

Recent Updates and Results from the NAIRAS Aircraft Radiation Exposure Model

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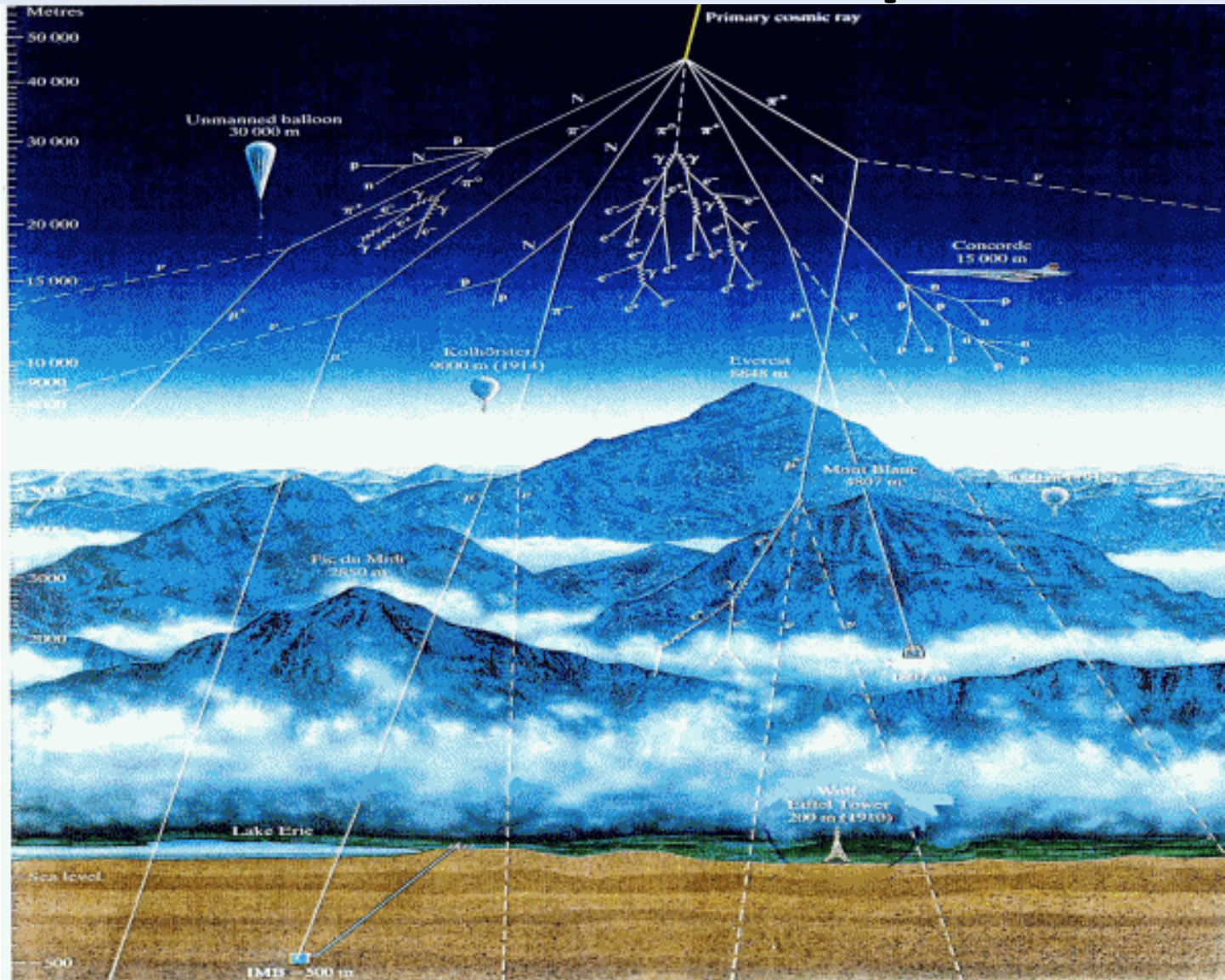
NAIRAS Team

- **Chris Mertens (PI), NASA Langley Research Center, Hampton, VA**
 - Cosmic ray transport; integration of NAIRAS models and data; V&V
- **Kent Tobiska, Space Environment Technologies, Inc, Pacific Palisades, CA**
 - Distributed data nerve center and conduit for input data – models – output data
- **Brian Kress, Dartmouth College, Hanover, NH**
 - Real-time magnetospheric transport / geomagnetic shielding model
- **Mike Wiltberger and Stan Solomon, NCAR/HAO, Boulder, CO**
 - Benchmark MHD magnetospheric magnetic fields
- **Joe Kunches, NOAA/Space Environment Center, Boulder, CO**
 - Guidance on research-to-operations; interaction with commercial aviation industry
- **Barbara Grajewski, CDC/NIOSH, Cincinnati, OH**
 - Aircraft radiation measurement data for V&V; epidemiological studies
- **Steve Blattnig, NASA Langley Research Center, Hampton, VA**
 - Cosmic ray nuclear interactions; transport physics
- **Xiaojing Xu, SSAI, Hampton, VA**
 - Scientific programming and data visualization tools
- **Ryan Norman (Post-Doc), NASA Langley Research Center, Hampton, VA**
 - Cosmic ray nuclear interactions; transport physics

Outline

- **What's Atmospheric Ionizing Radiation?**
- **Who Cares?**
- **What's NAIRAS?**
- **What Can We Learn From Solar Radiation Storms?**
- **What Do Measurements Say?**
- **What's Hot Off the Press?**
- **What's Next?**

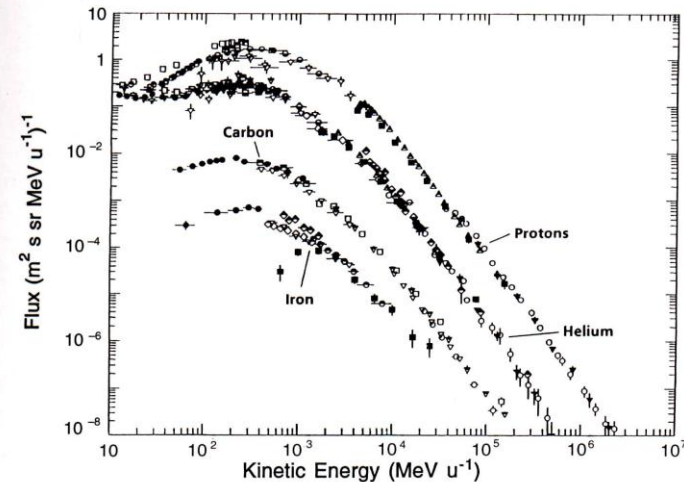
What Happens When Cosmic Rays Encounter the Atmosphere?



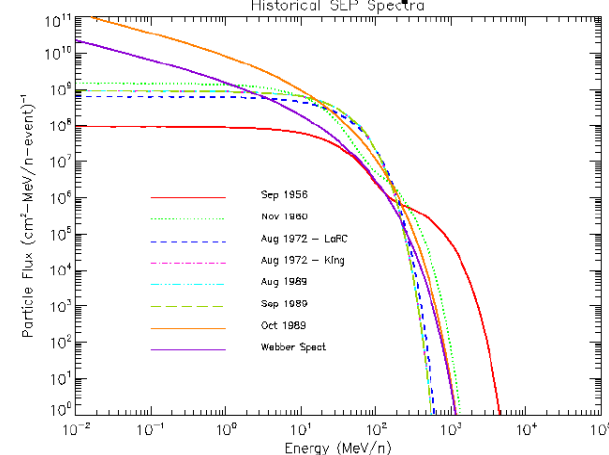
What are the Sources of Atmospheric Ionizing Radiation?

- **GCR (Galactic Cosmic Ray)**
 - 98% nuclei, 2% e^-/e^+
 - Nuclear component
 - 87% Hydrogen (protons)
 - 12% Helium (alpha)
 - 1% heavy nuclei
 - Particle Spectra (relative to SEP)
 - High energy component; few particle
 - High-energy > moderately influenced by Earth's magnetic field
- **SEP (Solar Energetic Particles)**
 - Protons, alphas, and electrons
 - Particle Spectra (relative to GCR)
 - Low-Medium energy component; many particles
 - Low-mid energy > significantly influence by Earth's magnetic field

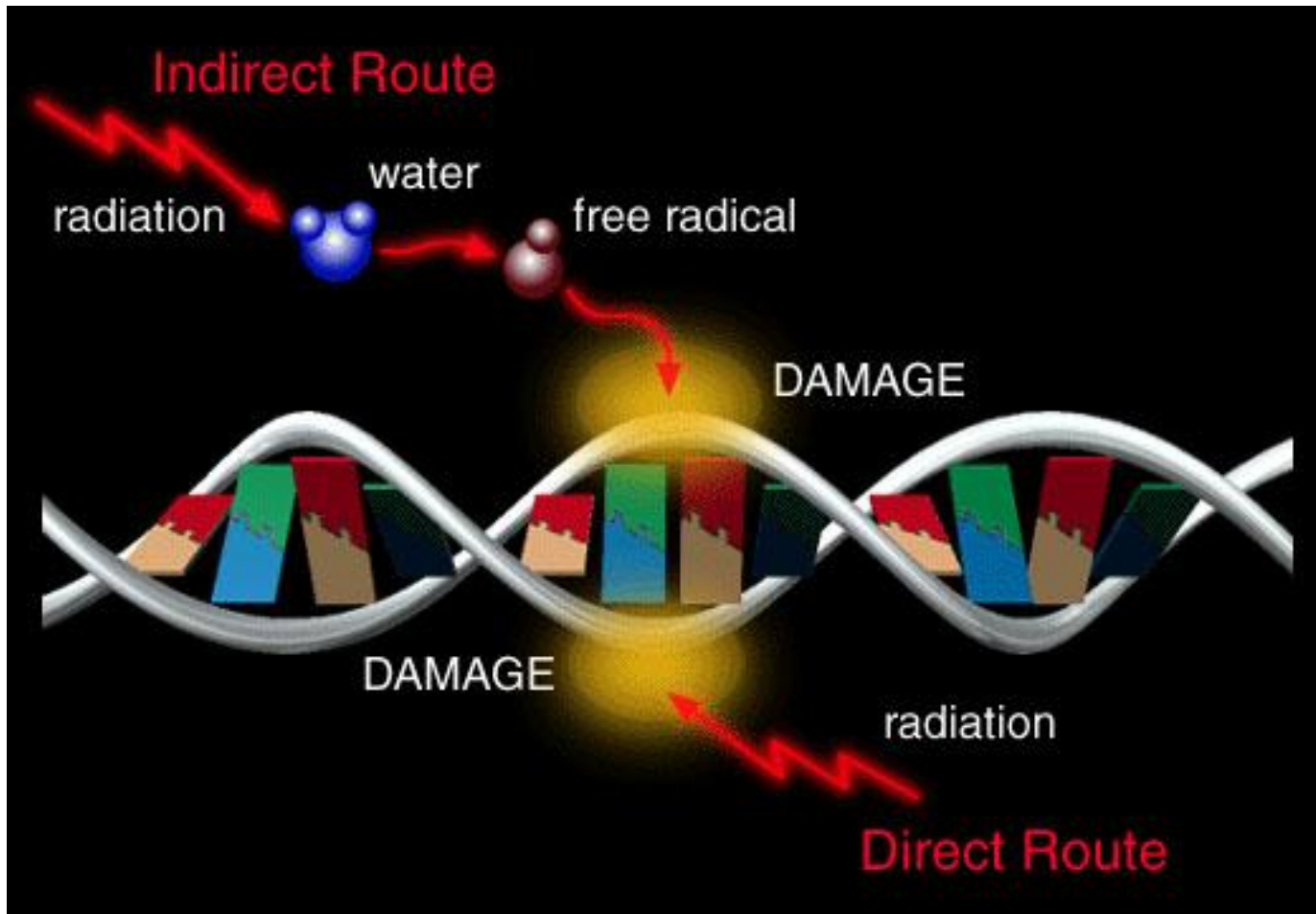
GCR Particle Spectra



SEP Proton Spectra



Ways to damage DNA



Atmospheric Ionizing Radiation: Who Cares?

- **Commercial Aircrew**
 - Classified as radiation workers by International Commission on Radiobiological Protection (ICRP)
 - Receive the largest annual radiation exposure of any occupational group
 - Only group exposed to unquantified and undocumented levels of radiation
- **National Institute of Occupational Safety and Health (NIOSH)**
 - NIOSH Flight Crew Research program has a longstanding commitment to understand the work environment of aircrew and their health
- **National/International Aviation Decision-Makers**
 - The need for aircraft radiation model/measurements specified in
 - ❑ FAA NextGen space weather requirements
 - ❑ International Civil Aviation Organization (ICAO) space weather ConOps -> WMO -> aviation weather requirements

Atmospheric Ionizing Radiation: Who Cares?

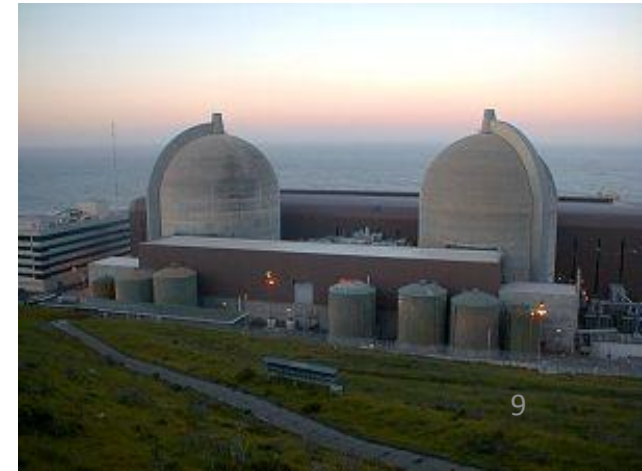
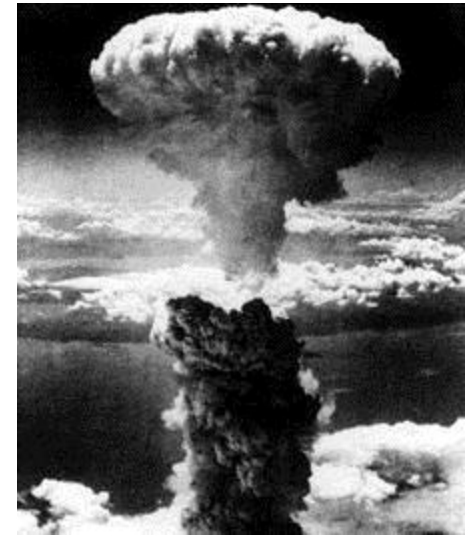
- NOAA Space Weather Prediction Center
 - Provider of operational space weather nowcast/forecast models
- NASA Heliophysics Living With A Star
 - Strategic Goal #1: “Penetrating particle radiation adversely affects aircraft avionics and potentially the health of airline crews and passengers on polar flights. The [LWS] program needs to deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth ...”

Radiation Doses

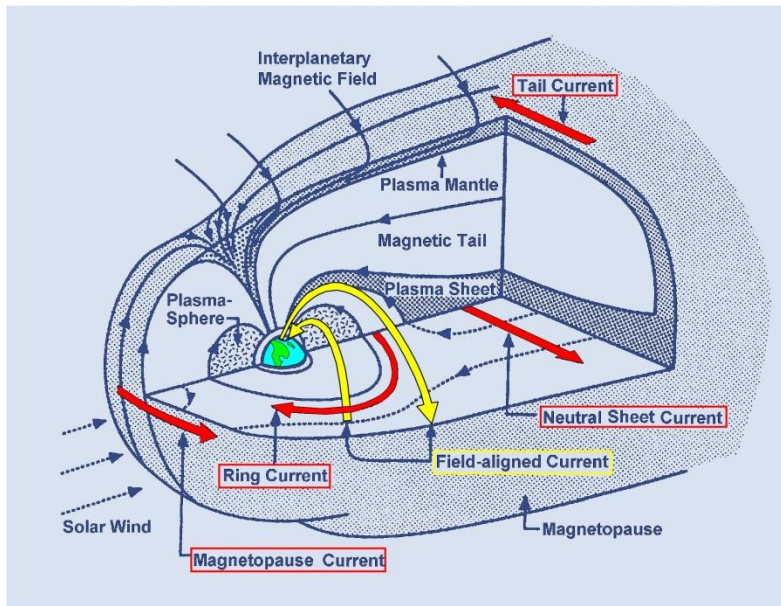
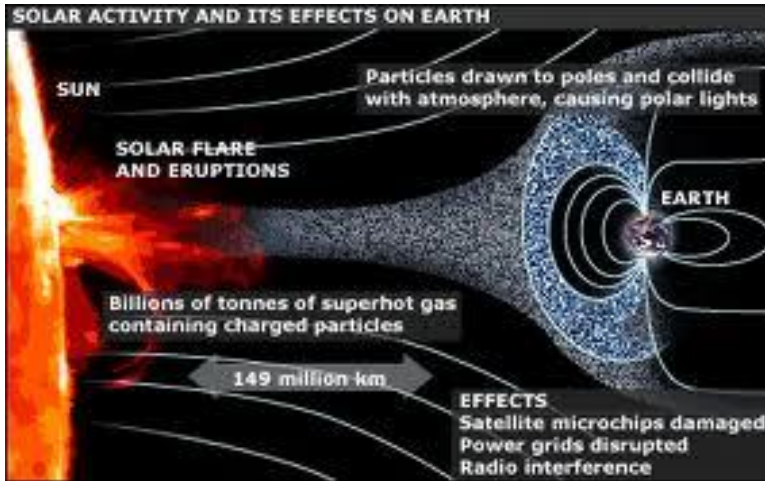
- Chest x-ray $\sim .1$ mSv
- Death > 3 Sv (instantaneous)
- ICRP Recommended Limits
 - Public annual limit < 1 mSv/yr
 - Prenatal limit < 1 mSv total; < 0.5 mSv any month
 - Radiation worker limit < 20 mSv/yr
 - ❑ *Pilots are classified as radiation workers*

ICRP Estimate

- 1 out of 20,000 of fatal cancer per 1 mSv dose (lifetime)



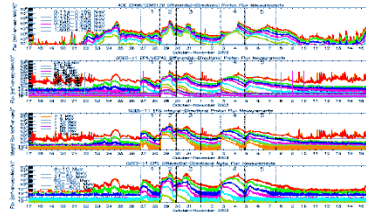
What is NAIRAS?



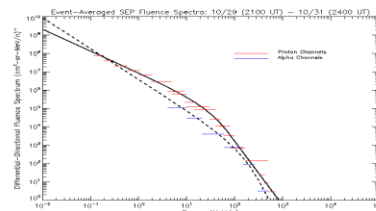
- **LaRC's Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model**
 - Prototype development funded by NASA Applied Sciences (ROSES)
 - Running in real-time at the LaRC/DAAC since April 2011
- **Distinguishing Features**
 - First real-time physics-based, global model
 - First real-time inclusion of SEP radiation
 - First real-time solar-magnetospheric effects on radiation
 - First real-time meteorological data used

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

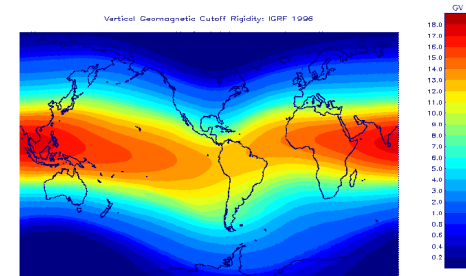
NOAA/GOES + NASA/ACE Data



Spectral Fitting



Cutoff Rigidity (IGRF)

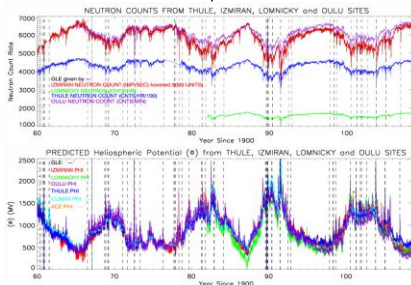


Magnetospheric
Magnetic Field
(e.g., T05)
Effects on
Cutoff Rigidity

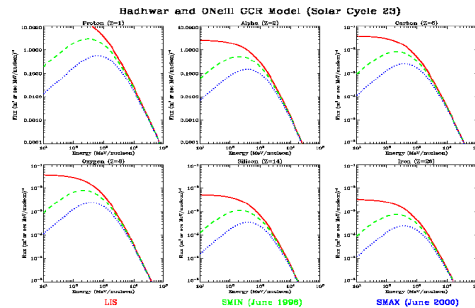
NASA/ACE Solar
Wind and IMF Data

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

Fit to Climax HP

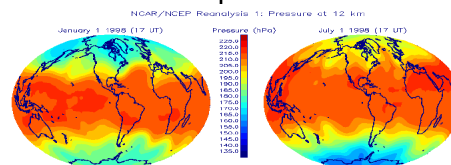


Badhwar+O'Neill GCR Model

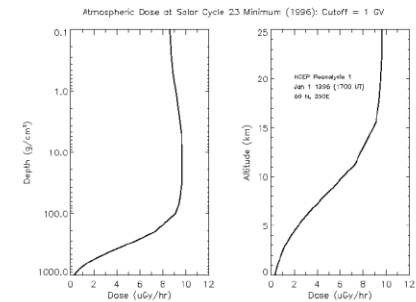


HZETRN
+
Dosimetry

Atmospheric Density



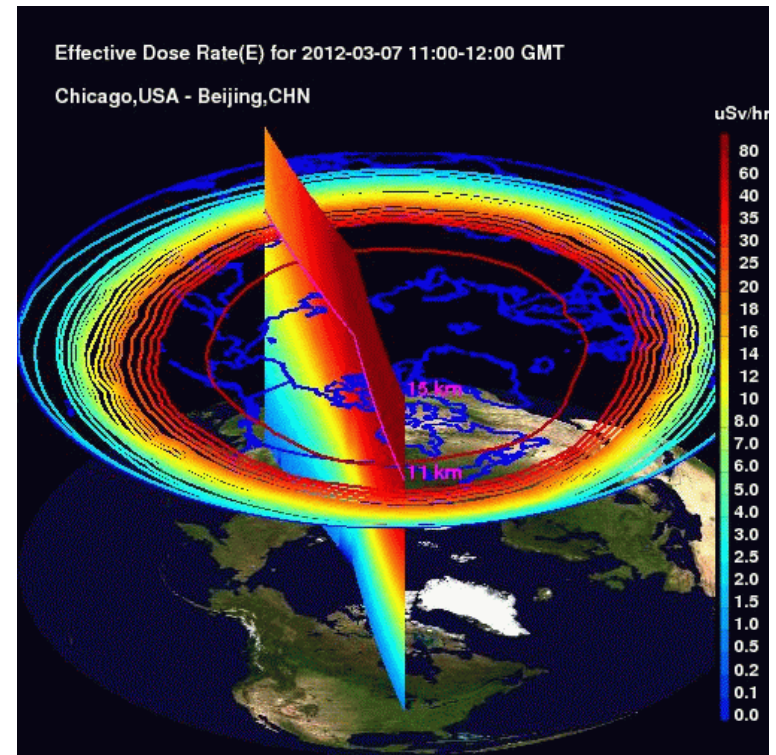
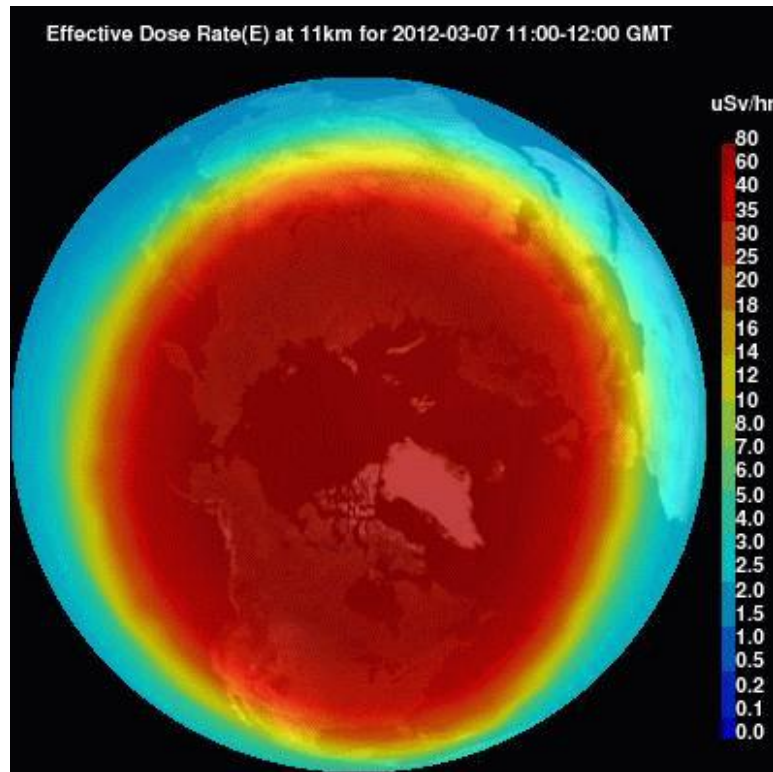
NCEP/GFS



Atmospheric Dose
and Dose Equivalent

NAIRAS Graphical Products

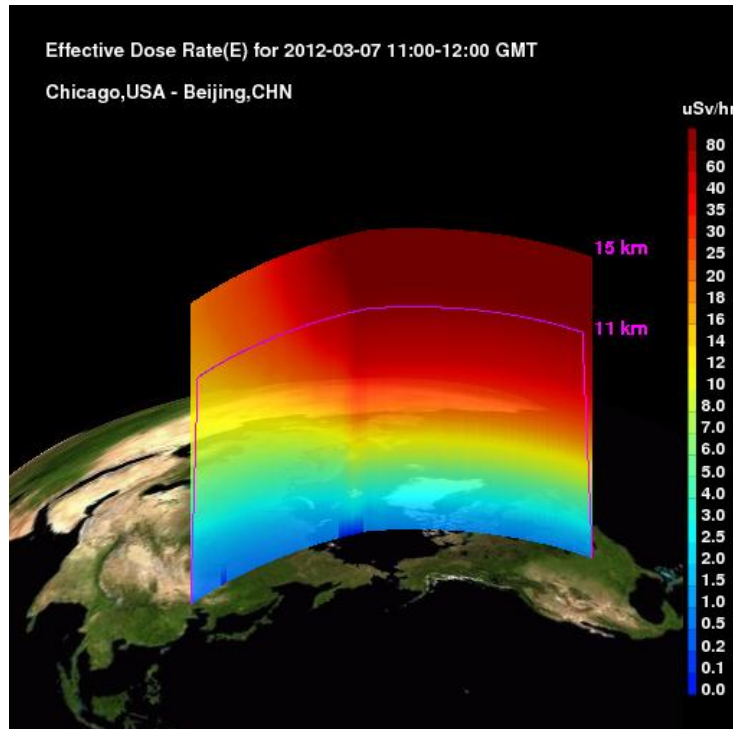
March 2012 Solar Storm Event



Public Web site: <http://sol.spacenvironment.net/~nairas/> (or google NAIRAS)

NAIRAS Graphical Products

March 2012 Solar Storm Event



Public Web site: <http://sol.spacenvironment.net/~nairas/> (or google NAIRAS)

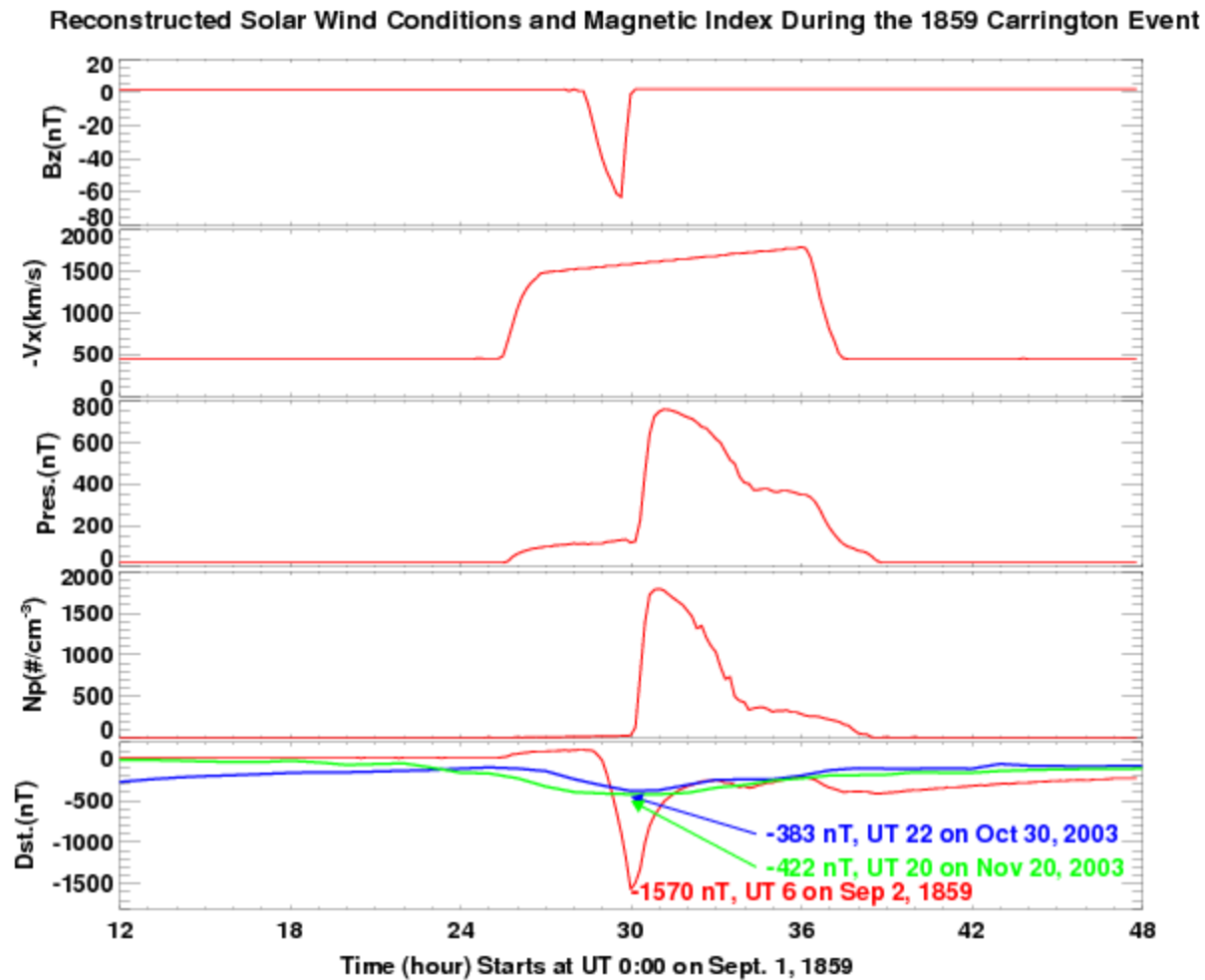
What Can We Learn From Solar Radiation Storms?

- **The 1859 Carrington Event**
 - Proxy for the “mother of all” storms
- **Halloween 2003 Storm**
 - The largest geomagnetic storm of solar cycle 23
- **March 2012 Storm**
 - High aircraft radiation dose
 - Alpha radiation storm

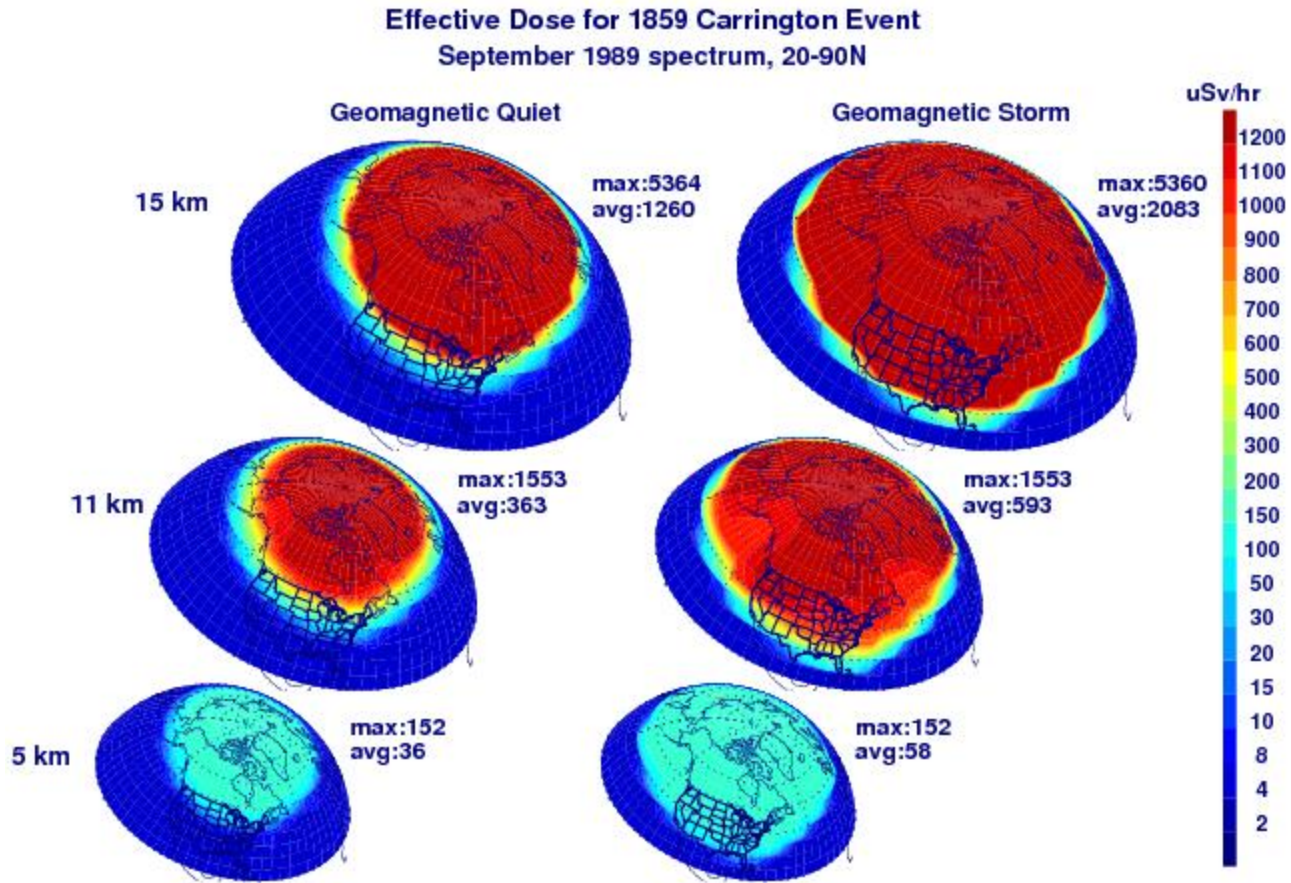
Carrington Event

- SEP Spectral Fluence [*Smart et al., 2006; Townsend et al., 2006*]
 - Assume a spectral shape
 - August 1972 (soft)
 - September 1989 (hard)
 - Normalize spectral shape to >30 MeV proton fluence determined by impulsive NOy deposition in polar ice cores [*McCracken et al. 2001*]
 - Lack of detectable increase in annual ^{10}Be deposition in polar ice favors a soft spectrum

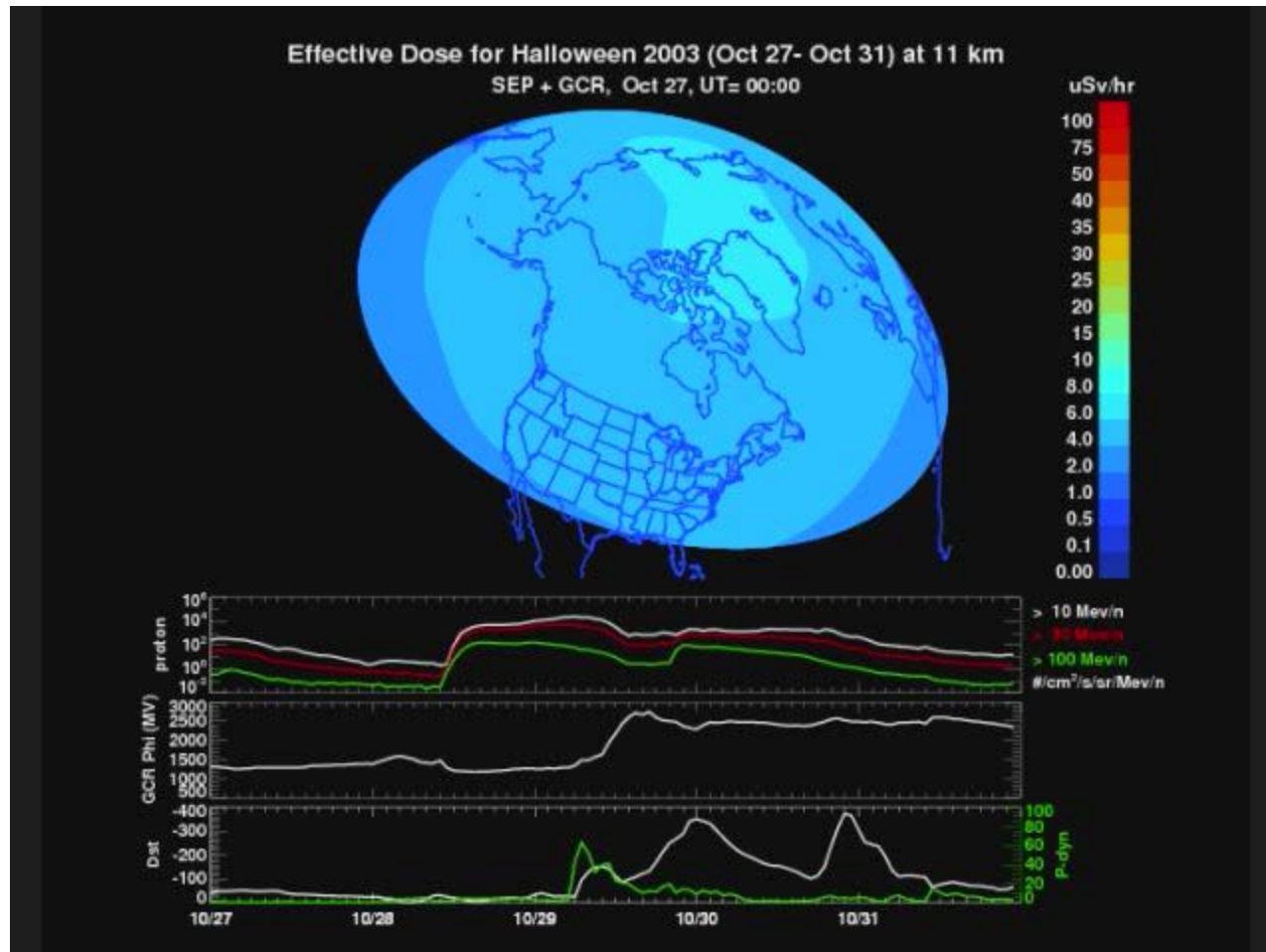
Carrington 1859



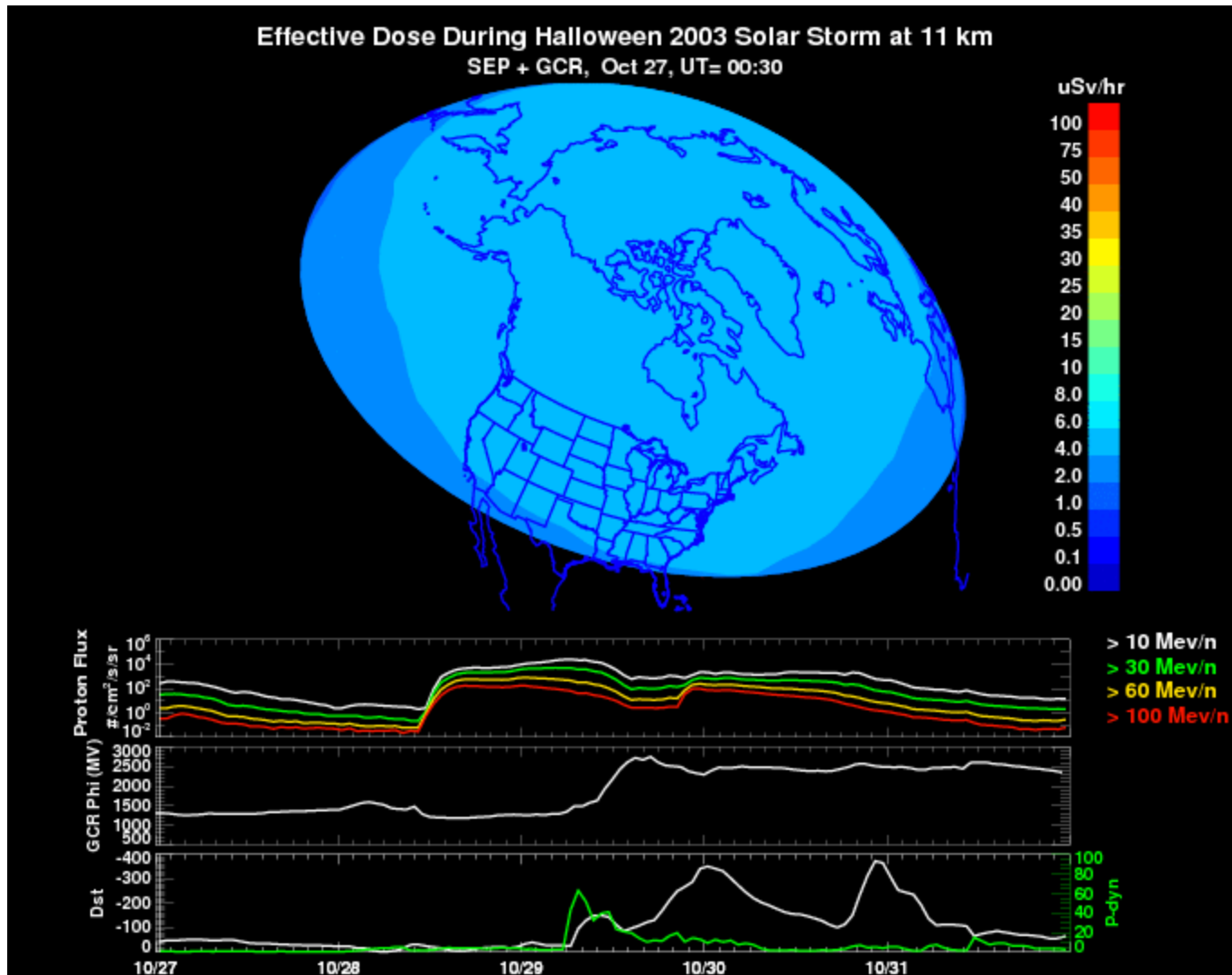
Carrington 1859



NAIRAS Model Predictions During Halloween 2003 Storm Events



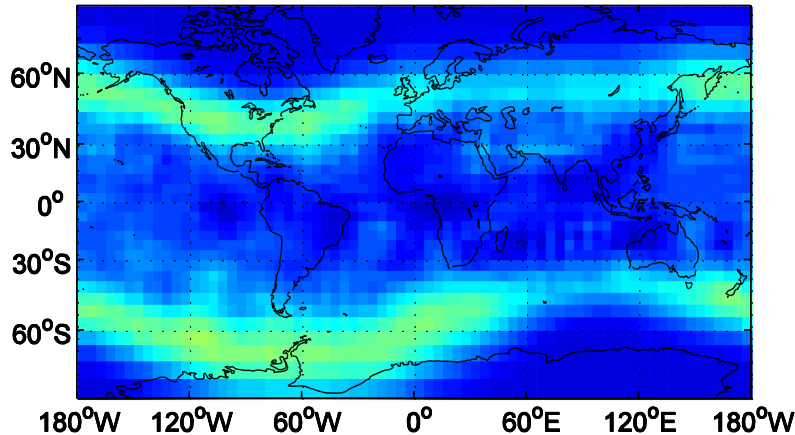
NAIRAS Model Predictions During Halloween 2003 Storm Events



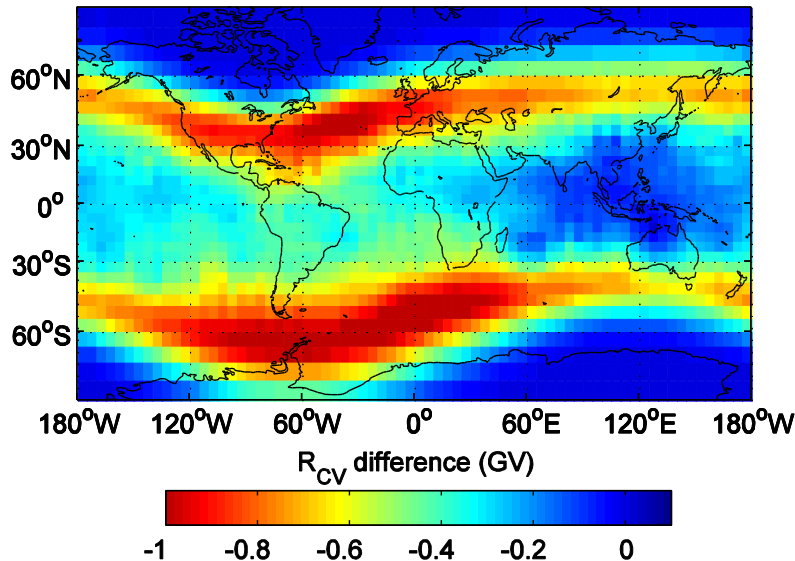
NAIRAS Storm Animations (html/QT)

Halloween 2003 Geomagnetic Storm

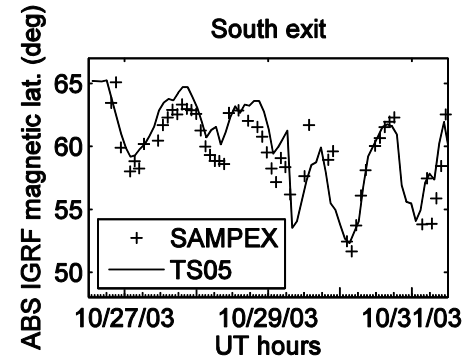
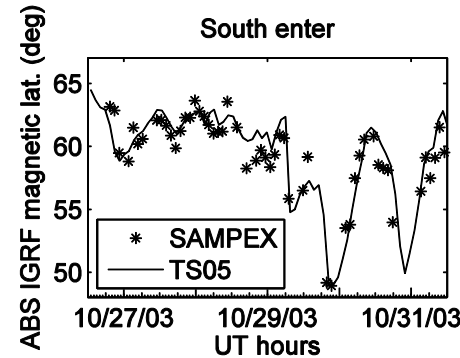
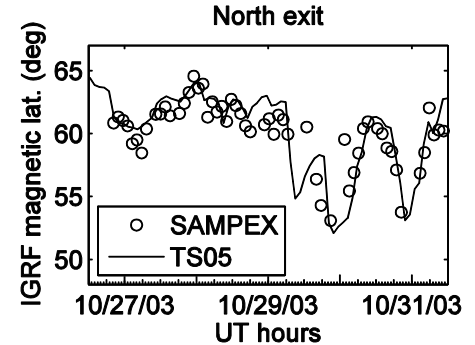
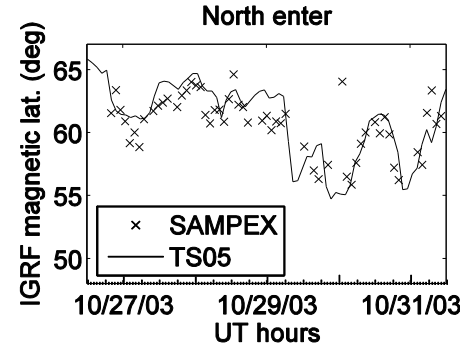
Difference between shock arrival and quiet cutoffs



Difference between minimum Dst and quiet cutoffs



Cutoff Latitude of ~ 20 MeV protons



- TS05 cutoff latitude accuracy: ~ 2-degrees
- TS05 cutoff accuracy significantly better LFM/MHD code
- 2-degree cutoff uncertainty in latitude can translate into factor ~2 or greater aircraft dose uncertainty

Flight Path Comparison

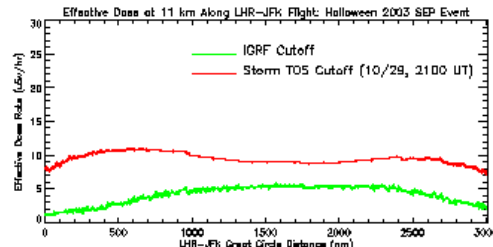
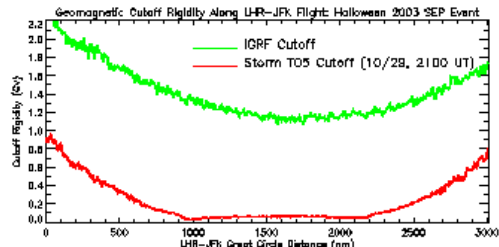
Halloween 2003 Storm Period

Geomagnetic Effects

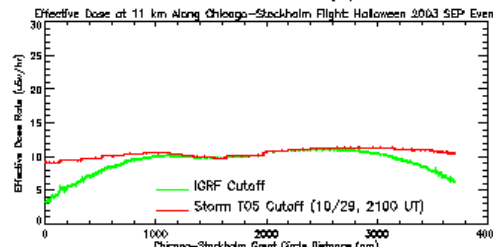
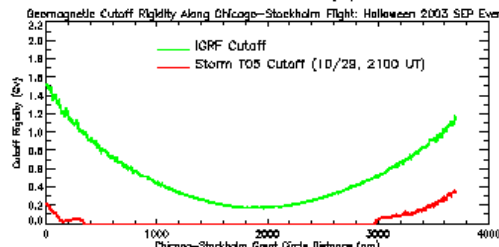
Cutoff – Magnetic Field Effect

Radiation Dose Effect

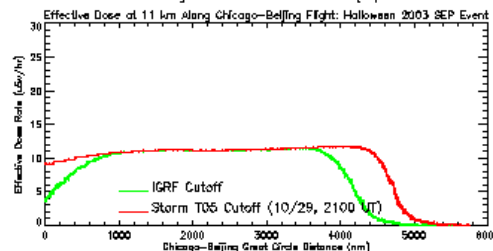
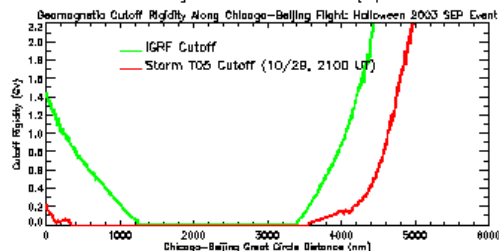
LHR-JFK



ORD-ARN



ORD-PEK



- **LHR-JFK flight path**
 - Significant differences because flight comes near to or crosses the open/closed field line boundary
- Geomagnetic effects introduce a factor ~ 2 or greater variation in dose
- **ORD-PEK flight path**
 - Limited differences since both models include passage into polar cap
 - Significant dosage is seen in both cases

NAIRAS Model Predictions During March 2012 Solar Storm Events

Effective Dose Rate¹(E) for 2012-03-07 11:00-12:00 GMT

5km (16,000 feet) Radiative Dose Rate (uSv/hr)								
lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	12.01	8.51	3.77	1.06	0.88	2.58	8.21	11.74
max	13.67	12.35	8.81	3.03	3.64	8.71	12.45	13.61
11km (35,000 feet) Radiative Dose Rate (uSv/hr)								
lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	63.79	43.36	15.16	2.69	2.14	9.45	41.37	66.03
max	69.41	66.18	47.22	10.15	13.08	45.58	67.98	72.08
15km (49,000 feet) Radiative Dose Rate (uSv/hr)								
lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	133.91	84.70	22.91	3.21	2.51	13.33	76.84	142.45
max	144.86	140.66	94.98	13.45	17.59	90.36	147.34	152.19

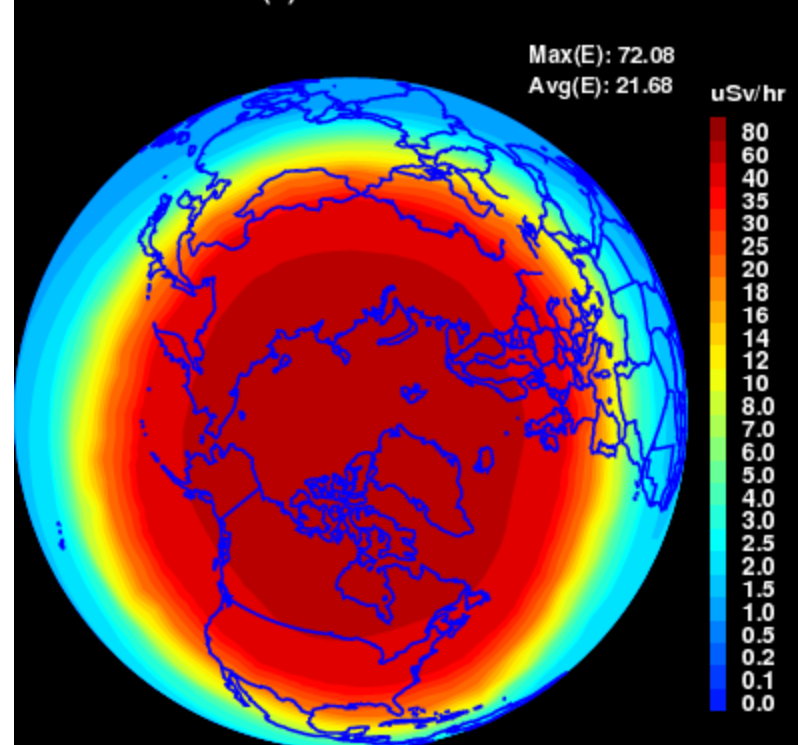
Representative High-Latitude Flights

2012-03-07 11:00-12:00 GMT

Flight Name	Time hours	Rate ¹ uSv/hr	Dose ¹ mSv	Safety Signal		
				Aircrew ²	Public ³	Prenatal ⁴
London,GBR - New York,USA	5.50	51.52	0.283	Yellow	Green	Yellow
Chicago,USA - Stockholm,SWE	8.50	63.09	0.536	Yellow	Yellow	Red
Chicago,USA - Munich,DEU	8.50	56.35	0.479	Yellow	Yellow	Red
Chicago,USA - Beijing,CHN	13.50	60.34	0.815	Yellow	Red	Red

Signal	Aircrew ⁵ Max_Annual(800hrs)	Public ⁶ one_trip	Prenatal ⁶ one_trip
Green	0-6.0mSv	0-0.330mSv	0-0.167mSv
Yellow	6.0-12.0mSv	0.330-0.670mSv	0.167-0.333mSv
Red	>12.0mSv	>0.670mSv	>0.333mSv

Effective Dose Rate(E) at 11km for 2012-03-07 11:00-12:00 GMT

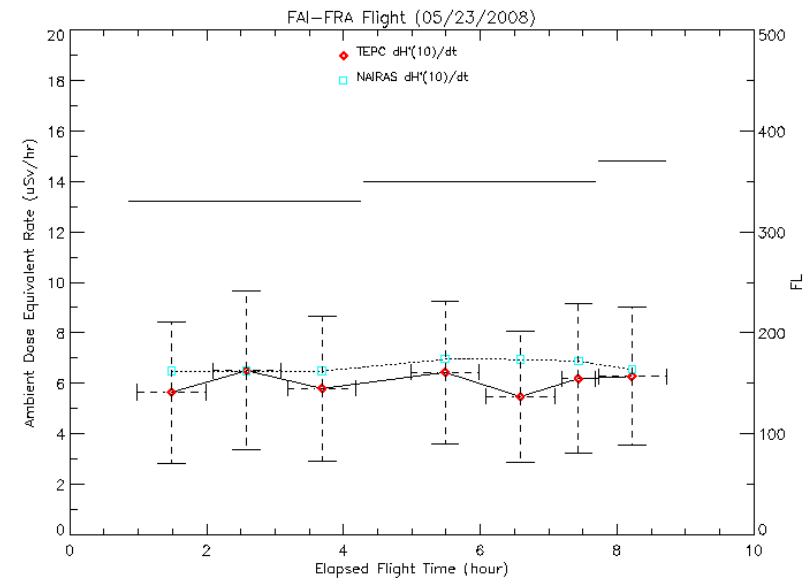
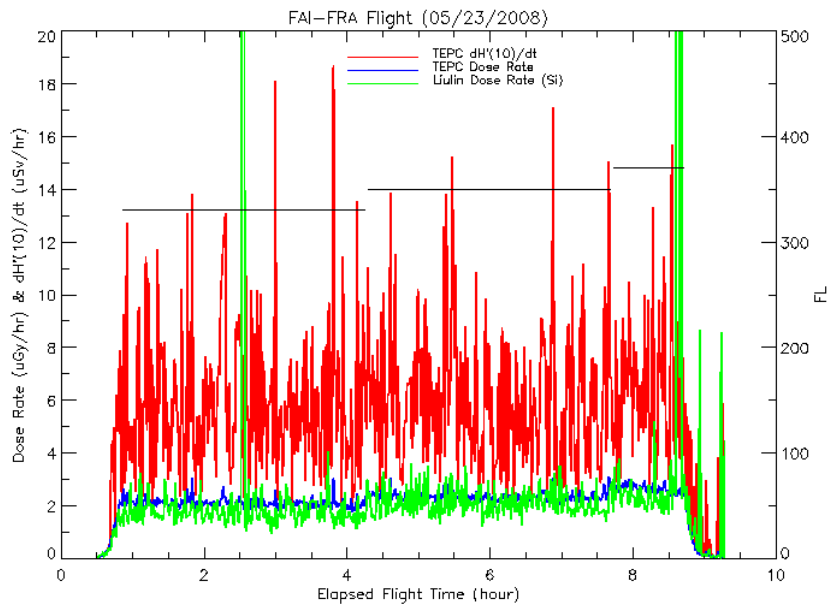


Public Web site: <http://sol.spacenvironment.net/~nairas/> (or google NAIRAS)

What Do The Measurements Say?

High-Latitude Flight

GCR

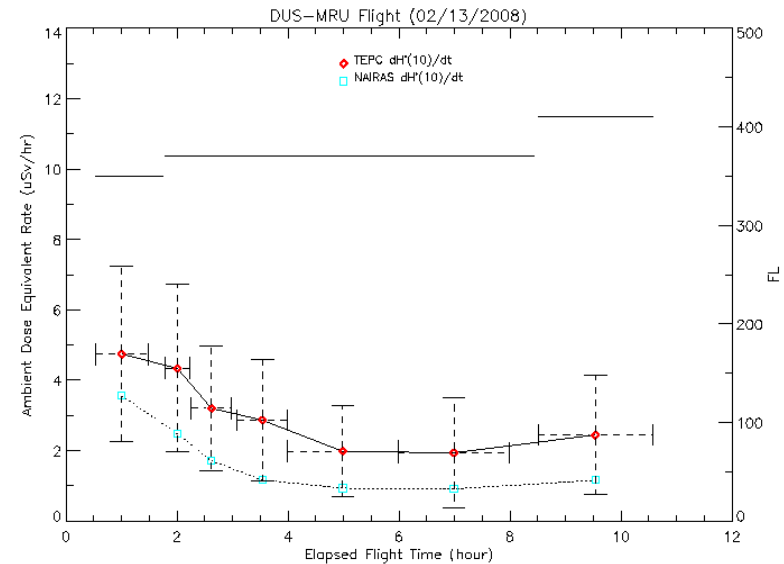
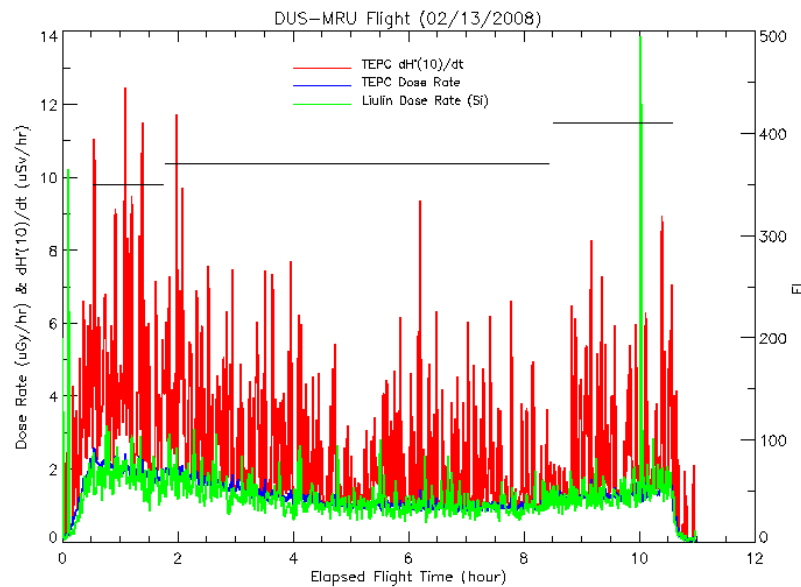


TEPC data courtesy of Matthias Meier (DLR)

What Do The Measurements Say?

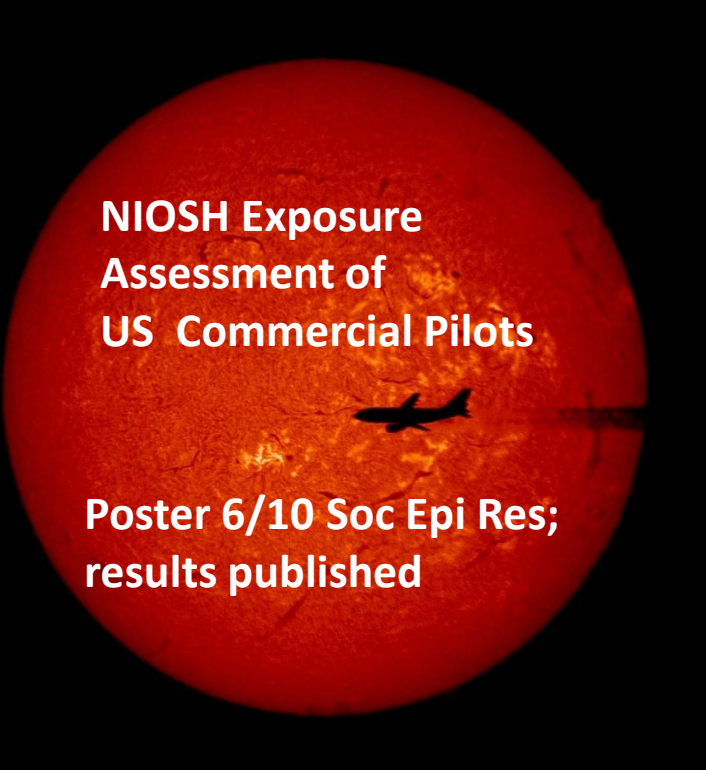
Low-Latitude Flight

GCR



TEPC data courtesy of Matthias Meier (DLR)

What's Hot Off the Press?



NIOSH Exposure
Assessment of
US Commercial Pilots

Poster 6/10 Soc Epi Res;
results published

Image courtesy of Kanzelhöhe Observatory

FIRST STUDY OF

- US commercial pilot career exposure profile from individual flight segments:
 - Cosmic radiation
 - Solar energetic particle events
 - Chronic circadian disruption

FINDINGS

- A median pilot incurred
 - 34.4 mSv GCR and flew through 6 SEPs in 28 y flying
 - 1.92 mSv in the last study year
- Exposure metrics increased markedly 1990+

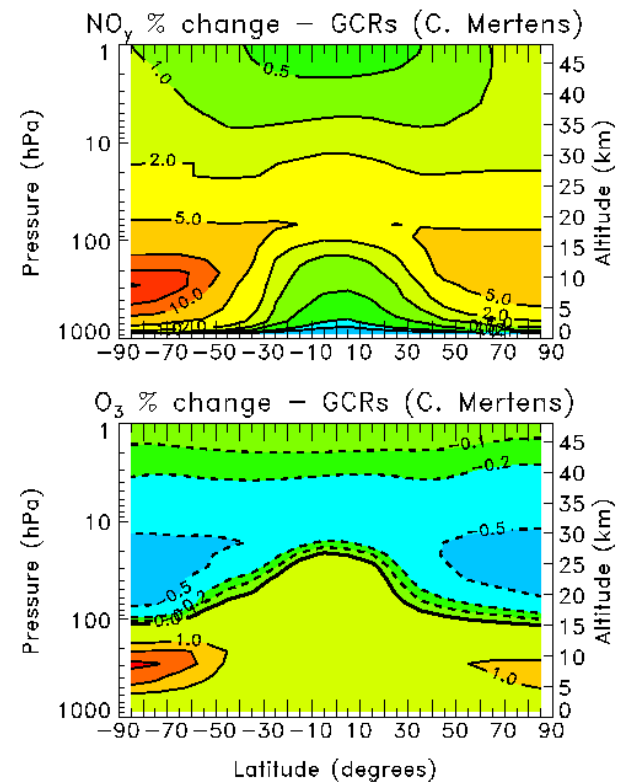
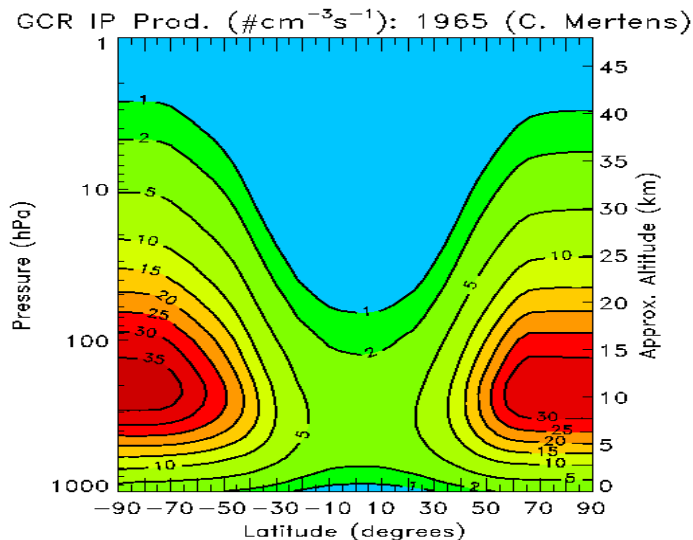
IMPLICATIONS

- No dose limits for US crew
- Median pilot would trigger EU radiation monitoring ($>1\text{mSv/y}$)
- A pregnant female pilot could exceed ICRP guidelines for pregnant radiation workers
- High-exposed pilots at increased risk

- ✨ **NAIRAS data can be expected to improve epidemiologic studies of flight exposures markedly compared to current methodology**
- ✨ **NAIRAS has already improved NIOSH's exposure assessment of this occupational group**

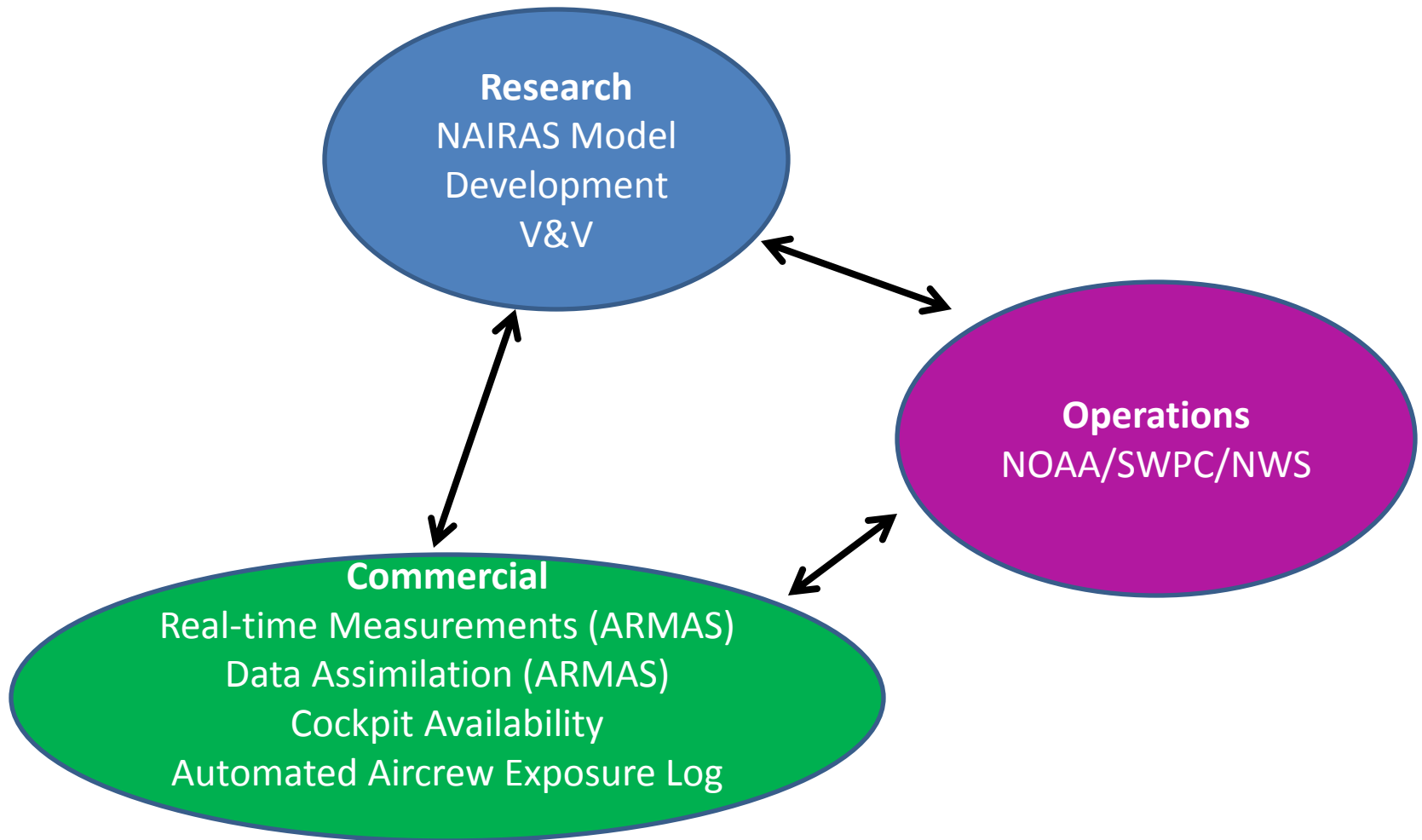
GCR Influence on Atmospheric Chemistry and Climate

GCR Influence on Strat/Trop Chemistry. Include Ionization Rates in WACCM (Jackman/GSFC)



Completed NAIRAS computations of 5-decades of annual-averaged GCR ionization rates for input into WACCM

NAIRAS Partnership Structure



NAIRAS Future Plans and Activities

Atmospheric Radiation Measurements

- **Automated Radiation Measurement for Aviation Safety (ARMAS) Project**
 - Phase II SBIR awarded to Space Environment Technologies
 - Measurement/Technology Goal: Global, real-time radiation measurements
 - Modeling Goal: Data assimilative nowcast/forecast
- **Radiation Dosimetry Experiment (RaD-X) Project**
 - Proposal to Hands-On Flight Experience (HOPE-4)
 - High-altitude balloon Flight (~30-35 km)
 - Science Objective: High-altitude radiation measurements and NAIRAS V&V
 - Technology Objective: Develop CubeSat infrastructure for multi-satellite space weather monitoring
- **Extension to Mars Atmosphere (NAIRAS-M)**

NAIRAS Future Plans and Activities

Model Development

- **NAIRAS Enhancements/Extensions Proposed to ROSES in March 2012**
 - **Aircrew Interface**
 - Add a web interface customized for pilots
 - Enable user entry of flight coordinates for exposure assessment
 - Enable easy access of current and archived data/graphical products
 - **Civil/Commercial Space Transportation**
 - Extension to LEO (NAIRAS-L)
 - **Model Development**
 - SEP high-energy tail and spatial anisotropy
 - Directional effects (cutoffs, transport ray trace)
 - Pion/EM-cascade effects
 - Microelectronic effects

NAIRAS

