Analysis of the diurnal variation of the global electric circuit (GEC) from different numerical models

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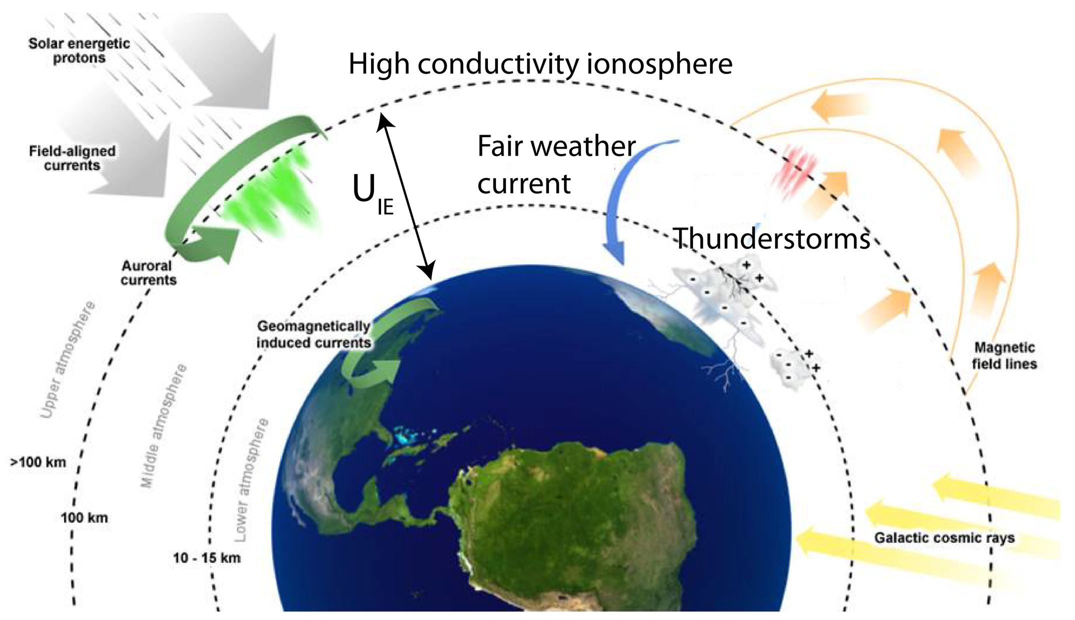
Introduction



- GEC – Layer between high conductivity Earth and Ionosphere.
- Main generators of GEC – Thunderstorms produce upward current.
- Downward fair weather current toward Earth closes GEC.
- Diurnal variations of the GEC are reflected in diurnal variations of the fair weather electric field measured near the ground.
- Variations of the fair weather electric field near the ground were first established based on measurements from the Carnegie ship in the first quarter of the 20th century and subsequently linked to diurnal variations of electrified clouds in our atmosphere [e.g., Williams and Mareev, Atm. Res., 135, 208, 2014].
- **Motivation:** Model and compare diurnal variation using several different modeling strategies [Jánský and Pasko, JGR, 119, 10184, 2014; Bayona et al., Geosci. Model Dev. Discuss., 8, 3007, 2015; Peterson et al., JAOT, 32, 1429, 2015; Lucas et al., JGR, 120, 12054, 2015; Kalb et al., JGR, submitted, 2016].

GEC model equations

- **Steady state continuity equation:**

$$\vec{\nabla}\cdot\vec{j} = S_{\mathrm{cur}}\,, \qquad (1)$$

where current density $\vec{j}=\sigma\vec{E}$ is the product of electric field $\vec{E}$ and conductivity σ, and S_{cur} is the current source term.

- Steady state continuity equation is solved in two steps:
  - Free of sources continuity equation to obtain resistance of atmosphere R_{a}

$$\vec{\nabla}\cdot\vec{j}_{\mathrm{f}} = 0\,,\quad U_{\mathrm{TIB}} = 1\,\mathrm{V} \qquad (2)$$

$$R_{\mathrm{a}} = \frac{U_{\mathrm{TIB}}}{I_{\mathrm{f}}}\,,\quad I_{\mathrm{f}} = \oint\!\!\oint_{\mathrm{TIB}} \vec{j}_{\mathrm{f}}\cdot \mathrm{d}\vec{S} \qquad (3)$$

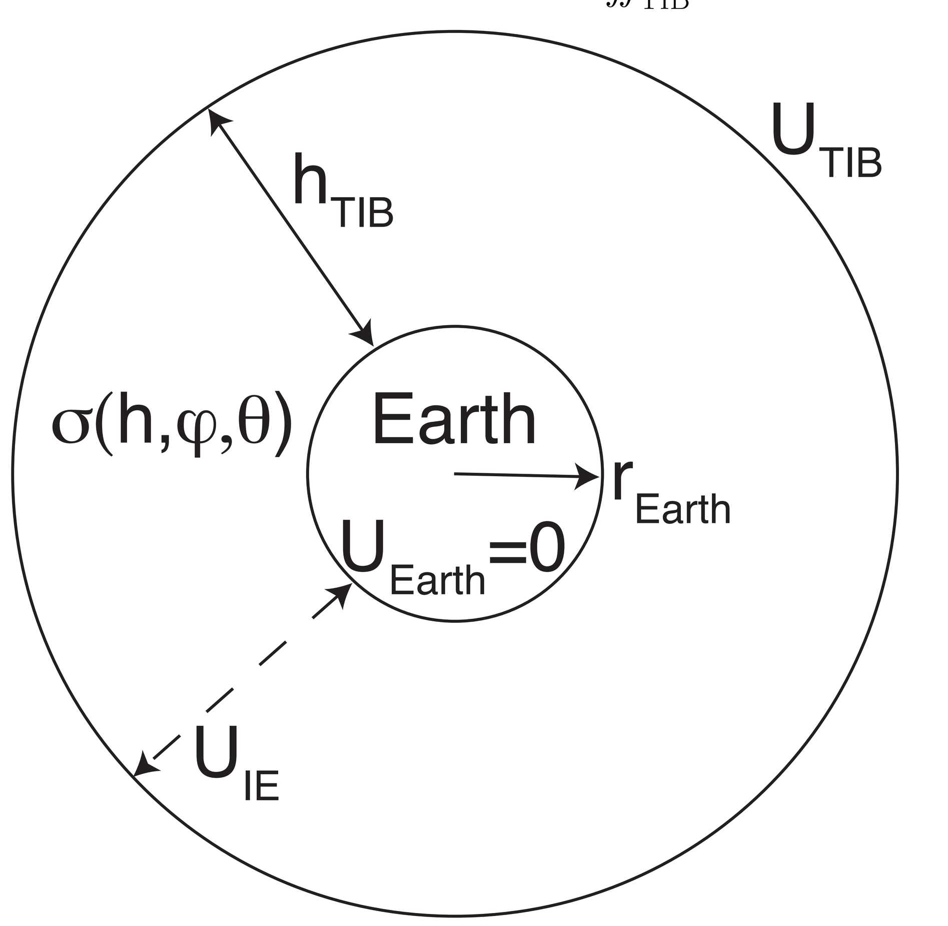
  - Continuity equation with dipole sources to obtain upward current

$$\vec{\nabla}\cdot\vec{j}_{\mathrm{u}} = S_{\mathrm{cur}}\,,\quad U_{\mathrm{TIB}} = 0\,\mathrm{V} \qquad (4)$$

$$I_{\mathrm{u}} = \oint\!\!\oint_{\mathrm{TIB}} \vec{j}_{\mathrm{u}}\cdot \mathrm{d}\vec{S} \qquad (5)$$

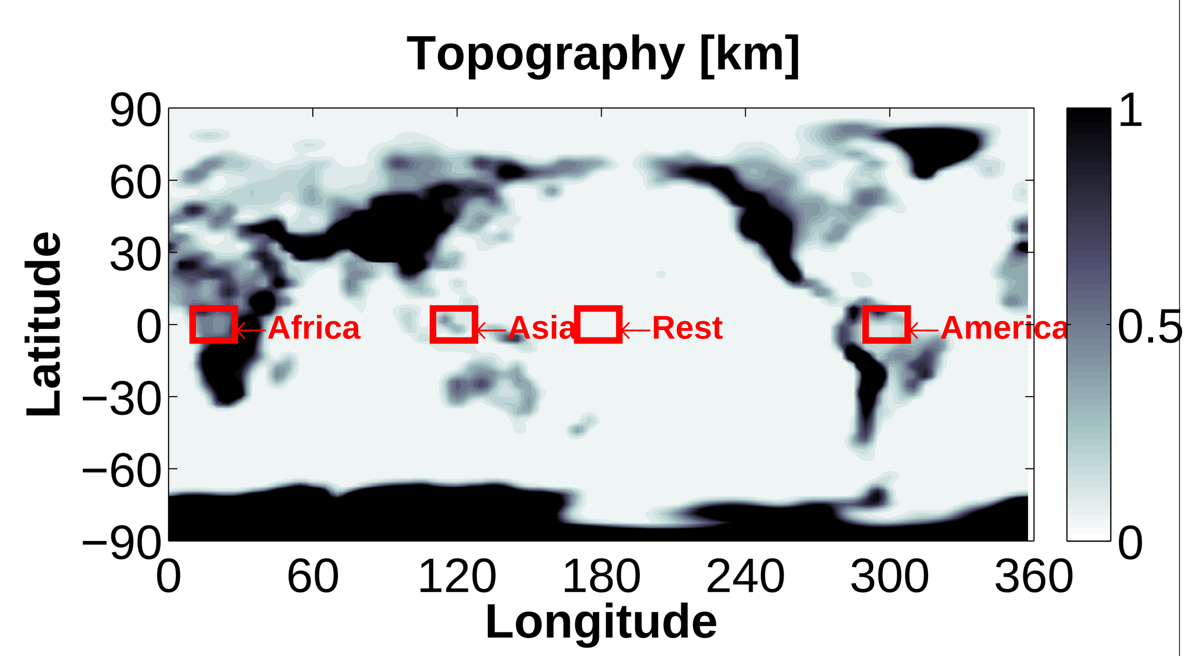
- Provides solution with balanced zero total current at TIB I_{TIB}

$$\vec{j} = \vec{j}_{\mathrm{u}} + R_{\mathrm{a}}I_{\mathrm{u}}/1\,\mathrm{V}\,\vec{j}_{\mathrm{f}}\,,\quad I_{\mathrm{TIB}} = \oint\!\!\oint_{\mathrm{TIB}} \vec{j}\cdot\mathrm{d}\vec{S} = 0 \qquad (6)$$

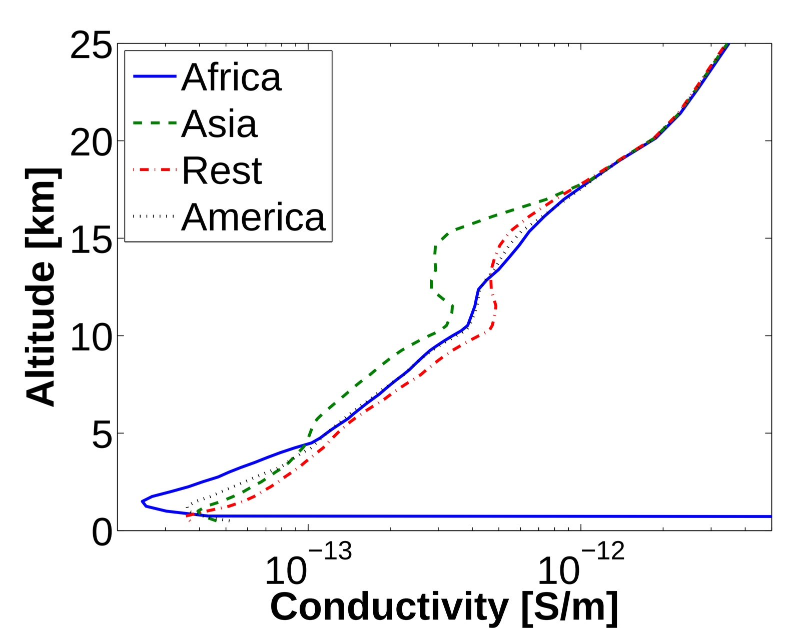


GEC models using current dipoles

- We use two 3-D GEC models:
  - RBF model based on radial basis function (GEC-RBFFD v1.0) [Bayona et al., 2015]. Code available at https://bitbucket.org/vbayona/gec_rbffd
  - FVS model based on finite volume method with structured mesh [Jánský and Pasko, 2014]
- $r_{\mathrm{Earth}} = 6371\,\mathrm{km}$, $h_{\mathrm{TIB}} = 60\,\mathrm{km}$
- Earth surface is used either flat or with topography.
- Source dipole currents are input based on data obtained from global circulation model INMCM4.0. [Mareev and Volodin, GRL, 41, 9009, 2014]. The location of source dipoles is shown in figure below.



- Conductivity inputs are either:
  - $\sigma(h) = 5\times10^{-14}\exp(h/l)\,\mathrm{S\,m^{-1}}$, $l = 6\,\mathrm{km}$
  - Conductivity from Whole Atmosphere Community Climate Model (WACCM) is calculated for the whole year 2007 with conditions including ^{222}Rn ionization, aerosol and clouds [Baumgaertner et al., JGR, 118, 9221, 2013; Baumgaertner et al., Atmos. Chem. Phys., 14, 8599, 2014].



Methods using current above storms

- The alternative method of obtaining current flowing upwards to the TIB, I_{u}, uses the knowledge of global distribution of current density at 20 km produced from thunderstorms and electrified shower clouds.
- Peterson et al. [2015,2016] use ice scattering signals from 85 GHz passive microwave observations to characterize the electric fields above clouds overflown by aircraft. Ice scattering signal is globally measured by TRMM satellite — these data are labeled TRMM-P15.
- Kalb et al. [2016] use mean currents above electrified clouds obtained from overflights combined with total storm count from precipitation and cloud feature database based on TRMM satellite observations [Liu et al., JAS, 67, 309, 2010] — these data are labeled TRMM-K14.
- Kalb et al. [2016] also develops method how to obtain current density at 20 km from climate model CESM — these data are labeled CESM-K16.

Resistance of the atmosphere

- First to validate the 3-D GEC models we evaluate only equations (2) and (3) and compare them with analytical result for exponential conductivity obtained from integral:

$$R = \left[\int_0^{2\pi}\!\!\int_0^{\pi}\left(\int_{\mathrm{surface}}^{60\,\mathrm{km}}\frac{\mathrm{d}r}{\sigma\,r^2}\right)^{-1}\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi\right]^{-1} \qquad (7)$$

- Resistances in Ohm, calculated by FVS and RBF models are compared with integral approach. The three cases of conductivity are compared. The first is using exponential conductivity, the second is exponential conductivity including topography and the third one corresponds to the yearly average of conductivity obtained from WACCM for conditions including ^{222}Rn ionization, aerosol and clouds.

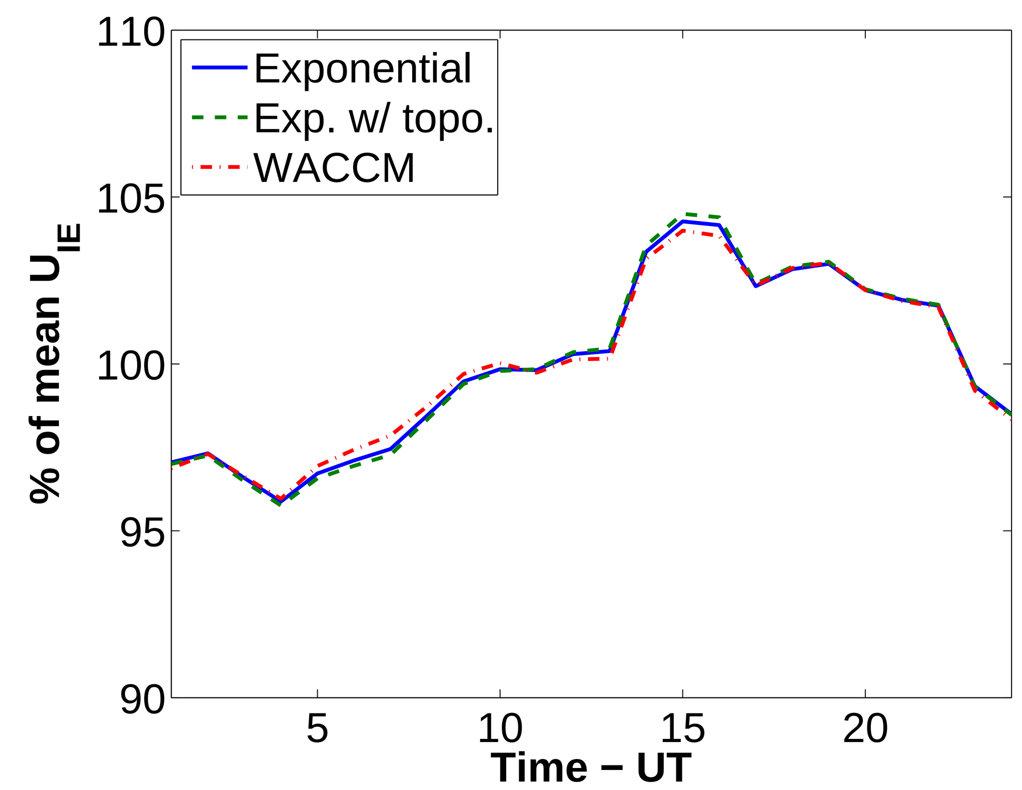
σ — Model	FVS	RBF	Integral
Exponential	234.9	235.4	234.8
Exp. w/ topo.	225.2	225.1	224.7
WACCM	190.7	190.0	193.5

GEC models with different conductivity

- We apply above mentioned three conductivity cases to FVS model with current dipoles derived based on work of Mareev and Volodin [2014].
- Diurnal variation of U_{IE} around its mean value $\overline{U_{\mathrm{IE}}}$ is plotted:

$$\%\ \text{of mean}\ U_{\mathrm{IE}} = \frac{U_{\mathrm{IE}}}{\overline{U_{\mathrm{IE}}}}\,. \qquad (8)$$

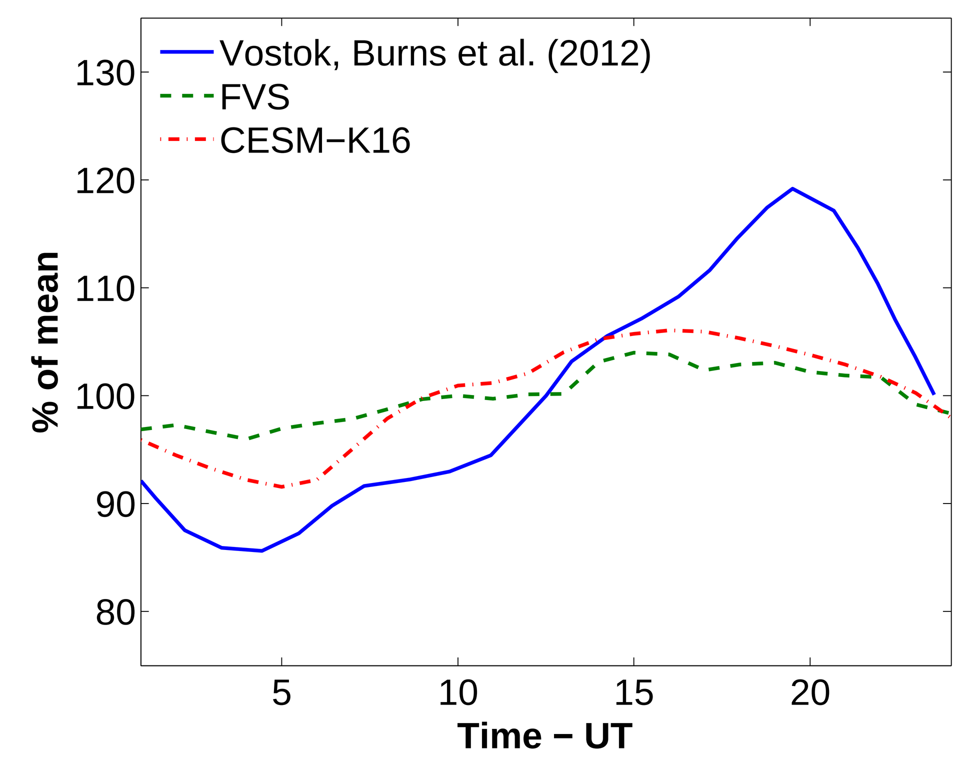
- Elevated terrain beneath the thunderstorm increases the ionospheric potential [Jánský and Pasko, JGR, 120, 10654, 2015] — The average elevation beneath the thunderstorms in Africa ∼500 m is not significantly higher than other regions causing very small variation for case Exp. w/ topo.
- The use of yearly averaged conductivity from WACCM doesn't modify diurnal variation either.



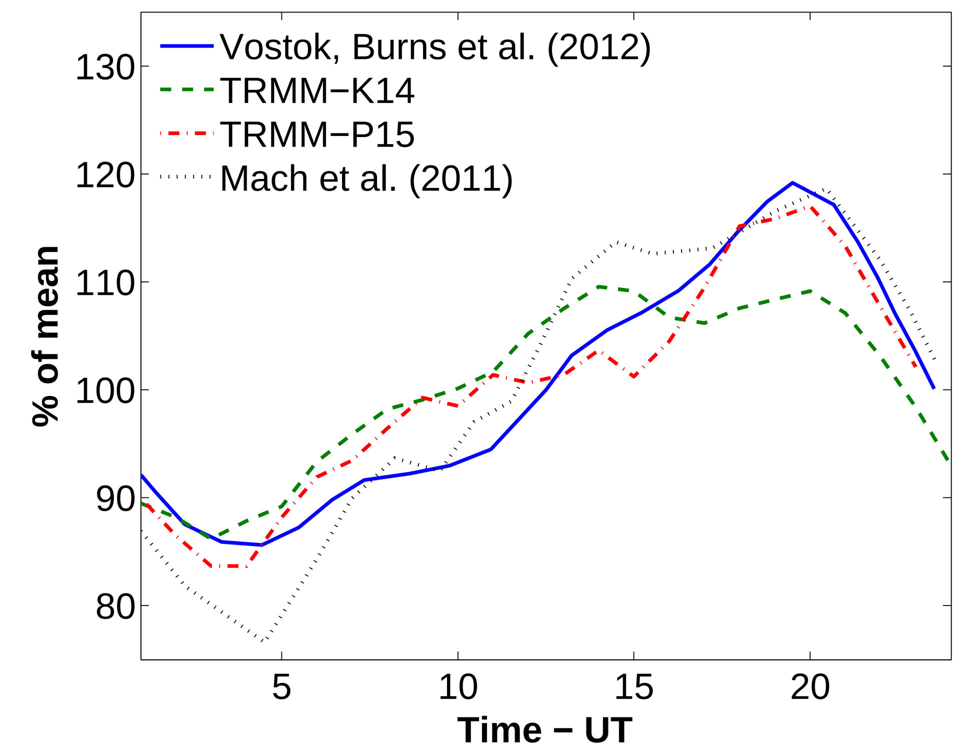
Conclusions

- The two GEC three dimensional models (RBF and FVS) are validated by applying them to fundamental GEC problems of calculating GEC resistance and fair weather electric field.
- It was found that model results obtained using topography and yearly averaged conductivity from climate model WACCM differ very weakly from diurnal variation obtained using exponential conductivity.
- Diurnal variation of GEC obtained using different methods were compared. In general results based on climate models show smaller amplitudes while methods using overflights combined with satellite data agree better with fair weather field measurements at Vostok.
- Full description of results will be published in [Jánský et al., JGR, 2016, to be submitted].

Comparison of diurnal variations



- Experimental measurements of fair weather electric field from Vostok are used as reference [Burns et al., JAS, 69, 2061, 2012].
- FVS model based on yearly averaged conductivity profile from WACCM and current sources from Mareev and Volodin [2014] shows small amplitude.
- Results obtained using parametrization developed by Kalb et al. [2016] combined with climate model CESM provides higher amplitude but it is still smaller than experimental data.



Model	Minimum Peak	Minimum Time	Maximum Peak	Maximum Time
Vostok, Burns et al. (2012)	86%	4:00	119%	19:30
FVS	96%	4:00	104%	15:00
CESM-K16	92%	5:00	106%	16:00
TRMM-K14	86%	3:00	110%	14:00
TRMM-P15	84%	4:00	117%	20:00
Mach et al. (2011)	77%	4:30	119%	20:30

- Results based on parametrization combined with satellite data provides better agreement with experiments.
- TRMM-K14 is based on mean current of clouds based on their location (land and ocean) and type (thundercloud and electrified shower cloud). Diurnal variation shows 2 maxima structure during afternoon.
- TRMM-K15 is based on ice scattering signals and distinguishes each electrified cloud contribution separately. The diurnal variation shows one maximum structure during afternoon agreeing with Vostok.
- Mach et al. [JGR, 116, D05201, 2011] presents the best agreement in available literature. However the role of electrified shower clouds in their work is not accurately known. It was demonstrated that if electrified shower clouds count would increase as observed by Liu et al. [2010], their results would be closer to TRMM-K14 than measurements from Vostok.
- TRMM satellite covers latitudes between [−35° : 35°]. Analysis from CESM model shows that the amplitude of diurnal variation is decreased by third if the whole Earth is used compared to TRMM latitudes.

Acknowledgements

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