Numerical modeling of metallic ion species Fe^+, Mg^+, and Na^+ and studies of the layer structures in mid-latitude ionosphere

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Abstract This study focusing on establishing a time dependent theoretical numerical model that are capable of simulating primary ion species/electron in mid/low-latitude ionosphere E-F-region. The layer structures in ionosphere including sporadic-E layers(Es), intermediate layers, neutral metal layers, thermospheric metal layers and related scientific questions are studied by the "Mid-latitude ionospheric layers model (MLIL)". In addition to nonmetallic species, the MLIL model take chemical reaction cycle of the metallic species Fe/Fe^+, Mg/Mg^+, and Na/Na^+ into account and consider the dynamic effects of diffusion, tidal wind, and Electric field in ionosphere.

1 Science goals:

(1) Establishing a numerical model that is capable of simulating ionosphere layer structure with taking metallic species Fe Mg Na into account. (2) Model simulating the case of rocket observation (Roddy et al. 2004) with appearance of Es layer & Intermediate layer in nighttime ionosphere E-region. (3) Estimating the ratio of O_2^+/NO^+ in Sporadic E layers where the O_2^+ & NO^+ densities reduce when the Sporadic E layer was developing.

2 MLIL model developments

Species considered in MLIL model

Nonmetallic Ion : $O^+(^2P)$, $O^+(^2D)$, N_2^+, $O^+(^4S)$, N^+, O_2^+, NO^+

Nonmetallic Neutral : O, O_2, O_3, H, H_2, $N(^2D)$, $N(^4S)$, N_2, NO, H_2O, CO_2

Metallic Ion (Fe) : Fe^+, FeO^+, FeN_2^+, FeO_2^+

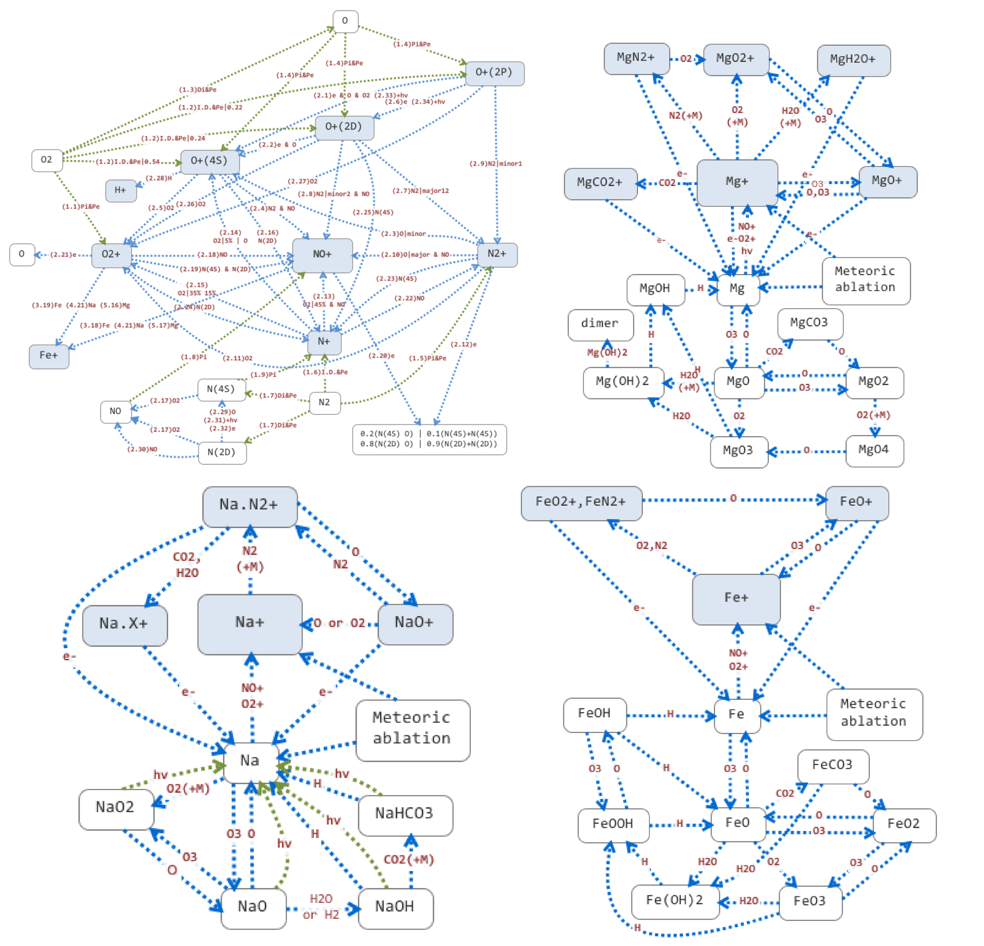
Metallic Ion (Mg) : Mg^+, MgO^+, MgN_2^+, MgO_2^+, Mg^+H_2O, Mg^+CO_2

Metallic Ion (Na) : Na^+, NaO^+, NaN_2^+, Na^+H_2O, Na^+CO_2

Metal Fe : Fe, FeO, FeO_2, FeO_3, FeOH, $Fe(OH)_2$

Metal Mg : Na, NaO, NaO_2, NaOH, $NaHCO_3$

Metal Na : Mg, MgO, MgO_2, MgO_3, MgO_4, $MgCO_3$, MgOH, $MgOH_2$



Continuity equation

$$\frac{\partial n_i}{\partial t} = S_{i\_M} + q_i^{P.I.} + q_i^{P.E.} + q_i^{D.I.} + Q_i^{C.R.} + L_i^{C.R.} - \nabla\left(n_i\vec{V_i}\right)$$

- S_{i_M}: Source inputs from meter Ablation and sputtering.
- $q_i^{P.I.}$: Photoionization production rate of i-th ion species. $\left(n_i\sum_\lambda \sigma_i^{(i)} p_{i,k} I\right)$
- $q_i^{P.E.}$: Photoelectron production rate of i-th ion species. $\left(n_i\sum_\lambda \sigma_i^{(i)} P_i p_{i,k} I\right)$
- $q_i^{D.I.}$: Dissociation ionization production rate of i-th ion species.
- $Q_i^{C.R.} + L_i^{C.R.}$: Ion production rate and ion loss flux by chemical reaction.
- $\nabla\left(n_i\vec{V_i}\right)$: Transportation term

Ion velocity

$$\vec{V_i} = \vec{V_i^N} + \vec{V_i^{GP}} + \vec{V_i^E}$$

Neutral wind effects:

$$\left(\frac{\vec{V_n}\cdot\vec{B}}{1+\xi^2}\frac{\vec{B}}{B^2} + \frac{\xi}{1+\xi^2}\frac{\vec{V_n}\times\vec{B}}{B} + \frac{\xi^2}{1+\xi^2}\vec{V_n}\right)$$

E-field effects:

$$\left(\frac{\xi}{1+\xi^2}\frac{\vec{E}}{B} + \frac{c}{1+\xi^2}\frac{\vec{E}\times\vec{B}}{B^2} + \frac{q\left(\vec{E}\cdot\vec{B}\right)\vec{B}}{m_i\nu_{in}\left(1+\xi^2\right)B^2}\right)$$

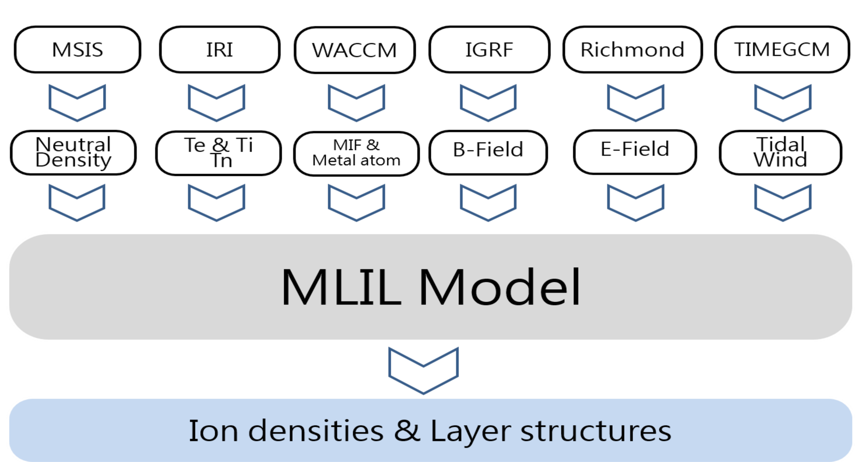
Gravity & pressure effects:

$$\left(\frac{\left(\vec{F_{gp}}\cdot\vec{B}\right)\vec{B}}{m_i\nu_{in}\left(1+\xi^2\right)B^2} + \frac{c\xi\vec{F_{gp}}}{\left(1+\xi^2\right)qB} + \frac{c\vec{F_{gp}}\times\vec{B}}{\left(1+\xi^2\right)qB^2}\right)$$

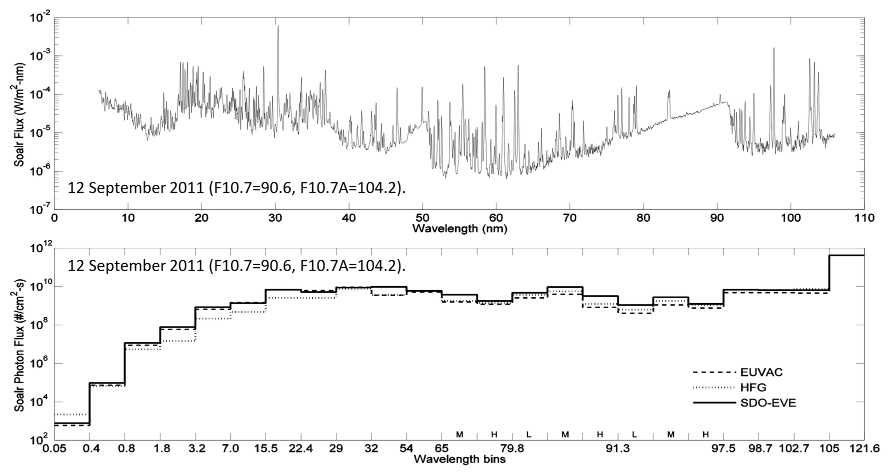
$\left(\xi = \frac{\nu_{in}}{\Omega_i}\right)\left(\vec{F_{gp}} = m_i g - \frac{\nabla p_i}{n_i}\right)$

c = speed of light
$\vec{V_n}$ = neutral wind velocity.
p_i = ionic pressure

Model Input



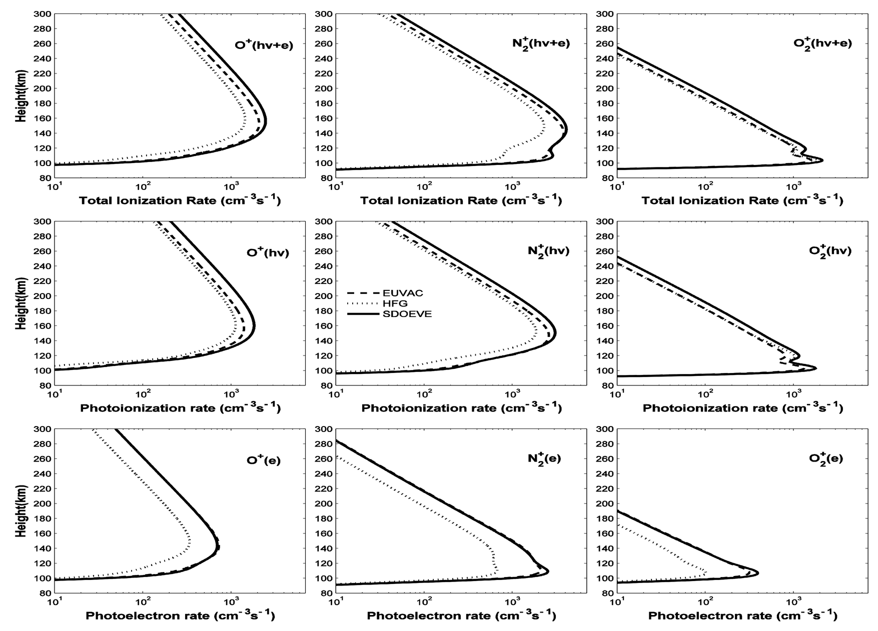
Solar irradiance flux (SDE-EVE,EUVAC,HFG)



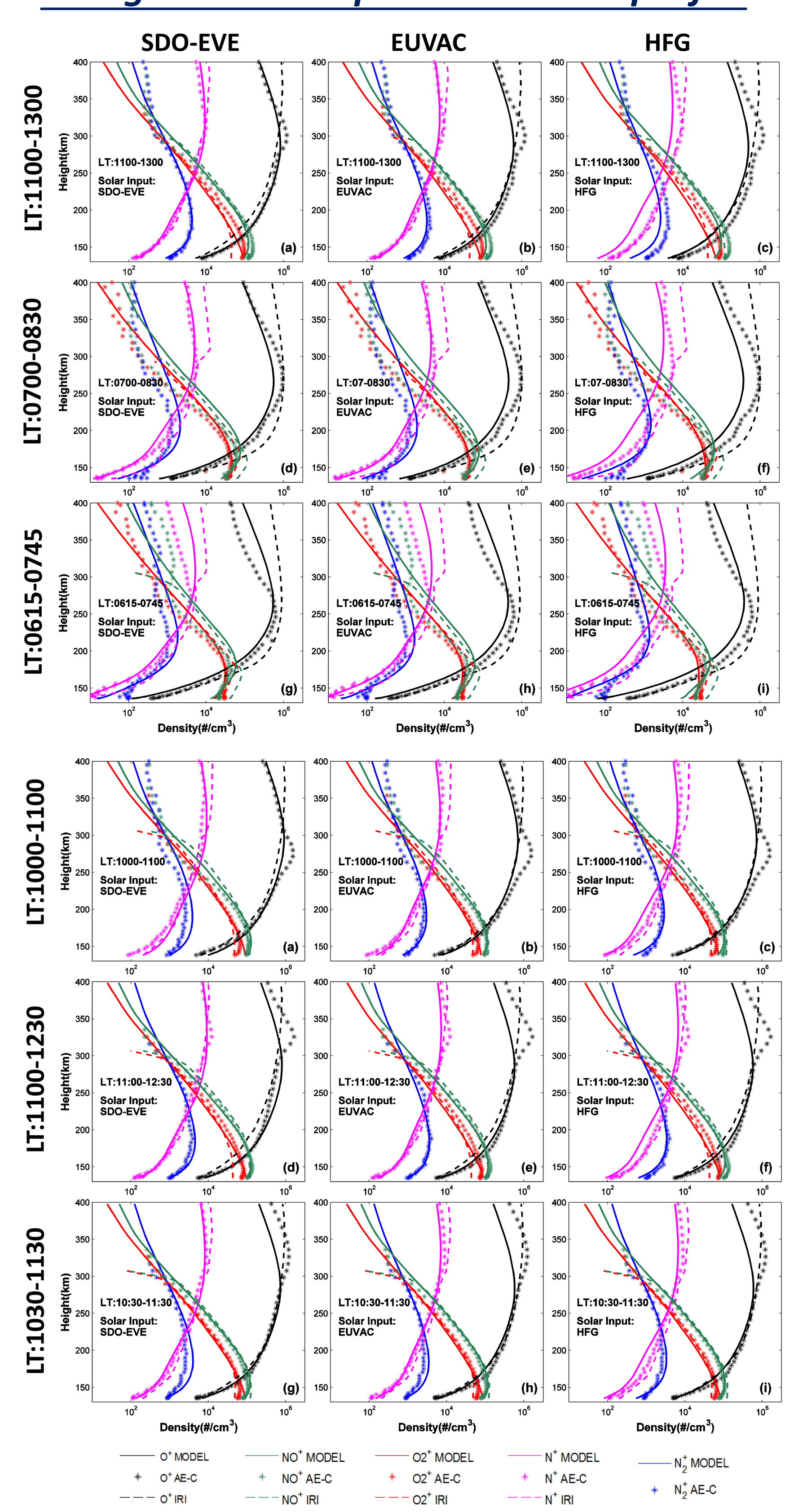
Production Rate

$$q_{ij}(l, z_h, \chi) = n_j(z_h)\sigma_j^{(i)} p_j(l) I(z_h)$$

$$q_{ej}(l, z_h, \chi) = n_j(z_h)\sigma_j^{(i)} p_j(l) Pe(\lambda, l) I(z_h)$$



Background ionosphere densities profile



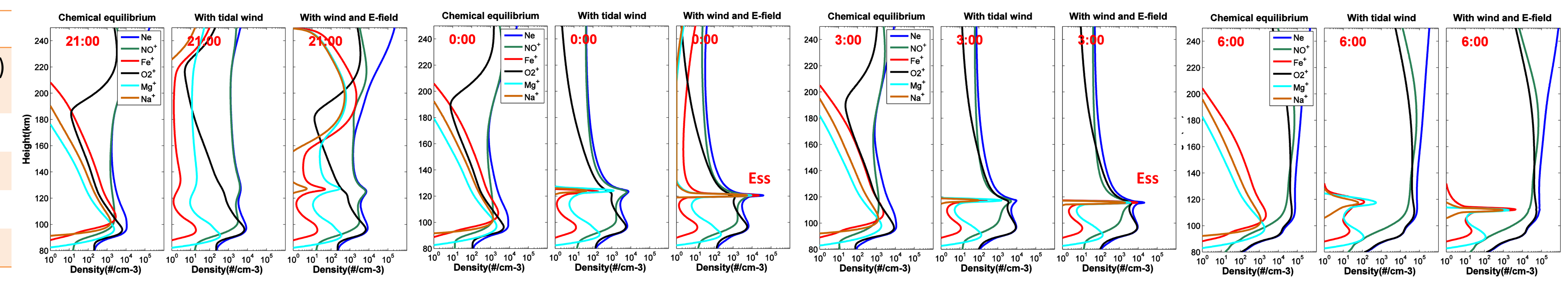
3 Simulating the layer structure

Left panel	Middle panel (Case : W)	Right panel (Case : WE)
• Chemical equilibrium • Diffusion	• Chemical reaction • Diffusion + Ambipolar diffusion • Tidal wind	• Chemical reaction • Diffusion + Ambipolar diffusion • Tidal wind • E-field

Densities profiles at Wallops, VA (orange frame) and Taipei, Taiwan (green frame) for Ne (blue), NO^+ (green), O_2^+ (black), Fe^+ (red), Mg^+ (cyan), and Na^+ (brown) species.

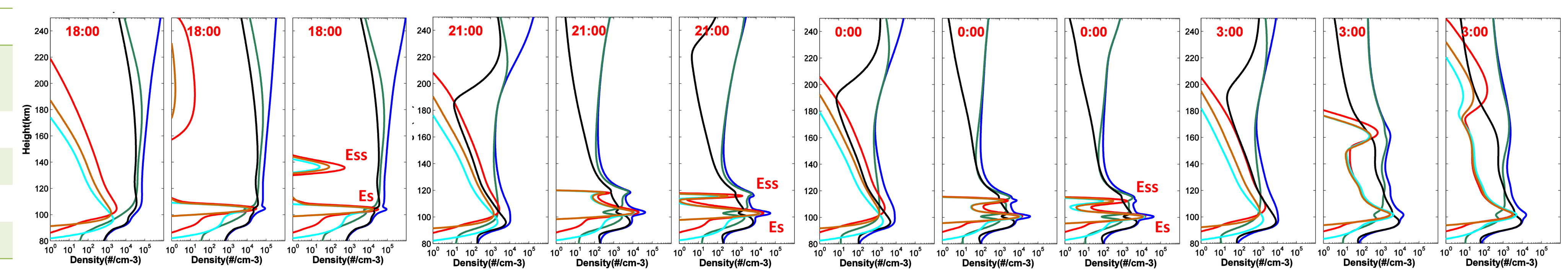
Ion densities profiles

Parameter	Values
Location	(37.8N , 75.4W) (Wallops, VA)
DOY	182
F107A	127.36
F107	131.1
Ap	8



- Only the intermediate layer(Ess) appears around 120km.

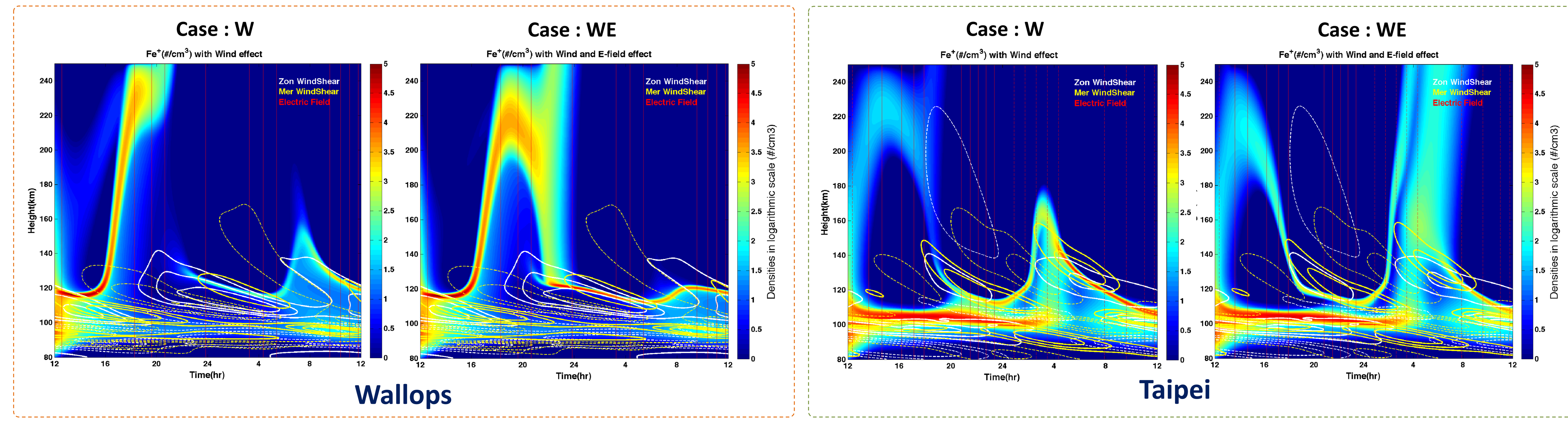
Parameter	Values
Location	(23.5N , 121E) (Taipei, Taiwan)
DOY	182
F107A	127.36
F107	131.1
Ap	8



- The Intermediate (Ess) layer develops from higher altitude and descends to 115km with average peak electron density of $8x10^3$ cm^{-3}. As to Sporadic E-layer (Es), the layer maintains an average altitude at around 100km and average peak electron density of $6x10^4$ cm^{-3}.
- The major compositions of Ess layer are nonmetallic NO^+ and O_2^+ species. The Es layers, by contrast, are composed by metallic ion species Fe^+, Mg^+, and Na^+.
- The peak heights of Ess layer are constrained above 115km. The Es layer occurs and develops between 95~115km.
- The O_2^+ & NO^+ densities are reduced to the magnitude that smaller than the metallic ions where within the Es layer the ratio of O_2^+ to NO^+ is around 10.

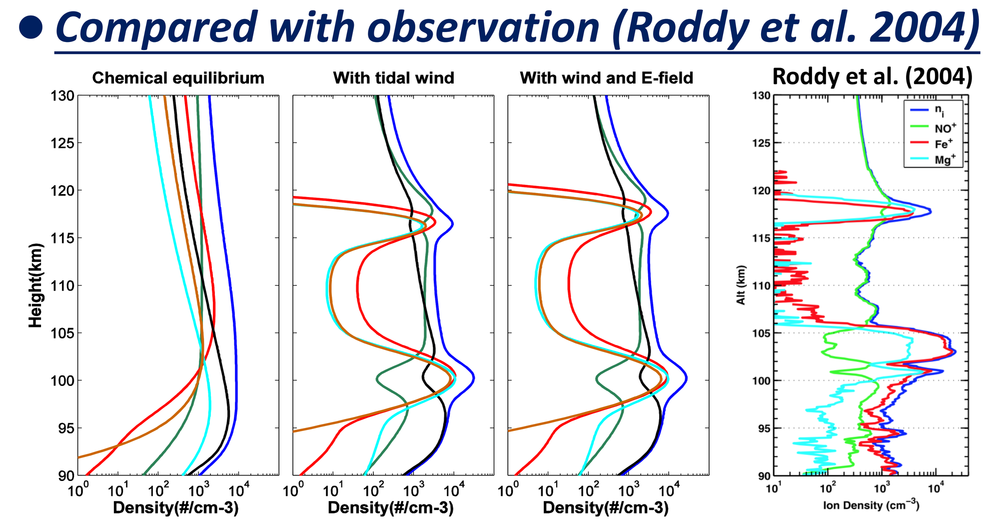
Fe^+ densities

These plots show the densities of Fe^+ (in background color map) with the tidal windshear (in curve line) and electric field (in red straight line).



- Both the Ess & Es layers are formed along with the zonal & meridional wind shear convergent region.
- Descending rates of intermediate layer (Ess) are 12~17km/h above 140km and 2~3km/h at around 120km which is identical with statistical results of Arecibo observation.
- Caused by long recombination rate with electron of metallic ion species is, and accompanies with low concentration of NO^+ and O_2^+ above E-region, the wind and E-field might easily transport the Fe^+, Mg^+, and Na^+ to higher altitude.

Compared with observation (Roddy et al. 2004)



- The results of Wallops case clearly show not in agreement with Roddy et al. (2004) rocket observation when MLIL model is inputted identical conditions (location, date, etc.).
- However, the results of Taipei case coincide with observation in pattern and magnitude, when the value of tidal wind and Electric field of Taipei (23N,121E) are used.

4 Conclusion and future work

- Overall, the SDO-EVE simulations of the densities of the atomic ionsO2+, NO+ ,O+, N+, and free electron are better than those using the EUVAC and HFG models
- Within the Es layers, the densities reduction of the ion species O_2^+ and NO^+ shows high O_2^+/NO^+ ratio.
- The metallic ion species might easily be transported to lower thermosphere from main deposition region(below 140).
- We are interested in whether it is possible to have metal atom Fe, Mg, and Na occurs above 140 km. By modulating the phase of tidal wind and E-field or change modeling location to simulate the occurrence of thermospheric Metal Layers in mid-latitude.
- Model simulating the mid/low latitude occurrence of layer structure and irregularities of ionosphere by considering / inputting the 2D tidal wind and E-field.

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