Solar Cycle Variations of D/E-region Electron Density (Ne) and Sporadic-E (Es) from GPSRO

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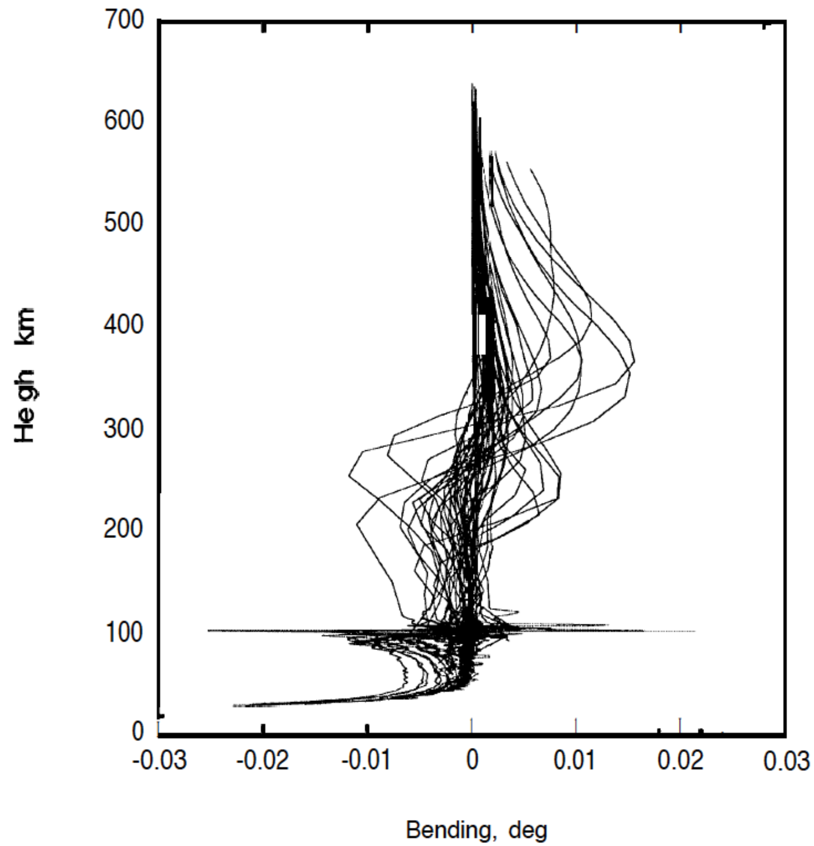
Motivations

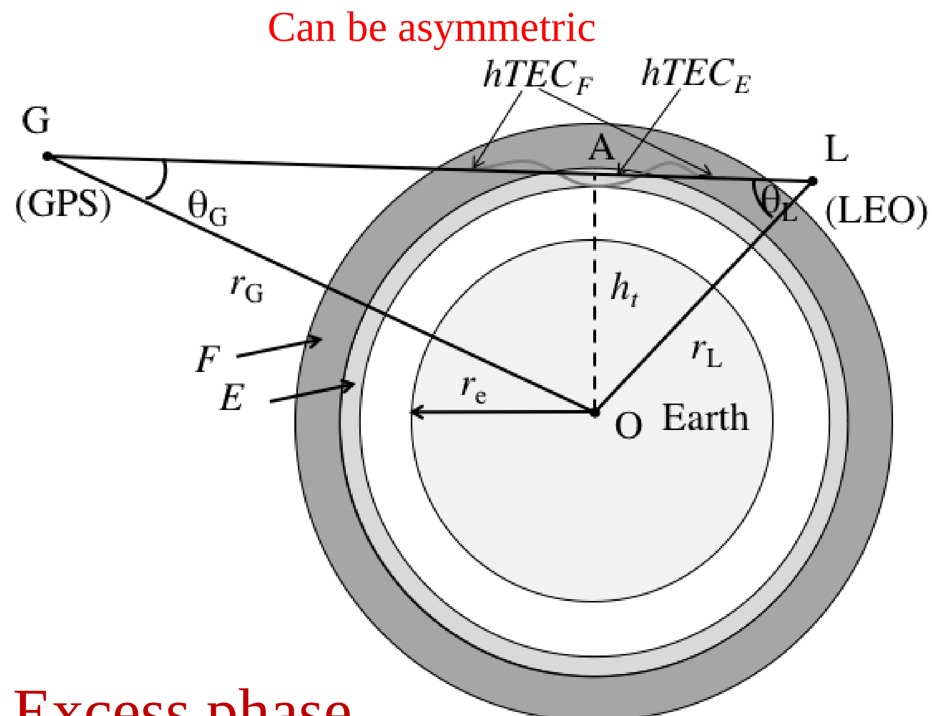
1. Impacts of solar (e.g., photochemical processes) and dynamical (e.g., tidal waves) forcings on observed ionospheric E/D region electron density (Ne) and sporadic-E (Es):
   - ❑ Consistent variations of background Ne between GPSRO and ionosonde (*f*oE) observations
   - ❑ Inconsistent variations on Es observations

2. Impacts of ionospheric Ne and Es on neutral atmospheric retrievals and GPSRO climate records (not main focus in this presentation)

Challenges in Retrieving E-Region Ne with GPSRO

Hajj and Romans (1998)





- Excess phase

$$\tau_{ex} = \tau_{bend} - \tau_p$$

- From bending: τ_{bend}
- From phase advance in plasma: τ_p

Radio Wave Propagation in Plasma

Dispersion Relation $$\omega^2 = c^2k^2 + \omega_c^2$$

Critical Plasma Frequency $$\omega_c = 56.4 \cdot N_e^{1/2} \text{ rad/s}$$

Phase and Group Velocity $$v_p \equiv \omega/k,\ v_g \equiv d\omega/dk,$$

Phase and Group Refr Indices $$n_p \equiv c/v_p\ n_g \equiv c/v_g$$

Advance $$n_p = \sqrt{1-(f_c/f)^2} \approx 1 - 40.3 \cdot N_e/f^2$$

Delay $$n_g = 1/\sqrt{1-(f_c/f)^2} \approx 1 + 40.3 \cdot N_e/f^2$$

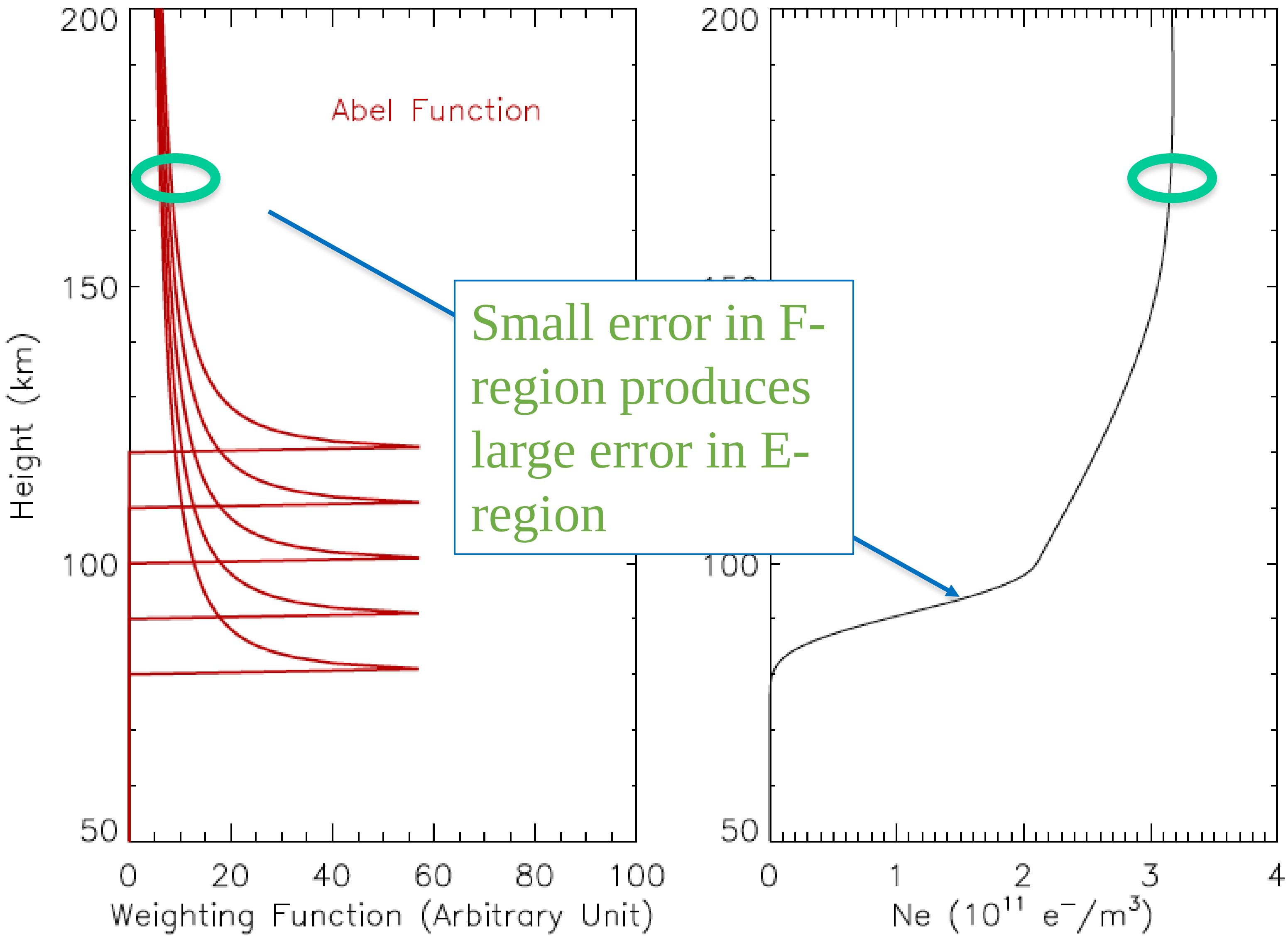
Higher-order terms neglected

Phase Delay from Bending $$\tau_{bend\_I}(\lambda_i, h_t) \propto 1/f_i^2$$

τ_{ex}(iono-free) = 2.5457 τ_{ex}(L1) - 1.5457 τ_{ex}(L2)

Delay due to F-region ionospheric bending is 1-2 m (Hoque and Jakowski, 2011)

Problems with the Abel Retrieval and Weighting Functions



Ne Retrieval from Phase Advance in τ_{ex}

Data:

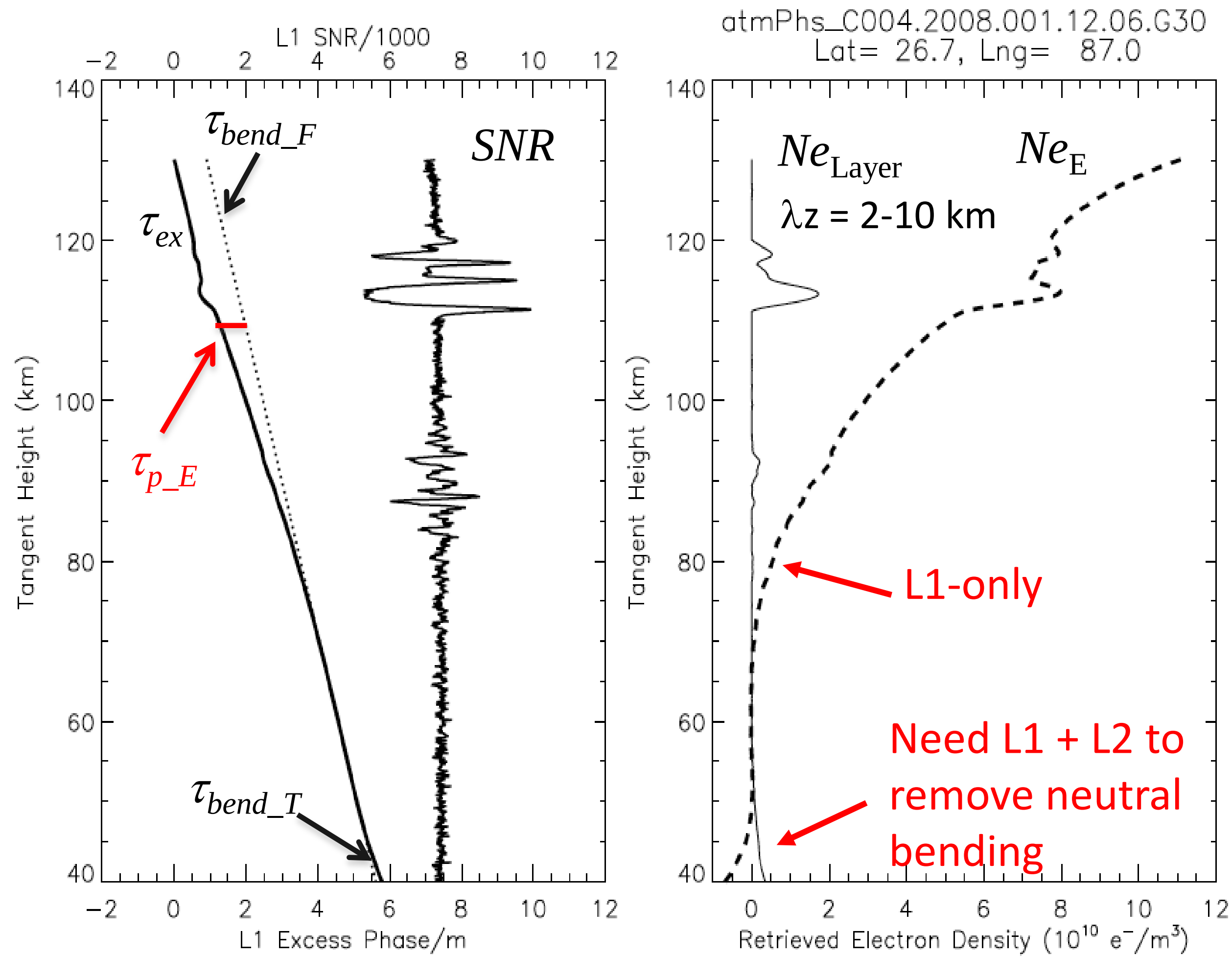
- L1 50-Hz profile τ_{ex}

Key Assumptions:

- Slowly-varying F-layer contributions
- Phase advance dominance from E-region Ne

Methods:

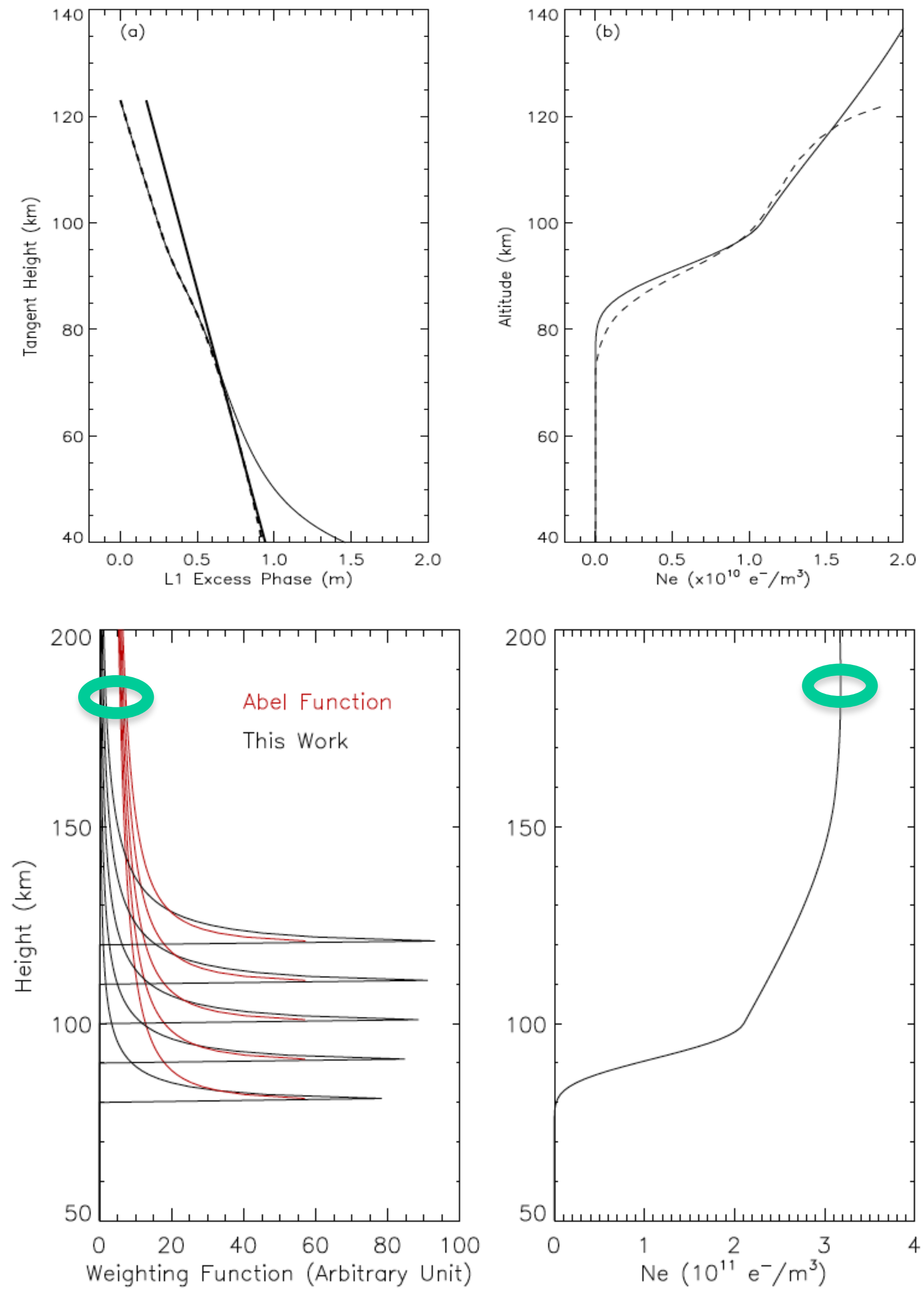
- Linear extrapolation of F-layer contributions for E-region Ne
- Bandpass filters for Es
  - Fluctuations: λz < 2 km
  - Layers: λz = 2-10 km
- L1 and L2 data for lower D-region Ne



Wu (JASTP, 2018)

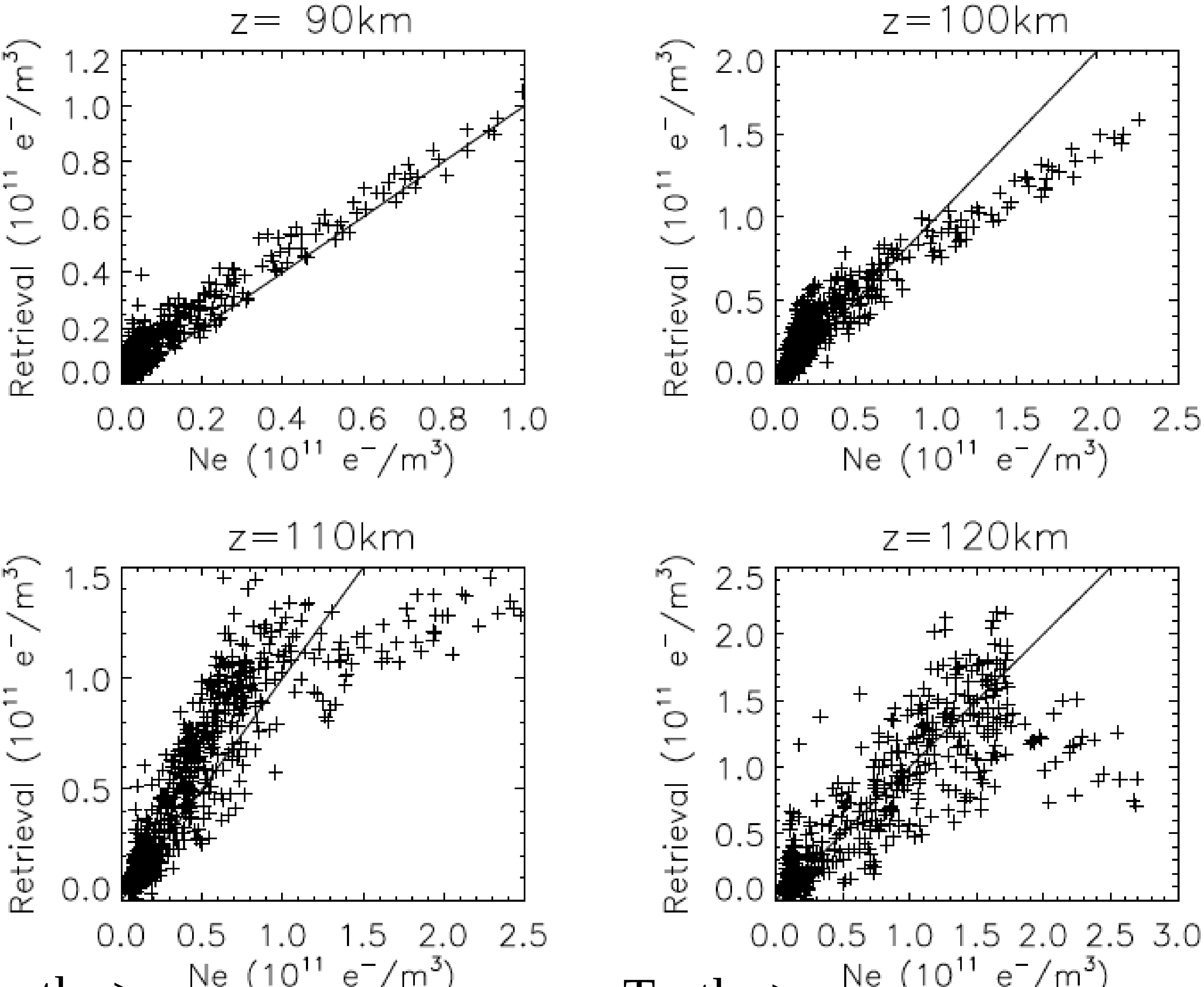
Ne Retrievals from Simulated Data (1/2)

- New method was applied to 920 UCAR-simulated profiles (courtesy of X. Yue).
- Bottom-up extrapolation works reliably for all simulated data.
- Much smaller F-region contributions are in the new weighting functions.
- Retrieved Ne profiles agree well with the truth.



Wu (JASTP, 2018)

Ne Retrievals from Simulated Data (2/2)

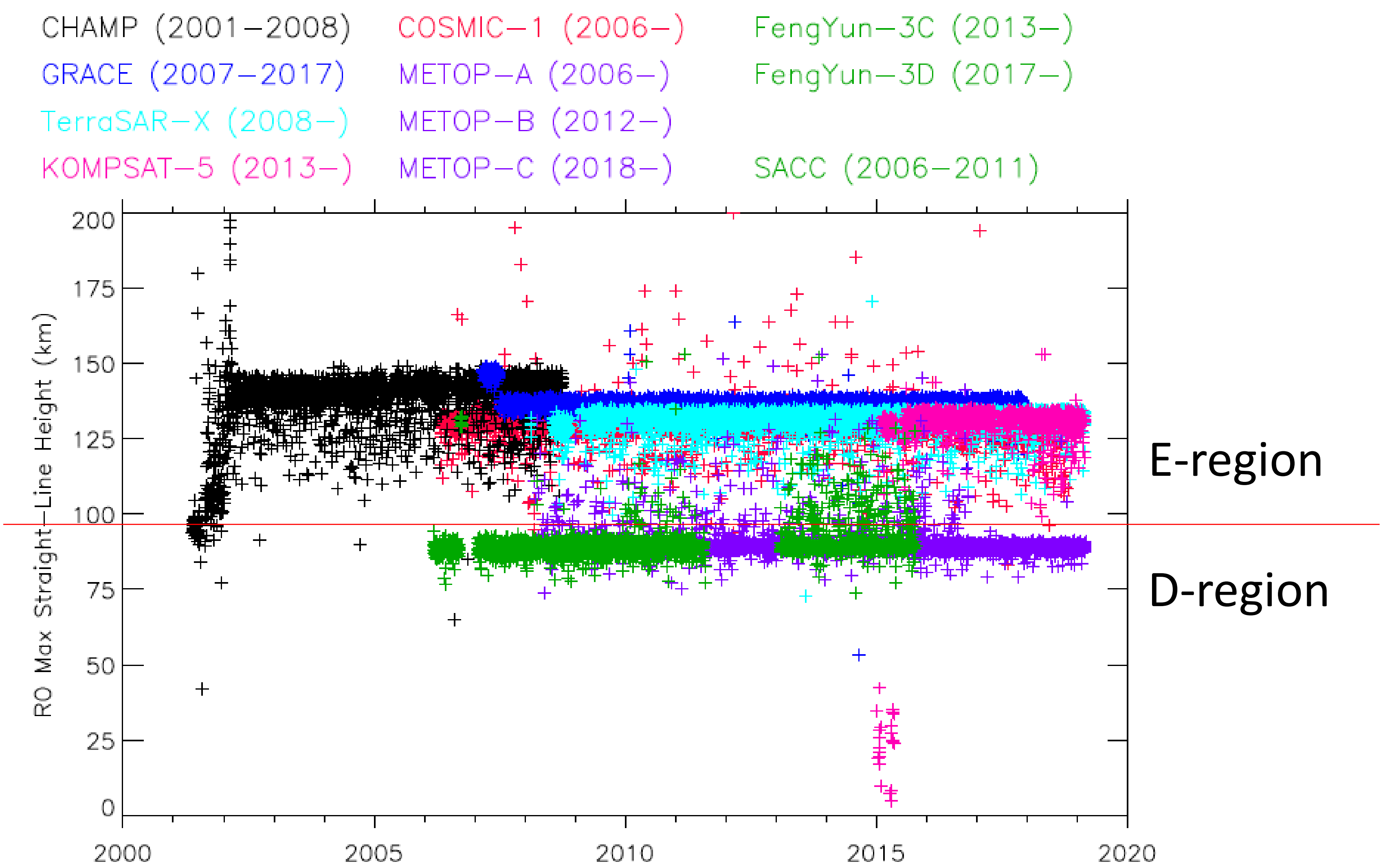


Truth ->

Truth ->

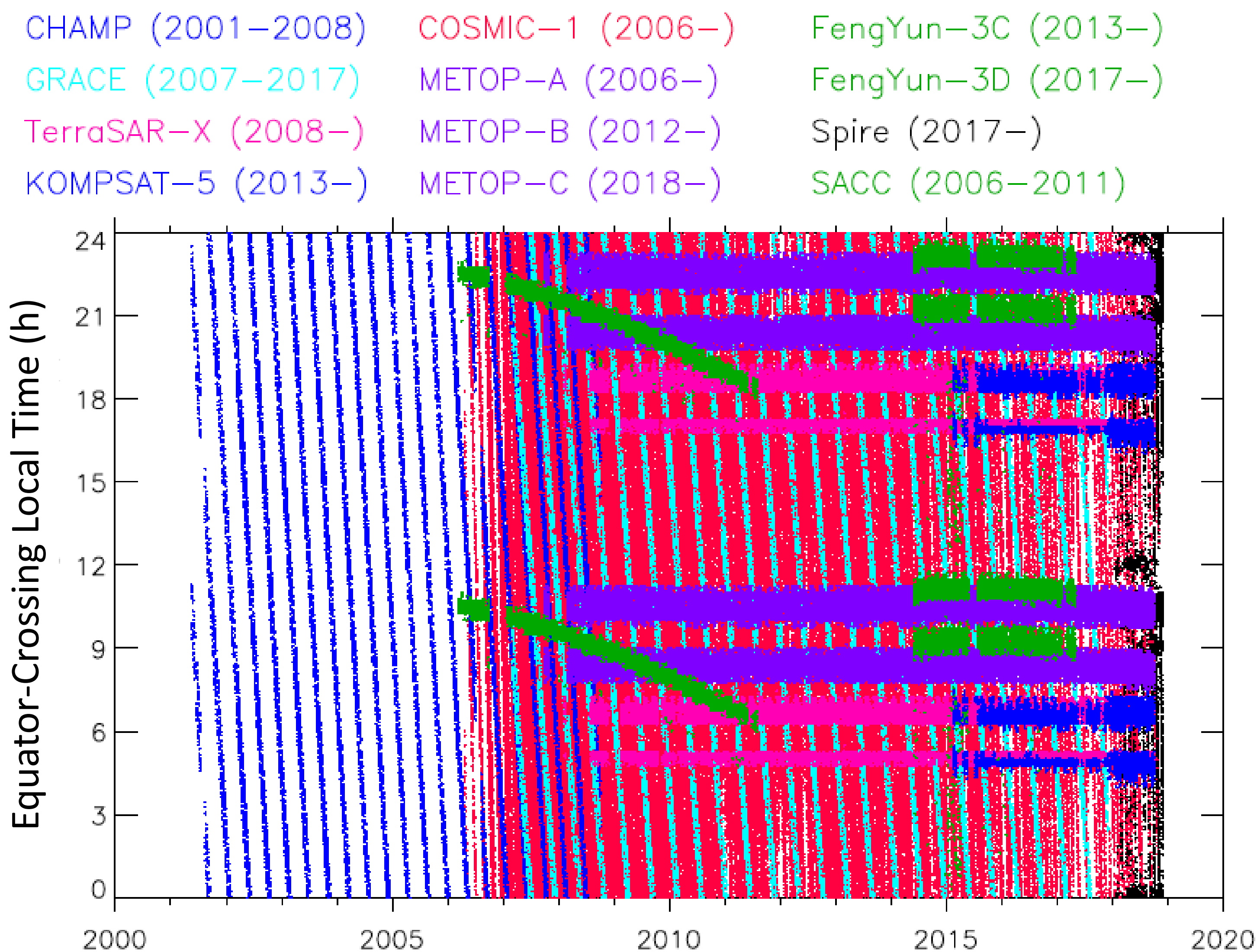
Wu (JASTP, 2018)

GPSRO 50/100-Hz Data Statistics: Max h_t



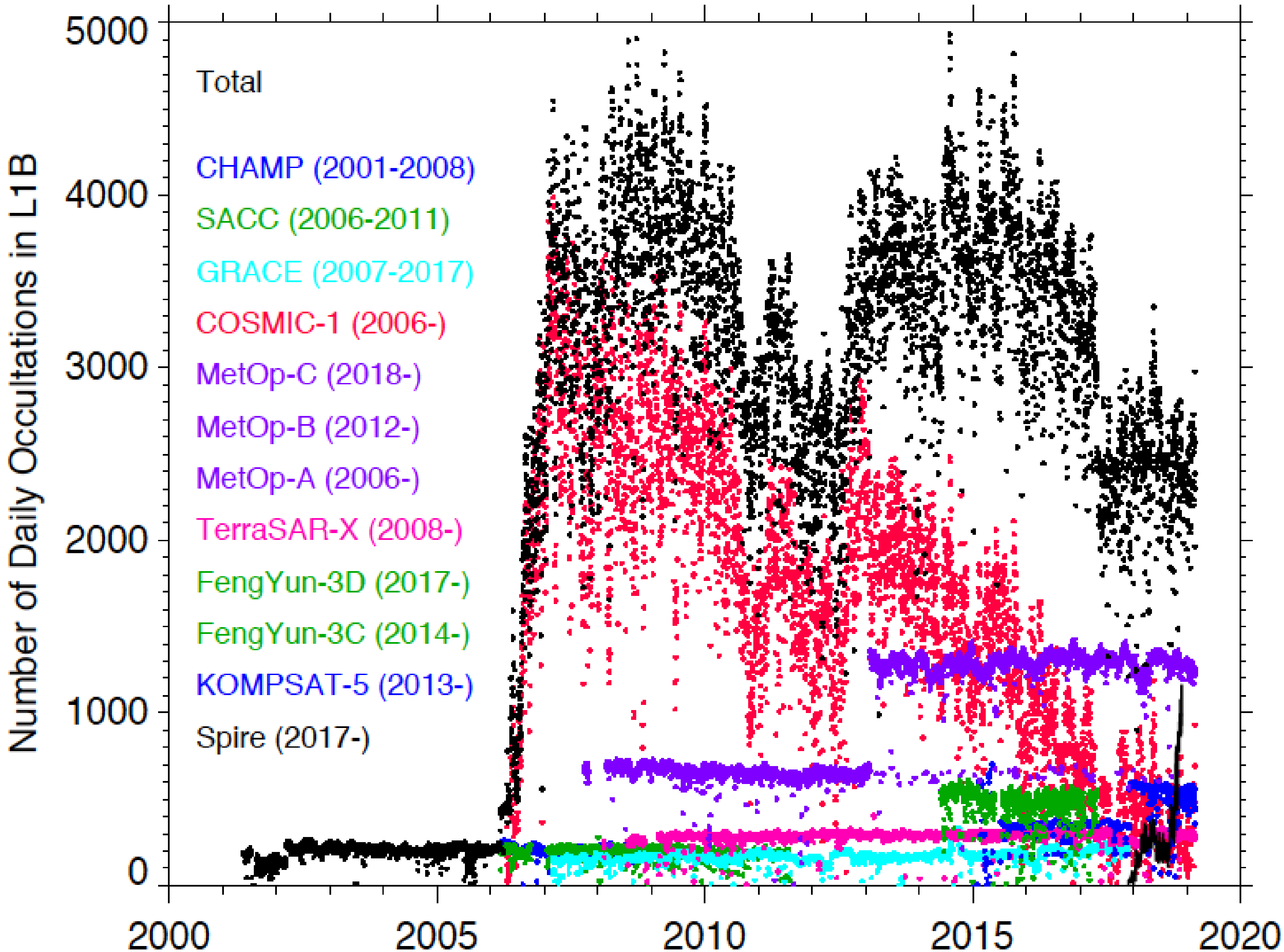
Acknowledgments: CDAAC Archive and Ehwa Womans U

GPSRO Data Statistics: Local Time Sampling



Acknowledgments: CDAAC Archive and Ehwa Womans U

GPSRO Data Statistics: Number of ROs

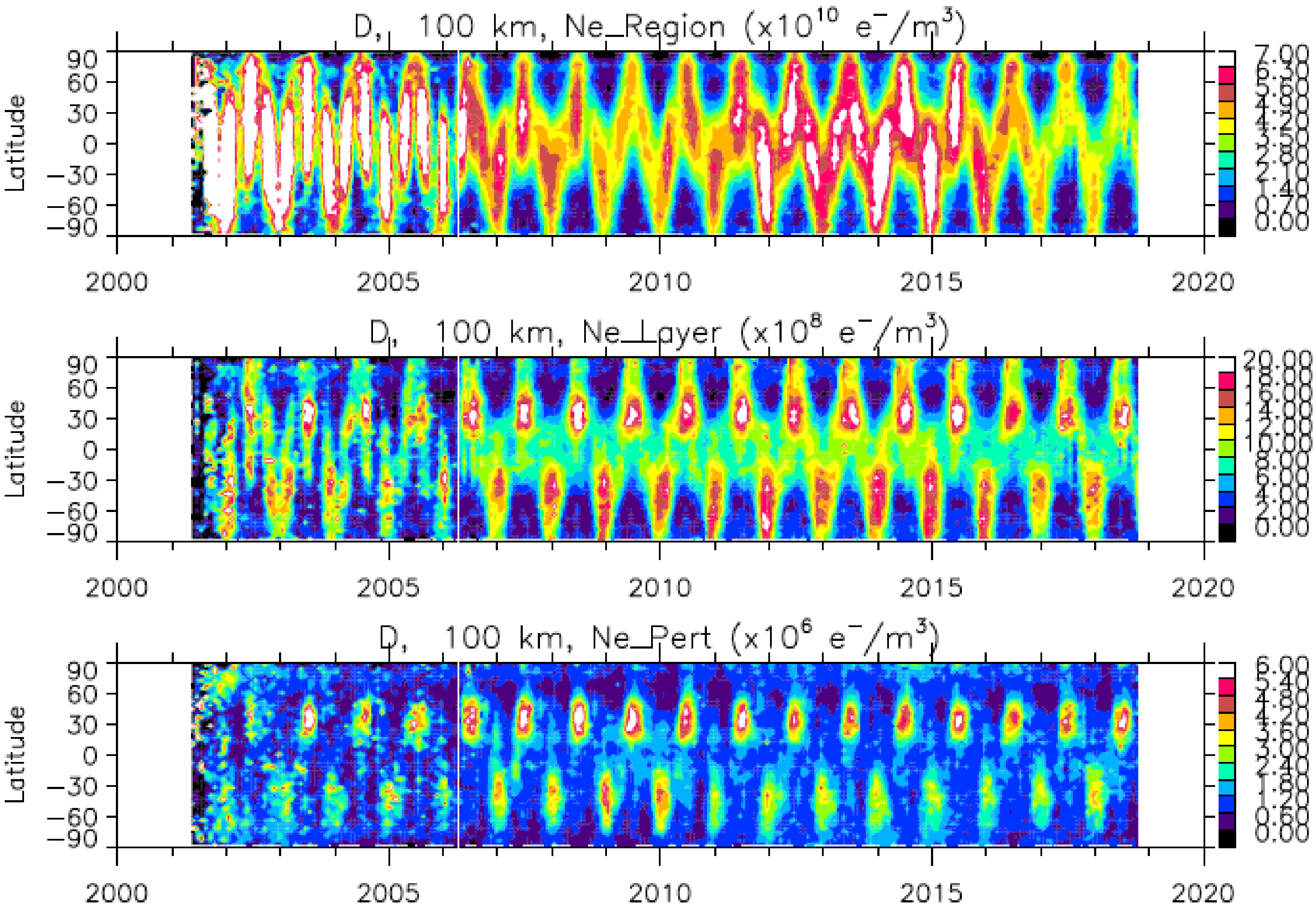


Acknowledgments: CDAAC Archive and Ehwa Womans U

Solar Cycle Variations in E-region Ne and Es

(Daytime at 100 km)

(All ROs, L1)



10^{10}

Ne

10^{8}

Es Layer
(λz=2-10km)

10^{6}

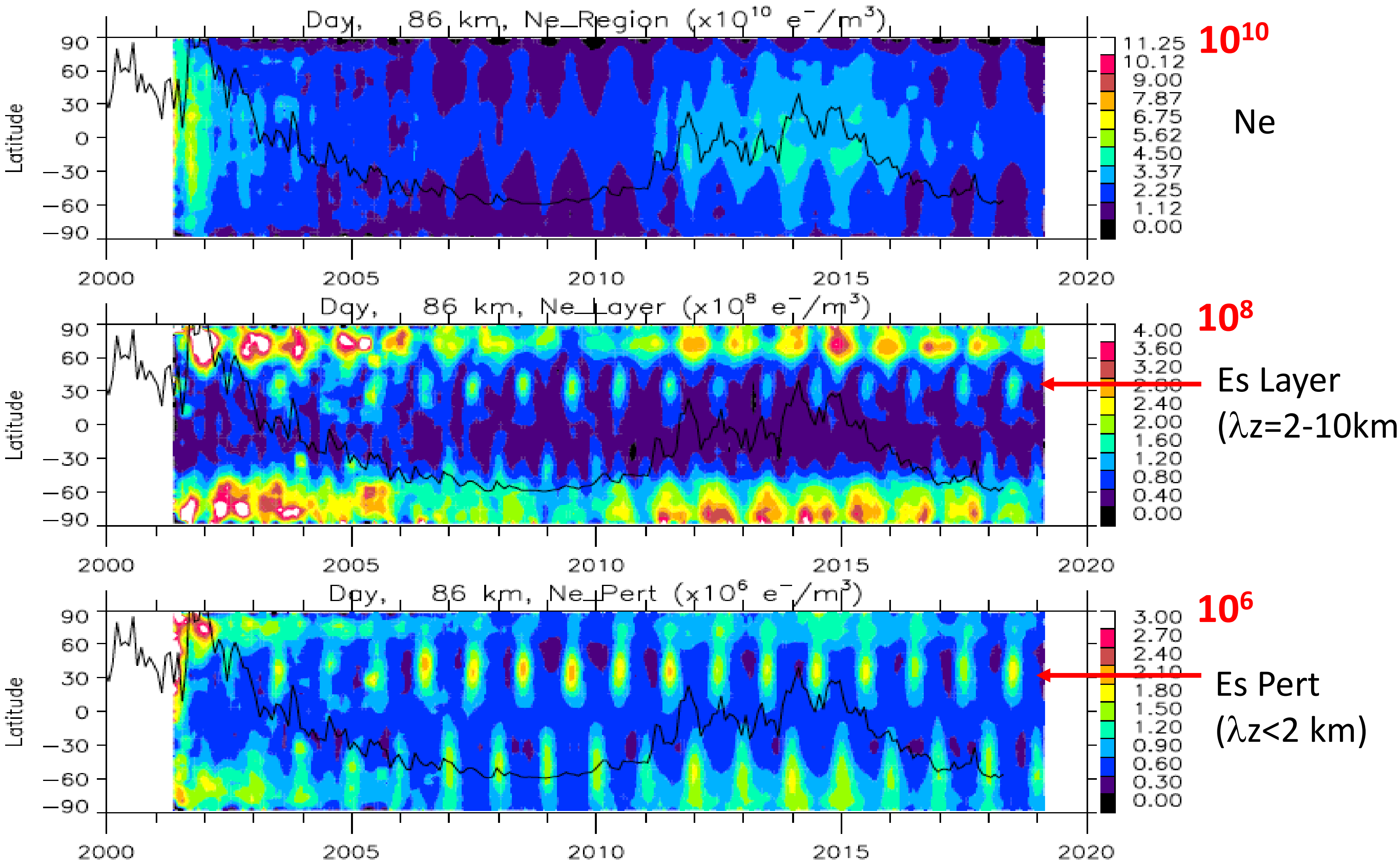
Es Pert
(λz<2 km)

Wu (JASTP, 2018)

Solar Cycle Variations of D-region Ne and Es

(Daytime at 86 km)

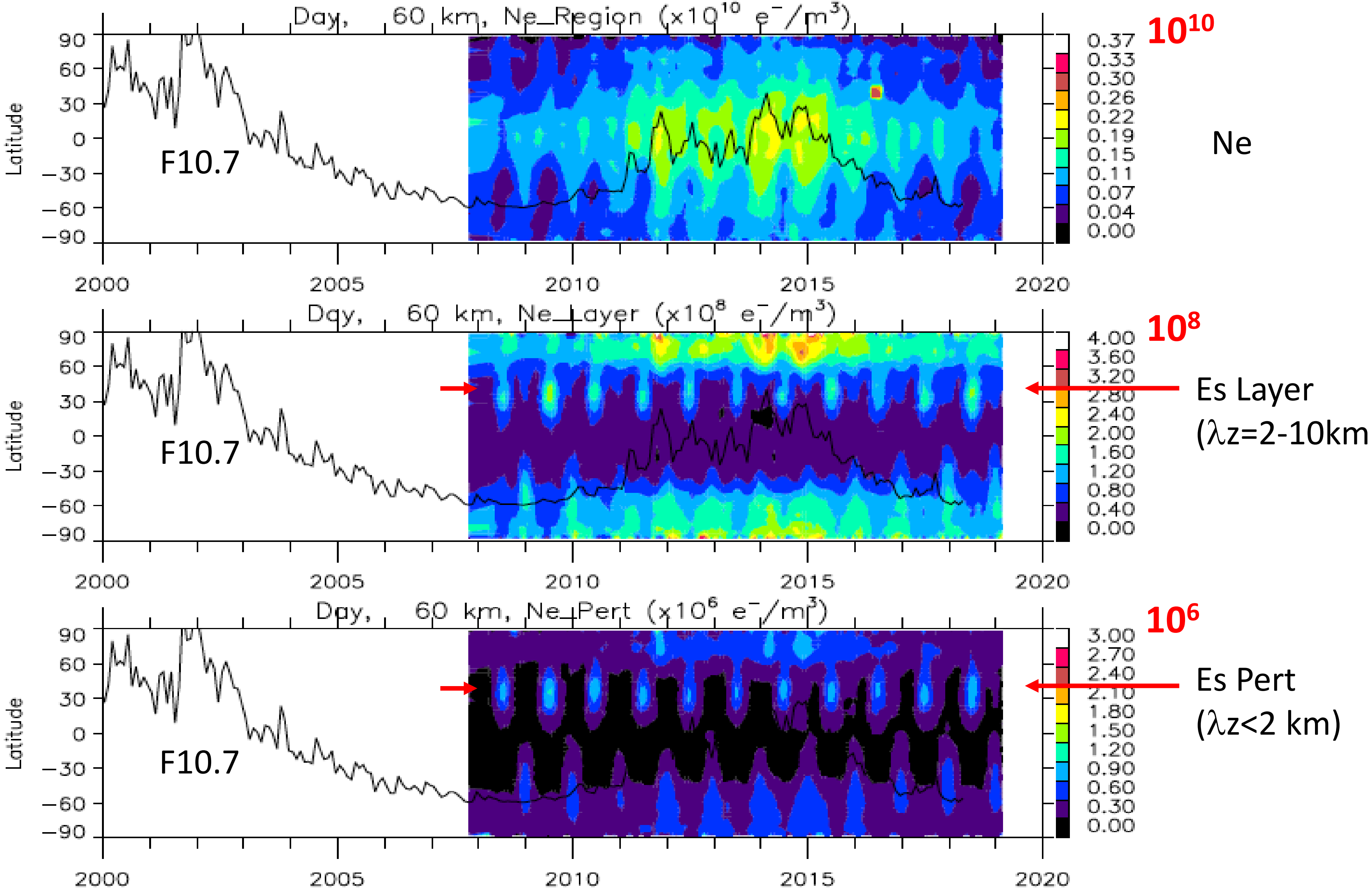
(All ROs, L1)



MetOp D-region Ne and Es

(Daytime at 60 km)

(MetOp-only, L1 and L2)

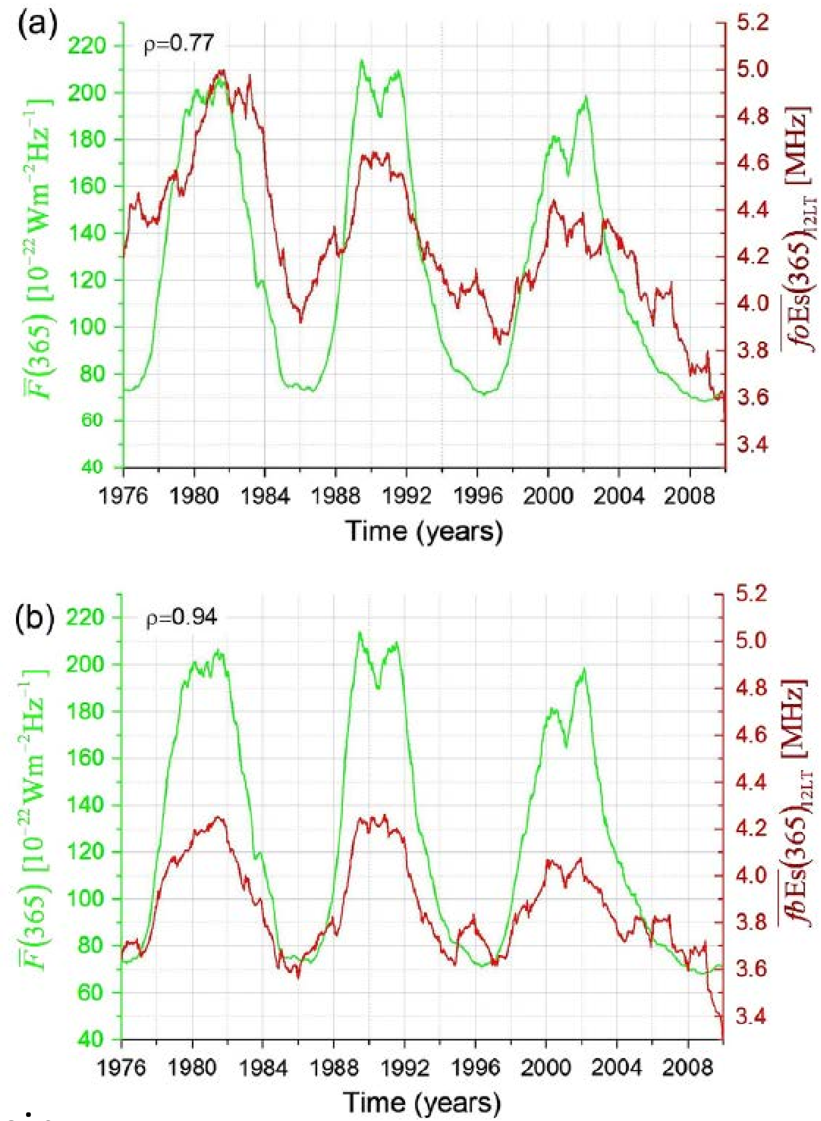


Solar-Cycle Variations of GPSRO Ne and Es

- Multi-satellite observations (2006-present) are ‘sufficient’ for diurnal sampling of Ne and Es, but become less uniform in recent years.
- E-region Ne and high-latitude Es (both daytime and nighttime) are in phase with the solar cycle, which is confirmed by MetOp-only observations.
- Daytime mid-latitude Es variations appear to be out of phase with the solar cycle, especially for Es (λz <2 km).
- Insignificant nighttime mid-latitude Es variations with the solar cycle.

Solar-Cycle Variations of Ionosonde Es

- Mid-latitude (Rome, Italy) Es solar cycle variability in 1976-2009
- Hourly critical frequency (*f*oEs) and blanketing frequency (*f*bEs) of Es measurements
- Positive F10.7-*f*oEs and F10.7- *f*bEs correlation
- Significant decreasing trend in *f*oEs

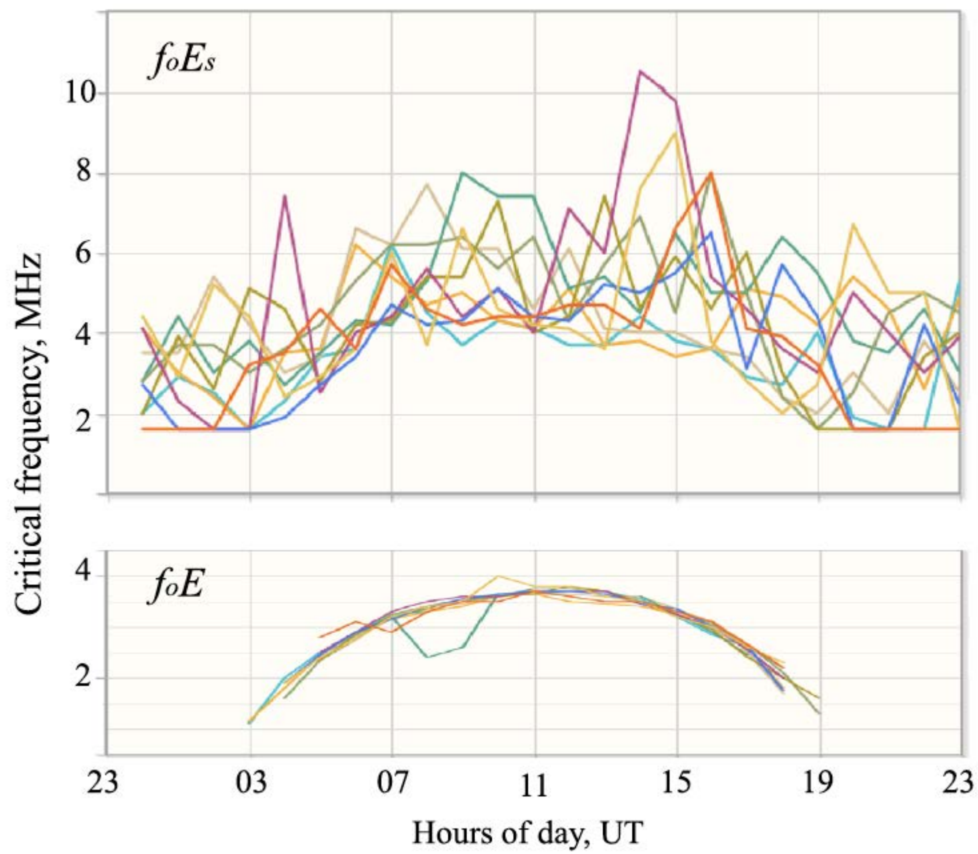


Pezzopane et al. (2005) + references therein

Impact of Diurnal Variation on *f*oEs Calculation

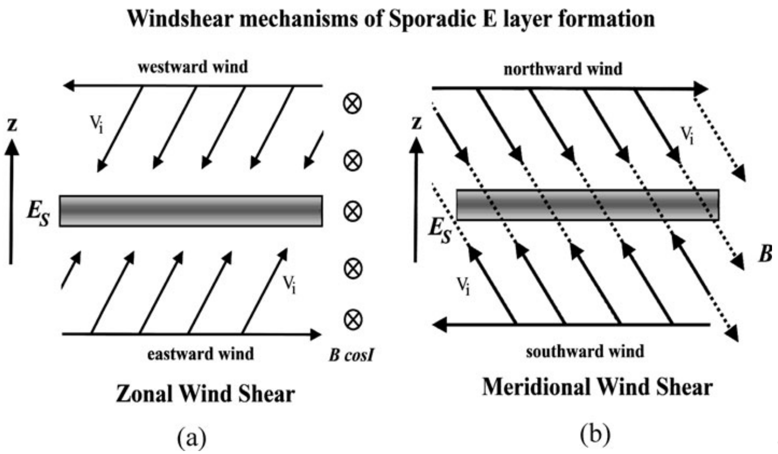
- Es are effectively a metal ion layer
- *f*oEs relates to sum of the layer metal and the E-region background plasma density.
  => Overestimated *f*oEs
- Unbiased estimate of Es layer intensity is proposed.
- The correction method should apply to both *f*oEs and *f*bEs,

Rome Ionosonde 10 day plots – 15/06/-24/06 1988



Haldoupis (2019)

Modulation of *Es* by Tidal Waves



Wind-Shear Mechanism (Whitehead, 1989) (Mathews, 1998)

Ne 10^{10}

Es Layer (λz=2-10km) 10^{8}

Es Pert (λz <2 km) 10^{6}

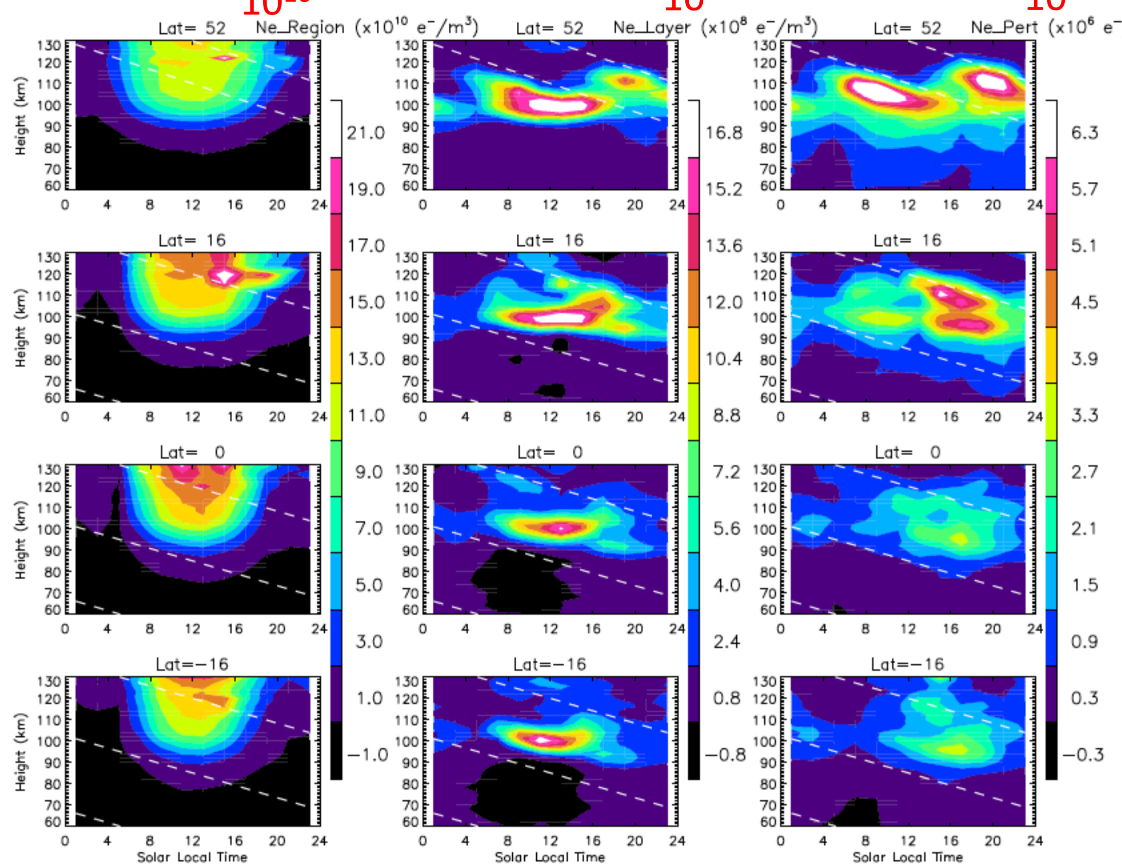
12-h Tide ➔ 52°N

24-h and 12-h Tides ➔ 16°N

24-h Tide ➔ 0°

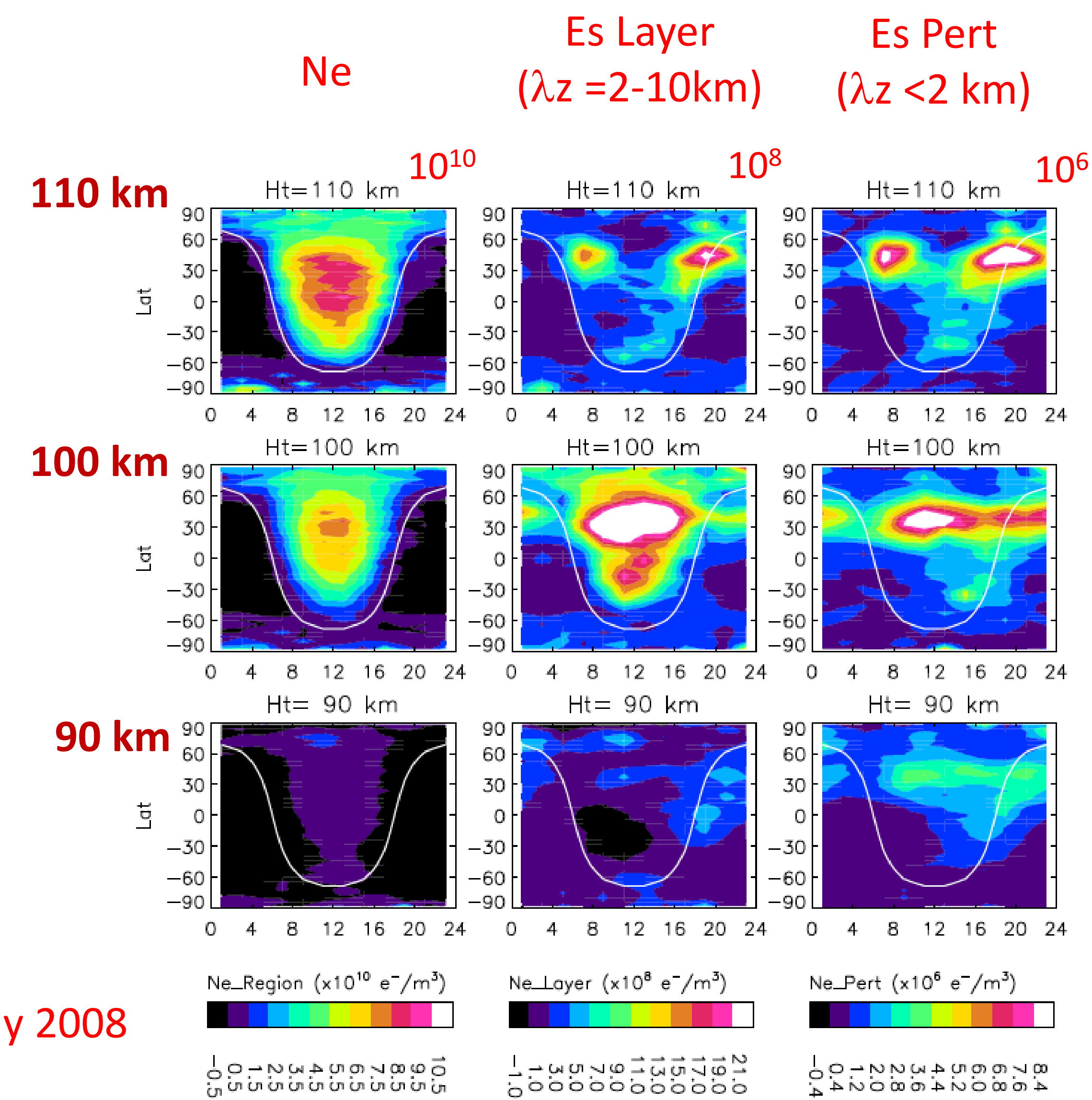
24-h Tide ➔ 16°S

(July 2008)



Diurnal Variations of GPSRO Ne and Es

- E/D-region Ne is largely determined by solar zenith angle.
- Es formation and variability need better understanding.
- Summertime mid-latitude Es are dominated by diurnal variation at 100 km and semidiurnal at 110 km.



July 2008

Summary

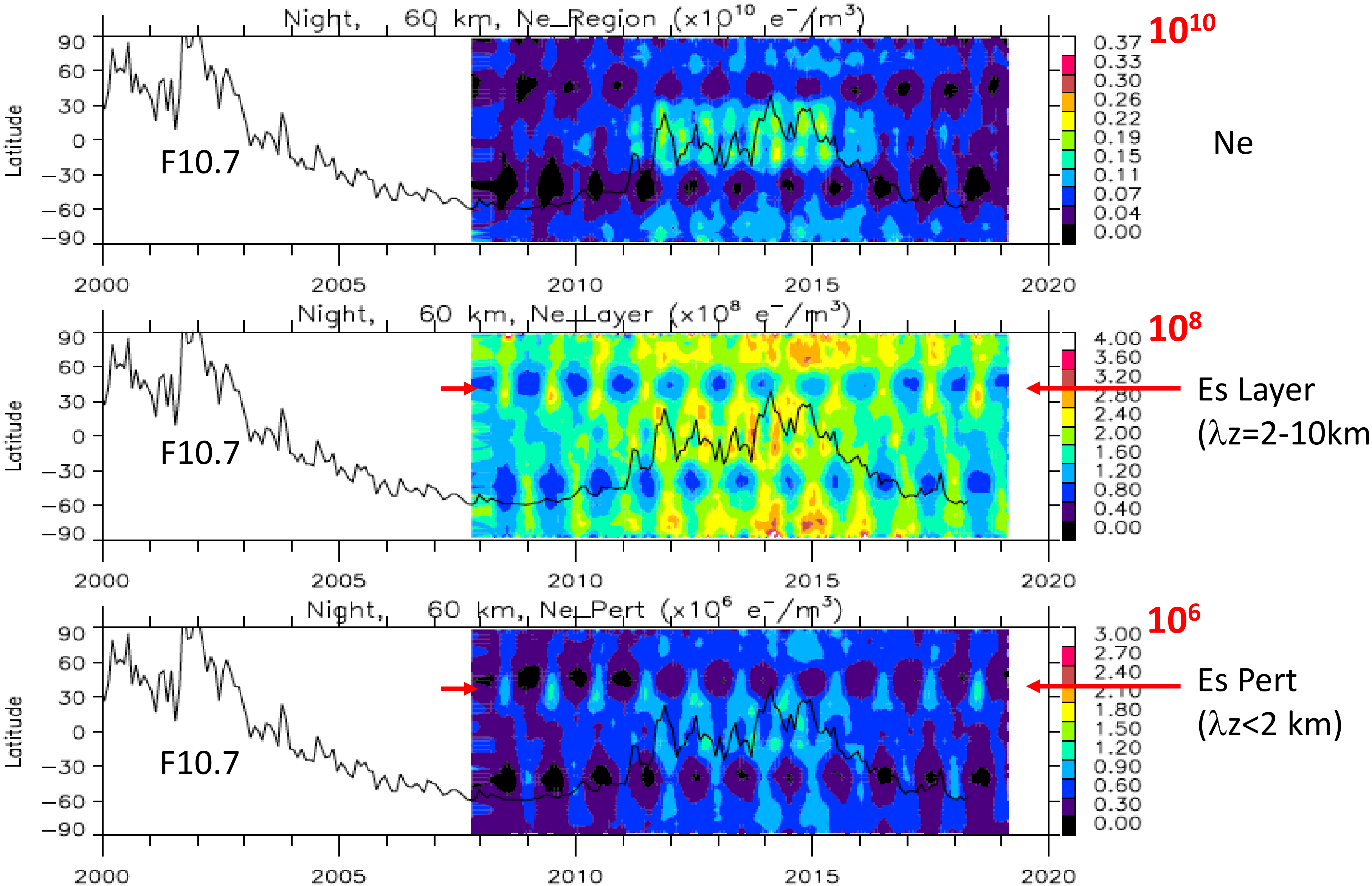
- E-region Ne and high-latitude Es (both daytime and nighttime) are in phase with the solar cycle.
- Daytime mid-latitude Es variations (from GPSRO) appear to be out of phase with the solar cycle, especially for Es (λz <2 km).
- Correction is likely needed for ionosonde *f*oEs and *f*bEs, in order to produce the consistent solar cycle variations with GPSRO observations.
- Global Es formation, variabilities, and coupling with other processes still need a better understanding.

Backups

MetOp D-region Ne and Es

(Nighttime at 60 km)

(MetOp-only, L1 and L2)



Ne

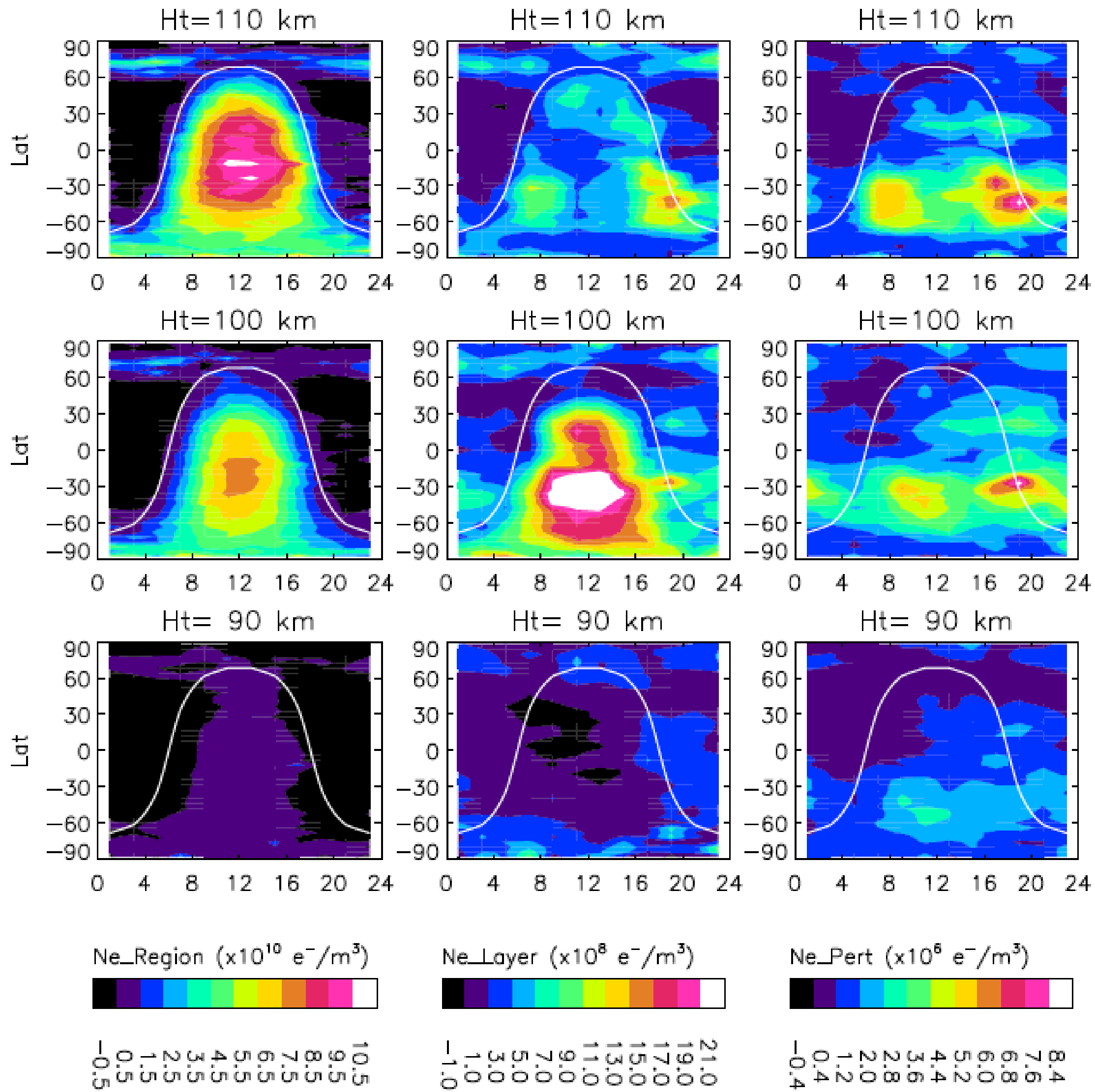
Es Layer
(λz =2-10km)

Es Pert
(λz <2 km)

110 km

100 km

90 km



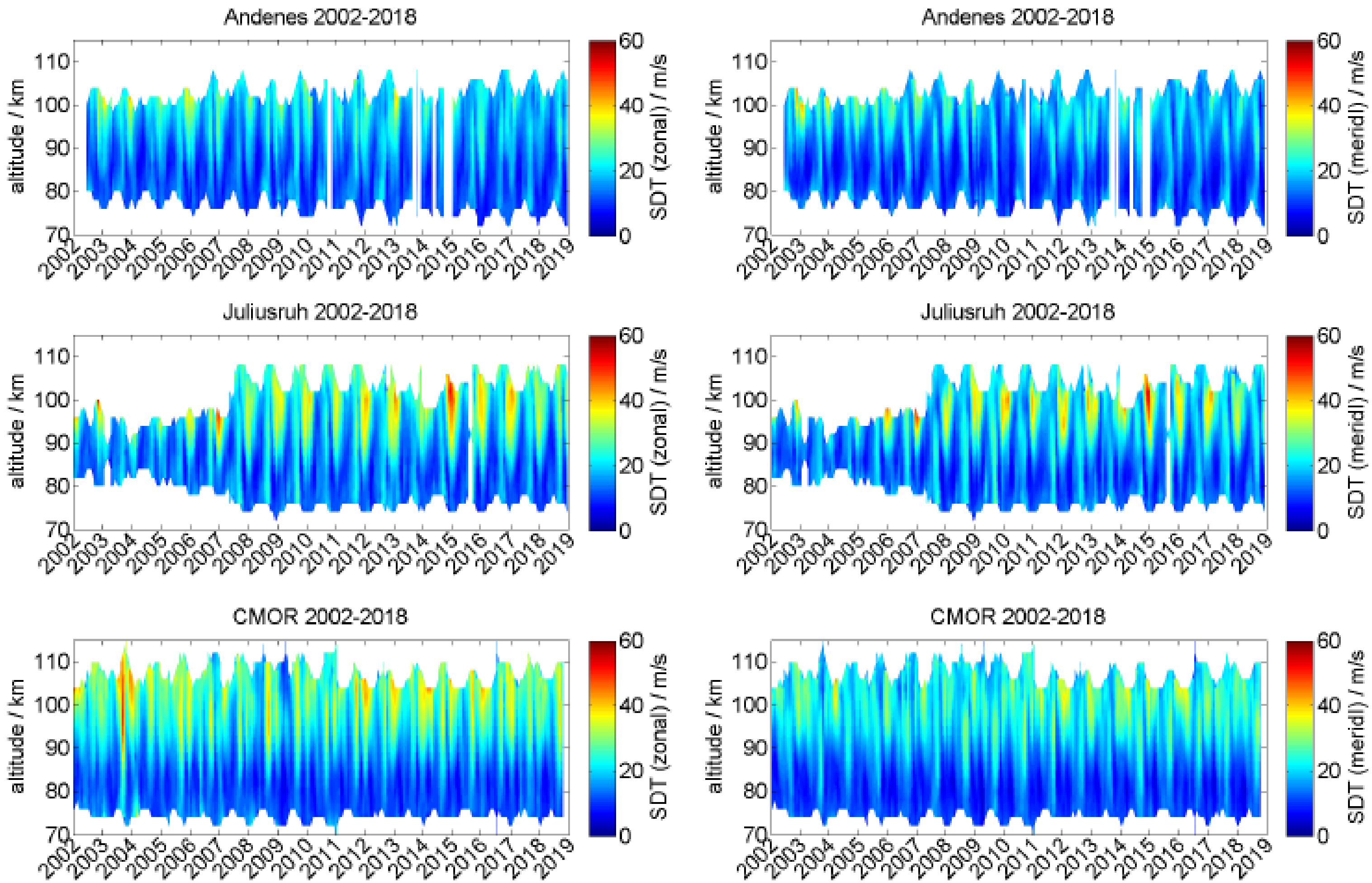
Jan 2008

Semidiurnal Tidal Amplitudes

Andenes
(69.3N, 16E)

Juliusruh
(54.6N, 13.4E)

Tavistock
(43.4N, 80.8W)



Wilhelm et al. (2019)