Initial Analysis of an Energetic Proton Capability

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Overview

Current environmental specifications for the energetic proton hazard focus on the South Atlantic Anomaly and the hazard at geosynchronous orbit, giving little or no quantitative information on the hazard for other orbits. Here we present a simple global model of the hazard and provide initial characterization of its accuracy by comparing it to CRRES PROTEL (PROton TELescope) data. The CRRES satellite flew July 1990 to October 1991, during solar cycle 22 maximum, in a geo-transfer orbit that allowed it to observe energetic protons from LEO to GEO. During this period the PROTEL instrument observed several solar energetic proton events with a range of magnitudes. In this study we compare the model results to observations during several of these events.

Model Description

Model Overview: The hazardous energetic proton population in the magnetosphere consists of trapped and transient populations. The trapped population is relatively stable allowing us to use the AE9 climatological model to simulate it. The transient populations originate at the Sun or are energized by a shock due to a coronal mass ejection and can vary by orders of magnitude in 10s of minutes to hours, so modeling requires real-time data input. To model the transient population we map GOES satellite observations to locations inside GEO.

AP9 Model: Part of the AE9/AP9/SPM suite, the AP9 model provides a climatological specification with variability and uncertainty statistics for trapped protons. It is derived from 9 satellite data sets (including CRRES PROTEL), most spanning a range of solar cycle phases. AP9 does not provide results specific to a particular solar cycle phase, instead giving statistics representing the range over the solar cycle. This is not a significant limitation given the relative stability of the proton belt, and given our objective of a nowcast model we use the AP9 median for results presented here.

Mapping Technique: At locations inside GEO we calculated the directional magnetic shielding using the Dartmouth-CISM (DC) model in conjunction with the Tsyganenko-Sitnov 2005 magnetic field model using Qin-Denton inputs. Then assuming isotropy of the interplanetary flux we integrated over the portion of this flux, observed at GOES, that had access to the locations and with energies above 10 MeV. Because precise shielding calculations are numerically expensive the DC model was used to calculate the shielding in the east, vertical and west directions at each CRRES location. We then interpolated between these directions using a function based on dipole theory where possible; otherwise a simple Gaussian form was sufficient.

Data Preparation

- CRRES PROTEL Proton differential Fluxes were provided by Dan Madden (Boston College)
- 5 minute integral GOES data was obtained from NGDC's SPIDR website: http://spidr.ngdc.noaa.gov
- The data were organized by LANLstar (L^*) using the Tsyagnenko-Sitnov 2005 model (Yu, Y et al., Space Weather 2012, doi:10.1029/2011SW000743)
- PROTEL integral flux calculation: the differential flux at the geometric mean of the bin boundaries was assumed to be equal to the bin averaged differential fluxes and a piecewise power law was fit between the means. We used the two lowest energy bins to extrapolate down to 10 MeV and the two highest energy bins to extrapolate up to infinity.
- To calculate integral fluxes above thresholds different than those provided by NOAA we again assumed a power law differential flux spectrum which was fit such that integrating it from the lower bounds of the two closest energy bins to infinity gave the observed integral fluxes for those bins. We then integrated the power law from the lower bound we required.

GOES/CRRES Data Calibration

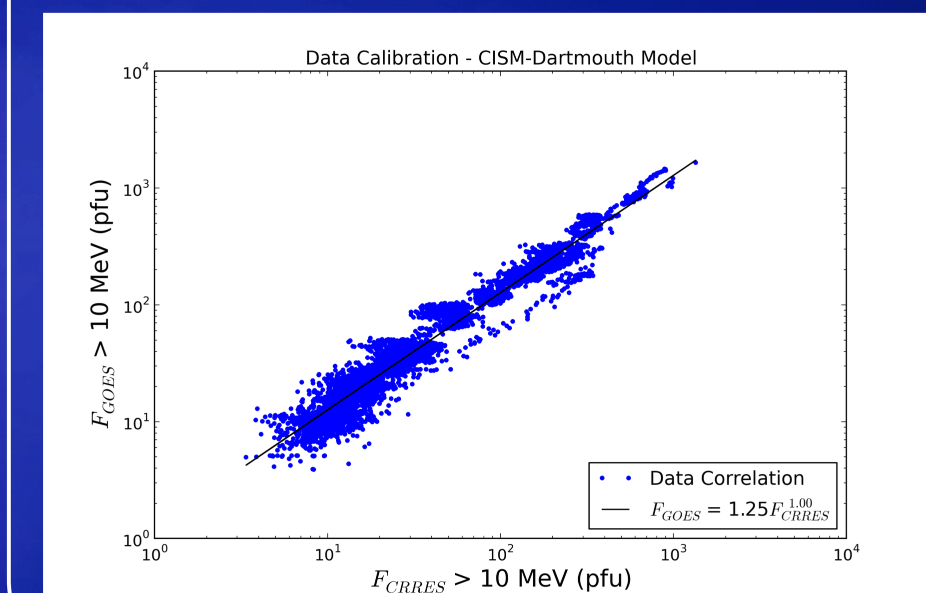


Figure 1: We assumed that PROTEL observed the interplanetary SEP spectrum for >10 MeV protons when $L^* > 6$ for a given CRRES location. The plot shows the calibration fit between the PROTEL observations and the corresponding GOES-7 observations.

The correlation function is:

$$F_{GOES} = 1.25 F_{CRRES}$$

Model/Flux Comparisons

For lower values of L^* the model is dominated by the mean values of the AP9 ensembles and it tends to over-predict the observed flux. For higher values of L^* it is dominated by the mapped GOES observations and agrees well with the observations, especially above $L^* = 5$. In the middle, where the logarithmic differences are the greatest between the model and observations, neither climatology nor the magnetic shielding model explain the observed particle fluxes. While, the median flux in this region is not hazardous, hazardous fluxes were observed and work needs to be done to better predict them.

At lower L^* the model's tendency to over predict the flux may be partially due to AP9's use of Olson-Pfitzer quiet time magnetic field based magnetic coordinates that do not adjust with magnetic activity. Also, note that the spread of the AP9 results represents only the range of AP9 median results at various CRRES locations relative to the magnetic equator, not the model's climatological range which would encompass more of the range of CRRES data.

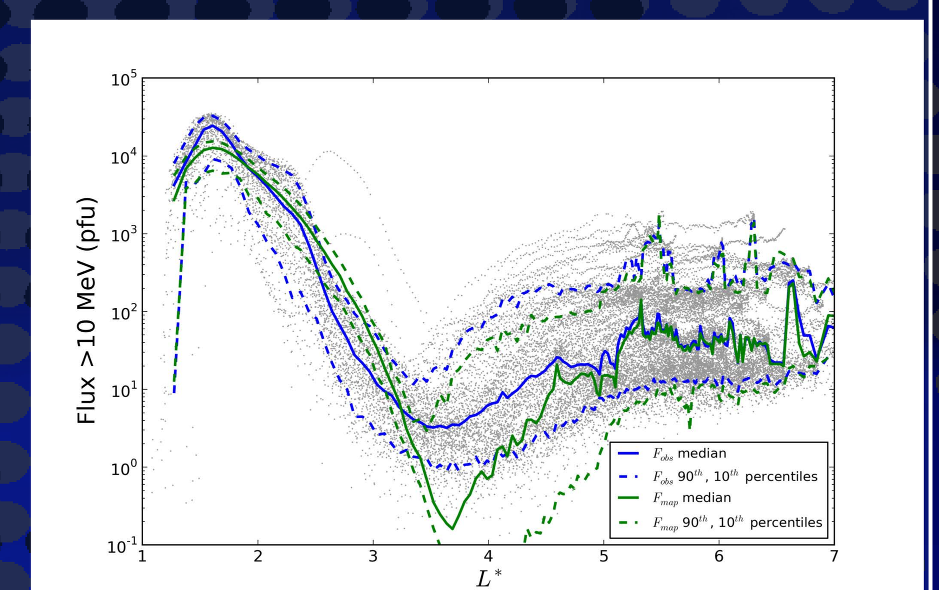
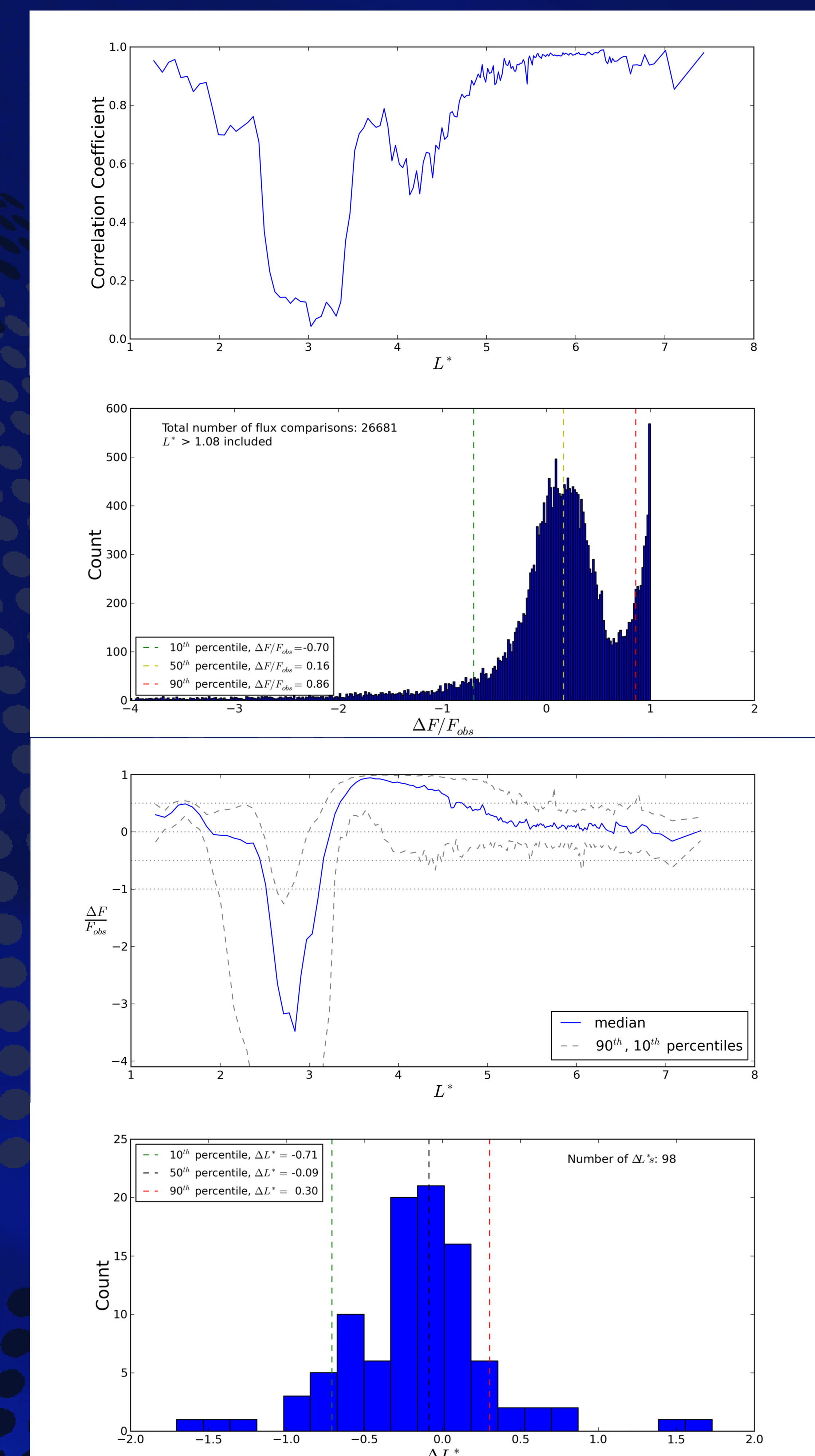


Figure 2: Samples of the 105 events examined in this study. The blue lines give statistical measures of the >10 MeV flux as observed by the PROTEL instrument on-board CRRES. The green lines are for the modeled flux. For each set of curves the solid lines represent the medians, the upper dashed line is the 90th percentile, the lower dashed curve is the 10th percentile. Individual flux observations are plotted in the background.

Analysis



Top: Modeled/Observed flux correlation vs. L^*. The correlation is best where mapped and observed fluxes are compared, but has a second peak at low L^* here observed and climatology are compared.

2nd panel: Relative error ($(F_{obs} - F_{mod})/F_{obs}$) histogram. The left mode compares mapped and observed SEP fluxes and peaks near zero. The right mode is dominated by flux comparisons in the middle region where the model does not account for the observed flux levels.

3rd panel: Relative error vs. L^*. The error is lowest for $L^* \geq 5$. Near GPS orbit ($L^* \sim 4.2$) the median mapped flux is 25% of the observed. As we would expect the worst relative error is in the middle region, but includes the relatively dynamic outer edge of the trapped population.

Bottom: $\Delta L = L_{obs} - L_{map}$ peaks near 0, but errs on the side of missing hazard predictions

Discussion and Summary

An accurate specification of the local proton hazard can be an important input to operational decisions. This work is part of an effort to quantify the current capability for specifying the energetic particle hazard. We compared CRRES PROTEL observations to a hybrid model comprised of two very different models, for the transient population we mapped GOES-7's Energetic Particle Sensor (EPS) observations from geosynchronous orbit and for the trapped population the AP9 climatological model of the inner proton belt was used. Our results indicate that for $L^* \geq 5$ the model is relatively accurate, and in the AP9 dominated lower L^* region the model tends to over predict the flux. The worst logarithmic errors occur for middle L shells where neither shielding theory nor climatology explain the existence of the observed fluxes. Fortunately, the medians of the fluxes in this region is not hazardous, however, there were hazardous flux levels observed in this region and further work needs to be done. The models are best correlated above $L^* = 3.5$, but they are well correlated in the AP9 region as well. A more operationally important metric is the ability of the algorithm to identify safe zones. While a higher flux threshold would be more relevant, we used a 10 pfu threshold to be able to include more events. The mapping predicted the safe zone to within 2/3 of an R_E 80% of the time.