Effective radiation dose for selected intercontinental flights during the GLEs on 20 January 2005 and 13 December 2006

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Abstract— **The radiation exposure of aircrew and frequent flyers due to cosmic rays has become an issue of increasing interest in the last several years. The effect of galactic cosmic rays has been rather well investigated by measurements as well as by computations. However the contribution of solar cosmic rays is still a matter of debate. The dose rates during solar cosmic ray events can vary over magnitudes in intensity.**

Close to the end of solar cycle 23, two large solar cosmic ray events were recorded by the worldwide network of neutron monitors. Both events occurred during a Forbush decrease and were extremely anisotropic during the initial and main phase. During the event on 20 January 2005 the interplanetary magnetic field near Earth had a large component perpendicular to the Earth's equatorial plane. In contrast, the interplanetary magnetic field lines were almost parallel to the equatorial plane during the event in December 2006, and the solar cosmic ray flux therefore had no pronounced north-south asymmetry.

From the recordings of the worldwide network of neutron monitors the characteristics of the solar particle flux near Earth during the two events were determined. This information on the solar cosmic ray flux near Earth was subsequently used as the basis for the computation of the additional secondary cosmic ray flux in the Earth's atmosphere with the Geant4 package PLANETOCOSMICS. The effective dose rates for specific flight paths were finally determined by interpolation from a global grid in latitude and longitude by using published flux to dose conversion factors. The paper shows the resulting preliminary effective doses on selected intercontinental flight routes during the two solar cosmic ray events. The obtained results are compared with dose values that were determined with other models.

I. Introduction

At sea level the contribution due to galactic cosmic rays (GCR) to the average natural radiation exposure is about 15%, i.e. ~0.03 μSv/h [3] [1]. In the atmosphere at flight altitudes cosmic rays are the only source of particle radiation effects. At an altitude of 8 km asl (26'000 feet, 360 g/cm^2) the effective dose rate is typically up to ~3 μSv/h at latitudes higher than ~60° and ~1–1.5 μSv/h near the equator. Compared to 8 km asl the effective dose rates are larger by a factor of about two at 12 km asl (39'000 feet, 200 g/cm^2). The 11-year solar modulation causes a variation of ~75% in the dose rates at latitudes higher than ~60°, whereas the variation is only marginal at the equator. The typical total effective dose due to GCR for a transatlantic flight, i.e. between Europe and North America, is therefore of the order of about 50μSv. Aircrew and frequent flyers may accumulate annual effective doses of a few mSv. This value is above the international dose limit for artificial exposure of 1 mSv per year for the normal population, but well below the average annual dose limit for radiological workers of 20 mSv/a as specified by the European Council Directive [2]. However, the effective dose to the unborn child, i.e. to pregnant women, is limited to less than 1 mSv during the rest of the childbearing period after the pregnancy has been discovered. To control the dose limits, the doses to aircraft crew are computed for each flight. There are a number of radiation transport codes and programs in current use to calculate dose rates and route doses caused by GCR, e.g. CARI-6 [3], EPCARD [4].

Transient, increased radiation dose rates can occur during solar cosmic ray (SCR) events that are observed on Earth, so-called ground level enhancements (GLE). As an example, an increased dose rate for a period of more than one hour was observed during the GLE on 15 April 2001 (GLE60). During this GLE, Spurný and Dachev [5] reported a maximum dose rate of about double that for GCR from the measurements on board a flight from Prague to New York. The measurements for this flight result in a total additional contribution to the dose from the SCR of ~20 μSv. For the largest observed GLE on 23 February 1956 (GLE05) Lantos and Fuller [6] estimate in a worst case scenario a maximal possible additional contribution by SCRs of more than 3 mSv for a subsonic flight from San Francisco to Paris with the semi-empirical model SiGLE [6] and even more than 6 mSv for a Concorde flight from Paris to New York.

After the GLE on February 1956, it was not until January 2005, i.e. after about 50 years, that a GLE with almost equal magnitude was observed at Earth. The south polar NM stations showed gigantic count rate increases of some thousands of percent on 20 January 2005 (GLE69). This GLE occurred close to the end of solar cycle 23. However, the Sun showed phases of enhanced activity in January 2005 and later in December 2006. The GLE recorded on 13 December 2006 (GLE70) is clearly smaller than the one on 20 January 2005, but it is among the largest in solar cycle 23, with count rate increases up to almost 100% at the NM stations Oulu and Apatity. Fig. 1 shows the relative count rates of selected NMs during the two GLEs. Both events were characterized by a very anisotropic SCR flux during the initial phase. During the event on 20 January 2005 the interplanetary magnetic field near Earth had a large component perpendicular to the equatorial

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[3]The Sievert (Sv) is the SI unit of the effective biological dose.

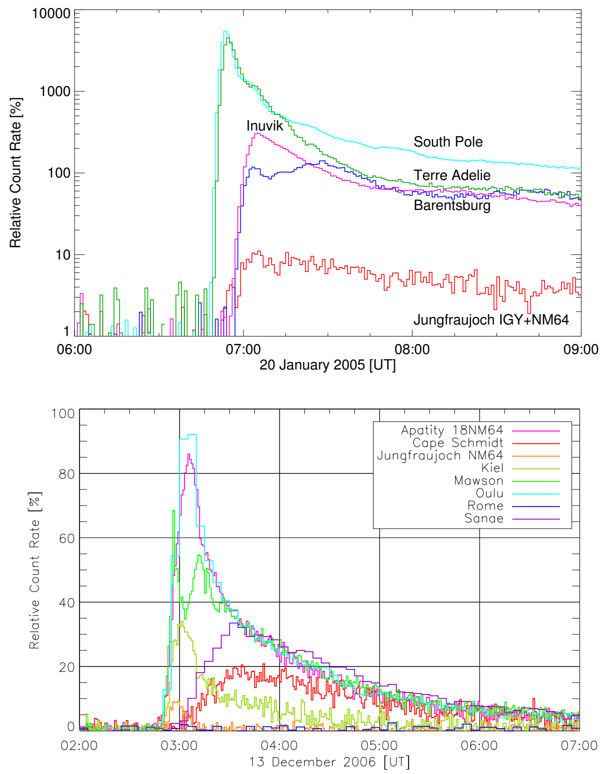

Fig. 1. Relative pressure corrected 1-minute count rates of selected NM stations for 20 January 2005, 0600-0900UT (top), and for 13 December 2006, 0200-0700UT (bottom). Note the difference in scale of the vertical axis.

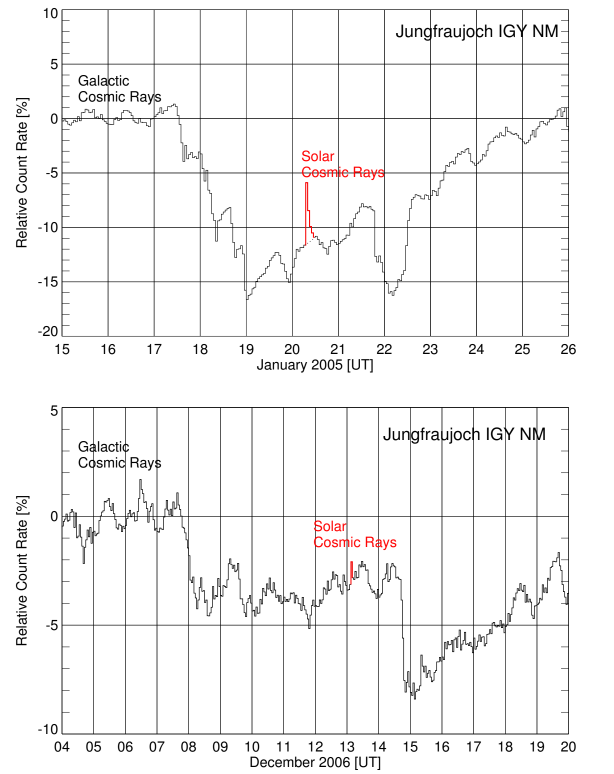

Fig. 2. Relative pressure corrected hourly count rates of IGY Jungfraujoch NM station for 15-25 January 2005 (top), and for 4-19 December 2006 (bottom).

plane. As a consequence, the solar cosmic ray flux hit the Earth primarily from the southern direction. In contrast, the interplanetary magnetic field lines were almost parallel to the equatorial plane during the event in December 2006, and the solar cosmic ray flux therefore had no pronounced north-south asymmetry. Both GLEs occurred during a Forbush decrease (Fd) as can be seen from the evolution of the count rate of the IGY neutron monitor (NM) at Jungfraujoch in January 2005 and December 2006 plotted in Fig. 2. The effective dose rate caused by galactic cosmic rays during the GLE periods, i.e. during the Fd, was diminished by $\sim$15% in January 2005 and $\sim$5% in December 2006 compared to the pre-Fd level.

From the recordings of the NMs the characteristics of the solar particle flux near Earth were determined. These characteristics were then used to compute the secondary cosmic ray flux in the Earth's atmosphere. Finally, effective dose rates along specific flight paths were calculated by interpolation of effective dose rates that were computed for a global grid in latitude and longitude for selected atmospheric depths. In section two we present the method of analysis. In section three the preliminary effective doses on selected intercontinental flight routes during the two GLEs are presented. The computed effective doses during GLE69 are compared to values published by Lantos [7]. In addition the GCR dose rates computed with our Geant4 [8] software PLANETOCOSMICS [9] are compared with the results obtained from the CARI-6 [3] and the EPCARD [4] model.

II. Analysis

The determination of the effective dose rates during GLEs is performed in several steps.

From the recordings of NMs of the worldwide network, the characteristics of the solar particle flux (spectrum, apparent source direction, pitch angle distribution) are determined for selected times during enhanced solar cosmic ray flux near Earth but outside the geomagnetosphere in the rigidity range $\sim$1–20 GV by using the method by Smart et al. [10] and Debrunner and Lockwood [11]. For the solar proton spectrum near Earth, I, a power law dependence on rigidity, R, was adopted as a function of time, t: $I(R,t) = A(t) \cdot R[GV]^{-\gamma(t)}$. In a trial and error procedure the GLE parameters are determined by minimizing the difference between the calculated and the observed NM increases for the set of selected NM data. Below 1 GV the differential solar proton flux per GV was assumed to be constant. The cutoff rigidity effects are calculated with the Geant4 code PLANETOCOSMICS for every time interval of interest. In the code, the magnetic field is specified by the IGRF model [12] for the internal field and by the Tsyganenko89 magnetic field model [13] for the magnetic field caused by external sources. The Tsyganenko89 includes the disturbances of the geomagnetic field by providing seven different states of the magnetosphere that are described by the integer Kp indices (0, 1, ..., ≥6) corresponding to different levels of geomagnetic activity.

In a next step the cosmic ray flux (solar and galactic cosmic rays) at the top of the Earth's atmosphere is computed at gridpoints with mesh size 5° x 5° in latitude and longitude by utilizing the GLE characteristics and the GCR flux immediately before the onset of the GLE, i.e. the current GCR flux level during the Forbush decrease.

Then the interactions of the SCR and the GCR with the Earth's atmosphere are computed by using the Geant4 PLANETOCOSMICS [9] code. For the 5° x 5° grid in geographic coordinates and as a function of the atmospheric depth, the flux of the different secondary particle species and the resulting ionisation of the atoms and molecules in the Earth's atmosphere are evaluated.

The effective dose rates caused by cosmic rays are calculated for selected atmospheric depths at the specified gridpoints from the secondary particle flux in the atmosphere by using the flux to dose conversion factors based on FLUKA calculations by Pelliccioni [14]. Finally the effective dose rates are summed up along selected flight routes to determine the effective doses.

III. Preliminary Results and Discussion

The computed effective dose rates at the atmospheric depth of 250 g/cm^2 (∼10.4 km asl) during the main phases of the two GLEs (20 January 2005, 0653-0655 UT and 13 December 2006, 0305-0310 UT) are plotted in Fig. 3 in the northern (left) and southern (right) hemisphere regions. During these phases a clear North-South anisotropy is present in the GLE on 20 January 2005, whereas in the GLE on 13 December 2006 the North-South anisotropy is much less distinct. The maximum value in the effective dose rate during the GLE on 20 January 2005 reached values up to ∼3.5mSv/h in a very localised region around 70°S and 130°E. During the GLE on 13 December 2006 the maximum values are ∼145 μSv/h in the northern and ∼160 μSv/h in the southern polar region.

Figure 4 shows the effective dose rates deduced from our analysis at an atmospheric depth of 230 g/cm^2 (altitude of ∼11 km asl) due to combined SCR and GCR versus time on 20 January 2005 at the geographic locations 72.5°S, 135°E, i.e. the location with the maximum dose rate, and at its antipodes at 72.5°N, 315°E. As can be seen from the plot, the dose rate in the South hemisphere was higher by more than one order of magnitude during the first ∼10 minutes of the energetic solar proton event that started at ∼0648 UT. Then the North-South anisotropy decreased, and it almost disappeared after about 0730 UT. The accumulated effective dose during the first hour of GLE69 at geographic location 72.5°S, 135°E and at atmospheric depth 230 g/cm^2 was 1.1 mSv, whereas it was 0.13 mSv at 72.5°N, 315°E (antipodes). The corresponding values for GLE70 are 0.05 mSv for the geographic location 62.5°S, 100°E and 0.02 mSv for the geographic location 62.5°N, 280°E. The effective doses during the whole GLE69 at the above given locations were ∼1.4 mSv at the location with maximum SCR flux at the beginning of the event respectively ∼0.4 mSv for the antipodes position. For GLE70 the corresponding values are ∼0.12 mSv and ∼0.08 mSv.

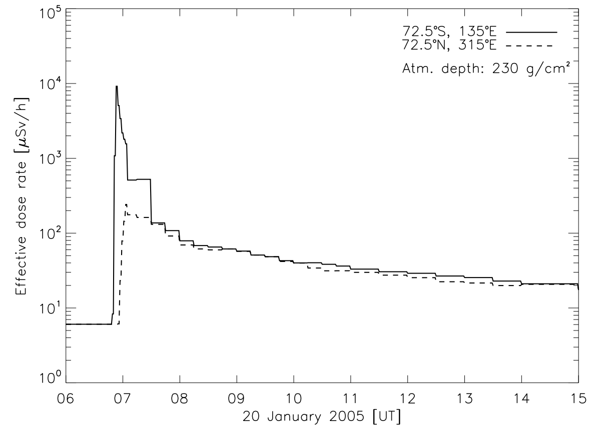

Fig. 4. Effective dose rates at an atmospheric depth of 230 g/cm^2 (altitude of ∼11 km asl) due to combined solar and galactic cosmic rays versus time on 20 January 2005 at geographic locations 72.5°S, 135°E (location with maximum dose rate, solid line) and 72.5°N, 315°E (antipodes, dashed line).

Currently there are no supersonic passenger flights, i.e. up to ∼18 km asl. However, planes are being planned that will fly higher than the cruising altitudes of present passenger planes to reduce fuel consumption. The effective dose during the first hour of GLE69 at the location with the maximum solar cosmic ray flux in the Earth's atmosphere at an altitude of 16 km asl was ∼8.7 mSv.

The effective doses computed with PLANETOCOSMICS during GLE69 and GLE70 are listed for selected flights in Table I. For comparison, the dose values for some flights during GLE69 are given from a work by Lantos [7]. In addition, information about the flight routes (duration of the flight, maximum altitude and maximum geomagnetic latitude during the flight) are listed. The departure times were chosen so that the effective doses are maximal, i.e. worst case scenario. As there is no information given about the flight profiles in the paper by Lantos [7], it is possible that the flight routes used by Lantos slightly differ from the ones used in our analysis.

The results by Lantos are significantly lower than the values determined in this work for most of the investigated flights, e.g. for the flight Paris-Tokyo the dose value by Lantos is lower by more than a factor of three! Unfortunately it seems that GLE69 was not measured on board any airplane. Therefore we have investigated a number of possible reasons in order to describe the difference in the results of the computed effective doses.

Our GLE analysis with the data of the worldwide network of NMs results in a rather soft rigidity spectrum during both GLEs. In the course of GLE69, the power law exponent, γ, is between 7 and 8, whereas Lantos [7] obtained a γ value roughly between 6 and 7 from ratios of Kerguelen and Moscow, Kerguelen and Newark, as well as Kerguelen and Kiel NM data. From the difference in the power law spectral

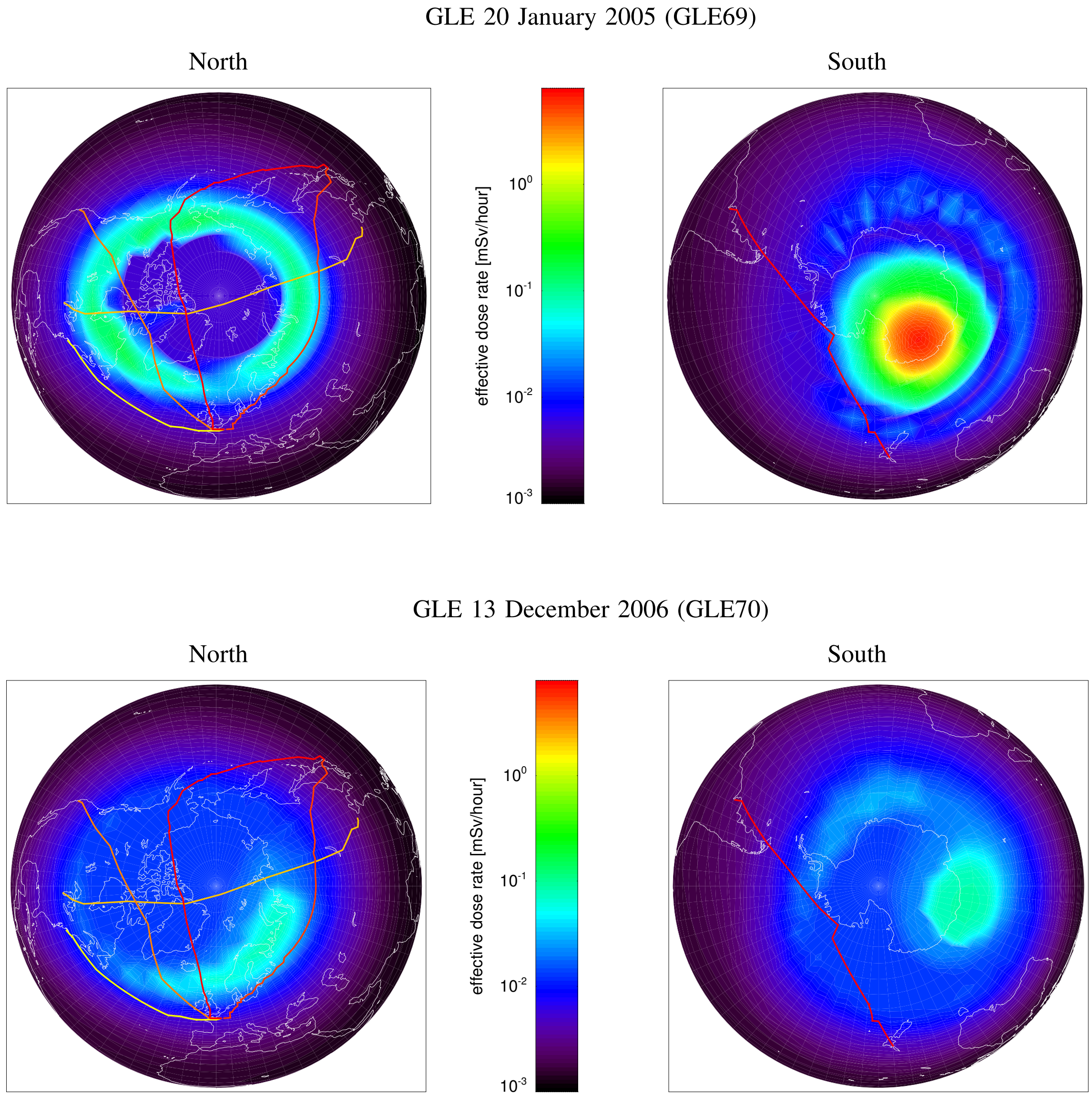

Fig. 3. Computed effective dose rates at an atmospheric depth of 250 g/cm^2 (altitude: ∼10.4 km asl) due to combined solar and galactic cosmic rays (GCR intensity corresponds to Fd level around GLE onset) during times with maximum solar cosmic ray flux for GLE69 (top) and for GLE70 (bottom) at northern (left) and southern (right) hemisphere regions. In addition, selected flight paths are plotted: Chicago–Beijing, Paris–New York, Paris–San Francisco, Paris–Tokyo, Tokyo–Paris (polar route), and Buenos Aires–Auckland.

Flight	Duration [min]	Max. alt. [km]	Max. geomag. lat. [°]	GLE69[1)] [μSv]	GLE69[2)] [μSv]	GLE70[1)] [μSv]
Buenos Aires - Auckland	980	12.2	66	550	—	190
Chicago - Beijing	791	11.3	86	282	—	114
Paris - New York	439	11.9	45	68	—	56
Paris - Washington	—	—	—	—	92.5	—
Paris - San Francisco	698	11.9	77	361	139.7	126
Paris - Tokyo	640	11.3	64	226	68.4	101
Tokyo - Paris (polar)	896	11.3	89	263	111.7	131

TABLE I

COMPUTED EFFECTIVE DOSES FOR SELECTED FLIGHTS DURING GLE69 AND GLE70 (COLUMNS 5–7). [1)]: THIS WORK, [2)]: ACCORDING TO THE WORK BY LANTOS [7]. IN ADDITION, THE DURATION OF THE FLIGHTS (COLUMN 2), THE MAXIMUM ALTITUDE (COLUMN 3), AND THE MAXIMUM GEOMAGNETIC LATITUDE (COLUMN 4) OF THE FLIGHT PROFILES USED FOR THE COMPUTATIONS MADE WITH PLANETOCOSMICS ARE LISTED.

parameter, it is expected that the effective dose for low latitude flights from our analysis should be lower than the values from the investigations made by Lantos. In fact, as can be seen from Table I, our value for the low latitude flights from Paris to New York is somewhat smaller than the value by Lantos for the comparable flight from Paris to Washington. Furthermore, the model SiGLE [6] does not take into account the anisotropy of the SCR flux. However, Lantos made a correction for the anisotropy for the flights from Paris to San Francisco and from Tokyo to Paris along the polar route due to the data of NM stations along the flight routes. Lantos [7] uses the CARI-6 model for the determination of the effective dose caused by GCR. The GCR contribution to the effective dose determined by Lantos for the selected flights during GLE69 is about 10% higher than the corresponding values computed with the PLANETOCOSMICS model. An exception is the flight route Paris to Tokyo where the GCR contribution determined with the two models is about equal.

Furher possible reasons for the difference in the computations of dose values with different models are:

1) the determination of the cutoff rigidities. PLANETOCOSMICS utilizes the updated geomagnetic field by using the models IGRF and Tsyganenko89 including the current Kp index; CARI-6 uses the IGRF model for 1995 period, and EPCARD uses IGRF for 1990 period.
2) different physics models of the interactions of cosmic ray particles with the atmosphere,
3) unequal conversion of secondary particle fluxes to dose rates, and
4) different conversion of altitude to atmospheric depth.

The check of the PLANETOCOSMICS model has been done by comparison of calculated effective doses caused by GCR with different models. The effective dose values computed with the PLANETOCOSMICS, CARI-6, and EPCARD models are listed in Table II. The effective doses are calculated for the same flight routes as in Table I and for GCR flux levels that correspond to the conditions in January 2005 and in December 2006. For January 2005 the heliocentric potential Φ=595 MV and for December 2006 Φ=375 MV are used. These values for Φ correspond to the GCR flux before the onset of the Forbush decreases. The dose values computed by CARI-6 are by trend lower than the values calculated by EPCARD (typically 10-15%) with the exception of the flight from Paris to Tokyo. The values computed with PLANETOCOSMICS differ from the values obtained with CARI-6 by -9% to 48% and with EPCARD by -11% to 20%.

Figure 5 shows the effective dose rates caused by the GCR versus geographic latitude computed with the models PLANETOCOSMICS, CARI-6, and EPCARD on 15 December 2007, 1200 UT, at geographic longitude 0° and at an atmospheric depth of 250 g/cm^2. This time period has been selected specifically because it represents a constant and high GCR flux. At high geographic latitudes the effective dose rates calculated by the PLANETOCOSMICS model are

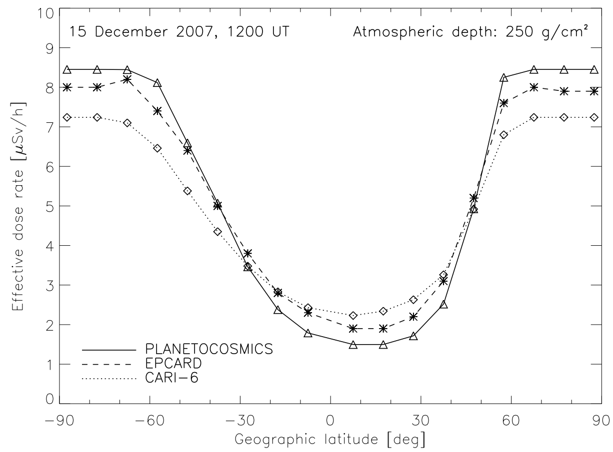

Fig. 5. Computed effective dose rates versus geographic latitude at geographic longitude 0° on 15 December 2007, 1200 UT with the models PLANETOCOSMICS, CARI-6, and EPCARD. The heliocentric potential Φ is 287 MV.

~6% higher than those determined by EPCARD and ~17% higher than those by CARI-6. However, at low latitudes the PLANETOCOSMICS model produces values that are lower than the EPCARD (22%) and CARI-6 (36%) values.

IV. Summary and Conclusions

Close to the end of solar cycle 23, the Sun showed two phases with high solar activity in January 2005 and in December 2006. During both periods two large GLEs were recorded by the worldwide network of NMs. Both solar cosmic ray events occurred during a Forbush decrease and were extremely anisotropic during the initial and main phase. The GLE69 was the second largest observed GLE after the event on 23 February 1956, and GLE70 was one of the largest in solar cycle 23.

The computations with PLANETOCOSMICS [9] during GLE69 show a relative increase in the effective dose for selected flight profiles of 90-500% compared to the dose level before the onset of the GLE. The corresponding increases during GLE70 were estimated with PLANETOCOSMICS to be 20-70%. For GLE69 Lantos [7] reported effective doses caused by GCR and SCR along selected flight routes that are significantly lower than the computations with PLANETOCOSMICS for high latitude routes. A possible reason for this discrepancy is the difference in the rigidity spectrum that was used in the two models. From the GLE analysis of the NM data we obtained a significantly softer rigidity spectrum (spectral parameter γ ~7–8) than in the work by Lantos [7] (γ ~6–7). The comparison of different models to compute the effective dose rate in the atmosphere caused by GCR showed that the values computed with the PLANETOCOSMICS model are higher than the values from the CARI-6 (~6%) and EPCARD (~17%) models at high latitudes. To understand the discrepancies between the results of the different models in detail and to enhance the quantitative quality of the models,

Flight	Duration [min]	Max. alt. [km]	Max. geomag. lat. [°]	GCR Jan 2005 CARI [μSv]	GCR Jan 2005 EPCARD [μSv]	GCR Jan 2005 this paper [μSv]	GCR Dec 2006 CARI [μSv]	GCR Dec 2006 EPCARD [μSv]	GCR Dec 2006 this paper [μSv]
Buenos Aires - Auckland	980	12.2	66	82	102	110	90	111	133
Chicago - Beijing	791	11.3	86	65	75	70	74	81	84
Paris - New York	439	11.9	45	32	47	42	37	50	49
Paris - San Francisco	698	11.9	77	60	75	71	70	82	85
Paris - Tokyo	640	11.3	64	57	56	52	64	60	61

TABLE II

COMPUTED EFFECTIVE DOSES DUE TO GCR ONLY FOR SELECTED FLIGHTS IN JANUARY 2005 (HELIOCENTRIC POTENTIAL Φ=595 MV, BEFORE FORBUSH DECREASE (FD)) AND IN DECEMBER 2006 (Φ=375 MV, BEFORE FD) BASED ON CARI-6 [3], EPCARD [4] SOFTWARE, AND AS DETERMINED IN THIS PAPER WITH GEANT4 SOFTWARE PACKAGE PLANETOCOSMICS [9]. IN ADDITION, THE DURATION OF THE FLIGHTS (COLUMN 2), THE MAXIMUM ALTITUDE (COLUMN 3), AND THE MAXIMUM GEOMAGNETIC LATITUDE (COLUMN 4) OF THE FLIGHT PROFILES ARE LISTED.

further investigations are needed. For example, the dose rates must be computed for a GLE when dose measurements on board an airplane were made, e.g. during GLE on 15 April 2001.

The analysis of GLE69 showed that the effective dose rates during solar cosmic ray events can increase several orders of magnitude at flight altitudes within only a few minutes.

We computed a dose of ∼1.4 mSv for the entire duration of GLE69 at the location of maximum solar cosmic ray flux (72.5°S, 135°E) and at an altitude of ∼11 km asl with the PLANETOCOSMICS model. This value corresponds to a typical effective dose received during ∼250 flight hours due to pure GCR. Due to the above mentioned facts it is important to determine dose rates at flight altitudes during a GLE as quickly as possible after the detection of a SCR event. Within the seventh framework program project NMDB [15] effective dose rates will be computed based on NM data in near real-time.

ACKNOWLEDGMENTS

This research was supported by the Swiss National Science Foundation, grant 200020-113704/1, by the Swiss State Secretariat for Education and Research, grant C05.0034, and by the High Altitude Research Stations Jungfraujoch and Gornergrat. We thank the investigators of the following NM stations for the data that we used for this analysis: Alma Ata, Apatity, Athens, Barentsburg, Cape Schmidt, Durham, Fort Smith, Hermanus, Inuvik, Irkutsk, Kerguelen, Kiel, Kingston, Larc, Lomnický Štít, Los Cerrillos Observatory, McMurdo, Magadan, Mawson, Moscow, Mt. Aragats, Nain, Nor-Amberd, Norilsk, Novosibirsk, Oulu, Peawanuck, Potchefstroom, Rome, Sanae, Terre Adelie, Thule, Tixie Bay, Tsumeb, Yakutsk. The information about the flight from Buenos Aires to Auckland were kindly provided by Dr. Vicente Ciancio, director of Aerospace Medicine, La Plata National University, Argentina. The other flight profiles were gratefully received from members of the EURADOS CONRAD WP6 / SG-B. We thank Vladimir Mares, German Research Center for Environmental Health, Helmholtz Zentrum, München, Germany who made the computations with the software EPCARD.

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