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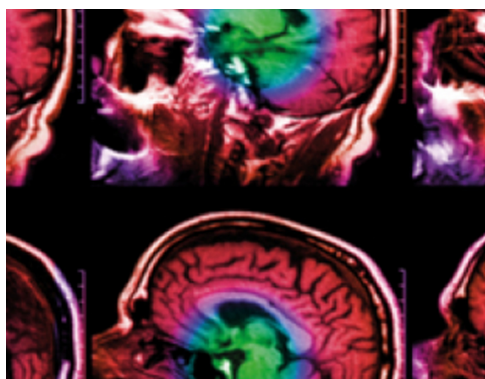
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Radiation dose to the global flying population

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Abstract

Civil airliner passengers and crew are exposed to elevated levels of radiation relative to being at sea level. Previous studies have assessed the radiation dose received in particular cases or for cohort studies. Here we present the first estimate of the total radiation dose received by the worldwide civilian flying population. We simulated flights globally from 2000 to 2013 using schedule data, applying a radiation propagation code to estimate the dose associated with each flight. Passengers flying in Europe and North America exceed the International Commission on Radiological Protection annual dose limits at an annual average of 510 or 420 flight hours per year, respectively. However, this falls to 160 or 120 h on specific routes under maximum exposure conditions.

Keywords: aviation, high altitude, aircraft

Online supplementary data available from stacks.iop.org/JRP/36/93/mmedia

(Some figures may appear in colour only in the online journal)

1. Introduction

Civil airliner passengers and crewmembers are exposed to elevated levels of galactic radiation due to the altitude aircraft operate at. The International Commission on radiological protection (ICRP) classifies the exposure aircraft crew experience as an occupational hazard (ICRP 1991). In response, the US federal aviation administration (FAA) developed educational programs to make flight crews aware of the cruise altitude radiation risk, while the European Union implemented radiation training and dose assessment as a legal requirement

(Barish 2004). Frequent flyers, however, are not addressed, and no global-scale assessment of their exposure has been conducted.

The concern for elevated radiation levels led to the deployment of tissue equivalent counters (TEPC) and the MDU-Liulin Si spectrometer on some routes operated by Iberia and Virgin Atlantic Airways (Jones *et al* 2005, Vergara and Román 2009). Aw (2003) highlighted that transpolar and ultra-long-haul flights experience elevated doses due to the combination of low geomagnetic shielding and long flight times. During solar particle events (SPE) aircraft will experience an increase dose rates of ten to twenty times their normal value (Barish 2009). Copeland *et al* (2008) estimated dose rates at 30 000, 40 000 and 50 000 feet to be 0.15, 0.52, and 1.3 mSv h⁻¹; however the hour long integrated dose of an aircraft flying at these altitudes was reported as 0.05, 0.16, 0.42 mSv respectively.

The in-flight dose has been associated with increases in crewmember cancer incidence (Barish 2009) and mortality (Hammer *et al* 2012) with doses of radiation estimated to yield a ~5.5% increase in cancer risk per Sv absorbed (ICRP 2007). One study found that airline pilots receive a greater annual dose than industrial, medical or nuclear workers (Barish and Dilchert 2010). However, epidemiological studies have not shown conclusive evidence of an increase in cancer incidence for radiation doses below 100 mSv, and it remains possible that very low doses are beneficial. With the lack of epidemiological evidence, caution should be taken when linking occupation radiation exposure to cancer incidents or mortalities. A better understanding of the mechanisms of low-dose radiation carcinogenesis is required to capture the effects of such exposure (Suzuki and Yamashita 2012). We therefore report our findings in terms of total population dose (i.e. people × Sv).

ICRP recommends annual effective dose limits of 20 mSv for crewmembers and 1 mSv for the public, averaged over a 5 year period. They also recommend a 2 mSv limit on the accumulated dose over nine months of pregnancy (ICRP 1991, 2007). Furthermore, it is recommended that the effective dose not exceed 50 mSv in any single year, barring special circumstances. Similarly, the National Council on Radiation Protection and Measurements (NCRP) recommends a lifetime occupational exposure less than the person's age times 10 mSv (NCRP 1995).

A study using FAA data of 32-city pair route doses concluded that the additional exposure for frequent fliers, who fly 137 000 km annually, should be considered an occupational hazard (Barish and Dilchert 2010). Previous studies (Aw 2003, Jones *et al* 2005, Bottollier-Depois *et al* 2009) have estimated single flight doses using CARI and EPCARD, validated by measured data from on-board dose counters (Jones *et al* 2005, Vergara and Román 2009). They estimated route dose sensitivity to solar cycle changes, finding a global mean increase of 20–30% between solar maximum and minimum scenarios.

Here we present the first estimate of both the total population exposure resulting from aviation on a global scale and its sensitivity to factors such as solar modulation and cruise altitude. Understanding these sensitivities and assessing all scheduled flights can further improve crewmember and passenger risk assessment compared to the specific estimates previously reported (Aw 2003, Jones *et al* 2005, Copeland *et al* 2008, Barish 2009, Bottollier-Depois *et al* 2009, Barish and Dilchert 2010).

We perform a global assessment of route dose for all scheduled flights from 2000–2013 for passenger and crewmembers, calculating the number of flight-hours passengers would require to exceed ICRP dose limits for each region of the world.

2. Methods

Due to the sun's quasi-periodic 11 year cycle (or a 22 year cycle if magnetic field reversal is considered) (ICRU 2010) particles impacting the earth can have different energy levels by

interacting with the solar wind. This means that calculating the effective dose an individual receives during flight requires solar modulation data, a measure of the effect of solar activity. The particle fluence, the number of particles per normal area (unit: cm^{-2}), is then transformed to effective dose by using conversion coefficients based on ICRP 2007. We use the Particle and Heavy Ion Transport code System based (PHITS) Analytical Radiation Model in the Atmosphere (PARMA), which uses the Sato *et al* (2009) fluence to dose conversion coefficients, to calculate the effective dose experienced at different altitudes (Tatsuhiko and Koji 2006, Sato *et al* 2008). Applying PARMA to the aircraft emissions inventory code (AEIC) (Simone *et al* 2013) estimated flight tracks allows us to calculate the global dose.

2.1. AEIC

AEIC uses official airline guide (OAG) schedules pulled from January 1st of each year, which include information about destination and originating airports, aircraft, and number of annual operations, to model traffic between 2572 airports around the world. AEIC captures 99% of OAG passenger enplanements from 2000 through 2013 (OAG 2013). Since only scheduled civil aircraft appear in the OAG, the model makes no adjustments for canceled, delayed, rerouted or unscheduled flights. In the case of unscheduled flights they are estimated to account for 9% of the global flights annually (Simone *et al* 2013). As such we expect our estimates to capture >90% of the worldwide flying population's radiation exposure.

AEIC generates unique airport–airport directional pairs from the OAG and assumes all aircraft follow a great circle path between departure and arrival airports, with lateral inefficiency factors to account for the additional time at altitude associated with air traffic routing inefficiency. The model uses GEOS-5 2005 wind data to account for tailwinds and headwinds. AEIC makes use of the Base Aircraft Data (BADA) to estimate aircraft performance, with a nominal aircraft cruise altitude of 7000 feet (ISA pressure altitude) below maximum cruise altitude (Simone *et al* 2013), an assumption which is verified using flight data recorder (FDR) archives (see electronic supporting information, SI) (stacks.iop.org/JRP/36/93/mmedia).

2.2. PHITS-based analytical radiation model in the atmosphere

Codes such as FLUKA, COSMOS and PLANETCOSMICS calculate the particle spectra at flight altitudes using Monte Carlo methods (Sato *et al* 2008). However, Monte Carlo simulations are time consuming and cannot be used to efficiently simulate cosmic-ray propagation for each flight route. In contrast, the empirical PARMA model can rapidly estimate atmospheric cosmic-ray spectra for particles with 1 MeV to 200 GeV at altitudes up to 20 km without the use of Monte Carlo methods (Sato *et al* 2008). Using solar modulation potential, cut off rigidity and altitude, PARMA reproduces the estimated fluence calculated in PHITS Monte Carlo simulations to within 5% for 99% of the global conditions, with a maximum inaccuracy of 10% over all scenarios (Sato and Niita 2006, Sato *et al* 2008). This is a consequence of PARMA being unable to reproduce proton spectra below 10 MeV and the helium-ion spectra at intermediate energies of 100 MeV/ nucleon.

2.3. Solar modulation potential and cut-off rigidity

The solar modulation potential values from 2000 to 2013 are used to account for inter-annual variability.

Although sunspot numbers can be used to calculate solar modulation (Usoskin *et al* 2002), in this study we use tabulated values developed empirically by fitting solar modulation values to neutron monitor data (Usoskin *et al* 2011, Sato 2013) (see SI table S2) (stacks.iop.org/JRP/36/93/mmedia).

We use the vertical cut off rigidity to calculate the energy required for a particle to penetrate the magnetic field of the earth at different locations. The model uses a global grid of vertical cut off rigidities with a $1^\circ \times 1^\circ$ horizontal resolution, calculated using the Magnetocosmics Geant4 application (Desorgher 2005). The variability of effective dose due to temporal variability in the magnetic field was neglected due to the effects being of the order of $1 \mu\text{Sv}$ per flight (Bartlett *et al* 2010).

2.4. Global dose calculations

We calculate the dose rate for every aircraft flying each unique airport–airport directional pair by integrating along the full flight path to estimate total exposure. These were converted to dosages using the ICRP 103 conversion coefficients, except where otherwise specified for comparisons to literature, which used the ICRP 60 or 74 coefficients. By multiplying the scheduled number of available seats by an annual and regional average load factor (the fraction of occupied seats) and summing over all flights, we calculate the global passenger dose (ICAO 2000–2013). Seasonal variations in load factor were not included due to lack of publicly available information.

Reduction in effective dose from aircraft structures has been calculated to range from less than 1% for a Boeing 747 (Copeland *et al* 2008) to 3.4% for an Airbus 340 (Battistoni *et al* 2005, Ferrari 2005). However, in this study the reduction is taken as an uncertain parameter, distributed uniformly between 10% to 15% as presented by Burda (2013).

AEIC with PARMA was run in Monte Carlo mode with 1000 draws for each year to account for uncertainty in cruise altitude, solar modulation, and load factor as seen in table 1. Load factor and fluence dose conversion coefficient bounds were chosen based on reported uncertainty (ICAO 2000–2013, Sato *et al* 2009). A normal distribution was used for solar modulation potential based on data acquired from Sato *et al* (2013). Due to lack of fleet wide cruise altitude FDR data a triangular distribution of altitude offsets is used with a bound of ± 7000 ft to represent variation around AEIC's nominal cruise altitude assumption of 7000 ft below the cruise ceiling.

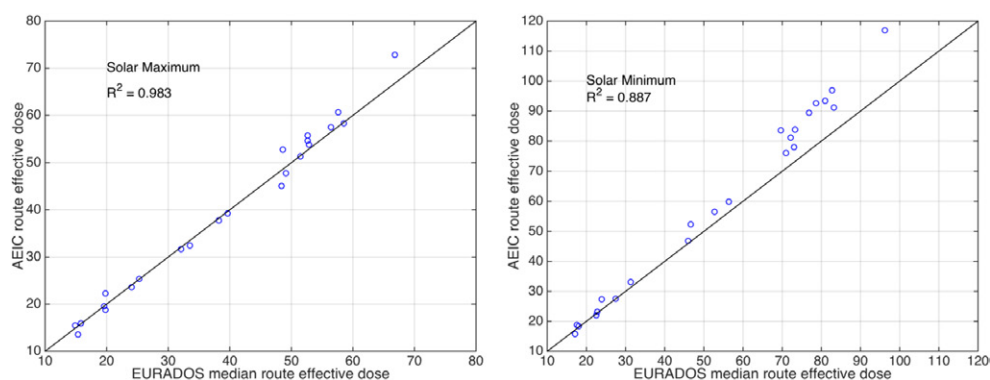
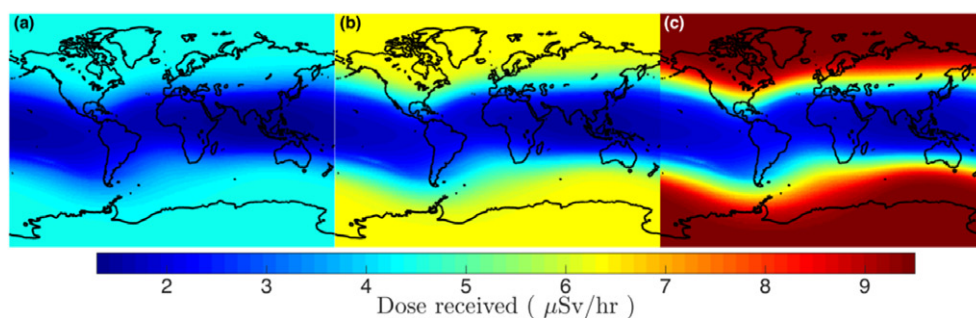
3. Results and discussion

3.1. Validation

Using FDR data from 1701 flights we confirm aircraft cruise altitude is on average 6500 ft below the BADA cruise ceilings. AEIC route dose was validated using the code assessment procedure developed by Bottollier-Depois *et al* (2009) for the European Radiation Dosimetry group (EURADOS). Effective dose testing was performed using ICRP60 definitions for (ICRP 1991) dose conversion coefficients to compare with EURADOS results. Using the flight routes and waypoints described in EURADOS (2012), during solar minimum AEIC effective dose was on average +8.94% from the median while during solar maximum it was +0.776%. Figure 1 shows a comparison between AEIC's effective route dose and the median presented by EURADOS during solar maximum and minimum. AEIC was found to be within 6.76 to 16.2 percentage points, which are within the recommended ± 30 percentage points

Table 1. Monte Carlo variables and the distributions used for uncertainty quantification.

Variable	Distribution type	Range	Mode
Altitude offset from Cruise	Triangular	−7 000 to + 7 000 ft	0 ft
Solar modulation potential	Normal		Year's mean value
Load factor	Triangular	−2% to +2%	Nominal load factor
Fluence dose conversion coefficient	Triangular	−5% to +5%	Nominal coefficient

**Figure 1.** Comparison of the effective dose calculated by AEIC and EURADOS median (2012) under solar maximum (left) and solar minimum (right) conditions.**Figure 2.** Global dose rate maps at 35000 ft for (a) maximum, (b) mean, and (c) minimum solar modulation potential.

interval (ICRU report 84 2010). AEIC had an R^2 greater than 0.83 for all reference values of ambient dose equivalent. See SI for further validation,

Figure 2 shows dose rates at 35000 ft as a function of location and solar modulation potential, covering one solar cycle. Bailey (2000) reported a $6 \mu\text{Sv h}^{-1}$ dose rate at 35000 ft. Assuming mean solar activity at 35000 ft we find that the global area weighted mean dose rate is $4.3 \mu\text{Sv h}^{-1}$, although the rates are strongly dependent on both location and solar activity.

Table 2. Top ten flights globally, ranked by the dose for a single passenger. Results shown for solar mean, and during solar minimum and maximum (which result in maximum and minimum doses).

Rank	Airport pair		Passenger dose (μSv)			Mean flights required to reach ICRP dose limit
			Min	Mean	Max	
1	Bangkok Suvarnabhumi	John F Kennedy	83.4	101.0	107.0	10
2	Singapore Changi	Hartford/ Springfield Bradley	79.5	100.0	108.0	10
3	Kuala Lumpur	Newark Liberty	54.7	99.2	109.0	10
4	John F. Kennedy	Beijing Capital	48.6	95.9	97.8	10
5	Detroit Wayne County	Hong Kong	68.8	94.9	100.0	11
6	Hong Kong	Hartford/ Springfield Bradley	80.4	93.2	98.3	11
7	Singapore Changi	Washington Dulles	93.0	93.1	93.1	11
8	Atlanta Hartsfield-Jackson	Seoul Incheon	46.8	93.0	98.0	11
9	Cairo	Los Angeles	92.6	92.6	92.6	11
10	Ahmedabad S. Vallabhbhai Patel	Newark Liberty	47.3	92.4	94.3	11

The minimum rate of $1.3 \mu\text{Sv h}^{-1}$ occurs during solar maximum at the equator. Conversely the maximum rate, $9.5 \mu\text{Sv h}^{-1}$, occurs during solar minimum at the poles.

3.2. Route dose and the ICRP dose limit

Table 2 shows the top ten flights ranked by the dose that a passenger receives. (The top 100 flights are given in the SI.) In cases where multiple aircraft types are used for a route, the weighted average was calculated based on the number of flights each aircraft type performs. These flights are predominately ultra-long-haul flights operating transpolar routes or above 45°N , which is in agreement with Aw (2003). Nine of the top ten routes ranked by individual passenger dose are ultra-long-haul US to/from Asia flights. For the maximum dose flight, which operates between Bangkok and New York, passengers would reach the annual dose limits after flying 5 return trips (round trips) in an average solar modulation year. We note that ultra-long-haul flights are susceptible to SPE—which are not modeled here—as their dose can increase by an order of magnitude, e.g. Barish (2009) finds that a 10 h flight at high latitudes could experience a total dose increase from 120 to 2,200 μSv .

Table 3 shows the top ten flights ranked by the their contribution to the global accumulated population dose. Five of the top ten routes are to or from London Heathrow, with the single route contributing the most to radiation exposure being San Francisco to Frankfurt. A passenger taking seven return trips on this route in a mean year would exceed the ICRP dose limit.

While the greatest trip doses arise from intercontinental flights, we also show in table 4 the number of flight hours required in a year for a passenger to exceed the ICRP dose limit for regional flights. In this context regional flights are domestic and international flights with an origin and destination within a single ICAO region. Results are given both for an average year, and for a solar minimum year (in which dose rates are highest). In North America as few as 120 flight hours may be needed in a year to exceed the ICRP dose limit in a solar minimum year, equivalent to a monthly round trip on a 5 h flight. Caribbean flights result in the lowest

Table 3. Top ten flights globally, ranked by the dose contributed to the global accumulated dose in a year. Results shown for solar mean, and during solar minimum and maximum (which result in maximum and minimum doses).

Ranking	Airport pair		Passenger dose (μSv)			Mean flights required to reach ICRP dose limit
			Min	Mean	Max	
1	Frankfurt	San Francisco	39.5	70.7	85.1	14
2	London Heathrow	Los Angeles	33.1	58.8	80.6	17
3	London Heathrow	San Francisco	33.9	61.5	80.6	16
4	Los Angeles	Seoul Incheon	31.2	50.5	59.5	20
5	London Heathrow	Chicago O'Hare	20.8	42.1	59.4	24
6	John F Kennedy	Hong Kong	52.5	79.7	102.5	13
7	Singapore Changi	London Heathrow	28.7	34.1	43.1	29
8	Tokyo Narita	John F Kennedy	43.4	63.8	93.0	16
9	London Heathrow	Washington Dulles	20.5	36.6	51.1	27
10	Los Angeles	Frankfurt	26.3	61.9	85.5	16

Table 4. The number of intraregional flight hours required in a year to exceed the ICRP dose limit. Minimum flight hours correspond to a solar minimum scenario; while the mean flight hours correspond to the average flight hours during a mean solar modulation of 662 MV.

ICAO region	Minimum flight hours to reach ICRP limit	Mean flight hours to reach ICRP limit
Caribbean	550	3480
Africa	310	1100
Middle East	350	1020
Asia	140	980
Latin America	380	960
Pacific	200	760
Europe	160	510
North America	120	420

dose rates, with passengers having to be airborne for 40% of an average year to exceed the ICRP effective dose limit for the public. A table for interregional flights is given in the SI.

3.3. Global accumulated dose

From 2000 to 2013, the flying population has increased by 79% (ICAO 2000–2013) while the solar modulation has completed a full cycle with solar minimum occurring in 2009, and solar maximum in 2003. The annual total population dose from 2000–2013 is shown in figure 3. With the growth in the flying population and the declining dose rates at a given altitude after 2009, the total annual dose peaked in 2009 at 15.1 kSv

To determine the primary drivers of the 1.7% reduction in dose between 2012 and 2013, we performed sensitivity simulations for both years. We find 0.39% of the reduction is due to the decrease in enplanements between 2012 and 2013. Modeling the 2012 schedule with the 2013 solar modulation potential shows that the solar cycle is responsible for a further 0.42% decrease in total dose. The remaining 0.89% decrease is explained by a change in the global distribution of flights, figure 4. Specifically, the passenger-weighted mean vertical rigidity, which is approximately inversely proportional to absolute latitude, increased by 1.3% between

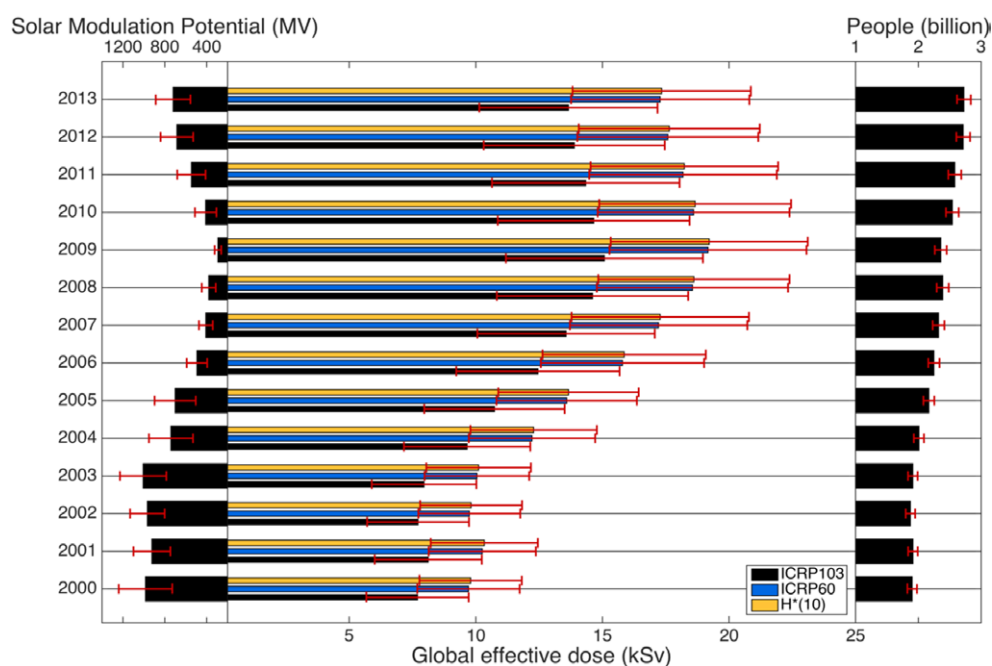


Figure 3. Global annual accumulated dose for the flying population (2000–2013), solar modulation potential, and number of passenger enplanements. All years were simulated using ICRP103 and ICRP60 effective dose conversion coefficients along with ICRP74 equivalent dose conversion coefficients. Error bars show 95% confidence intervals.

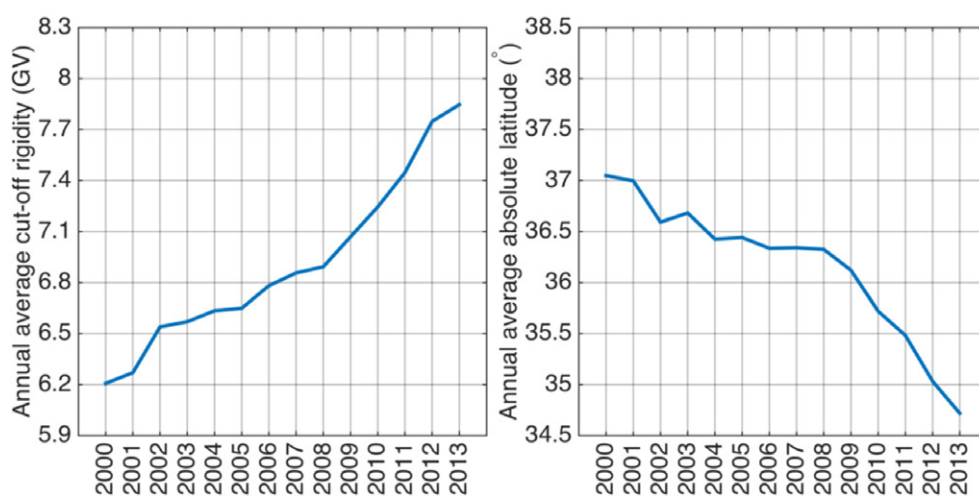


Figure 4. Global annual passenger-weighted mean cut-off rigidity (left) and absolute latitude (right).

the 2012 and 2013 schedules. The increasing passenger-weighted mean vertical rigidity corresponds to greater passenger traffic nearer to the equator, and therefore in low dose-rate regions.

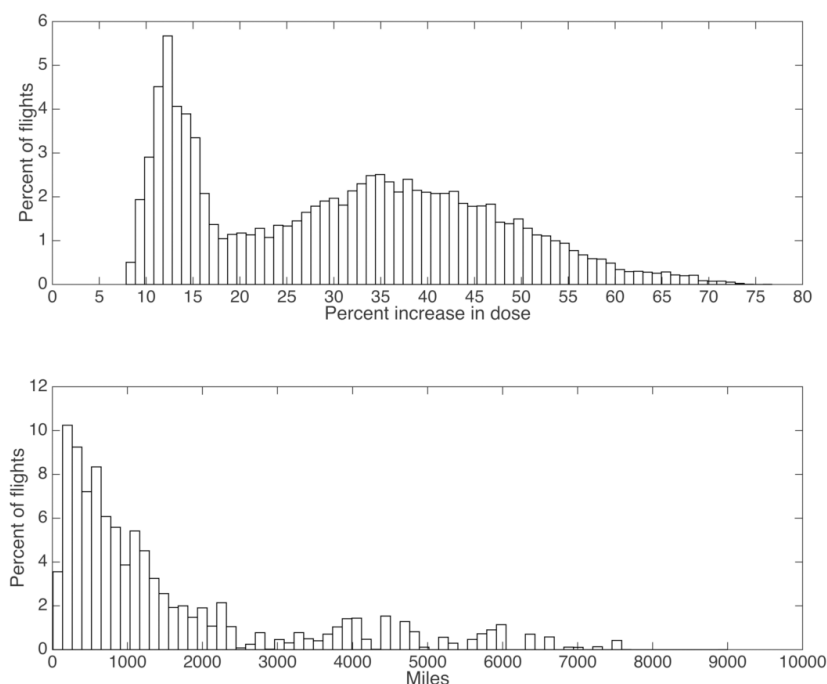


Figure 5. Distributions of percent increase in dose from solar maximum and minimum for flights operating in 2013 (top) and the distribution of distance traveled by flights operated in 2013 (bottom).

3.4. Solar modulation and altitude effects

We find changes in solar activity can increase route dose between solar maximum and minimum by more than the 20–30% previously estimated by other studies (Aw 2003, Bottollier-Depois *et al* 2009). The percent increase in route dose between solar maximum and minimum using the 2013 schedule are shown in figure 5.

Figure 5 shows how the effect of the solar cycle is distributed. All flights experience at least a 7.8% increase in effective dose between the solar maximum and minimum, and we find a median dose increase of 34.1%. There are two clustered sets of data—one which experiences a 7–18% increase in effective dose, and another which receive a 18–76% increase in effective dose.

The first cluster experience a relatively low increase, and include 17.7% of all flights and are sub-1000 mi routes, which spend a proportionally greater percentage of their time climbing and descending. This cluster also contains flights taken by small aircraft with low cruise ceilings. The remaining flights in this cluster are medium- to long-haul. These flights are predominantly mid-latitude, such as the transatlantic corridor or routes between Europe and China. A second cluster of short-haul flights experiences between a 30 and 55% increase in effective dose, which encompasses 24% of all flights. This corresponds to flights in the US and Europe which are in regions with lower cut-off rigidities. Finally, a diffuse set of medium-haul flights in the 22–76% increase range corresponds to high latitude and trans-polar flights, which experience the greatest relative change in dose rate as shown in figure 5, encompassing 34% of all flights.

4. Conclusions

We develop the first assessment of total radiation dose to the worldwide flying civilian population, accounting for all scheduled flights from 2000–2013. We find a total population accumulated dose of 164 kSv summed from scheduled flights from 2000 to 2013. However, the total population accumulated dose can vary by at least 9% due to the OAG data limitations from unscheduled, rerouted and cancelled flights.

As few as five North America-Asia return trips in a year can cause an individual to reach the ICRP effective dose limit for the public in an average year. In a solar minimum year, where dose rates are at their peak, accumulating 120–160 intraregional flight hours in North America, Europe, or Asia can result in the limit being exceeded. These results suggest that frequent flyers can exceed the ICRP effective dose limit for the public. In particular, passengers who take five or more ultra-long haul return trips or who log more than 120 flight hours in a year may be beyond the ICRP limit for the public. However, with the occupational limit being twenty times higher, a person would have to be airborne for 27% of the year in Europe to exceed the occupational limit during a solar minimum.

Our results show that changes in solar activity can increase route dose between solar minimum and maximum by more than the 20–30% previously estimated by other studies (Aw 2003, Bottollier-Depois *et al* 2009). The solar cycle can increase the global dose by 16.5% when operating in solar minimum or decrease route dose by 11.8% when operating in solar maximum with respect to the mean solar modulation potential. North American and Europe can experience annual increases in total region dose of 35.2%, and 29.9%, and decreases of 18.4% and 18.4%, respectively, relative to the mean solar activity.

Future work should focus on the effects of high-energy particle exposure at cruising altitudes to aircrew and passengers, as well as reducing the uncertainty in conversion coefficients for effective dose at high energy levels. Further analysis should also focus on the changes in the integrated global dose due to SPEs.

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