

# Leveraging GNSS Radio Occultation for Enhanced Ionospheric Monitoring and Space Weather Preparedness

d cc c D l aD c l c  
d lac l d ac c rftc c r l  
ac c rftc c ar l c rc  
R c r l d l l l l c

• ac c rftc c r l



# Outline

- r l ar l
- ac c rftc co c c r l l ftc c
- l l ftc a r l ac
- c ac c rftc r rc
- l l ftc a r l ar
- l a l

# Space Weather is a National Priority

- **Space weather is a national priority because of its effects on our society and economy.**
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- **Space weather is a national priority because of its effects on our society and economy.**
- **Enhanced space weather decision support is a national imperative.**



**Weather, Water, and  
Climate Strategy**  
FY 2023-2027



# NOAA's Space Weather Charter

- **Building capacity to advance space weather policy**

ac r l                    c c r r l l d r l                    ac c r f t c r r c                    ar l  
D l l r    c c a f t                    c r l l d    ac c r f t c r l                    l c r f t c D l c a r  
l d l l l                    ar

- **Accelerating growth in NOAA and its space weather services**

c r d                    r d                    c r l c r l r l                    l r l c r l  
l c r c a a r c                    c c r l c                    d c a r l ar  
r l a c r d a                    r c a f t l l a                    ac r l l c r l  
l r l                    r c c a r l ar r c r l d r                    r c a f t l l                    l c c  
c c ac                    l ar

- **Integrating approach and collaboration between research and operations**



# Space Weather Requirements: Ionosphere

NOAA NESDIS



NESDIS-REQ-4500.3

WEATHER NEXT PROGRAM OBJECTIVES

July 2023

SPACE 1

Table 18: Ionospheric Electron Density Profiles Observational Parameters

Observation Component	Threshold	Objective
Observational Extent	90–1500 km	
Vertical Resolution	10 km	1.5 km
Measurement Range	Ne: $10^{10}$ – $10^{13}$ electrons $m^{-3}$	
Measurement Uncertainty	Ne: Less than $\pm$ max ( $3 \times 10^{10} m^{-3}$ , 10%)	
Quantity of Global profiles per day	12,000	50,000
Median Data Latency	60 min	5 min

Table 19: Total Electron Content Observational Parameters

Observation Component	Threshold	Objective
Observational Extent	90–1500 km	
Measurement Range	1–200 TEC Units vertical equivalent	
Measurement Uncertainty	3 TECU	
Refresh Rate Quantity of Global profiles per day	12,000 observations $day^{-1}$	50,000 observations $day^{-1}$
Median Data Latency	60 min	5 min

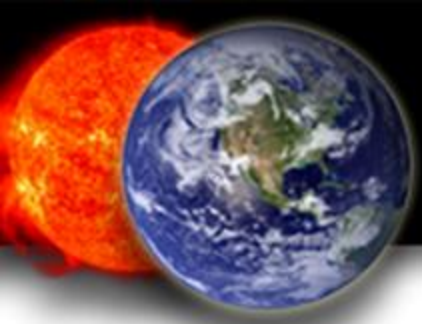


U.S. Department of Commerce  
National Oceanic and Atmospheric Administration (NOAA)  
National Environmental Satellite, Data, and Information Service (NESDIS)



Prepared by:  
U.S. Department of  
National Oceanic and  
Atmospheric Administration  
National Environmental





# Radio Occultation (RO)

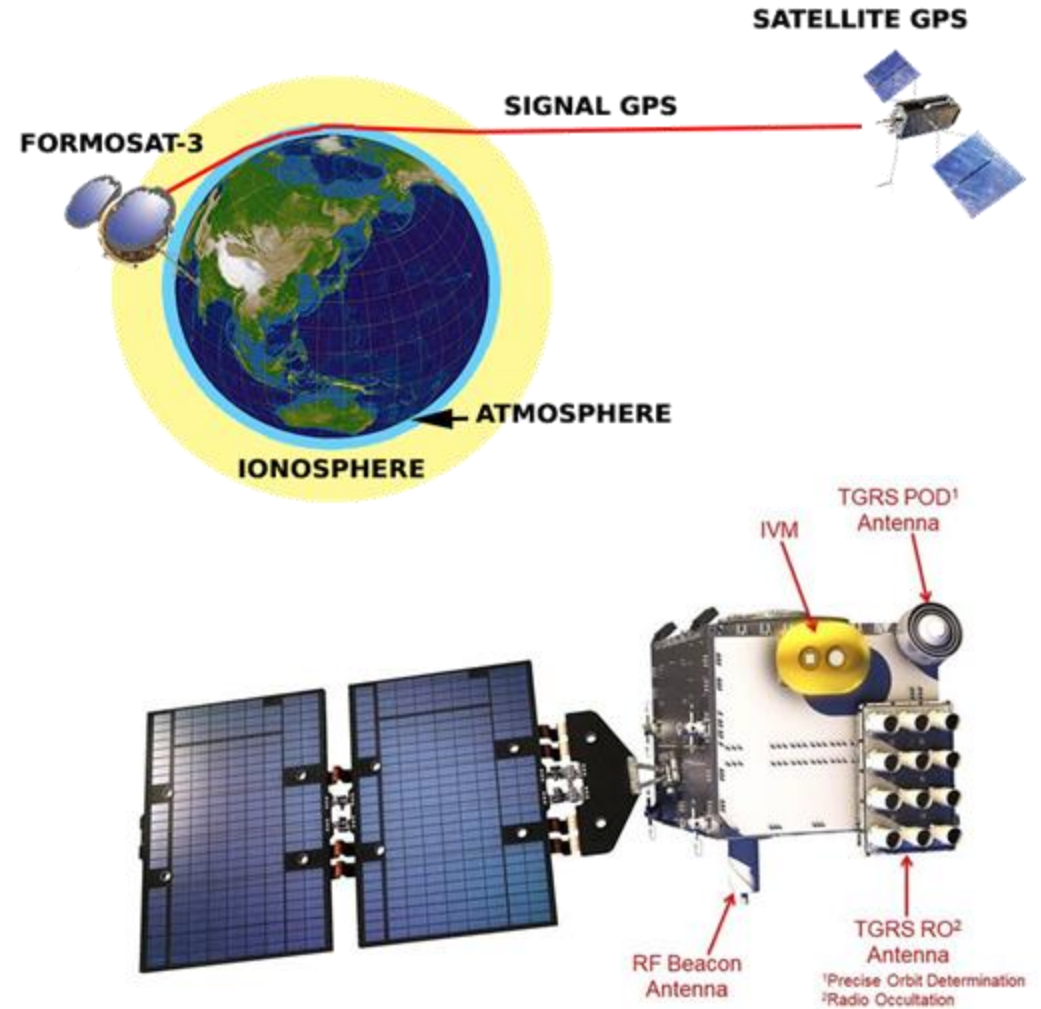
Satellite missions with RO capability:

all  
 D  
 FORMOSAT-7/COSMIC-2

ac r  
 c r c aft c D c aft  
 c | | | cr rc rc

Spire LEMUR cubesats

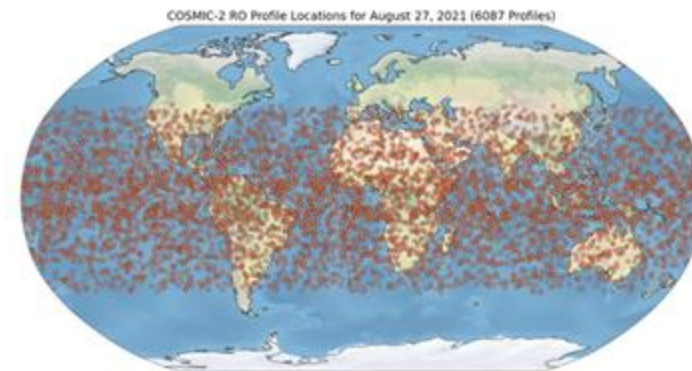
PlanetIQ GNOMES microsats



# RO Constellations and Data

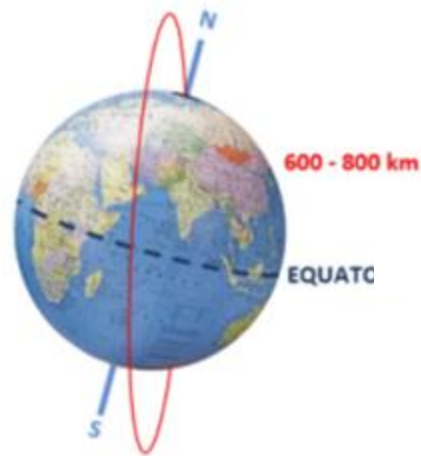
- **FORMOSAT-7/COSMIC-2**

- aftc c d l c r l a r l
- arl c cr
- c lrc c r
- r

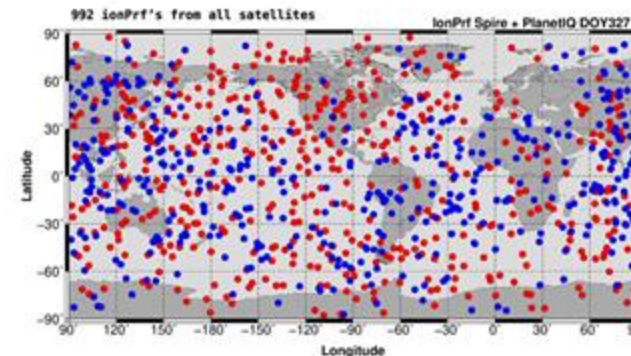


- **Spire LEMUR**
- **PlanetIQ GNOMES**

- 
- r



SUN-SYNCHRONOUS ORBIT (SSO)



PlanetIQ Spire



# Ground Receiver Data

- **Ground GNSS networks - Geodetic:**

- ca l ca rc
- ll o r rc c ac r rft
- ll ft c r
- l c l rl
- r l D c c c r
- ll

- **Ground GNSS networks - Scintillation:**

- rc
- a c c r rl
- c rc o r
- cac c a a rc cra!
- l c l a rl o r



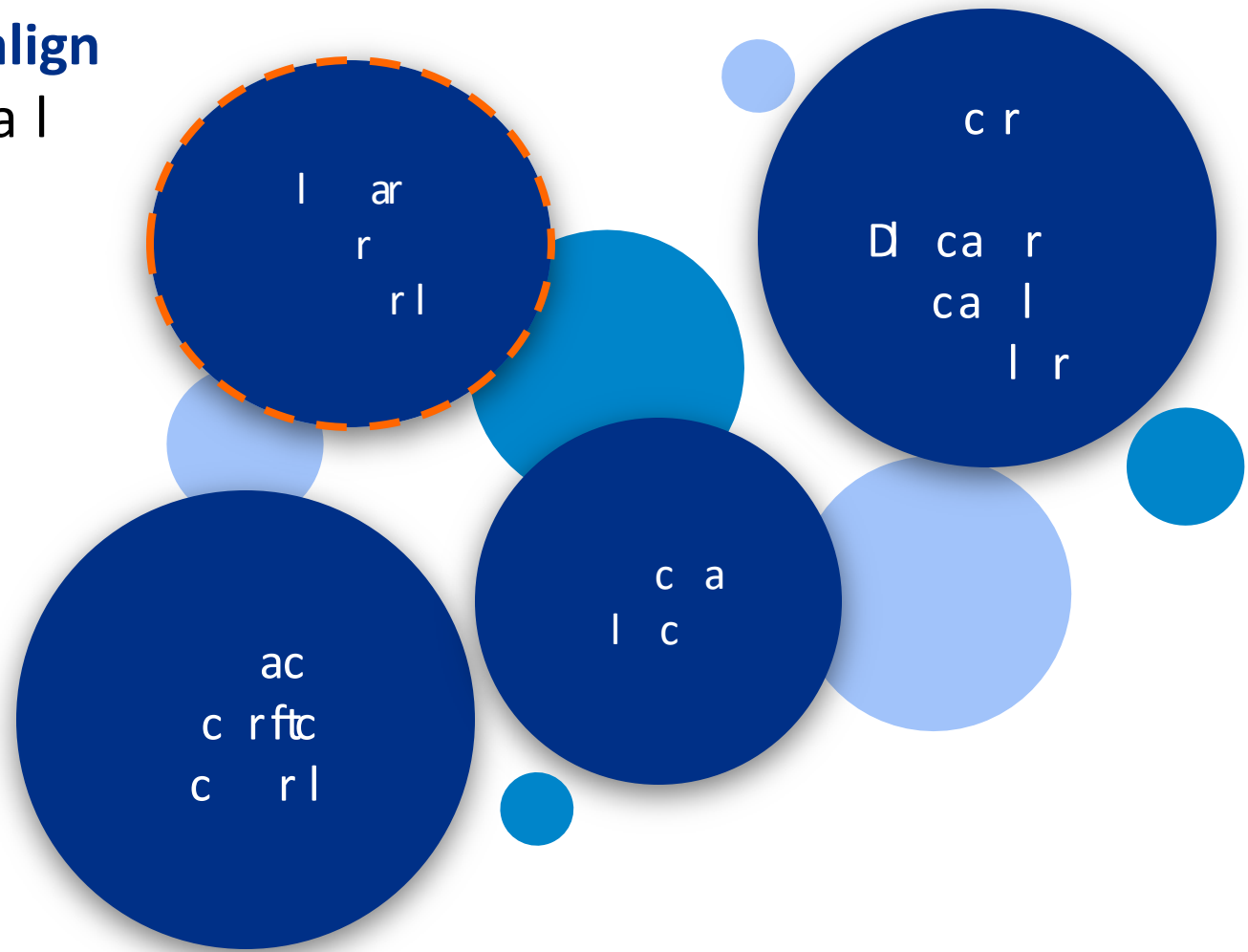
IGS Stations, 2019



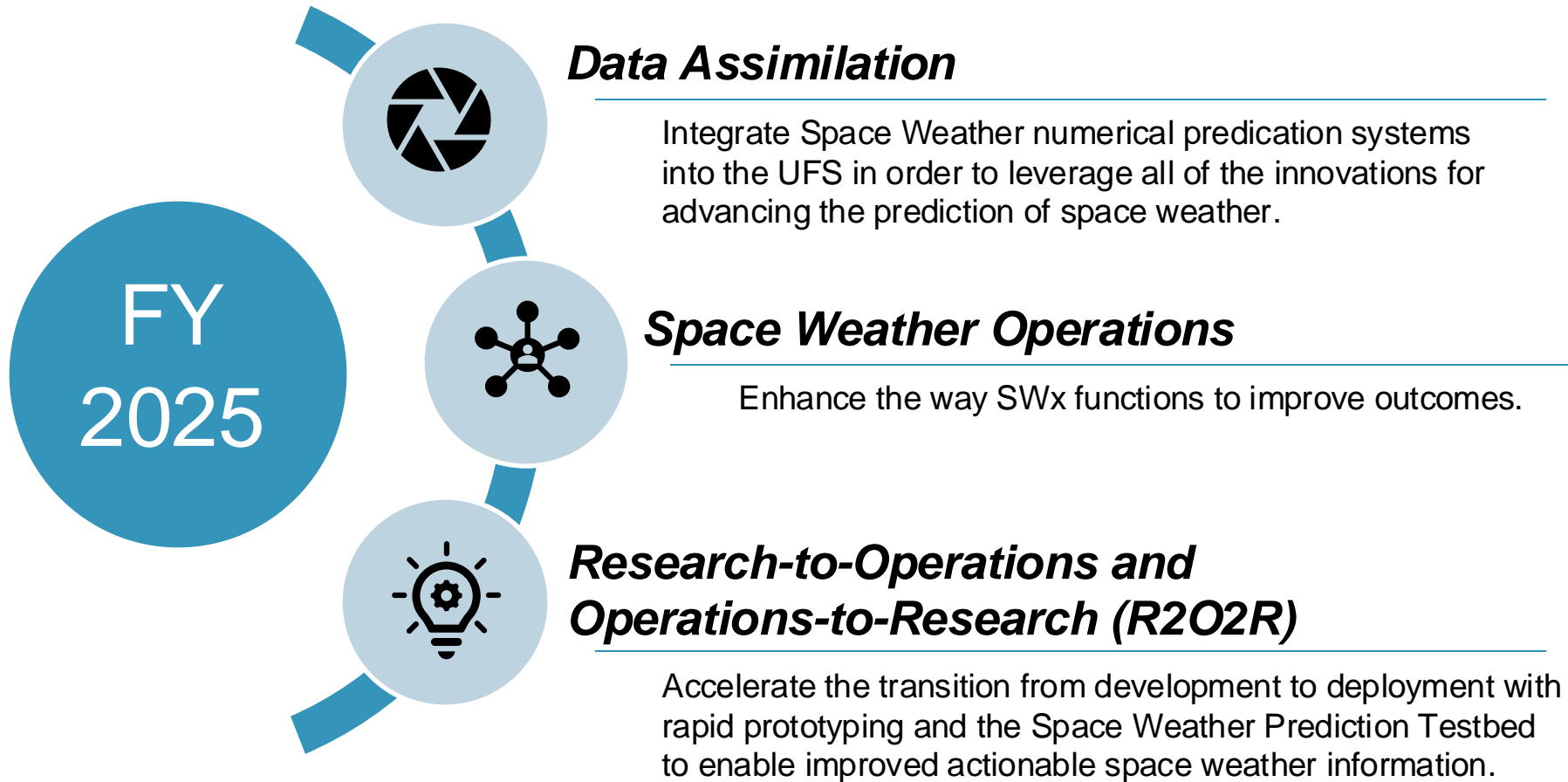


# Advancing the NOAA Space Weather Enterprise

- c ac c rftc r rc rl align  
priorities build connective tissue a l  
c l d lac
  - 
  - 
  -

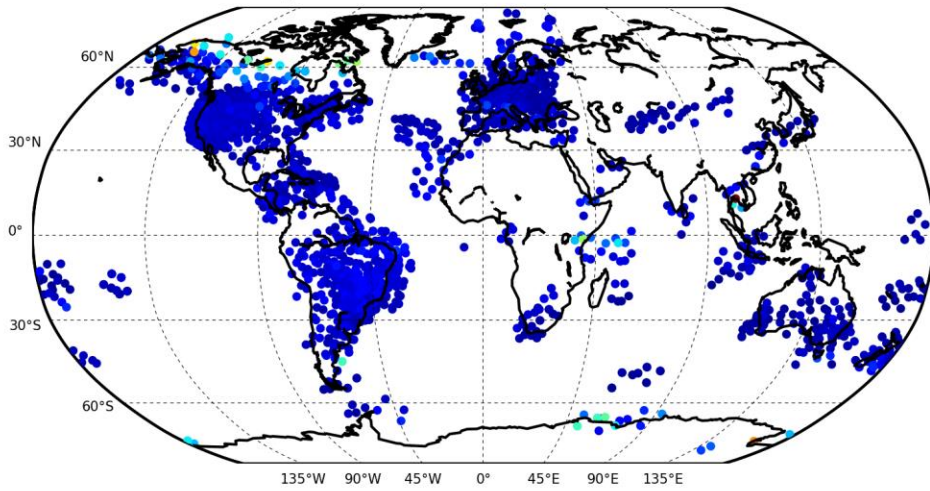


# The Current Focus is on Three One-NOAA SWx Priorities

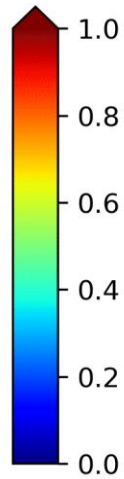


# Rate of TEC Index (ROTI)

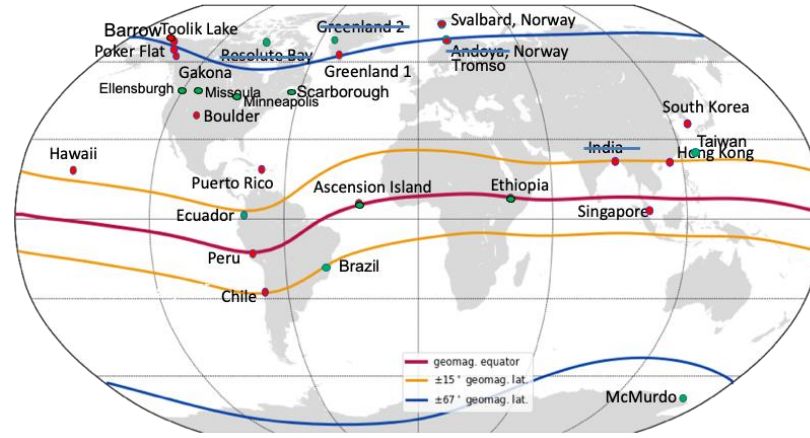
Ground based ROTI  
10-May-2024 from 17:00 to 17:10 UT



ROTI to S4



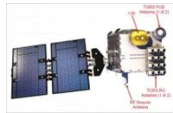
# Real-time GNSS Scintillation Receivers



J. Morton



# COSMIC-2 and Commercial Scintillation Products

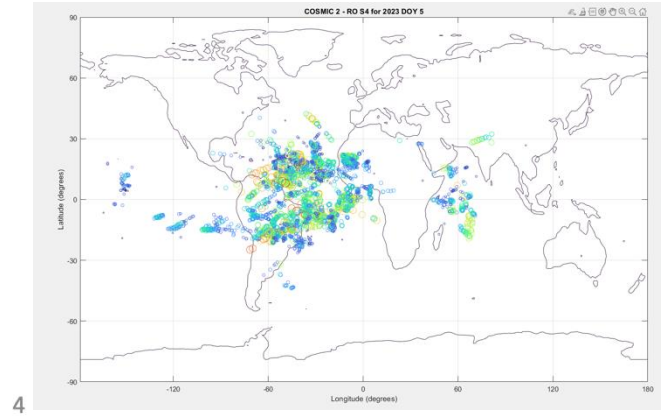


## All-Clear

COSMIC-2 All Clear Product Map - 2021/03/11 (070) 12:00 UT

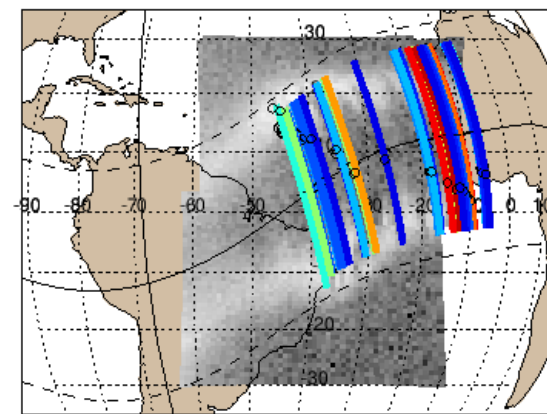


## Geolocation



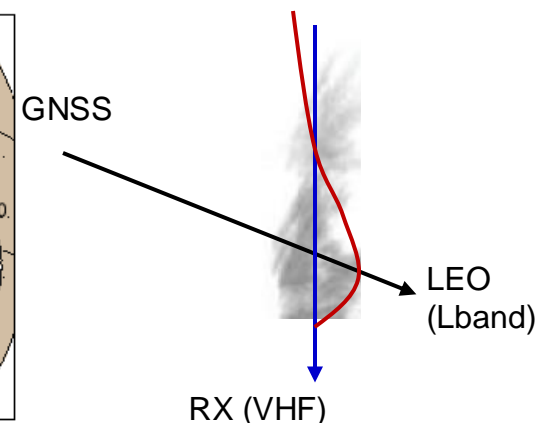
## Bubble Map

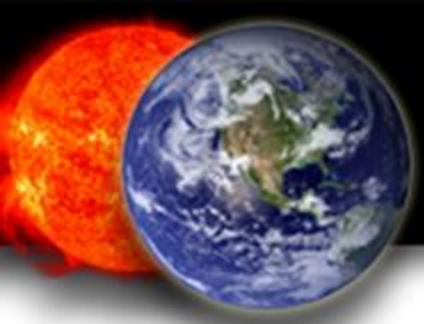
TGRS Bubble Map 2021 Day 068, 22:30 - 23:00 UT



## Limb to Disk Zenith

Zenith





# GNSS PNT and Satellite Communication

## GloTEC (nowcast)

Global 3D **electron density** data assimilation

Gauss-Markov **Kalman filter** - GMRES solver

a | l | c

Real-time **ground-based GNSS** observations

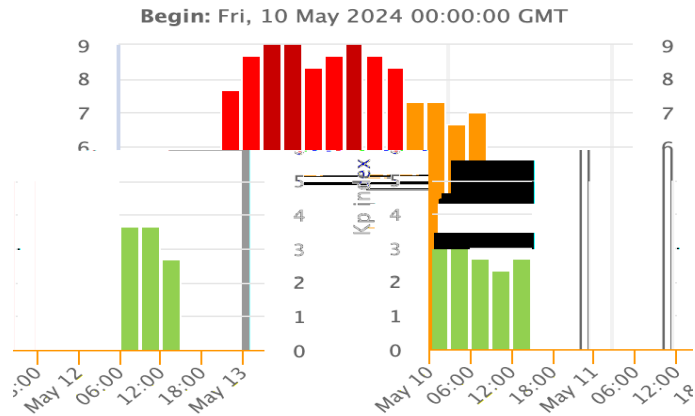
R

| c

**Space-based GNSS observations (RO)**

<https://www.swpc.noaa.gov/experimental/glotec>

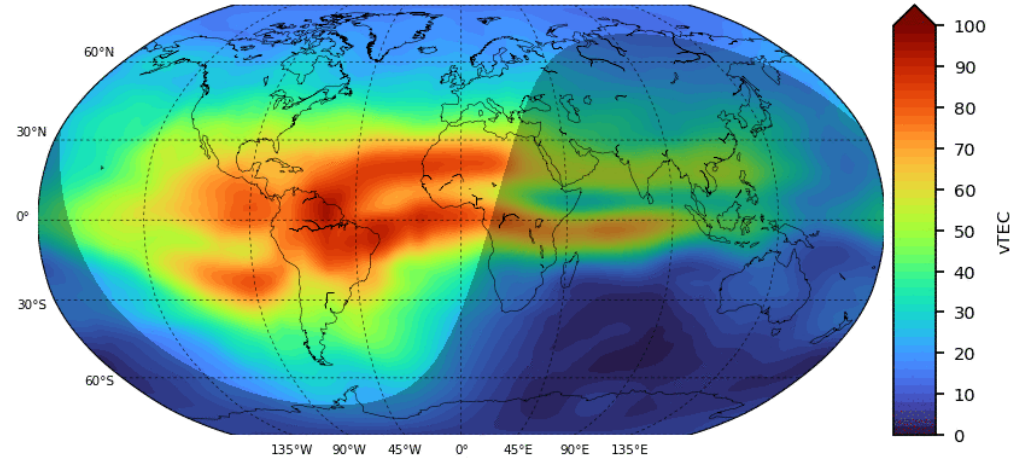
Estimated Planetary K index (3 hour data)



Time  
her Prediction Center

Univers:  
Space Weat

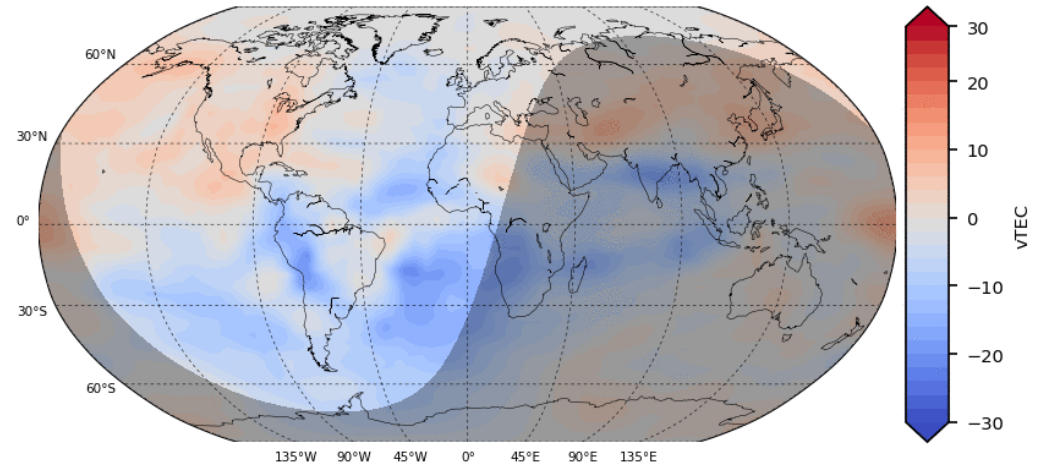
Global Total Electron Content ( $10^{16} * m^{-2}$ )



2024-05-10 from 17:00Z to 17:10Z

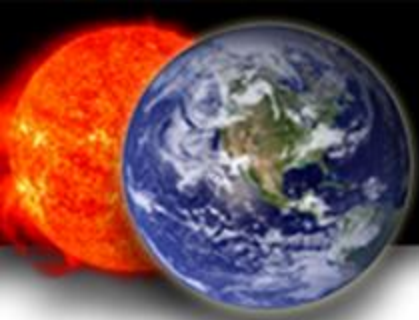
NOAA/SWPC Boulder, CO USA

TEC Difference from 30-Day Median ( $10^{16} * m^{-2}$ )



2024-05-10 from 17:00Z to 17:10Z

NOAA/SWPC Boulder, CO USA



# GloTEC Ray Segments

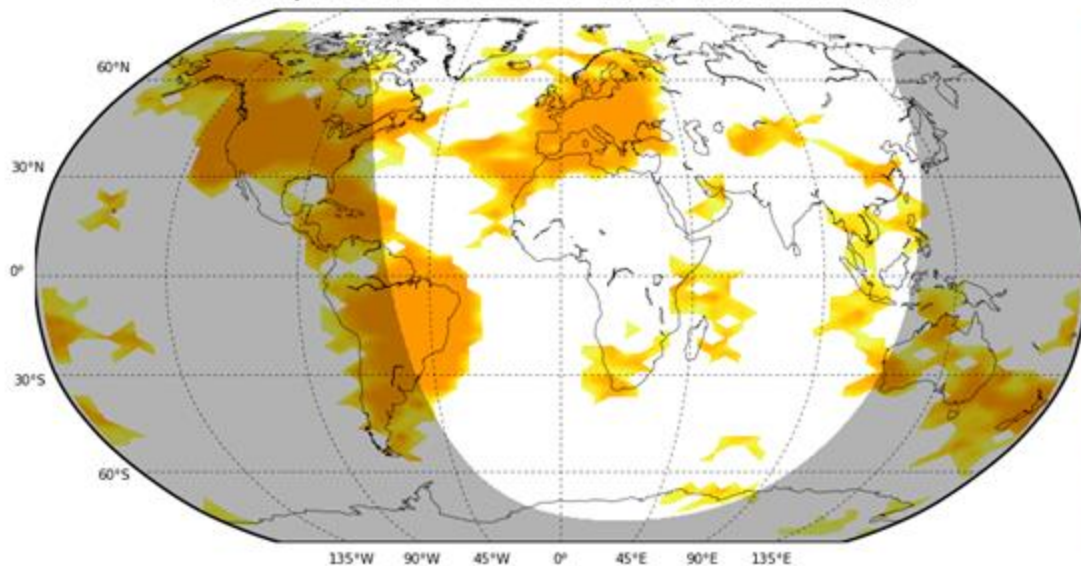
l r l c r l r f t c D c l l c !

c r r d a r l c D c l r f t c r !

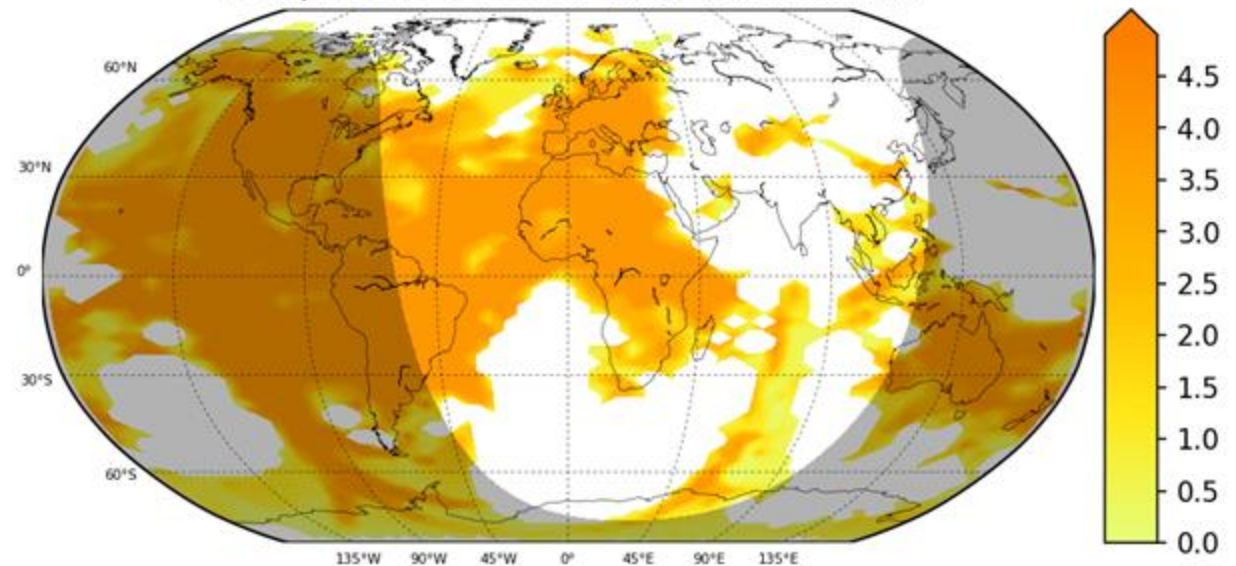
**A)** l r r l l

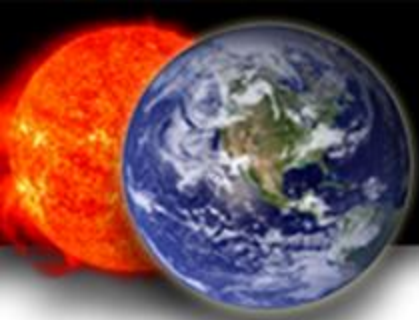
**B)** l c l r r l

Global RAY  
23-Apr-2023 09:55 UT Max: nan Min: nan



Global RAY  
23-Apr-2023 09:55 UT Max: nan Min: nan





# GIOTECH VTEC

l a c r d l  
f t c a l l c

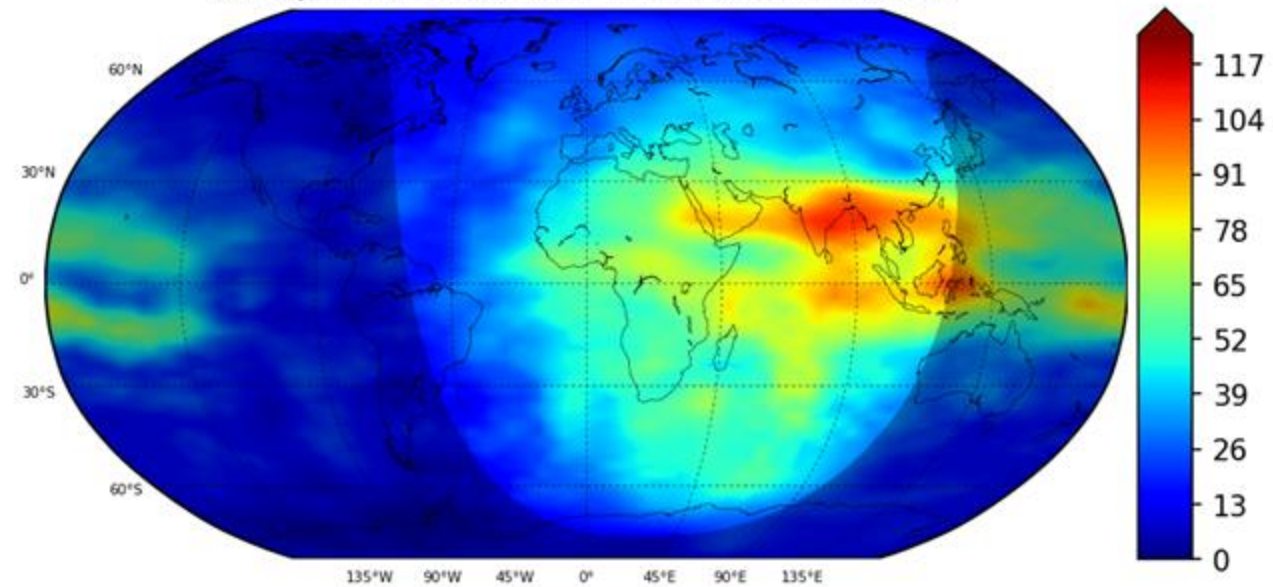
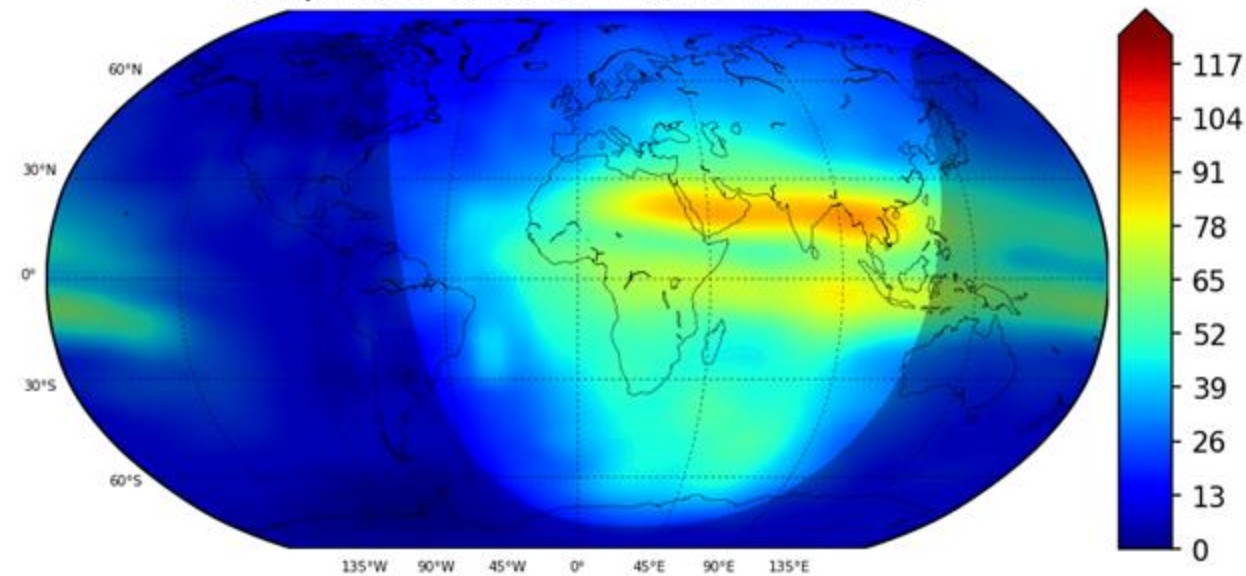
l c c d l l c r l !  
c r f t c r c D !!

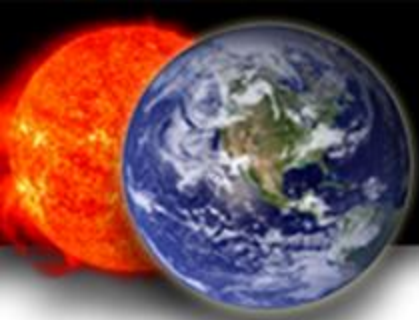
A) l r r l l

B) l c l r r l

Global TEC ( $10^{16} \text{m}^{-2}$ )  
23-Apr-2023 09:55 UT Max: 94.4 Min: 4.9

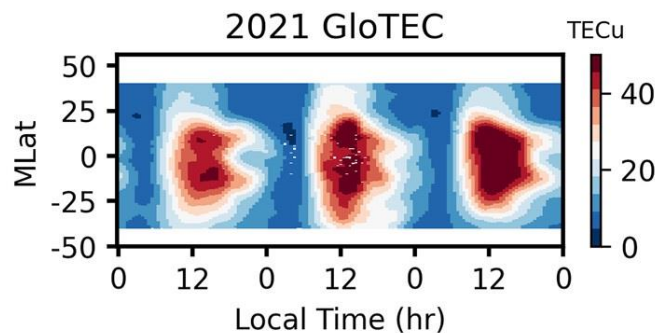
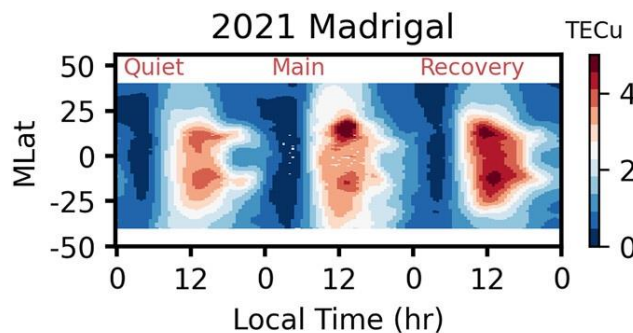
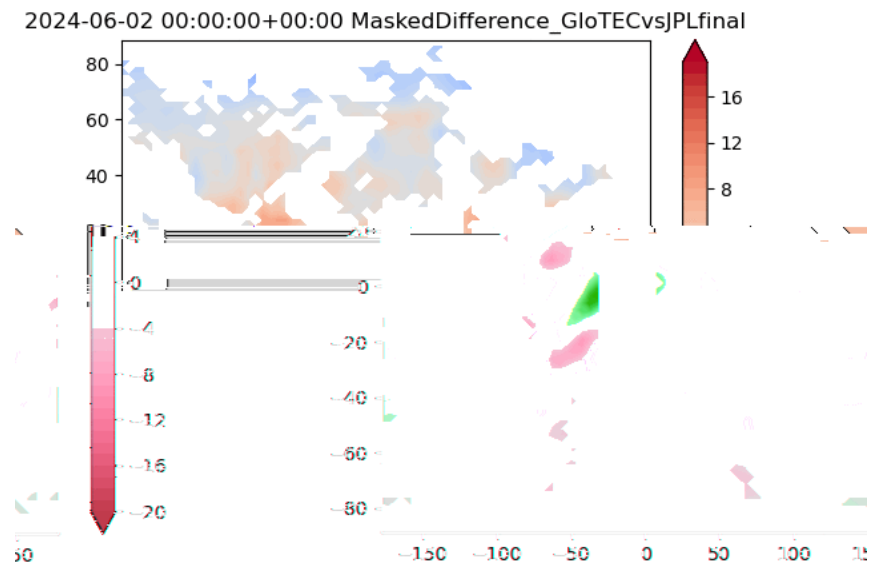
Global TEC ( $10^{16} \text{m}^{-2}$ )  
23-Apr-2023 09:55 UT Max: 108.8 Min: 3.3





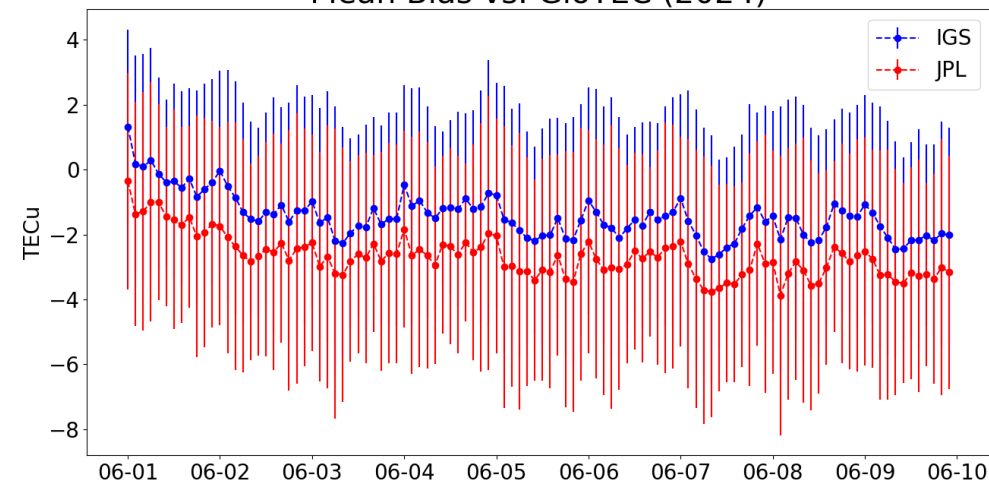
# GloTEC TEC Bias Assessment

/ l c c d ac rftc rl c l ft c cc  
 c l c rc ftl cr ! !  
 / l c l c r rfrftc l r r dl H  
 r l a r l ftc c l  
 ft r al c c cr ftc r c rc rl  
 rl ra c rc l c c d ac l c rl  
 crr !



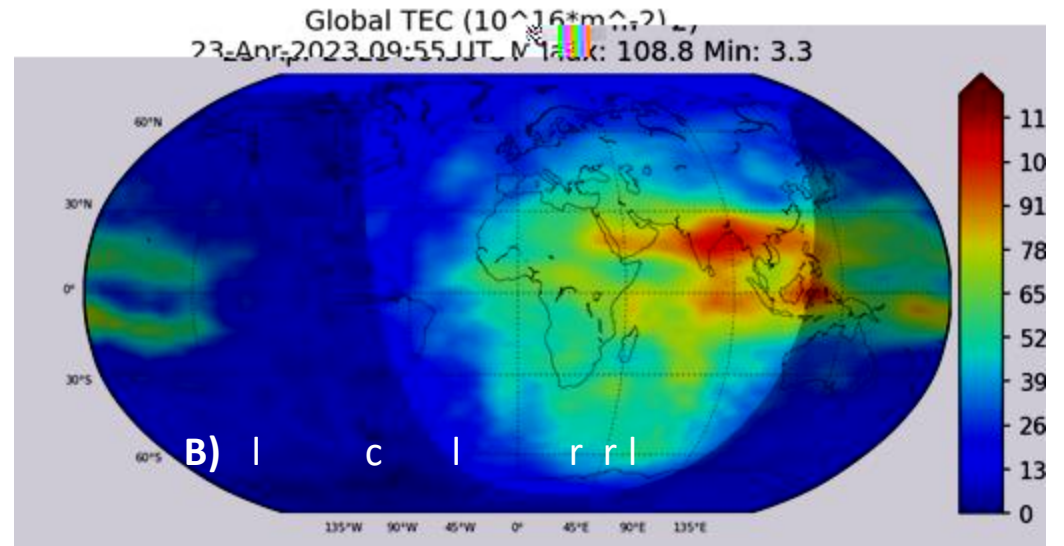
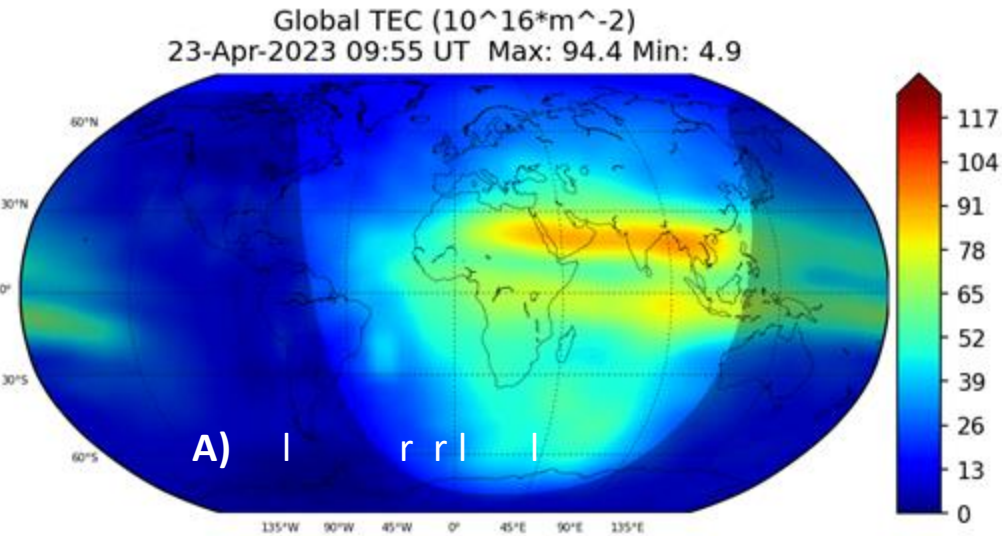
Chou et al. (2023)

Mean Bias vs. GloTEC (2024)



# Conclusions

- ac c rftc r r c !
- r c cc c rl aa rc c crl ftc c l l ftc c rftc l ftc c  
l c a r crftc rl rc l r l drftc rc rft co c  
d c r !



- cac r r c ft c ft rftc cc d l l c r l rc rl l c  
c ar l