Investigating the physical mechanisms that establish electric fields in the atmosphere

Thesis Defense for Greg Lucas

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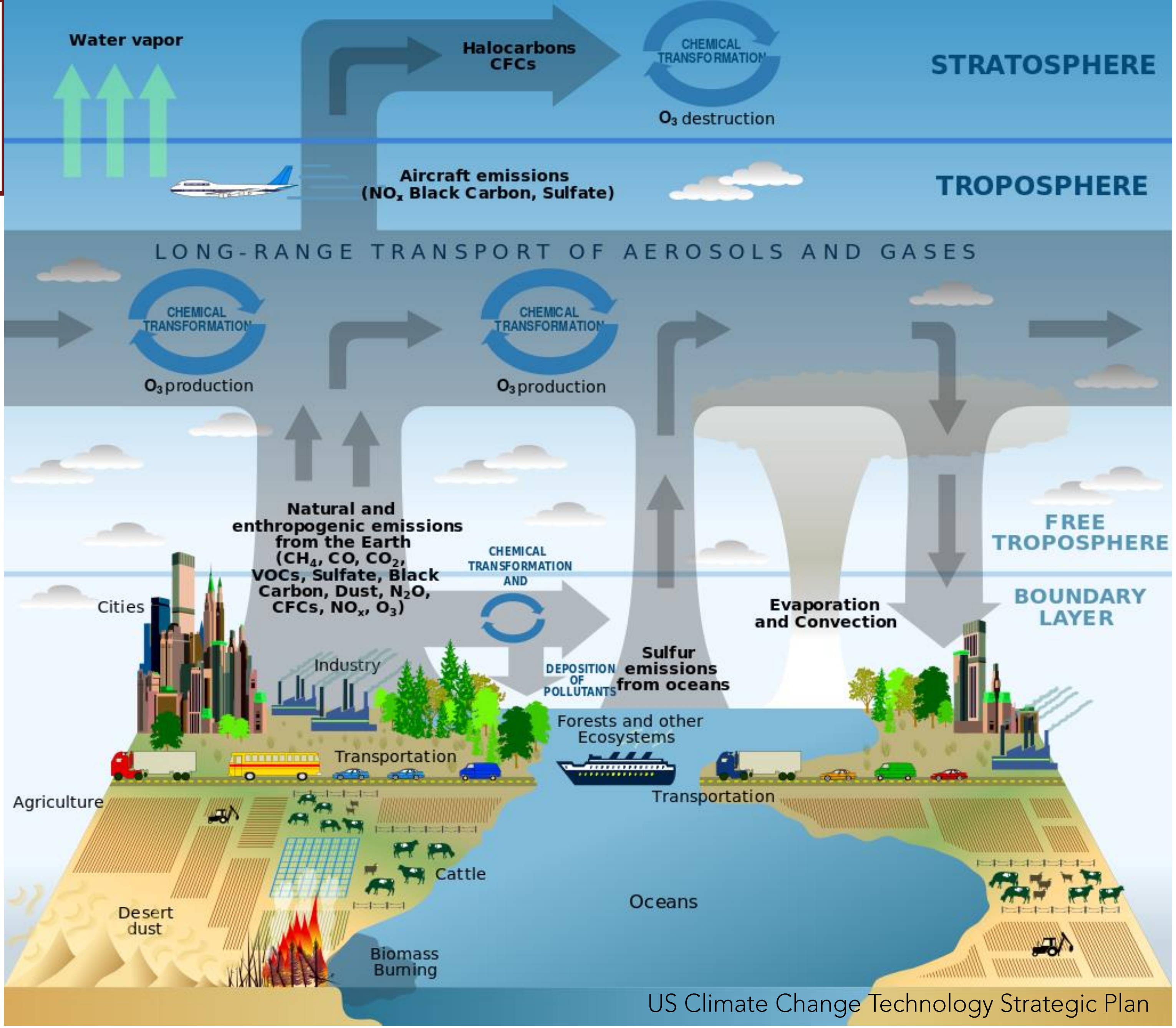
CCAR

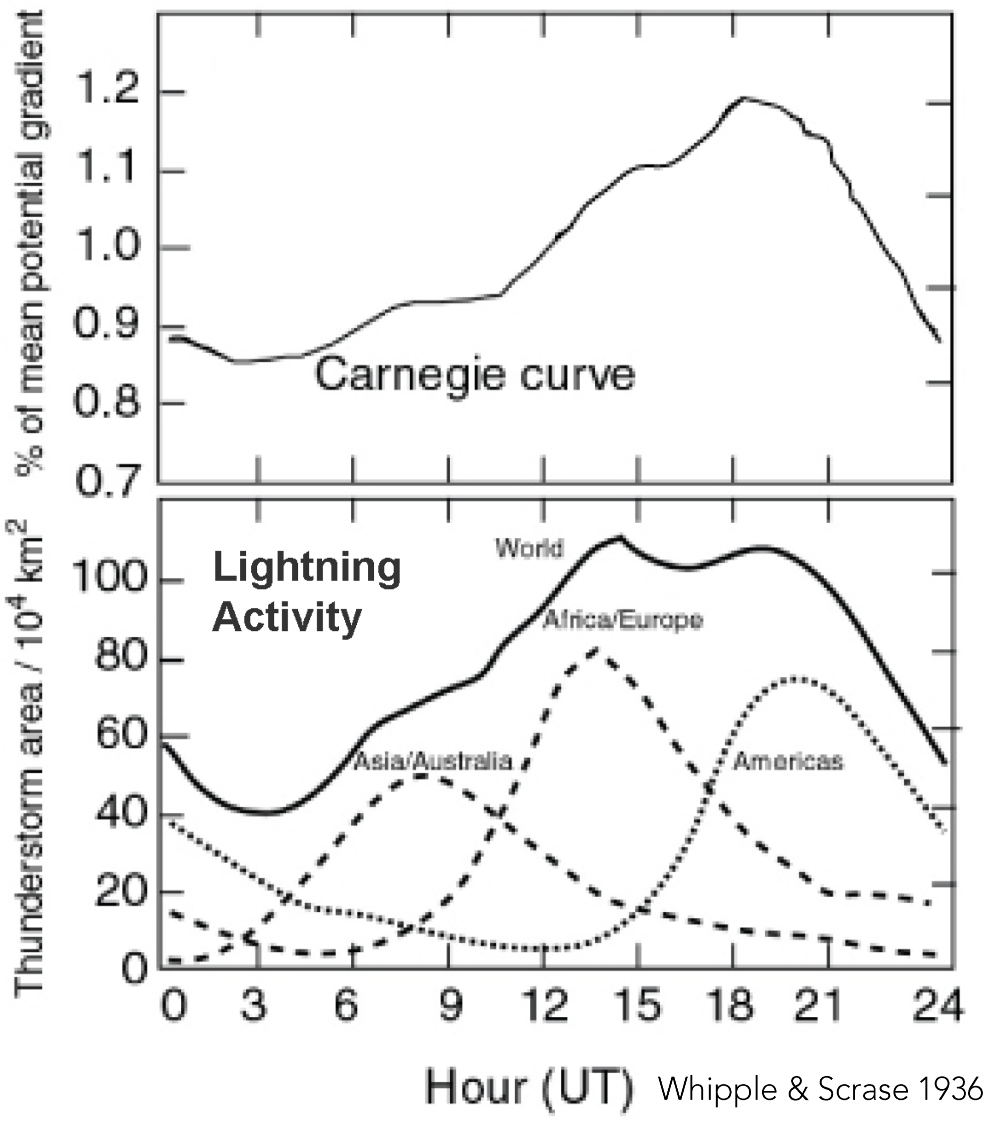
What is in a climate model?

- Dynamics
- Radiation
- Chemistry
- Electrical?



Electric fields have been measured for over a century

- Typically think of lightning flashes and very short duration events, but there is also a small background electric field present throughout the atmosphere
- This background field is correlated with the global thunderstorm distribution

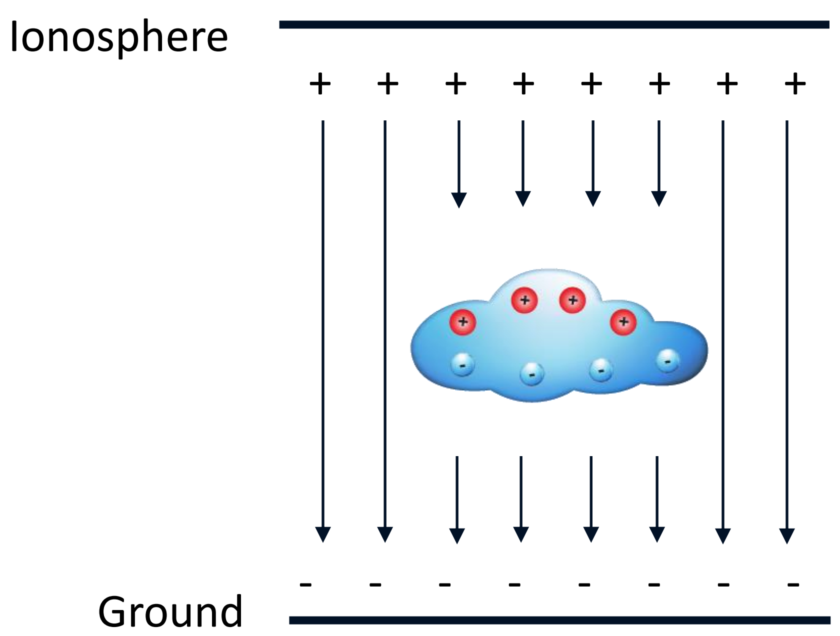


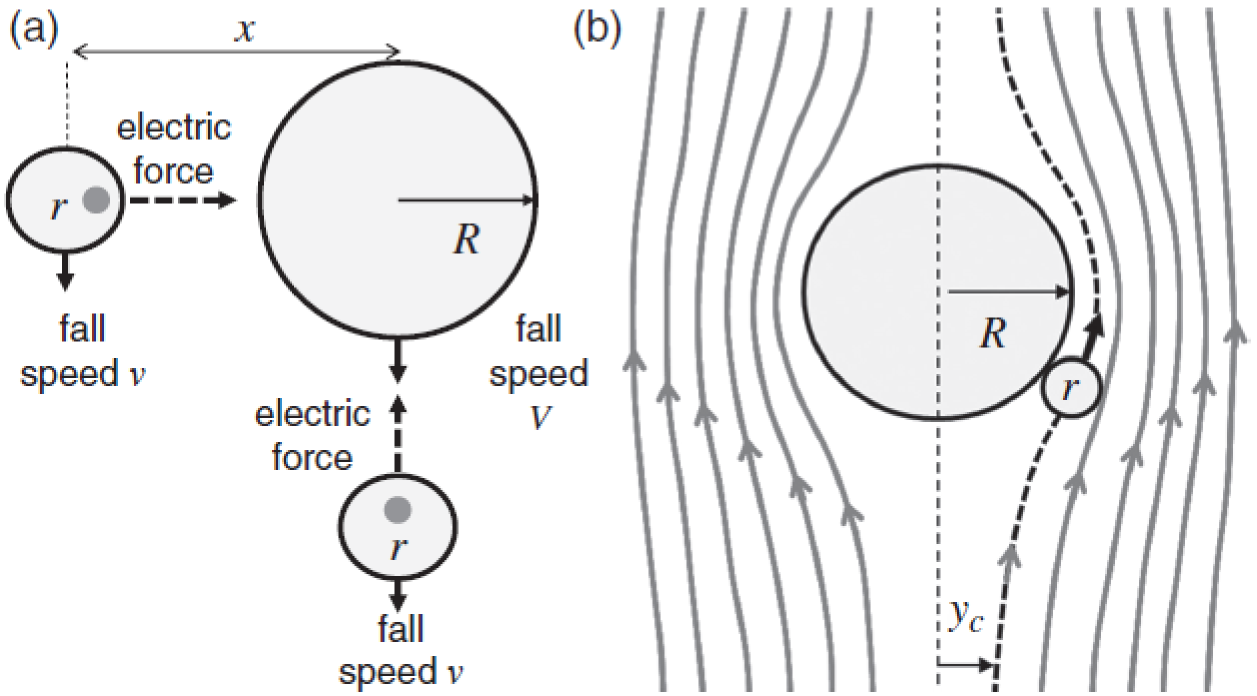
Whipple & Scrase 1936

Electric forces are small, but may play a large role in microphysical processes

Are cloud heights modified by the electric field?

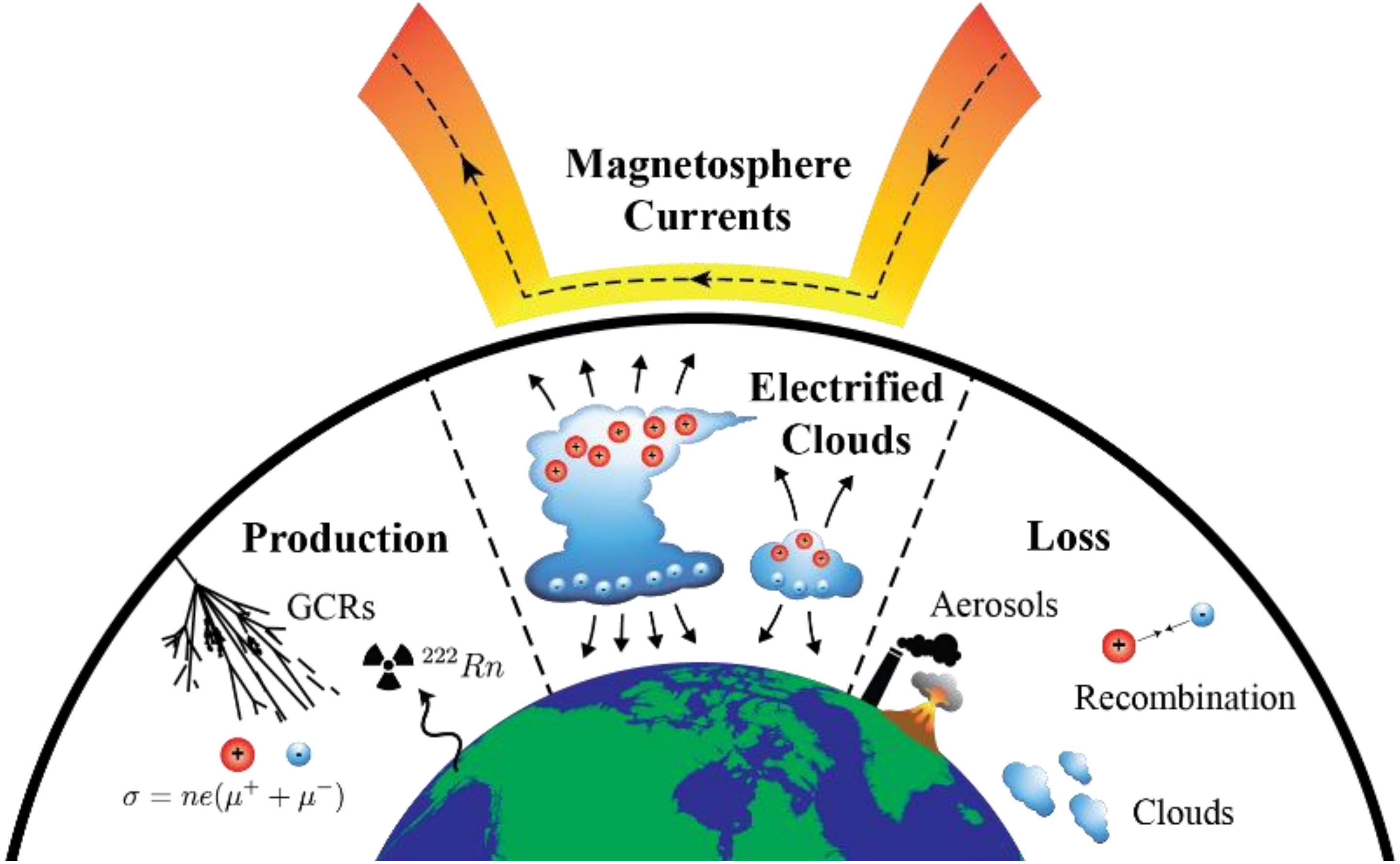
Are cloud growth processes different in an external field?





Harrison et al. 2015

How do physical ion production and loss mechanisms affect electric fields in the atmosphere on both global and local scales?

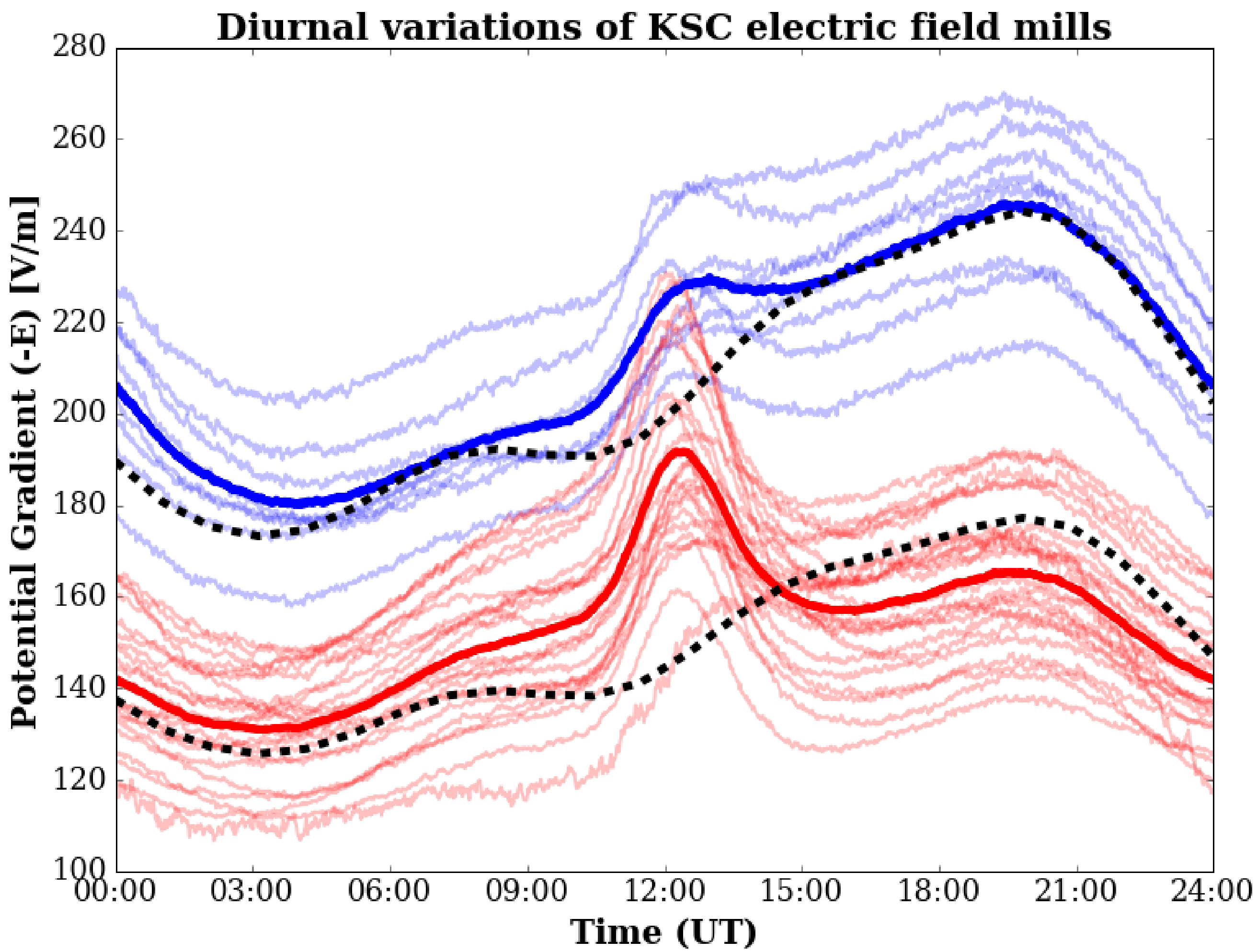


How do physical ion production and loss mechanisms affect electric fields in the atmosphere on both global and local scales?

1. What impact do local meteorological processes have on the measurement of atmospheric electric fields?
2. How does the global conductivity and source distribution influence local atmospheric electric field measurements?
3. How does the magnetospheric current system influence atmospheric electric fields in the global electric circuit?
4. What impact do strong conductivity perturbations have on the global electric circuit?

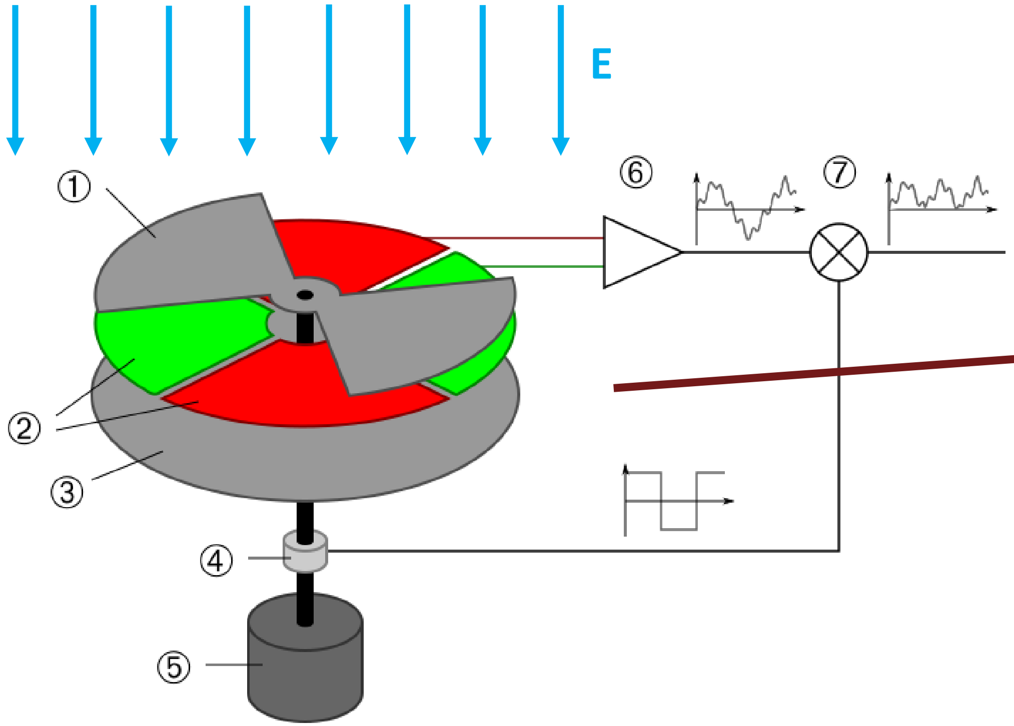
1. What impact do local meteorological processes have on the measurement of atmospheric electric fields?

31 field mills located in the same region, but producing different electric fields



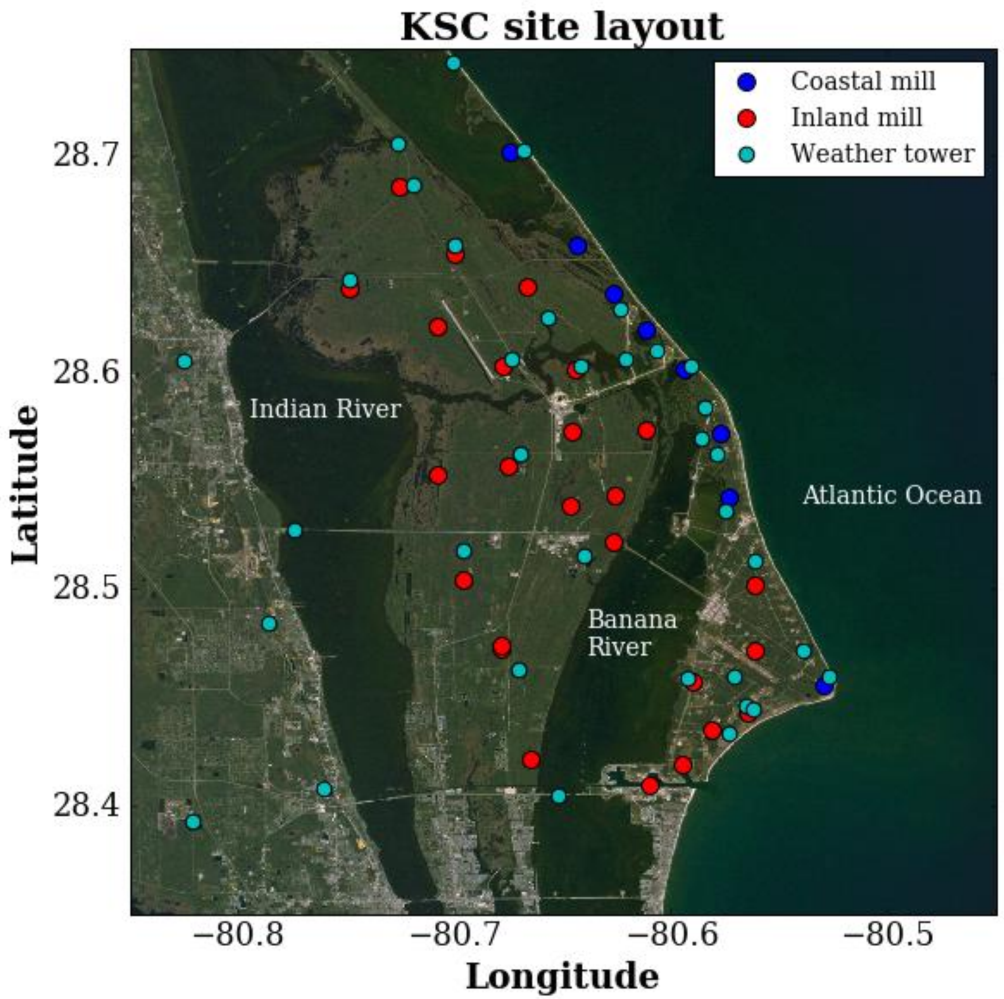
Electric field mills are used to measure atmospheric electric fields

- A spinning rotor alternately shields/exposes a sense plate

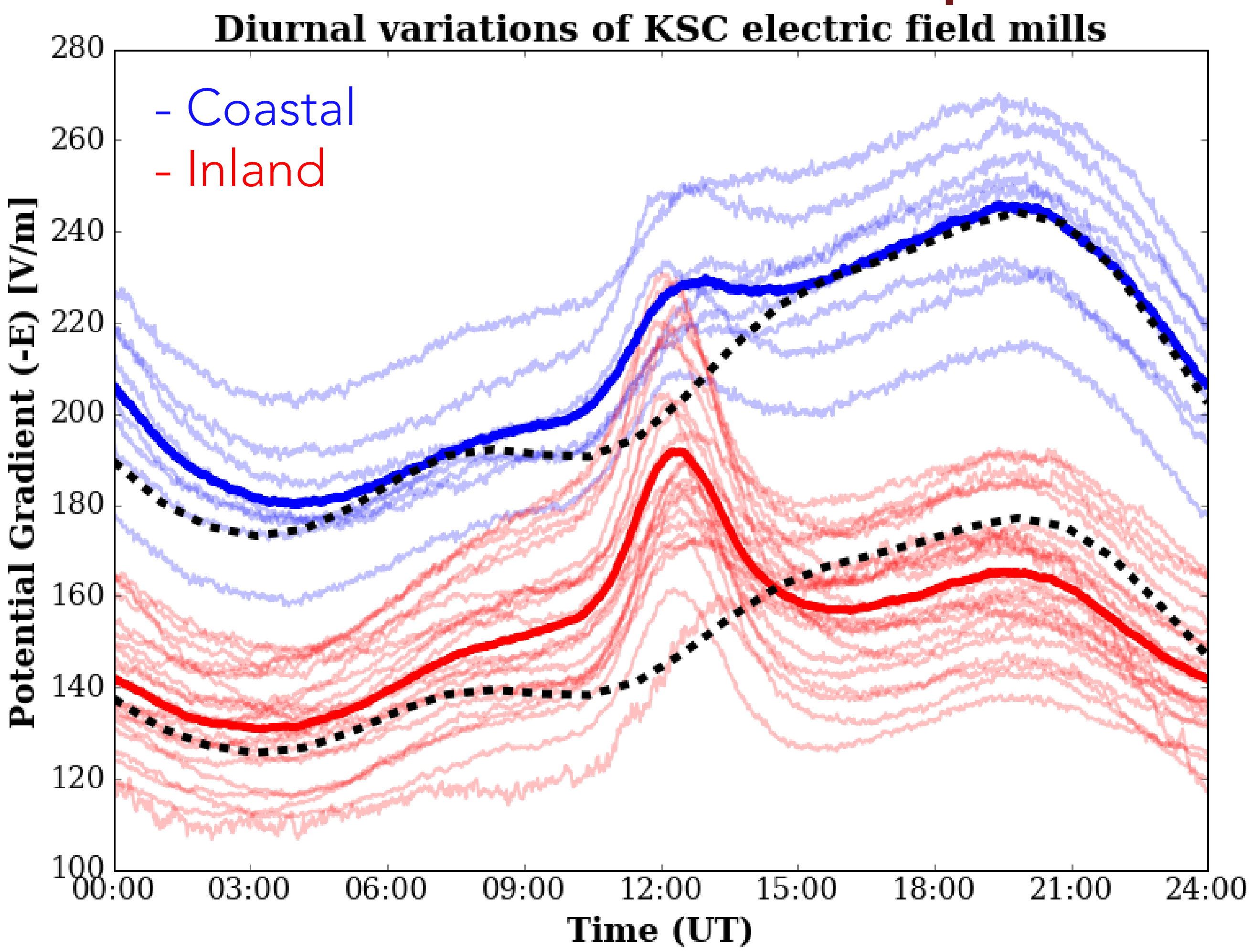


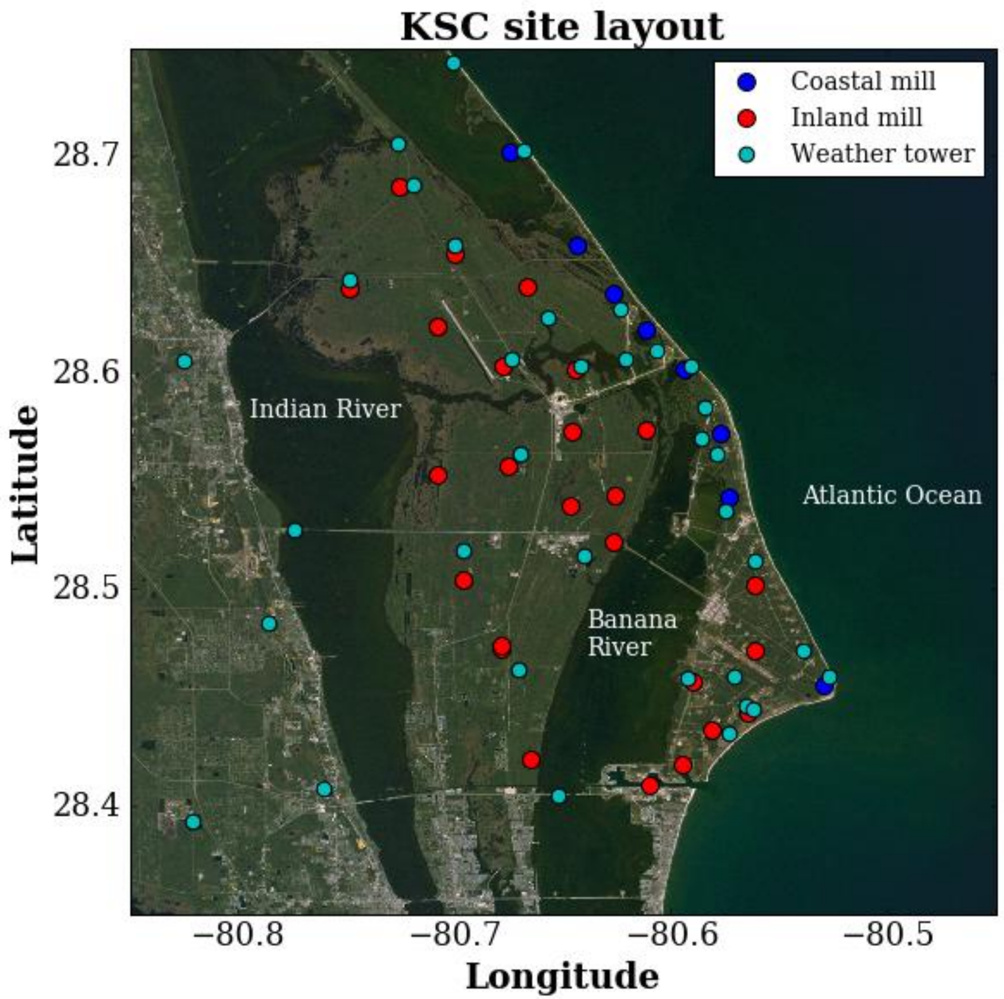
A statistical analysis of 18-years worth of data from an array of field mills

- First in-depth analysis of the fair-weather measurements from KSC
- Analyze spatial relationships with the **distributed array** of field mills
- Investigate **statistical** trends within the data rather than looking at case studies

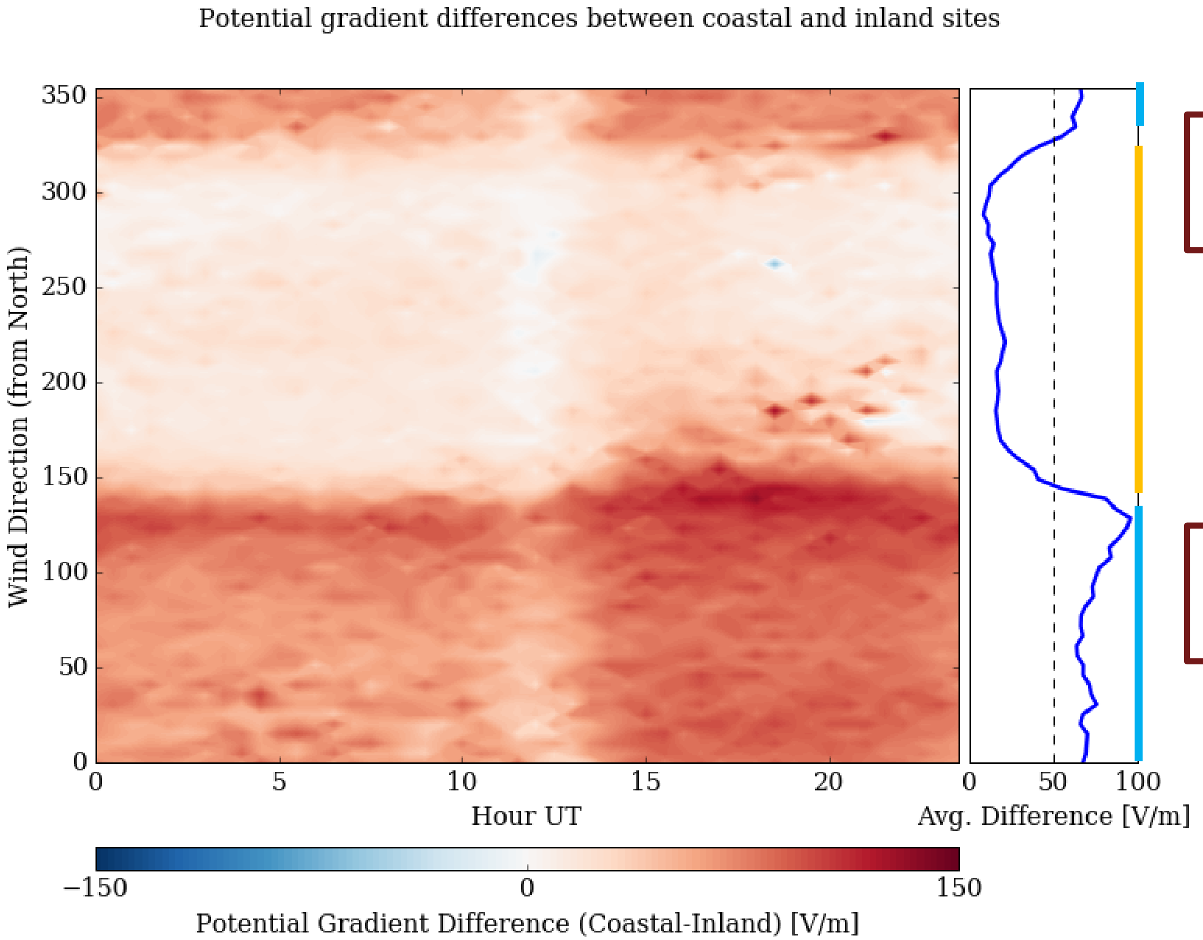


K-means clustering algorithm identified two distinct groups of field mills



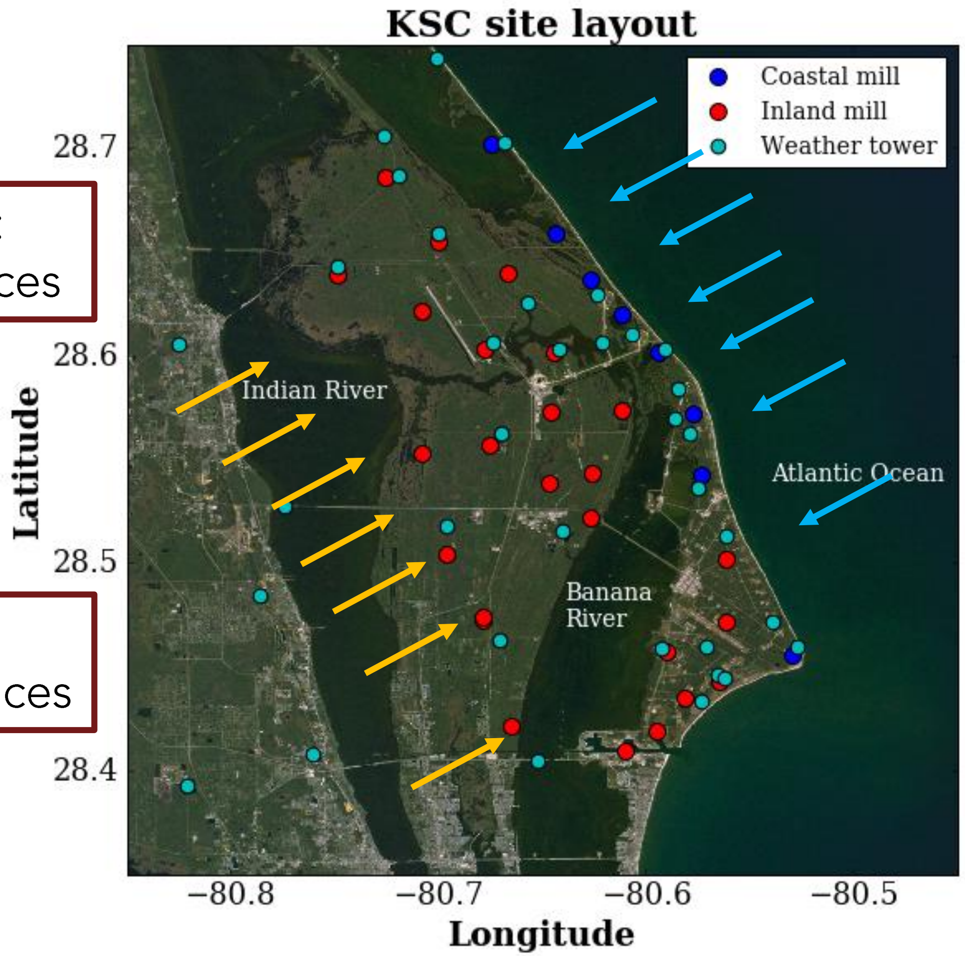


Wind direction creates a difference between coastal and inland mills



Southwest wind:
Minimal differences

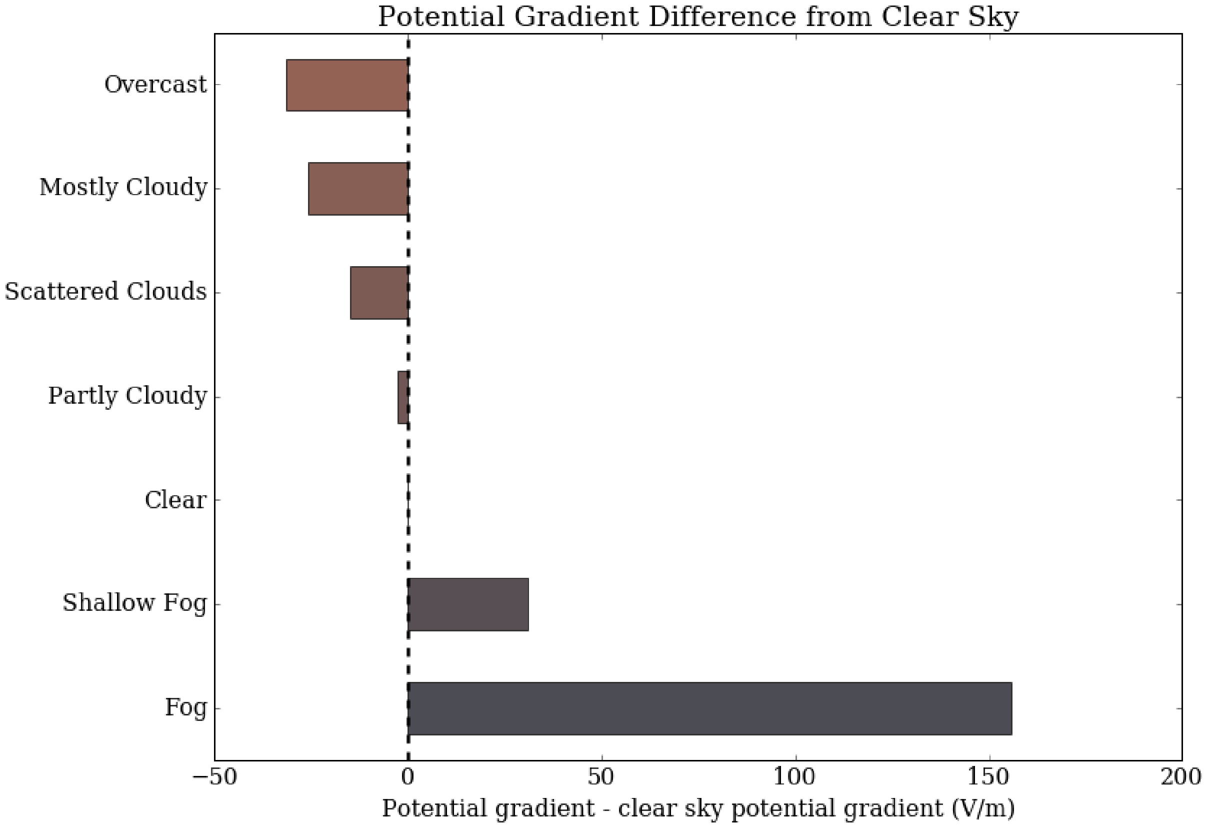
Northeast wind:
>50 V/m differences



Wind data from local weather towers

Clouds act like resistors, modifying the local electric fields

- Conductivity is known to be reduced within clouds
- The magnitude of the reduction is speculated to be more than 1/10 in other models
- Rather than looking at individual clouds, we look at the statistical occurrence of clouds and electric fields over 18 years worth of data



Cloud cover obtained from METARs

Clouds act like resistors, modifying the local electric fields

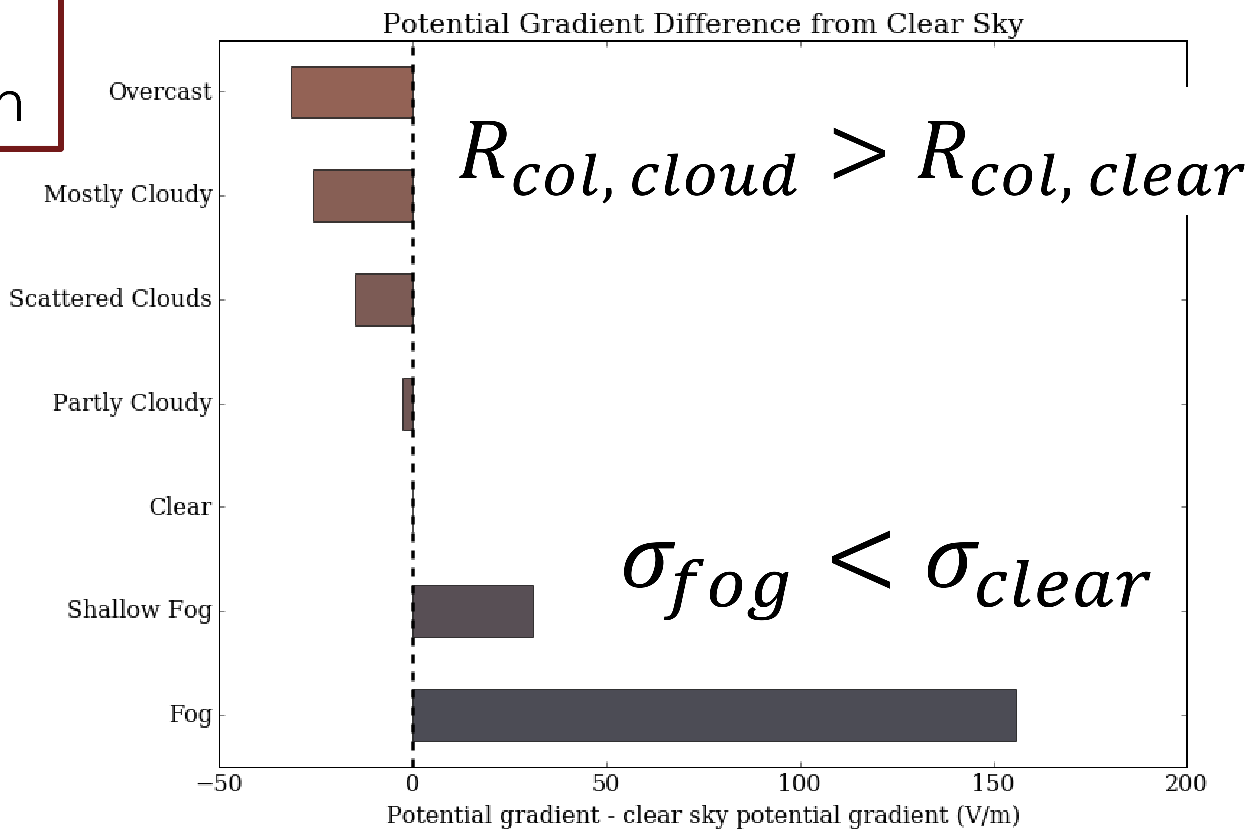
$$J_{col} = \frac{PD_{iono}}{R_{col}}$$

Constant current density in the column

$$E_{surf} = \frac{J_{col}}{\sigma_{surf}} = \frac{PD_{iono}}{\sigma_{surf} R_{col}}$$

Overhead clouds: $\uparrow R_{col} \quad \downarrow E_{surf}$

Local fog: $\downarrow \sigma_{local} \quad \uparrow E_{surf}$



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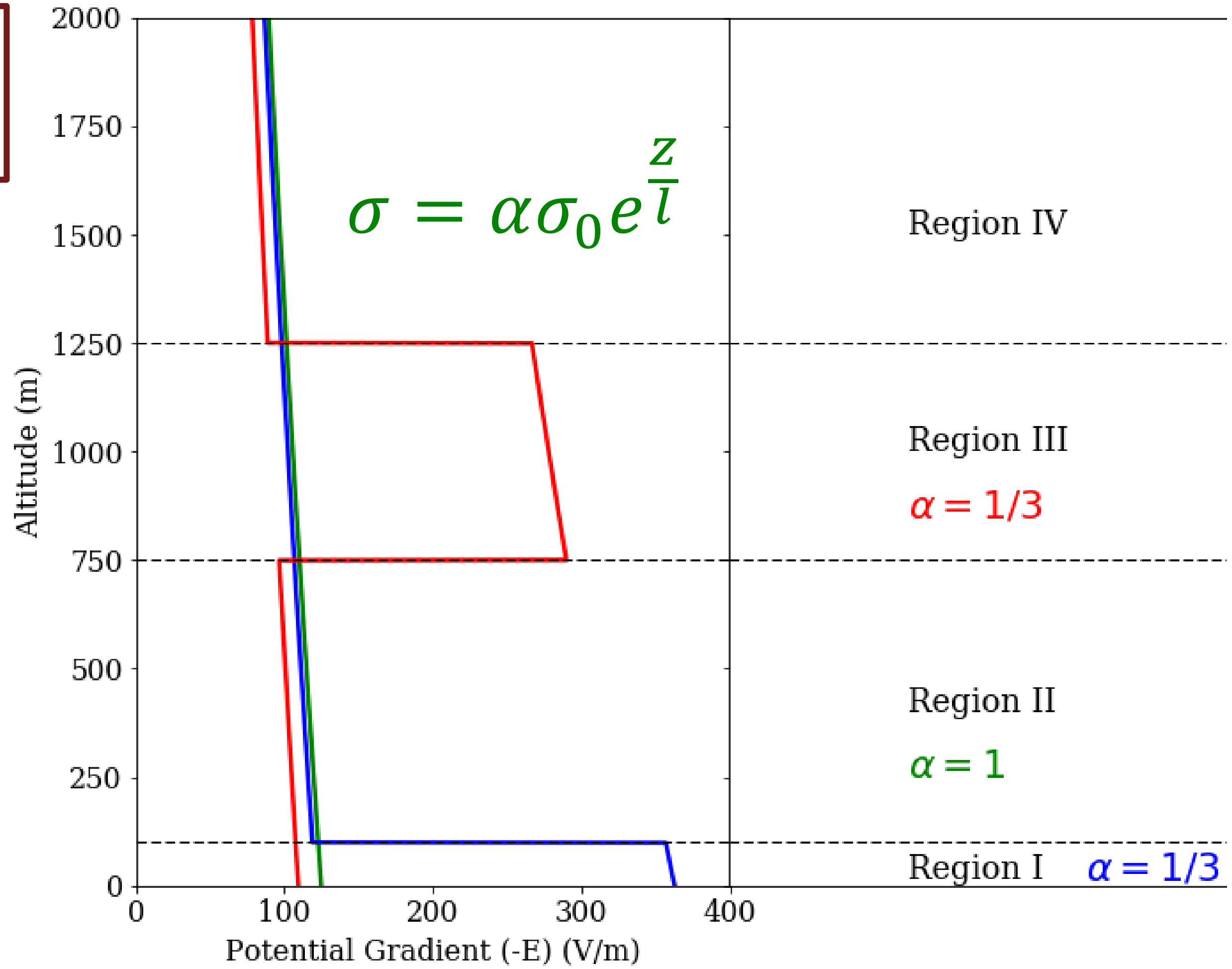
Local fog: $\downarrow \sigma_{local} \quad \uparrow E_{surf}$

Conductivity change within clouds, $\boldsymbol{\alpha}$, is around 1/3



1. What impact do local meteorological processes have on the measurement of atmospheric electric fields?

- **Distributed array** of field mills shows spatial dependencies of inland and coastal sites to the local wind direction

Winds from the ocean create a 50 V/m enhancement in the coastal mills

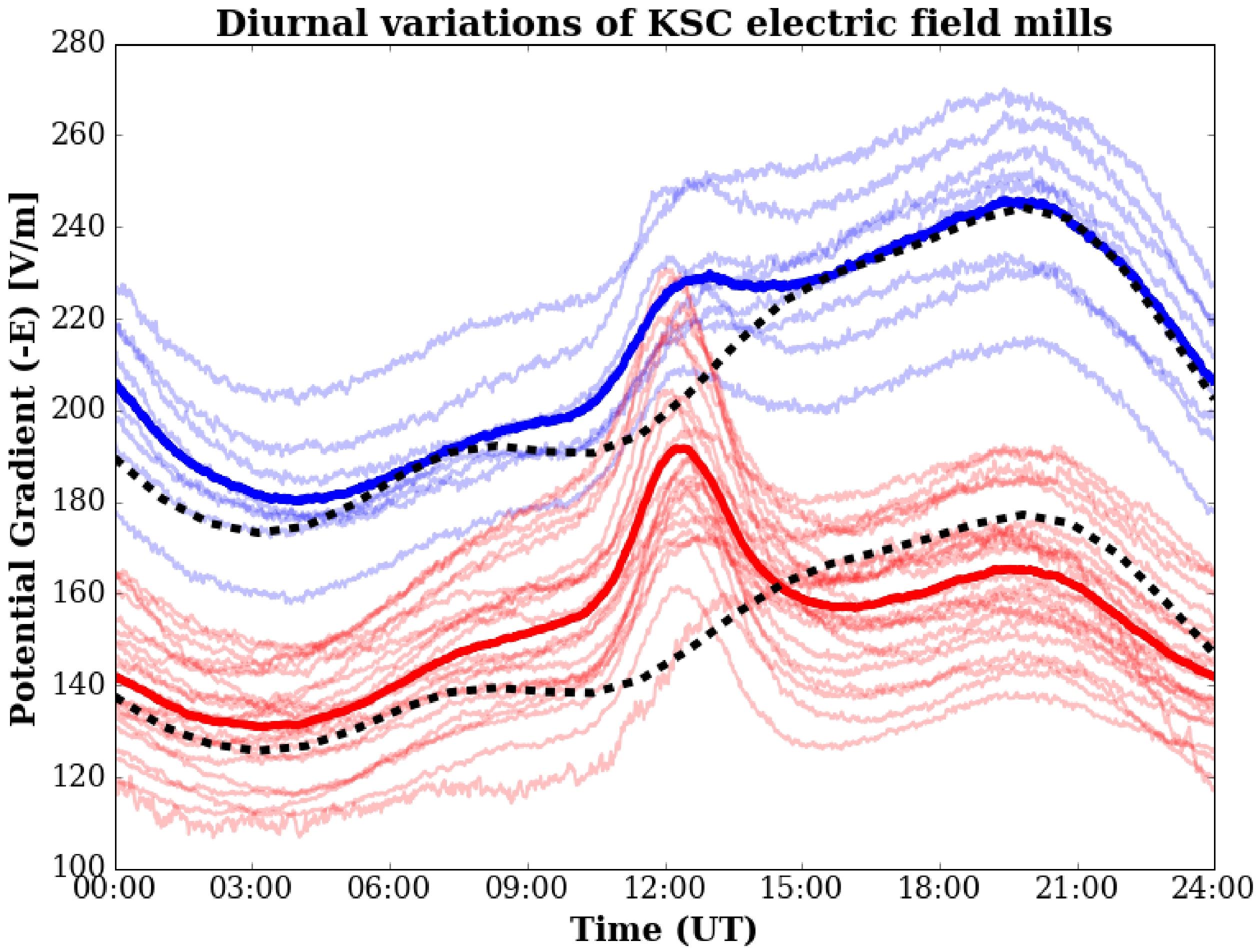
- **Statistical** nature of the dataset puts a limit on the conductivity change within clouds

METARs observation of cloud cover show a conductivity change of ~1/3

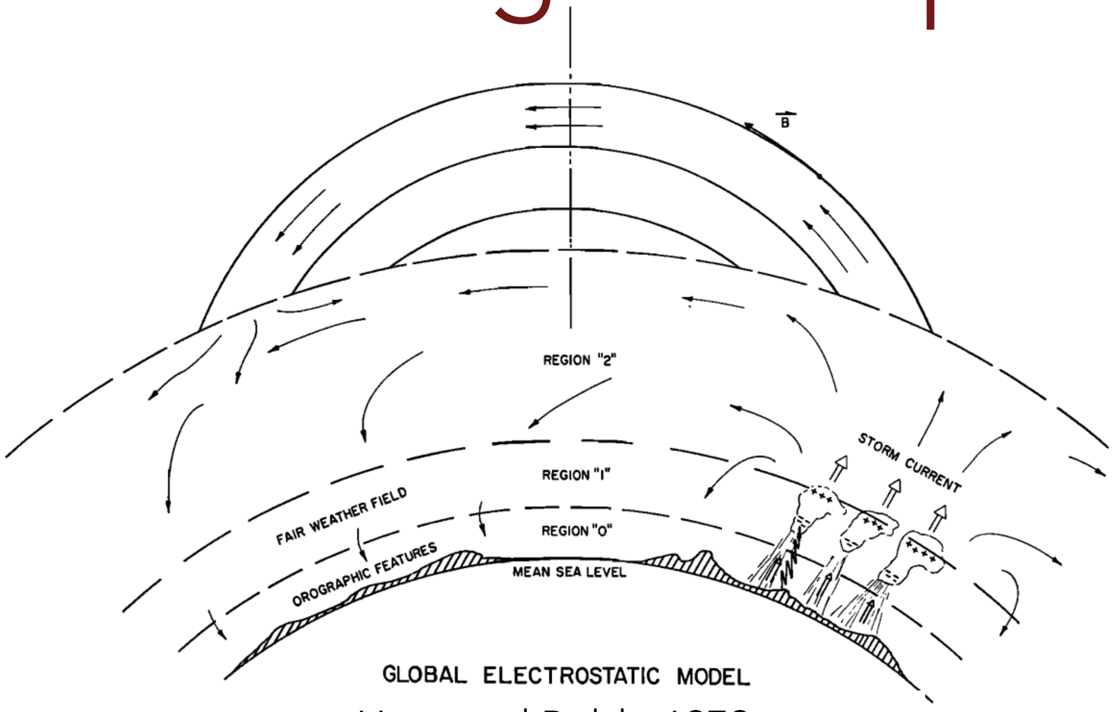
Lucas et al. 2017

2. How does the global conductivity and source distribution influence local atmospheric electric field measurements?

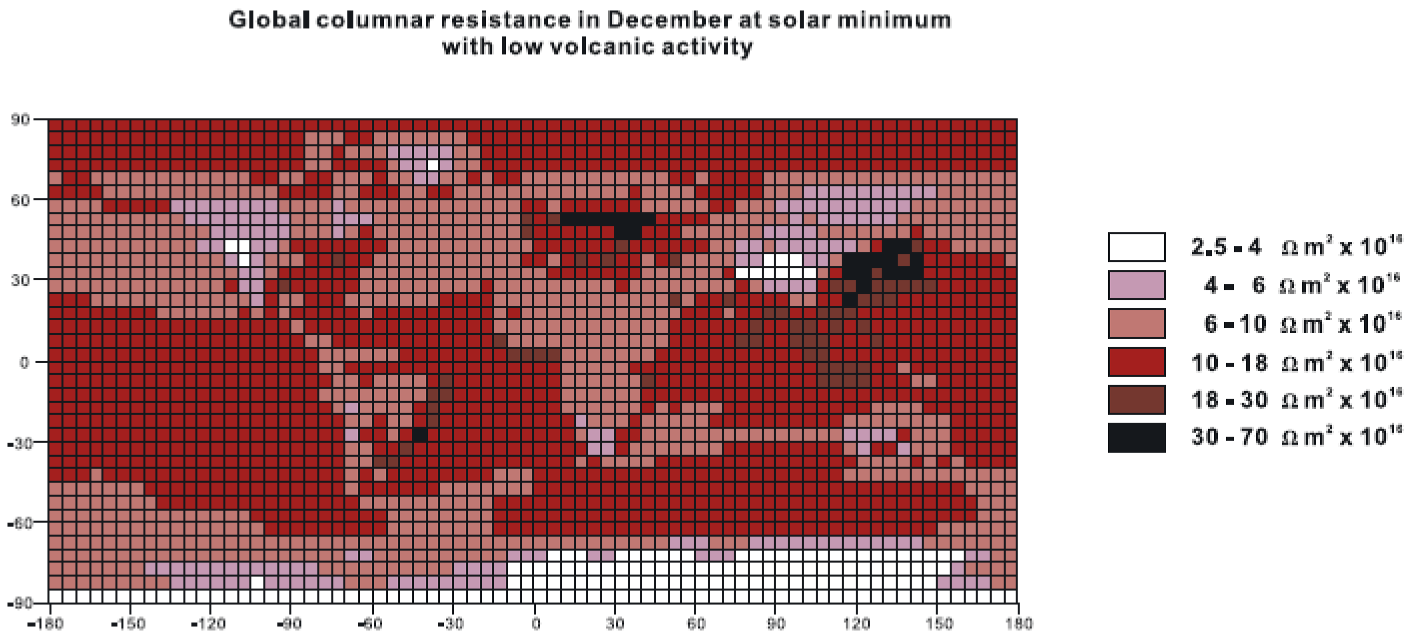
Although the magnitudes are different, there is still a similar trend for all mills produced by the global electric circuit



Previous GEC models make many limiting assumptions to obtain a solution



Hays and Roble 1979



Tinsley and Zhou 2006

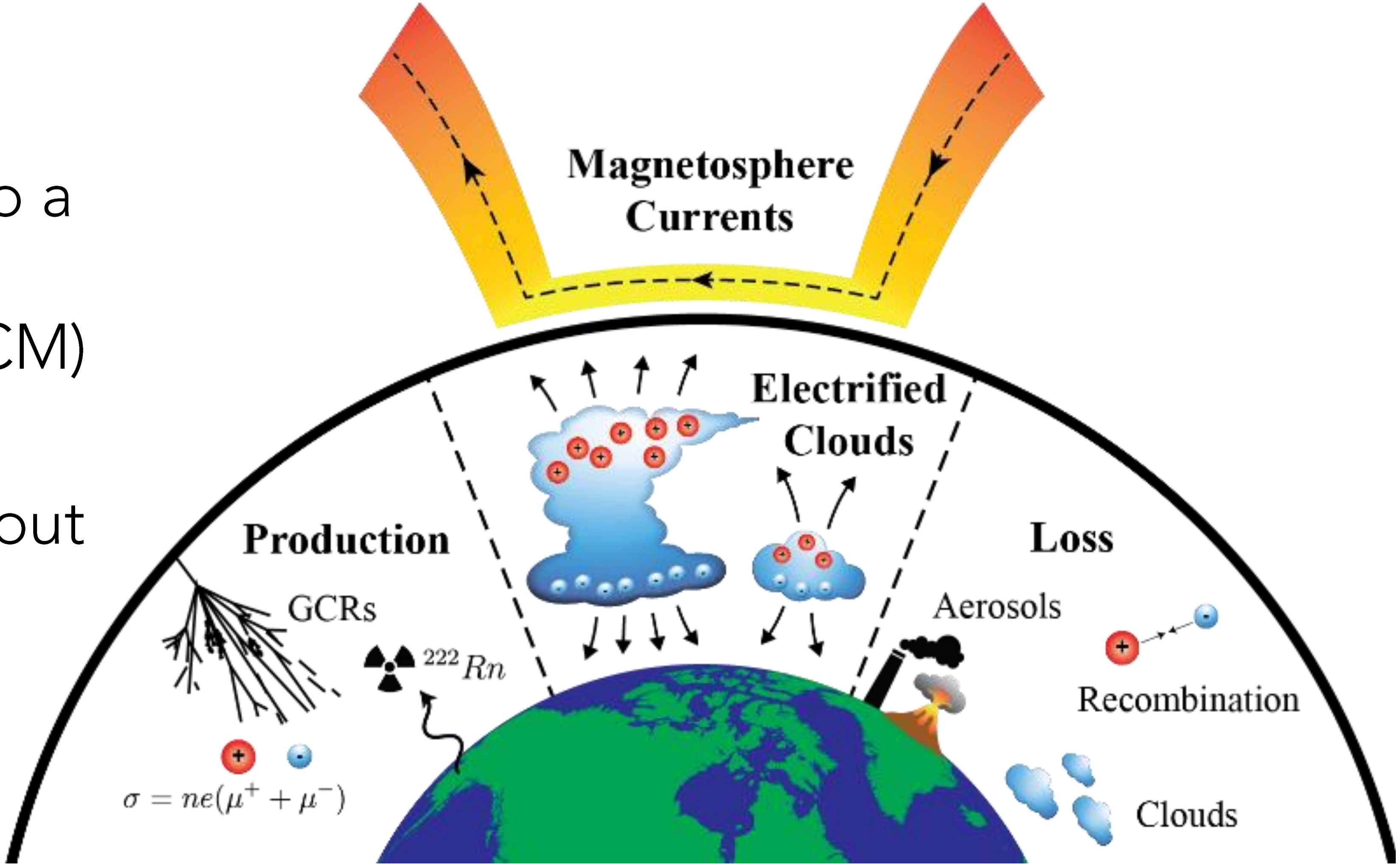
- Parameterization of conductivity
- 3 regions with analytic solutions

- Parameterization of ion production and losses
- No incorporation of source currents

WACCM-GEC is the first self-consistent physics-based GEC model

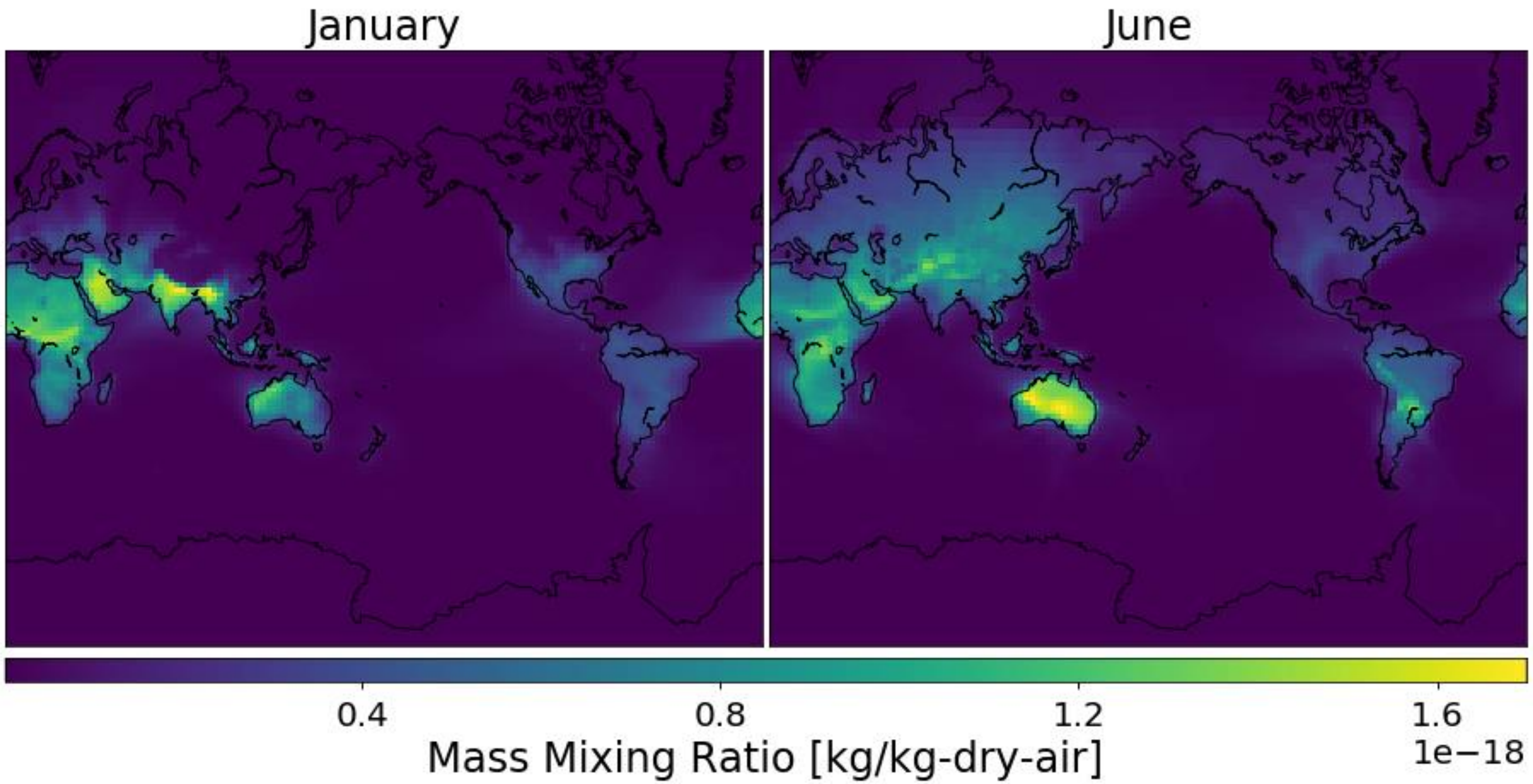
- Incorporate an electrical system into a community climate model CESM(WACCM)
- Current continuity maintained throughout the atmosphere

$$\nabla \cdot \sigma \nabla \phi = S$$



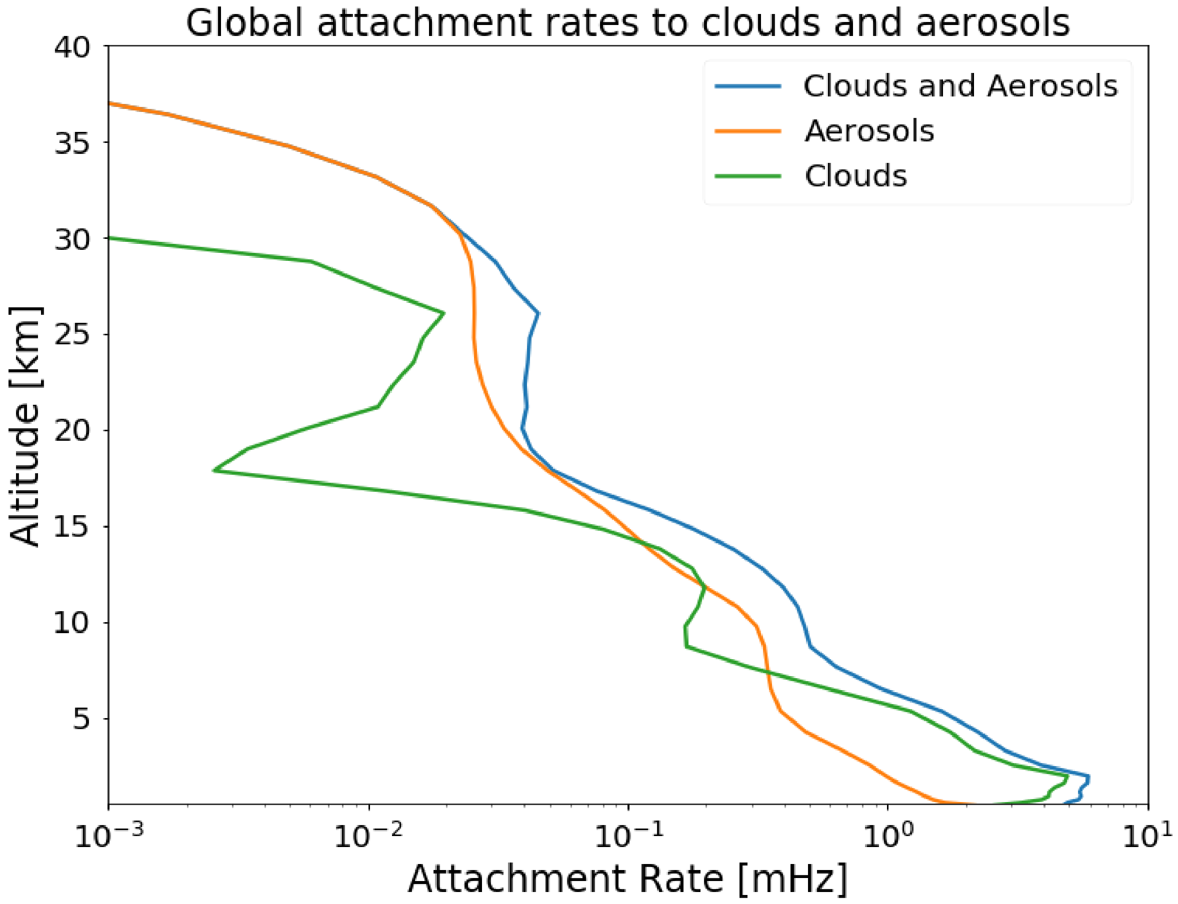
Production and loss of the ions are handled self-consistently in the model

- Radon is only released from ice-free land surfaces
- Radon is advected within the model (this is why there is radon over the oceans)



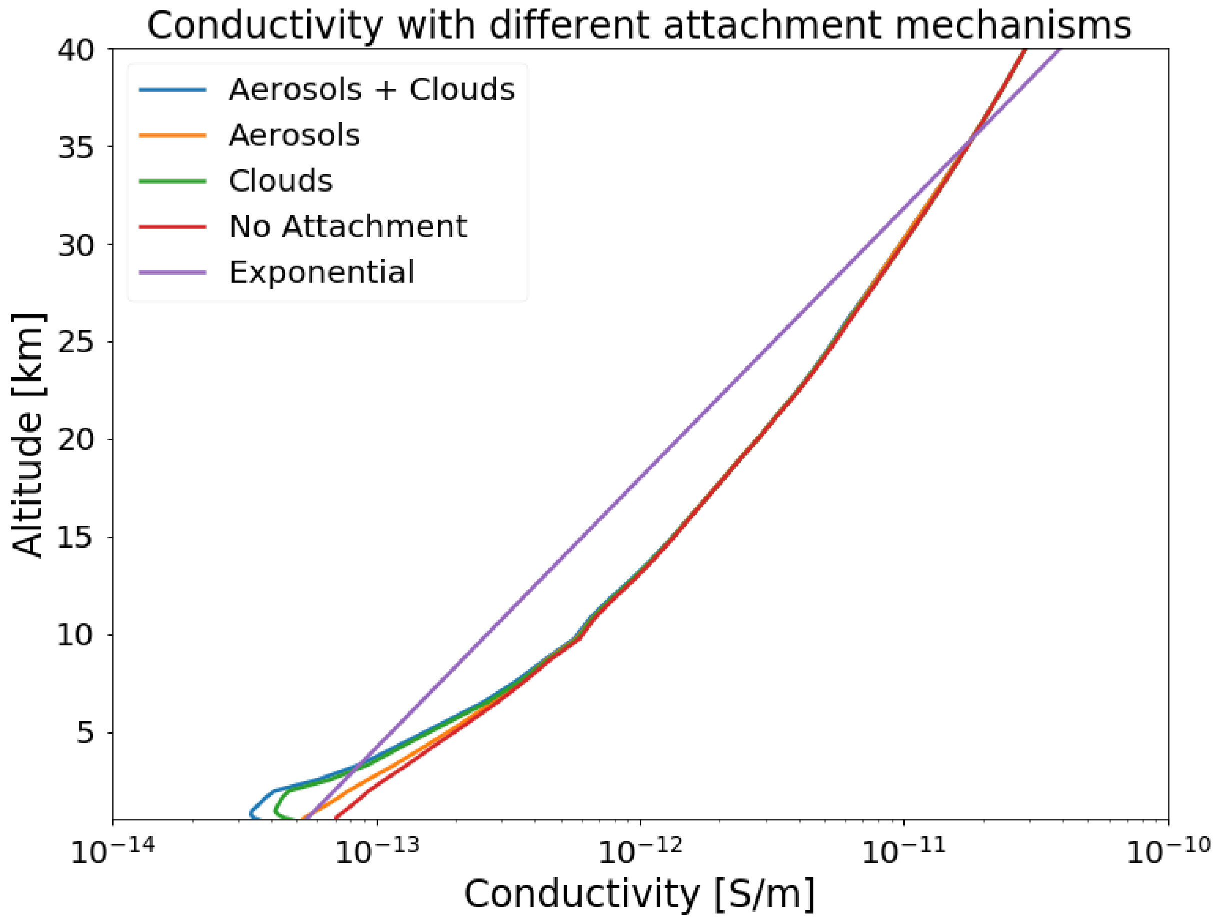
Production and loss of the ions are handled self-consistently in the model

- Attachment to clouds utilizes 2-moment microphysics
  - Physically representative, rather than conductivity reduction factors
- 4-mode aerosol module is used to produce aerosols in the model (includes biomass and volcanoes)
- Clouds are the dominant source of attachment below 10 km

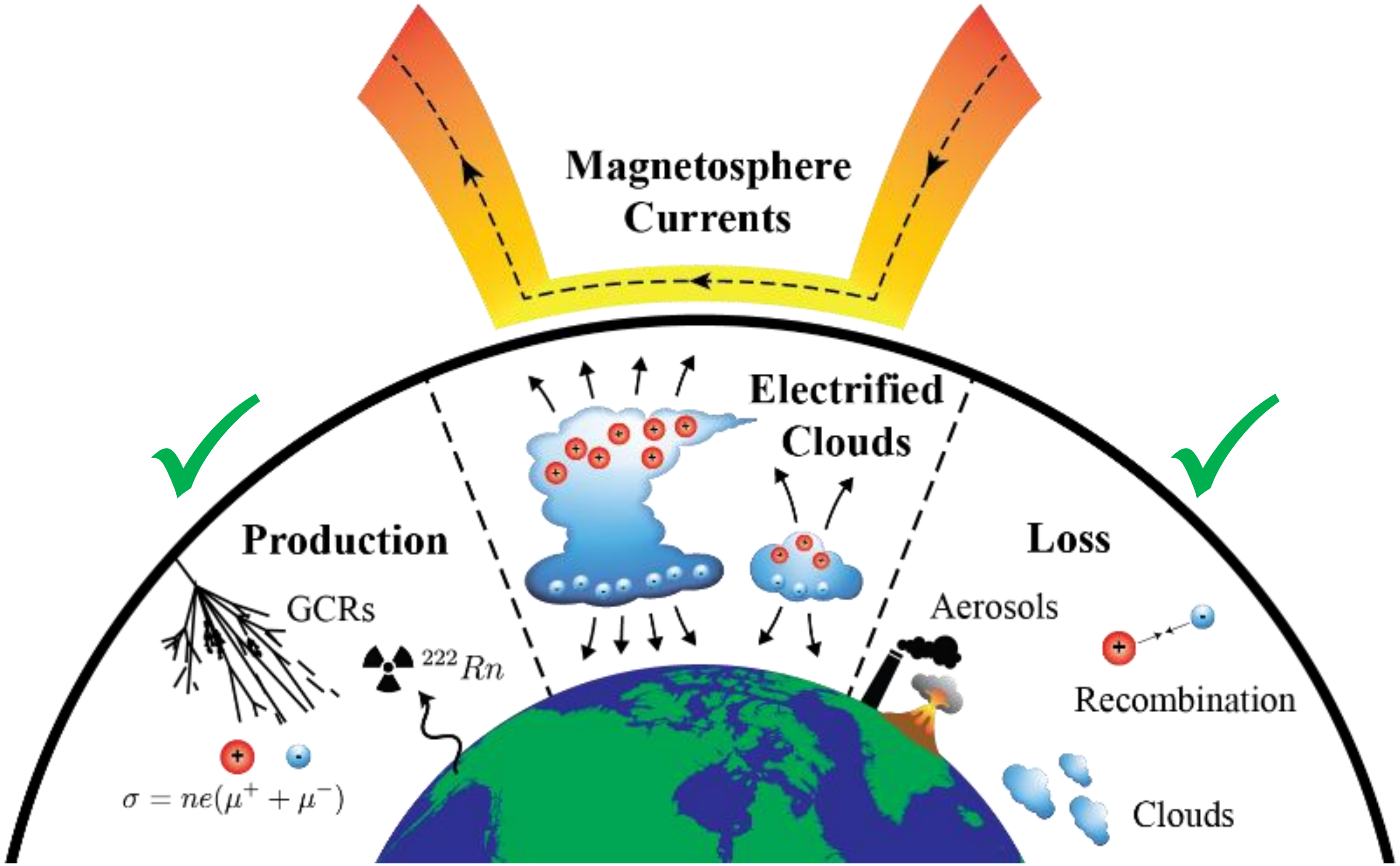


Realistic conductivity profiles are created with WACCM-GEC

- Model production includes: GCRs, radon, solar energetic particles
- Model losses include: Clouds, aerosols, recombination
- Incorporation of all these processes causes significant deviations from analytic expressions



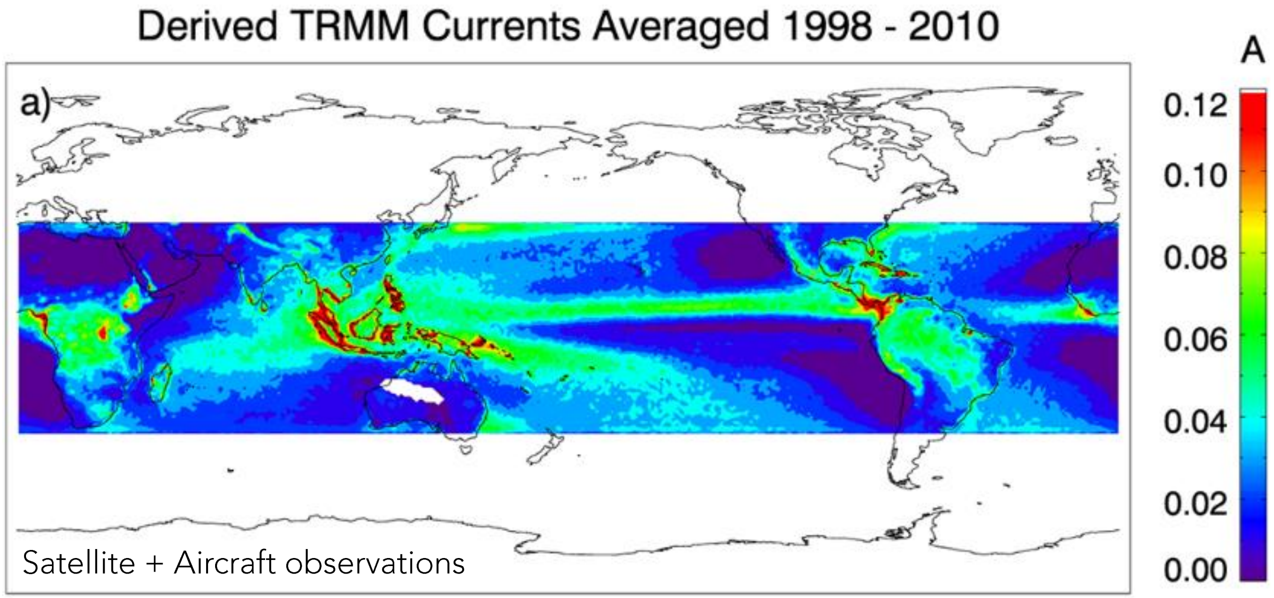
Physical representation of ion production and loss mechanisms implemented

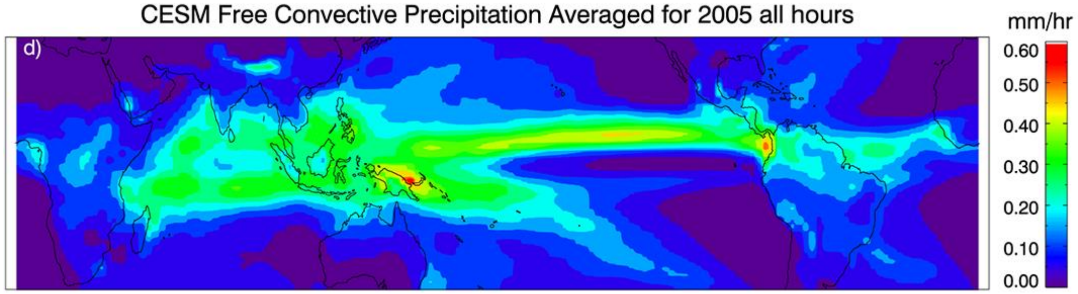


Convective precipitation rate of storms dictates the strength of currents

- Previous work has shown that convective precipitation rate has good skill when predicting currents

$$\boxed{I_{GEC} = f(Convective\ Precipitation\ Rate)}$$





Kalb et al. 2016

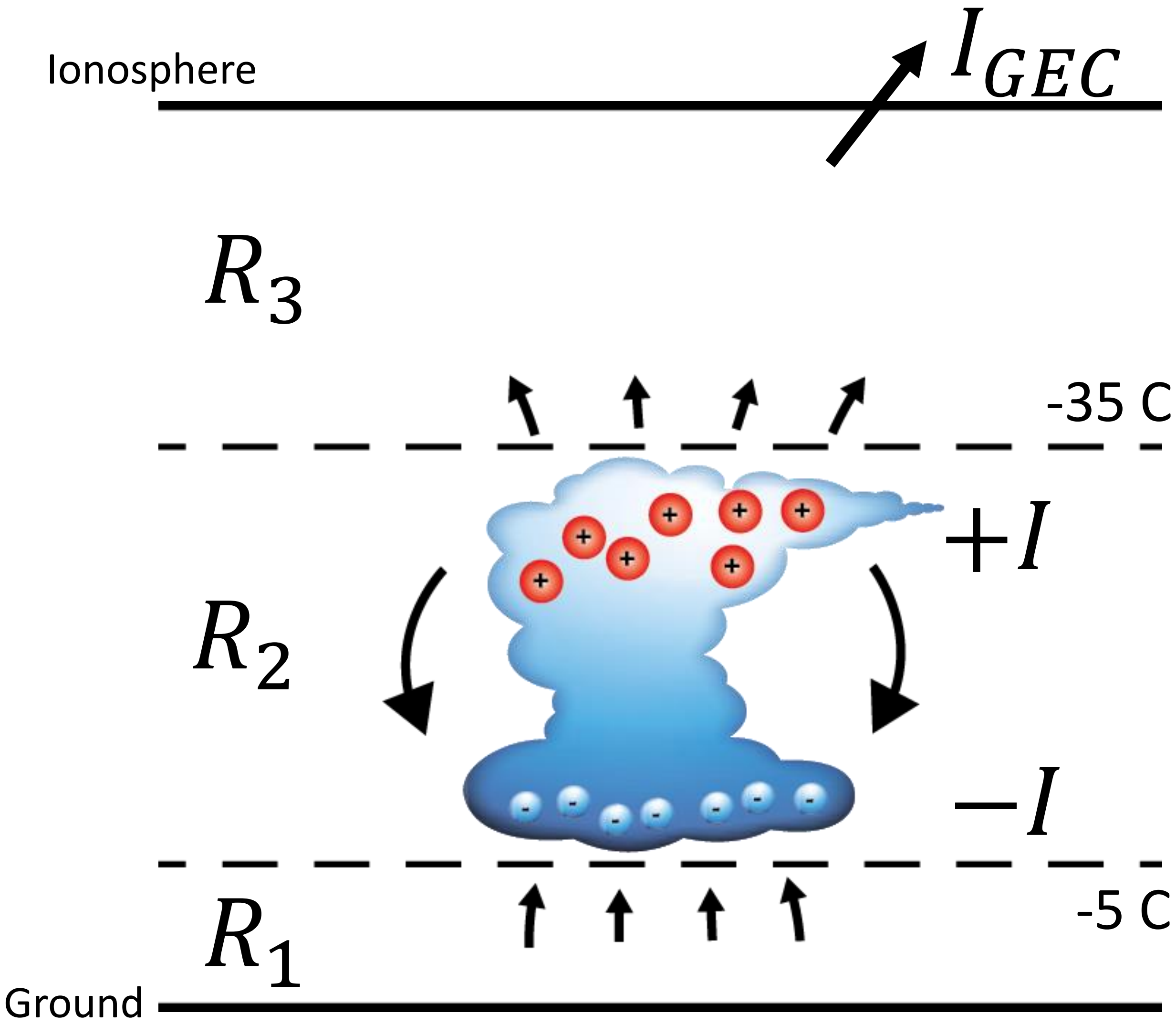
Electrified clouds act as a current source

- Internal resistance of the dipole current source is important for global current production

$$\boxed{I_{GEC} = I * R_{ratio}}$$

- Efficiency factor for producing a global current:

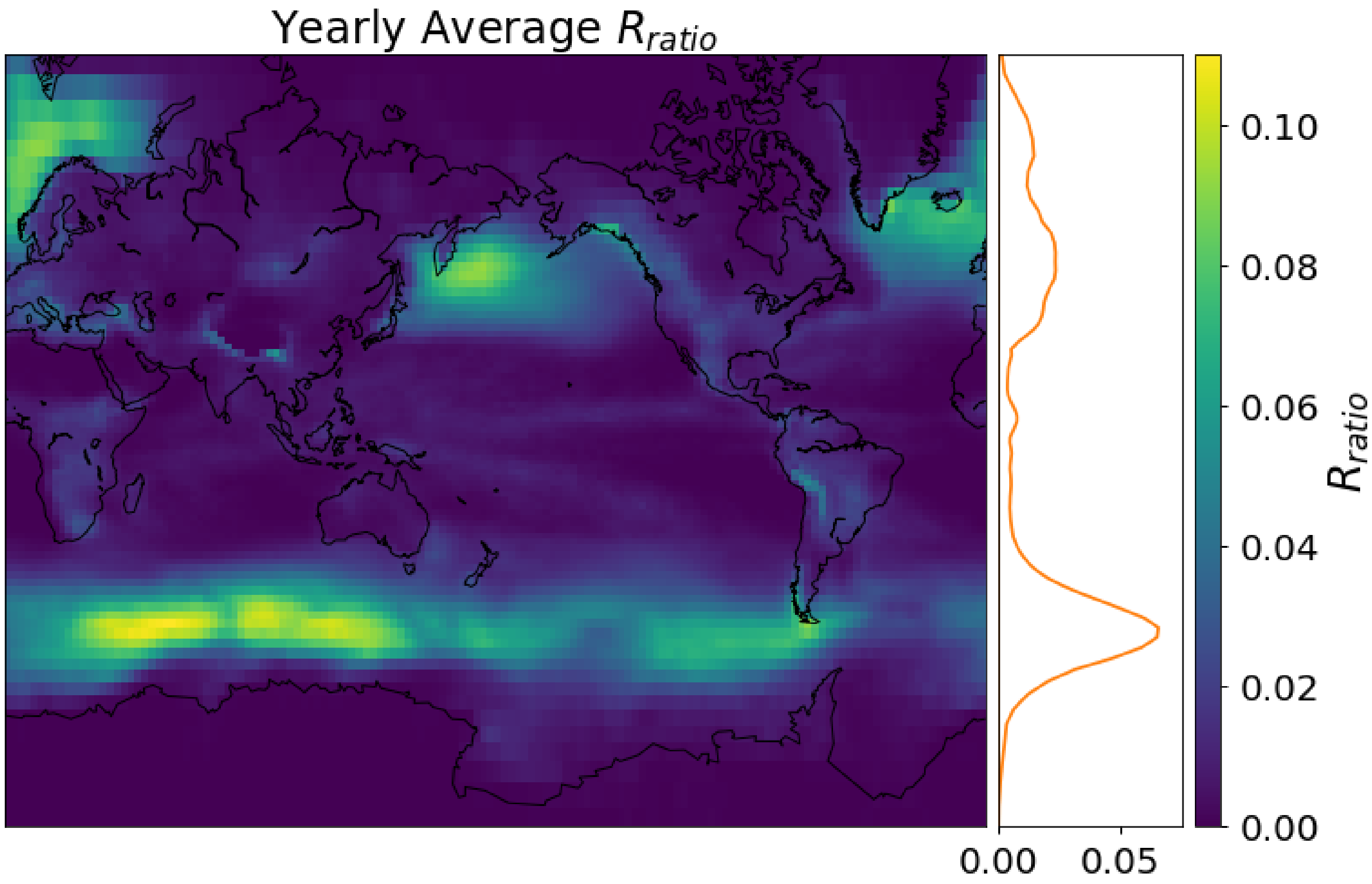
$$\boxed{R_{ratio} = \frac{R_2}{R_1 + R_2 + R_3}}$$



Storms are more efficient at higher latitudes

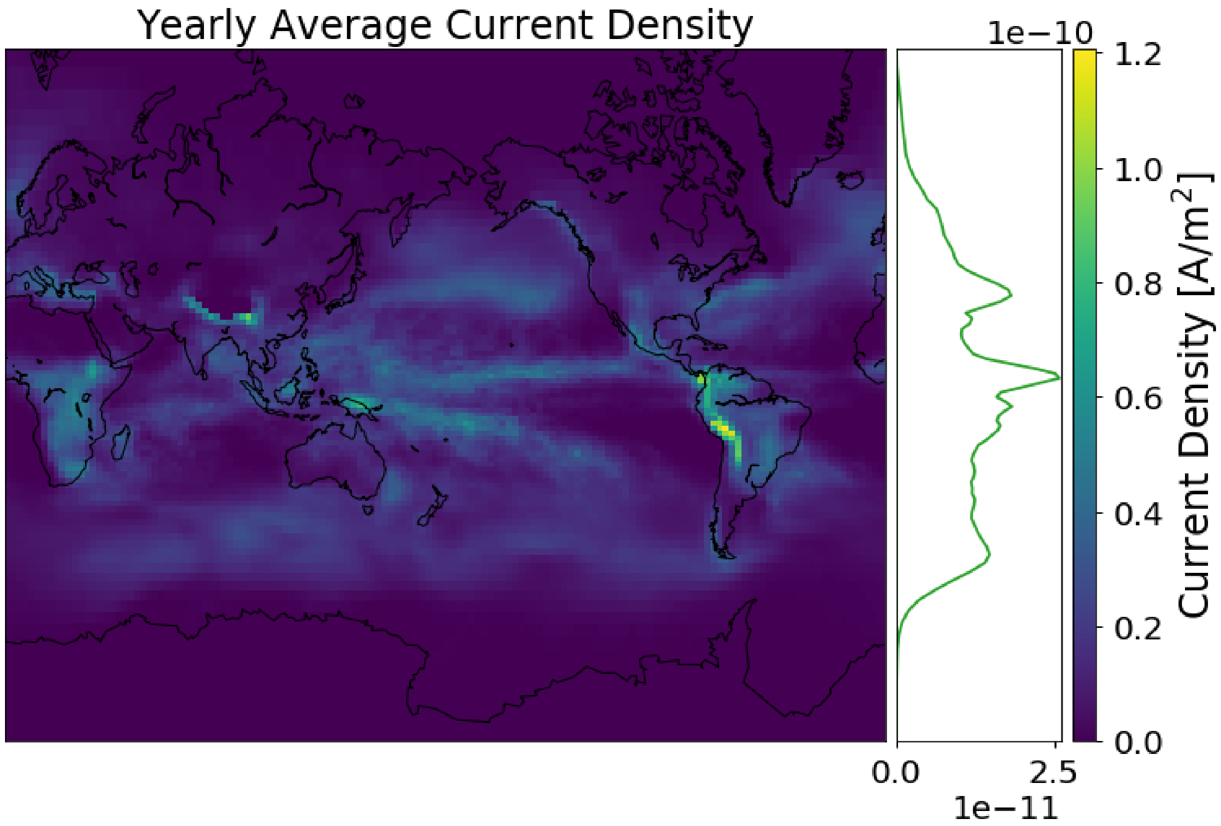
- Internal resistance has never been accounted for in other global models
- 3D storm location is determined by temperature (-35 < T < -5) and updraft

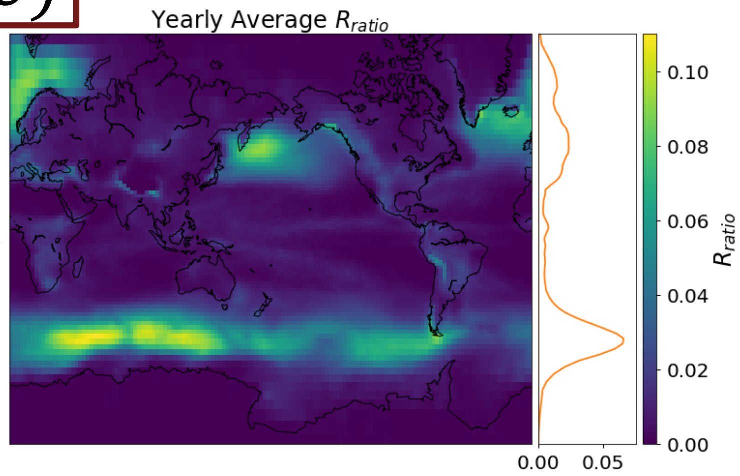
$$R_{ratio} = \frac{R_2}{R_1 + R_2 + R_3}$$

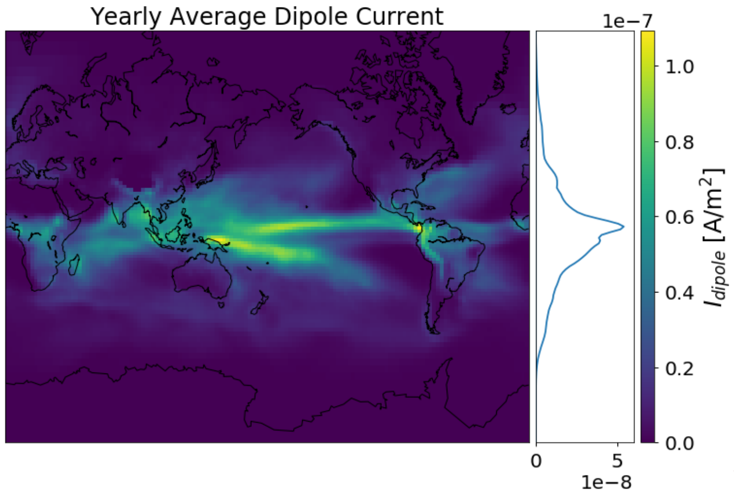


The global current from a storm is a combination of strength and efficiency

$$\boxed{I_{GEC} = R_{ratio} * f(Convective\ Precipitation\ Rate)}$$

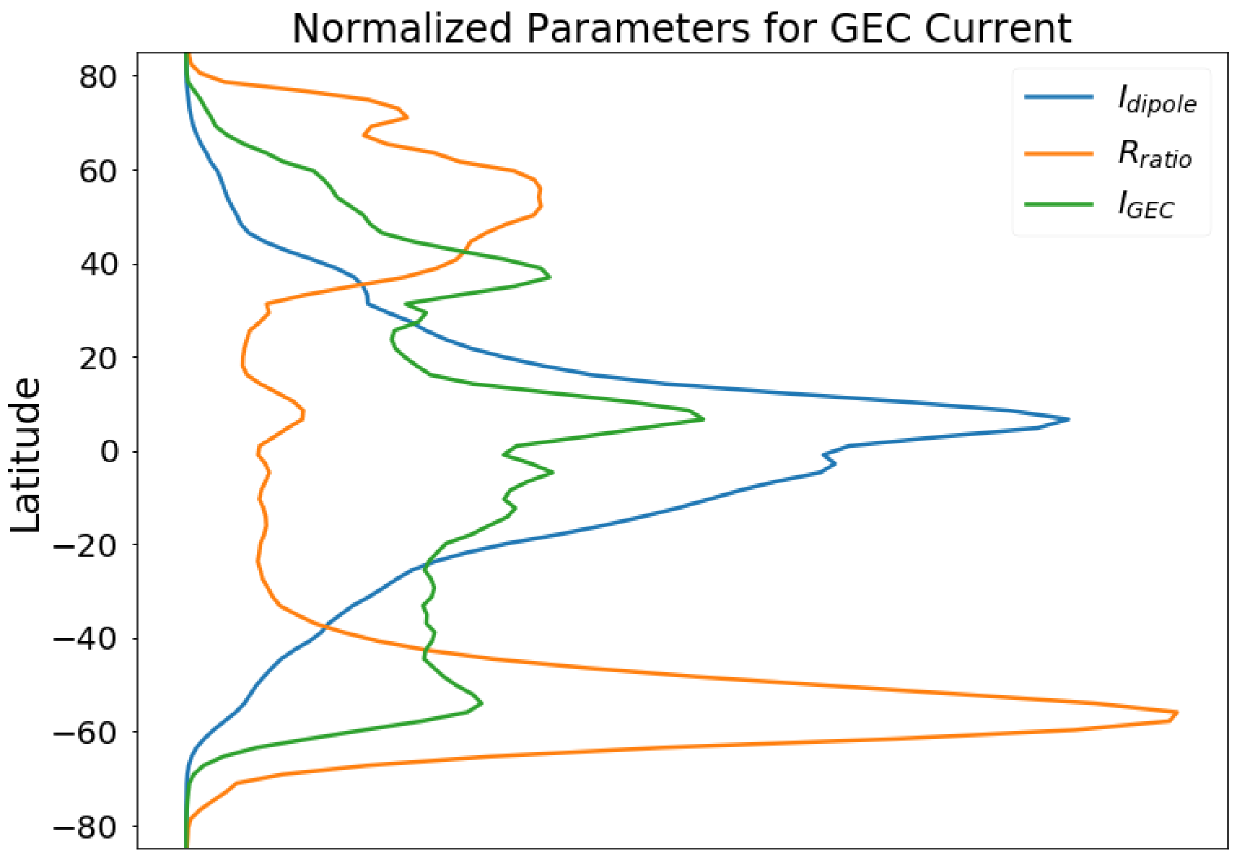




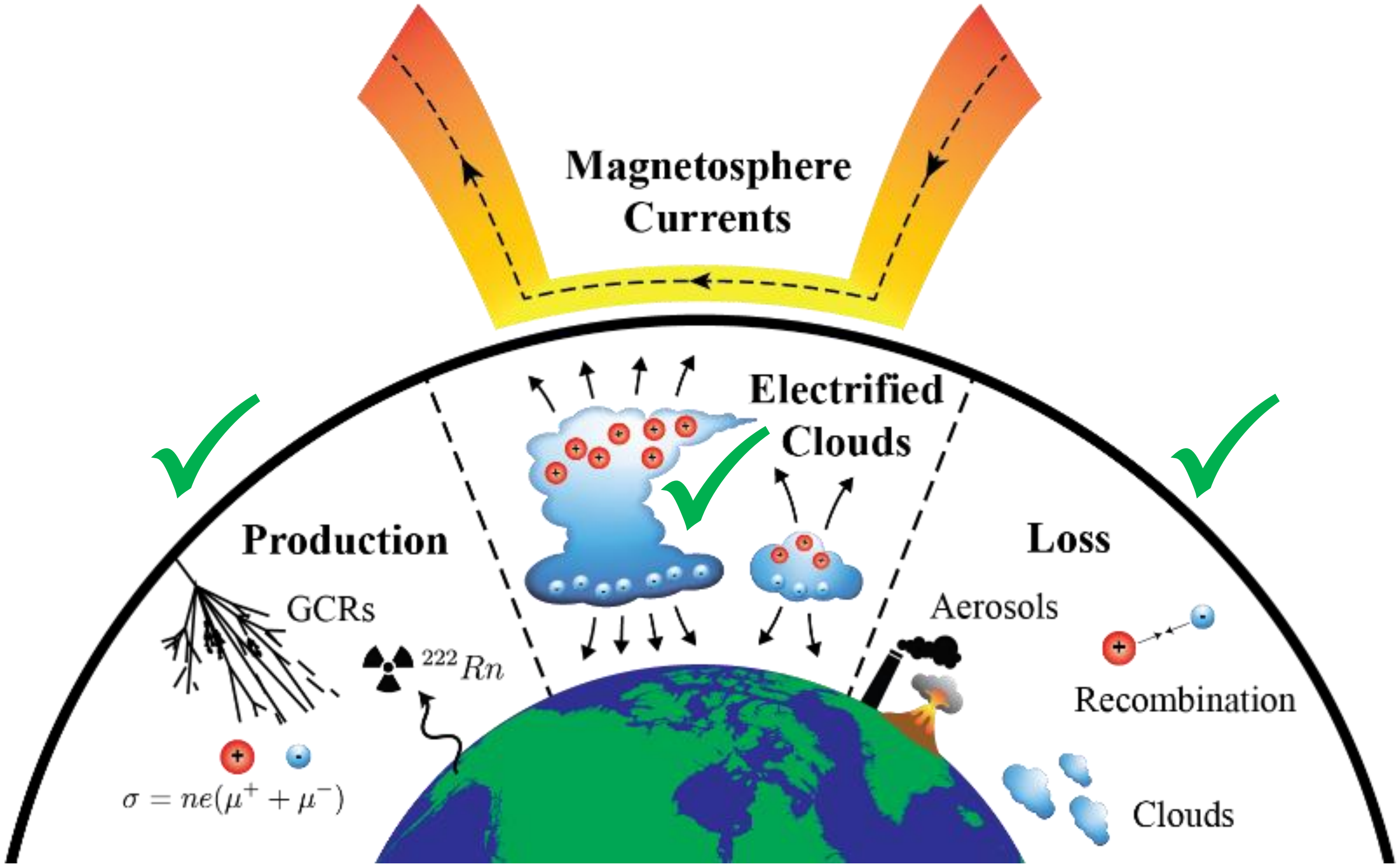


The global current from a storm is a combination of strength and efficiency

- Dipole source strength is peaked near the equator
- Efficiency is peaked towards the poles
- Global current is smoothed towards mid-latitudes



Current sources are implemented with a dependence on conductivity

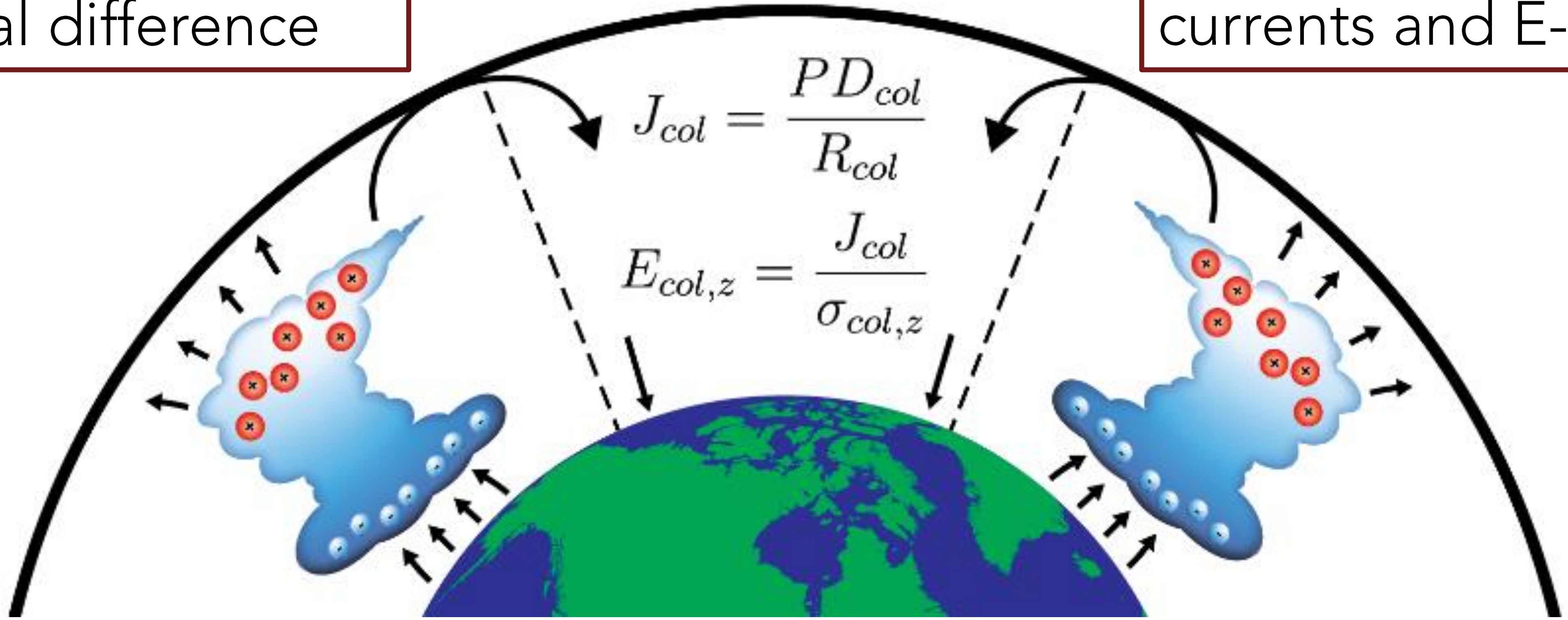


2. How does the global conductivity and source distribution influence local atmospheric electric field measurements?

Create an ionospheric potential difference

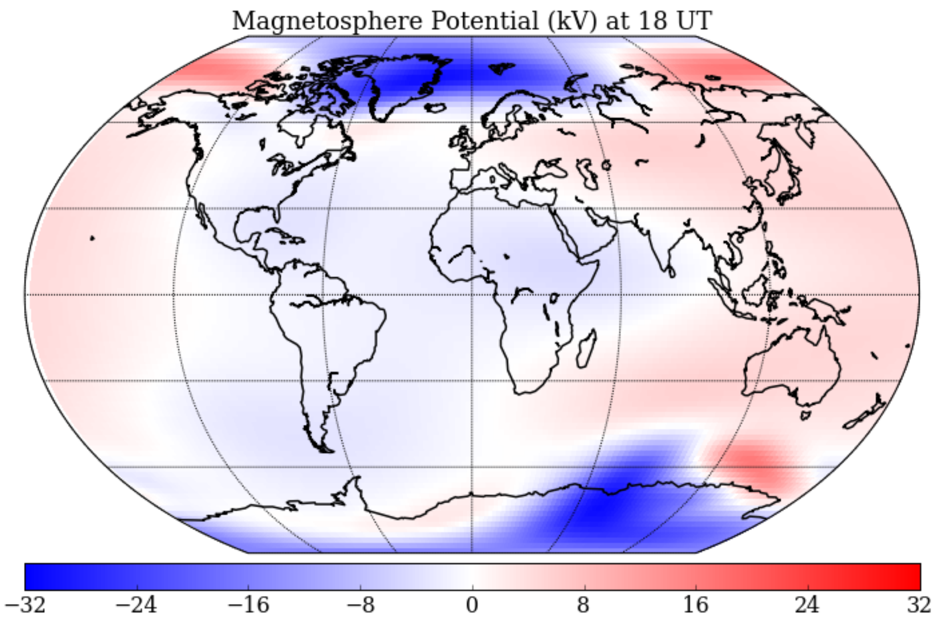
$$PD_{col} = I_{tot} R_{tot}$$

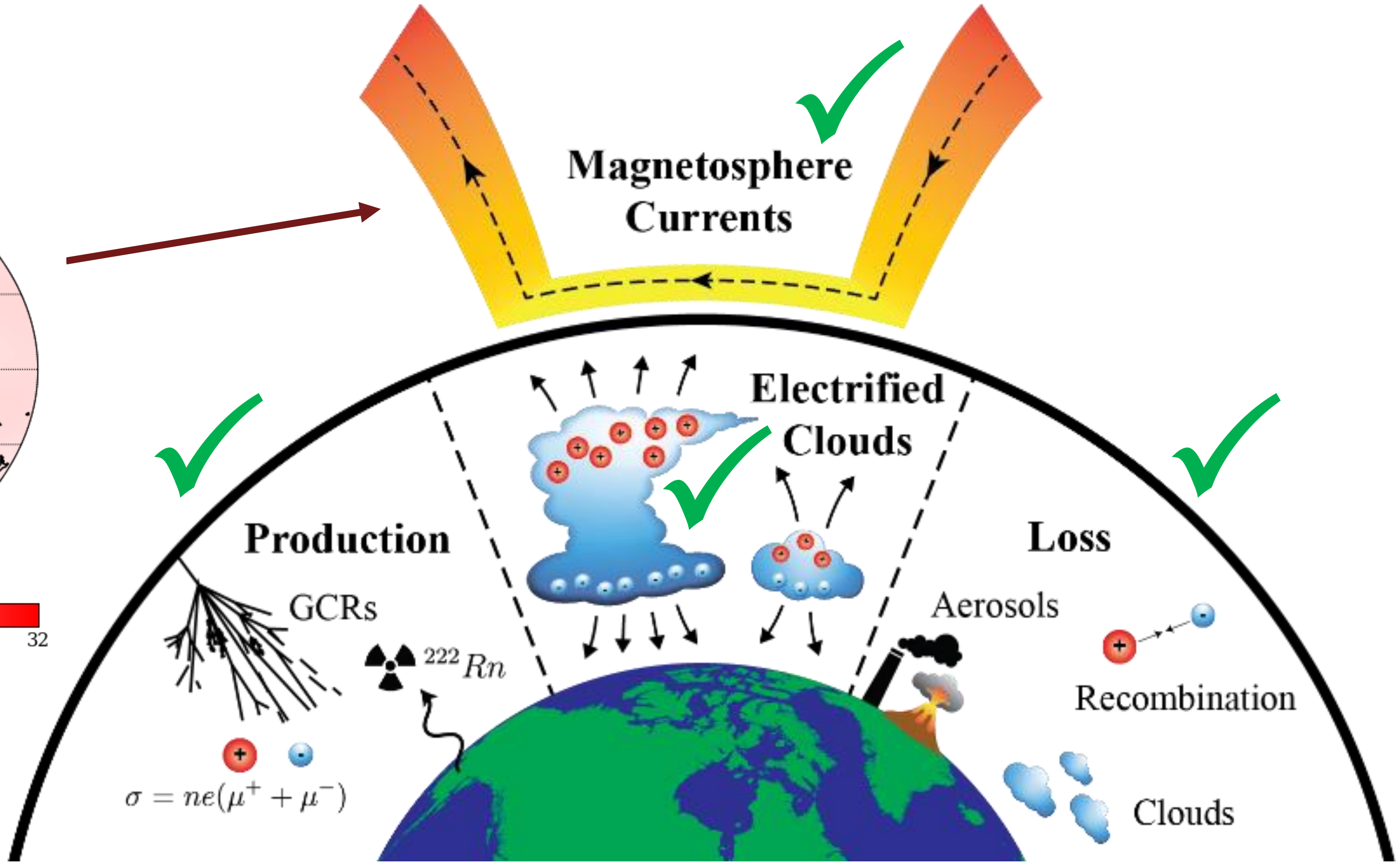
PD produces return currents and E-fields



Lucas et al. 2015

3. How does the magnetospheric current system influence atmospheric electric fields in the global electric circuit?



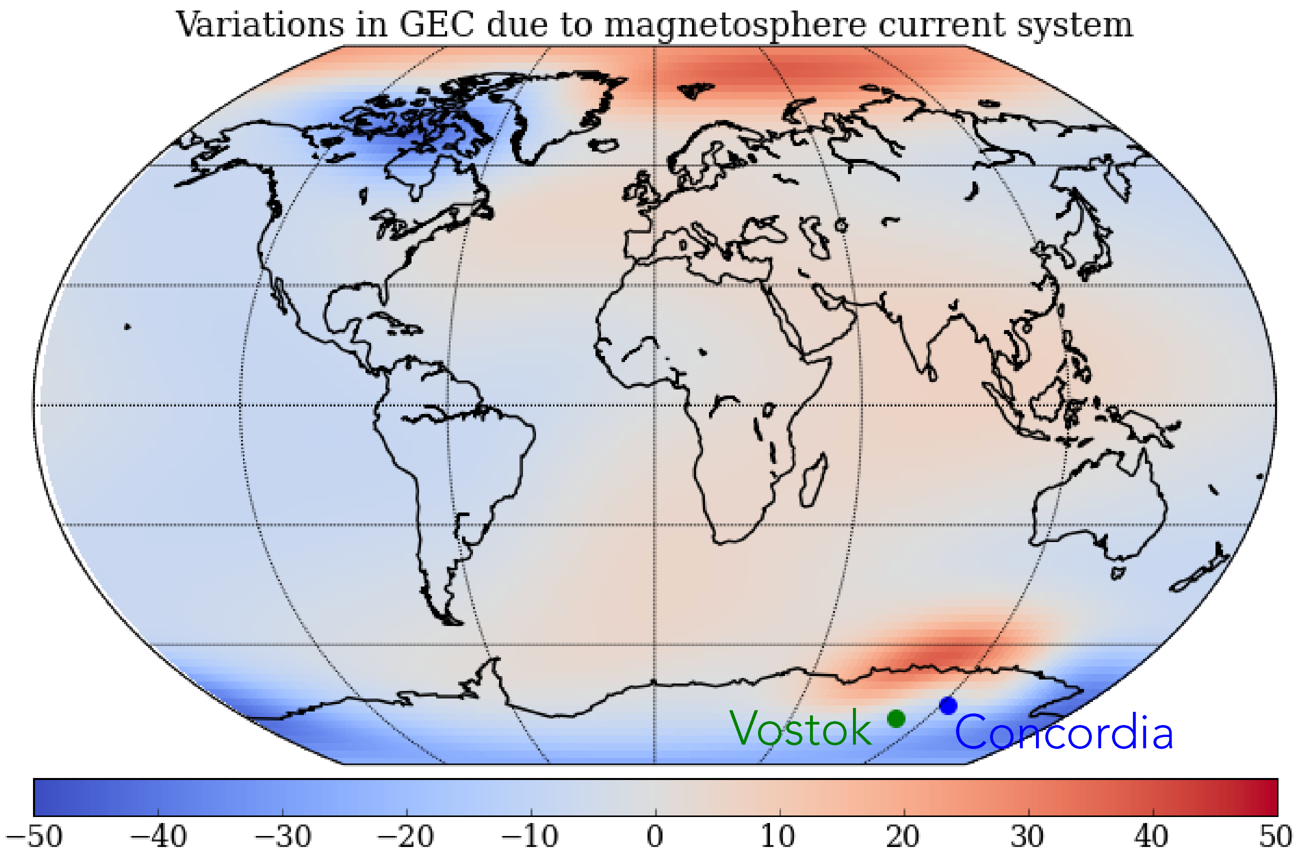


Lucas et al. 2015

3. How does the magnetospheric current system influence atmospheric electric fields in the global electric circuit?

Unique phasing seen at high latitudes that agrees with measurements

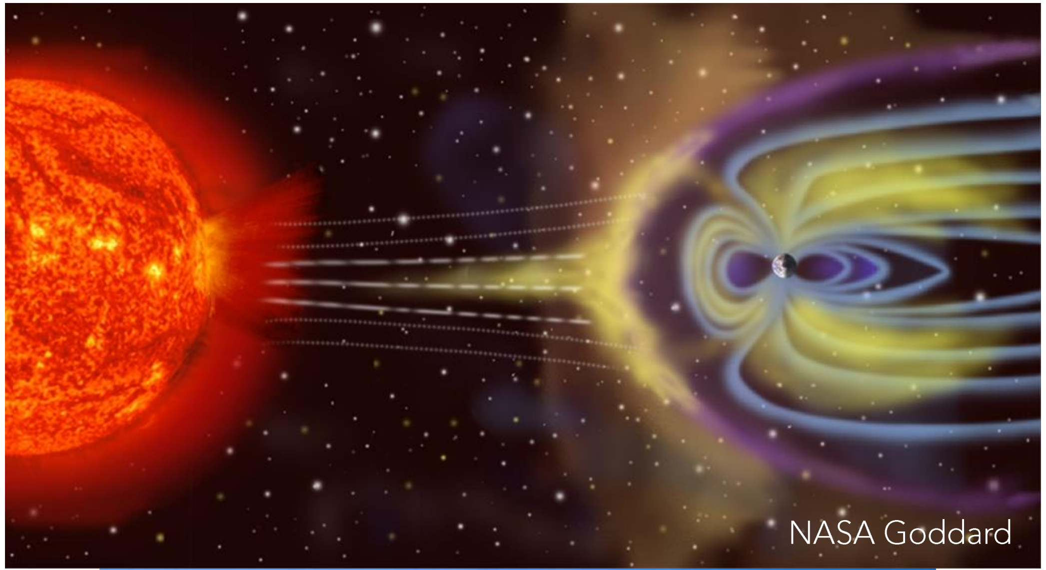
Covered in comprehensive exam, so won't go into details here



Lucas et al. 2015

4. What impact do strong conductivity perturbations have on the global electric circuit?

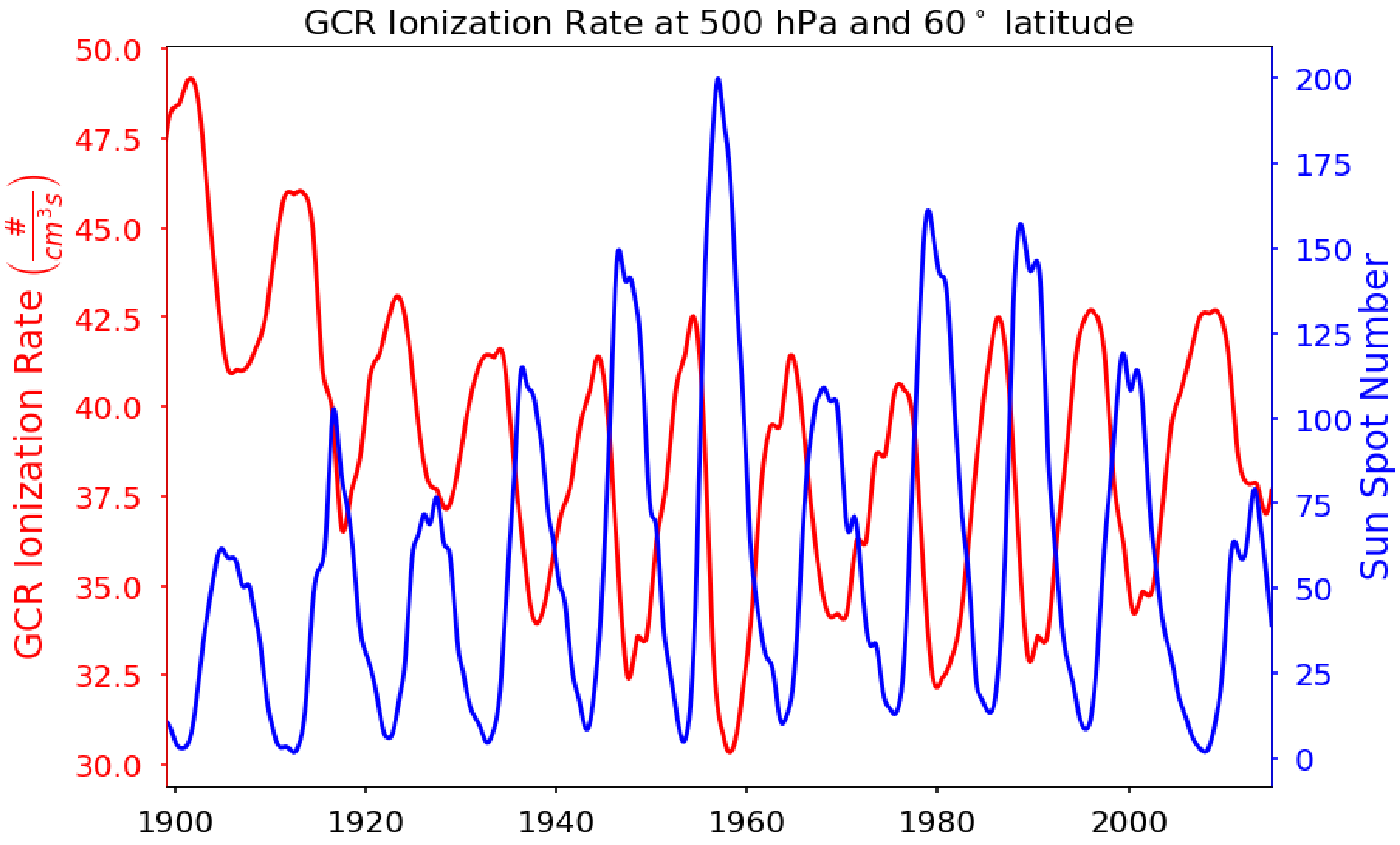
GCR variability and volcanic eruptions modify the conductivity of the atmosphere, but by how much?


NASA Goddard


Live Science

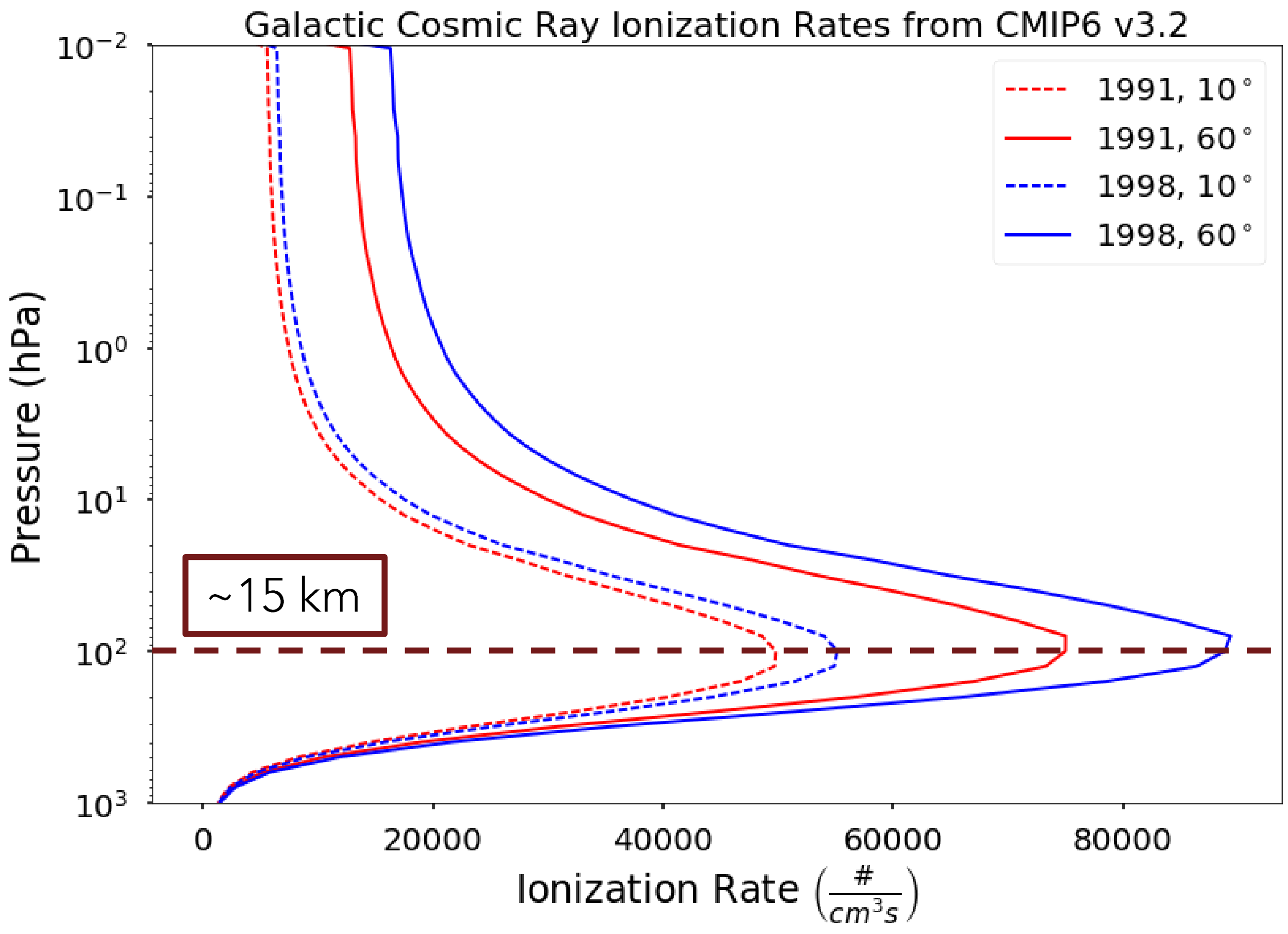
The 11-year solar cycle changes the flux of galactic cosmic rays

- GCRs are anti-correlated with the solar cycle
- GCR data obtained from neutron monitor counts and modeled ionization rates (CMIP6 is used)



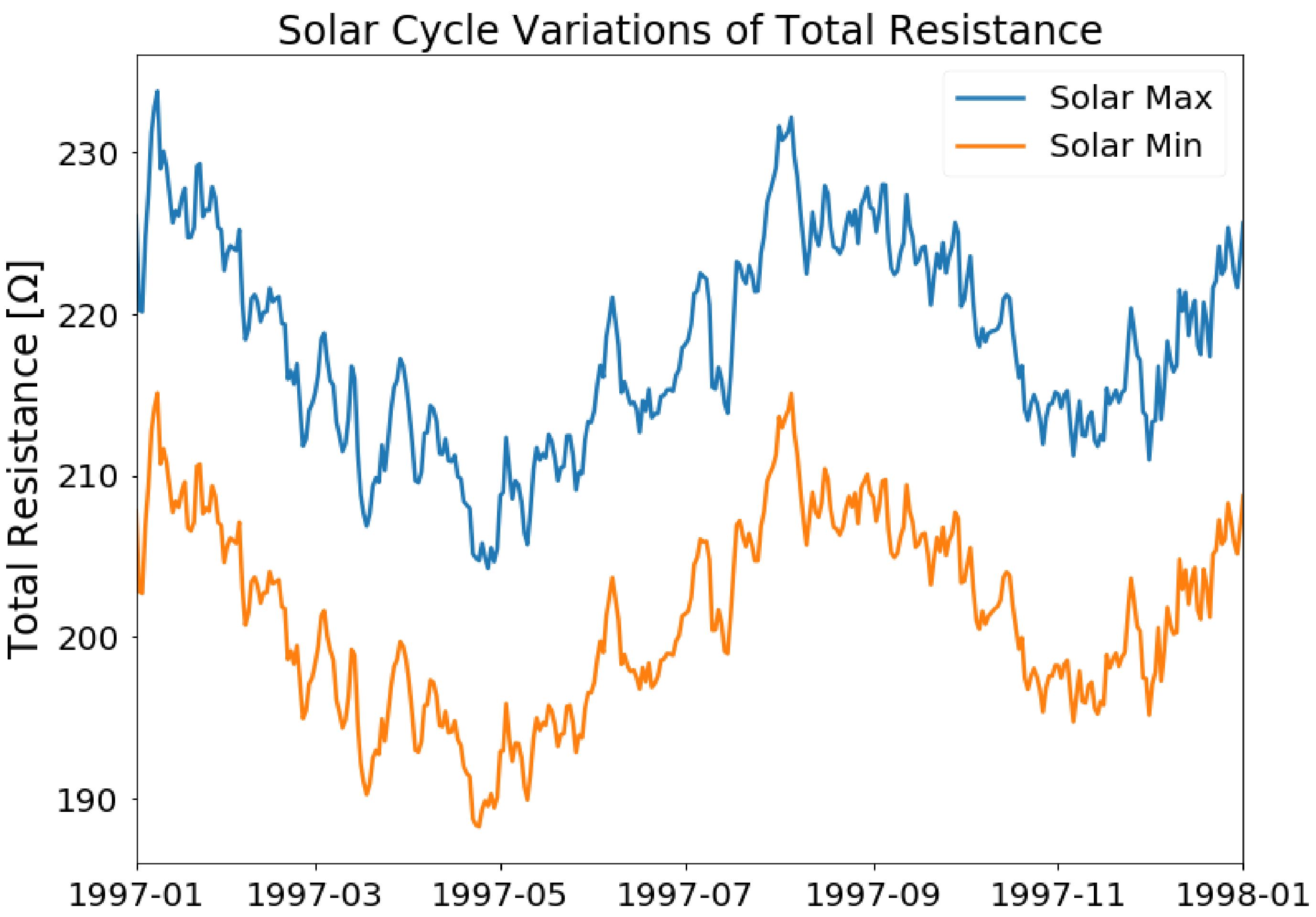
GCRs are the dominant ion production mechanism in the middle atmosphere

- Solar min (GCR max) in 1998 produces more ionization than solar max (GCR min) in 1991
- Differences are not as noticeable near the surface, or at lower latitudes (dashed lines)



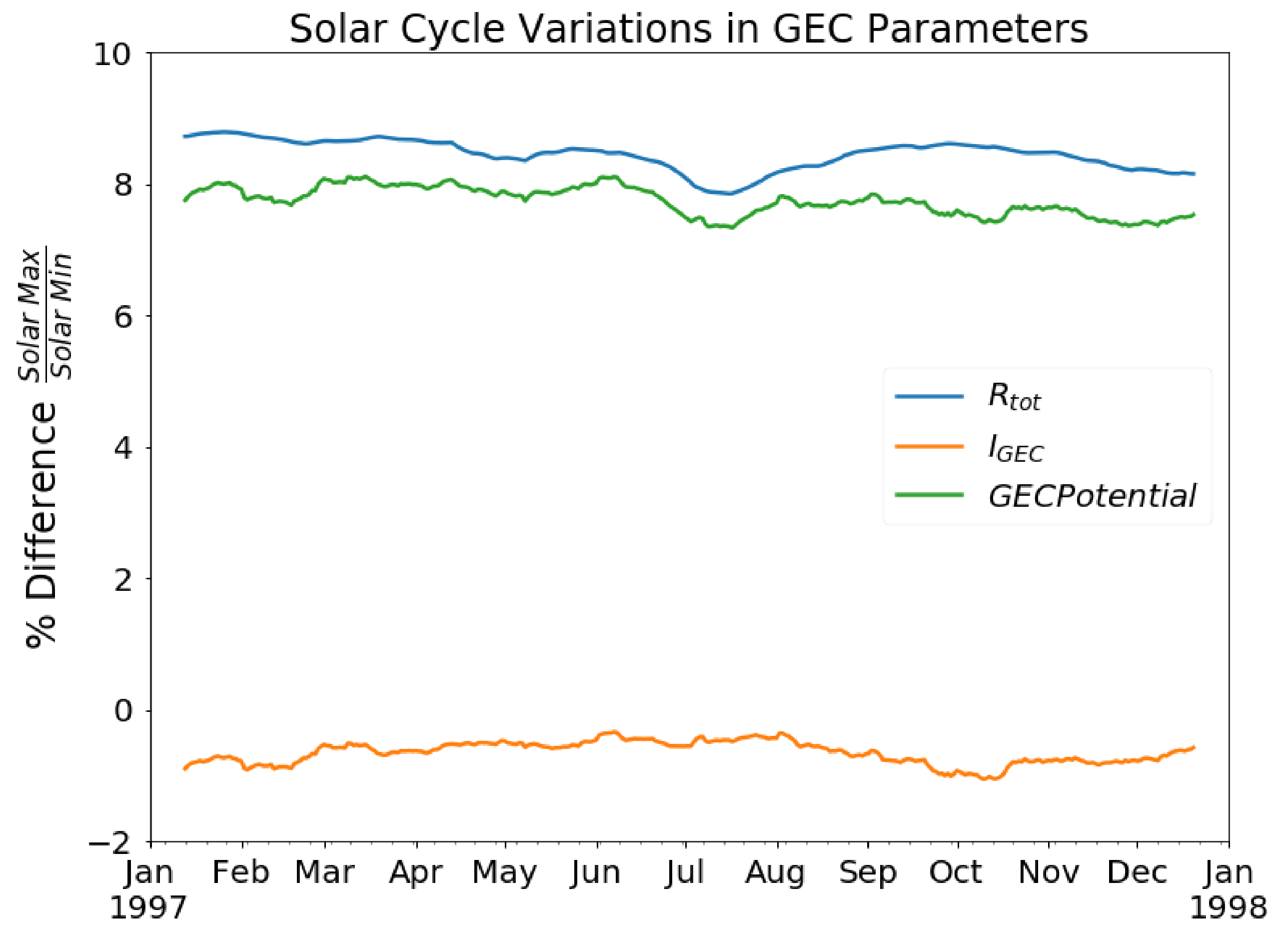
Changing ionization rates leads to a 20 Ω difference in solar max/min conditions

- Model run for 1997
- Only changed the GCR ionization rate from solar min to solar max (leave all other production and loss mechanisms the same)
- ~10% change in total resistance of the atmosphere



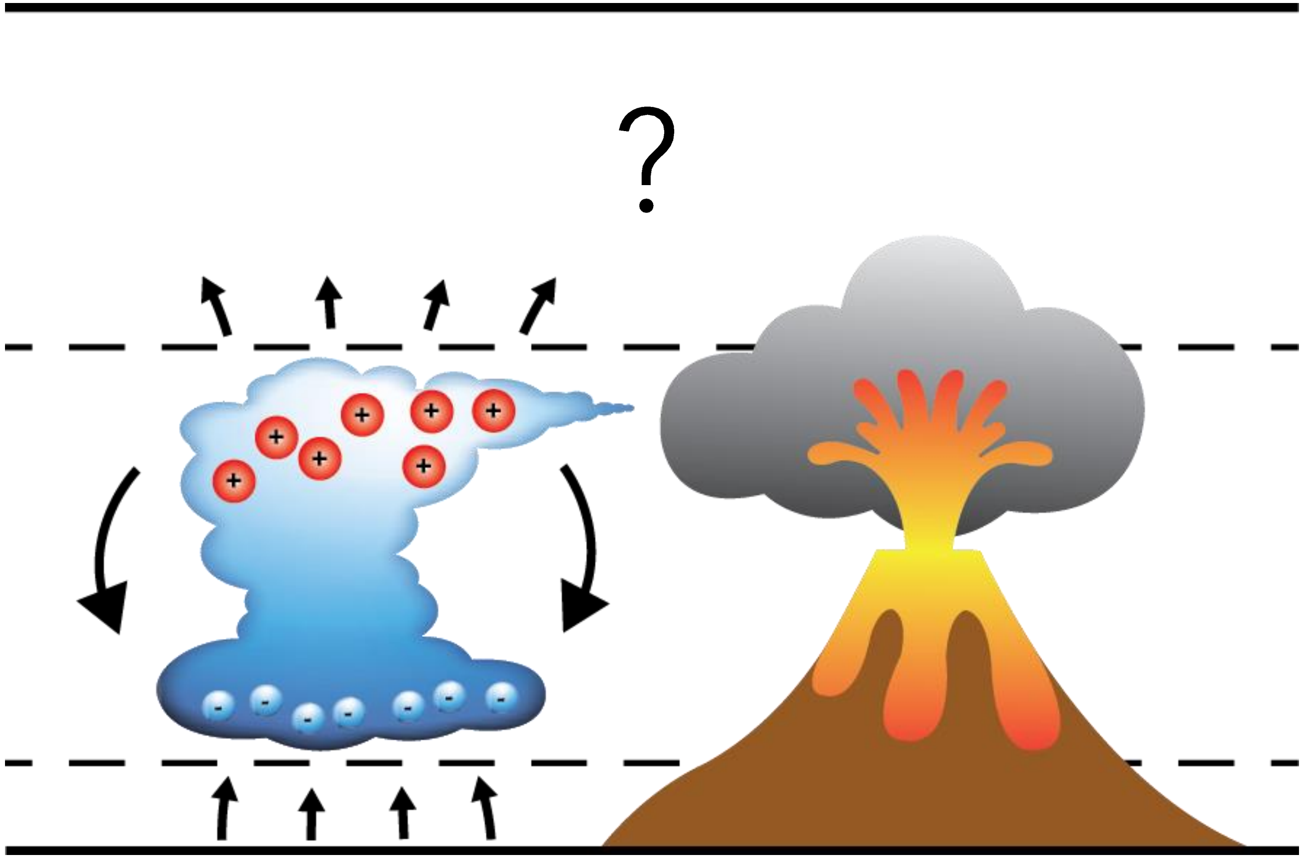
Solar cycle variations of around 10% can be seen in the GEC potential

- Reduction of source strengths by 1% during solar max (GCR min)
- Accounting for source and resistance changes leads to an 8% change in the GEC potential



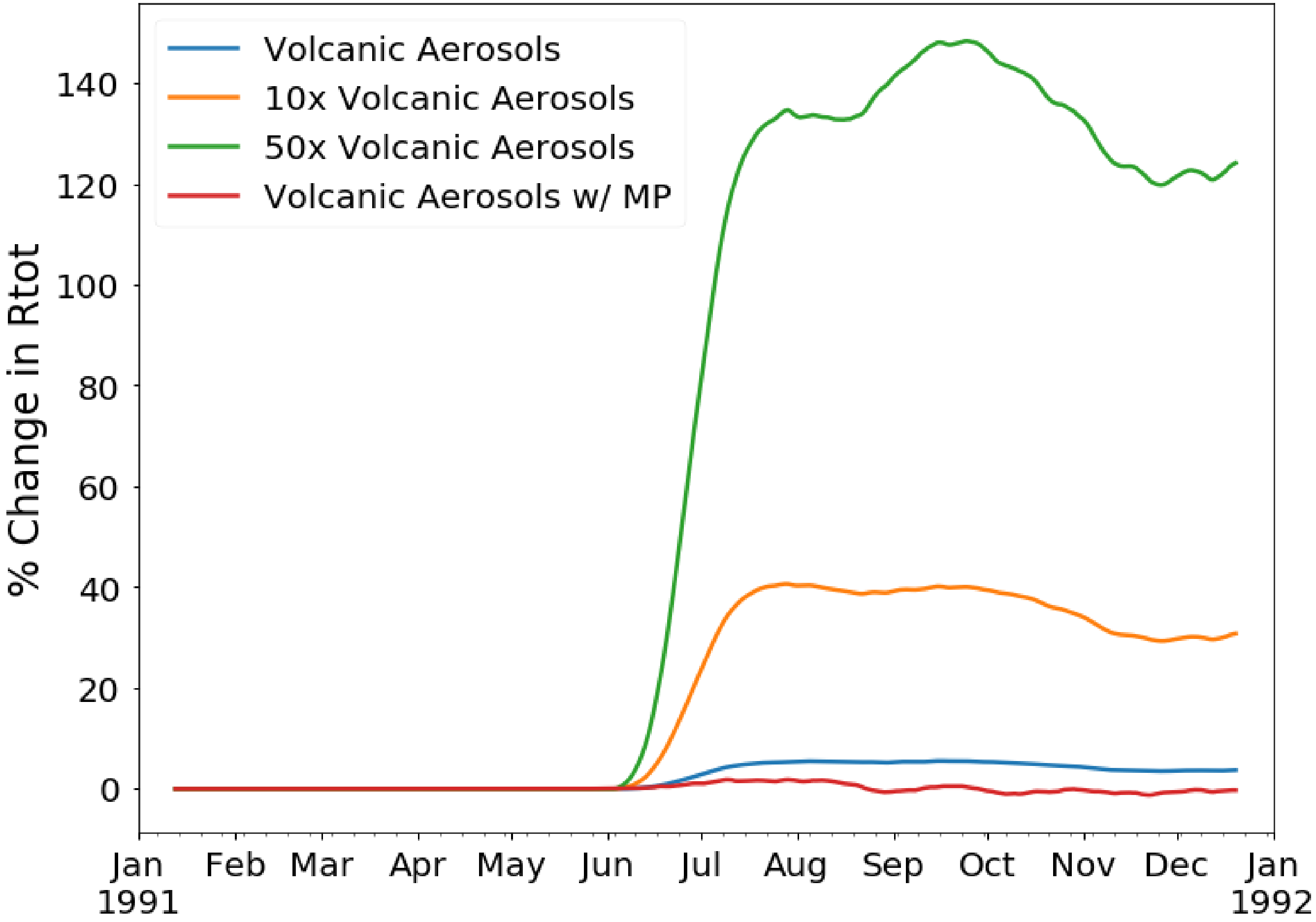
The Pinatubo eruption of 1991 is the most recent major explosive volcano

- Aerosols were ejected into the stratosphere and were circulated around the globe over several months
- Running over the year 1991, the impact that this volcanic eruption had on the global electric circuit can be investigated



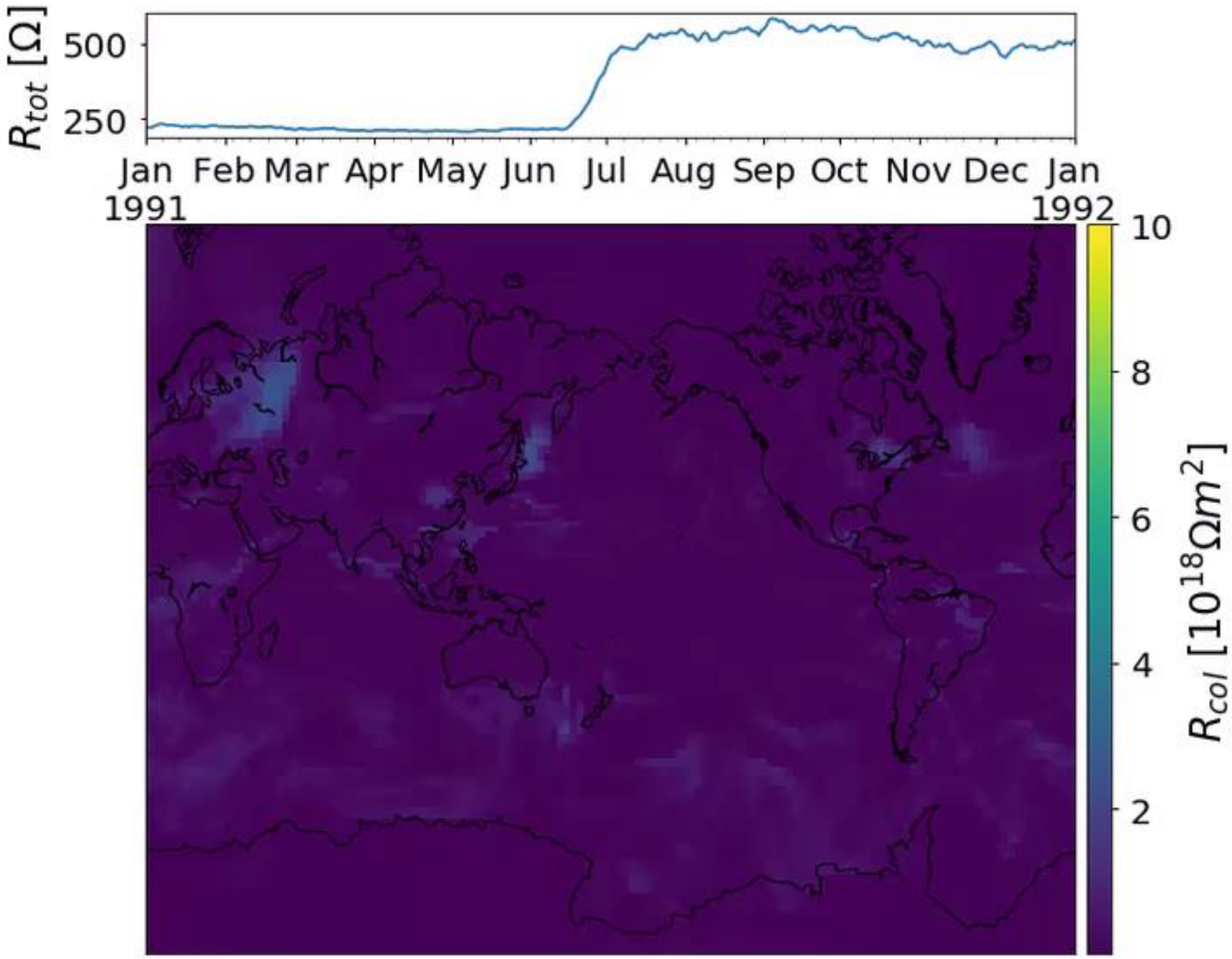
Total resistance of the atmosphere is increased from ion-aerosol attachment

- Increasing the aerosol content of the atmosphere increases the ion loss rate
- Pinatubo eruption has little influence on the total resistance, but a volcano 50x the size more than doubles the total resistance



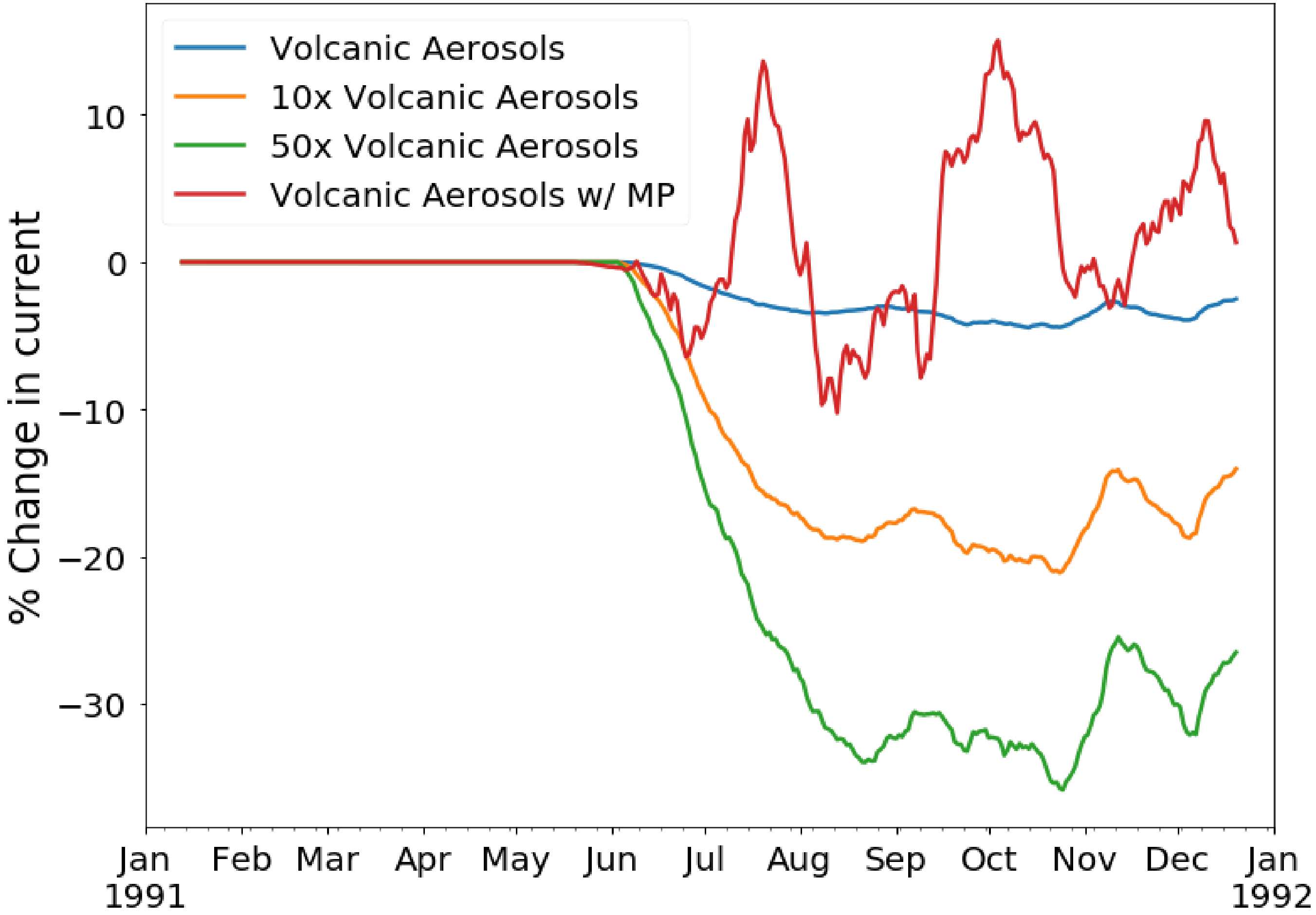
50x Pinatubo Run

- Column resistance changes over time from a 50x Pinatubo run
- Volcano erupts in mid-June increasing the column resistance across the globe



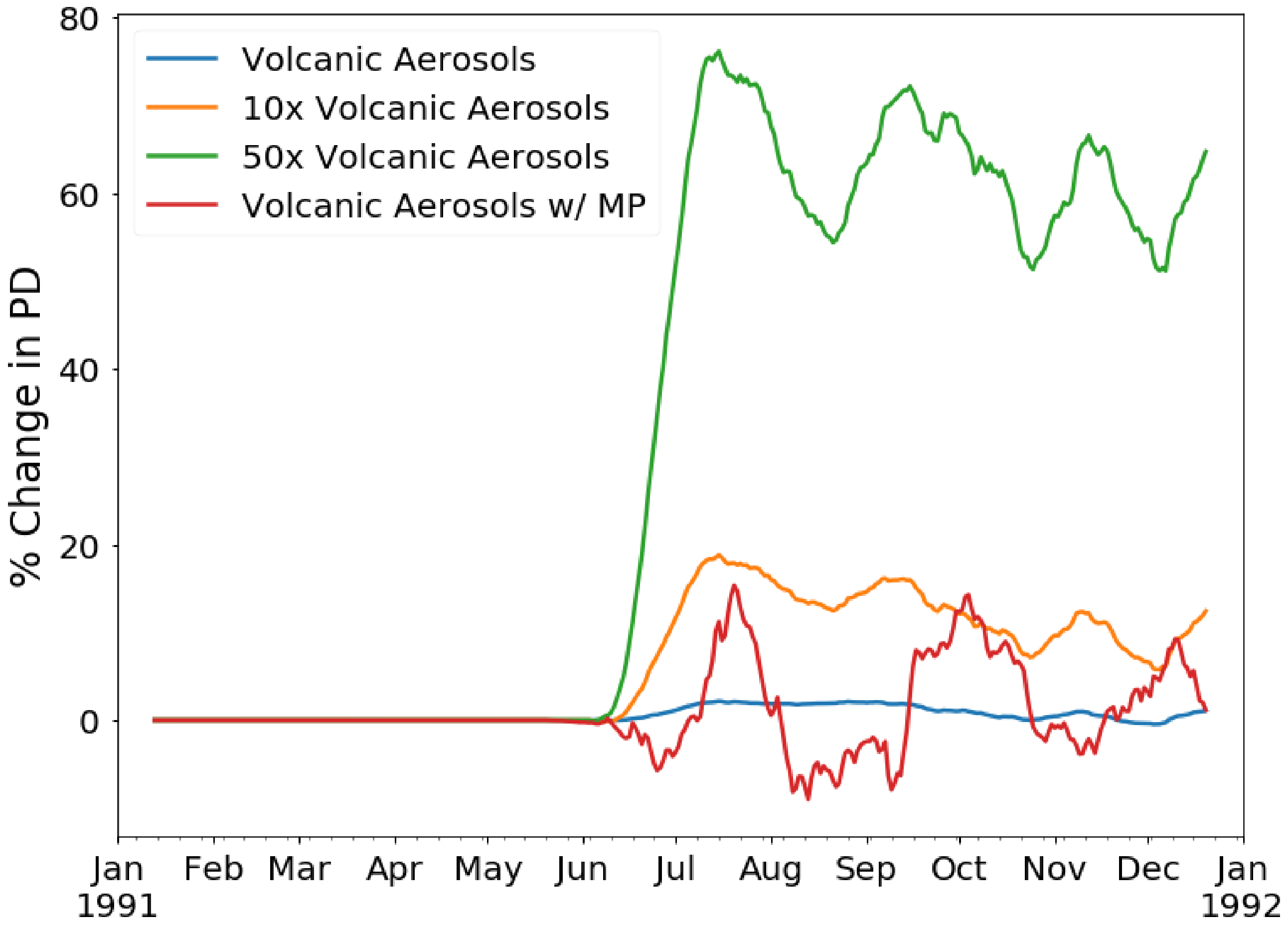
Sources are more complicated than resistance changes alone

- Volcanic aerosols feedback on the microphysical cloud and radiative properties of the atmosphere
- Run with MP includes feedback mechanisms
- All other runs have aerosol feedback turned off



Microphysical feedbacks within the climate models need to be included

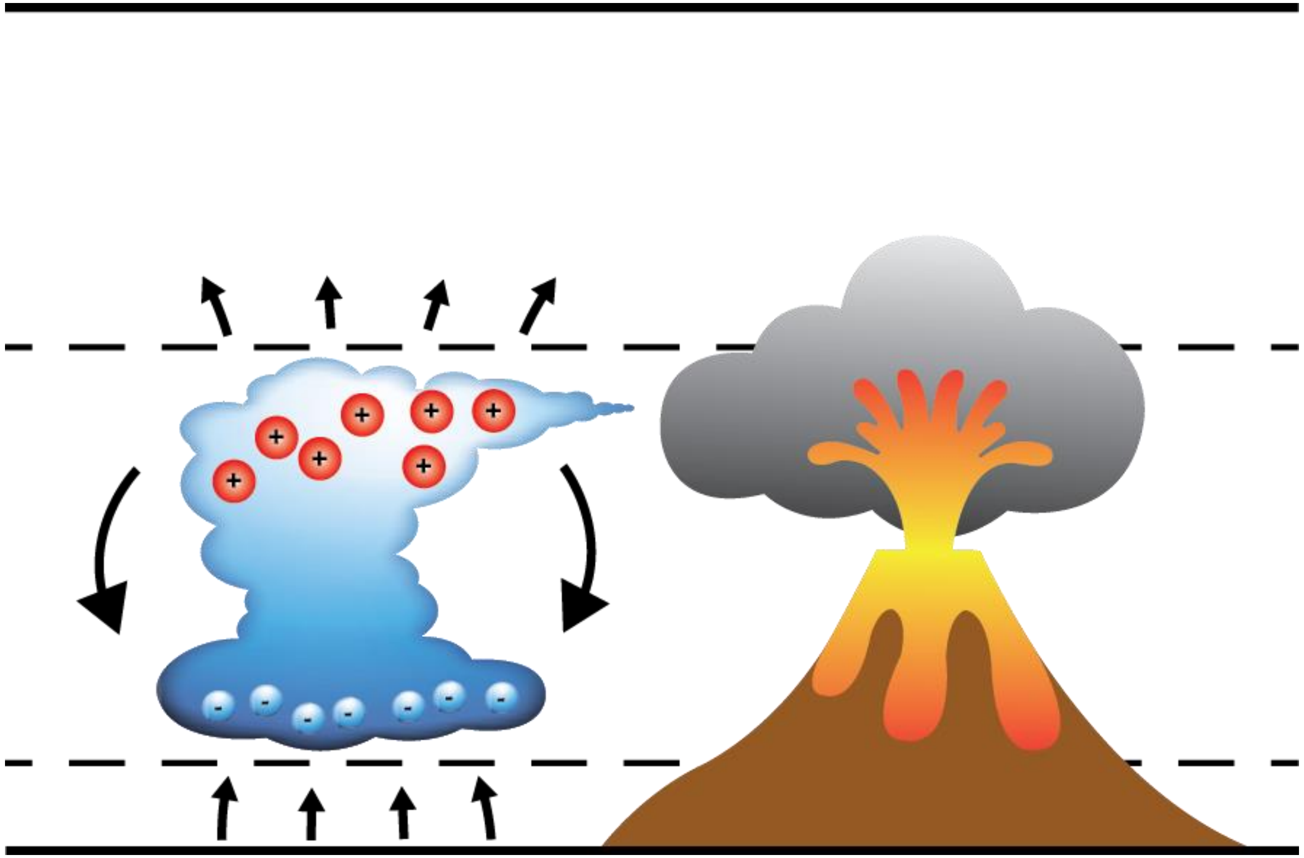
- Potential is increased when volcanic aerosols are included
- Complicated microphysical coupling in storm creation creates unique influences that a simple electric circuit model cannot account for



4. What impact do strong conductivity perturbations have on the global electric circuit?

Solar cycle and volcanic eruptions have around a 10% influence on the GEC, unless gigantic events are considered

Microphysical feedbacks within the climate models need to be considered, not just simple equivalent circuits



Lucas et al., In preparation

Several major milestones were completed during the thesis

- I identified the impact of local meteorology on the measurement of near-surface electric fields and emphasized the importance of spatially distributed and temporally extensive electric field observations in distinguishing global and local phenomena.
- I created the most advanced 3-D, physics-based global electric circuit model which produces a complete and internally consistent description of conductivity, currents, and electric fields in the atmosphere.
- I demonstrated that, with this sophisticated model, physical effects on the global electric circuit, from solar influences to cloud microphysics, can be explored for the first time.

Future extensions of the work

- This thesis focused on building and using the GEC model for the determination of electric fields. I have not investigated how these electric fields couple back into the microphysics. Future researchers can build off of my work and implement the feedback mechanisms
- WACCM-GEC is not able to resolve the features seen in the local observations, so I also created a local conductivity model within a local weather model (WRF)
- The modeling work within this thesis provides a consistent way to evaluate theories related to observations of electric fields in the atmosphere

Papers produced during this thesis

- 2 first author, 4 co-authors
  - Baumgaertner, A. J. G., Thayer, J. P., Neely, R. R., & **Lucas, G.** (2013). Toward a comprehensive global electric circuit model: Atmospheric conductivity and its variability in CESM1 (WACCM) model simulations. Journal of Geophysical Research: Atmospheres, 118(16), 9221-9232
  - Baumgaertner, A. J. G., **Lucas, G. M.,** Thayer, J. P., & Mallios, S. A. (2014). On the role of clouds in the fair weather part of the global electric circuit. Atmospheric Chemistry and Physics, 14(16), 8599-8610
  - Liu, X., Wang, W., Thayer, J. P., Burns, A., Sutton, E., Solomon, S. C., ... & **Lucas, G.** (2014). The winter helium bulge revisited. Geophysical Research Letters, 41(19), 6603-6609
  - Bayona, V., Flyer, N., **Lucas, G. M.**, & Baumgaertner, A. J. G. (2015). A 3-D RBF-FD solver for modeling the atmospheric global electric circuit with topography (GEC-RBFFD v1. 0). Geoscientific Model Development, 8(10), 3007
  - **Lucas, G. M.**, Baumgaertner, A. J. G., Thayer, J. P. (2015). A global electric circuit model within a community climate model. Journal of Geophysical Research: Atmospheres
  - **Lucas, G. M.,** Thayer, J. P., Deierling, W. (2017). Statistical analysis of spatial and temporal variations in atmospheric electric fields from a regional array of field mills. Journal of Geophysical Research: Atmospheres 122(2), 1158-1174
- 1 first author submitted soon, 1 co-author currently under review

Thank you to all my family and friends!

- I have accepted a two-year post-doc position at the USGS working with magnetometer data related to geomagnetic storms (switching from E to M for a little while)
- Thanks to my family for all of their support
  - My parents for instilling in me a desire to learn
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