Mesoscale Gravity Wave Impacts on the Neutral Wind Dynamo Using General Circulation Models

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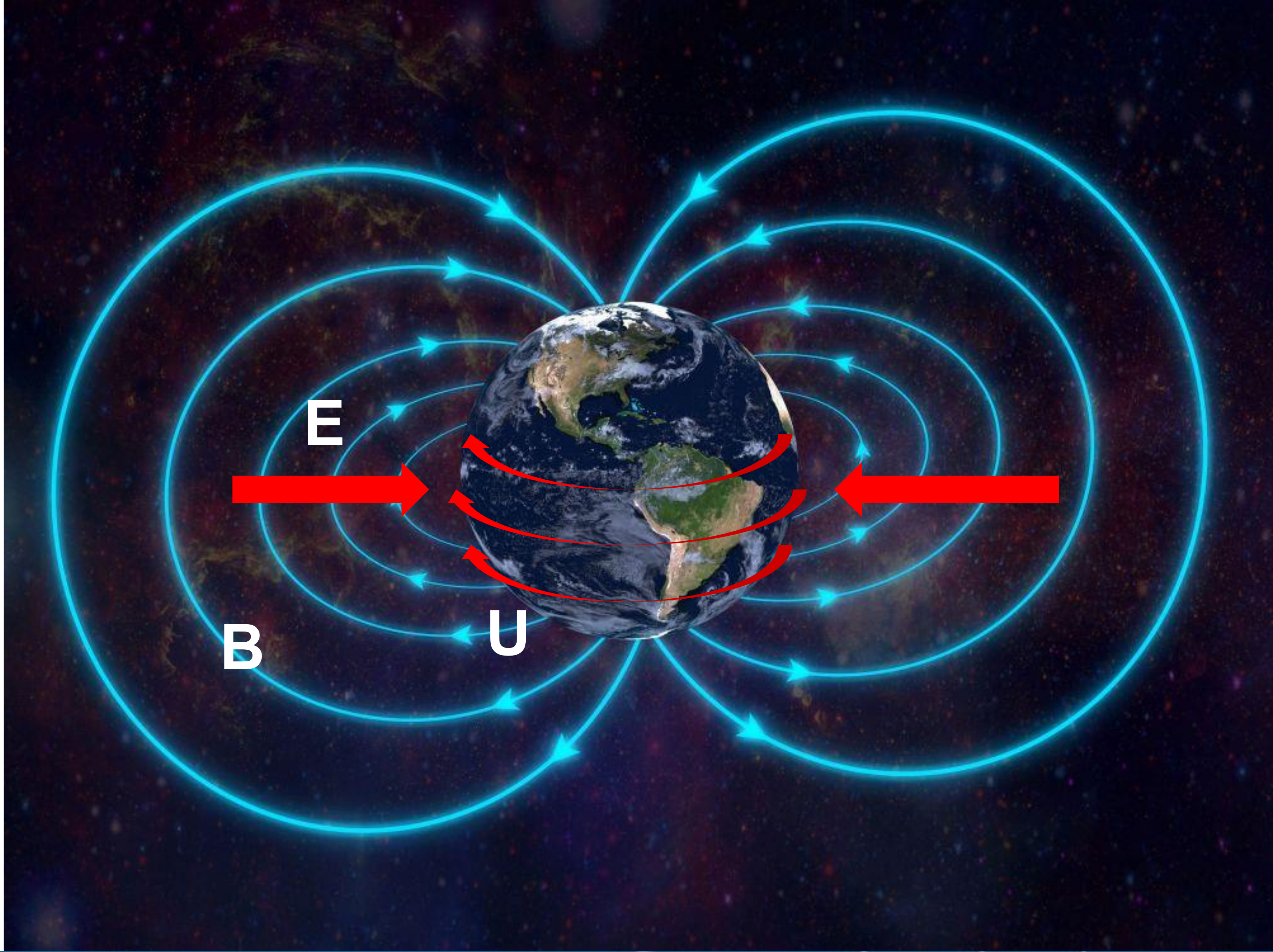
Wind Dynamo

Neutral air winds blowing across the magnetic field cause a slow transverse drift of the positive ions, perpendicular to both the winds and the magnetic field. This drift sets up an electric polarization field which can only be neutralized by currents flowing along magnetic field lines and through the E-layer.

Rishbeth (1971)



Governing Equations

Current continuity:

$$\nabla \cdot \boldsymbol{J} = 0$$

Current sources:

$$\boldsymbol{J} = \boldsymbol{J}_P + \boldsymbol{J}_H + \boldsymbol{J}_\parallel$$

Ionospheric currents:

$$\boldsymbol{J}_P = \sigma_P(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B})$$

$$\boldsymbol{J}_H = \sigma_H \boldsymbol{b} \times (\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B})$$

Electrostatic assumption:

$$\boldsymbol{E} = -\nabla\Phi$$

Governing Equations (Continued)

$$\frac{\partial}{\partial x_1}\left[\Sigma_{11}\frac{\partial \Phi}{\partial x_1} + (\Sigma_{12} + \Sigma_H)\frac{\partial \Phi}{\partial x_2}\right] + \frac{\partial}{\partial x_2}\left[(\Sigma_{21} - \Sigma_H)\frac{\partial \Phi}{\partial x_1} + \Sigma_{22}\frac{\partial \Phi}{\partial x_2}\right] = \frac{\partial Q_1}{\partial x_1} + \frac{\partial Q_2}{\partial x_2} + J_{\parallel}\Big|_p^q$$

Field-line integrated conductance:

$$\Sigma_{ij} = \int \frac{\boldsymbol{a}_i \cdot \boldsymbol{a}_j}{W}\sigma_P\,\mathrm{d}x_3 \qquad \Sigma_H = \int \frac{-\boldsymbol{b}\cdot(\boldsymbol{a}_1 \times \boldsymbol{a}_2)}{W}\sigma_H\,\mathrm{d}x_3$$

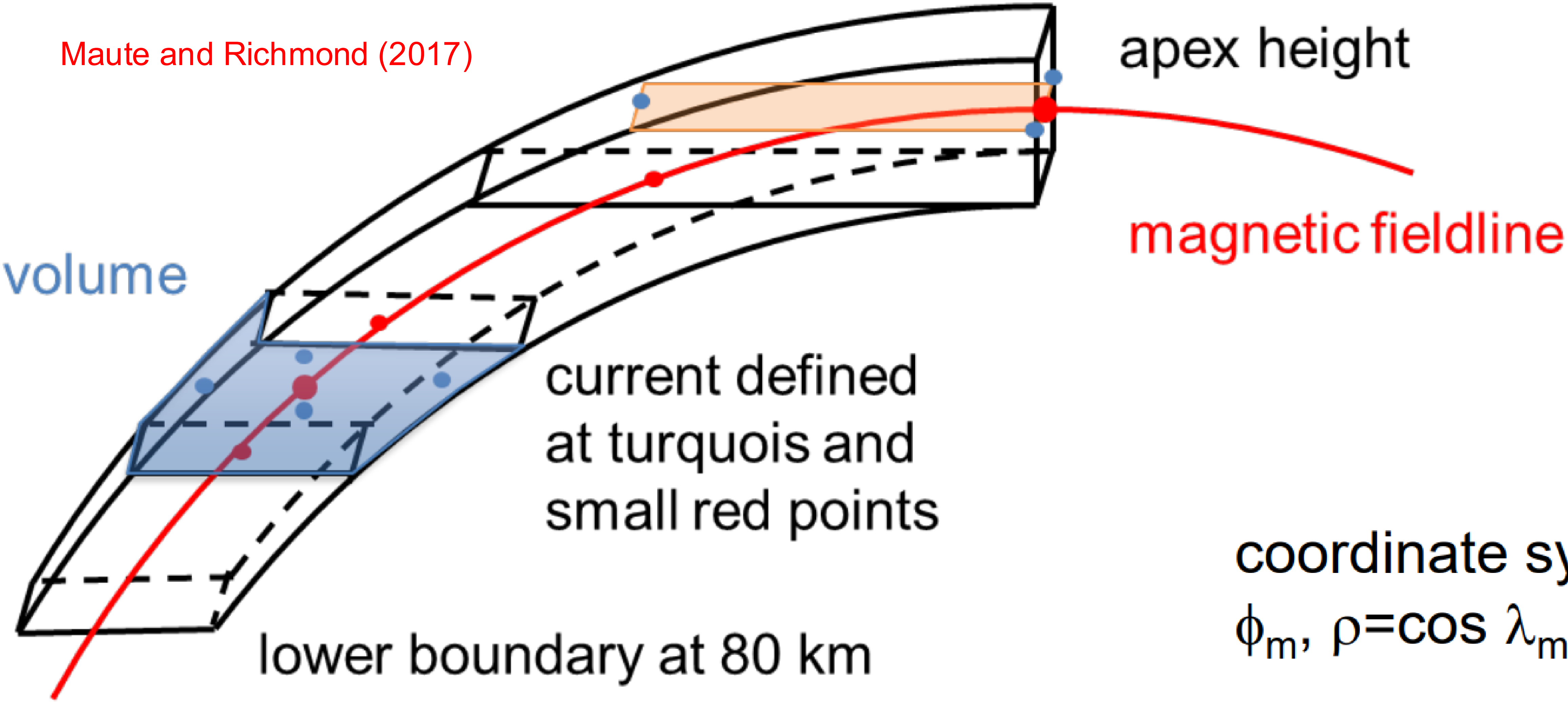
Driving forces by neutral winds:

$$Q_i = \int \boldsymbol{a}_i \cdot (\sigma_P \boldsymbol{u} \times \boldsymbol{B} + \sigma_H B \boldsymbol{u})\,\mathrm{d}x_3$$

Richmond (1995)

Spatial Discretization

Maute and Richmond (2017)



coordinate system:
ϕ_m, $\rho=\cos\lambda_m$, h

Comparisons of the Old and New Wind Dynamo

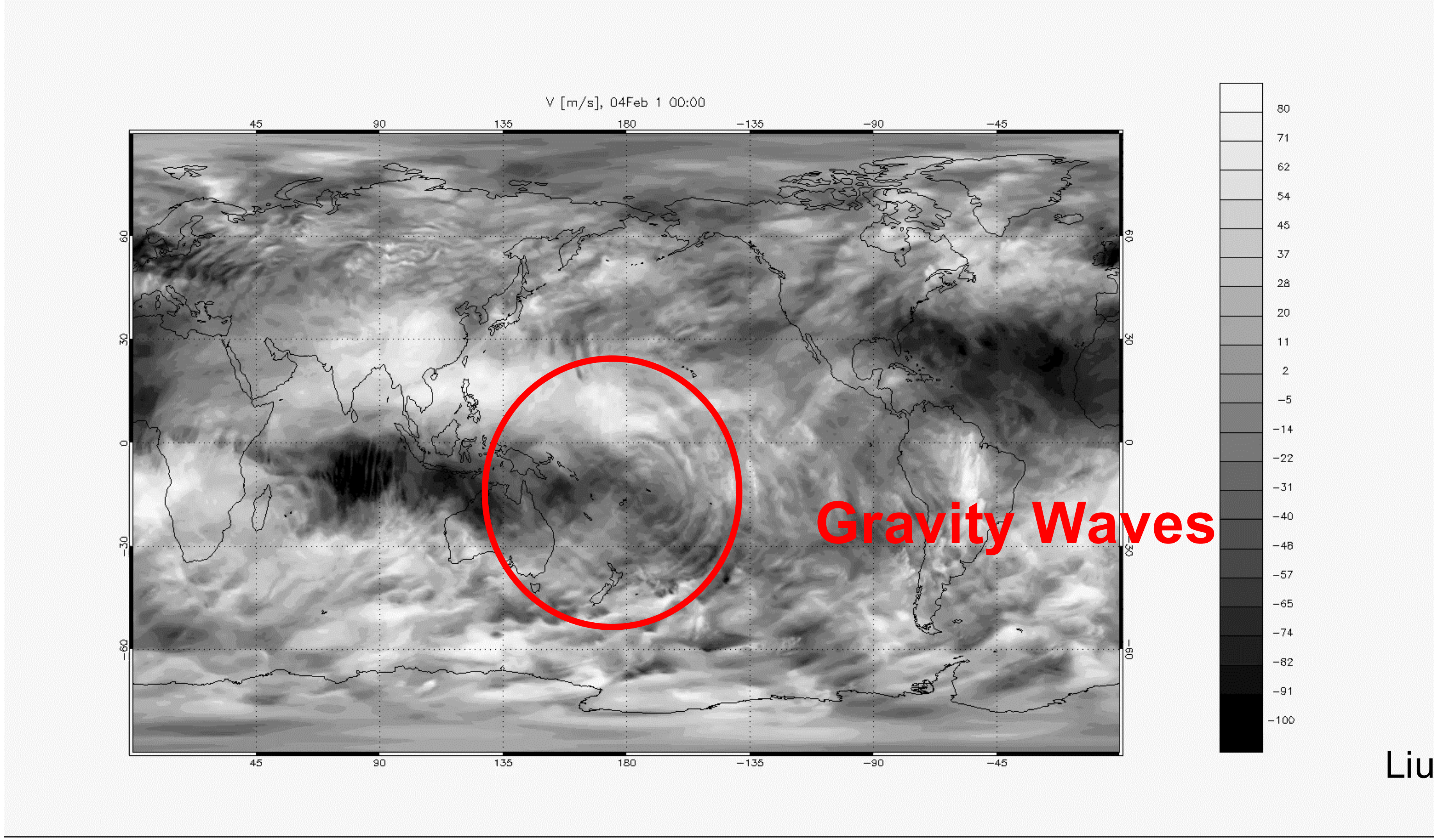
Old (Richmond et al. 1992)

- Finite difference formulation.
- Field-line integration is approximated by assuming the quantity is varying in a certain form along the field line
- Current continuity is not strictly satisfied especially in the transition region.
- Limited choices of resolution.
- Serial iterative multi-grid matrix solver.

New (Maute and Richmond 2017)

- Finite volume-style formulation.
- Field-line integration is carried out strictly (no approximation).
- Current continuity is enforced global wise.
- Flexible grid setup and resolution.
- Parallel direct sparse matrix solver.

Driving Forces: Meso-Scale Winds



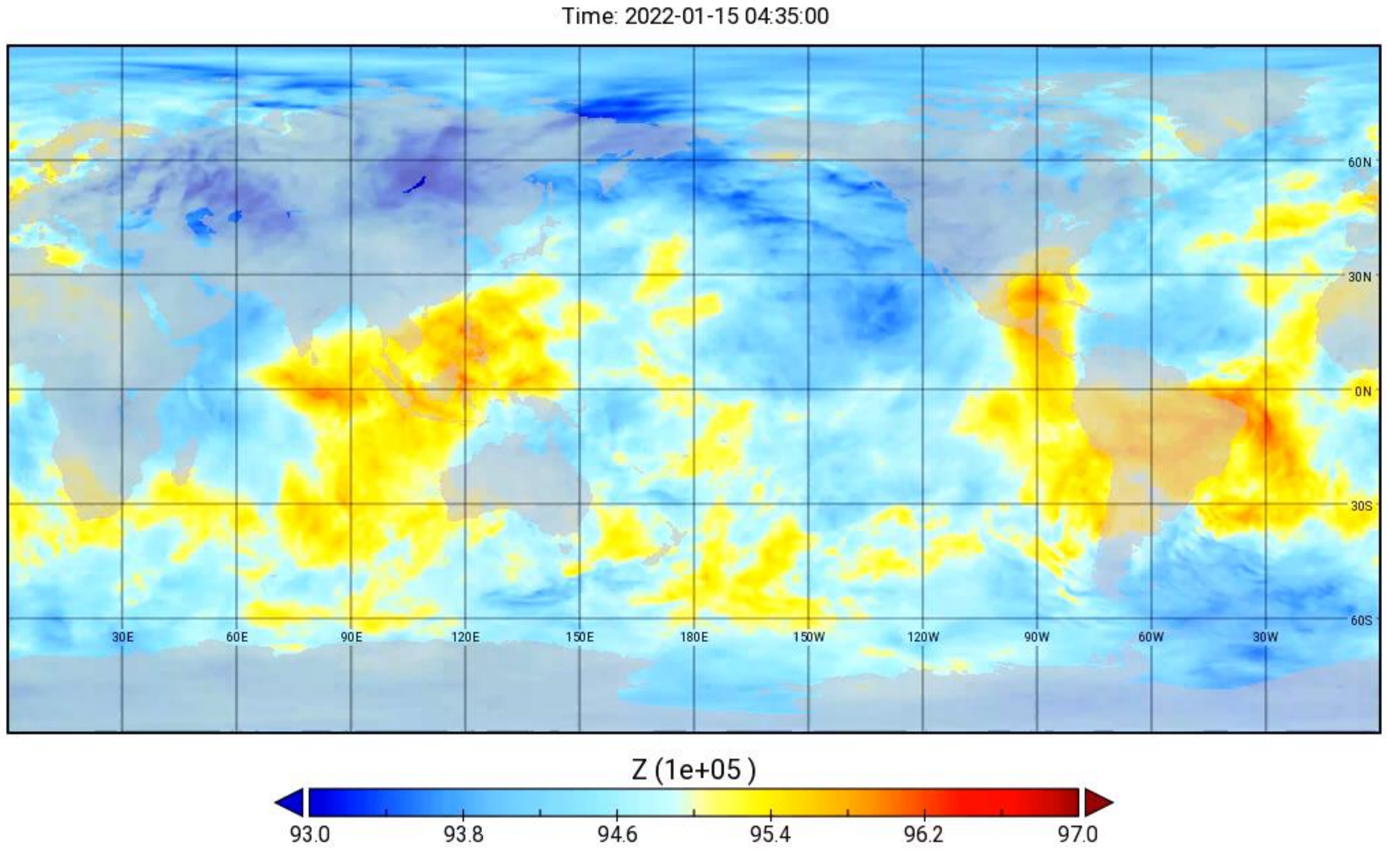
Liu et al. (2014)

Numerical Experiment

- Choose Tonga volcano eruption on Jan 15, 2022 as a demo case.
- TIEGCM 3.0 runs at 1.25° horizontal resolution and 1/4 scale height.
- Lower boundaries (T, U, V, Z) are nudged to WACCM-X SE simulations.
- Old wind dynamo (Richmond et al. 1992) and new wind dynamo (Maute and Richmond 2017)

TIEGCM Lower Boundary (WACCM-X)

Z @ 97km

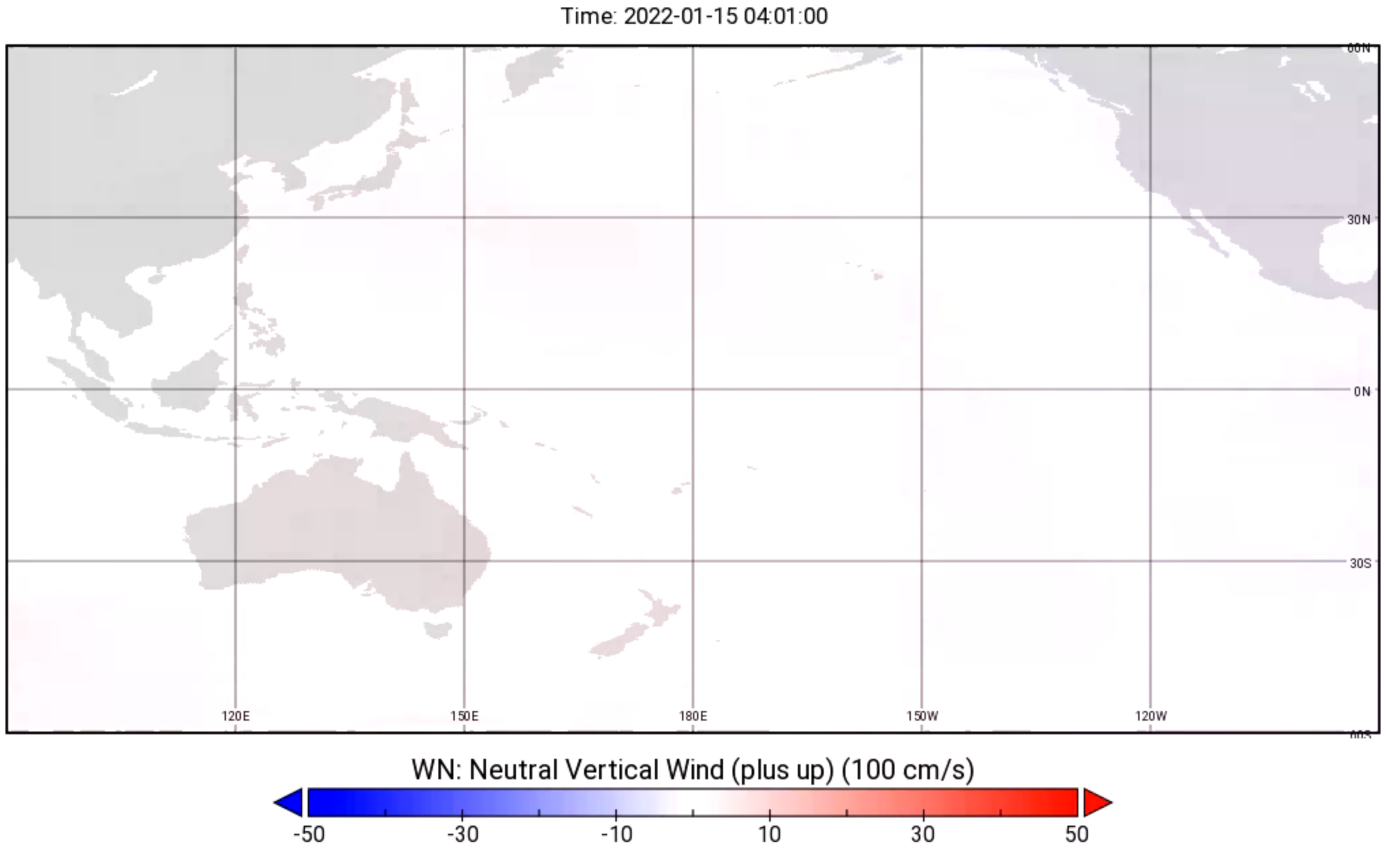


Liu et al. (2023)

Concentric ring patterns are used as a model input.

Neutral Responses in TIEGCM

Wn @ 310 km



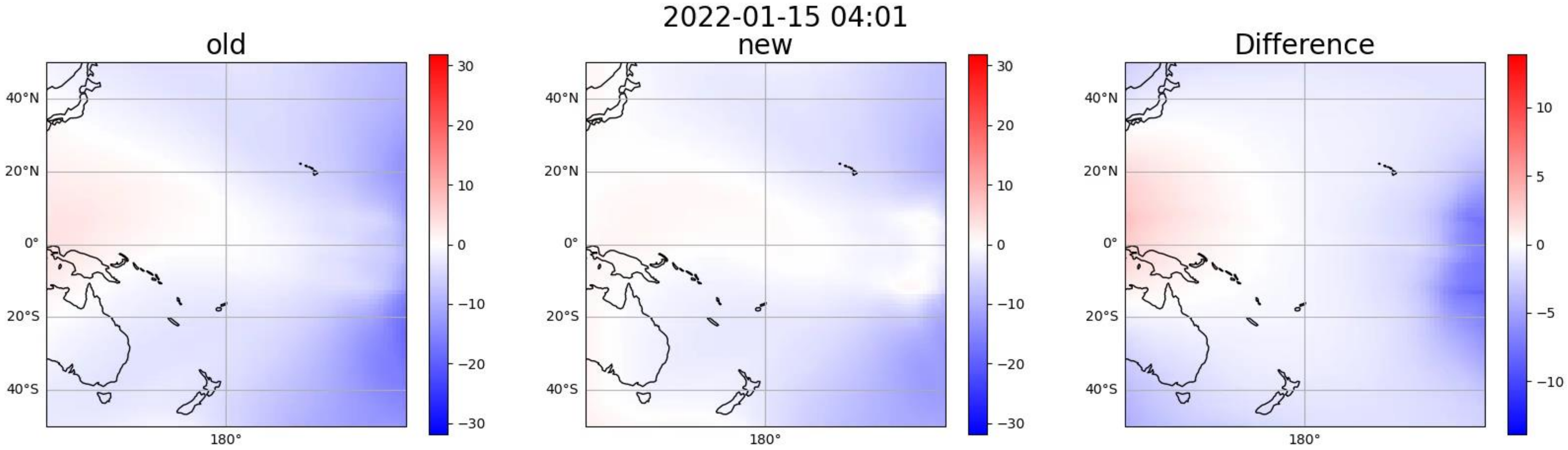
Wu et al. (2023)

Concentric ring patterns are clearly from lower boundary forcing.

Electrodynamic Responses in TIEGCM

Wi @ 97 km

Old Dynamo @ 1°   New Dynamo @ 1°

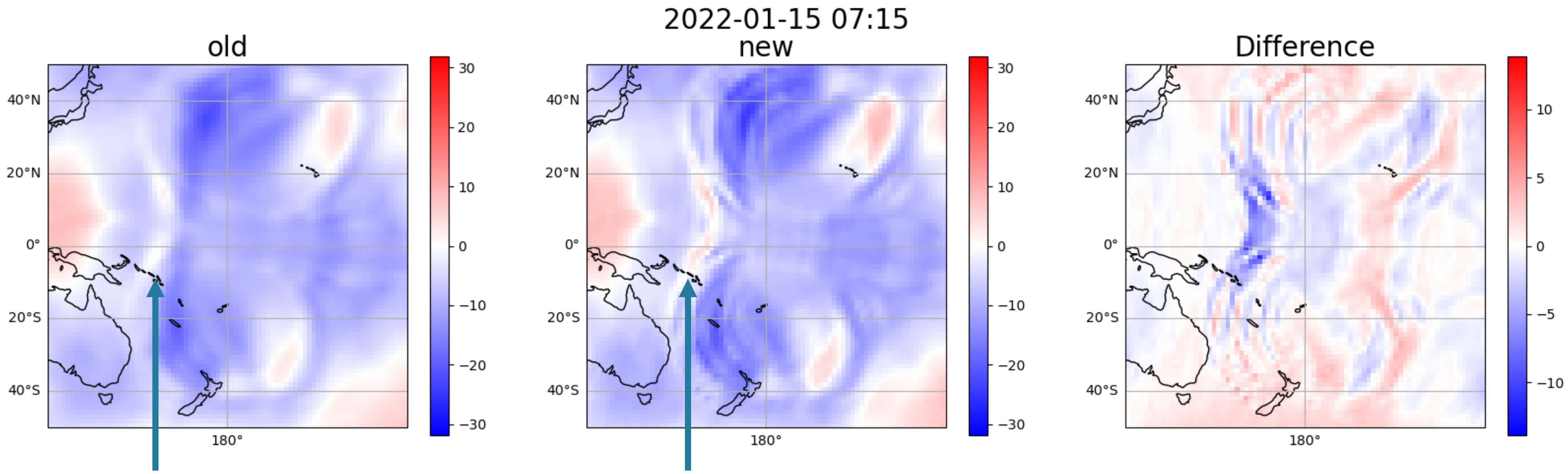


Concentric ring boundaries are sharper in the new dynamo than the old dynamo.

Electrodynamic Responses in TIEGCM

Wi @ 97 km

Old Dynamo @ 1°　　New Dynamo @ 1°

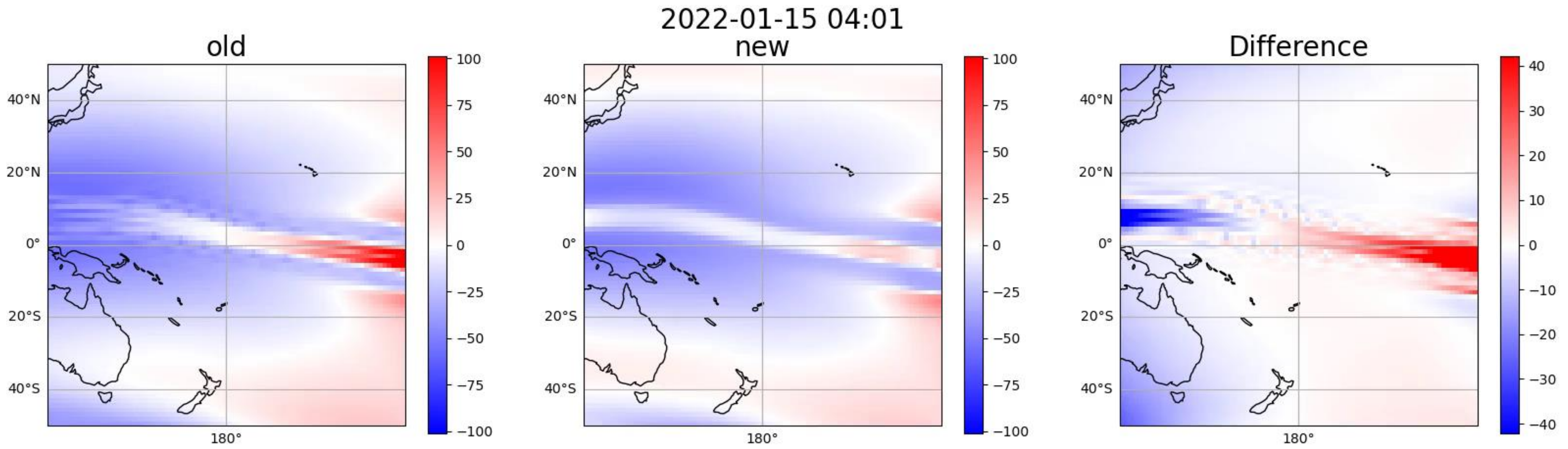


Blurry Boundary　　Sharp Boundary　　On the order of 30%

Electrodynamic Responses in TIEGCM

Ui @ 97 km

Old Dynamo @ 1°   New Dynamo @ 1°

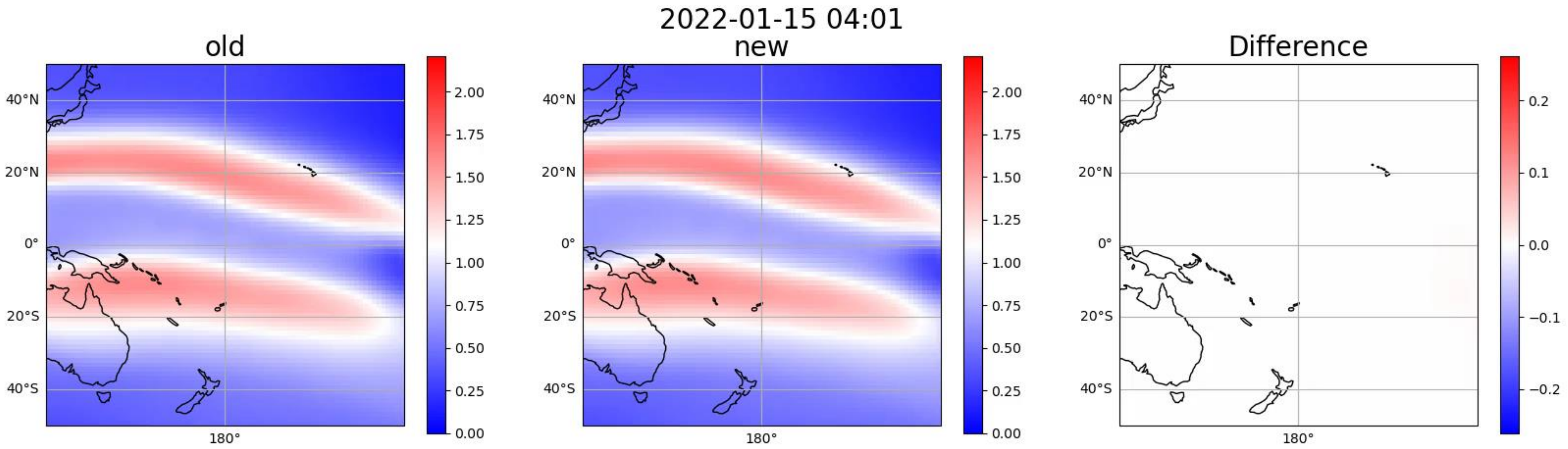


EEJ is generally stronger in the new dynamo.

Ionospheric Responses in TIEGCM

Ne @ 310 km

Old Dynamo @ 1°   New Dynamo @ 1°



Impacts on electron densities are relatively minor (~10%).

Summary

- A new wind dynamo solver (Maute and Richmond 2017) has been integrated into TIEGCM to replace the old wind dynamo solver (Richmond et al. 1992).
- The new wind dynamo better resolves sharp ion drift gradients caused by large wind gradients than the old wind dynamo.
- Ionospheric responses using the new wind dynamo is similar to the old wind dynamo.

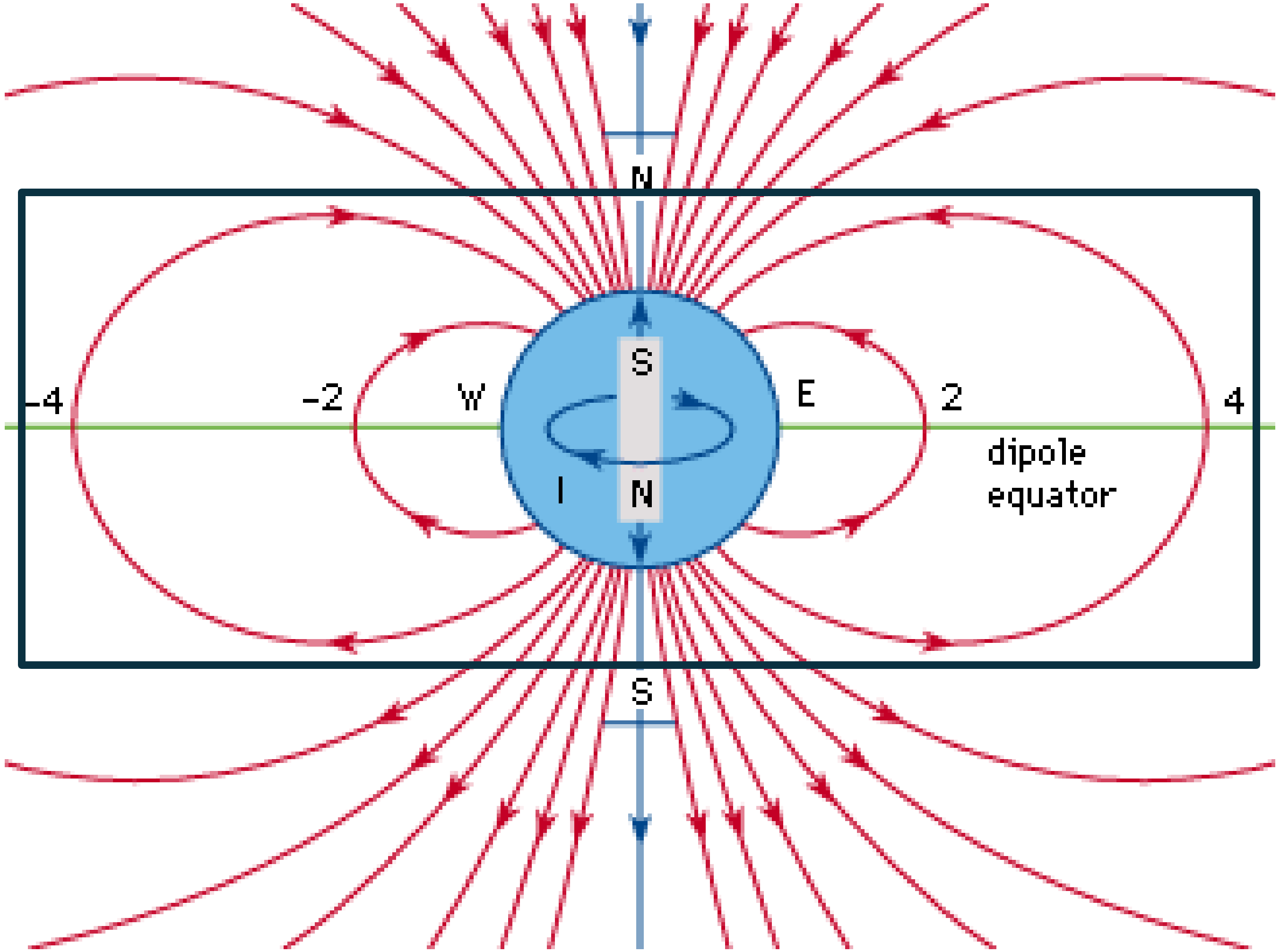
Future Objectives

- Incorporate the global potential solver (Maute and Richmond 2024) into TIEGCM which includes both wind dynamo and magnetospheric current input. This will better resolve the penetration electric field.

- Integrate with the Multiscale Atmosphere-Geospace Environment (MAGE) model.

Thanks!

About Field-Aligned Currents



$J_{\parallel}$ vanishes at foot points

$J_{\parallel}$ is from magnetosphere