 2 \cdot 10^5 \text{cm}^{-3}$
- Relates to magnetic signatures and GNSS scintillations!

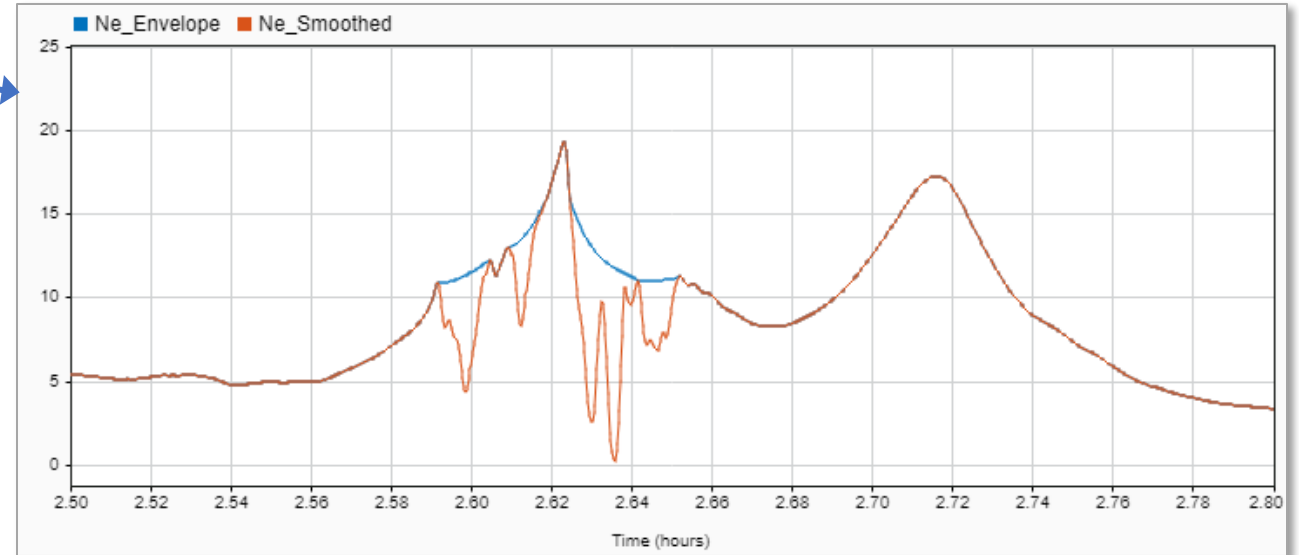
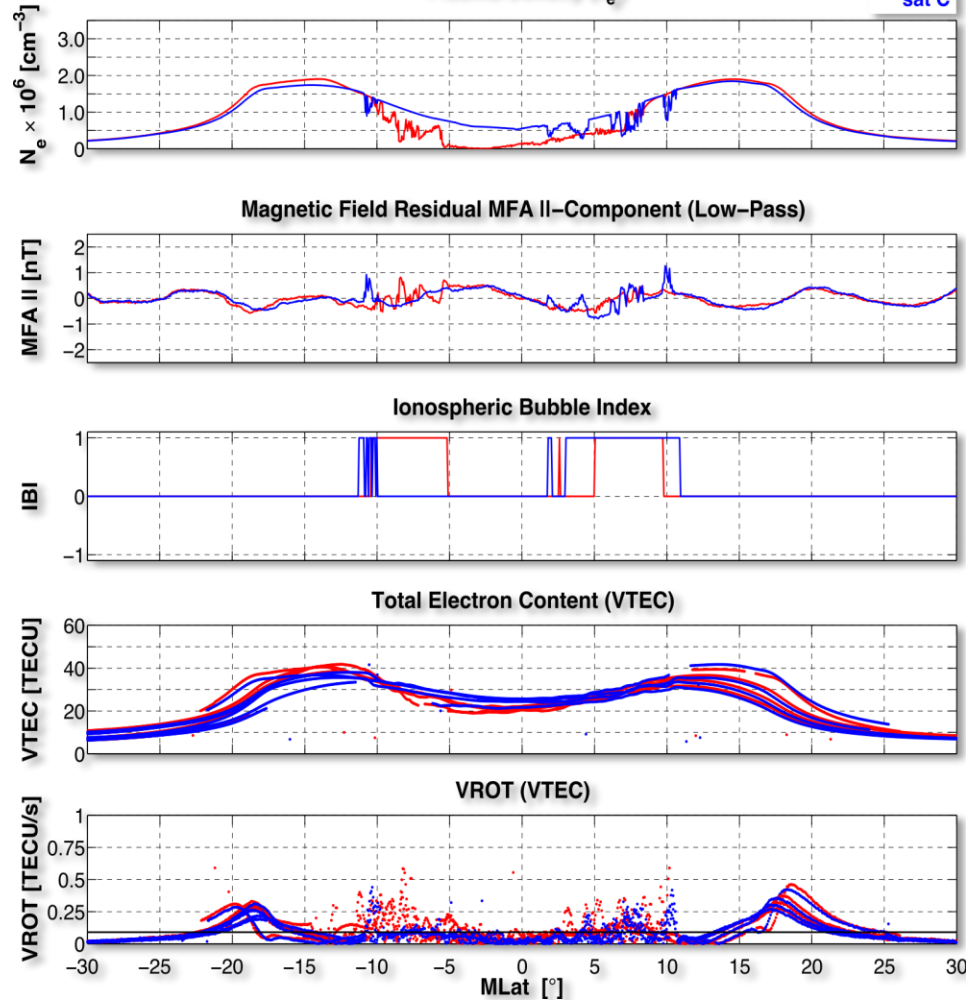
# Detecting irregularities in Swarm plasma density data

Swarm, 07-Mar-2015, UT: 21:06 - 21:24

Plasma Density ( $N_e$ )

Kp < 4

— sat A  
— sat C



Rolling Barrel Method

- Width:  $< 7^\circ$  QDlat
- Absolute threshold:  $0.5 \cdot 10^5 \text{cm}^{-3}$  (shallow)  $2 \cdot 10^5 \text{cm}^{-3}$  (deep)
- Relative threshold: 10%
- $18 \leq LT \leq 06$ ;  $H_p30 \leq 3$ ;  $F10.7 \leq 250$

# Swarm data statistics of **p-density** depletions and **magnetic** signatures (IBI)

2014 – 2024

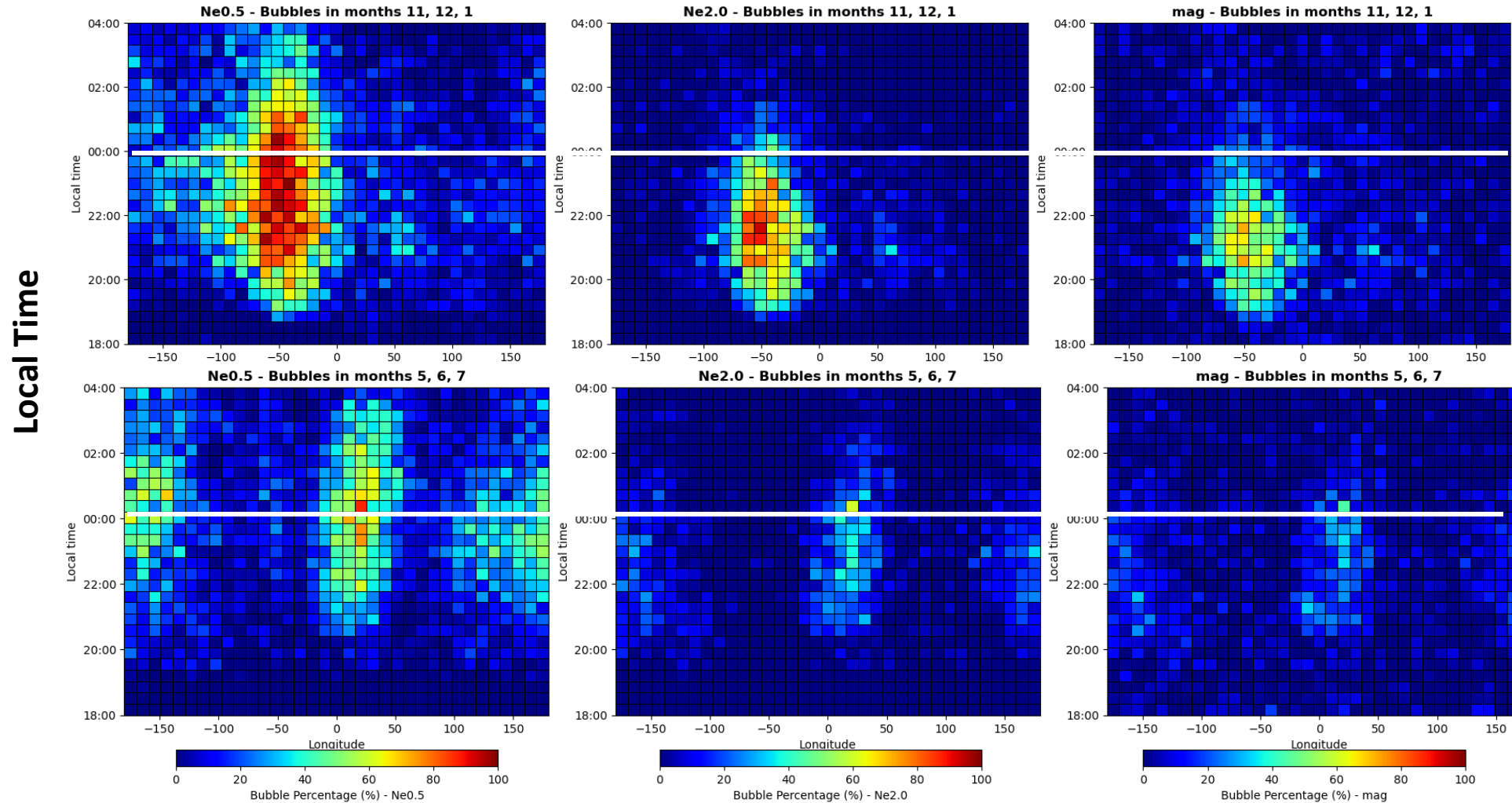
**shallow**  $\Delta N_e > 0.5 \cdot 10^5 \text{cm}^{-3}$

**deep**  $\Delta N_e > 2.0 \cdot 10^5 \text{cm}^{-3}$

**IBI**

Nov, Dec, Jan

May, Jun, Jul



# ML model and validation against GRACE Ne

## Model type: Multilayer Perceptron (MLP)

Input layer: 7 neurons

Hidden layers: [64, 62, 63]

Activation functions: LeakyReLU(0.01)

Output layer: 1 neuron (Sigmoid)

Data Split: (80% training, 20% testing)

Loss Function: MSE (Mean square error)

# of Epochs: 100

## Input features:

Local time = [-6.0, 6.0]

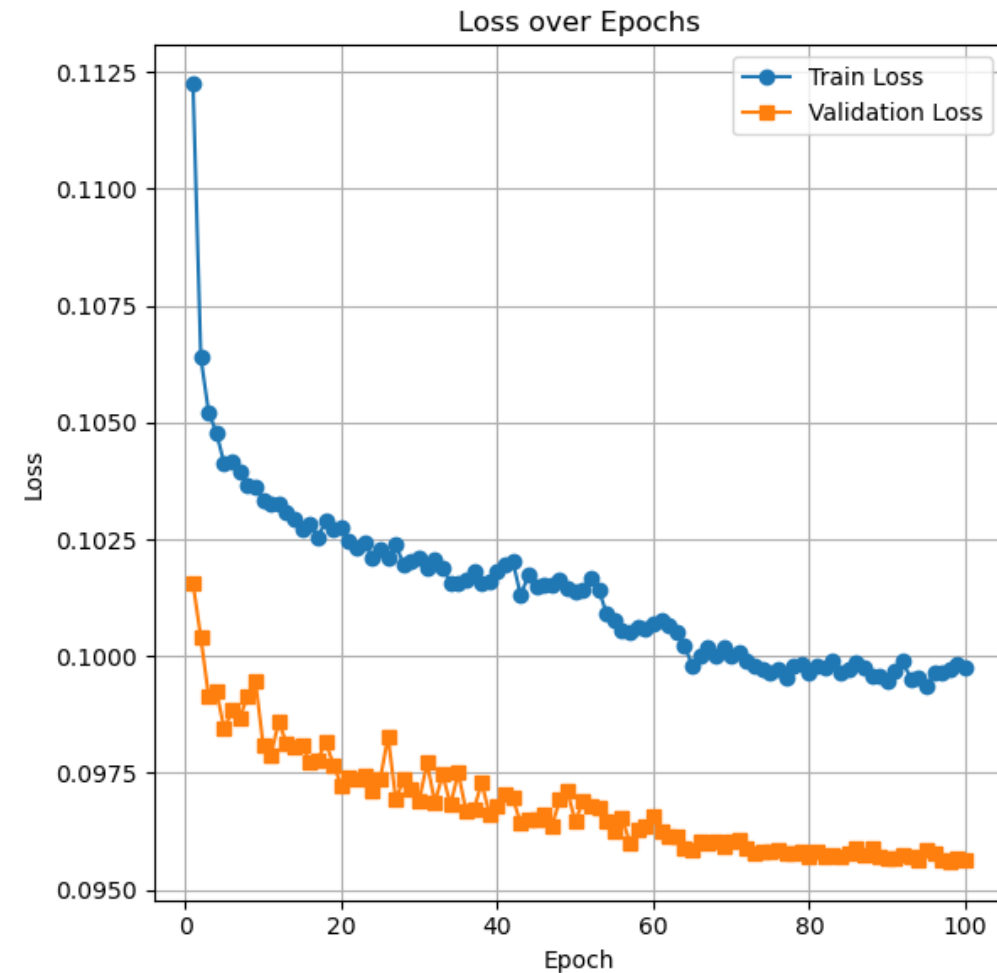
Day of year = [1, 365]

Longitude = [-180, 180]

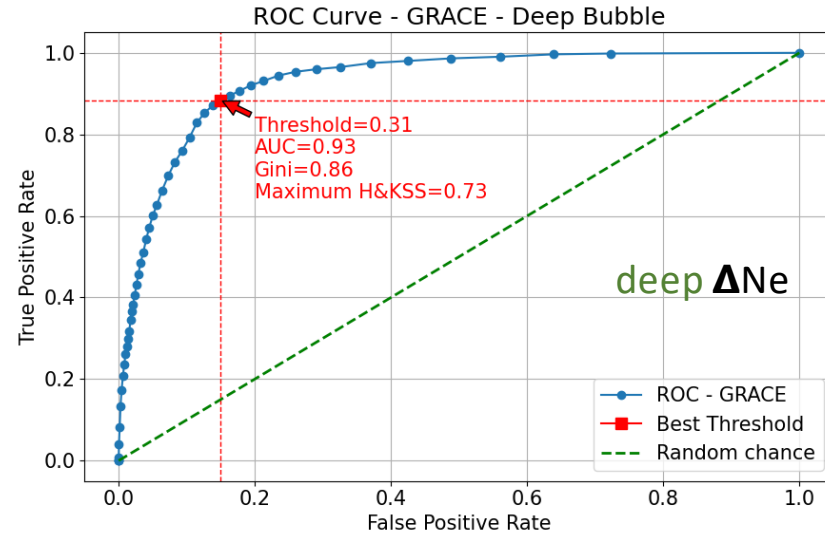
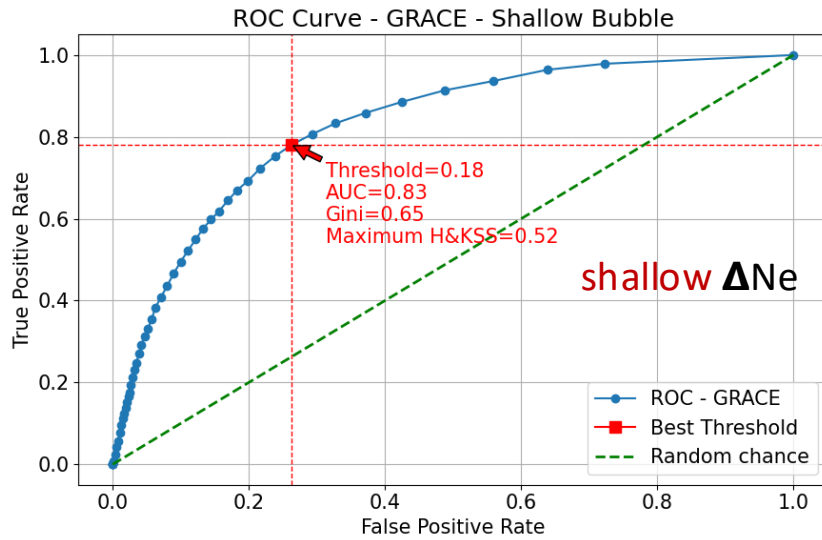
F10.7 = [50, 250]

## Output:

Probability of depletion irregularity = [0, 1]



# Model validation against GRACE Ne

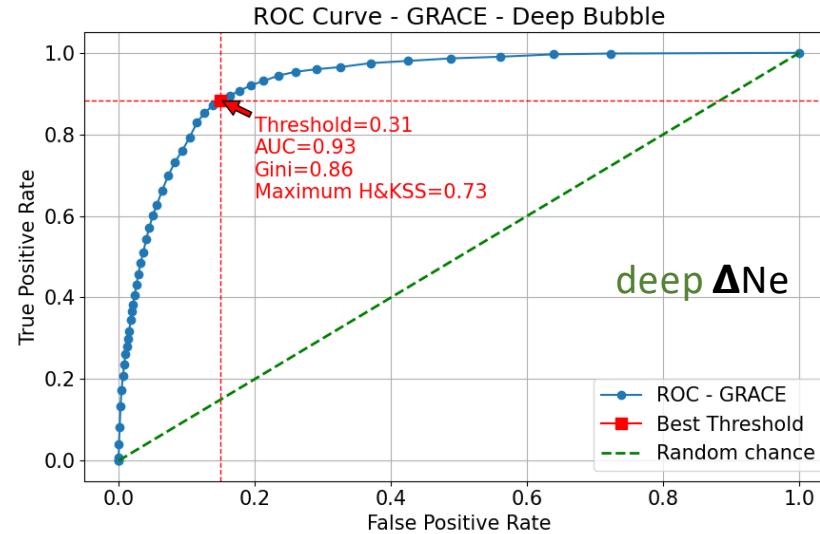
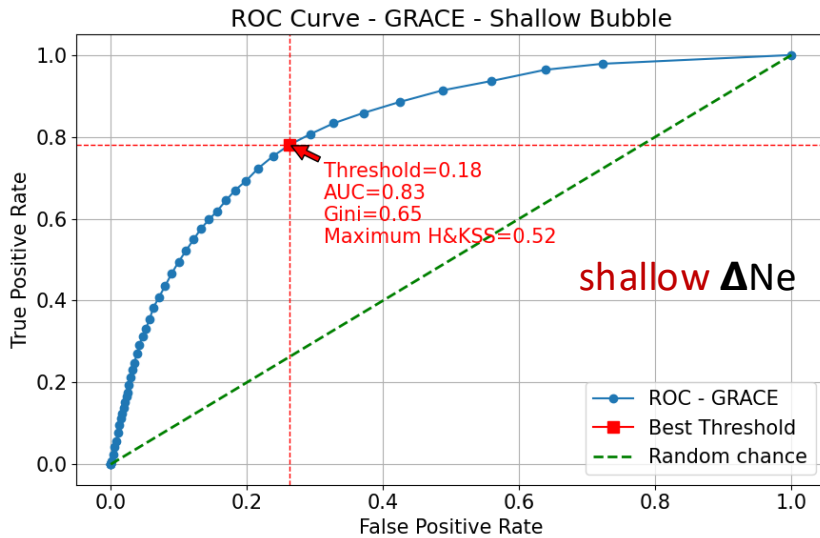


## Model based on $\Delta\text{Ne}$ :

GC ( $\Delta\text{Ne} < 2 \cdot 10^5 \text{cm}^{-3}$ ) = 0.65  
Threshold = 18 %

GC ( $\Delta\text{Ne} > 2 \cdot 10^5 \text{cm}^{-3}$ ) = 0.86  
Threshold = 31 %

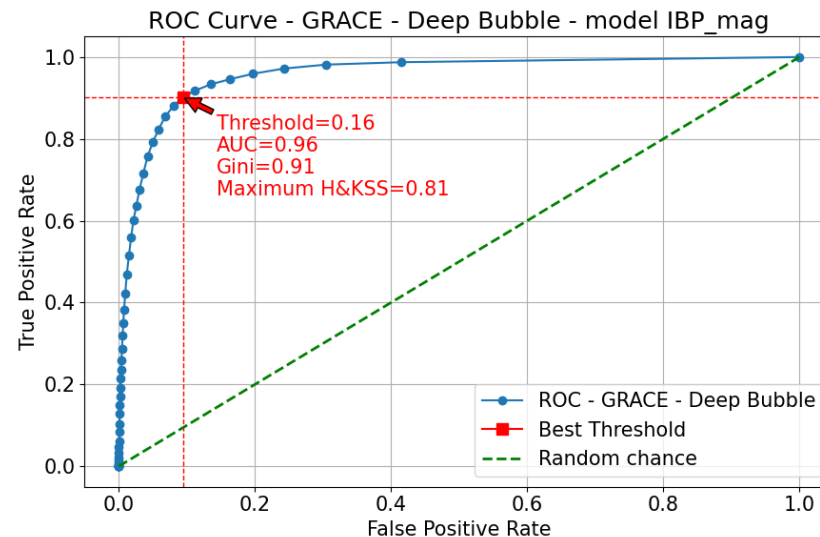
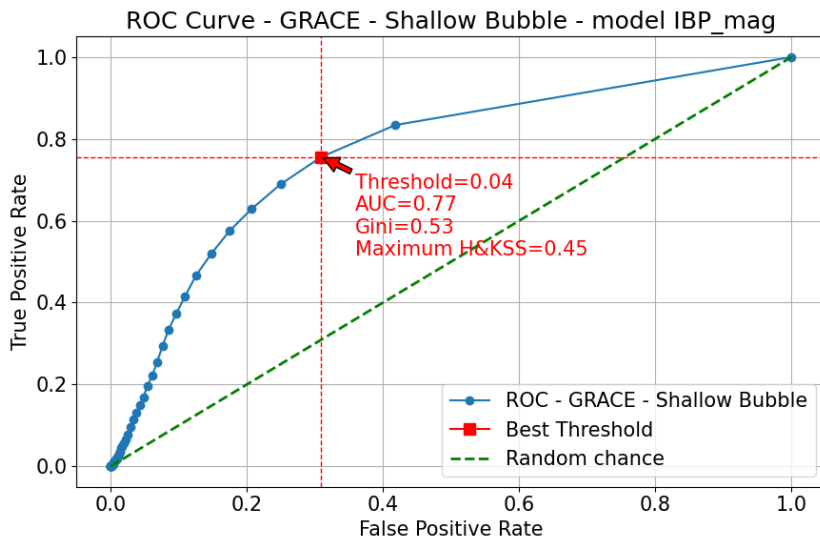
# Model validation against GRACE Ne



## Model based on $\Delta Ne$ :

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GC ( $\Delta Ne > 2 \cdot 10^5 \text{cm}^{-3}$ ) = 0.86  
Threshold = 31 %



## Model based on $\Delta B$ :

GC ( $\Delta Ne < 2 \cdot 10^5 \text{cm}^{-3}$ ) = 0.53  
Threshold = 4 %

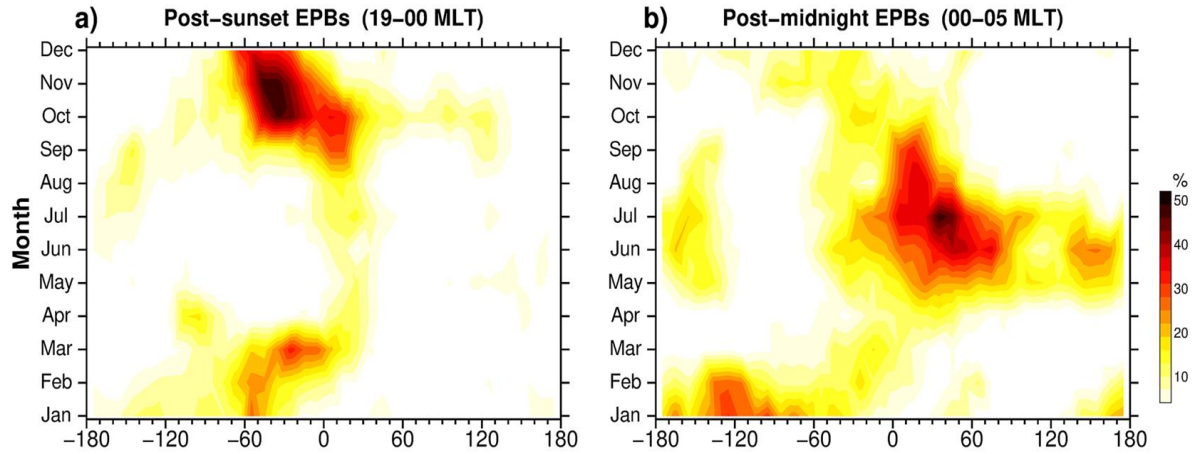
GC ( $\Delta Ne > 2 \cdot 10^5 \text{cm}^{-3}$ ) = 0.91  
Threshold = 16 %



# Modelling pre-midnight and post-midnight depletions

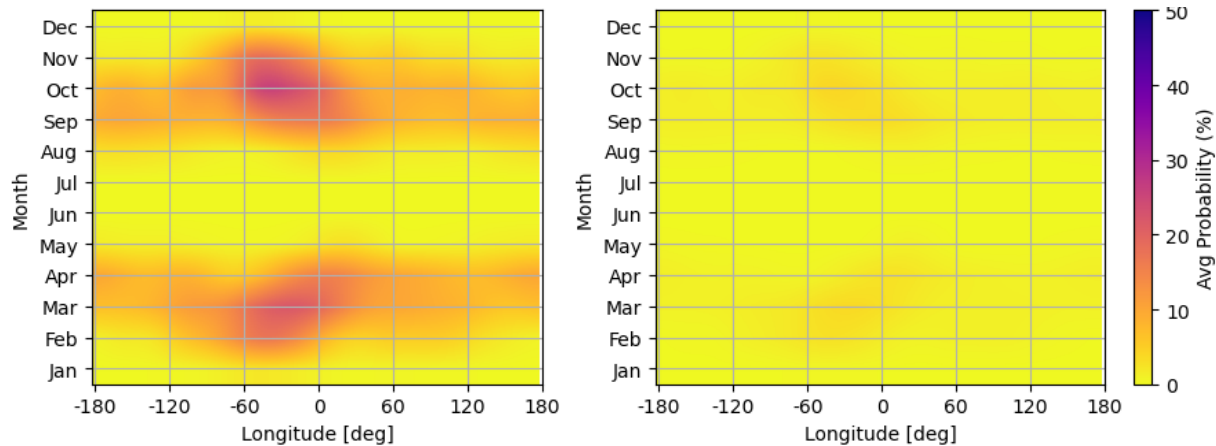
Zakharenkova et al., 2023; COSMIC-2 statistics, 2021

F10.7  $\approx$  75 sfu



Pre-midnight Swarm/CHAMP statistical model (IBI) Post-midnight

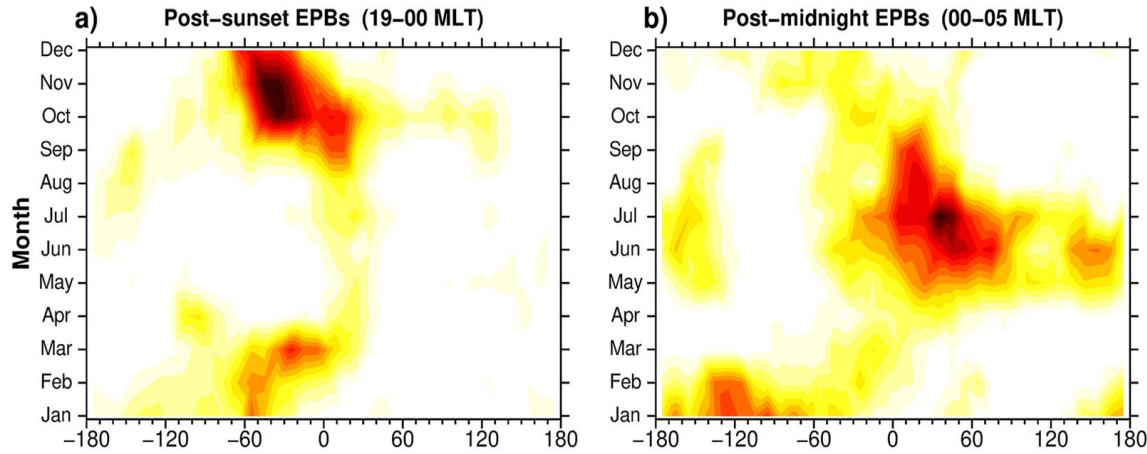
F10.7 = 80 sfu



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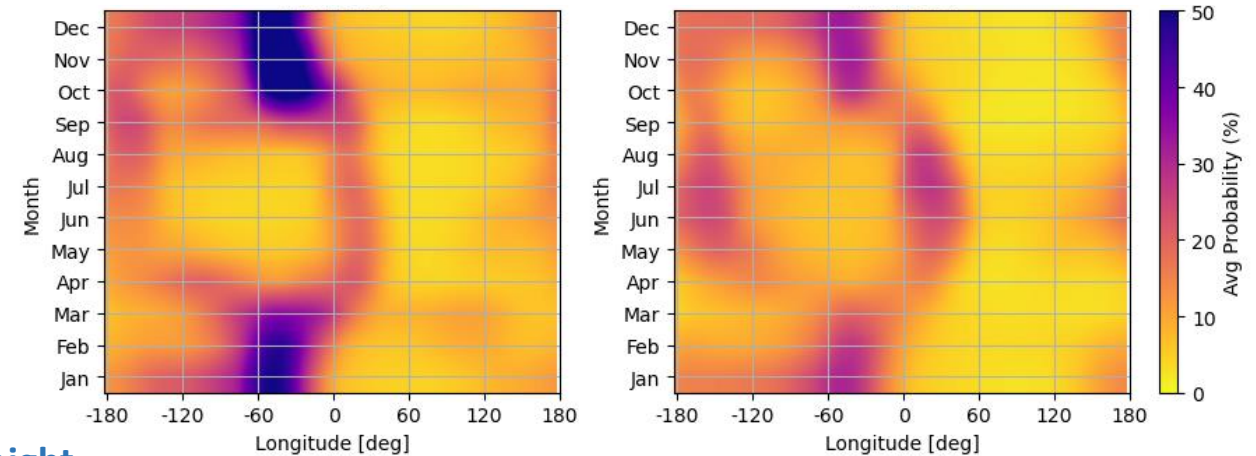
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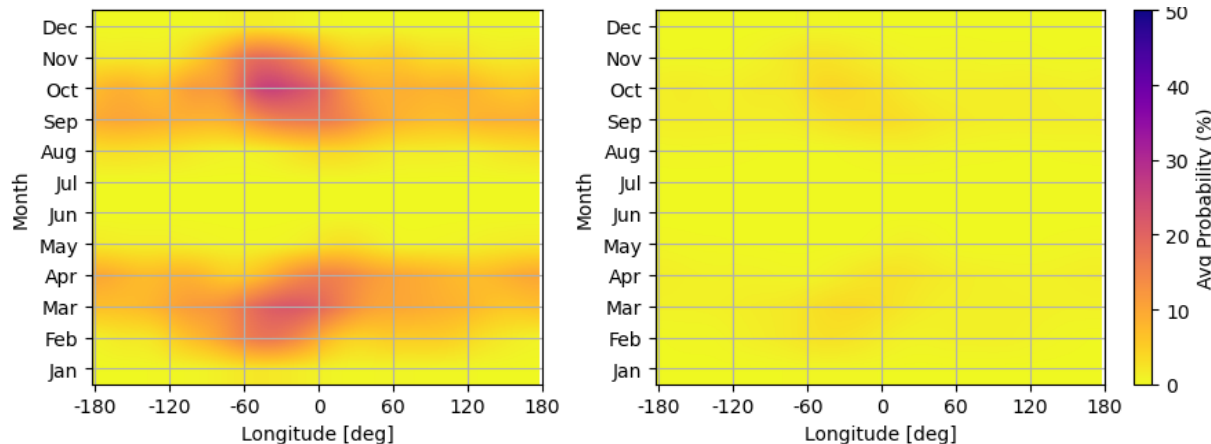
Pre-midnight Swarm Ne ML model Post-midnight

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Pre-midnight Swarm/CHAMP statistical model (IBI) Post-midnight

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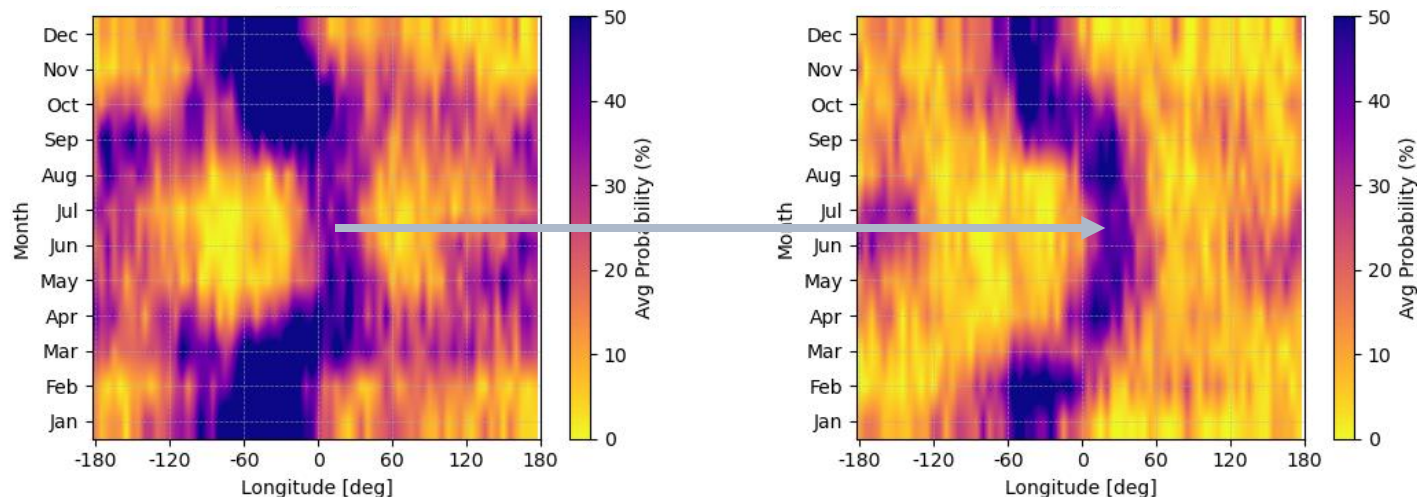


The new more sensitive ML model based on 11 years of Swarm electron density data also reproduces:

- post-midnight irregularities
  - during June solstice months
  - at African sector
  - at low solar flux levels

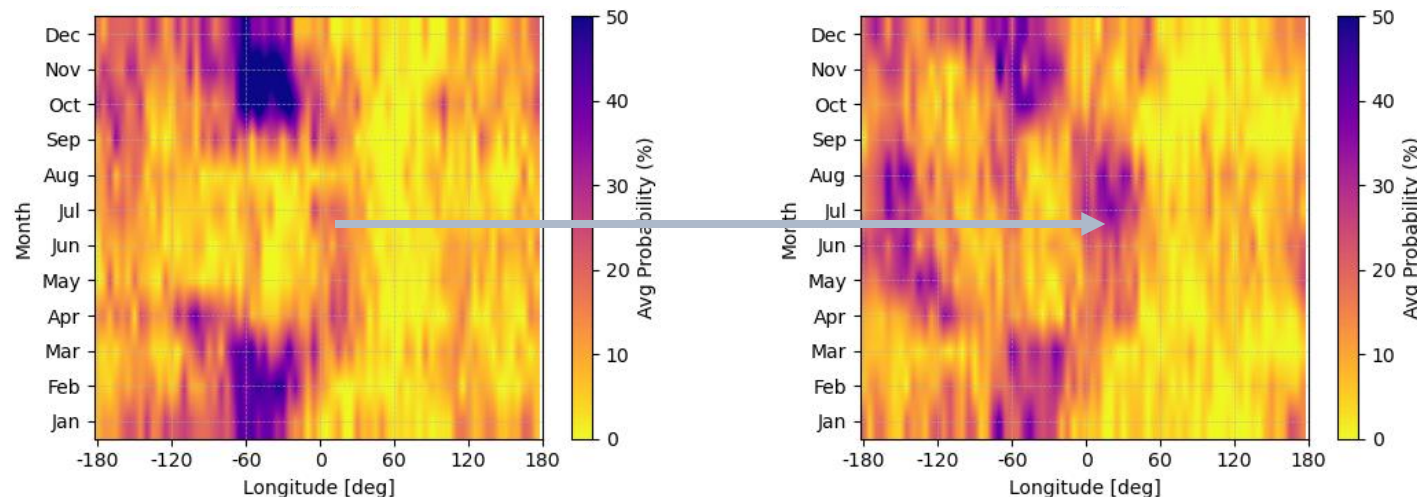
# Pre-midnight and post-midnight depletions

Pre-midnight    Swarm statistics  $F_{10.7} > 80$  sfu    Post-midnight



- Occurrence of depletions increases over Africa at post-midnight in June
- Also during moderate/high solar flux levels
- June maximum is more isolated during low solar flux

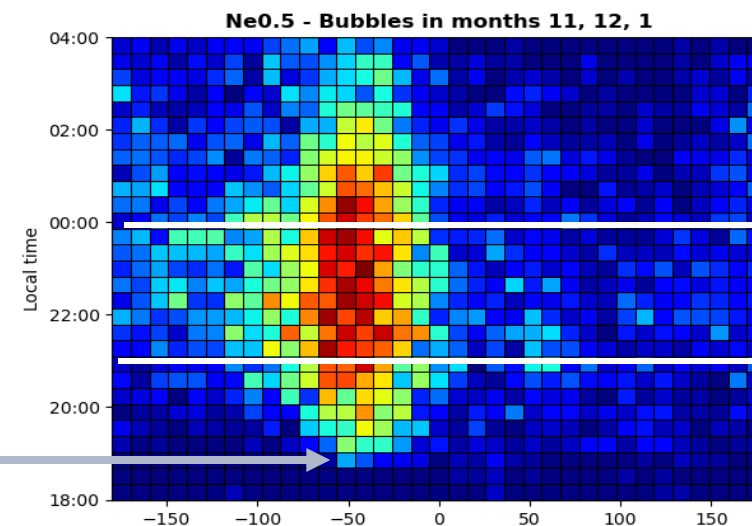
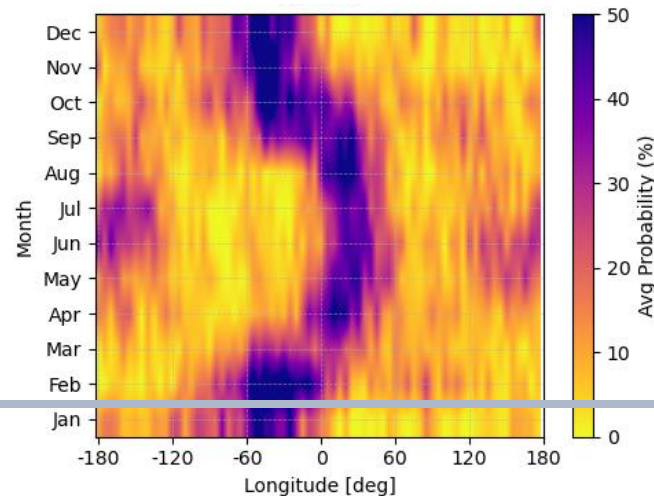
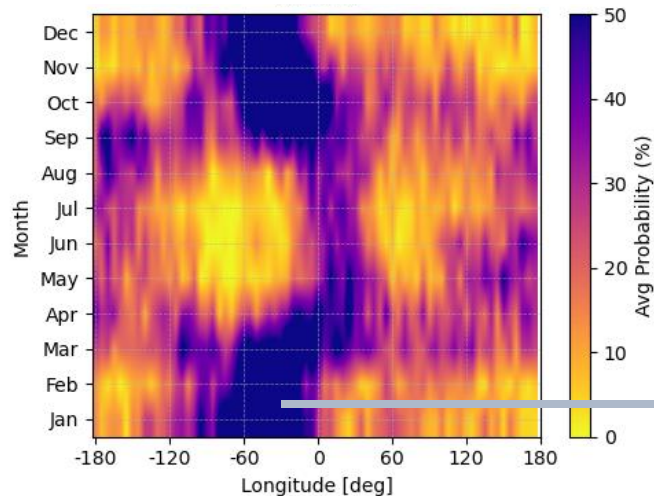
Pre-midnight    Swarm statistics  $F_{10.7} \leq 80$  sfu    Post-midnight



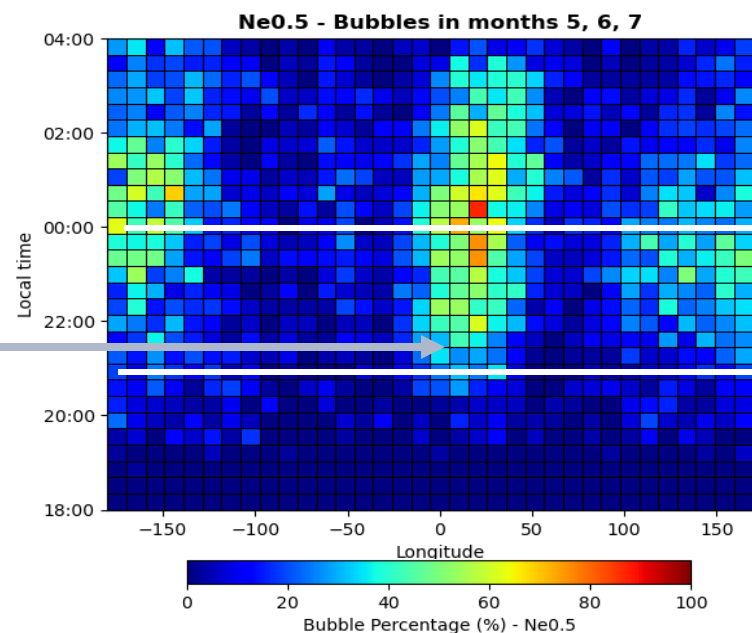
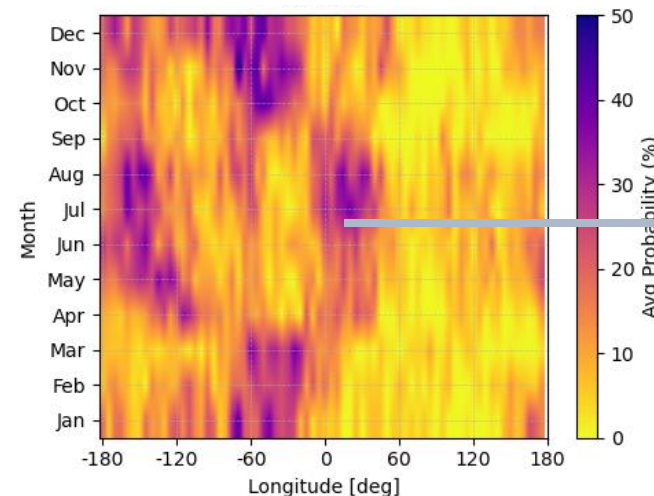
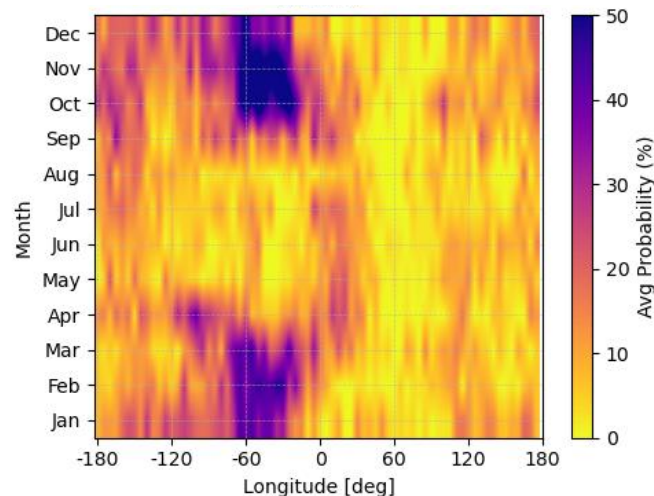


# Pre-midnight and post-midnight depletions

Pre-midnight Swarm statistics  $F10.7 > 80$  sfu Post-midnight



Pre-midnight Swarm statistics  $F10.7 \leq 80$  sfu Post-midnight



# Summary

- **Conclusion:** 11+years of Swarm magnetic and plasma density data
  - enable **representative** empirical models of equatorial plasma irregularities
  - model predictions **consistent** with independent data from other missions
- **Published:** Statistical model based on **magnetic** data
  - Compares well with ground-based GNSS scintillations
- **Newly developed:** ML model based on **p-density** data
  - Also sensitive to shallower post-midnight irregularities
- **Next steps:**
  - Test ability of new ML model to compare with (ground-based) GNSS scintillations
  - Publish new ML model and provide it publicly available

