Atmospheric Precipitation Predictions

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Abstract: The dynamic magnetic field of Earth leads to several interesting phenomena in the inner magnetosphere. A better understanding of the variability of the particle populations allow a better understanding of space weather. Previous work by Shekhar et al. [2017; 2018] have emphasized the use of NOAA POES satellites for the study of atmospheric precipitation of relativistic electrons, focussing primarily on the spatial scales and energy spectrum. Several processes occur in the magnetosphere that can lead to influx, energization and atmospheric loss of particles from the radiation belts. Relativistic electrons in the radiation belts can lead to internal and surface charging that can damage instruments. Hence, the study of the relativistic electrons is an important aspect of space weather. The loss of electrons into the atmosphere, known as precipitation, is important for radiation belt dynamics. The estimation of spatial scales of relativistic electron precipitation (REP) is critical for quantifying the global loss of particles from the radiation belts. However, our knowledge is limited by sparse spatial REP data.

We are proposing to use the large repository of National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellites (POES) data with machine learning tools to predict the spatial occurrences of relativistic electron precipitation from the radiation belts. This will help us quantify the atmospheric relativistic electron loss which is critical for understanding the radiation belt dynamics.

1 Background Science

The charged particles in the magnetosphere go through three kinds of motion due to the Earth's magnetic field; gyro motion (around a singe magnetic field line), bounce motion (along the field line) and drift motion (around the Earth) with their associated adiabatic invariants [Michael Schulz 1974]. If there are electric or magnetic field variations occurring on the timescale of any of these three motions, the associated adiabatic invariant will be violated. ULF (Ultra Low Frequency) waves in the magnetosphere that have mHz frequency, higher frequency waves such as whistler mode chorus, magnetosonic waves or magnetic field compressions and hot plasma injections from the nightside contribute to the enhancements of outer zone electrons [Millan and Baker 2012].

In previous studies, REP events have been found to extend from tens of minutes to hours [Millan et al. 2002] and statistically confined to L shell widths of 0.5 and MLT widths of 3 hours [Shekhar et al. 2017]. The spatial extent and duration of the precipitation may depend on the spatial distribution and the duration of the mechanism causing the energy transfer leading to the scattering of particles in the loss cone. Electromagnetic ion cyclotron (EMIC) waves have been found to resonantly scatter MeV electrons from the radiation belts [e.g, Lyons et al. 1972, Miyoshi et al. 2008, Ukhorskiy et al. 2010, Li et al. 2014, Woodger et al. 2018]. Recently Capannolo et al. [2019] showed, through analysis of 3 geomagnetic storms coincident with EMIC wave activity on RBSP spacecrafts, that REP was latitudinally localized but could occur in different locations within a rather broad L-MLT region (up to $\sim$1.4 L shells and $\sim$4.4 hr MLT). However, the contribution of EMIC waves towards global precipitation of electrons from the radiation belts remains unexplored. A few efforts in this direction are being made through estimation the spatial scale of EMIC waves and REP [e.g Blum et al. 2017, Shekhar et al. 2017, Capannolo et al. 2019].

Although significant progress has been made in improving our understanding of these processes, the spatial distribution of atmospheric precipitation is not well characterized. Except for a few event case studies like the study of a REP event on 18-19th January 2013 by Blum et al. [2013] and Zhang et al. [2017] using conjunctive measurements from different instruments, and the statistical study by Shekhar et al. [2017], the spatial extent of REP events and it's association with the mechanisms driving precipitation are unexplored.

2 Relevance of Proposed work

Previous studies have indicated that spatial scales [e.g Shekhar et al. 2017] and energy spectra [e.g Shekhar et al. 2018, Smith et al. 2016, Comess et al. 2013] vary with L and MLT locations and hence may be closely tied to the mechanism involved.

A few previous case studies like Blum et al. [2013] and Zhang et al. [2017] have focussed on spatial scales of precipitation and quantified the electron loss for a REP event on 18-19th January 2013 observed in proximity to EMIC waves. They used observations from BARREL payloads and CSSWE cubesat. Millan et al. [2002] quantified MeV precipitation events observed on MAXIS (MeV Auroral Xray Imaging and Spectroscopy) balloon payload. Quantification of observed precipitation is limited by sparse spatial data and hence POES/MetOp data, with better spatial resolution could be useful in estimation of observational loss of relativistic electrons from the radiation belts at a statistical level. It will address several science questions mentioned below.

1. **What are the spatial scales of REP and how do they vary with the mechanisms driving them?**
2. **What is the quantitative contribution of precipitation to global loss and how does it vary with the mechanisms driving the precipitation?**
3. **How does the spatial scale of precipitation compare with the spatial scales of various plasma waves?**
4. **How does the energy spectrum vary with the spatial location and how does that relate to mechanisms driving the precipitation?**

3 General Methodology

3.1 Dataset

The POES (Polar Operational Environment Satellite) network of spacecraft occupy sunsynchronous polar orbits (typical parameters: nominal altitude 870 km, orbital period 102 min, inclination 98.7^o) and are three axis stabilized such that their orientation is fixed relative to direction of travel and the local zenith [Yando et al. 2011]. The Space Environment Monitor subsystem (SEM), now upgraded to SEM-2, is designed to measure particle fluxes in low Earth orbit. It includes the Medium Energy Proton and Electron Detector (MEPED) which has two pairs of directional telescopes (0^o and 90^o) with 3 electron and 6 proton energy channels (Shekhar et al. [2017] Table 1). The directional telescopes have a $\pm 15^o$ field of view and in this study 0^o telescope has been used as at high latitudes it detects the electrons that are in the bounce loss cone [Rodger et al. 2010]. The data can be used to observe REP events effectively except for very weak diffusion events [Rodger et al. 2013], after some processing mainly to deal with cross species contamination issue [Rodger et al. 2010, Yando et al. 2011, Asikainen and

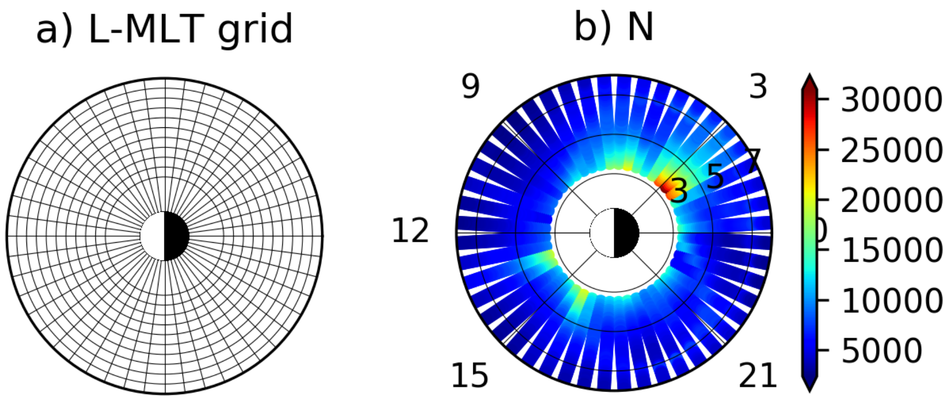

Figure 1: a) L–MLT grid to segregate the temporal variations in electron precipitation. b) Number of 16 s POES/MetOp precipitation data points available in each location bin for 14 years (2001-2014)

Mursula 2013] and leakage of drift loss cone relativistic electrons in the P6 channel [Horne et al. 2009].

3.1.1 Quantification of loss

The loss of electrons observed by POES/MetOp satellites would be quantified using the methodology used by O'Brien et al. [2004] and Blum et al. [2013], where the electrons lost to the atmosphere were calculated using Equation 1.

$$\#e^{-} = \Delta f \cdot \Delta T \cdot A \cdot 2 \cdot \pi \tag{1}$$

where Δf is the magnitude of the bounce loss cone flux, ΔT is the duration of the precipitation in hours UT, and A is the area of the precipitation region at the satellite altitude. This method was used by Shekhar et. al., 2020 (Accepted for publication at JGR: Space Physics) to quantify atmospheric REP on 17th January 2013 using multiple POES/MetOp satellites along with BARREL payloads.

3.2 Spatial and Temporal Segregation of POES/MetOp Data

The problem of creating a spatio–temporal precipitation map is complex. However, due to several POES/MetOp satellites being in orbit for time duration of over a solar cycle (2001-2014), we approached the problem through segregation of data in space and time. We used L shells and MLT locations of satellites to obtain precipitation and solar wind data in each L-MLT bin shown in the grid plot in Figure 1a. Figure 1b shown the number of 16 second data points available in each bin. It can be seen that we have roughly 10,000 data points in each location bin.

Figure 2 shows time series plot of the variation of solar wind parameters and precipitation fluxes for the year 2013 from all the POES/MetOp satellites in the location bin L=3.55, MLT=0.25. The goal is to extrapolate precipitation data in time through the temporal variations of the solar wind data in each location bin.

3.3 Test and develope a System for Prediction of Loss

We plan to use the large repository of POES/MetOp data in a neural network as used by Bortnik et al. [2016] to create a data based prediction model for atmospheric REP capable of extrapolating particle flux data to the entire low altitude radiation belt region at every timestep,

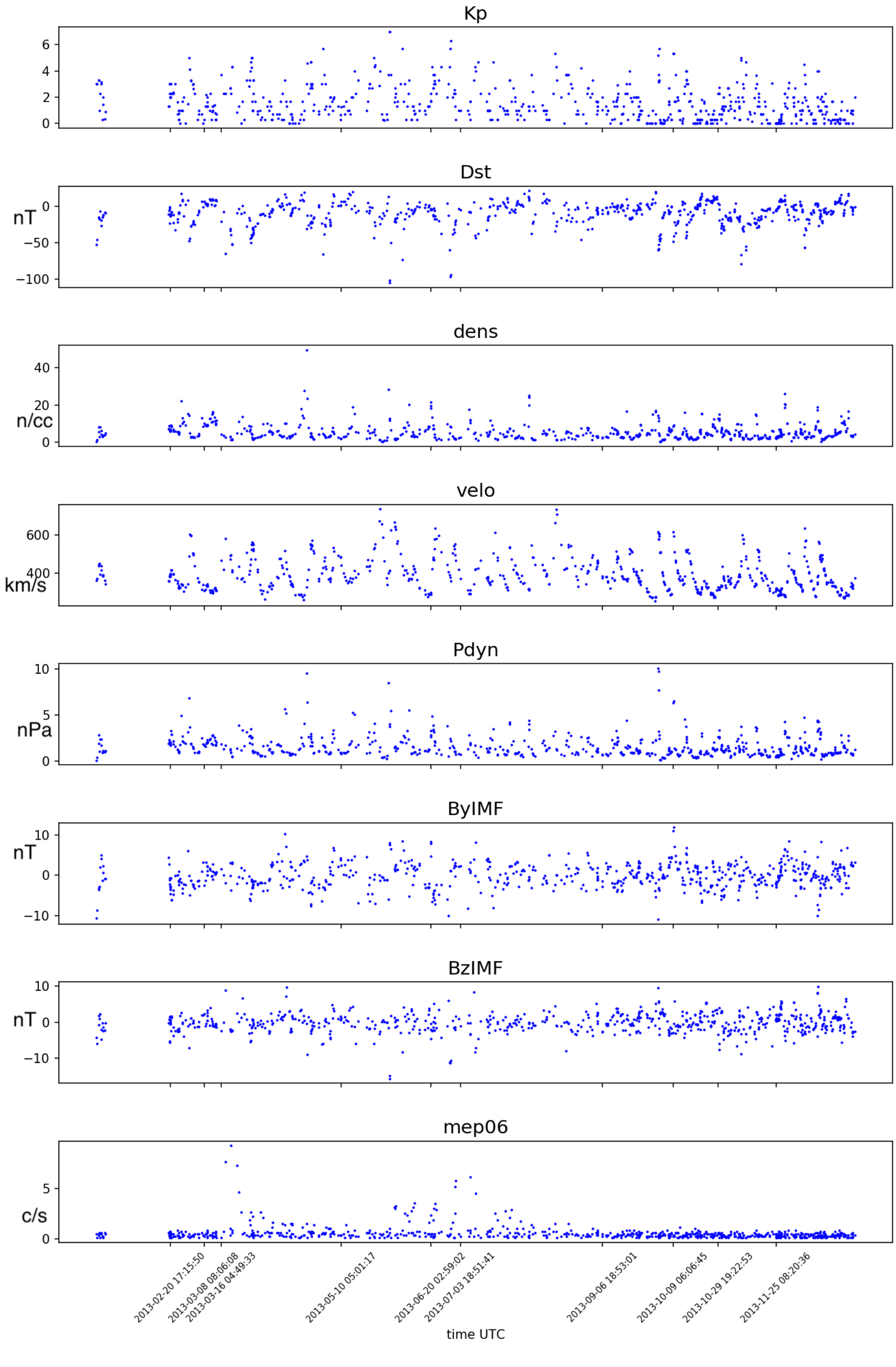

Figure 2: Data from all POES/MetOp satellites in the location bin L=3.55, MLT=0.25 in 2013.The solar wind data is also shown with the relativistic electron flux (bottom panel).

enabling the observation of the variation of spatial scales of precipitation and their correlations with solar wind parameters and waves present. Finally, in the next couple of years, we expect our low altitude capability to be enhanced with the launch of new satellites. As more low altitude particle data become available, they can be added to improve the model.

4 Conclusions and Summary

Earth's radiation belts impact space technology and hence need to be understood better. Despite of a number of instruments available in space, it is extremely expensive to be able to obtain complete spatial coverage and hence observe global dynamics of radiation belt electrons. The proposed research will allow the use of data from the network of POES/ MetOP satellites to observationally quantify loss and understand the contribution made by mechanisms such as EMIC wave particle scattering, current sheet scattering and other processes that lead to atmospheric loss.

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