NAIRAS Model Predictions of Aircraft Radiation Exposure during the Halloween 2003 Storms

Christopher J. Mertens
NASA/Langley

NAIRAS Team

- W. Kent Tobiska (Co-I), Space Environment Technologies, Pacific Palisades, CA
- Brian T. Kress (Co-I), Dartmouth College, Hanover, NH
- Michael Wiltberger (Co-I), NCAR High Altitude Observatory, Boulder, CO
- Stanley C. Solomon (Co-I), NCAR High Altitude Observatory, Boulder, CO
- David Bouwer (Collaborator), Space Environment Technologies, Pacific Palisades, CA
- Joe Kunches (Collaborator), NOAA Space Weather Prediction Center, Boulder, CO
- Barbara Grajewski (Collaborator), CDC/NIOSH, Cincinnati, OH
- Steve Blattning (Collaborator), NASA Langley Research Center, Hampton, VA
- Xiaojing Xu (Collaborator), SSAI, Inc., Hampton, VA
- John J. Murray (Collaborator), NASA Langley Research Center, Hampton, VA
Outline

- Overview of the NAIRAS Model Concept
- Halloween 2003 Storm Case Study
- Summary and Conclusions
Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

- Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMICKY)
  - Fit to Climax NMC
    - Badhwar+O’Neill GCR Model
      - HZETRN + Dosimetry
        - Spectral Fitting
          - NOAA GOES Data
            - Cutoff Rigidity (IGRF)
  - Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity
    - NASA/ACE Solar Wind and IMF Data
        - Atmospheric Density
          - NCEP/GFS
            - Atmospheric Dose and Dose Equivalent
Analysis of Halloween 2003 Event

• Complexity of simultaneous processes
  – Largest geomagnetic storm of solar cycle 23
  – Forbush decreases
  – Ground Level Events (GLE)
  – Anisotropic SEP distribution

• Initial analysis
  – Case study to assess geomagnetic storm influences on radiation exposure
  – Compute SEP event-averaged flux and let geomagnetic effects vary in time

• Current analysis
  – Full time-dependent SEP radiation exposure
  – GCR component including Forbush decrease
Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMICKY)

Fit to Climax NMC

NOAA GOES Data

Cutoff Rigidity (IGRF)

Hzetrn + Dosimetry

Spectral Fitting

Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity

Badhwar+O’Neill GCR Model

NASA/ACE Solar Wind and IMF Data

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

Atmospheric Density

Atmospheric Dose and Dose Equivalent

NCEP/GFS
SEP Fluence and Spectra

- GOES observes proton fluxes and we need the fluence and spectral characteristics of these events
- For the Halloween storms a single power-law did not work
  - Used a double power law spectrum as suggested by Mewaldt, 2003
    - Includes a corona and flare seed population
    - Require the power-law functions and first derivatives to be continuous at merge energy
Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMICKY)

NOAA GOES Data

Cutoff Rigidity (IGRF)

HZETRN + Dosimetry

Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity

NCEP/GFS

NASA/ACE Solar Wind and IMF Data

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

Fit to Climax NMC

Spectral Fitting

Atmospheric Density

Atmospheric Dose and Dose Equivalent

Badhwar+O’Neill GCR Model

Cutoff Rigidity (IGRF)

Atmospheric Dose and Dose Equivalent

NASA/ACE Solar Wind and IMF Data

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMICKY)

NOAA GOES Data

Cutoff Rigidity (IGRF)

HZETRN + Dosimetry

Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity

NCEP/GFS

NASA/ACE Solar Wind and IMF Data

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

Fit to Climax NMC

Spectral Fitting

Atmospheric Density

Atmospheric Dose and Dose Equivalent

Badhwar+O’Neill GCR Model
Geomagnetic Shielding

• Severe geomagnetic storms suppresses geomagnetic shielding allowing SEPs access mid- latitudes.
  – Due primarily to a build up of the ring current
  – Shock arrival can also be significant
• Particles with rigidities below the a cutoff value cannot access that point in space
  – We compute these using the TS05 storm magnetic field model and a particle tracing codes
    • During the Halloween storms we find 1 and 0.5 GV suppression during main phase and shock arrival
Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

- Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMICKY)
- Fit to Climax NMC
- Badhwar+O’Neill GCR Model
- Spectral Fitting
- HZETRN + Dosimetry
- Atmospheric Density
- Atmospheric Dose and Dose Equivalent
- NOAA GOES Data
- Cutoff Rigidity (IGRF)
- Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity
- NASA/ACE Solar Wind and IMF Data
- NOAA/GFS
- Atmospheric Dose and Dose Equivalent

HZETRN
+ Dosimetry

- Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity
- NOAA GOES Data
- Cutoff Rigidity (IGRF)

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model
HZETRN Dose Calculations

- High Z Transport code solves the linear Boltzmann equation including:
  - Ion-Electron Scattering
  - Elastic nucleon scattering
  - Nuclear reactions
Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMICKY)

Fit to Climax NMC

Badhwar+O’Neill GCR Model

NOAA GOES Data

Cutoff Rigidity (IGRF)

HZETRN + Dosimetry

Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity

NASA/ACE Solar Wind and IMF Data

Atmospheric Density

Atmospheric Dose and Dose Equivalent

NCEP/GFS
Effective Dose for Halloween Storm

- Using the all aspects of the SEP portion of NAIRAS we are able to calculate the effective dose at various altitudes and then include typical flight paths
  - We are also able to consider the role of the magnetic field model by varying which method is used to calculate the cutoff rigidity
Flight Path Comparison

- **LHR-JFK and ORD-ARN flight paths**
  - Significant differences because flight nears or crosses the open/closed field line boundary

- **ORD-BJK flight path**
  - Limited differences since both models include passage into polar cap
  - Significant dosage is seen in both cases
### Summary of Total Dose Equivalent Effects

<table>
<thead>
<tr>
<th>Flight Path</th>
<th>Dose Eq. T05S (mSv)</th>
<th>Dose Eq. T05Q (mSv)</th>
<th>Dose Eq. IGRF (mSv)</th>
<th>Dose Ratio T05S/IGRF</th>
<th>Dose Ratio T05S/T05Q</th>
<th>Dose Ratio T05Q/IGRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFK-LHR</td>
<td>0.063</td>
<td>0.030</td>
<td>0.024</td>
<td>2.62</td>
<td>2.10</td>
<td>1.25</td>
</tr>
<tr>
<td>ORD-ARN</td>
<td>0.155</td>
<td>0.104</td>
<td>0.078</td>
<td>1.99</td>
<td>1.49</td>
<td>1.33</td>
</tr>
<tr>
<td>ORD-PEK</td>
<td>0.210</td>
<td>0.195</td>
<td>0.160</td>
<td>1.31</td>
<td>1.08</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Neglect geomag effects underestimates dose by ~ factor 3

IGRF underestimates geomag quiet condition by ~ 30%
SEP Variability

- We have recently completed runs which include the variability of SEP fluence
  - Note the levels seen during the storm exceed the typical GCR dose rates
Conclusions

• Programmatic
  – NAIRAS has adopted a terrestrial weather prediction paradigm to space weather generated radiation field
    • Year 1 work has been completed beginning year 2 including GCR effects
  – Prototype model completion expected in 2011
• Halloween 2003 SEP Case Study results
  – Atmospheric radiation exposure during event may have exceed 22% of ICRP recommend prenatal limit for a typically polar route
    • Passengers and crew did not come close to approaching ICRP exposure limits
  – Neglecting time-dependent geomagnetic storm influences on cutoff rigidity may significantly underestimate exposure
  – IGRF field can result in underestimation of ~30% even with storm effects
Radiation Exposure Quantities Overview

- Unit of absorbed dose from particle $R$ ($D_R$):
  - Unit: 1 Gray == 1 J/kg

- Equivalent Dose in Tissue ($H_T$):
  - Unit: Sievert = Gray x $w_R$
  - $w_R$: radiation weighting factor

\[ H_T = \sum_R w_R \cdot D_R \]

- Effective Dose ($E$):
  - Unit: Sievert: Sievert x $w_T$
  - $w_T$: tissue weighting factor

\[ E = \sum_T w_T \cdot H_T \]

- ICRP estimate:
  - 1 in 20,000 risk of fatal cancer per 1mSv dose (lifetime)