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Improved space weather observations and modeling for aviation radiation

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In recent years there has been a growing interest from the aviation community for space weather radiation forecasts tailored to the needs of the aviation industry. In 2019 several space weather centers began issuing advisories for the International Civil Aviation Organization alerting users to enhancements in the radiation environment at aviation flight levels. Due to a lack of routine observations, radiation modeling is required to specify the dose rates experienced by flight crew and passengers. While mature models exist, support for key observational inputs and further modeling advancements are needed. Observational inputs required from the ground-based neutron monitor network must be financially supported for research studies and operations to ensure real-time data is available for forecast operations and actionable end user decision making. An improved understanding of the geomagnetic field is required to reduce dose rate uncertainties in regions close to the open/closed geomagnetic field boundary, important for flights such as those between the continental US and Europe which operate in this region. Airborne radiation measurements, which are crucial for model validation and improvement, are lacking, particularly during solar energetic particle events. New measurement campaigns must be carried out to ensure progress and *in situ* atmospheric radiation measurements made available for real-time situational awareness. Furthermore, solar energetic particle forecasting must be improved to move aviation radiation nowcasts to forecasts in order to meet customer requirements for longer lead times for planning and mitigation.

KEYWORDS

space weather, radiation, forecasting, aviation, airborne measurements, radiation modeling, neutron monitors, geomagnetic field

1 Introduction

Ionizing radiation from background galactic cosmic rays (GCR) and transient solar energetic particle events (SEPs) contributes to the radiation environment experienced by crew and passengers on flights at altitudes typical of civil aviation. A customer requirements survey for the NOAA Space Weather Prediction Center (SWPC), published in 2019 (Abt Associates, 2019), highlighted the need for improved space weather products and services tailored to the aviation industry. Geographically targeted forecasts and warnings of the radiation environment, available with longer lead times and confidence intervals were highlighted as requests from users.

In November 2019, SWPC assumed responsibility as one of three (now four) global space weather centers providing space weather advisories for the International Civil Aviation Organization (ICAO). These new advisories alert operators to the possibility of space weather impacts on Global Navigation Satellite Systems (GNSS), communication systems, and to enhancements in the radiation dose rates at aviation flight levels. Radiation advisories are issued for six 30° latitude bands and altitudes between 25,000 ft and 60,000 ft. A moderate (MOD) advisory is issued when the effective dose rate exceeds 30 μSv/hr and a severe (SEV) advisory is issued when the effective dose rate exceeds 80 μSv/hr.

While the Geostationary Operational Environmental Satellite [GOES: Sauer (1989); Kress et al. (2020)] energetic particle measurements are used to characterize particle spectra at the top of the atmosphere and ground-based neutron monitors measure corresponding secondary neutrons on the ground, there are no routine observations of the radiation environment at altitudes used by aircraft. Modeling is required to simulate the global radiation environment in the atmosphere. Several models exist in the United States and international research communities (e.g., CARI-7 Copeland et al. (2008); Copeland (2017), NAIRAS Mertens et al. (2010, 2016), WASAVIES Kataoka et al. (2014); Kubo et al. (2015), MAIRE Hands et al. (2022) to name a few). These models generally include descriptions of the incoming GCR and SEP particle spectra, a representation of the geomagnetic field to determine access of these particles to the atmosphere and a subsequent model component which simulates the atmospheric response to ionizing radiation. From the simulated secondary particle distributions, conversions are made to infer radiation dose rates.

2 Neutron monitor observations for aviation radiation model development and space weather operations

Recommendations:

- Financial support is required to ensure the robust operation and availability of globally distributed neutron monitors for research and space weather operations.
- Studies are required to quantify the dependence of aviation radiation model outcomes on the number and location of neutron monitors.
- Studies should be carried out to determine if retired stations can be brought back online and new stations placed in geomagnetically important locations to provide coverage for scientific closure.
- Model development and new data for validation studies are required to improve the effectiveness of neutron monitor data in aviation radiation models.

Neutron monitors provide crucial observational inputs for aviation radiation models. Most models use GOES particle measurements and/or neutron monitor observations to characterize SEP proton and alpha particle spectra during solar radiation storms. High energy (≥500 MeV) particle intensity and spectral shape, most impactful for the radiation environment at aviation flight levels, cannot be accurately determined from the GOES particle sensors alone. While some models use the GOES measurements to define the low energy (≥10 MeV) spectral shape and as a starting point for high energy spectral extrapolation in conjunction with neutron monitor measurements (Copeland et al., 2008), other models use neutron monitor yield functions alone to define the primary particle spectra entering the atmosphere (Matthiä et al., 2018).

The global neutron monitor network consists of stations distributed across geomagnetic latitudes and longitudes. These stations are independently run by several funding bodies and institutes. While around 25 stations return data in near real time, *via*, e.g., the European Neutron Monitor Database (NMDB: https://www.nmdb.eu/), the network is not operationally supported (e.g., back up data streams and support staff for real time 24/7 operations) which could result in data being unavailable for models supporting forecast and user operations. Furthermore, the network is not ideally distributed to accurately capture particle anisotropies present at the onset and peak of an SEP event when the radiation dose rates are highest. This anisotropy can lead to significantly different dose rates in regions of the globe with similar geomagnetic shielding. In 2021, the Simpson Neutron Monitor Network (SNMN) was created. It consists of neutron monitors owned and operated by US institutions. One of the priorities of the SNMN is to address these issues by securing, maintaining, and extending the NM observations for the coming decades. See the white paper by Ryan et al. (2022) titled The United States and Global Neutron Monitor Network for Heliophysics and Space Weather for more details on this topic. [1]Modeling studies are required to optimize the expansion of the global neutron monitor network, e.g., Mishev and Usoskin (2020). Further research is required to routinely characterize particle pitch angle distributions from neutron monitor observations and incorporate them in aviation radiation models.

3 Improved understanding of the geomagnetic field

Recommendations:

- Model development and validation are required to improve the accuracy of geomagnetic cutoff latitudes and to quantify uncertainties using space and ground-based observations.
- Data assimilation methodologies hold great potential and are a growing area of research. Capabilities should be developed to improve the accuracy of cutoff predictions from available data for incorporation into aviation radiation models.
- Particle data in low Earth orbit (LEO) for assimilation and validation of cutoff models is currently extremely coarse and limited. Analysis is needed to determine the data latency, spatial coverage, composition, and energies required to assimilate into and improve cutoff models and provide meaningful validation.
- Improved magnetic field mapping from geosynchronous orbits to LEO and the ground will further enable better forecasting of cutoff and rigidity models which make use of GOES and POES data as inputs. Similarly, improved magnetic field mapping between the hemispheres will increase the reliability of using northern or southern hemispheric stations to determine the radiation environment in the other hemisphere.

Access of primary particles to Earth's atmosphere is controlled by the geomagnetic field. Maps of geomagnetic cutoff rigidities can be used to define the latitude to which particles can penetrate. Equatorial regions where closed magnetic field limits the access of particles, have higher cutoff rigidities and offer the most protection from incoming radiation. Geomagnetic polar regions, with open magnetic fields, have lower cutoff rigidities and allow particles to easily access the atmosphere offering little protection from incoming radiation.

Different approaches have been developed to model global geomagnetic cutoffs, from simulations which trace particle trajectories (Kress et al., 2004; Kress et al., 2010; Mertens et al., 2010) to precalculated cutoff rigidity tables based on an empirical magnetic field model that is characterized by the geomagnetic index (Smart et al., 2000; Smart and Shea, 2005). Uncertainties in the modeled geomagnetic field, particularly during periods of geomagnetic storming when the field is highly disturbed, can shift the open/closed geomagnetic field boundary poleward/equatorward by several degrees. This motion of the boundary in turn shifts the associated gradient in latitudinal radiation dose rates by two degrees (Kress et al., 2010; Mertens et al., 2010). That level of uncertainty is significant since, e.g., flight routes between the continental US and Europe are parallel and close in distance to the open/closed geomagnetic field boundary. An uncertainty of two degrees in the open/closed field boundary maps to an uncertainty in whether the transcontinental flight is exposed to the solar energetic protons or not. The difference in the predicted dose rates ranges from factors of two or more for moderate to strong solar radiation storms to orders of magnitude or more for extreme solar storm events (Mertens et al., 2010).

Recent work suggests that using real time ion fluxes measured by satellites in LEO orbit to define geomagnetic cutoffs is more accurate than using statistical techniques or precalculated cutoff tables (O'Brien et al., 2018; Green et al., 2021). Increasing measurement density in local time with a low-latency REACH-like observing system is even more promising (Guild et al., 2020). This data driven approach is of course limited by the availability and quality of data and the empirically derived mapping functions required to fill in regions not sampled. It has not yet been rigorously compared with particle tracing techniques. The ideal solution will likely be to combine particle tracing techniques with measured data, but such an assimilative approach needs further research and refinement. A data assimilative cutoff model will likely also demand higher quality real time measurement than is currently available. At present, near real time data is available from 6 POES/MetOp satellites with proton fluxes measured in four broad energy bands and telemetered to the ground every 90 min.

1 https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-heliophysics-2024-2033.

4 Airborne observations for model validation and improvement

Recommendations:

- Systematic radiation measurements should be made aboard a variety of airborne platforms including commercial, business and military aircraft, high altitude research aircraft, and high-altitude balloons and Unmanned Aerial Vehicles (UAVs).
- Measurements of linear energy transfer (LET) spectra that can distinguish the contribution to absorbed dose and biologically weight dosimetric quantities made by high LET radiation including neutrons, protons and heavy ions, from that made by low LET radiation such as X-rays, gamma-rays, electrons and positrons are required. Operational total ionizing dose detectors are needed to complement the LET measurements for providing real-time global context for the atmospheric radiation environment.
- Measurement campaigns which characterize the steady state atmospheric ionizing radiation environment (SSAIRE) during SEPs should be funded to validate and improve models.

There is a scarcity of measurements of the ionizing radiation environment at aviation altitudes, in spite of the fact that there are ~10,000 aircraft in the air around the world at any time. With some exceptions (Goldhagen et al., 2002; Benton, 2004; Gersey et al., 2012; Mertens et al., 2016; Tobiska et al., 2018) there have been few systematic radiation measurement campaigns carried out by the United States. The Automated Radiation Measurements for Aerospace Safety (ARMAS) has conducted more than 1,000 flights over a solar cycle providing science quality data records from the surface to 550 km. However, these measurements are intermittent. For altitudes between that of civil/commercial aviation and LEO, there are even fewer measurements. Measurements, particularly of LET spectra that can distinguish the contribution to absorbed dose and biologically weight dosimetric quantities made by neutrons, protons and heavy ions, from that made by low LET radiation such as X-rays, gamma-rays, electrons and positrons are needed in order to validate aviation radiation models. Augmenting these studies with total ionizing dose measurements it is possible to gain a better understanding of the spatial (altitude, geomagnetic) and temporal (diurnal, seasonal, solar epoch) dynamics of the SSAIRE and how it is affected by space weather (Meier et al., 2020) from all sources, including galactic cosmic rays, solar energetic particles, and trapped particles.

Radiation measurements in the SSAIRE are particularly lacking immediately before, during, and after SEP events. While space-based instruments aid the space weather and aviation communities in forecasting and nowcasting SEPs above the atmosphere, there is currently a statistically insignificant number of measurements made during SEPs in the atmosphere itself. Furthermore, significant questions remain unanswered concerning the appropriate response of pilots and air traffic planners/controllers in light of the possible onset of an SEP. Rerouting aircraft or reducing aircraft altitude may reduce the radiation exposure of an aircraft and its occupants but comes at a high cost in terms of time and fuel. Radiation measurements obtained at, and above aircraft altitudes are needed to better understand the impact SEPs are likely to have on aircrew, passengers and avionics as functions of the magnitude, spatial extent and magnetic influence of the SEP event. It is only with such knowledge that appropriate and effective action can be taken.

5 Solar energetic particle forecasts

Recommendations:

- New data from multiple platforms (particle instruments in low Earth orbit, and *in situ* in the atmosphere) for validation studies are required to improve the effectiveness of solar energetic particle access, energy spectra, and pitch angle data in aviation radiation models.
- Research should be supported which targets better scientific understanding of the processes which characterize SEP energy spectra and pitch angle distributions.
- Empirical, machine learning and physics-based SEP modeling approaches should be advanced to achieve accurate and robust forecasts of SEP time profiles and spectral properties to progress aviation radiation models from nowcasts to forecasts.

Due to a lack of accurate, real-time forecasts of solar energetic particle intensities and spectra (see Bain et al. (2021) for a review of current SEP forecast products and skill), aviation radiation modeling is generally capable of producing nowcasts only. To achieve model forecasts with actionable lead times [e.g., 2 days, Abt Associates (2019)] for the aviation industry, research is required to better understand, model, and forecast SEP events. At present, SEP models running in real-time with the goal of forecasting are typically based on correlations between solar phenomena (e.g., X-ray flare intensity and fluence, coronal mass ejections, type II and IV radio bursts, active region parameterizations) and SEP occurrence, see Whitman et al. (2022b) and references within. Empirical models such as UMASEP and RELeASE can achieve probability of detection scores between 60%–90% with false alarm ratios of 12%–30%, with lead times of tens of minutes to a couple of hours (Malandraki and Crosby, 2018; Núñez, 2022). Such models could support deterministic proton forecasts such as the NOAA SWPC Warning products, but further work is required to assess their ability to produce time profile forecasts of SEP characteristics capable of driving, e.g., aviation radiation models. To understand and forecast SEP energy spectra and pitch angle distributions advances in physics-based SEP modeling are required. SEP modeling is a complex topic which requires scientific understanding of active region production of eruptive events, the propagation of coronal mass ejections and their associated shocks, and particle acceleration and transport in the heliosphere. All the challenges associated with SEP forecasting are not covered fully here, except to highlight the need for such capabilities. See the white papers by Whitman et al. (2022b) titled Advancing Solar Energetic Particle Forecasting Burkepile et al. (2022) titled Helio 2050: Observations for Improving SEP Forecasts and Warnings for more perspectives on this topic[2].

6 Discussion

To advance our scientific understanding of the radiation environment in the Earth's atmosphere and provide accurate nowcasts and forecasts for users in the aviation industry:

- The operation of the ground-based neutron monitor network should continue to be supported, and studies carried out which assess the benefits of expanding the network to provide better coverage.
- Studies which improve our understanding of the geomagnetic field should be supported, in particular, studies which explore the potential of data assimilation methodologies.
- Airborne radiation measurement campaigns must be funded to assess and improve aviation radiation models as well as providing data feeds for data assimilative models. It is especially important to make measurements during SEP events and to understand the nature of additional higher latitude radiation enhancements that are measured in sub auroral regions.
- Studies which advance our understanding of, and ability to forecast, SEP intensity profiles and spectral properties should be carried out.

2 https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-heliophysics-2024-2033.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

HB led the organization of this article. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

JG was employed by Space Hazards Applications, LLC. TG was employed by the Aerospace Corporation. WT was employed by Space Environment Technologies.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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