Prokhorov, B., Zolotov, O. V. (2017): Comment on “An improved coupling model for the lithosphere-atmosphere-ionosphere system” by Kuo et al. [2014]. - *Journal of Geophysical Research*, *122*, 4, pp. 4865—4868.

DOI: http://doi.org/10.1002/2016JA023441

AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Space Physics

COMMENT
10.1002/2016JA023441

This article is a comment on *Kuo et al.* [2014] doi:10.1002/2013JA019392.

Key Points:
- Kuo et al. (2014) reported an improved model of LAI coupling
- Their formulation for ground-to-ionosphere region of the Earth is equivalent of Ohm's law with homogeneous conductivity
- Therefore, Kuo et al. (2014) formulation seems not to describe correctly electric currents, flowing between the Earth and ionosphere

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Citation:
Prokhorov, B. E., and O. V. Zolotov (2017), Comments on "An improved coupling model for the lithosphere-atmosphere-ionosphere system" by Kuo et al. [2014], *J. Geophys. Res. Space Physics*, *122*, 4865–4868, doi:10.1002/2016JA023441.

Received 8 SEP 2016
Accepted 16 FEB 2017
Accepted article online 23 MAR 2017
Published online 4 APR 2017

Comment on "An improved coupling model for the lithosphere-atmosphere-ionosphere system" by Kuo et al. [2014]

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Abstract The lithosphere-atmosphere-ionosphere coupling problem is a challenge nowadays. It requires understanding of (a) the physical mechanism that is responsible for plasma disturbances generation at ionospheric heights, (b) the penetration of seismogenic impact from the ground into the ionosphere through the underlying neutral atmosphere, and (c) on-the-ground (in-the-ground) sources generation. Kuo et al. (2014) reported an improved model of lithosphere-atmosphere-ionosphere coupling that includes the ionosphere as well as the underlying neutral atmosphere (from the ground up to the ionosphere altitudes, i.e., 60–80 km above the Earth's surface). The main feature of the Kuo et al. (2014) approach is that they find ground-to-ionosphere currents from $\nabla \cdot \vec{J} = 0, \vec{J} \equiv -\nabla\psi$ system of equations. In contrast to Kuo et al. (2011), where well-known $\nabla \cdot \vec{J} = 0, \vec{J} = \hat{\sigma}\vec{E}, \vec{E} = -\nabla\phi$ equations are used, Kuo et al. (2014) looks better as it does not require the knowledge of electric conductivity σ profile. In this paper we show that the Kuo et al. (2014) equations can be obtained as a special case of the Kuo et al. (2011) ones, given the electric conductivity tensor is a spatially invariant scalar. Therefore, Kuo et al. (2014) formulation may not describe correctly electric currents flowing between the Earth and the ionosphere.

1. Introduction

In the paper by *Kuo et al.* [2014], an improved coupling model for the lithosphere-atmosphere-ionosphere (LAI) system is presented in order to explain total electron content (TEC) variations preceding strong earthquakes. The *Kuo et al.* [2014] paper is a further development of the *Kuo et al.* [2011] research. The principle feature of *Kuo et al.* [2014] in contrast with *Kuo et al.* [2011] is that they obtain atmosphere electric currents from the solution of $\nabla \cdot \vec{J} = 0, \vec{J} \equiv -\nabla\psi$ equations. It could be a step toward understanding of LAI coupling processes. In this paper we discuss the solution proposed by *Kuo et al.* [2014] and show that it could not be accepted in current form.

2. Rationale

Nowadays, a number of papers report a possible linkage of ionosphere plasma disturbances with strong earthquakes' preparation process. Nevertheless, a full noncontradictory explanation of LAI coupling theory has not been formulated yet. The hypothesis should consistently explain all (quantitatively describe) the observed features and possibly predict the new ones.

To explain the penetration of seismic processes into the ionosphere, three channels have been considered: (a) chemical channel; (b) wave channel, including internal gravity and acoustic gravity waves; and (c) electromagnetic channel. The chemical channel is usually rejected due to its low efficiency and small speed of the impact propagation. The electromagnetic channel is the focus of *Kuo et al.* [2014] as well as many other researchers. The electromagnetic channel itself can be divided into three separate parts: (a) the physical mechanism that is responsible for plasma disturbances generation at ionospheric heights, (b) the penetration of seismogenic impact from the ground into the ionosphere through the underlying neutral atmosphere, and (c) on-the-ground (in-the-ground) sources generation.

In the frame of the electromagnetic mechanism of LAI coupling there are a few attempts to model TEC disturbances' formation at ionospheric altitudes using 3-D ionosphere models [e.g., *Namgaladze et al.*, 2009;

Liu et al., 2011; *Klimenko et al.*, 2011; *Zolotov et al.*, 2012]. The seismic influence in those studies is imposed as ionosphere lower boundary conditions (at 60–80 km altitude) for electric currents or fields. The results obtained depend strongly on the conditions being used. To model "seismogenic impact," electric fields of presumably seismic origin are set according to a few available observations [e.g., *Zolotov*, 2015]. The electric currents are set to obtain the electric fields' disturbances similar to a few observed ones. No in situ measurements of presumably seismogenic electric currents crossing the lower boundary of the ionosphere are available. This lack of measurements engenders skepticism of the model experiments, such as the following remark from an anonymous reviewer: "There should be at least any experimental evidence of such current existence. Except papers of Sorokin et al. who also introduce artificial current to obtain necessary results there no any paper reporting such currents reality. So it looks like reproduction of pseudo-science. One paper based on the wrong assumptions gives birth to other paper and creates impression of some trend, but in reality this trend is based on nothing" (anonymous reviewer). Moreover, the lack of LAI coupling models for neutral atmosphere (altitudes between the Earth's surface and the ionosphere) prevents physically consistent attribution of observed ionosphere total electron content (TEC) disturbances' with strong earthquakes' preparation processes. Therefore, development of LAI coupling models is necessary to substantiate ionospheric responses to seismic events and to investigate the physical mechanism of the observed TEC disturbances. *Kuo et al.* [2014] use the well-known ionosphere SAMI-3 model [*Huba et al.*, 2000, 2008] to reproduce ionosphere variations, setting currents at the Earth's surface as lower boundary conditions and self-consistently deriving currents flowing between the Earth and the ionosphere. The last part, namely, the Earth-ionosphere currents solution, is considered in this article.

3. Kuo et al.'s Approach to Model Neutral Atmosphere Electric Currents

Let us consider the *Kuo et al.* [2014] formulation: "The three dimensional current system is solved using $\nabla \cdot \vec{J} = 0$, where current density $\vec{J}$ is expressed by $\vec{J} \equiv -\nabla\psi$ and ψ is defined as the potential function for current density. The usage of ψ is similar to the electric potential ϕ, where the electric field $\vec{E} = -\nabla\phi$." In short, they solve

$$\nabla \cdot \vec{J} = 0, \quad \vec{J} \equiv -\nabla\psi. \tag{1}$$

Unfortunately, *Kuo et al.* [2014] do not discuss the physical meaning of the introduced potential function ψ for the electric current density. According to Helmholtz's theorem, a general vector field $\vec{F}$ (under certain conditions) can be expressed as a sum of curl-free and solenoid terms:

$$\vec{F} = -\nabla\Phi + \nabla \times \vec{W}, \tag{2}$$

where Φ is a scalar potential and $\vec{W}$ is a vector potential function. It is clear (cf. equation (1) versus equation (2)) that the *Kuo et al.* [2014] formulation neglects the term $\nabla \times \vec{W}$. *Kuo et al.* [2014] do not discuss the physical rationale for this approximation of electric currents of presumably seismic origin flowing between the Earth (ground) and the ionosphere (60–80 km above the Earth's surface).

Let us also consider the well-known formulation, used by *Kuo et al.* [2011]:

$$\nabla \cdot \vec{J} = 0, \quad \vec{J} = \hat{\sigma}\vec{E}, \quad \vec{E} = -\nabla\phi, \tag{3}$$

where $\vec{E}$ is the electric field vector, $\hat{\sigma}$ is the electric conductivity tensor, and ϕ is the potential of electric field.

4. Discussion

First, let us perform the substitution of terms for equation (1). Then, one has

$$\nabla \cdot \vec{J} = \nabla \cdot (-\nabla\psi) = -\nabla^2\psi = -\Delta\psi = 0. \tag{4}$$

Let us perform substitution for equation (3) as well and then one has

$$\nabla \cdot \vec{J} = \nabla \cdot [\hat{\sigma}(-\nabla\phi)] = -\nabla \cdot [\hat{\sigma}\nabla\phi] = 0. \tag{5}$$

Now let us compare equation (4) with equation (3) formulation. To solve equation (5), one needs to define the electric conductivity $\hat{\sigma}$ tensor. Equation (4) is simpler that it does not require knowledge of electric conductivity $\hat{\sigma}$ profile.

Let us try to derive equation (4) from equation (5). Assuming that $\hat{\sigma}$ is a zeroth-order tensor (i.e., a scalar σ) that does not depend on coordinates, we can do the following transformations:

$$-\nabla\cdot[\sigma\nabla\phi] = -\nabla\cdot[\nabla(\sigma\phi)] = -\nabla^2(\sigma\phi) = 0. \quad (6)$$

Let us denote $\psi\equiv\sigma\phi$ in equation (6) and have

$$-\nabla^2\psi = \Delta\psi = 0,$$

which is exactly equation (4).

Thus, we can conclude that equation (1) is a special case of the more general equation (3). To derive equation (1) from equation (3), the following assumptions are to be made: (a) $\hat{\sigma}$ is isotropic (valid for the neutral atmosphere) and (b) spatially uniform (not valid, especially for the altitude coordinate). Therefore, the solution of equation (1) is unlikely to consistently describe currents that flow between the Earth's surface and the ionospheric lower boundary. Moreover, it is clear that both papers (cf. equation (1) versus equation (3)) use Ampere's law formulated as $\nabla\cdot\vec{J} = 0$. But whereas *Kuo et al.* [2011] use Ohm's law (see equation (3)) $\vec{J} = \sigma\vec{E}$, $\vec{E} = -\nabla\phi$, *Kuo et al.* [2014] simplify Ohm's law directly to $\vec{J} = -\nabla\psi$ (see equation (3)). Unfortunately, *Kuo et al.* [2014] do not discuss the correctness of their Ohm's law reduction to the form $\vec{J} \equiv -\nabla\psi$ (where ψ is defined as the potential function for current) for the case of the neutral atmosphere (ground-to-ionosphere region).

The issues discussed above raise the question: Is equation (3) better than equation (1) for modeling seismogenic currents in the ionosphere? Besides *Kuo et al.* [2011], other papers have discussed Earth-to-ionosphere penetration of electric currents [*Kim et al.*, 2002; *Sorokin et al.*, 2001, 2006; *Pulinets et al.*, 2003; *Ampferer et al.*, 2010; *Denisenko et al.*, 2008]. To obtain the required electric currents (or fields) at the lower boundary of the ionosphere, one has to (a) set very large currents at the Earth's surface or (b) significantly increase conductivity values at the lower part of the conductivity profile. Otherwise, additional electric currents appearing at the ionospheric heights are insufficient to generate (at least in model cases) the observed TEC disturbances (as well as other ionosphere plasma parameters). Thus, the $\vec{J} = \sigma\vec{E}$ formulation (i.e., considering that currents are due to only the conduction) is unlikely to have a reasonable solution that describes ground-to-ionosphere currents of presumably seismic origin.

Kuo et al. [2011] encountered the above problem. To obtain reasonable disturbances, they increased the electric conductivity values by an order of magnitude at the bottom of the electric conductivity profile: "The conductivity profile used in our model is similar to the conductivity profile by *Rycroft et al.* [2008], except the value near the Earth surface. The conductivity near the ground is 2×10^{-13} S/m, which is higher than the conductivity 2×10^{-14} S/m in work by *Rycroft et al.* [2008], to partially include the contribution from molecule ionization caused by rock currents (the σ_1 term)." Unfortunately, *Kuo et al.* [2011] did not provide quantitative estimations of molecule ionization deposition in the resulting conductivity profile values values they used in the model. Therefore, it is not clear whether their solution is realistic.

5. Conclusions

The problem of an electromagnetic mechanism of lithosphere-atmosphere-ionosphere coupling has yet to be solved and has main three parts: (a) physical mechanism of plasma disturbances' generation at ionospheric heights, (b) penetration of seismogenic impact from the ground into the ionosphere through the underlying neutral atmosphere, and (c) on-the-ground (in-the-ground) sources' generation. The "in-ionosphere" disturbances are simulated using mature ionosphere models. The main drawback is the need for physical justification of the lower boundary conditions used, i.e., for additional of presumably seismic origin electric fields or currents crossing the lower boundary of the ionosphere. Therefore, this is the most poorly investigated problem in the frame of LAI coupling and is a subject for ongoing research.

Kuo et al. [2014] reported the model of LAI coupling, which includes the ionosphere as well as the underlying neutral atmosphere part, i.e., that is claimed to resolve the first two parts. For the in-ionosphere part they used the well-known SAMI-3 model. To describe ground-to-ionosphere currents, *Kuo et al.* [2014] introduced the following system of equations:

$$\nabla\cdot\vec{J} = 0, \quad \vec{J} \equiv -\nabla\psi.$$

In this paper we show that the above system of equations is a special case of the *Kuo et al.* [2011] formulation:

$$\nabla\cdot\vec{J} = 0, \quad \vec{J} = \hat{\sigma}\vec{E}, \quad \vec{E} = -\nabla\phi$$

under the assumption that electric conductivity tensor ($\hat{\sigma}$) is a spatially uniform scalar. This assumption is not justified, and therefore, the resulting system of equations (used in *Kuo et al.* [2014]) may not describe correctly the electric currents flowing between the Earth and the ionosphere.

Thus, there are two major problems.

1. *Kuo et al.* [2011] require drastically increased conductivity values at the bottom part of the electric conductivity profile. Such an increase requires physically consistent explanation, which is not done. *Kuo et al.* [2014], being the special case of *Kuo et al.* [2011], must have the same problem. But *Kuo et al.* [2014] do not use the conductivity in the equations formulation, and therefore, the problem just moves (or hides) into the newly introduced potential function ψ. Vanishing of the conductivity σ term from Ohm's law with introduction of some scalar potential function ψ only (to describe the neutral atmosphere electric currents) is, as far as we know, a pioneering approach. It requires careful physical justification.
2. *Kuo et al.* [2011] (and *Kuo et al.* [2014] as a special case as well) use formulation that describes the electric currents as conductivity currents, i.e., that are due to the conductivity only (in other words, are due to the action of electromagnetic forces only).

The so called "seismogenic" (or "external") ground-to-ionosphere currents are often considered as a result of vertical turbulent transport of charged particles and their gravitational sedimentation. Therefore, it is not obvious that seismogenic electric currents are able to be described as conductivity currents (i.e., neglecting all the nonelectromangetic forces).

Acknowledgments
The author (B.P.) acknowledges Deutsche Forschungsgemeinschaft (DFG). This work was partially supported by DFG. The authors are grateful to the reviewers for the fruitful discussion.

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