Radiation Belt Climatology: Current Understanding and Methods

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Outline

• What is Climatology
• Proton Belt Climatology
• Electron Belt Climatology
• Climatology Methods for new discoveries
  – Reanalysis
  – Principal component analysis
  – Covariance analysis
What is Climatology? I

• In some contexts, climatology is just an average model of the environment, with or without indications of the variability of the environment: a farmer’s almanac for the space environment

We typically see climatology in the nightly weather report: today’s high/low as compared to normal and records (above)

• A static view (right) divides the radiation belts into inner and outer belts, with a slot in between. The inner belt includes protons and electrons, while the outer belt includes only electrons
What is Climatology? II

In the most sophisticated case, “reanalysis climatology”, we obtain a global specification of the environment over a long time scale (e.g., one or more solar cycles) for an actual time interval.

In this example, the Salammbo electron radiation belt model is run for 11 years driven by LANL GEO and GPS observations.

It’s still a work in progress, but it’s already revealing interesting intra-cycle variation.
Proton Belt Climatology

- Solar particle events combined with shocks create transient belts that last for weeks to months. Transient belts are more common at higher L (>2) and lower energy (<100 MeV)
- Solar-cycle modulation of GCRs (the source of much of the inner belt) leads to belt intensity anti-correlated with sunspot number
- Solar-cycle modulation of the upper atmosphere leads to periodic losses at inner L shells and higher K’s
- Secular variation of the internal magnetic field brings ever lower K’s into the atmosphere.

Above figure from Selesnick et al., 2007, JGR, doi:10.1029/2006SW000275

Figure at right from Lorentzen et al., JGR, 2002, doi:10.1029/2001JA000276.
During storms, the inner belt electrons can be enhanced or depleted, in association with a slot filling event. These state changes last for many months due to the stability of the inner belt. What causes the dynamics at L<2?
One of the earliest electron belt climatological results was the presence of a slot, which was explained by Lyons et al., 1972.

They explained, “long-term stability of the inner radiation zone, the location of its outer edge as a function of electron energy, and the removal of electrons to levels near zero throughout the slot”.

• Variation in the outer zone over long timescales is correlated with solar wind speed
• The location of the inner edge of the outer zone appears to be associated with the location of the plasmapause
Reanalysis

• The big news in radiation belt climatology is reanalysis
• Reanalysis combines long-term data and simulations via data assimilation
• A “reanalysis” is the resulting long-term, global, dynamic specification of the radiation belt (a “movie” of the global belt configuration)
• A reanalysis typically covers many storms, if not many years
• Reanalysis enables a variety of statistical and case studies that are difficult, if not impossible to do with individual data sets.
• For example, orbit phase and evolution tend to make direct comparison between observations of different storms difficult or impossible
In this example, from Maget et al. [2007], the Salammbo model is run for 11 years with many waves but no EMIC, no cross-diffusion.

- The model assimilates Data from LANL GEO & GPS via Direct Insertion.
- Interval: 11 years
- Additional analysis shows that adding chorus to diffusion outside plasmasphere creates too much PSD.
- Other electron reanalyses: LANL/DREAM, UCLA/VERB.

Figure from Maget et al., 2007, doi:10.1029/2007SW000322.
Principal Component Analysis

• Principal component analysis breaks the “movie” into independent spatial patterns and temporal indices
• These PCs are from the Selesnick inner zone (proton) model
• PC1 captures solar cycle and secular variation interactions with the upper atmosphere
• PCs 2 and 3 capture different aspects of solar particle injection
From climatological covariance to physical insight

• Diffusion is a linear time-evolution operator
• The time-forward operator relates the spatial correlation function to the spatiotemporal correlation function of the system
• Climatology can give us the spatial ($\Sigma$) and spatiotemporal ($\bar{R}$) correlation functions we need to fully specify the time-forward operator (even if it’s not diffusion) under specified geomagnetic conditions $\theta$ (e.g., Kp)
• Subsequent linear operations can extract the diffusion coefficients from the linear operator

$$
\dot{f}_t = \hat{D}_t f_t + S_t
$$

$$
\hat{D}_\theta \approx \left(R^T \Sigma^{-1} - I\right) \frac{1}{\Delta t}
$$

- $f_t$ = Phase space density at time $t$
- $\dot{f}_t$ = Time derivative of $f_t$
- $\hat{D}_t$ = Continuous diffusion operator at time $t$
- $S_t$ = Sources + losses at time $t$
- $\theta$ = Magnetic conditions, e.g., Kp
- $\Delta t$ = Time step
- $\Sigma_\theta$ = Discrete spatial covariance conditioned on $\theta$
- $\bar{R}_\theta$ = Lag spatial covariance conditioned on $\theta$
- $\hat{D}_\theta$ = Discrete diffusion operator conditioned on $\theta$
Conclusion

• Thinking climatologically can give us new insights into the physical processes that govern radiation belt topology and dynamics
• Reanalysis is a promising tool for combining observation and simulation knowledge
• The results of reanalysis enable time series and multivariate analysis that is difficult if not impossible to do with conventional in situ data alone
• Climatological correlations enable the deduction of diffusion coefficients or other properties of the dynamic equations that govern the radiation belts