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Atmospheric Chemistry and Physics Discussions

Interactive comment on "On the role of non-electrified clouds in the Global Electric Circuit" *by* A. J. G. Baumgaertner et al.

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We thank the reviewer for the comments on the manuscript, which helped to improve the revised version.

I suggest the term "semi-fair weather clouds"

Reply It is indeed difficult to find a term that is not misleading in some way. The atmospheric electricity community uses the term "electrified clouds" also for "electrified shower clouds", so we think that "slightly electrified clouds" could be mistaken for clouds where electrification occurs through mechanical (riming etc) reasons. We have therefore now chosen to term these clouds "clouds in the fair weather part

of the GEC", or "clouds in the current return path", without an adjective.

I would prefer the authors to start with Gauss' law, one of Maxwell's four fundamental equations, and then to consider Poisson's equation.

Reply For the revised manuscript, we have rewritten and clarified the derivation of the relevant PDE: While mathematically the concerned PDE is of Poisson-type, strictly speaking it is neither Poisson's equation or the Laplace equation of electrodynamics, because conductivity is not constant. Therefore, the PDE is not named, but the approach later refered to as the "current continuity approach", as the PDE is based on the current continuity equation. We have revised this section to the following: "The defining equations for current flow are the current continuity equation and Ohm's law (Zangwill: Modern electrodynamics, Cambridge University Press, 2013, chapter 9.4):
$\nabla \cdot J = S$
$J = \sigma E$,
where J is the current density, S is the negative time derivative of charge density, which describes thunderstorms and electrified clouds, σ is conductivity, and E is the elctric field. If no changing magnetic fields are present, the electric field is defined as the gradient of a potential Φ: $E = -\nabla\Phi$, in which case Ohm's law can be written as
J=-$\sigma\nabla\Phi$.
Combining Ohm's law and the current continuity equation yields the partial differential equation (PDE)
-$\nabla \cdot [\sigma\nabla\Phi] = S$.
To solve this for the current density and potential distributions, we employ a finite element model formulation, which requires a variational formulation of the PDE. [...]"

Then, considering the reduced conductivity inside a cloud, there have to be

electric charges on the top and bottom of the cloud. How large the charge density is depends on the thickness of the cloud edge. What charge densities are calculated here? Therefore the paper should also discuss clearly what is the vertical resolution of the model.

Reply Indeed the charge density depends on the thickness of the cloud edge. We have not modeled realistic cloud edges. If a vertical resolution of 100m is chosen, charge densities similar to those reported by Nicoll and Harrison (2010) are calculated. However, the charge density is the only variable that is affected by vertical resolution of the model. The figures in the paper have been produced using a vertical resolution of 200m, but they are identical for other vertical resolutions, e.g. for 50m or 1km. This is explained in more detail in the revised manuscript: "The GEC model has a flexible horizontal and vertical resolution. For the following section, the resolution and domain size were adjusted to suit the studied cloud size, such that the cloud and the region below the cloud are resolved. For example, for a cloud with 10 km diameter, a horizontal resolution of 1 km, a vertical resolution of 100 m, and a domain diameter of 50 km are suffcient."

Is there a standard layer separation in the model? From Figure 6, I might surmise that the vertical resolution used is 1 km. Am I correct? Or is there a more complicated type of mesh, the size of which varies according to the details of the problem considered? This issue needs to be explored clearly in this paper, in my opinion.

Reply Figure 6 is used as a demonstration of the parametrization, and had a simple vertical layers of 350m, 750m, 1500m and then 1 km steps. However, when used in CESM/WACCM the vertical grid is a hybrid sigma pressure system, as many climate models use. Geopotential height is calculated at every timestep, and differs from grid point to grid point. This is explained in more detail in the re-

vised manuscript: "Note that the vertical coordinate system of CESM1(WACCM) is mostly based on atmospheric pressure, which is very adequate for conductivity and column resistance calculations because of the exponential increase in conductivity. The level spacing is approximately 300 m near the surface and increases to several kilometers in the stratosphere, although this depends on the chosen vertical resolution. The horizontal resolution of CESM1(WACCM) is also very flexible, and can range from 25 km to 500 km in latitude and longitude, depending on the chosen simulation grid. The simulations presented below use a grid with 1.9 degrees resolution in latitude and 2.5 degrees in longitude."

I like the diagrams shown in Figure 1. However, it is not clear why some arrows are of different lengths from others. Does the length represent the magnitude of the current density flowing?

Reply Yes, the length represents the magnitude of the current density, although only qualitative and not quantitatively (especially for Fig c and d this would not be possible)

It could beneficially do that, I think; if so, that should be stated.

Reply This is explained in more detail in the revised manuscript: "Arrows denote current direction and the current density magnitude in a qualitative sense."

In Figure 1 b), I think that the current density flowing through the cloud should be the same as that flowing in the fair weather region to the sides of the cloud.

Reply If only vertical currents are allowed: J=V/Rcol. This leads to a smaller J for larger column resistance, so the current density is smaller than the fair-weather region current density. For Fig a, where the current is flowing around the cloud, J above and below the cloud is not reduced, so J is larger than for Fig 1.b), so the arrows should be longer. However, Fig 1.a was corrected as shown below.

In Figure 1 c), discussed on page 8, the curved arrows should thus be shortened. As seen in Fib 2a, the current density becomes very large close to the edge of the cloud. Therefore, On page 6, please spell out how the curvature of the currents illustrated is calculated. What assumptions, if any, are made? It would be a good idea here to introduce here the concept of the conductivity inside the cloud (see page 12) being a factor of about 10 (or 50) less than the conductivity of cloud free air. Somewhere in the paper, referring to the literature, these numerical values should be justified.

Reply Fig 1c will be corrected in the revised manuscript. For Fig. 2a and 3a, the shown streamlines have a vigorous mathematical definition (instantaneously tangent to the current vector), and can be calculated given a set of starting points at the boundary (see e.g. Granger, R.A. (1995). Fluid Mechanics. Dover Publications. ISBN 0-486-68356-7., pp. 422–425.) The numerical values for eta are justified with literature references in section 3, 1st paragraph

Section 2 is written from the viewpoint of a mathematician, rather than a physicist. Whilst there is nothing wrong with that approach, I believe that the paper would be more valuable to chemists and physicists if the equations (16) and (19) were explained physically too.

Reply We now included the definition of Ω (the problem domain), explained the meaning of Dirichlet boundary condition and detailed the derivation of the relevant PDE (current continuity equation and Ohm's law). The physical explanation is therefore contained in the preceding paragraph, and the equations 16 through 19 only contain the way the relevant PDE is formulated in the GEC model. It is not required for the reader to be able to follow this in order to understand the results and discussion. However, we feel the equations should not be taken out, to provide interested readers with some detail of the model, as this GEC model has not been published in other places so far.

The feature which strikes me from Figure 2 is that the effective radius of this cirrus cloud at this height is about twice its actual radius. This suggests that the current density inside the cloud should be about a quarter of its value outside, as the numerical values presented demonstrate. Is there any experimental evidence for such a variation of current densities? This topic is also mentioned toward the bottom of page 14. How could such different current densities be detected?

Reply So far there is no published experimental evidence. However, in principle the use of a array of electric field mills could be used to study this. The authors are currently investigating if data from existing field mill arrays (such as from Kennedy Space Center) could be used for this purpose.

The numerical values for the resistances stated for different conditions are valuable, for modellers and experimenters alike. Both Figure 5 and Table 1 show clearly the magnitudes of the expected effects of different clouds. The authors might like to discuss how the results shown in Figure 7 could be used by other researchers.

Reply Fig 7 is mainly meant to demonstrate several features of the model simulations, and is the only one showing the result of the parametrization. Since this is showing parameterized conductivity for the fair weather part of the GEC, this can not be validated with conductivity measurements. However, satellite measurements of aerosol, water vapour concentration etc could be used to reproduce these results using the same technique. The modeled surface vertical electric fields or current density could be evaluated with measurements.

I feel that the discussion in section 5 could be "sharpened up" a bit, to advantage.

Reply We have improved the section for the revised manuscript as much as possible.

The Conclusions section should be rewritten to specify slightly electrified clouds (and not non-electrified clouds).

Reply Rewritten as discussed above.

"Allowing to assume" (on line 10) is not a very elegant expression.

Reply corrected to “such that only vertical current flow on the scale of grid columns needs to be considered”

There are a few errors in the references list.

Reply We were not able to find these errors, but will make every effort together with the copernicus staff to have these correct in the final version.

In line 4 of page 5, I suggest that it should read: Note, however, that the ... .

Reply This will be corrected in the revised manuscript as suggested.

Interactive comment on Atmos. Chem. Phys. Discuss., 14, 9815, 2014.