Nowcast of Atmospheric Ionizing Radiation for Aviation Safety

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Abstract

The Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) is a prototype operational model for predicting commercial aircraft radiation exposure from galactic and solar cosmic rays [*Mertens et al., 2008, 2010*]. The NAIRAS model addresses an important national need with broad societal, public health and economic benefits. The prototype development is currently funded by the NASA Applied Sciences / Aviation Weather Program. The anticipated completion date of the operational prototype is June 2011. In this white paper we propose a research-to-operations activity to transition NAIRAS to operations. In addition, during the prototype development phase, the NAIRAS team has identified new science questions that must be addressed in order to obtain a reliable and robust operational model of atmospheric radiation exposure. Thus, we also propose an operations-to-research activity that addresses emerging science questions concomitant with the research-to-operations activity.

1. Introduction

An important atmospheric state variable, driven by space weather phenomena, is the ionizing radiation field. The two sources of atmospheric ionizing radiation are: (1) the ever-present, background galactic cosmic rays (GCR), with origins outside the solar system, and (2) the transient solar energetic particle (SEP) events (or solar cosmic rays), which are associated with eruptions on the Sun's surface lasting for several hours to days with widely varying intensity. Quantifying the levels of atmospheric ionizing radiation is of particular interest to the aviation industry since it is the primary source of human exposure to high linear energy transfer (LET) radiation. High-LET radiation is effective at directly breaking DNA strands in biological tissue, or producing chemically active radicals in tissue that alter the cell function, both of which can lead to cancer or other adverse health effects [*Wilson et al., 2005a, 2003*]. Adverse health effects include, but are not limited to, reproductive disorder and prenatal injury [*Lauria et al., 2006; Waters et al, 2000; and Aspholm et al., 1999*]. The International Commission on Radiological Protection (ICRP), the Environmental Protection Agency (EPA), and the Federal Aviation Administration (FAA) classify crews of commercial aircraft as radiation workers [*McMeekin, 1990; ICRP, 1991*]. It's estimated that, on an annually basis, aircrew are exposed to considerably more radiation than the average nuclear power plant worker [*Wilson et al., 2003*]. However, aircrew are the only occupational group exposed to unquantified and undocumented levels of radiation. Furthermore, the current guidelines for maximum public and prenatal exposure can be exceeded during a single solar storm event for commercial passengers on intercontinental or cross-polar routes, or by frequent use (~ 10 flights per year) of these high-latitude routes even during background conditions [see also, *Dyer et al., 2009; Copeland et al., 2008; AMS, 2007*]. As a result, there is a need for a capability to predict real-time radiation levels for the commercial aviation industry.

Over the last decade, airspace over Russian and China has opened up to commercial traffic, allowing for polar routes between North America and Asia [*AMS, 2007*]. These cross-polar routes reduce flight time and operational cost; thus, the number of cross-polar commercial routes has increased exponentially. The typical cost savings from a cross-polar route from the US to China is between $35,000 and $45,000 per flight compared to the previous non-polar route [*DOC, 2004*]. However, the polar region receives the largest quantity of radiation because the shielding provided by Earth's magnetic field rapidly approaches zero near the magnetic pole. On the other hand, the economic loss to an airline to reroute a polar flight can be a factor of three greater than the original cost-savings of flying the polar route if fuel stops and layovers are necessary. Thus, the cost to reroute a cross-polar route can be as much as $100,000 per flight [*DOC, 2004*]. Consequently, an aircraft radiation prediction model must also be accurate to minimize radiation risks while simultaneously minimizing significant monetary loss to the commercial aviation industry.

The goal of the NAIRAS model is to provide a new decision support system for the NOAA Space Weather Prediction Center (SWPC) that currently does not exist, but is essential for providing the commercial aviation industry with data products that will enable airlines to achieve the right balance between minimizing flight cost while at the same time minimizing radiation risk. Thus, NAIRAS model addresses an important national need with broad societal, public health and economic benefits. For example, during the Halloween 2003 storm period the FAA issued an advisory that high-latitude flights were subject to excessive levels of radiation exposure. One major airline was cautious and rerouted six polar flights to non-polar flights requiring fuel stops in Japan and/or Anchorage [*DOC, 2004*]. Rerouting polar flights can add an additional cost to airlines up to $100,000 per flight if fuel stops are necessary. However, the actual radiation levels did not pose a significant risk during this storm period [*Mertens et al., 2010; Copeland et al. 2008*]. If the NAIRAS model had been available at this time, it could have potentially saved this airline up to $600,000. On the other hand, the radiation levels during the January 2005 storm period were sufficient to exceed the guidelines for maximum annual public and prenatal exposure [*Copeland et al., 2008*], and the availability of the NAIRAS model could have provided the guidance to minimize the radiation risk from this SEP event.

NOAA/SWPC enthusiastically embraces NAIRAS as a viable candidate for operations at the National Weather Service [*Bogdan et al., 2010*]. However, a robust verification and validation (V&V) program is needed as part of the transition to operations activity in order to demonstrate the robustness and efficacy of the NAIRAS model over the full dynamic range of space weather conditions. In addition, in developing the NAIRAS operational prototype, the NAIRAS team has identified new science questions that must also be addressed before full operational implementation. These topics are discussed in more detail in sections 3 and 4. In the next section we describe the major components of NAIRAS model and the model/data system architecture.

2. NAIRAS Distributed System Architecture

The NAIRAS model is based on analytical-numerical solutions of couple Boltzmann transport equations, which are solved on a global grid and in real-time at a 1-hour time cadence [*Mertens et al., 2010*]. The solutions of the transport equations are obtained using NASA Langley Research Center's HZETRN code [*Wilson et al, 1991, 2005b*]. Effective dose and ambient dose equivalent are computed using neutron and proton fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients, respectively, tabulated by *Ferrari et al.* [*1997a, 1997b*]. The dosimetric contributions from the other ions are obtained by scaling the proton conversion coefficients by Z^2_j according to the stopping power dependence on charge. Geomagnetic shielding specified by vertical cutoff rigidity is calculated from the model of *Kress et al. [2010]*, which is based on the Tsyganenko and Sitnov TS05 magnetospheric magnetic field model [*Tsyganenko and Sitnov, 2005*]. The real-time input data used by the cutoff rigidity model are Dst, and solar wind dynamic pressure and interplanetary magnetic field data measured by the NASA/ACE satellite. The cutoff rigidities are also calculated on a global grid and in real-time at a 1-hour time cadence. Solar cycle modulation is taken into account using an extension to the Badhwar and O'Neill GCR model [*O'Neill, 2006*]. The GCR model propagates the local interstellar spectrum of each element of the GCR composition from outside the heliosphere to 1 A.U. and, thus, provides the fluence rate boundary conditions for transport through the magnetosphere and atmosphere using the cutoff rigidity and HZETRN codes, respectively. The Badhwar and O'Neill model was extended by fitting the solar modulation potential to high-latitude, real-time neutron monitor count rate measurements. The real-time neutron monitor measurements currently used by NAIRAS in the GCR model are Oulu, Thule, Lomnicky, and IZMIRAN. During SEP events, NOAA/GOES ion flux measurements and NASA/ACE low-energy proton flux measurements are used in a spectral fitting algorithm to derive the SEP ion fluence rate boundary conditions for transport through the magnetosphere-atmosphere system. Real-time NCEP Global Forecasting System (GFS) meteorological data are used to specify the overhead shielding by the atmospheric mass.

Due to insufficient community funding for research-to-operations activities, the NAIRAS operational prototype model has adopted the distributed network paradigm – automated systems of models, data streams and algorithms at multiple, geographically dispersed facilities linked by operational servers [*Tobiska, 2009*]. Space Environment Technologies (SET) developed the critical input data stream formats and I/O interface modules between the input datasets and the SET server database. There are two redundant sources for each input dataset to ensure operational continuity. SET processing of the input data is continuous and a 4-day buffer for the 1-5 minute cadence input data are maintained on the SET server. The NAIRAS code runs continuously at NASA Langley Research Center (LaRC). When the NAIRAS code is ready for a new 1-hour update, the code automatically retrieves the required input datasets from the SET server. After NAIRAS has finished computing the global radiation exposure quantities for the current 1-hour period, the radiation exposure data are further processed and graphical and tabular data products are derived. These derived products are pushed back to the SET serve for dissemination and are available at the NAIRAS public web site (http://sol.spacenvironment.net/~nairas/index.html). Currently, NAIRAS is operating in a 4-hour demo mode until the code is completely ported and tested at LaRC Atmospheric Sciences Data Center.

3. Emerging Science Questions

In the process of developing the NAIRAS prototype, a number of new science questions have emerged that need to be adequately addressed in order to obtain a reliable and robust operational aircraft radiation exposure prediction model. One new science question concerns how to account for the high-energy tail of the incident SEP ion spectral fluence rates. The highest energy GOES ion flux measurements (~ 500 MeV/n) can vary by more than an order of magnitude over the duration of a SEP event [*Mertens et al., 2010*]. Because there are no GOES measurements greater than ~ 500 MeV/n, the high-energy tail of the SEP ion spectral fluence rates, determined by our spectral fitting algorithm, are unconstrained. Therefore, the high-energy tail is subject to orders of magnitude uncertainty. During the January 20, 2005 SEP event, the equatorial neutron monitor station at Tibet (cutoff rigidity ~ 14.1 GV) registered a Ground-Level Enhancement (GLE), indicating a sufficient number of ~ 14 GeV SEP protons to increase the baseline neutron monitor count rate by 2.4% [*Plainaki et al., 2007*], indicating the possibility of very high-energy SEP protons that cannot be measured by satellite. As a result of the large uncertainties in the high-energy SEP ion spectra from satellite measurements, the atmospheric radiation exposure rates will be subject to orders of magnitude of uncertainty. *Dyer et al. [2009]* has noted that retrospective model calculations of atmospheric radiation exposure during SEP events have differed by up to an order of magnitude.

Another new science question concerns how to account for spatial anisotropy in the incident SEP ion flux. The January 20, 2005 was a recent SEP event that exhibited large anisotropies. This is evident by the fact that only the Tibet neutron monitor station registered a GLE at equatorial latitudes (i.e., at very high energy) [*Plainaki et al., 2007*]. *Matthia et al. [2009]* showed that the anisotropy persisted for more than 12-hours during this event. The peak incident SEP proton flux and atmospheric radiation exposure rates occurred at the beginning of this event in the southern hemisphere only. SEP spatial anisotropy can also introduce large uncertainties in atmospheric radiation exposure predictions if an isotropic distribution is assumed, as is typically done [*Dyer* *et al., 2009*]. Currently, NAIRAS assumes that the SEP ion flux is isotropic, with a factor of one-half applied to account for Earth shadowing.

We propose to account for SEP spatial anisotropy and the SEP high-energy tail by utilizing data from a world-wide distribution of neutron monitor stations. We will develop robust, automated algorithms suitable for real-time application. This is now possible by the recent availability of a world-wide network of real-time neutron monitor data [*Mavromichalaki et al., 2005*], and generalized neutron monitor yield functions [*Fluckiger et al., 2008*]. Neutron count rates measured by a neutron monitor station can be simulated by convolving the incident cosmic ray spectrum with a yield function specific to the neutron monitor site, which depends primarily on atmospheric depth at the altitude of the site and on the cutoff rigidity at the geographic location of the site [*Matthia et al., 2009; Fluckiger et al., 2008; Vashenyuk et al., 2007; Cramp et al., 1997*]. Our nominal SEP spectral fitting algorithm that uses the GOES and ACE ion flux measurements will be augmented with neutron monitor data. This will enable the incident SEP proton fluence rate to be fit from ~ 100 keV to ~10 GeV and alphas from ~ 1 MeV to ~ 5 GeV. We can quantify the improvement made by utilizing the neutron data by comparing measured and calculated neutron counts rates at neutron stations not used in developing the incident SEP spectra fit. In accounting for SEP spatial anisotropy, we will explore the efficacy of assuming a Gaussian or a linear dependence on the pitch-angle distribution [*Vashenyuk et al., 2007; Matthia et al., 2009*]. We will decide on the best approach by comparing measured and calculated neutron counts rates at neutron stations not used in developing the fit in pitch-angle distribution.

There are several new science questions regarding the modeling of cutoff rigidities [*Kress et al., 2010*]. Our recent analysis of the Halloween 2003 storm period showed that the radiation exposure rates at commercial and executive jet cruising altitudes are highly sensitive to the cutoff rigidity, especially along the open-closed magnetosphere boundary [*Mertens et al., 2010*]. *Kress et al. [2010]* demonstrated that the uncertainty of the state-of-the-art in calculating the cutoff latitude for ~ 20 MeV protons is around two degrees in latitude. If this uncertainty is indicative of the uncertainty in modeling the location of the open-closed magnetosphere boundary, then the prediction of aircraft radiation exposure for international flights along the North Atlantic corridor connecting the US and Europe can have uncertainties greater than a factor of two [*Mertens et al., 2010*]. The NOAA/POES mid-energy proton flux data are available in real-time and we will explore the possibility of using these measurements in a data assimilation capacity to better constrain the cutoff model. We'll also explore if a non-uniform grid, such as the distorted spherical grid, can better resolve the cutoff variation with latitude.

Another important science topic is the role of anisotropy in representing the local cutoff rigidity. The previous discussion on anisotropy dealt with large-scale variations in the global distribution of incident SEP ion flux. Here we refer to small-scale, local variations: i.e., the variation of the cutoff rigidity with solid angle in computing the number of ions arriving in the atmospheric at a particular geographic location and altitude. We compute a vertical cutoff rigidity at a single altitude and assume it does not vary locally with altitude or solid angle, which are the usual assumptions [*Kress et al., 2010*]. These assumptions work well at the Earth's surface, but become less accurate with increasing altitude. The issue in real-time applications is that it is impractical to compute by rigorous numerical particle trajectory simulations a global grid of cutoff rigidities as a function of altitude and solid angle at each geographic grid point. We will quantify the uncertainty in these assumptions on GCR and SEP atmospheric radiation exposure rates and assess if simple angle-altitude scaling using Stormer theory can adequately reduce the uncertainty, or develop other alternatives [*Kress et al., 2010*].

We will assess the reliability and feasibility of predicting the real-time geomagnetic cutoff rigidities using the physics-based LFM MHD magnetic fields. The LFM MHD code may be run as a stand alone model or coupled with other geospace models currently under development within CISM. For example, the LFM magnetospheric magnetic fields may be coupled with the Thermosphere-Ionosphere Nested Grid (TING) model [*Wang et al., 2004*] and/or with the Rice Convection Model (RCM) [*Toffoletto, 2004*], which models the ring current. The semi-empirical TS05 model provides more accurate cutoff rigidities than the stand alone LFM MHD model, as determined by comparisons with satellite observations during a Halloween 2003 geomagnetic storm [*Kress et al., 2010*]. This is mainly due to the lack of a full kinetic description of the ring current in the MHD model, which typically causes the LFM fields to be too high. We anticipate that the fully coupled LFM-RCM-TING model currently under development will significantly improve the simulations of cutoff rigidities compared to the stand along LFM MHD model. Furthermore, the physics-based LFM-RCM-TING model will be able to incorporate short time-scale dynamics not included in empirical magnetospheric magnetic field models. When the code development within CISM reaches sufficient maturity, we will assess the influence of short time-scale magnetospheric dynamics on the atmospheric ionizing radiation field using the fully coupled LFM-RCM-TING model.

4. Transition to Operations

As stated previously, NOAA/SWPC enthusiastically embraces NAIRAS as a viable candidate for operations at the National Weather Service [*Bogdan et al., 2010*]. However, a robust V&V program is needed as part of the transition to operations activity in order to demonstrate the robustness and efficacy of the NAIRAS model over the full dynamic range of space weather conditions. We propose a three-pronged, comprehensive V&V program with a path towards real-time data assimilation of global onboard aircraft radiation measurement to improve NAIRAS predictions, in much the same way that meteorological weather forecasts models ingest real-time atmospheric state variable measurements to constrain and improve their forecasts.

The first prong of our three-pronged V&V plan is to compare NAIRAS with historical aircraft measurements made by Tissue Equivalent Proportional Counter (TEPC) instruments, or compare with other models when possible. TEPC instruments measure the ambient dose equivalent rate, which is a reasonable proxy for the dosimetric quantity directly related to biological risk – the effective dose rate [*Clucas at el., 2005*]. NIOSH has agreed to provide the NAIRAS team with TEPC measurements for 32 flight segments under background GCR conditions. The German Aerospace Corporation (DLR) has provided TEPC measurements for a few flight segments. In addition, it may be possible to obtain aircraft TEPC measurements from Dachev et al., Spurny et al., and Lewis et al.

The second prong of our three-pronged V&V plan is to establish collaboration with the NASA Stratospheric Observatory For Infrared Astronomy (SOFIA) Program. SOFIA is an airborne (Boeing 747) observatory of infrared telescopes and instruments for astrophysics and astronomy research. The SOFIA aircraft will fly approximately 1000 hours per year at various latitudes, longitudes, and altitudes, reaching altitudes over 40 kft, and will make observations for two decades. The SOFIA mission provides an extraordinary collaborative opportunity between the Astrophysics, Heliophysics, and Applied Science communities, through the addition of radiation instruments on the SOFIA aircraft, to conduct NAIRAS V&V analysis over two solar cycles. These long-term measurements, combined with the extensive altitude range, will enable solar cycle modulation and cutoff rigidity effects to be separated out. As a result, the fundamental mechanisms and cross sections that produce the showers of secondary particles can be quantitatively assessed. The SOFIA mission provides an opportunity to conduct physics-based V&V of the NAIRAS model.

The third prong of our three-pronged V&V plan is to make new automated onboard TEPC measurements with a path toward global, real-time data assimilation of these measurements into the NAIRAS model. This approach will be implemented in three phases. In Phase I (~ 1-2 years), we will deploy a TEPC instrument on three flights: domestic cross country flight, high-latitude flight connecting the US with Europe, and a polar flight. High-latitude TEPC measurements are not widely available and to our knowledge no radiation measurements have been made along a polar route. FedEx has agreed to cooperate with us and the three TEPC measurements will be conducted on FedEx flights. The TEPC instrument and data analysis will be provided by our team members at CREESE and Boeing [*Gersey et al., 2002, 2007a-b*]. This first phase provides initial NAIRAS V&V for the high-latitude and cross-polar routes, and also provides a technology demonstration of new ways advanced by our CREESE team member of quantifying the important neutron contribution to radiation exposure and biological risk. In Phase II (~ 2-5 years), continuous TEPC measurements will be made on perhaps a dozen aircraft, and the data will be transmitted to the ground through aviation systems such as AirDat's network of airborne sensors called Tropospheric Airborne Meteorological Data Reporting (TAMDAR), which provide a continuous stream of real-time observations. This phase enables extensive V&V for quantitative characterization of the NAIRAS model uncertainties as is necessary for data assimilation. Moreover, this phase enables the design and the implementation of the software for which the SET distributed network system serves as the communication nerve center and I/O data hub between the real-time onboard radiation measurements and the NAIRAS model predictions. CREESE and Boeing will participate in developing the interface software between the TEPC instruments and the real-time aircraft data downlink, and develop analysis tools to monitor and assess the health of the instruments. Phase III (~ 3-5 years) will be a large-scale implementation of Phase II into operations, with data assimilation capacity, that will dramatically improve aviation radiation health and safety while simultaneously providing economic benefit to the aviation industry.

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