Modeling the Global Impact of Lightning-Induced Electron Precipitation on the Ionosphere

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Abstract

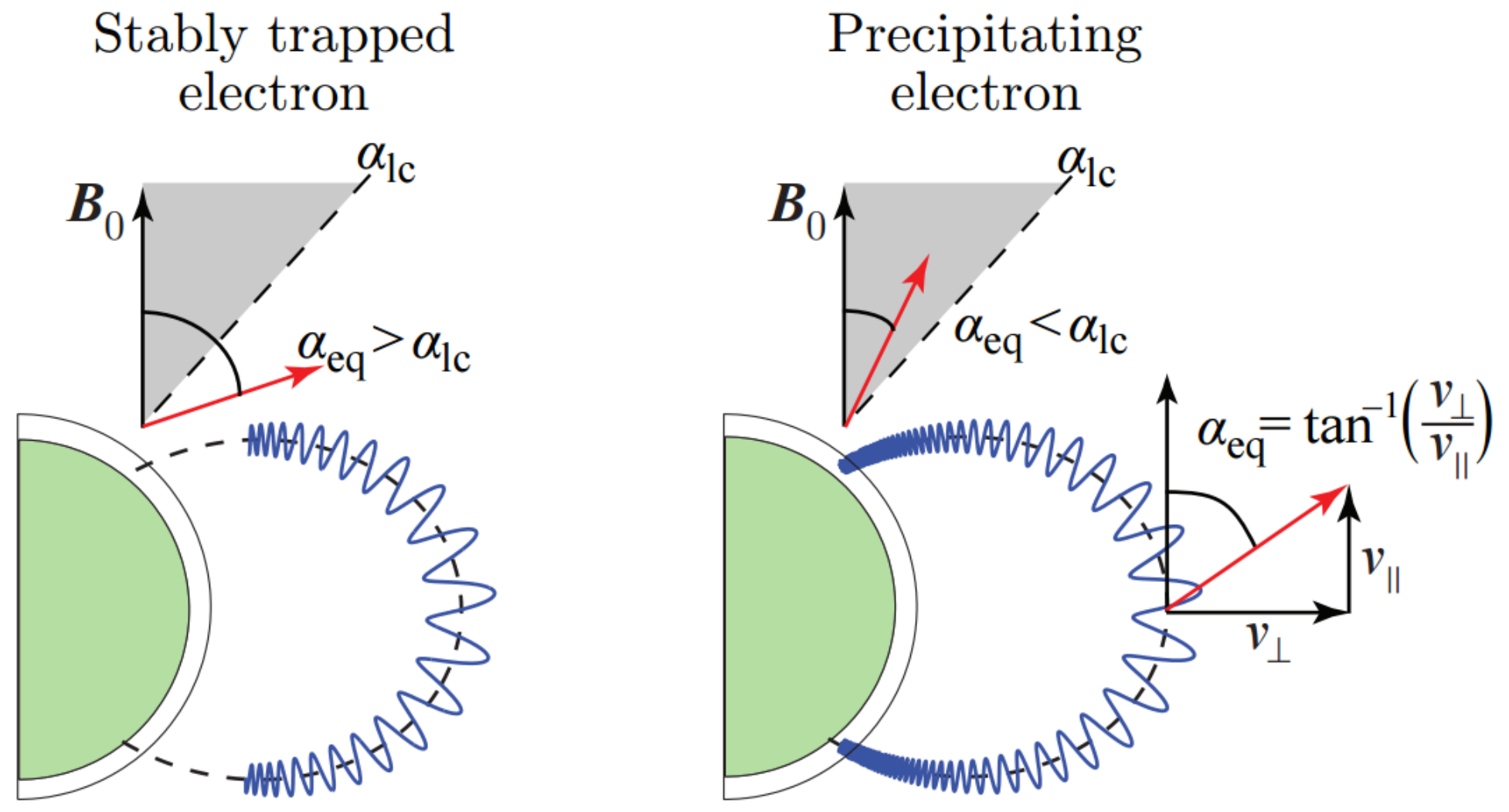
Lightning-induced Electron Precipitation (LEP) is thought to be a major loss function in the Earth's electron belts. VLF (~3-30kHz) whistler-mode waves can coherently interact with radiation belt electrons (~100 keV - 1 MeV), altering their pitch angles, and thereby modifying their mirror altitudes; when scattered to a low enough altitude, electrons can be removed from the magnetosphere by collisions with ionospheric constituents. Lightning provides a natural, constantly-occurring source of VLF whistler-mode waves.

LEP naturally regulates the population of so-called "killer" electrons, which pose an ongoing threat to spacecraft operating in the radiation belts. Additionally, LEP represents a natural and constant energy-coupling mechanism between the magnetosphere, ionosphere, and troposphere.

LEP-driven electron density enhancements have been measured via spacecraft [*Gemelos* 2009] and by terrestrial VLF remote sensing [*Rodger* 2005, *Cotts* 2011]. However the relative impact of LEP on a global scale has yet to be concretely assessed.

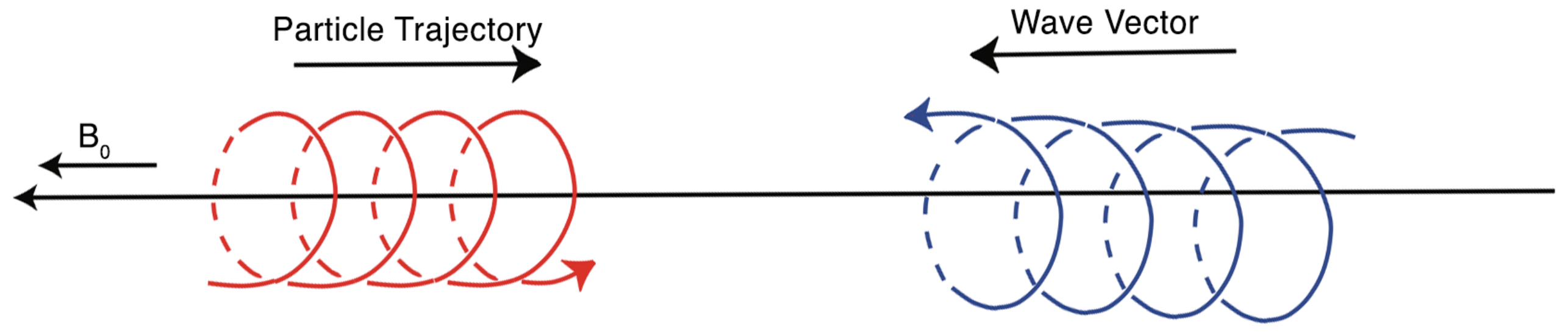
In this work we use a 2D end-to-end numerical simulation of LEP to estimate the total energy flux induced by a single lightning flash. We then interpolate and scale these results over longitude and lightning power to generate global precipitation maps at a given input time, using real lightning activity measured by the GLD360 lightning detection network. The assembled model can be used to identify spatial and seasonal trends in LEP-driven energy deposition.

Wave-Particle Interactions

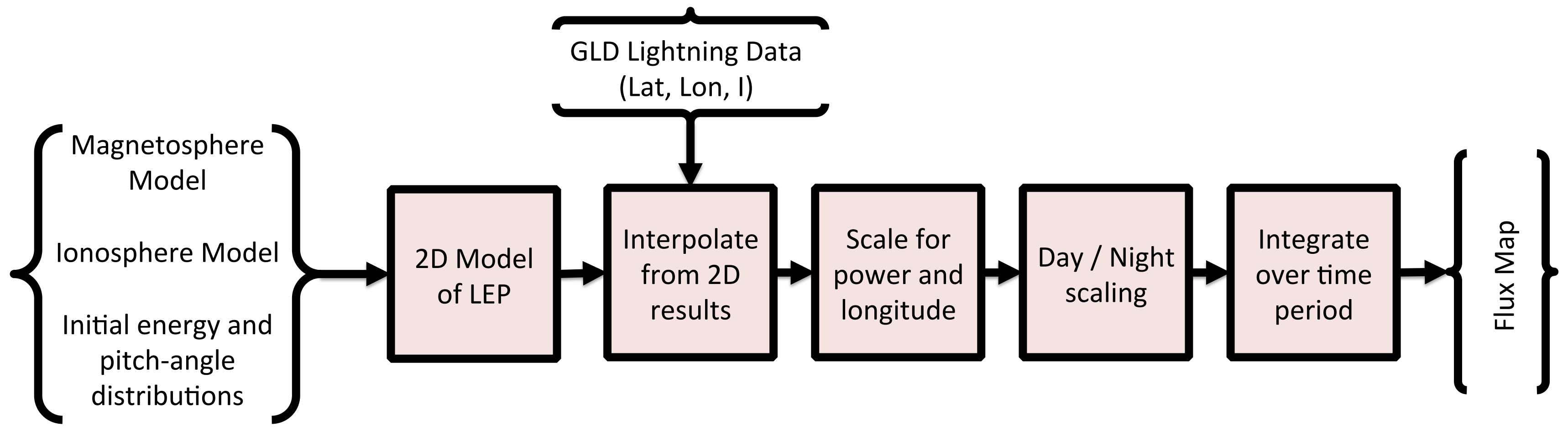


The altitude at which a geomagnetically-trapped particle will reflect is dependent on the ratio of kinetic energy in the parallel and rotational modes. This ratio is known as the *Pitch Angle.*

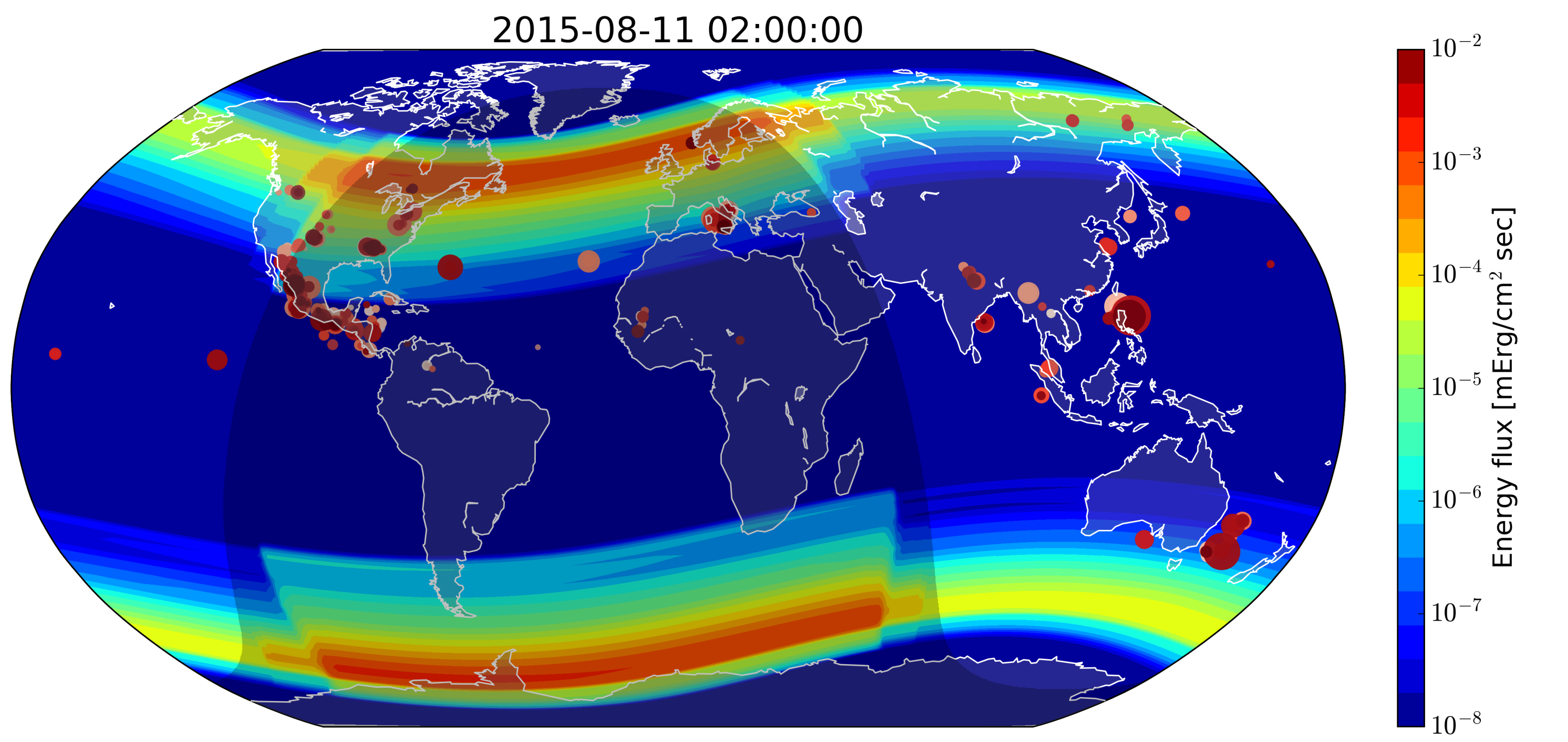
Particles that penetrate to an altitude lower than 100 km have a high probability of scattering against neutral constituents, and will be precipitated; the *Loss Cone* defines the minimum pitch angle required for which a particle will precipitate.



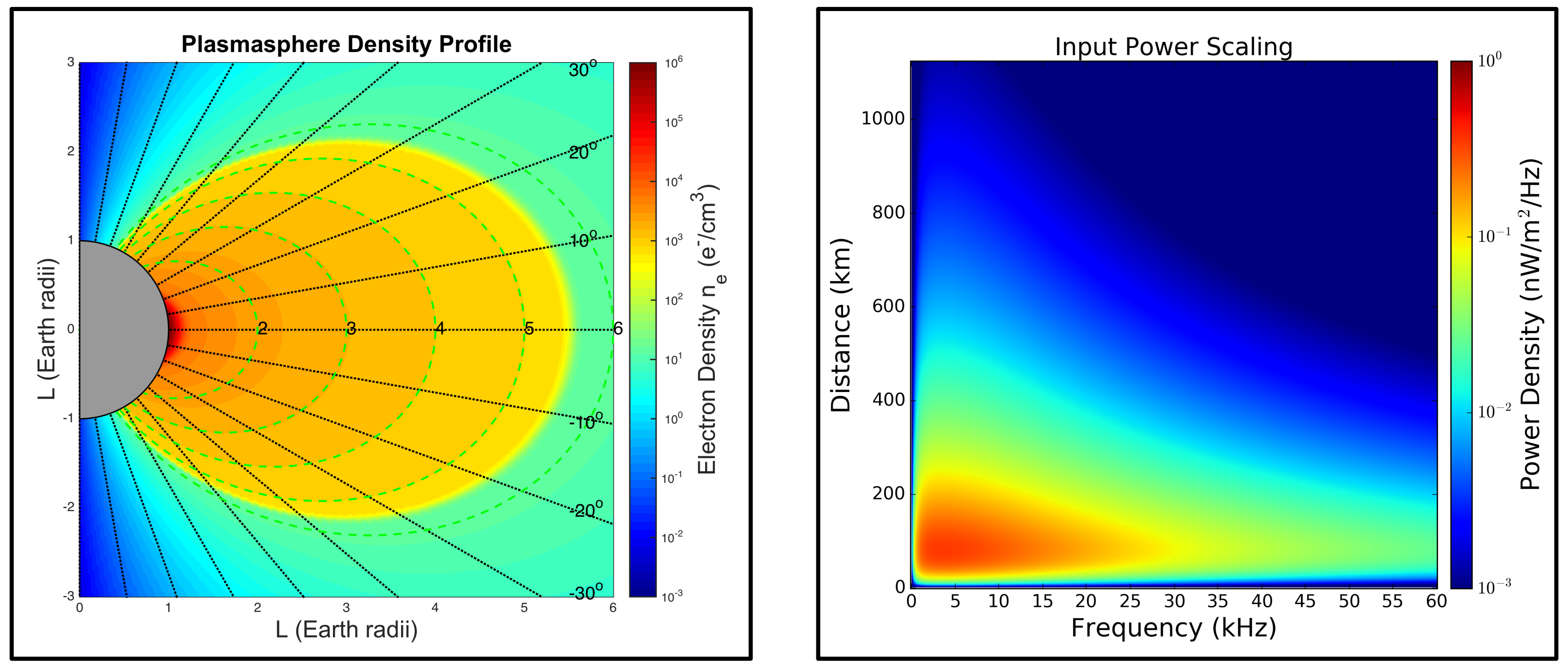
At resonance, circularly-polarized whistler-mode waves coherently interact with particles, and can transfer energy between parallel and perpendicular modes, thereby changing the particle's reflection altitude.



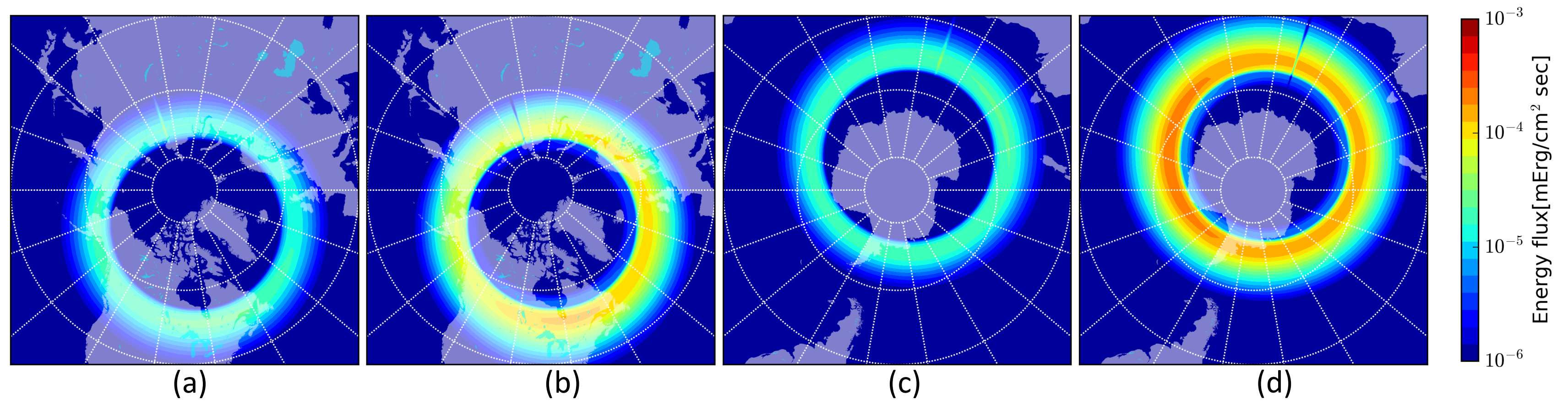
Above: A block diagram of the model. We precompute precipitation for a single lightning flash using a 2D (latitude and radius) model [*Bortnik* 2005]. We then interpolate, scale, and integrate the 2D results for real lightning data measurements to determine average flux at any given time.



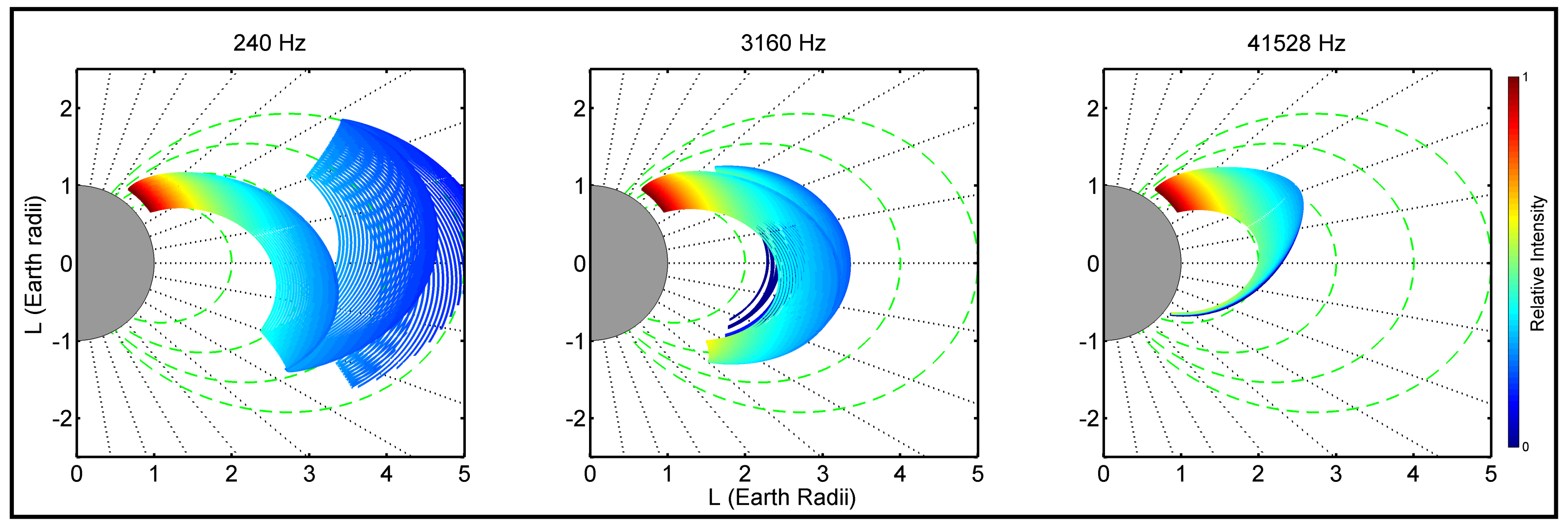
Above: Energy flux within a 1-minute window. Red dots indicate lightning flashes. Radius is proportional to peak current; color indicates the delay between flash and simulation time. Longitudinal variance is accomplished by scaling the 2D model by 1/R. We account for day/night variation by attenuating an additional 20 dB during local daytime at the flash latitude.



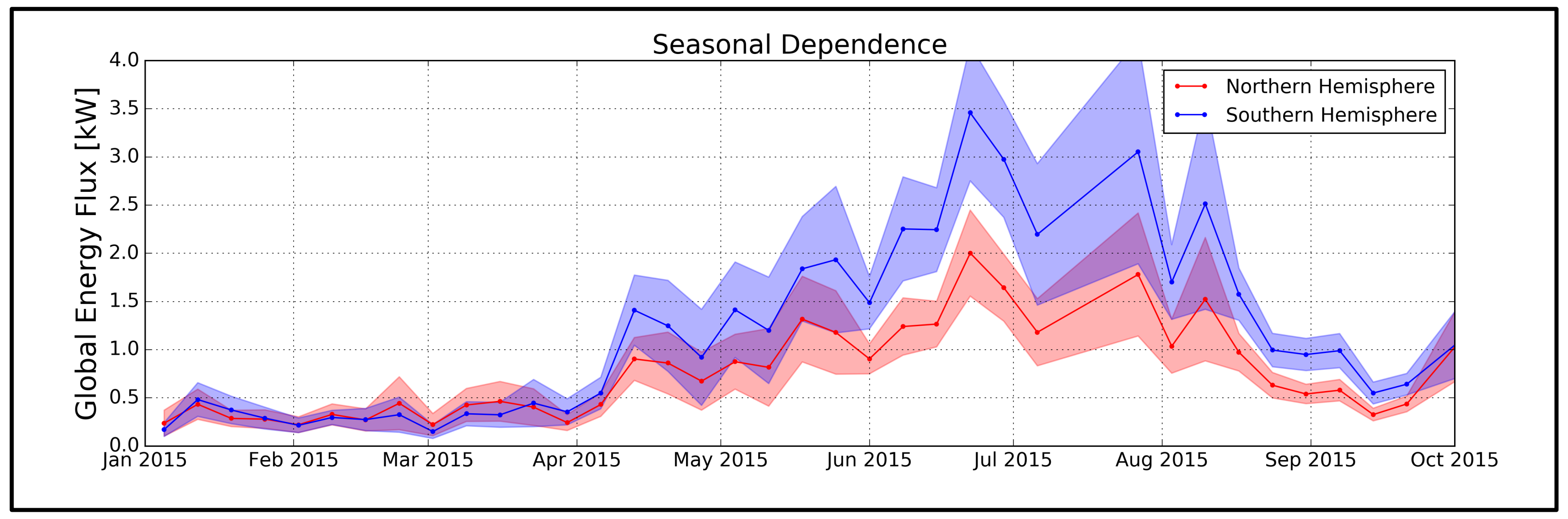
Left: Plasmasphere electron density profile used in the 2D simulation. Plasmapause location at L=5.5 is typical at quiet conditions (K_p=0) [*Moldwin* 2002]
Right: Wave power density at the bottom of the ionosphere, shown for a lightning flash with 100kA peak current.



Above: Average energy flux for January (a, c) and June (b, d) 2015. Averages are the result of 1-minute simulations performed every 30 minutes. A slight spatial enhancement can be seen in June, over the east coast of the United States.

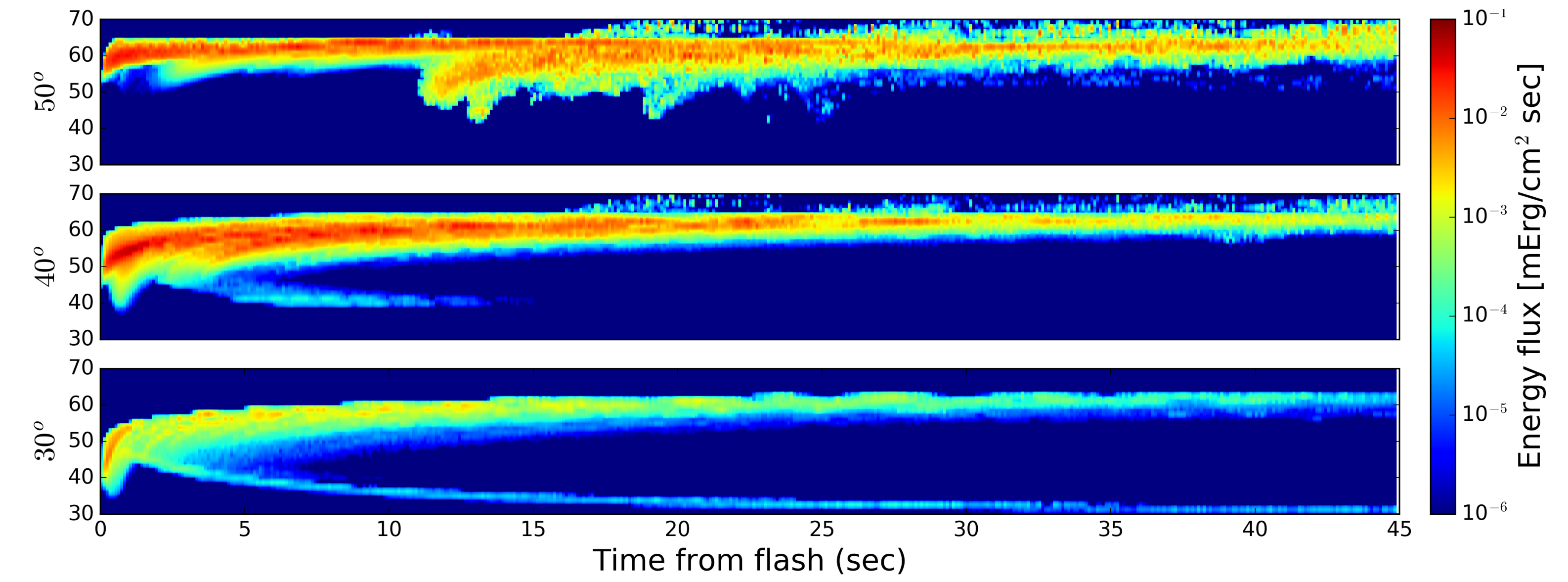


Above: Raytracing results from the 2D model, showing propagation of lightning-generated whistler-mode waves. Higher frequencies experience greater deflection and quicker attenuation; Lower-frequency rays persist for up to ~60 seconds.



Above: Integrated energy flux over northern and southern hemispheres as a function of week, resulting from 1-minute simulations performed every 30 minutes.

2D Simulation Results



Above: Energy flux as a function of time and geomagnetic output latitude for a 100kA peak current flash, shown at 30°, 40°, and 50° input latitudes. To account for a wide range of flashes, we compute the 2D model for a range of input and output latitudes, and interpolate over the results.

Conclusions and Future Work

Initial results are consistent with seasonal trends apparent GLD lightning data, which is concentrated over land masses and strongest in the summer months; however they fail to capture the small-scale spatial enhancements seen in satellite measurements. Lack of structure suggests that longitude dependence scales faster than 1/R.

The 2D model is linear with wave magnetic field intensity, and does not account for any wave growth or particle-particle interactions. Only RMS scattering is computed; however outlying particles may likely experience prolonged resonance [*Lauben* 1999], which could result in the strong, sporadic precipitation as seen by VLF remote sensing.

We assume a constant magnetosphere with K_p=0. Modifying the plasmapause location with K_p may spread precipitation out over a wider range of latitudes.

We use a tilted-dipole magnetic field model, which is symmetric in longitude, and fails to capture precipitation due to the drift loss cone.