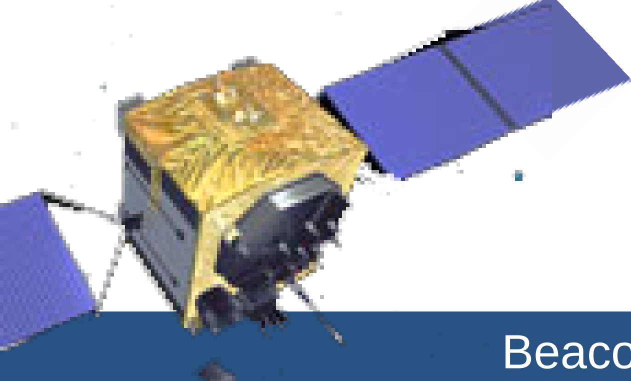
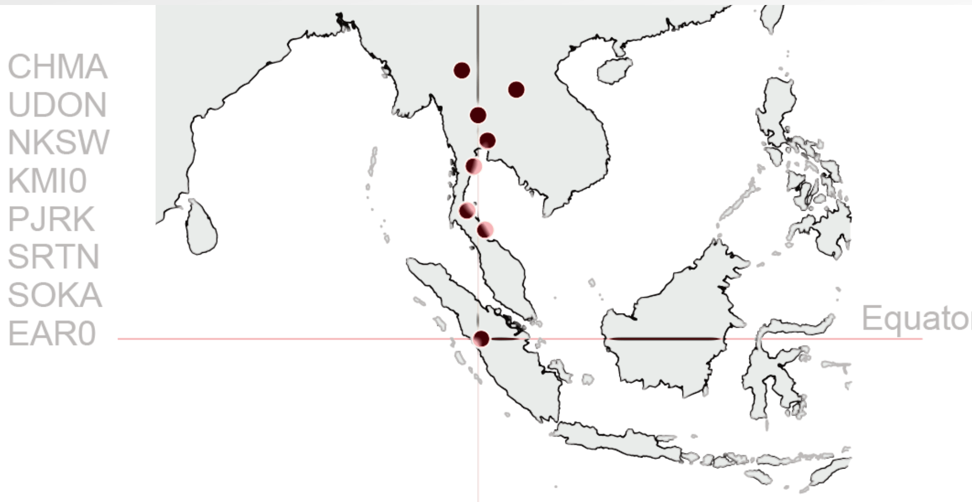


Beacon Satellite Symposium 2019, Olsztyn

Total electron content derived from GNSS signals by double thin-shell model and implication in ionospheric dynamics near the magnetic equator



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Introduction

L-band signals transmitted from GNSS satellites are widely used for the study of ionospheric total electron content (TEC) by measuring differential propagation delay between two frequencies, f_1 and f_2

$$\tau = \delta t_2 - \delta t_1 = b\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)\int_s n_e \mathrm{d}s$$

$$\int_s n_e \mathrm{d}s = TEC_{sl}$$

$$\textit{Group delay}: \tau \sim TEC_{sl}^{obs} = TEC_{sl} + b_r + b_s$$

There is a basic problem of instrumental biases due to signal delays in the electronics of satellites and receiver.

Thin-layer approximation

In widely used techniques, the TEC and instrumental biases are solved together from the observations.

A thin-layer approximation of the ionosphere is commonly used to convert the slant TEC to the vertical TEC at the ionosphere piercing point (ipp).

$$TEC_V = TEC_{sl} \cos\chi$$

χ : satellite zenith angle at ipp

The ipp is obtained in the next slide.

Thin-layer approximation

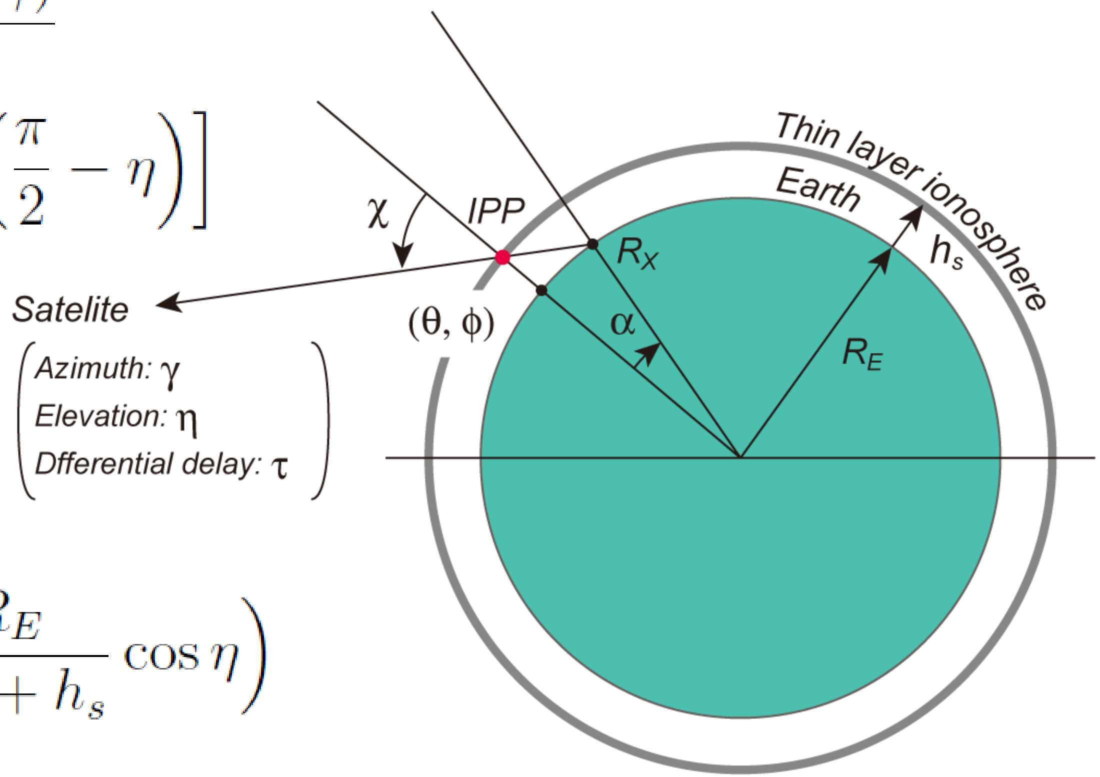
Observed parameters: γ, η, τ

Coordinate of ipp (λ, ζ) and local zenith angle (χ)

$$\lambda = \sin^{-1}\left(\sin\lambda_R\cos\alpha + \cos\lambda_R\sin\alpha\cos\gamma\right)$$

$$\zeta = \zeta_R + \frac{\sin^{-1}\left(\sin\alpha\sin\gamma\right)}{\cos\lambda}$$

$$\chi = \sin^{-1}\left[\frac{R_E}{R_E+h_s}\sin\left(\frac{\pi}{2}-\eta\right)\right]$$



$$\alpha = \frac{\pi}{2} - \eta - \sin^{-1}\left(\frac{R_E}{R_E+h_s}\cos\eta\right)$$

Problems with the classical single-layer approach

- **Constant thin-shell height**

  No theoretical basis for choosing this height.

  Pierce point related with slant TEC varies with the shell height.

  Ionospheric height and vertical distribution largely vary with location and time.

- **Levelling procedure**

  For the use of precise phase advance, the code-phase leveling is needed to remove the ambiguity of phase origin.

  Noises and multipath effect on the code delay deteriorate the code-phase levelling.

[Detailed discussion on these issues is found in *Hernandez-Pajares et al., JASTP, 2000]*

Double-shell model

To resolve the problems in conventional approach

Parameterization of the ionosphere by two thin shells

TEC (partial electron content) associated with each shell is modeled by the spherical harmonics fitting.

Direct use of phase data without levelling

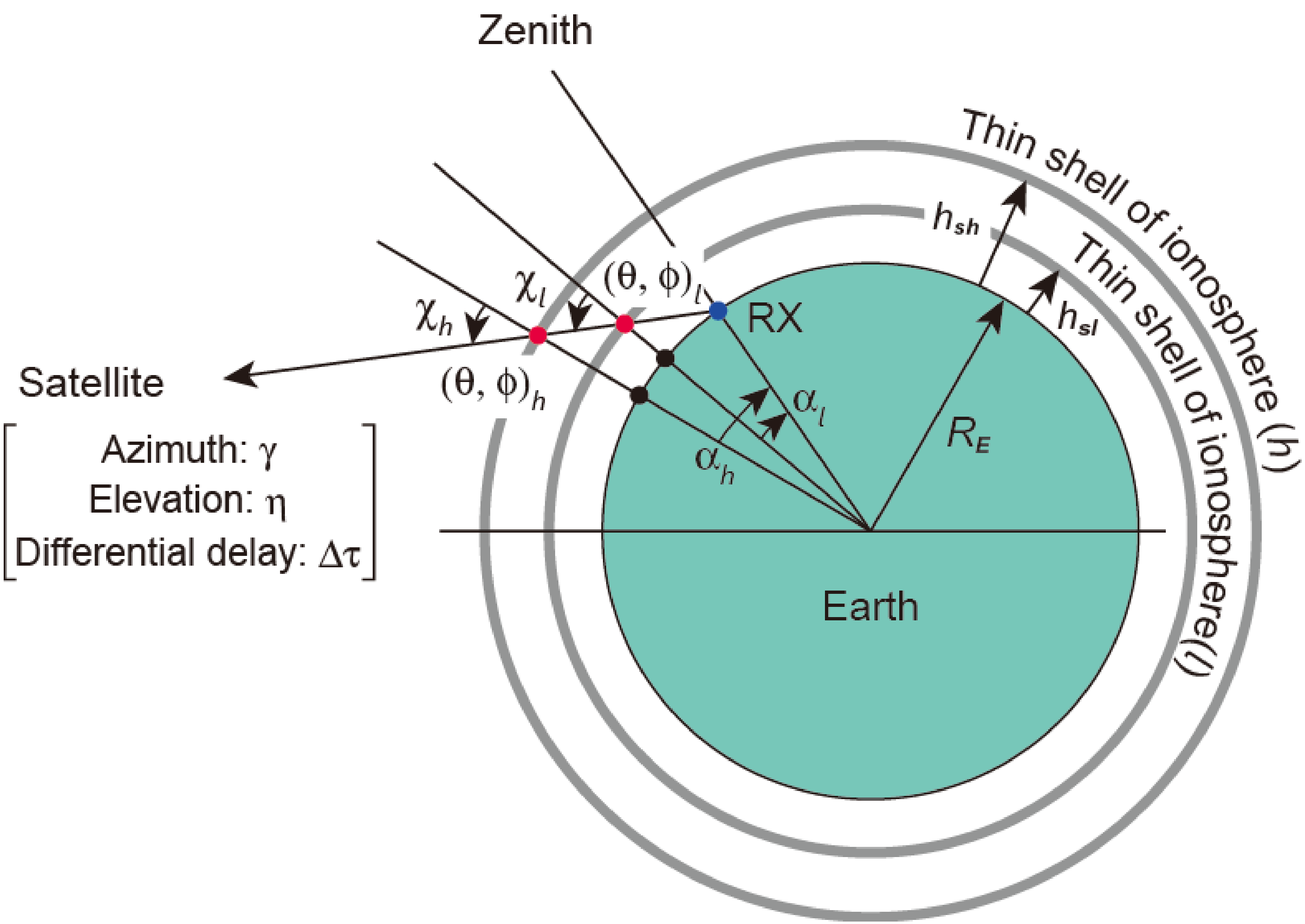
Arc total biases containing instrumental biases and phase ambiguity are estimated without the levelling procedure.

Neural network implementation of the fitting

To assure non-negative TEC, a nonlinear element is introduced in the output layer. (TEC in one of the shell can be negative in nighttime without this.)

Double-shell model

Two ipps corresponding to higher and lower shells



Surface harmonics fitting

$$TEC_V(\theta,\phi) \;=\; TEC_{V\,Lo}(\theta,\phi) + TEC_{V\,Hi}(\theta,\phi)$$

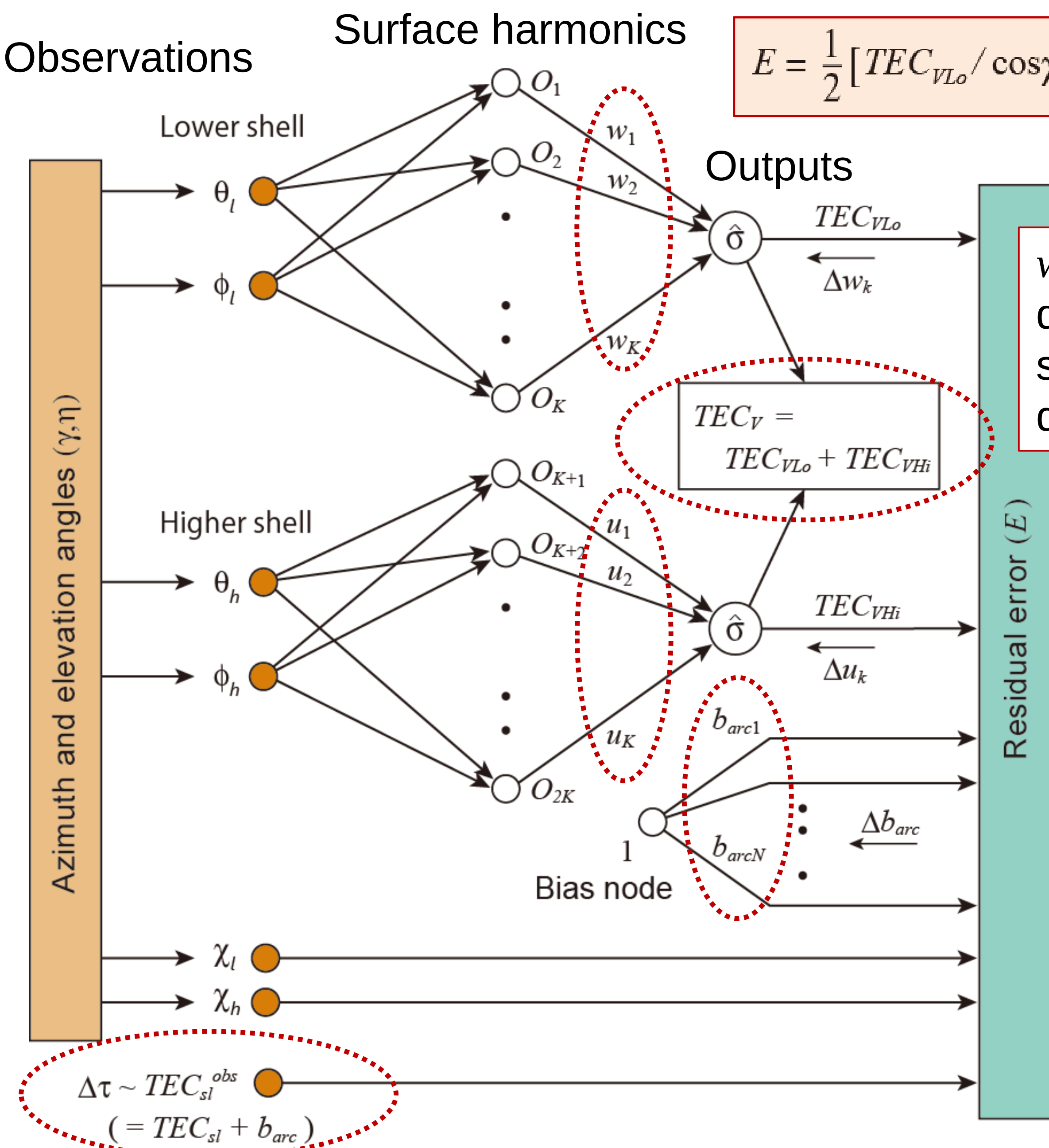
$$TEC_{V\,Lo}(\theta,\phi) \;=\; \sum_{m=0}^{M}\sum_{n=m}^{N}(A_{nm}\cos m\phi + B_{nm}\sin m\phi)P_n^m(\cos\theta)$$

$$TEC_{V\,Hi}(\theta,\phi) \;=\; \sum_{m=0}^{M}\sum_{n=m}^{N}(\tilde{A}_{nm}\cos m\phi + \tilde{B}_{nm}\sin m\phi)P_n^m(\cos\theta)$$

The coefficients $A_{nm}, B_{nm}, \tilde{A}_{nm}, \text{and } \tilde{B}_{nm}$ are determined together with the arc biases b_{arc} from the observations

(N = 7; M = 5 in this study.)

Orthogonal neural network



$$E = \frac{1}{2}\left[TEC_{VLo}/\cos\chi_l + TEC_{VHi}/\cos\chi_h - \left(TEC_{sl}^{obs} - b_{arc}\right)\right]^2$$

$w_1, \ldots, u_1, \ldots b_{arc}$ are determined to minimize the sum of error by the gradient decent method

Output layer activation

$$\hat{\sigma}(x) = x + \ln\left(1 + e^{-x}\right)$$

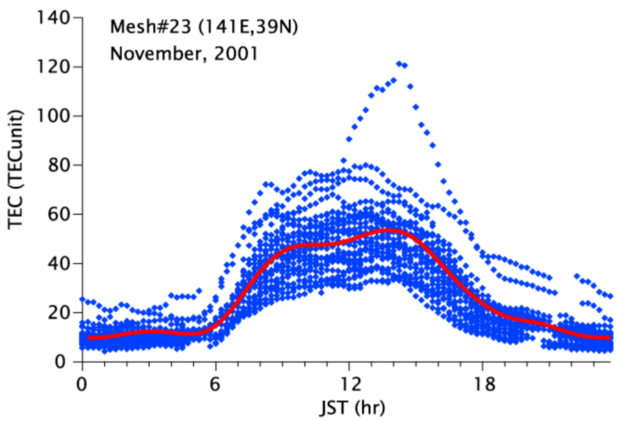
$$x = \sum_{i=1}^{K} w_i O_i \quad \text{(Lower shell)}$$

$$= \sum_{i=1}^{K} u_i O_{K+i} \quad \text{(Higher shell)}$$

($2K$ = 58 for N = 7; M = 5)

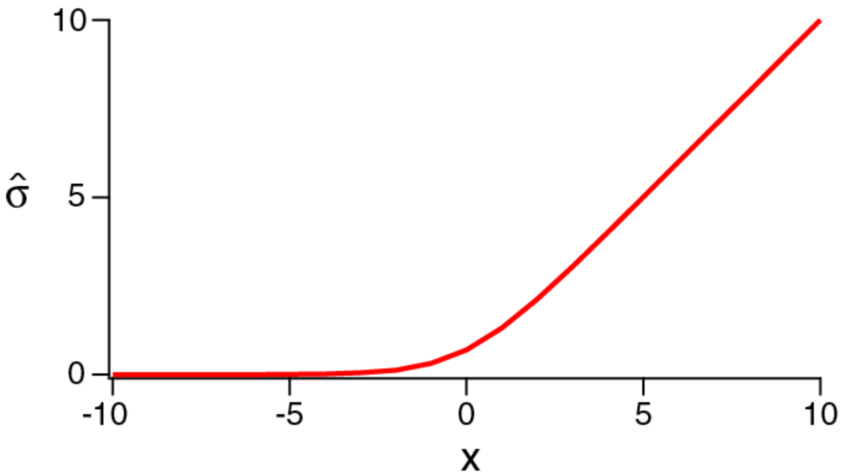
Activation function for the output layer

Generally, diurnal variation of TEC has a relatively Flat in nighttime with small TECs.



A higher order of harmonics are required to model transition between daytime and nighttime features preventing negative TECs.

The activation function in the output layer assures non-negative TECs with limited degree and order of harmonics .



Output layer activation

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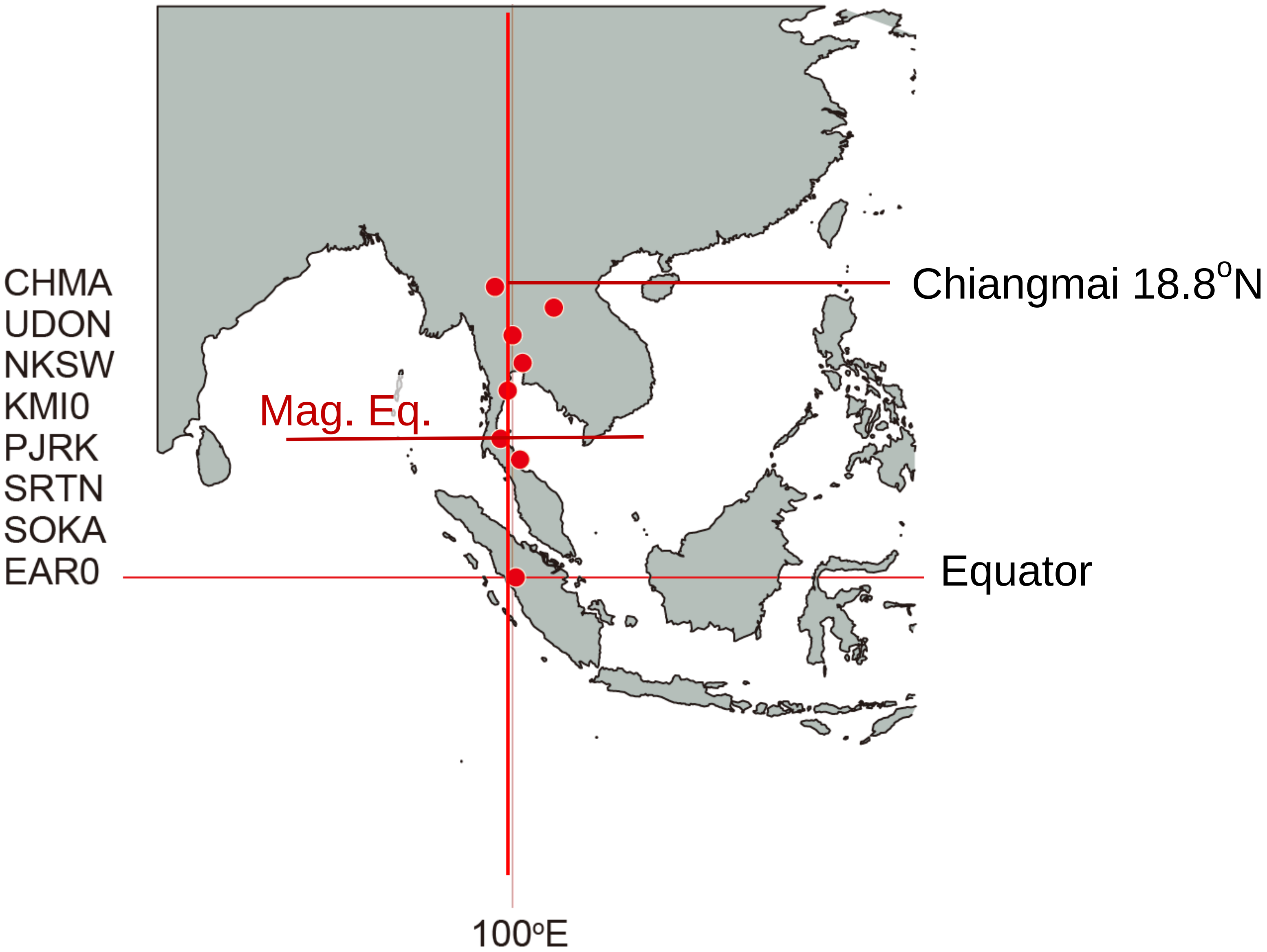
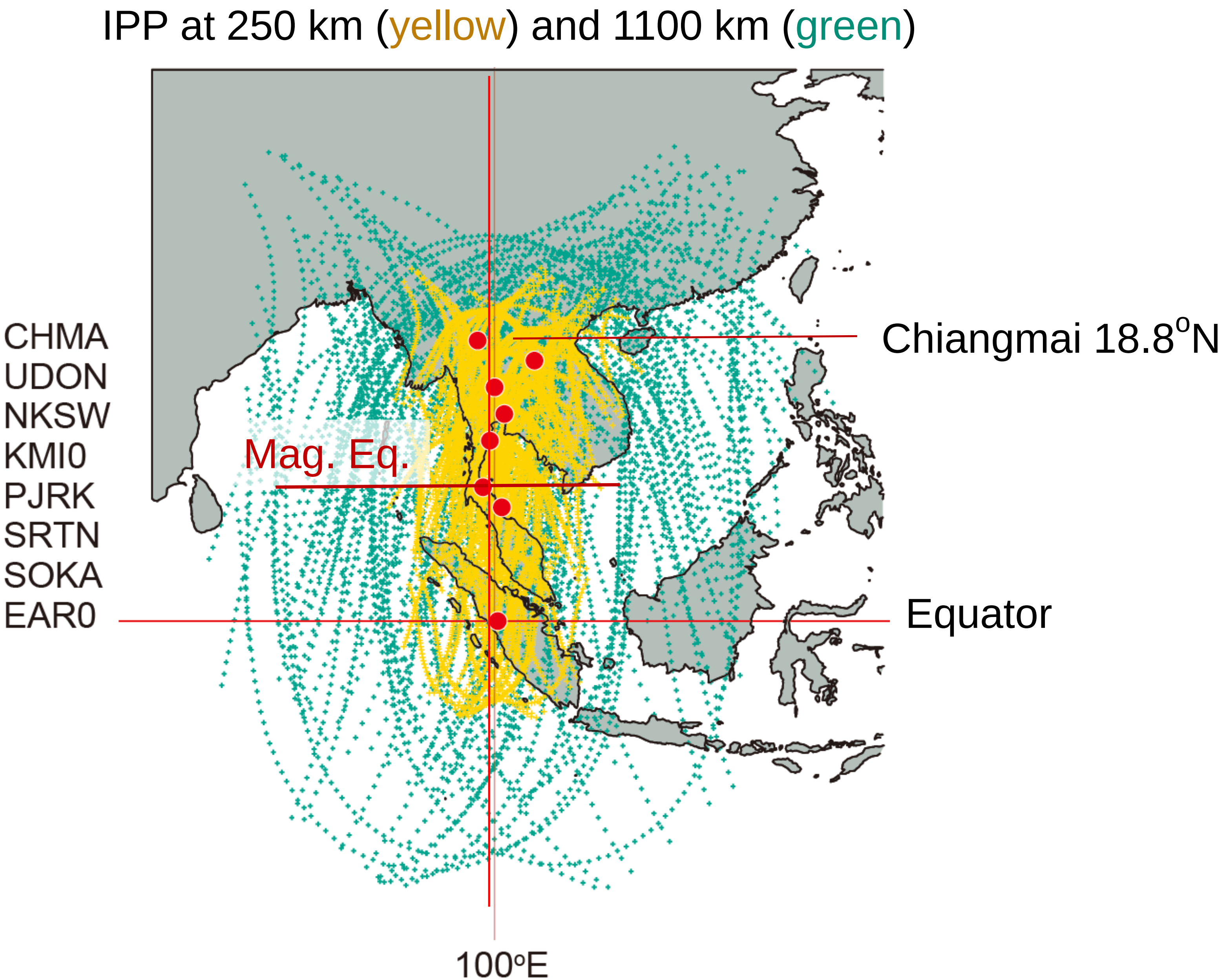
Application to equatorial ionosphere

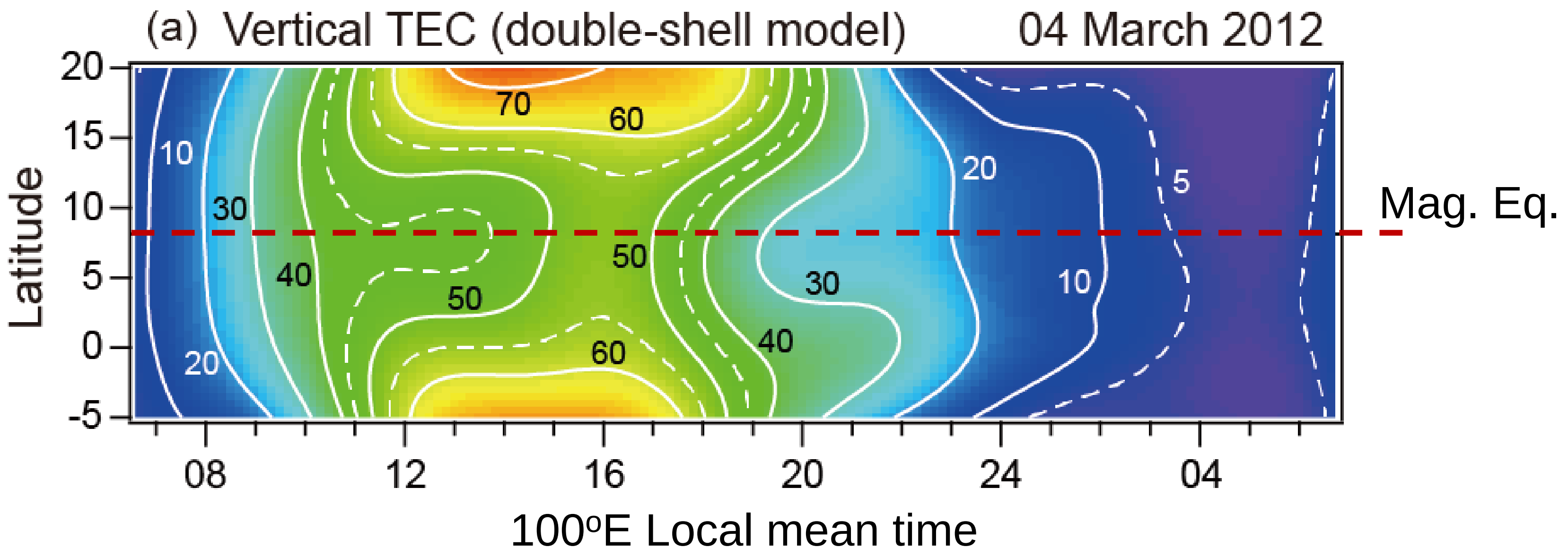
Eight GNSS receivers along the 100°E meridian



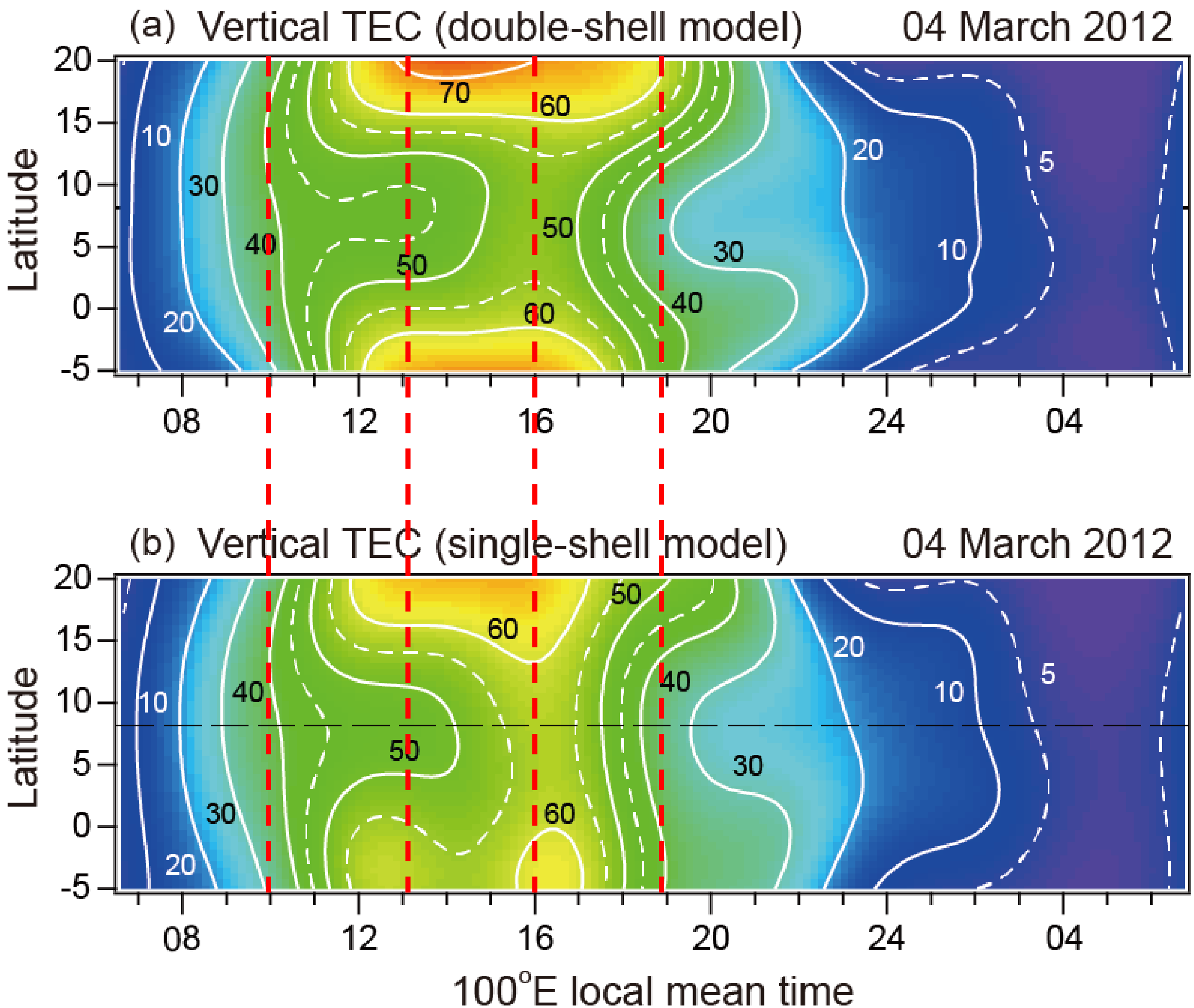
Ionosphere pierce points at two shell heights



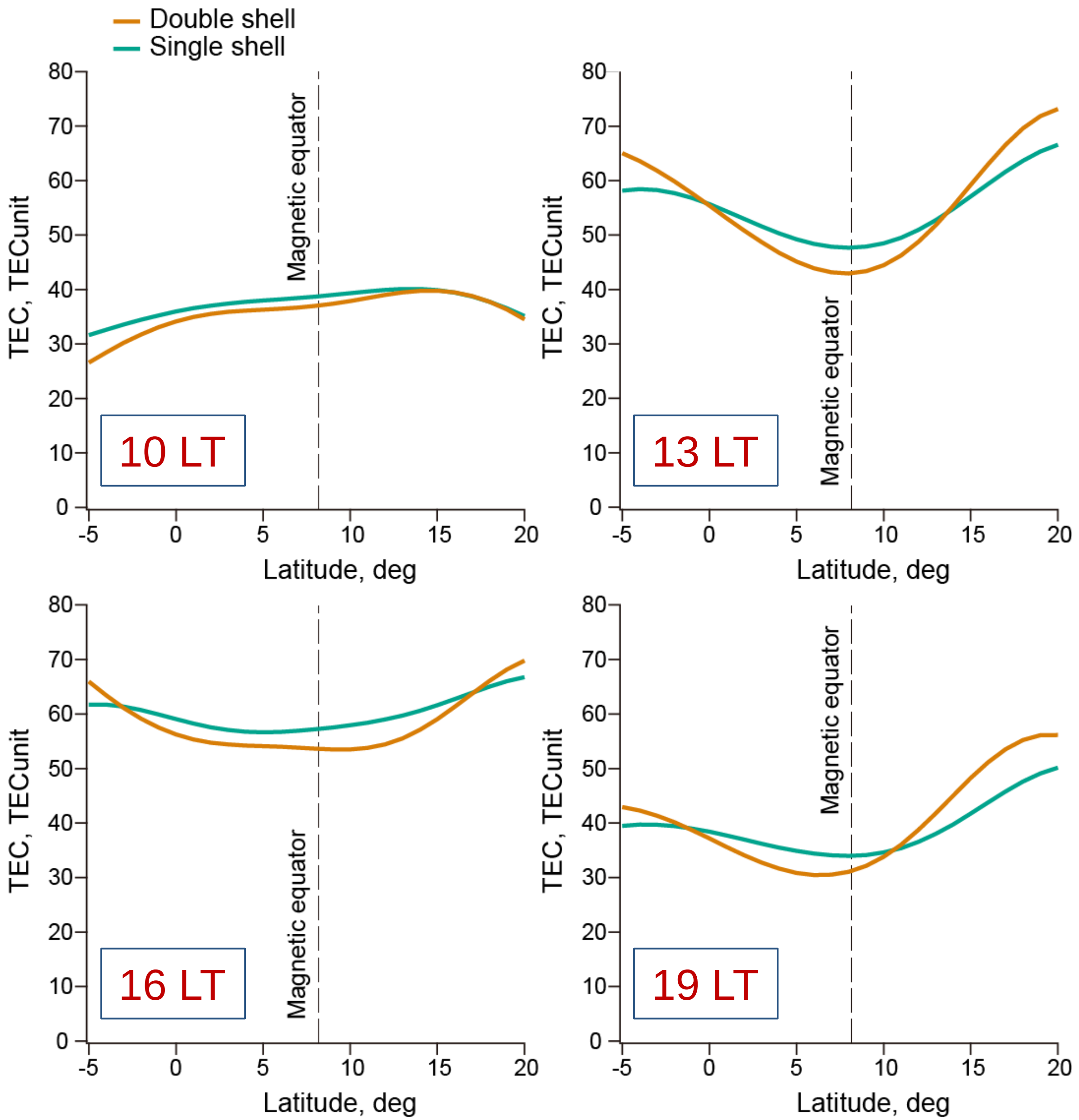
Result: TEC time-latitude variation



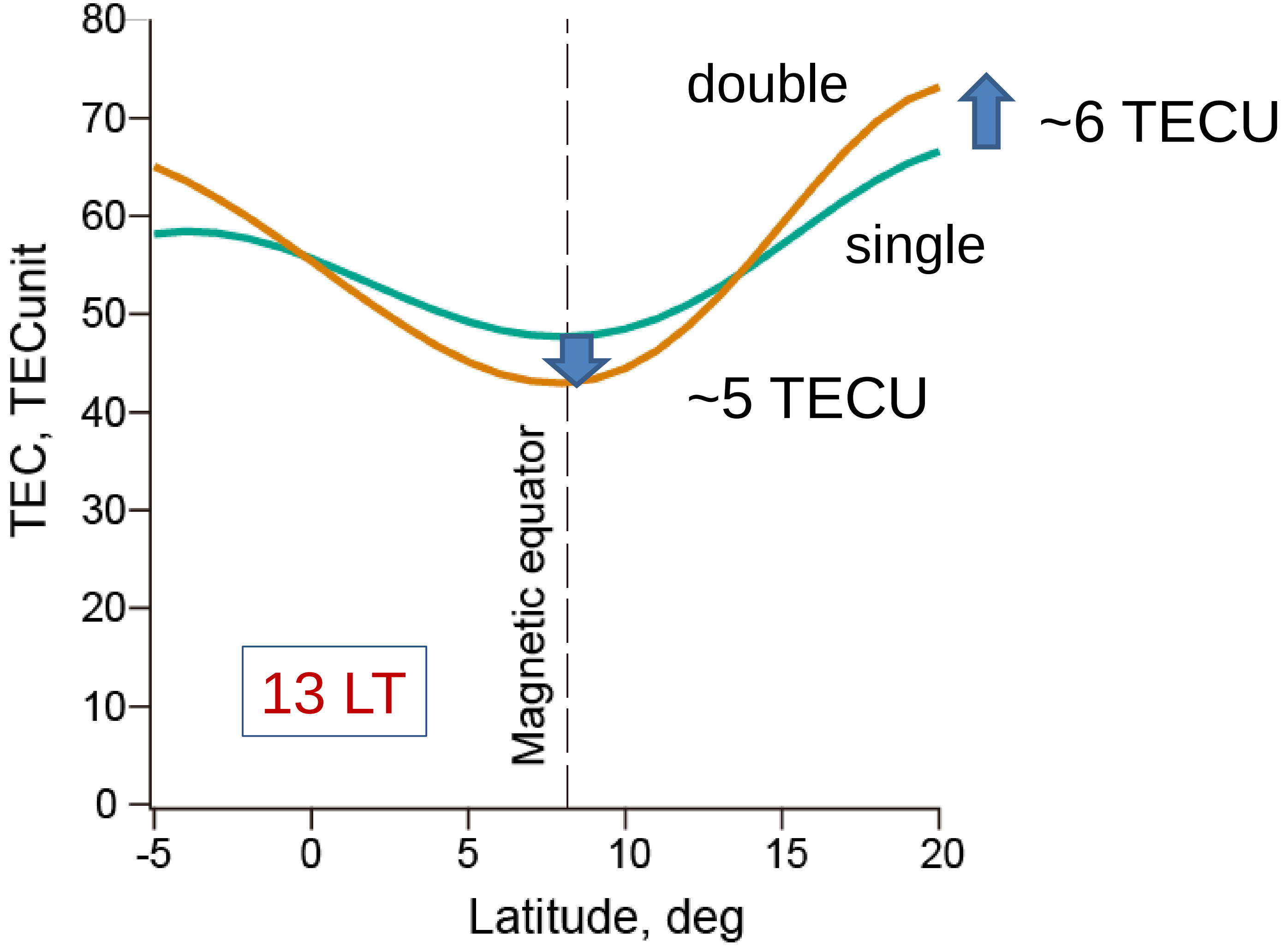
Comparison: double- and single-shell models



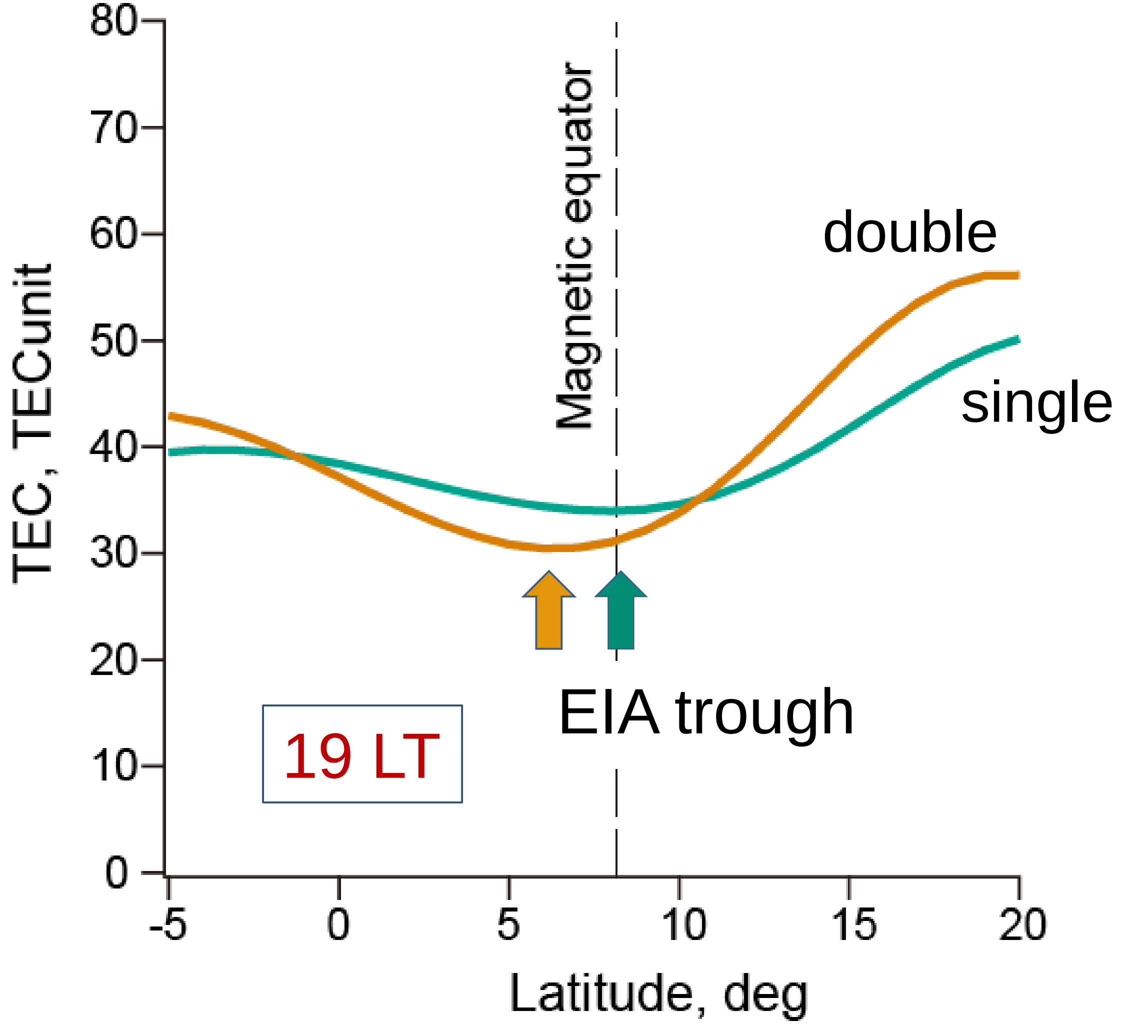
Comparison: double- and single-shell models



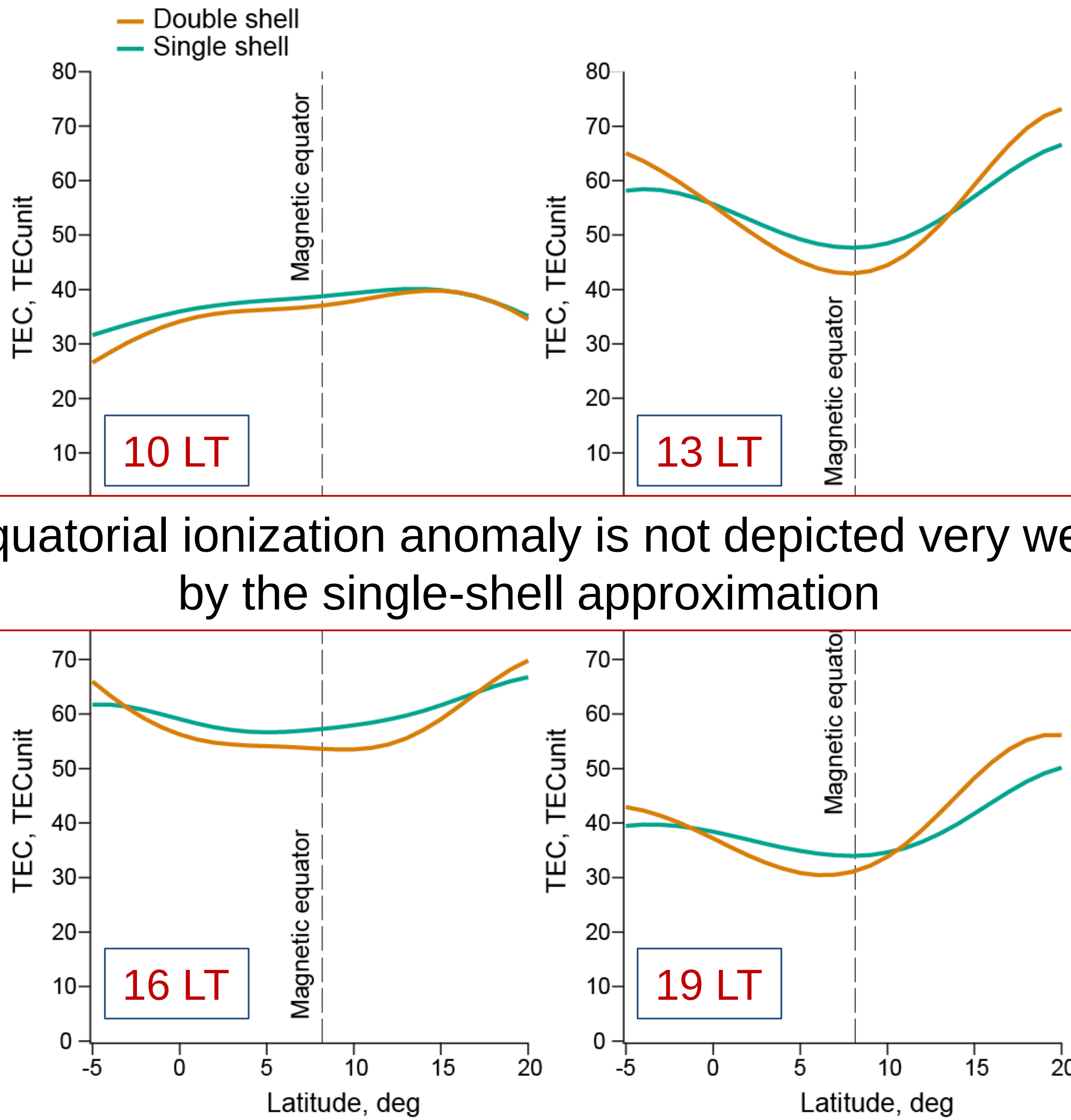
Comparison: double- and single-shell models



Comparison: double- and single-shell models

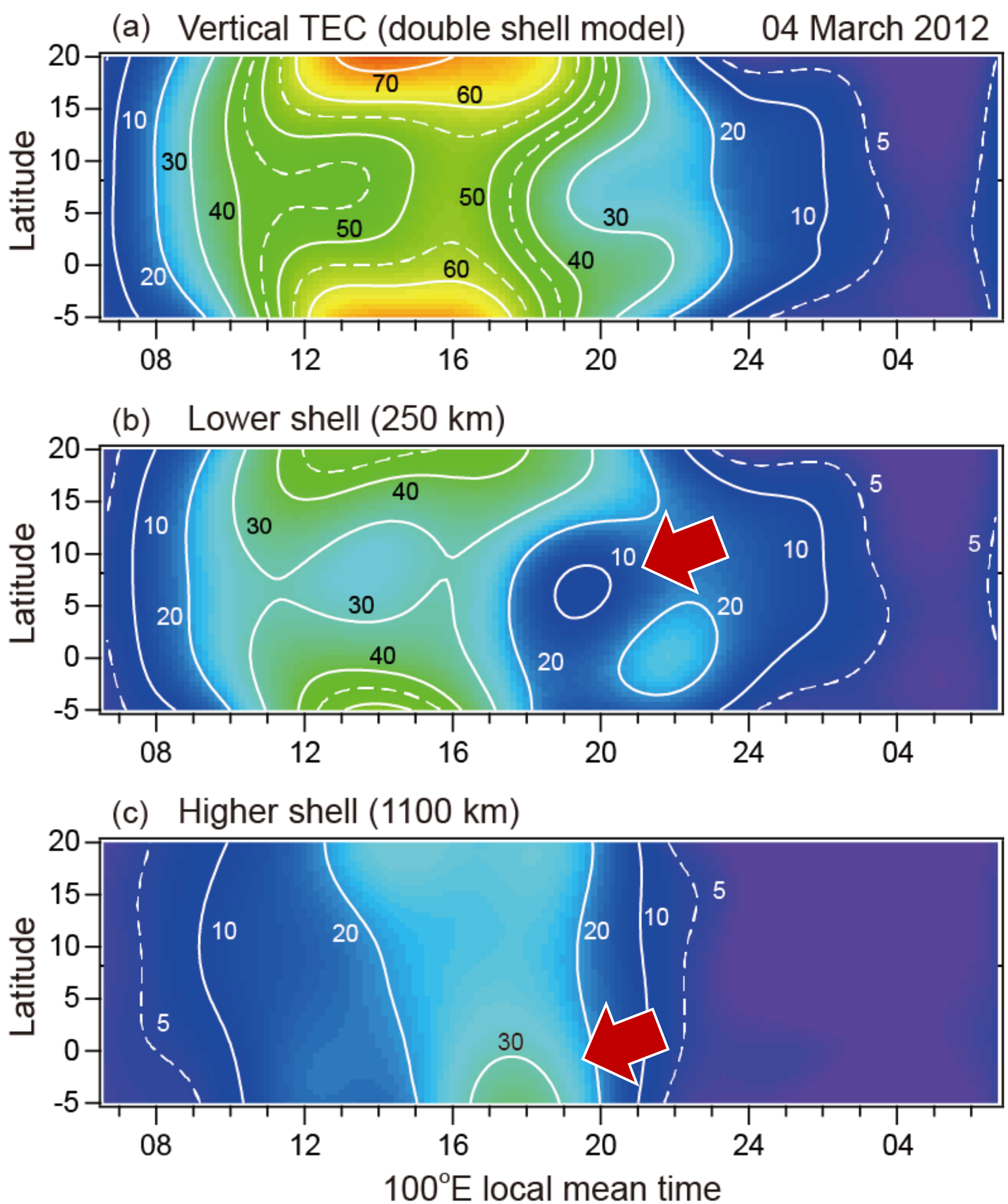


Comparison: double- and single-shell models



Equatorial ionization anomaly is not depicted very well by the single-shell approximation

Each shell of double-shell model

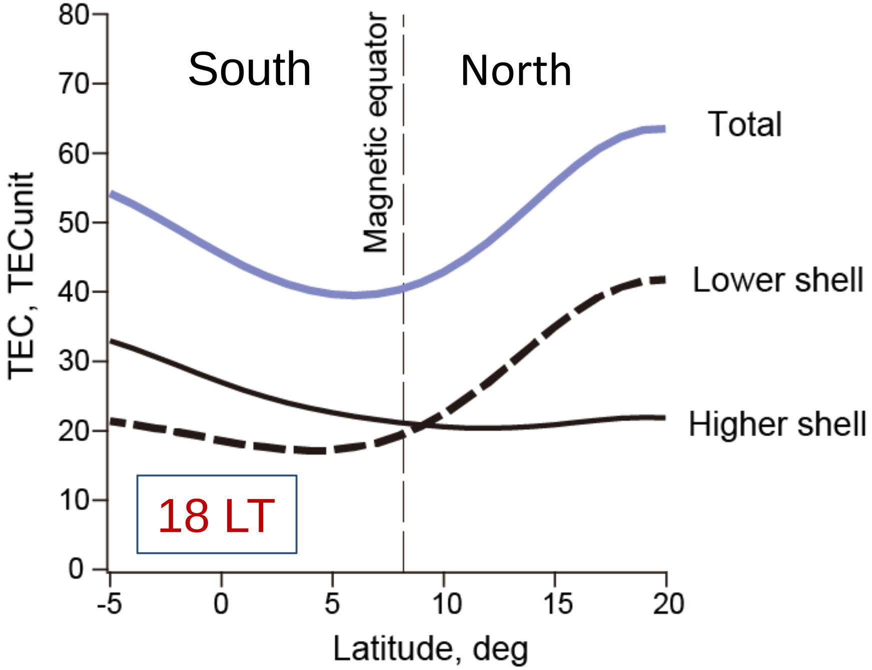


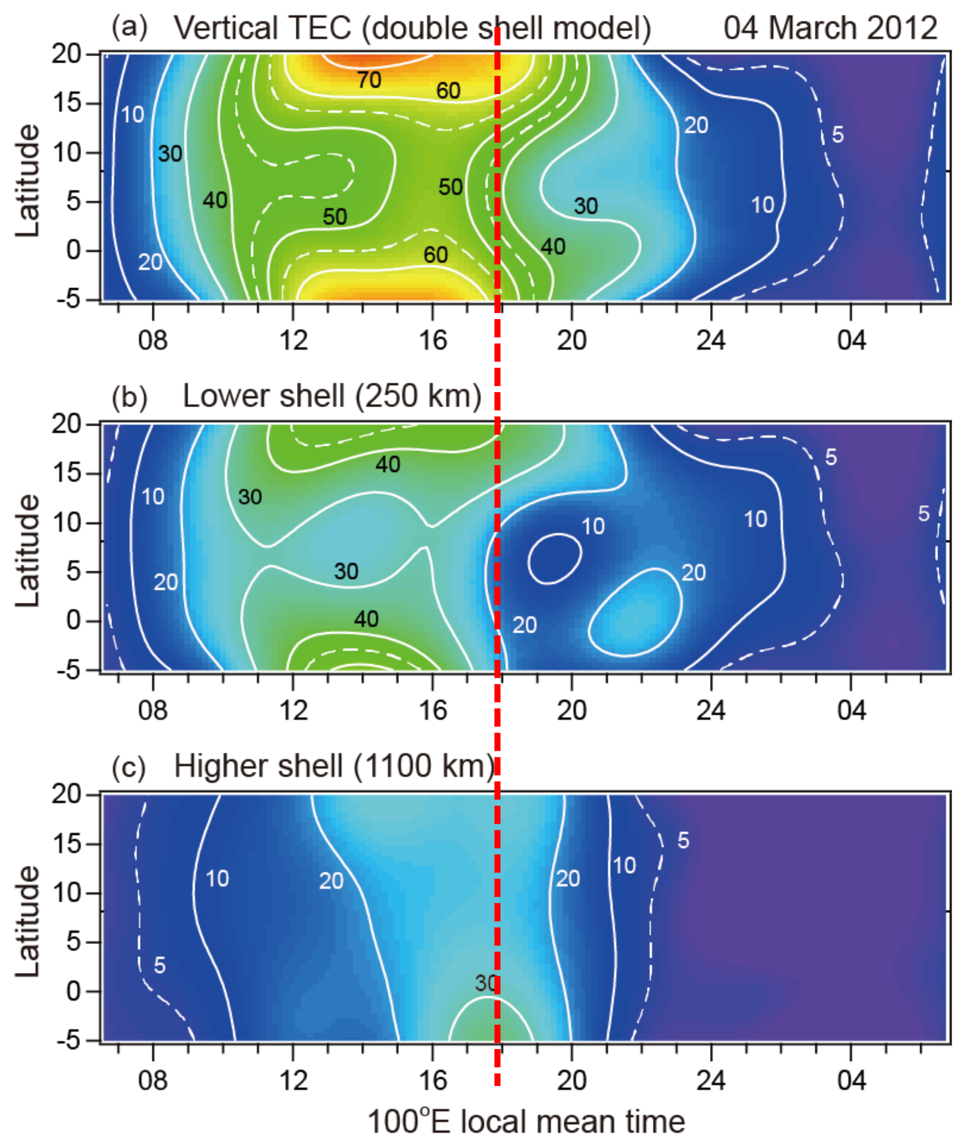
Total

Lower shell

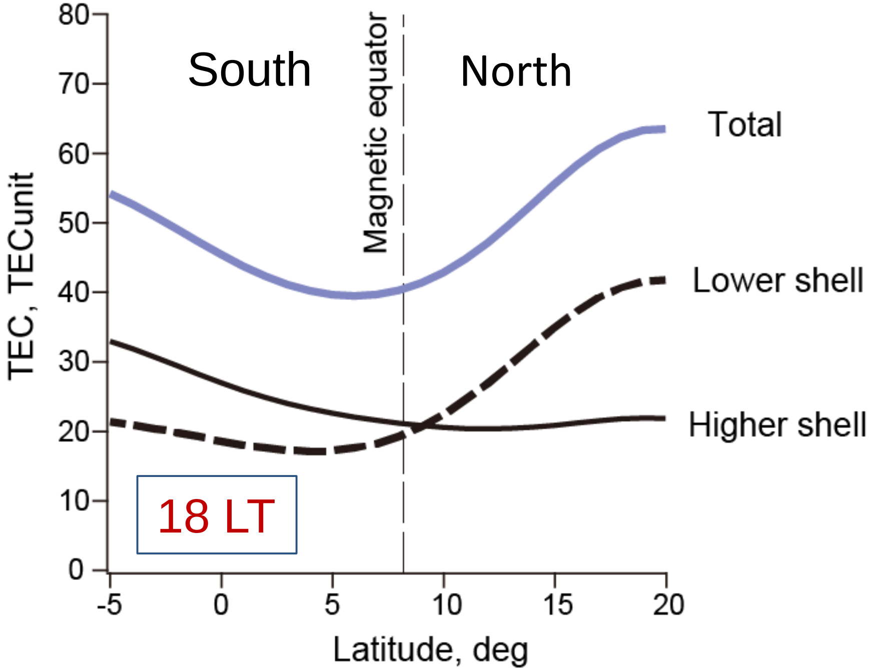
Higher shell

North-south asymmetry in each shell

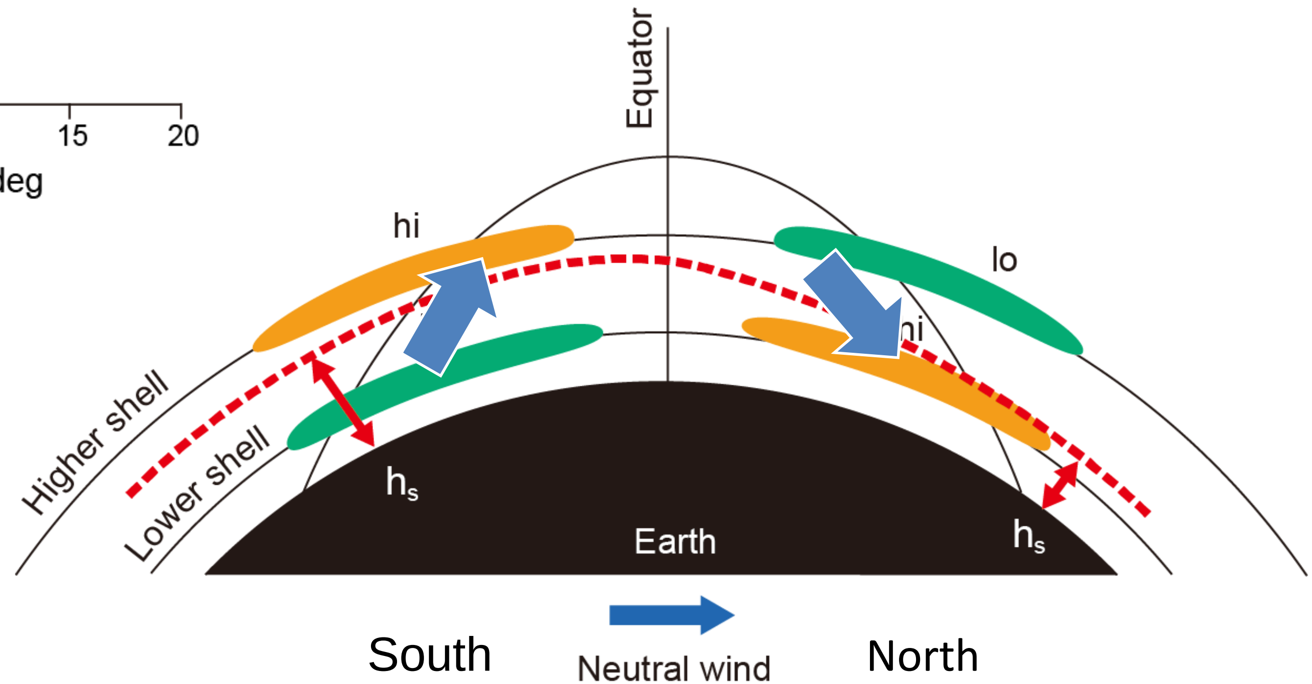




Interpretation of N-S asymmetry



Hemispheric asymmetry can be a measure of the neutral wind.



Summary

double-thin shell parameterization in TEC estimation achieved that:

⇒ The accuracy of TEC estimation is improved.

⇒ Equatorial ionization anomaly is more correctly captured compared with single-layer model.
(Single-layer model is not very suitable for the equatorial ionosphere.)

⇒ The method provides information on the ionosphere and thermosphere dynamics.

End of slides