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Classification and Communication of Aviation Related Space Weather Radiation Events

*Meier MM** and Matthiä D*

German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology Department, Linder Höhe, Germany

Abstract

Space Weather impacts on the radiation field at aviation altitudes have been a matter of concern and discussion for many years. This situation has led to a growing demand for corresponding high-quality information in the aviation industry. As a consequence, the Space Weather D-scale was introduced to provide aviation users and the interested public with relevant information about the development of the radiation field at flight altitudes during solar particle events (SPEs). The corresponding D-index for warnings of elevated radiation levels in the atmosphere can be assessed both by measurements and model calculations. The classification of the different grades of this space weather scale for the radiation field at aviation altitudes and operational aspects of the D-index are discussed in this paper. For example, it is demonstrated that the use of the D-index can avoid false alarms and facilitate proportionate mitigation measures. Furthermore, guidelines for action levels using the D-scale are derived from current FAA recommendations.

Keywords: Space weather information for aviation; Solar particle events; Radiation exposure of aircrew; False alarms; D-Index

Introduction

The assessment of space weather events in general and warning situations associated with action levels in particular depends on the variation of suitable observable or measurable physical quantities as well as on their impacts and consequences. The general challenge of the quantification for all practical purposes consists in finding a relevant space weather index that connects an observable physical quantity with the degree of the impact in question. Furthermore, it should also facilitate the understanding of the relative severity of the corresponding impacts and of the consequences of a particular space weather event which is important for the effective communication to the non-expert. For this purpose, the National Oceanic and Atmospheric Administration (NOAA) already introduced their Space Weather Scales, i.e. the R-Index for radio blackouts, the G-Index for geomagnetic storms, and the S-Index for solar radiation storms in 1999 [1,2]. However, an index that has proved to give good assessment for a particular field of application might fail in another, even if the applications appear to be similar at first sight. This could be particularly learned from the assessment of the impacts of the well-known Halloween storms on aviation in 2003, when several airlines reacted to the information of an ongoing severe solar radiation storm, S 4 on NOAA Space Weather S-scale, on 29th October 2003. As a consequence of this radiation alert, some flights on routes from the U.S. to Asia and Europe were altered, e.g. flown at lower altitudes, during this solar radiation storm, since the corresponding airlines had established their radiation storm action level at the S 3 threshold [3,4]. Although there might have been some positive response to these well-meant precautionary measures in the media during these events, a detailed retrospective analysis showed that they were more or less ineffective, at least in terms of mitigating radiation exposure on the corresponding flights. Nevertheless, these measures resulted in higher cost, fuel consumption and atmospheric pollution.

The outcome of the analysis of the impact of the Halloween storm events on the radiation field at aviation altitudes seems to be surprising at first sight, since the NOAA Space Weather S-scale for solar radiation storms is based on the flux of cosmic particles. The restriction, however, is that the S-index is based on the integral particle flux level with energies above 10MeV, which are detected onboard the corresponding GOES spacecraft in a geosynchronous orbit outside the Earth's atmosphere. Thus, it provides useful information for the prompt assessment of radiation impacts on the near Earth space environment, e.g. on the operation of satellites and manned spaceflight, and facilitates rapid action in order to mitigate consequences. At aviation altitudes, however, the

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***Correspondence:**
Meier MM, Radiation Biology, German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology Department, Linder Höhe, 51147 Köln, Germany.
Tel: *+49 2203 601 2789*
E-mail: *Matthias.Meier@dlr.de*

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Table 1: Values of the Space Weather D-index from D 0 up to D 5 and their classification.

Index D	Classification	Dose rate interval [µSv/h]	Additional radiation exposure is comparable with
D 0	Quiet	$\dot{E}_{sol} < 5$	Variation of the natural background at cruising altitudes
D 1	Nominal	$5 \le \dot{E}_{sol} < 10$	Natural background at high latitudes up to FL400
D 2	Minor	$10 \le \dot{E}_{sol} < 20$	Natural background at high latitudes between about FL400 and FL600
D 3	Moderate	$20 \le \dot{E}_{sol} < 40$	Average dose rate inside the International Space Station (ISS)
D 4	Strong	$40 \le \dot{E}_{sol} < 80$	Average dose rate during an extra-vehicular activity (EVA) on the ISS
D 5	Severe	$80 \le \dot{E}_{sol} < 160$	Dose of a North Atlantic return flight per hour

situation is quite different from the near Earth space environment due to the shielding influence of the Earth's magnetosphere and atmosphere. Solar particles that are energetic enough to penetrate the magnetosphere reach the atmosphere and interact with their constituents.

While the flux of the primary particles decreases with increasing atmospheric shielding, a secondary radiation field is generated. It could be shown using model calculations that the threshold for impinging cosmic protons to overcome the atmospheric shielding and to contribute to the radiation field at commercial aviation altitudes is about 600MeV [5]. However, most of the particles impinging on Earth during the Halloween storms, i.e. far more than 99%, had energies below this threshold and did not contribute to the radiation field. As a result, the radiation intensity in the atmosphere was temporarily only slightly increased during the Halloween storms, e.g. direct measurements at aviation altitudes showed an increase in dose rates of only about 30% [6].

Furthermore, the neutron monitor of the University of Oulu in Finland, an instrument to observe effects of cosmic radiation on the atmosphere, proved a variation in count rates of about 5% at sea level during the course of the associated ground level enhancement GLE 65. This demonstrated the shielding capability of the magnetosphere and the atmosphere which reduced an increase in the flux of the impinging cosmic particles > 10MeV of about 5 orders of magnitude observed onboard the GOES satellite to only moderate increases in dose rates at aviation altitudes and an increase of only about 5% measured using a neutron monitor in Oulu. The subsequent shielding from a part of the galactic cosmic radiation component by the so-called forbush effect even brought about a decrease in the radiation intensity in the atmosphere which lasted for several days. A detailed discussion of this event and its impact on the radiation field at aviation altitudes can be found e.g. in Meier & Matthiä [8].

Since the Halloween Storms, airlines and aircraft operators have been interested in timely and accurate information about actually significant increases in the radiation intensity in the atmosphere. This information can help reduce the radiation exposure of aircrew and passengers to a level which is as low as is reasonably achievable, e.g. by temporarily reducing flight altitudes [7].

The Space Weather D-Index

The misconception of the radiation exposure situation at aviation altitudes during the Halloween storms, which was based on the S-index, raised the awareness of the demand for a relevant space weather index in the aviation industry. This led to the development of the concept of the space weather D-Scale with an index for warnings of elevated radiation levels that is directly based on the additional solar contribution to the radiation exposure in the atmosphere and derived from the corresponding effective dose rate $\dot{E}_{sol}$, which can be assessed both by measurements of the ambient dose equivalent rate and model calculations. The space weather D-index permits to cover a wide range of solar contributions to the radiation exposure at aviation altitudes with comparatively small natural numbers using a multiple of 2 of the corresponding dose rates [8]. Although the total dose rate at flight altitudes is an interesting quantity as well, the reduction to the solar contribution offers a more favorable base for a specific space weather index in terms of dynamics. This important characteristic is easy to understand: when the solar contribution is smaller or comparable to the omnipresent galactic background, the D-index is not dominated by this background and can provide information about an ongoing space weather event more specifically. During intense space weather events, however, the radiation exposure at flight altitudes is strongly dominated by the solar contribution which renders the galactic background temporarily negligible. The total dose of an affected flight can be calculated as the sum of the dose due to the regular galactic cosmic radiation background, which is already assessed in many countries using correspondingly qualified programs, and the additional solar contribution $\dot{E}_{sol}$.

The practical meaning of the different grades of the D-scale can be described similar to the grades of the NOAA space weather scales. The D-indices from D 0 up to D 5, their classification, corresponding ranges of dose rates, and comparison with other natural radiation sources are listed in Table 1. An index D 0 represents a quiet space weather situation in terms of radiation exposure at flight altitudes within the variation of the natural galactic cosmic ray background. An event at D 1 level indicates a slight increase in radiation exposure in the atmosphere. Although the corresponding solar contribution is only of the order of the natural background, it reflects a nominal space weather radiation event. The next grade D 2 describes minor events when solar contributions begin to dominate the radiation field. A moderate space weather radiation event is characterized by a D-index of 3. Although even an exposure of 10 hours at D 3 level would hardly contribute to exceeding the monthly limit for pregnant women recommended by the Federal Aviation Administration (for details see FAA Advisory Circular No: 120-61B, https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_120-61B.pdf), it might be considered as an action level for moderate mitigation measures, in particular for comparatively long-lasting space weather radiation events and long haul flights. The following grades represent strong (D 4) and severe (D 5) radiation events. Since the recommended monthly limit for pregnant women could be already exceeded after three hours when exposed at D 5 level, mitigation measures should be considered to avoid this scenario, in particular for long haul flights at high latitudes.

A comparatively quiet space weather situation is characterized by a D 0-, D 1- or D 2-level. The D 3-level, i.e. an additional dose rate of more than 20μSv/h, indicates elevated radiation intensity that is used by the FAA to trigger a corresponding radiation alert using its Solar Radiation Alert System (ESRAS) if it is exceeded at any altitude between 30,000 and 70,000 ft. for each of three consecutive 5-min periods [9]. Thus, the concept of the D-index can also be used within the framework of already existing warning systems.

An important feature of the D-index is its application for the assessment of the exposure situation at a particular position in the atmosphere. Thus, it can be used to gain and communicate a differentiated picture about the radiation field in different geographic regions and at different altitudes similar to the communication of fundamental quantities in the field of terrestrial weather, e.g. temperature, air pressure, etc. The analysis of increased radiation exposure in a particular region can also be generalized for civil aviation and a local warning index D_L can be derived from the maximum dose rate in that region at a flight level of 41,000ft. (FL410), which characterizes the upper airspace as worst case scenario. Individual flights would usually be exposed at lower radiation levels depending on the actual cruising altitude of a particular flight. Furthermore, a global D-index D_G might be used as the maximum local D_L-index, anywhere in the world, as worst case scenario for general information about an ongoing space weather event. However, such a global index is not specific anymore and would not help towards proportionate mitigation measures in other regions.

Operational Aspects of the D-Index

The concept of the space weather D-index supports not only the provision of appropriate information about space weather radiation events for aircrew and the public but also operational aspects for airlines, air traffic controllers (ATC), etc. The D-index has already been used to provide several European airlines with space weather information since 2014. In future applications, this information will be used to avoid false warnings, detect real warning situations and facilitate proportionate mitigation measures.

Avoidance of false warnings

The use of the S-scale to generate warnings of increased radiation intensity at aviation altitudes has caused an unacceptably high number of false alarms, based on S 3 level or higher, for many years. Reactions to false alarms result usually in additional costs without any benefit and should be avoided. During the solar maximum of cycle 24 in 2012, for instance, false positive alarm situations in terms of the radiation field at aviation altitudes were inferred from S 3 alerts issued on 23rd January 2012 and 7th March 2012 (no GLEs). The situation on 23rd January 2012 is another good example that an S 3 alert can be compatible with a quiet radiation situation at cruising altitudes as demonstrated in Figure 1, which shows the 5-minute averaged integral proton flux ≥ 10MeV (protons · cm^{-2} · s^{-1} · sr^{1}) as measured by the SWPC primary GOES satellite in comparison with the increase in the count rate of the Oulu Neutron Monitor between 22th and 25th January 2012.

Mitigation measures

The acceptance of an action level triggered by an S 3 alert has not only produced a lot of false positive alarms but also false negative alarms, i.e. mitigation measures were not taken although the radiation intensity in the atmosphere was strongly increased. This additional unwanted shortcoming of the use of the NOAA S-scale

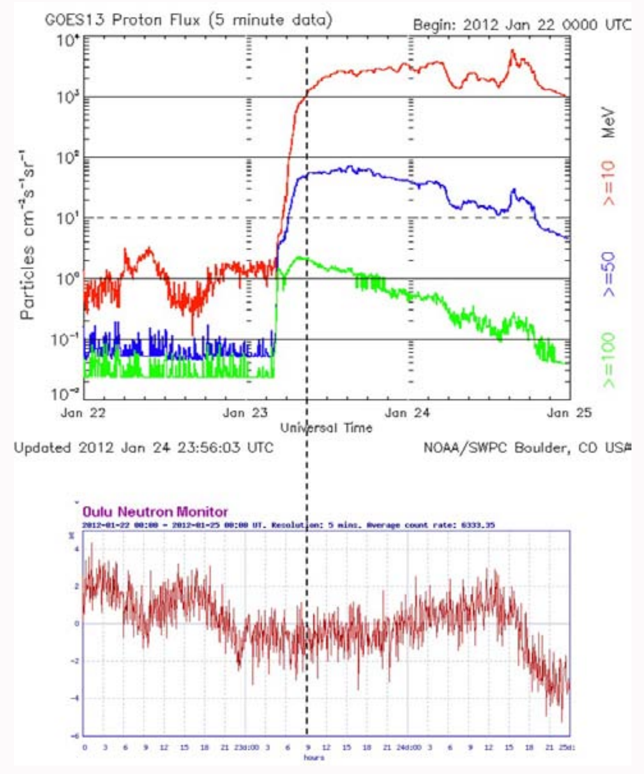

Figure 1: GOES 5-minute averaged integral proton flux (protons · cm^{-2} · s^{-1} · sr^{-1}) as measured by the SWPC primary GOES satellite for energy thresholds of ≥ 10 (red line), ≥ 50 (blue line), and ≥ 100MeV (green line) in comparison with the relative variation of the count rate of the Oulu Neutron Monitor between 22th and 25th January 2012.

for an assessment of the radiation field at aviation altitudes and the advantage of the application of the D-index can be demonstrated with the example of GLE 70, which took place on 13th December 2006. The comparison of measurements of the cosmic ray intensity by the ground based neutron monitor network and GOES reveals how an analysis in terms of radiation exposure at aviation altitudes based on GOES data alone, i.e. the S-scale, can be misleading. The solar radiation storm associated with GLE 70 triggered only an S 2 alert (Figure 2), i.e. below the chosen action level, although it brought about a significant increase in dose rates at cruising altitudes up to D 5 level at maximum exposure which was reached at 03:10 UTC, about 15 minutes after the onset of the event. The initial hot spots had leveled out according to the geomagnetic latitude at 03:35 UTC, about 40 minutes after the onset of the event, and the derived global D_G-index declined from D 5 to D 3 (Figure 3).

Mitigation measures should be proportionate depending on the D-index at the corresponding altitude in a particular region. A reduction to moderate D levels might be taken into consideration if possible, i.e. other critical factors such as weather taken into account. The effectiveness of mitigation measures and their economic impacts in terms of delay and fuel consumption for a transatlantic flight during GLE 70 were investigated by Matthiä et al. (2015) [7]. If the increase in radiation intensity, expressed by the D-index, were communicated to the cockpit through the Aircraft Communications Addressing and Reporting System (ACARS) in time, appropriate measures could be taken. The investigated reaction to the increased Space Weather D-index was lowering the flight altitude after the increase of the dose rates, adapting the flight speed and returning to

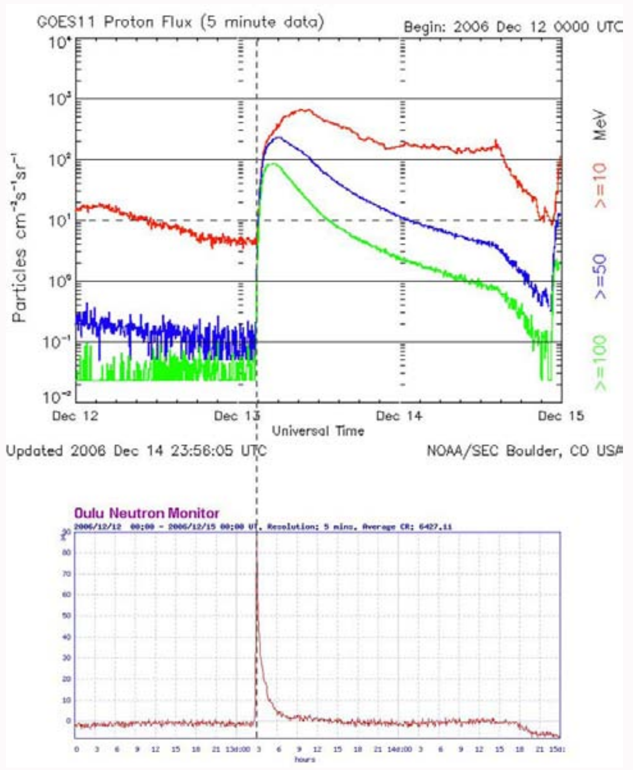

Figure 2: GOES 5-minute averaged integral proton flux (protons · cm^{-2} · s^{-1} · sr^{-1}) as measured by the SWPC primary GOES satellite for energy thresholds of ≥ 10 (red line), ≥ 50 (blue line), and ≥ 100MeV (green line) in comparison with the relative variation of the count rate of the Oulu Neutron Monitor between 12th and 15th December 2006.

nominal flight altitudes after the additional dose rates had dropped below a threshold. It was demonstrated that in the case of a prompt response to the radiation event caused by this GLE, the total effective dose on the flight could have been reduced by up to 42% by lowering the flight altitude and using the contingency fuel of the aircraft, i.e. a 5% additional fuel consumption. For the investigated flight scenario, the D-index would have remained at D 1 rather than at D 3 in case of no response.

Regional warning centers

The radiation field at flight altitudes is very complex in terms of its composition of different sorts of particles and their energy distribution, which depend on the incoming direction of the primary particles, local geomagnetic shielding and altitude. The corresponding dose rate characterizes this radiation field for operational purposes and shows a comparatively strong variation as well (Figure 3). In contrast to a global space weather index, the D-index permits more specific assessment of these effects on particular geographic regions. Furthermore, the application of the D-index is independent of the radiation model used for its assessment. In this respect, it also supports the concept of Regional Warning Centers (RWCs) or regional elements of a global system, which has been successfully used in the field of terrestrial weather for many years, i.e. the responsible authorities for different countries or regions can choose a model in due consideration of their particular needs. In this context, it is worth mentioning that the regional assessment of the D-index can be verified with qualified measuring instruments, similar to other weather parameters, e.g. temperature [10,11]. Thus, RWCs are provided with the capability of establishing corresponding procedures for quality assurance of the assessment of the D-index by measurements in regional airspace, which might also foster the competition among models and contribute to improving their quality.

Although a global forecast of the occurrence and development of SPEs which cause an increase in radiation intensity at aviation altitudes is still not - and perhaps will never be - possible, the geographic anisotropy of the increase in dose rates during the onset of e.g. GLE 70 is an interesting feature that deserves closer attention in the future. A nowcast of a radiation event by an RWC in an initially affected region, represented by a corresponding D-index, might offer a possibility for issuing regional warnings by other RWCs for areas which are not yet affected during the initial phase.

Conclusion

The intensity of the radiation field due to cosmic radiation at aviation altitudes during quiet space weather conditions is, in terms of dose rate, more than one order of magnitude higher than the average radiation environment from all natural sources on ground in most countries. As a consequence, aircrew and frequent flyers are exposed to higher levels of ionizing radiation than the average population. Space weather radiation events might bring about an additional, albeit short-term increase in radiation exposure of several orders of magnitude. Although the actual total exposure at cruising altitudes during such an event would be quite moderate in comparison to the ordinary annual radiation exposure from other natural and artificial sources in most cases, the situation might leave many people insecure about the way their health might have been affected. This unsettledness is only natural since human beings do not have a sense to perceive ionizing radiation. Thus, the psychological effects of being exposed to additional contributions of radiation during a space weather event must not be underestimated, in particular when potentially exaggerated by the media. Therefore, it is necessary to provide appropriate information about the actual variation of the radiation field during an event to stakeholders and the public, which can easily be communicated using a corresponding index.

The usability of a space weather index for the assessment of the radiation field at aviation altitudes during space weather events requires a close connection between an observable physical quantity and the degree of the impact. This requirement led to the development of the D-index, a bespoke space weather index for this scenario that is directly based on the dose rate, which is the fundamental physical quantity used for the characterization of radiation fields in radiation protection. Thus, the D-index is an application-related tool to provide the capability of giving timely and useful space weather information to the users and the public in order to avoid false alarms and facilitate mitigating measures. In contrast to a global space weather index, the D-index permits more specific assessment of the effects on particular geographic regions. Furthermore, the application of the D-index is independent of the radiation model used for its assessment. In this respect, it also supports the concept of RWCs which has been successfully used in the field of terrestrial weather for many years, i.e. the responsible authorities for different countries or regions can choose a model in due consideration of their particular needs.

The feasibility of mitigating measures during a space weather event was discussed and demonstrated in a first study using the example of GLE 70 by Matthiä et al. [7]. It could be shown that timely space weather information based on the D-index might have been used to reduce the radiation exposure of crew and passengers

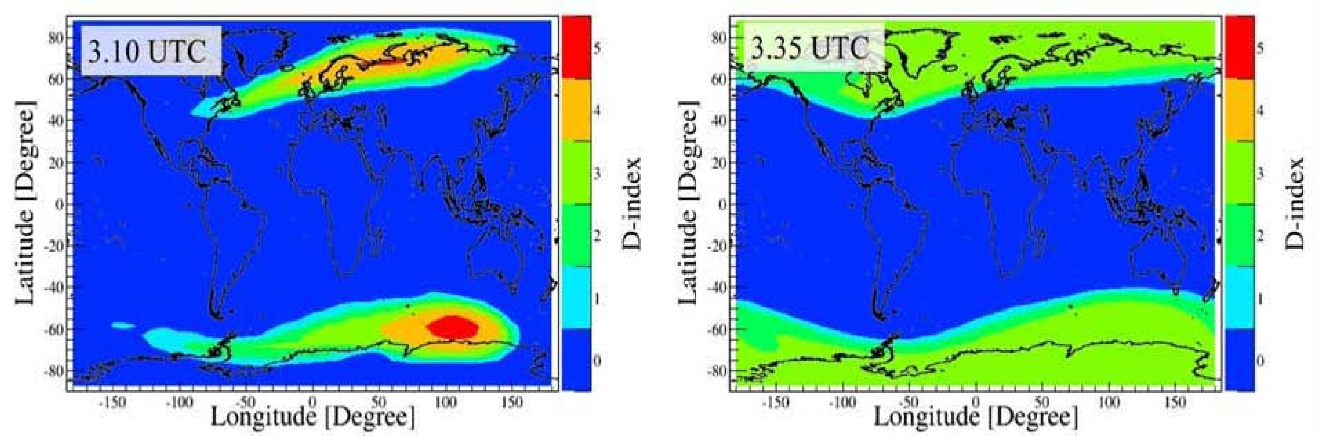

Figure 3: World map showing areas of increased dose rates due to solar protons represented by the corresponding D- indices at an altitude of 41,000ft.

during this event from D 3 to D 1 for the investigated scenario. The geographic anisotropy of the increase in dose rates during the onset of a space weather radiation event, e.g. an initial hot spot in a particular location of the globe represented by the D-index, might offer a possibility for issuing regional warnings for areas which are not yet affected during the initial phase. This could provide a lead time for mitigating measures, e.g. delay of flights, in the order of about half an hour.

The capabilities and the use of the D-Index for characterizing space weather radiation events for aviation have been intensively discussed since 2014, e.g. at the Space Weather Workshop, the European Space Weather Week, etc. It was recommended as effect metric by the Radiation and Plasma Effects Working Group at the first Community Coordinated Modeling Center's (CCMC) International CCMC-LWS Working Meeting held in 2017.

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