# Development of Risk Assessment Framework and Policy Recommendation for Improving Social Resilience

Moe Fujita

**Doctor of Philosophy**

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Moe Fujita

Graduate School of Advanced Integrated Studies in Human Survivability, Kyoto University

March 2022

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**Abstract**

This thesis develops a framework for the quantification of LPHC risk in the aerospace industry to enhance and improve social resilience, and also discusses and proposes the necessary framework.

First, various types of natural disasters in human and global history are classified according to frequency and damage scale, such as low-probability, high-consequence (LPHC) events and high-probability, low-consequence (HPLC) events. LPHC occurrences have a very low probability of occurring, but they would have catastrophic consequences. HPLCs occur more frequently, with most of them having decadal frequency. They cause local fatalities, but they are never global in scale. In this study, these events are classified and evaluated based on the potential risk for human civilization. Above all, I will focus on the risks in the operation planning of modern man-made artificial objects such as aircrafts.

Second, I present a systematic approach to effectively assess the potential risk costs of exposure to solar particle events (SPEs) resulting from solar flares for the aviation industry. Associated health risks from radiation were evaluated using ExoKyoto, in order to provide relevant alternative ways to minimize economic loss and opportunity. The estimated radiation dose induced by each Solar Particle Event (SPE) for the passengers of each flight is calculated using ExoKyoto and Particle and Heavy Ion Transport code System (PHITS). We determine a few scenarios for the estimated dose limit at 1 mSv, and 20 mSv, corresponding to the effective dose limit for the general public and occupational exposure, respectively, as well as a higher dose induced by an extreme superflare event. A hypothetical airline shutdown scenario was set at 1 mSv for a single flight per passenger, due to legal restrictions under the potential radiation dose. In such a scenario, I calculate the potential loss in direct and opportunity cost under the cancellation of the flight based on a simple single-dimensional model. In the next chapter, the model is extended to a four-dimensional model for quantification.

Moreover, the risk assessment of cosmic ray exposure shown in Chapter 3 was quantified in consideration with the location and temporal changes of the earth, and quantified based on actual aircraft operation routes. I evaluated the risks associated with the cost of measures to reduce Solar Energetic Particles (SEP) doses and dose rates for eight flight routes during five ground-based level rise events (GLEs). A four-dimensional dose-rate database developed by the Warning System for Aviation Exposure to Solar Energetic Particles (SEP), WASAVIES, was employed in

the SEP dose evaluation. As for the cost estimation, we considered two countermeasures; one is the cancellation of the flight, and the other is the reduction of flight altitude. Then, we estimated the annual occurrence frequency of significant GLE events that would bring the maximum flight route dose and dose rate over 1.0 mSv and 80 μSv/h, respectively, based on past records of GLE as well as historically large events observed by the cosmogenic nuclide concentrations in tree rings and ice cores.

Finally, the series of risk assessments conducted in this paper as LPHC risk countermeasures for the aerospace industry was made into a framework, the possibility of parametric insurance was discussed, and policy recommendations were discussed. First, based on the quantitative risk assessment process proposed by previous studies, I organized and constructed a framework for quantifying LPHC risks in the aerospace industry. Next, I defined parametric insurance, as well as its mechanisms, advantages and disadvantages, and discussed the possibility of designing parametric insurance using the index proposed in Chapter 4. Finally, I proposed a system of public-private-academic collaboration, laws and regulations, and databases that are necessary to design such parametric insurance.

## 1. Introduction

This paper proposes a new approach to low-frequency, large-scale combined risk events, especially aerospace exposure risk.
Given the recommendations of NASA and ICRP that it is necessary to respond to cosmic radiation exposure, we need to take measures for it.
In addition, the space business is more active than ever, and more than 1000 venture companies have entered the market and it is lively (numerical value required).
Against this background, this paper systematically organizes and abstracts the options for risk assessment, calculation of economic loss, and risk management means for LPHC in the aerospace industry, and proposes them.
Specifically, I first trace the history of LPHC outbreaks back in thousands years, organize them, and then calculate the cost required to change the aircraft operation plan to reduce radiation exposure when solar flares occur under a one-dimensional model. bottom. The model was further expanded to calculate the frequency of GLE occurrence during solar flares in the 4D model and the cost required to change the aircraft operation plan to reduce radiation exposure.
Finally, as a future direction, I will consider application not only to the aircraft business but also to the space industry.

If the frequency and the amount of economic loss are clear, use the two variables.
For example, we will introduce it into a model of parametric insurance or weather derivatives based on PEII or PEI, and propose those products as a risk financing method such as flight cancellation insurance of Moonshot and Swiss Re.

I proposed the necessary systems and policy suggestions (for example, risk identification, prioritization, risk assessment response, integrated database construction, and communication with the field in industry, government, and academia).

## 1.1 Necessity of measures against solar flare risk in aircraft and spacecraft operations

The International Committee on Radiological Protection（ICRP） recognizes the cosmic-ray exposure to aircrews as an occupational hazard and provided an updated guidance on radiological protection from aircrew exposure, considering the current ICRP system of radiological protection[i]. In response to these publications, the International Civil Aviation Organization (ICAO) has recently decided to use radiation dose as mandatory information requested from space weather information providers.

Therefore, we need to take steps to address that risk.

Moreover, Space travel plans by SpaceX, Virgin Galactic, Blue Origin and others are expected to increase the risk of solar radiation exposure, so we used the method constructed in this study to quantify the risk and its results. Proposals for radiation dose reduction measures based on this will become even more important.

## 1.2 Methodology and Research Scope

In recent years, the necessity for measures against Low Probability-High Consequences (LPHC) has increased. In the 1980s, large-scale explosion of chemical complex and fuel base and accident at Chernobyl and Three Mile Island occurred (Ikeda, 2016). Above all, in the 21st century, Since the 9/11 terrorist attacks in Manhattan, international food safety risks starting with BSE in the UK, large-scale cross-border floods and hurricanes Katrina, SARS and new infectious diseases such as bird flu emerged (Ikeda, 2016).

Low Probability-High Consequences (LPHC) is defined as “LPHC events, which can have significant consequences but are not likely to occur. They are characterized by very large releases of energy, large numbers of breakdowns and involve many people.” (Arangio et al, 2013).

On the other hand, High Probability-Low Consequences (HPLC) is defined as “HPLC events, intended as those that have a high probability to happen but that well designed structures can usually withstand with low consequences. They are usually characterised by small releases of energy, a small number of breakdowns and involve only few people.” (Arangio et al, 2013).

As an approach from "risk science (analysis)" to low-frequency and large complex risk events, a number of analytical frameworks have been developed in the 1980s, such as elucidation and response to the characteristics of "risk events" (Ikeda, 2016). Efforts for risk governance in a new form of collaboration, including collaboration at the international level, have begun (Ikeda, 2016).

In Europe, the OECD's Systemic Risk Project (OECD, 2003), the IRGC (International Risk Gover-nance Council)'s Risk Governance Project (Renn, 2008), and the study of Extreme Events in Germany ( Albeverio et al., 2006), etc (Ikeda, 2016). The US SRA published a series of essays by successive presidents in its journal, Risk Analysis, from 2002 to 2004, and responded to traditional risk management. We approach the extremely low frequency and huge complex risk that cannot be done from both objective science (formal mode) and empirical science (experiential mode) as "surprise" or "extreme risk". It has suggested the development of interdisciplinary approaches in a more realistic way (Anderson, 2002).

On the other hand, in Japan, since the Great Hanshin-Awaji Earthquake and the Salin Terrorism Incident in 1995, each specialized society / industrial sector has "low frequency / huge loss" for individual risk events related to safety, health, and disaster prevention. Has increased its commitment to potential risk events, for example in the field of natural disasters (Ikeda, 2016). Although efforts have been made to reduce the loss from disasters such as “disaster prevention to mitigation” or to adapt to it, the area has become huge and widespread, including the Japan Risk Research Association, where the author was involved. ， It must be said that the development of coping with complex risk events (Japan Society for Risk Research, 2006) was immature（Ikeda, 2016）.

Then, “all-hazards” approach will be desirable to tackle with LPHC. In order to manage LPHC, it is first necessary to “visualize” risks through the all-hazards approach. In Japan as well, it will be necessary to first introduce the all-hazards approach, formulate an overall strategy, and implement a national risk assessment based on it. We should start with risk mapping in all-hazards and prioritize based on it, including events that are still "out of scope", such as caldera eruptions, asteroid collisions, and diverse superflares. With regard to global risk, it will be necessary to strengthen cooperation with international organizations such as the OECD not only in terms of evaluation but also in terms of management. (Kishimoto, 2015）.

Moreover, recommendation of suitable financial scheme is also necessary. In order to effectively reduce disaster risk, both seismic strengthening investment and risk control represented by hydraulic engineering projects and risk financing through disaster insurance are required. Disaster prevention investment is a risk control technology that reduces disaster risk. On the other hand, the remarkable development of risk finance technology has made it possible to increase the resources for insurance payments and reduce the disaster insurance premium rate. The expansion of the disaster insurance market may improve local residents' awareness of disaster prevention and self-disaster prevention. From this point of view, it is important to establish a desirable risk management system that considers risk control technology and risk finance technology at the same time.（Kobayashi, 2002）.

Historical facts in the field of risk assessment have followed such a transition.
In particular, risk assessment research in the aerospace field has been attempted to quantify with the aim of how to safely carry out manned space flight (Cooke, 2006).
Since the death of an astronaut in the Apollo test in 1967, risk assessment studies such as the probability of rocket failure and the probability of successful landing on the moon have been conducted.

When it became clear that the lunar landing had a 5% chance of success, NASA felt that it could have an irreparable blow and saw it as an event that overturned the safety guidelines it had set up

(Cooke, 2006). On the other hand, regarding the cause of the shuttle accident, since not all parts pose the same threat, simple quantitative methods such as identifying lossy airframe accidents were said to be limited (Garrich, 1989).

After the shuttle accident, NASA started and implemented a quantitative risk analysis program to maintain safety during the design and implementation of manned flights. It has resulted in NASA risk assessment efforts reaching a high level of favorable reception in SAIC risk assessment (Fragola, 1995). In other words, this shows that the probability of the most likely cause of an accident has been significantly reduced.

Garrick (1988) explore the basics of commonalities, standards, and commonalities in the framework of risk management approaches in the three industries of nuclear power, space systems, and chemical processes, and to answer the quantitative question "What is risk?" Organized. Pate-Cornell (2001) reviews and reviews the history of NASA's Probabilistic Risk Analysis (PRA) on the Space Shuttle Program and describes the development of software for the Quantitative Risk Assessment System (QRAS) that executes PRA. Altavilla (2002) summarizes some of the most important risk assessment methods applied and developed by Alenia in the field of space systems, with a particular focus on manned space transport aircraft.

For all projects undertaken by an organization, it is difficult to prioritize overall risk processing from an organization's risk management perspective, as each project can have different methods of identifying, assessing, and determining risk. In order to intuitively identify the status of risk management at the top level, it was necessary to develop a standardized quantitative method that could integrate risk at the level of each project (Ahn, 2018).
To that end, this paper introduces an index-based scheme for risk management at the organizational level, and by analyzing index trends, R-Model intuitively identifies risks and makes top-level decisions. Contribute to. It is important to develop standardized quantitative methods that can integrate risks at the level of each project and to validate the schemes proposed through case studies of actual projects of major aerospace research institutes (Ahn, 2018).

Even after reviewing these previous studies, no study has yet been conducted to evaluate the risk to the economic loss amount of aviation exposure due to GLE during solar flare events in the aviation industry. Therefore, this study can be said to provide new value.

The following research questions are posed in this paper:
Can we introduce a systematic approach to effectively assess the potential risk costs of exposure

to solar particle events (SPEs) due to solar flares in the aviation industry and calculate the potential direct and opportunity cost losses if flights are cancelled based on a simple one-dimensional model?

Can we evaluate the cost of measures to reduce SEP dose and the risk associated with the dose rate by proposing some indicators for eight flight routes during five ground level elevation events (GLEs)?

Can a series of risk assessments conducted in this paper be used as a framework for LPHC risk countermeasures in the aerospace industry, and can the possibility of parametric insurance be discussed, policy recommendations be made, and the necessary systems and elements to be considered for implementation in society be presented?

## 1.3 Outline of the Thesis

This thesis develops a framework for the quantification of LPHC risk in the aerospace industry to enhance and improve social resilience, and also discusses and proposes the necessary framework.

In Chapter 2, various types of natural disasters in human and global history are classified according to their frequency and damage scale. Disasters that caused extinction events in Earth's history include (1) volcanic disasters, (2) asteroid impacts, and (3) climatic disasters, which are classified as low- probability, high-consequence (LPHC) events. On shorter timescales, however, humans are subject to more frequent disasters such as (i) major floods, (ii) epidemics, (iii) earthquakes, (iv) tsunamis, and (v) medium-sized volcanic eruptions, which are known as high-probability, low-consequence (HPLC) events. Above all, I will focus on the risks in the operation planning of modern man-made artificial objects such as aircrafts.

Chapter 3 presents a systematic approach to effectively assess the potential risk costs of exposure to solar particle events (SPEs) resulting from solar flares for the aviation industry. In addition, based on a previous study (Yamashiki *et al*. 2019 ApJ), ExoKyoto was used to assess the associated health risks of radiation and provided relevant alternatives to minimize economic losses and opportunities. In this chapter, the potential risk costs caused by the aviation industry's exposure to solar particle events (SPEs) from solar flares were estimated by a simple one-dimensional model. In the next chapter, the model is extended to a four-dimensional model for quantification.

In Chapter 4, the risk assessment of cosmic ray exposure performed in Chapter 2 was quantified in consideration with the location and temporal changes of the earth, and quantified based on actual aircraft operation routes. Cosmic ray exposure to flight attendants and passengers is called aeronautical radiation exposure and is an important topic, especially against the radiation protection of solar high energy particles (SEPs). Therefore, I evaluated the risks associated with the cost of measures to reduce SEP doses and dose rates for eight flight routes during five ground-based level rise events (GLEs). A four-dimensional dose rate database developed by WASAVIES, which is a warning system for aviation exposure to solar energetic particles, was employed for SEP dose assessment. For the cost estimation, two measures were considered. One is the cancellation of flights and the other is the reduction of flight altitude. Next, I estimated the annual frequency of significant GLE events with maximum flight path doses and dose rates exceeding

1.0 mSv and 80 μSv/ h, respectively, based on historical GLE records and historically significant events observed by cosmic-ray neutron and radiocarbon analysis results. Calculations indicate that a GLE event of sufficient magnitude exceeding the above dose and dose rate thresholds to require a change in flight conditions would occur once every 47 and 17 years, respectively, and that the conservatively estimated annual risk associated with the cost of countermeasures would be up to about US$1.5 thousand for daily long-haul flights.

In Chapter 5, the series of risk assessments conducted in this paper as LPHC risk countermeasures for the aerospace industry was made into a framework, the possibility of parametric insurance was discussed, and policy recommendations were made. First, I overviewed what parametric insurance is, its definition, mechanism, advantages and disadvantages, and discussed the possibility of designing parametric insurance using the index proposed in Chapter 3. Finally, I proposed a system of public-private-academic collaboration, laws and regulations, and databases that are necessary to design such parametric insurance.

## 2. Prioritization of Different Kinds of Natural Disasters and Low- Probability, High-Consequence Events

In the history of terrestrial lifeforms, several different kinds of natural disasters can be classified in biological history since the Phanerozoic period. The most serious disasters can be classified as (1) volcanic disasters, (2) asteroid impacts, and (3) climate disasters, in reference to the root cause of low-probability, high-consequence (LPHC) events. LPHC events, which can have significant consequences but are not likely to occur. They are characterised by very large releases of energy, large numbers of breakdowns and involve many people (Arangio, 2013).

However, on a shorter timescale, mankind is more vulnerable to frequent disasters, such as (i) large floods, (ii) epidemics, (iii) earthquakes, (iv) tsunamis, and (v) small-medium scale volcanic eruptions. These are known as high-probability, low-medium-consequence events (HPLC). HPLC events, intended as those that have a high probability to happen but that well designed structures can usually withstand with low consequences. They are usually characterised by small releases of energy, a small numbers of breakdowns and involve only few people (Arangio, 2013). LPHC occurrences have a very low probability of occurring, but they would have catastrophic consequences. HPLCs occur more frequently, with most of them having decadal frequency. They cause local fatalities, but they are never global in scale. In this study, these events are classified and evaluated based on the potential risk for human civilization. We also discuss how to incorporate different considerations related to prioritizing different disasters, focusing on whether insurance mechanisms can be applied or not.

### 2.1. Introduction

In the past, large-scale extinction events and epidemics were frequent. Mass Extinction Events (MEEs) are events characterized by rapid decreases in biodiversity during the Phanerozoic Eon. Mass extinctions are defined as the extinction of a significant proportion of the Earth's biota over a geographically widespread area in a geological insignificant period of time, often one that appears instantaneous when viewed at the level provided by the 25 geological record (Woodridge, 2008).

Mass Extinction Events (MEEs) can be categorized as LPHC events if they are considered to have occurred in the period of human history. They can be categorized into (1) volcanic disasters, (2) asteroid impacts, and (3) climate disasters, according to the root cause of the above five distinct MEEs (considering that (C)P-T and (D)T-J extinction as (1)volcanic disaster, (E)K-T extinction as (2) asteroid impacts, and (A)O-S and (B)L-D extinction as (3)climate disaster) . However, on a shorter timescale, mankind is more vulnerable to earthquake (seismic) and flood disasters, including (i) large floods, (ii) epidemics, (iii) earthquakes, (iv) tsunamis, and (v) small-medium volcanic eruptions. These are considered as high-probability, low-medium-consequence events (HPLC).

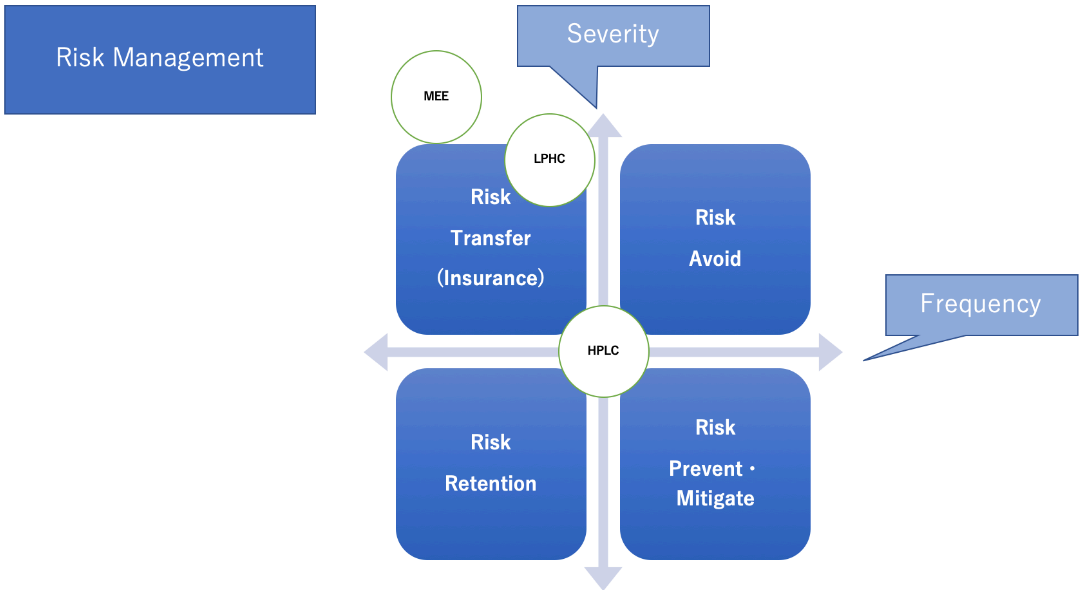



Fig. 1. Risk map classified by Frequency and Severity

We draw Fig.1 as a risk management by classifying LPHC, HPLC and MEE based on the dependence of Frequency (X-Axis) and Severity (Y-Axis). In general, Low Frequency and High Severity Risk will be taken care of by Risk Transfer, for example, Insurance. Low Frequency and Low Severity will be taken care by Risk Retention. High Frequency and High Severity will be taken care by Risk Avoid, and High Frequency and Low Severity will be taken care by Risk Prevention and Mitigation, also private company as an insurance.

LPHC such as volcanic disasters, asteroid impacts, and climate disasters are categorized for all four risk management tools. It's because of that LPHC "are caused by a lot of different reasons and include multifaceted aspects, so they are almost impossible to frame into any well-recognized probabilistic format." (Arangio, 2013). HPLC such as large floods, epidemics, earthquakes, tsunamis, and small-medium scale volcanic eruptions are categorized as Risk Prevention and Mitigation.

MEE such as the rapid decreases in biodiversity during the Phanerozoic Eon will be categorized as above and left of LPHC.

Furthermore, Emerging Risks are defined "Risk that was previously unexpected or that was previously expected but found to be far more frequent and serious than previous expectations" by

Yoshizawa (2018), and we employed some Emerging Risks that are equal to LPHC in this paper, for example, volcanic disasters, and climatic disasters.

Higher concern for mankind when it comes to HPLC rather than LPHC can be caused by (1) the development of civilizations in human history causing a new type of vulnerability that would not have been threat had there been no civilizations with stable settlements. Stable settlements are vulnerable to small-scale perturbations of nature, including floods, earthquakes, and tsunamis, which were not considered serious disasters for a long time when people could freely move away from the affected areas. (2) Small- to medium-scale (up to VEI 6–7) volcanic eruptions happened very frequently and only killed people locally, not globally, such as the VEI 8 volcanic eruption, which occurred relatively recently, only 70,000 years ago in Toba. Another consideration is that throughout history we only recognized small-scale disasters, such as (i) floods, (ii) epidemics, (iii) earthquakes, (iv) tsunamis, and (v) volcanic eruptions.

We have confirmed the largest scale events (v) that took place in the past, but we are not sure about other large-scale disasters. The following is the historical record for each type of disaster.

(i) Flood: The largest flood in recorded history occurred at the very end of the last ice age, around 85 hundred years ago, when the black seas were created and large flood events occurred. Of course, it may be the largest ever recorded, but, if the sea levels changed in the past as a consequence of global temperature fluctuation, a “large flood” may have occurred in every glacial and warm period cycle. These large floods may have occurred in every cycle of polar ice melting in the Northern Hemisphere and in Antarctica.

(ii) Epidemic: It is very difficult to tell how large past epidemics have been. The only large epidemic in recorded history was the Bubonic Plague, or Black Death. It is difficult to surmise the scale of past epidemics because every piece of organic evidence ceases to exist after a long enough period of time. Epidemics might have occurred repeatedly throughout human history, but homogeneity has increased the risks of different kinds of diseases and extinctions. Keeling (2000) states that glandular plague (Yersinia pestis) is generally considered to be a historical disease, which still accounts for about 1000 to 3000 deaths annually around the world. In this paper, they have extended the analysis of the glandular plague model covering disease dynamics in rats, fleas, and human populations. Sebbane (2005) stated: “The plague caused by the gram-negative bacterium Yersinia pestis primarily affects rodents, but is also said to be an important human zoonotic disease.” He developed a glandular plague model using an inbred Brown Norway strain of Rattus norvegicus to characterize the progression and kinetics of infection after intradermal inoculation of Y. pestis and the host immune response. Duncan (2005) considered the black death and all European plagues (1347-1670) throughout the twentieth century to be epidemic of each plague, but this view is incorrect in the opinion of this review. Evidence is provided that the disease is a viral hemorrhagic fever characterized by a long incubation period of 32 days, which made its wide spread possible, even in a time of limited transport like the Middle Ages. Alvarez, M. Lucrecia, *et al*. "Plant-made subunit vaccine against pneumonic and bubonic plague is orally immunogenic in mice." Vaccine 24.14 (2006): 2477-2490. The plague pathogen Yersinia pestis, the causative agent of the plague, it is a highly pathogenic bacterium, but there is no approved vaccine to protect against it, so they propose a vaccine that is easy to handle, which has mucosal effects, and is safe. They have developed a new production and delivery system for the plague vaccine of a tomato-expressed Plasmodium f1-V antigen fusion protein to achieve sexuality, rapid extensibility, and cost.

(iii) Earthquakes: Seismic activity accompanied by strong vibrations may not have been a serious threat throughout human history unless cities and associated structures were built above the affected regions. The biggest earthquake disasters recorded in human history have been the following: (1) the earthquake in Lisbon in 1755, (2) the earthquake in San Francisco in 1906, (3) the earthquakes in the former Tokyo metropolitan zone in 1923, (4) the earthquakes in Mexico City in 1985, and (5) the earthquakes in East Japan in 2011. All of these are associated with the presence of a big city, except (5), which struck coastal cities and nuclear power plants. In the past, there were frequent earthquakes in the Edo area, but all of them are associated with structural damages during the earthquakes. These structural damages never extended beyond one country's border.

(iv) Since March 11, 2011, tsunami disasters have been considered as one of the biggest threats to those living in coastal zones. A tsunami could destroy a coastal city completely or even destroy a nuclear power plant. Tsunamis are recognized as the one of the most horrible disasters for human life. However, it is also recognized that tsunamis can be induced by more than seismic activity under the ocean. They can be caused by volcanic eruptions in the sea, such as the Krakatoa volcano in 2018.

(v) (Tsunami Associated with Asteroid Impact) Tsunami disasters can also be caused by asteroids hitting the ocean, as in the case of the Chicxulub impact in 65 Ma. There could have been other tsunami disasters associated with the asteroid impact, which could have killed most of the population of the Earth. The Chicxulub can be classified not only as one of the largest asteroid impacts, but also as a large flood that affected a large portion of life on Earth. Accordingly, if a similar incident happens, it would affect a large population much like a tsunami caused by a collision with a celestial body. Ward (2000) investigated the generation, propagation, and probabilistic hazard of tsunamis spawned by oceanic asteroid impacts. Chapman (1994) says that although impacts on the Earth by asteroids and comets (magnitude) are so infrequent as to be beyond our personal experience, the long-term statistical hazards are comparable to that of many other, more familiar natural disasters, raising the question of whether mitigation measures should be considered and assessed as a hazard. Matsui (2002) studied the mechanism of tsunami generation by meteorite impact on a shallow ocean at 65 Ma and modeled the propagation of that tsunami in the Gulf of Mexico. They found that the water flow into and out of the crater cavity causes most tsunamis. Gisler (2003) states that on a geological time scale, impacts of asteroids and comets with the earth must be considered as a relatively frequent occurrence, causing significant disturbances to biological communities and strongly perturbing the course of evolution.

As for five distinct MEEs, there are three considerable classifications are (1) a volcanic eruption, (2) an asteroid impact, and (3) climate change as described above. As previously stated, the root causes and frequency should be carefully evaluated before considering them as a potential threat for human beings in future generations.
According to Avin (2018), we homo sapiens are exposed to threats like volcanic super-euptions.

(1) A volcanic eruption, known as the Siberian Traps Flood Basalt Event, is the MEE that has been the biggest cause for concern since the Cambrian Explosion. According to the hypotheses, the lava equivalent of the size of Siberia was released from inside the earth, causing a significant increase in temperature.
(2) The K-T asteroid impact event is the only historical event that has been confirmed by the existence of a crater. However, considering the number of asteroids crossing the Earth's orbit at any moment in the past, such impacts have probably been more frequent than we realize. There are hypotheses that P-T MEE was caused by an asteroid, just as the other two were. However, finding evidence for asteroid impacts is not an easy task. It should be considered that 70% of the Earth's surface is covered by oceans, and this automatically reduces the possibility of geological proof of an asteroid impact. Oceanic erosion may have accelerated the deformation of an under-water crater. The thick ocean layer may have reduced the deformation of Earth's surface by asteroid impacts unless the location of the impact was in shallow water, as was the case with Chicxulub. However, in such a case, the tsunami impact becomes the first disaster in association with the asteroid. The following table shows the estimated magnitude, in accordance with the size of the asteroid.
(3) Climate change is key in this discussion. Volcanic super-eruption and asteroid impact also cause large scale climate change, first cooling due to the shading effect of a darkened sky by aerosols and then global warming due to the release of GHGs on large scale. For example, after a volcanic eruption, it will be cool for the first three and a half years, and then it will be warm for hundreds of years. This would be the same in the case of an asteroid impact. Other climatological impacts can be caused by different sources, such as solar activity changes, Earth's orbital

fluctuations, etc. The root causes of climatic disasters have not been confirmed yet.

Table.1 The conceptual classification of different kinds of disasters, according to frequency and occurrence.

| | Target | Cause | Frequency | Last disaster (place) | Last disaster (time) | Future Threat | Affected People | Death Toll | Economic Loss | Literature |
|---|---|---|---|---|---|---|---|---|---|---|
| GRB | Destruction of Ozone Layer - more | Long GRB-Hypernova / Short GRB - Binary neutron star | 10 to the 9th power | Global / Ocean Surface | 440 MY | ?? | | | | (Melott et al. 2014) |
| Super volcanos | Killing locally by lava& Ash | magma chamber | 10 to the 4th - 6th power | Toba | 74000 | Yellowstone | 12.5 million (Hoei Eruptions) | 13,600 (Hoei Eruptions) | 2.5 trillion $(Hoei Eruptions) | Cabinet Office of Japan (2004) |
| | Killing Globally by gas | | | | | Aso (VEI-7) | | | | |
| | | | | | | Kikai (VEI-7) | | | | |
| Asteroid Attack | ELE | NEOs | 10 to 8th - 10th power | Chicxulub | 65 MY | ?? | 1200 | 0 | $ 30 million | |
| | Locally | | 10 to the First-Third power | Tunguska | 1908 | | | | | |
| Superflare | Modern civilization | Solar activity | 10 to the third power | Carrington | 1859 | Global | | | $100 million ～ | |
| Climate Change (Natural) | Everything | Solar activity / GHGs / Orbital distance | 10 to the Fifth power | | | | 60 million | 60,000～ | $96.2 billion | WHO(2018), Christian Aid(2018) |
| Climate Change (Anthropogenic) | Everything | GHGs | ? | | ongoing | Global | | | | |
| Outbreak of Infectious Diseases | Human | | 10 to the First - third power | | 2014 (Ebola) | ?? | 11,315 | 28,637 | $550 million | The World Bank (2015), BBC News(2016) |
| Terrorism | Human | human | 10 to zero-first power | | 2015 | ?? | 10,000 (9.11) | 3,043 | (Melott et al. 2014) | The Institute for Safer and Securer Society (2007), Yahoo (2018) |
| | | | | | | | | | | |
| Earth quakes | Urban structure | seismic activities | 10 to the first power | | | Kanto, Nankai | 468,600 | 15,897 | $16.9 trillion | Asahi (2019) |
| Tsunami | Coastal structure | seismic activities under the sea | 10 to second power | | | Nankai | | | | |
| Flood | River | extreme precipitation | 10 to zero power | | | Coming soon | 6.9 miliion (Hurricane Harvey) | 82 | $160 billion | Masington Post (2017) |
| AI singularity | Modern civilization | Improvement of AI | ? | | | Coming within 20 years | | | | |

In this table, we merge many possible disaster types into one. Individually,

(i) the Gamma Ray Burst (GRB) is the biggest explosion that has been observed, in terms of energy. There are about 1000 GRBs per year in other galaxies. If there is ever a GRB in our galaxy, the Milky Way, it will be extremely catastrophic. Even if there were one within 8,000 light years of the Earth, it could have negative effects on our atmosphere. If there were one within 100 light years away, it would destroy the ozone layer. Since a longer GRB may be caused by the explosion of a super massive star, as in the case of Wolf-Reyet 104, it seems long GRBs are infrequent. However, as shorter GRBs may be caused by collisions of binary neutron stars, they may be more

common in the Milky Way. There is no evidence that there has ever been a GRB near Earth, but Bruce Liberman insists that the Oldovisian-Silrian Mass Extinction might have been caused by this type of GRB. We assumed the occurrence ratio (occurrence of GRBs in our galaxy) was once every billion years (Melott *et al*. 2014), but the ratio might be more frequent if those stars are found to be more common. Costa (1997) states that establishing the nature of γ-ray bursts is one of the greatest challenges in high-energy astrophysics. The rapid locating of this γ-ray burst instigated a multi-wavelength observational campaign that culminated in the identification of a fading optical transient in a position consistent with the X-ray transient reported here. Piran (1998) researched the comparison of theoretical models with afterglow observations; we calculate here the broadband spectrum and corresponding light curve of synchrotron radiation from a power-law distribution of electrons in an expanding relativistic shock. They gave explicit relations between the spectral index and the temporal power-law index. Klebesadel (1973) did observations of Gamma-Ray Bursts of Cosmic Origin and concluded that significant time structure within bursts was observed. Paciesas (1999) presents tables of the burst occurrence times, locations, peak fluxes, fluences, and durations. In general, results from previous BATSE catalogs are confirmed here with greater statistical significance for the Fourth BATSE Gamma-Ray Burst Catalog (Revised). Nousek (2006) presents new observations of the early X-ray afterglows of the first 27 gamma-ray bursts (GRBs) well observed by the Swift X-Ray Telescope (XRT).
(ii) Supervolcano (VEI-8) occurred 74 thousand years ago in Toba, which caused the Toba Bottleneck theory, an explanation of the reduction in population in regions of India. There is no clear evidence of how violent the Yellowstone supervolcano eruption was, as there is no clear evidence in the fossil record associated with a Yellowstone eruption, but there is some evidence of smaller scale (VEI-7) eruptions, e.g., Tambora, Krakatoa, Aso, and Kikai. VEI-8 eruptions are thought to occur once every 10–100,000 years, but smaller (VEI-7) eruptions might occur every 10 to 100 years. These are very frequent, and they affect many people. (iii) Asteroid collisions such as the Chicxulub event occur every hundred million years, which may be very rare, but smaller scale impacts (with the energy equivalent of the Hiroshima atomic bomb) occur almost annually. Most of these only produce an explosion in the atmosphere, which, in a practical sense, does not have any harmful effects, but once every hundred years, they sometimes occur very close to where people live. Robock (2009) has made six climate model simulations of the National Aeronautical Research Community Climate System Model 3.0 (CCSM 3.0) and the National Aeronautics and Space Administration Goddard Space Laboratory Model E. These simulations support the theory that the Toba eruption may indeed have contributed to a genetic bottleneck. Rose (1987) describes that, as one of the most known eruptions on earth, the 75 ka Toba eruption erupts at least 2800 km3 of magma, of which at least 800 km3 is deposited as a fall of ash. It is said that ash may be widely dispersed. The oldest yearly Tohiwa Tuff (YTT) eruption that

occurred in Indonesia 74,000 years ago is one of the largest known volcanic events on earth, but the widespread succession of Central Paleolithic technologies through the YTT event is said to suggest that humanity has survived this major eruption event (Petraglia, 2007).

(iii) Asteroid Attacks

The Chicxulub event was only scientifically recognized MEEs occurred 65 MY ago. However it is considered that there must be other smaller-scale catastrophic events associated with asteroid attacks. Most of asteroids and comets approaching Earth may fall into the ocean without giving clear evidence of the impact. Bruce Masse and Dallas Abbott stated that comet fall into the ocean may create Burckle creater around 4,800 BC. Smaller-scale asteroid attacks are very frequent, however the big one which may cause mass extinction is generally considered occurring once in every 10 to 100 million years (Gusiakov, 2010).

(iv) Superflares occur almost every year, but the biggest one recorded was the Carrington Flare, which occurred in 1859. Because human civilizations were not very developed, it did not have a serious impact, but if such a flare occurred in our modern civilization, there would be serious damage in the form of satellite failures, power plant failures, GPS system failures, and other associated damages. Since there is no clear evidence that events such as these have occurred, a group at Kyoto University (Maehara *et al.*) demonstrated the frequent occurrence of superflares in Sun-like (G type) stars through their observations with the Kepler space telescope. According to their observational results, as Sun-like stars have much more frequent and strong stellar flares, serious concerns about solar activity were raised.

(v) Earthquakes, as the representative HPLC disaster compared with MEE. The source of the 1906 San Francisco earthquake was studied (Wald, 1993). They then made a more detailed source analysis using Morgan Hill S body waves as empirical Green's Functions in a finite fault subevent summation, and “moved” the largest 1906 asperity into the Loma Prieta region. Peak ground velocity amplitudes are substantially greater than those recorded during the Loma Prieta earthquake. The ground motions estimated by the 1906 San Francisco earthquake (Aagaard , 2008). It was making use of the recently developed the source model that combines the available geodetic and seismic observations and recently constructed 3D geologic and seismic velocity models (Song, 2008). The effects of local geological conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake was researched (Borcherdt, 1976). They concluded that the maximum intensity map predicted on the basis of this data delineates areas in the San Francisco Bay region of potentially high intensity for large earthquakes on either the San Andreas Fault or the Hayward fault. The map provides a crude form of seismic zonation for the region and may be useful for certain general types of land-use zonation. Interim results of an ongoing study of building damage and losses likely to occur due to a repeat of the 1906 San Francisco earthquake was presented (Kircher, 2006). He was using the HAZUS technology. For

the 1906 San Francisco earthquake, the two previously mismatched source models were adjusted so that the rupture velocity exceeds the shear wave velocity, resulting in a model that satisfies both triangulation and seismic data (Song, 2018). Tsunami-induced coastal and estuarine morphology changes in Miyagi Prefecture, Japan, and the subsequent recovery process in the study area were presented (Tanaka, 2012). Furthermore, severe breaching was observed on sandy coasts where a former river mouth was located, due to strong return flow from the catchment area. Characteristics of liquefaction in the Tokyo Bay area by the 2011 Great East Japan Earthquake was presented (Yasuda, 2012). They state that the reclaimed lands that have been improved by the sand compaction pile method, the gravel drain method, or other methods, have not liquefied. "Based on the results of field surveys, coastal dike failures caused by the Great East Japan Earthquake were classified into eight patterns. The results of hydraulic model experiments related to major failure patterns reinforced the proposed failure processes. In addition, the aggregated length of each failure pattern showed that failure from scouring at the landward toe is the dominant failure pattern." (Kato, 2012)
Whether the Great East Japan Earthquake and tsunami, and the subsequent meltdown at the Fukushima Daiichi nuclear power plant, presents the Japanese state and society with a watershed opportunity to rethink regional revitalization and national energy procurement strategies was examined (Matanle, 2011).

## 2.2. Method

### 2.2.1. Insurance Mechanisms for LPHC Disasters

In recent years, the necessity for measures against Low Probability-High Consequences (LPHC) has increased. So how much should we prepare for the emerging risks, especially classified as LPHC disasters? Obviously, it is not realistic that human beings will be prepared for a potential GRB scenario and insurance and/or evacuation means. At the same time, asteroid impacts, which were long-time considered as very low frequency risk, are now considered one of the most important emerging risks, at least for NASA. This is because of the statistics and calculation results which took into account the number of asteroids surrounding the orbital path of Earth. Also, for floods and other climate disasters, no one has ever been prepared for them. However, it is an emerging risk which has serious economic effects. Would it be possible then that insurance companies prepare to issue these?

In general, most insurance companies will provide such insurance products for Emerging Risks at the last moment. This is because most insurance companies will not lose an opportunity if they do not make such efforts. On the other hand, no preparation for these insurance products has ill effects, and it's a lost opportunity for the public to be aware of these potential risks. Insurance companies have been trying to commercialize emerging risk insurance, but they have not always responded well to the needs of society (Yoshizawa, 2018).

Risk assessment is an obstacle, especially when insurance companies take on emerging risks. However, the insurance industry has an insurance underwriting method that allows it to undertake risks that are difficult to assess (post-insurance premium adjustment and fileite insurance). Insurance companies are expected to further refine these insurance underwriting methods and actively undertake emerging risks. In addition, the government is required to provide institutional coverage of such insurance underwriting methods (Meiji, the meiji certification standard for insurance).

While the development of insurance products that cover new emerging risks is expected, it should also be taken into consideration that there is an emerging risk that has been covered by existing products.

It can be said that there is a possibility of insuring emerging risk under certain conditions.
Although the insurance industry has been striving to commercialize emerging risk insurance, it cannot always be said that it is fully responding to the needs of society. Regarding emerging risks related to new technologies, the introduction of timely and appropriate insurance products promotes the application and dissemination of new technologies (Yoshizawa, 2018),.

In fact, emerging risks are not covered by conventional insurance products. Insurance companies are aggressively working on new insurance product development conducted by screening operations. In addition, profiling and risk assessment will be conducted that lead to the commercialization of insurance (Of course, there are many emerging risks that do not result in insurance products, even with the aim of commercializing new insurance). With regard to emerging risks related to new technologies, the introduction of appropriate insurance products in a timely manner promotes the application and dissemination of new technologies.

It is important to note here that even if these efforts by the insurer do not result in the launch of a new product, or even if the insurer did not do any of this, at least in the short term, the insurer will not lose a lot. Rather, instead of embarking on the commercialization of emerging risks, it is better to develop new insurance products that cover the emerging risks when they are transformed into normal risks. Because profiling and risk assessment are possible, it is much easier and safer. However, for individuals and businesses with emerging risks, the inability to prepare a risk transfer method called insurance has to be reluctant to accept emerging risks, and in the context of recent emerging risks it can be said that there is a fear that some technological innovation and its application will be hindered. Therefore, in order to reduce such social losses, it is necessary for insurance companies to give them an incentive to develop new insurance products that cover such risks for emerging risks that were not covered by conventional insurance products. Or, new products that cover emerging risks usually require more time and money to develop products than insurance products that cover risks, and since the diversification of the underwriting risk is also large, it is necessary for society to allow the insurance company to set the premium level to secure excess profit.

Table. 2 Economic damages for Emerging Risks.

| Disaster Types | Economic Damage | Source |
|---|---|---|
| Flood | $160 billion | NOAA (2018) |
| Tsunami, Earthquake | $16.9 trillion | Cabinet Office of Japan (2011) |
| Terrorism | $6.35 trillion | Institute for Economics & Peace (2015) |
| Ebola | $500 million〜$6.2 billion | The World Bank (2015) |
| Climate Change | $100 billion | Christian Aid (2018) |
| Supervolcano | • $2.5 trillion (Hoei Eruption)<br>• $98.5 trillion (Biggest in Europe) | • Cabinet Office of Japan (2004)<br>• Munich RE (2002) |

Accordingly, in order to establish emerging risks (classified as LPHC events) into insurance products, the risks should be presented to the public so that insurance premiums can be collected. Such kind of issues should be highlighted and discussed at higher attention seeking for higher support from governmental and academic sector. One subject might be the potential risk induced by asteroid impacts. This issue has recently been widely discussed among the public, by the leadership of NASA and other space agencies. Another would be volcanic eruption risk, for this case the potential cost for Mt Fuji eruption is calculated as roughly 20 billion USD if an eruption similar to the Hoei eruption in 1707 occurs.

The cost of Hurricane Harvey exceeded $125 billion, Hurricane Katrina was approximately $160 billion, and Hurricane Irma was $50 billion (NOAA, 2018).
The estimated amount of damage to capital stock during the Great East Japan earthquake was approximately $16.9 trillion (The Cabinet Office, 2011). According to the Institute for Economics & Peace (2015), the economic loss caused by Terrorism was $6.35 trillion. According to the World Bank (2015), the economic damage of Ebola is estimated to be at least $500 million in sub-Saharan Africa and at most $6.2 billion. The amount of economic damage caused by climate change is estimated to be approximately $100 billion (Christian Aid, 2018). The assumed amount

of damage caused by the Mt. Fuji eruption in Japan is assumed to be $2.5 trillion, derived from a model of the Hoei eruption (The Mt. Fuji Hazard Map Review Committee, 2004). Etna, the biggest volcano in Europe, likewise caused enormous damage when it erupted in 2001 and again in 2002/03. In 2002, the ash-rain alone caused economic losses of around $98.5 trillion (Munich RE, 2002).

Unlike an HPLC, there are no positives to being prepared before a real LPHC disaster. This is because it is low frequency and does not benefit the company. However, the amount of damage and the scale are enormous.
Therefore, in Chapter4, I will introduce some political implication to prepare for LPHC.

Summarry of Chapter 2

In this chapter, I reviewed in detail the historical facts of various disasters including MEE, LPHC, and HPLC, and explained the background of this paper. In the next chapter, I will quantify the flight risk of GLE based on a one-dimensional model.

## 3. Cost of Estimation for Alternative Aviation Plans against Potential Radiation Exposure Associated with Solar Particle Events for the Airline Industry

In this chapter, we present a systematic approach to effectively evaluate potential risk-cost caused by exposure to Solar Particle Events (SPEs) from solar flares for the airline industry. SPE is defined as the enhancement of solar energy particles with a proton flux of energy Ep> 10 MeV greater than or equal to 10 part / cm .s.sr (10 pfu) up to a background level near 1 AU (Kurt, 2004). we also evaluate associated health risks from radiation by using ExoKyoto, in order to provide relevant alternative ways to minimize economic loss and opportunity. The estimated radiation dose induced by each Solar Particle Events (SPE) for the passengers of each flight is calculated using ExoKyoto and PHITS. We determine a few scenarios for the estimated dose limit at 1 mSv, and 20 mSv, corresponding to the effective dose limit for the general public and occupational exposure, respectively, as well as a higher dose induced by an extreme superflare.

We set a hypothetical airline shutdown scenario at 1 mSv for a single flight per passenger, due to legal restrictions under the potential radiation dose. In such a scenario, I calculate the potential loss in direct and opportunity cost under the cancellation of the flight. At the same time, we considered that, even under such a scenario, if the airplane flies at a slightly lower altitude (from 12 km to 9.5 km, corresponding to the slight increase of atmospheric depth from 234 g/cm2 to 365 g/cm2), the total loss becomes much smaller than flight cancellation, and the estimated total dose now goes down from 1.2 mSv to 0.45 mSv, which is below the effective dose limit for the general public.

In the case of flying at an even lower altitude (7 km corresponding atmospheric depth with 484 g/cm2), the estimated total dose becomes much smaller, to 0.12 m Sv. If we assume the increase of fuel cost is proportional to the increase in atmospheric depth, the increase in cost becomes 1.56 and 2.07 for the case of flying at 9.5 km and at 7 km respectively. Lower altitude flights provide more safety for the potential risk of radiation doses induced by severe SPEs. At the same time, since there is total loss caused by flight cancellation, we propose that considering lower flight altitude is the best protection against solar flares.

### 3.1. Introduction

According to ICAO 's Manual on Space Information in Support of International Air Navigation (ICAO, 2008), space weather advisory messages must be issued as follows. Solar radiation storms are one type of space weather event that may require a fast response due to the immediacy of their impact. In certain situations, the lead time for a radiation advisory may be only a few minutes at most. In order to avoid radiation exposure, considerations of time, distance, and shielding allow decisive actions for mitigation of the threat. Shielding can mitigate solar radiation storms. Shielding from radiation consists of protection by (a) the overhead atmosphere and by (b) the geomagnetic field. When the field vector is more horizontal than vertical, charged particles are turned aside. The Earth's magnetic field is vertical at the poles and horizontal at the equator, so flying at lower latitudes increases the shielding. As for the FLIGHT CREW, advisories of imminent or on-going disruptions to HF, GNSS, and occurrence of radiation effects allow alternate route planning, or delayed use of polar routes. Options may include: a) Time – Delayed entry into regions specified in the advisory. b) Distance – Not only avoiding specified regions, but in the case of radiation, flying at a non-optimal but lower altitude for more shielding by the atmosphere. The best situation is to be able to plan 12-24 hours ahead of the occurrence, making allowances for flight reroutes, fuel, and crew schedules beforehand. Long-haul flights may be the most problematic as options are constrained by fuel, particularly if the airplane is on route when an unpredicted event occurs. According to ICAO, which defines the current flight operation standards, the policy for avoiding exposure as described above is established. Thus, for people working in the aviation industry, the exposure dose received during working hours is a serious problem.

The risks of radiation exposure from flying in an aircraft are detailed in various previous studies.

"Man-rad" evaluated as \$10-25 by classifying a tolerable dose and justifiable dose for professionals and the public (Dunster and Mclean, 1970). The former is to set the upper limit value of human exposure, and it is decided based on social factors, which is almost equal to the risk in other categories except radiation. They calculate the risk from actual radiation exposure, from the comparison with an age-specific death statistics table from the UK. In principle, it is considered to be somewhat higher than the maximum allowable line L of ICRP. They also mention that the tolerable dose becomes a collective dose, but the details are omitted.
The justifiable dose is determined by economic factors, and because of this, it is not possible to determine numerical values in a general theory, and it is necessary to carry out a cost-benefit balance in the context of a certain situation. The basic concept is not to compare the total costs and total benefits, but rather to compare the marginal cost of dose-reduction with the benefit of reducing the probability of cancer occurrence.

"Man-rad" evaluated as \$100-250 (Hedgran, 1970). As a general theory, decision-making in individual human activities or groups in society takes into consideration both cost and benefit. While cost includes direct cost and indirect cost (such as risk, benefit), it is also described as including substantial benefit and moral or ethical imaginary benefit.

For example, if you decide to go somewhere by airplane, Total cost = Airplane cost + Risk when you use the airplane (where, risk = accident rate x Q, Q is implied dollor The equivalent toahuman life) is compared with the benefit of using an airplane.

“Man-rad” evaluated as $200 (Otway, 1970). They stated that risk (or cost)-benefit assessment has come to attract attention in determining the soci*et al* acceptability of the technological applications. They conducted extensive reviews on the method of analysis and the amount of life to calculate the amount of man-rad, and then briefly introduced their own special method of estimating cost.

“Man-rad” evaluated as $100-250 (Lederberg, 1971). His calculations are based on the cost of health care and the biological effects of natural radiation in the United States. In other words, he estimates the risk of radiation exposure, and considers only cancer and mutations at low doses. He estimated that radiation exposure increases the cancer incidence rate by 1% for natural background levels (0.1 rad / year). (300,000 people die annually in the United States from cancer, and 300 of them die by natural radiation.) Despite such calculations, Lederberg is not very optimistic for cost-benefit analysis. One of the reasons is that people prefer qualitative judgment and points out that this cannot be judged quantitatively.

“Man-rad” evaluated as $250 (Cohen, 1970). In his paper, the health and physical aspects of the Plowshare plan are considered, which attempts to use nuclear explosions to facilitate peaceful use, particularly the extraction of gas from gas wells. Since rem is a unit of cost due to radiation exposure in his paper, he proposed a new unit called mer (the opposite of rem) as a unit of benefit that can justify the activity that brought about nuclear explosion.

He did not calculate the amount of merman on his own, but according to the results of the literature survey, it was assumed that $250 would be a reasonable value, which would be $250,000 for a lethal dose of 1000 rem. He stated it does not contradict arbitrage or lifetime earning ability.

“Man-rem” evaluated as $30 (Sagan, 1972). He calculated the total human cost for nuclear power generation at each of the series of processes from uranium mining to spent nuclear fuel reprocessing which is related to nuclear power generation. He calculated it by the figure of radiation exposure and accidental death in a general occupational accident. He employed man-rem $30 as the radiation exposure received by professionals and the general public and the value of life at $300,000 for accidental death in a general occupational accident that is not related to radiation exposure for workers.

“Man-rem” evaluated as $12-120 (Lederberg, 1972). The total cost of healthcare in the United States in 1970 is $8 x $10^{10}$ a year, and the population of the United States is approximately 2 x $10^{8}$, so the annual cost for healthcare per capita is $400.
Here, considering the genetic effects of radiation, it can be said that the medical cost per person per generation becomes 12,000 (= $ 400 / year × 30 years) dollars.

Next, if we assume the exposure of 5 rem (0.17 rem / year) in 30 years, this increases the amount of illness by 0.5 to 5% (It means that the genetic doubling dose of radiation is 200 to 20 rem), which will increase from 0.1 to 1%, an exposure of 1 rem would increase, accordingly, from 0.1% to 1%, resulting in (12,000 × 0.1 to 1% = $ 12 to $ 120.)

Therefore, if we continue until radiation exposure of 1 rem per one generation for 30 years reaches equilibrium, the amount of illness equivalent to the cost of 12 to 120 dollars per person per 30 years is added. That is, the amount of harm done by 1 rem is equivalent to a cost of $12 to $120 as an integral value over all future generations, regardless of whether or not it reaches equilibrium.

It is important to calculate cost-benefit of radiation exposure not only based on “man-rem” but also based on dollar-value by introducing the announcement of ICRP (Inaba, 1977).

Moreover, guidelines and regulations for radiation exposure to protect passengers and airline companies have recently been issued.

As for EU Member States, in accordance with Council Directive 96/ 29/EURATOM, 13 May,1996, “By ordinance, by May 2000, the necessary measures, such as laws, regulations, and administrative regulations, should be introduced, so that the company will carry out cosmic ray exposure measures for flight crews whose annual exposure dose exceeds 1 mSv in accordance with the directive. “This is characteristic of the EU, that many countries take an institutional response.

As for North America and Australia, there are no laws or regulations, but they respond by issuing guidelines etc. independently. For example, in the US:
・”Advises on radiation exposure of aircraft crew” (FAA: Federal Aviation Administration :

Advisory Circular 120-52)

・“Advice on training aircraft crews regarding cosmic radiation exposure during operation” (FAA: Federal Aviation Administration: Advisory Circular 120-61)

Australia

・”Recommendation 3022 for Limitation of Ionizing Radiation Exposure” (Australia National Occupational Health and Safety Commission (NOHSC))

・ Developing guidelines for business operators (Australian Radiation Protection and Nuclear Safety Agency: ARPANSA)Etc.

On the other hand, as for Asia, such as Thailand, Indonesia, and Malaysia, no response has been made at the present time. This is because the countries are located at a low latitude where the influence of cosmic rays is small.

In addition, some devices to protect people from radiation exposure in aircrafts have appeared, such as ARMAS Flight Module 5. It measures on-demand, real-time radiation doses from all sources at all altitudes based on the demand of global situational awareness. It has exposure alerts and flight path solutions during significant radiation storms as well as GPS location and Iridium plus Bluetooth connectivity.

In this chapter, I propose an insurance design as a measure of cost-benefit analysis and risk management for radiation exposure.

Estimated exposure to ionizing radiation due to secondary generated radioactive particles may cause health risks for passengers taking national and international flights. The exposure level to ionizing radiation induced by solar activities and cosmic rays becomes higher in proportion to the altitude, due to thinner atmospheric depth. The airline industry however, tends to fly at a higher altitude, around 12 km above the ground, situated at the tropopose, which separates the troposphere and stratosphere. Thinner atmospheric depth may reduce fuel consumption for each flight, which is advantageous for economic flights in many situations. Also, since the tropopose is situated above the troposphere, where continuous or sudden vertical convection due to ground heating in meteorological and hydrological processes occurs, flying at a higher altitude than the tropopose provides more stable flights for each airframe, avoiding serious vertical mixing.

On the other hand, the reduction of the estimated radiation dose has been raised with increased concern against ionizing radiation exposure, especially for the crew. For general passengers, it is an unnecessary concern for long-term exposure through radiation. However, concern should be raised in the case when extreme radiation exposure is expected upon certain conditions. The most serious scenario happens when Solar Particle Events (SPEs) occur.

The international standards for radiation protection have been studied from the time when radiation use became widespread, such as the application of X-rays to medicine. The International X-ray and Radium Protection Committee (IXRP) was established in 1928 as the organization responsible, and in 1950 the International Commission on Radiological Protection (ICRP) , "ICRP") was reorganized. Since then, the ICRP has issued international recommendations on the basic idea of radiation protection and the standards based on it, and those recommendations are respected in many countries in the world, as well as being applied to laws and safety administrations related to radiation protection. These have been widely adopted. Among the many ICRP functions, the main recommendations, which are the basic ideas regarding radiation protection in general, have been updated almost every 10-15 years. In the ICRP Publication 60, it was recommended that exposures from four natural radiation sources (described later), including aircraft accrual, be included as part of occupational exposure. Thus, we need to consider the effects of radiation exposure for the crew and passengers when flying.

The recommended critical dose for the general public is 1 mSv / year. In most situations, however, we are exposed to a natural dose of around 2.4 mSv/year, so this goal is not easily achieved. There are visible effects due to radiation dose when exposure is over 100 mSv, accordingly a low-level dose in the order of a few mSv is not considered serious or fatal. However, at the same time, the recommended dose to distinguish a radioactive protection area is 1.3 m Sv within three months. According to these trends, to circumvent radiation exposure of more than 1 mSv, it would be a safer criterion for the general public to minimize concern associated to radiation exposure. The potential exposure for an air flight crew and passengers are below a few mSv per year, whereas for astronauts, the average dose per day is a few mSv. In this study, we will therefore consider evaluating the potential risk for a very small level dose for the airline industry.

**3.2. Methods**

Dose evaluation for ionizing radiation for different scenarios have been performed by Sato *et al* (2018) using PHITS introduced into the ExoKyoto program. The outline of the method is written in Yamashiki *et al*. 2019. The outline is as follows (1) Determine the maximum flare event that occurred in every determined period. (2) Estimate the proton fluence and spectra using one of the hardest spectra as GLE43 (in order to estimate the most severe exposure case) (3) Perform Monte Carlo simulation using PHITS for dose calculation in every atmospheric depth to provide value in Gray and Sievert, then (4) Evaluate the final dose by extending the results, applying a filter function to represent magnetosphere. We consider the following five different solar flare scenarios; (1) Flares with the statistical occurrence frequency of (1) once in 1/10 year, (2) once in

1 year (Annual Maximum Flare), (3) once in 10 years (Decadal Maximum Flare), (4) The largest flare under current Solar activity (Spot Maximum Flare) and (5) Possible Maximum Flare. For each scenario, we calculate the above procedure and estimate the possible radiation exposure during one flare event (over a period of a few hours to one day). Compared to the next chapter, this chapter utilizes the one-dimentional model.

I propose insurance for radiation exposure incidents during airline flights in order to estimate the potential cost for each possible scenario, to circumvent exposure.

Frequency × Severity＝ Premium

In the above equation, 'Frequency' means a percentage of the incidents that occur, 'Severity' means the amount of damage. 'Other exposure' implies other types of exposure, rather than the target incident. In this study we have not evaluated exposures other than radiation exposure due to secondary particles. 'Premium' is the price of insurance.

We propose establishment of new regulations to reduce radiation exposure during flights.
If these new regulations are to be established, and the expected (estimated) dose by radiation exposure exceeds 1 mSv, the flight company should cancel the flight. In this scenario, there may be three options:
1) Cancelling flight for every passenger.
2) Flying at a lower alternative altitude ((a) 9.5 km / (b) 7 km) than the original planned altitude (normal flight altitude) (12 km).

In the first case (1), according to Wendover Productions, the loss will be $25,200 (each flight fee $175 × 144 passengers = Net Sales) which includes opportunity cost. It also includes the total cost which is equal to 'sales cost' + 'sales, general and administrative expenses' for one flight. We assume a flight from New York to San Francisco. In this case, it will be $11,820, broken down in the following table.

Table3. Flight cost estimation

| Type of cost | Amount |
|---|---|
| Fuel cost | $3,000 |
| Personnel expenses for one Airplane | $640 |
| Airport Fee for JFK | $1,089 |

| | |
|---|---|
| Airport Fee for SFO | $1,005 |
| Tax | $15.6 |
| Cost of Airplane | $1,783 |
| Personnel Fee at Airport | $4,000 |
| Insurance Fee | $288 |
| Total | $11,820 |

For the second case, if the estimated exposure of radiation exceeds 1mSv, but the flight company will change the flight altitude from 12km to 9.5km, the fuel costs would be multiplied by 1.56, which is we set for this formula, thus, the loss would become $4,680.

For the third case, if radiation exposure exceeds 1mSv but the flight company will change the altitude from 12km to 7km, the fuel costs will be multiplied by 2.07, thus, the loss for them will become $6,210.

According to the occurrence of Ground Level Enhancement (GLE) in which a neutron particle reaches ground level, we first have to estimate the rough probability of the occurrence of each event, by analyzing historical GLE (from GLE1 to GLE70). Ground-level augmentation (GLE) is a sudden, sharp, and short-lived increase in cosmic ray intensity recorded by a neutron monitor. These enhancements occur during a large solar flares (Firoz, 2010). Using the current survey we simply estimated the probability of an occurrence of the same scale as GLE42/43 using the X scale. GLE42/43 is considered X13, the probability of which is larger than the GLE 43 event, which is 0.4 (0.25). We calculated the number of GLE incidents, which is larger than GLE 43. We estimated the probability of GLE by using this number and drew a graph with logarithmization. In our calculations, we estimated the probability of a Carrington Event (estimated as X45, Cliver &Dietrich 2013) as once every 160 years (0.006) since it occurred in 1859, and a Miyake class Event as once every 1300 years (0.0007) because it occurred in 774-775 AD as the magnitude of 141 times larger than GLE69.

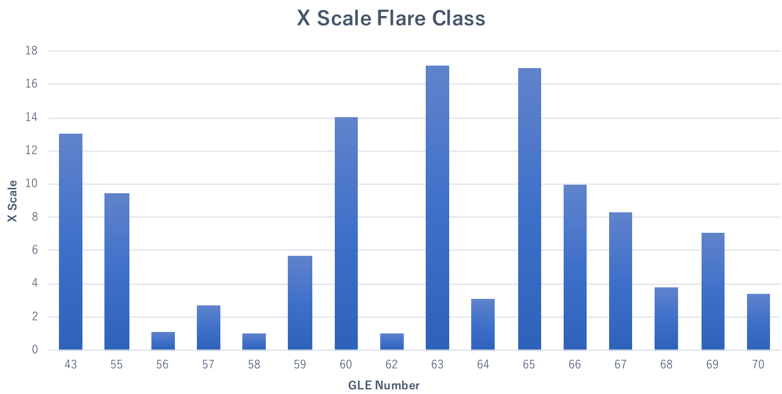



Figure 2. Major GLE events and their X scale measured by satellite GOES, after GLE 43 occurred in 1989.

In this study, we estimated the frequency of radiation exposure events, not only accounting for the historical observed GLE events, but also by using the relationship between sunspot area and flare frequency, described in Yamashiki *et al*. 2019 (Figure 2 Flare frequency vs flare energy for Solar Flares).  Using the above, we can estimate the potential global-average radiation exposure at aviation altitude. Please note that this study does not consider the spatial distribution of the location.

**Forecasting Period**

To accurately predict CME that causes severe radiation exposure, we now have to use information captured by the satellite GOES, as well as other means. Geostationary Operational Environmental Satellites (GOES) observes high-energy proton fluxes (Sato, 2019).

However, it is difficult to predict. In most cases, the alert will only come a few hours before, when actual optical / X ray signals are captured. For this reason, it is difficult to forecast and make necessary preparations in order to appropriately cancel a flight. According to above analyses, the cancellation of a flight causes huge losses, the alternative of flying at a lower altitude and other similar means will provide a better solution.

**Flight Path**

However, in real flights, a polar flight route will result in a much higher radiation dose compared with lower latitudes, due to the characteristics of energetic particles accumulated in the dypoles of the Earth, known as aurora. Cancellation of flights should be carefully evaluated, considering the flight route for each case. Changing the horizontal flight path to avoid polar regions may be another alternative solution, which should be evaluated in the next study.

**Possible Risk for Superflare**

As far a flare risks go, what should be considered in the future? According to our scenario, for the very active sun (sunspot area Aspot = 0.003 MSH (Micro Solar Hemisphere); 1MSH=3.32 × $10^{16} cm^2$ ), the Spot Maximum Flare energy is calculated at 3.64 x $10^{33}$ ergs. It was already discussed that a superflare may occur for a Sun-like G star according to observations using Kepler (Maehara *et al.* 2012 and Maehara *et al.* 2019). This implies we should prepare for many more superflares. In such cases, what would the potential radiation risk be? We set the Possible Maximum Flare, assuming that the sun surface was covered by 20% of sunspots – which is larger than estimated. It should be noted that this value was estimated assuming that sudden atmospheric escape would not happen. If sudden atmospheric stripping occurs the effect would be catastrophic.

## Normal Sun

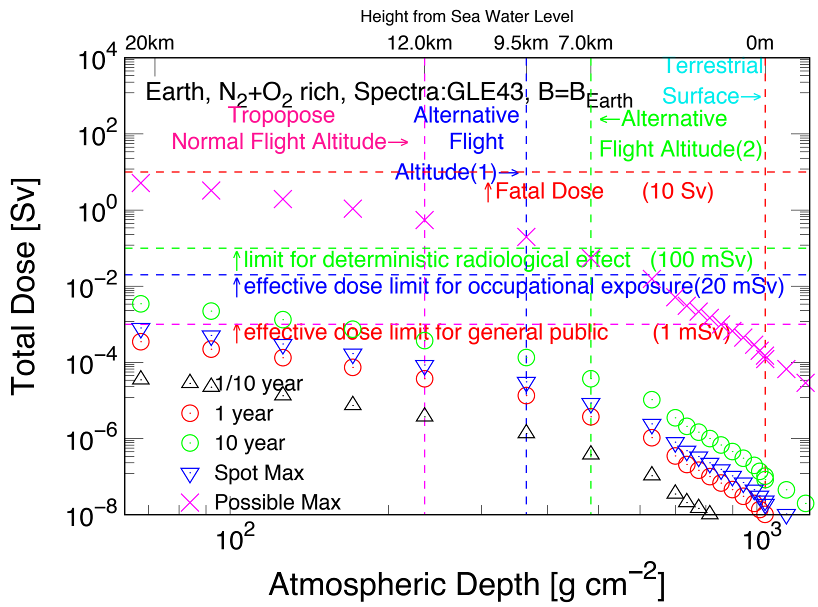



Figure 3. Vertical profile of radiation dose (Sv) on Earth under normal sun

Active Sun

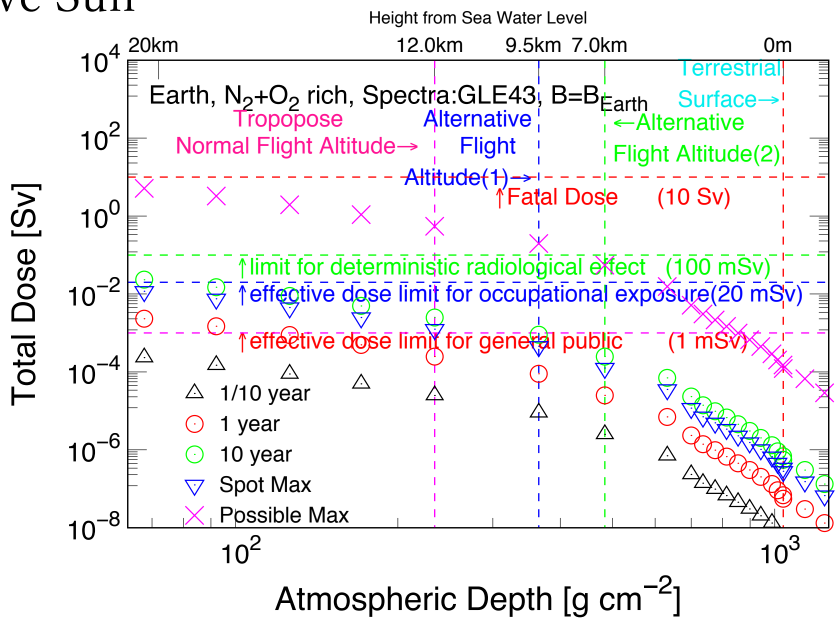



Figure 4. Vertical profile of radiation dose (Sv) on Earth under active sun

Figure 3 and 4 are vertical profile of radiation dose (Sv) on Earth for possible flares on several different scales under normal Sun (normal solar activity period, Aspot = 0.0005) and active Sun ( very active solar period, Aspot = 0.003), caused by hard proton spectrum (imitating GLE 43) penetrating N2+O2 rich (terrestrial type) atmosphere for Earth with flares every 1/10 year (36 days, black triangle), one year (red circle), decadal (green circle), spot maximum (blue triangle), possible maximum (pink cross). The vertical legend shows the three-typical aviation altitude reference layers: Normal Flight Altitude equivalent to 243 g/cm$^2$, Alternative Flight Altitude equivalent to 365 g/cm$^2$, and Alternative Flight Altitude equivalent to 484 g/cm$^2$, and Terrestrial Surface equivalent to 1037 g/cm$^2$. Note that the value is not identical to the real observation data but the nearest value employed in the Monte-Carlo numerical simulation using PHITS included in ExoKyoto.

### 3.3. Results and Discussion

Figure 3 and 4 introduce the frequency and energy of Annual Maximum Flares, and Spot Maximum Flares for (a) normal sun (sunspot area = 0.0005) and (b) active sun (sunspot area = 0.003). If we set up different criteria with the figures, we show three critical doses for human life;(i) 1m Sv as the effective dose limit for the general public, determined by ICRP, (ii) 20 mSv as the effective dose limit for occupational exposure, and (iii) 100 mSv, a limit for deterministic radiological effects. Also, we explicitly displayed 10 Sv as a fatal dose. According to the figures for fatal dose exposure, no scenario offers such a risk, neither for the fatal dose or the deterministic limit, except in the Possible Maximum Flare (PMF) scenario, with the estimated energy as 1.98 X $10^{36}$ ergs. The PMF is a extreme flare, which is an occurrence that we should consider for Young Sun but normally do not have to consider for our current Sun, it would only be considered for extreme conditions. If such a PMF happens, the radiation dose at normal flight altitude (12 km) may reach 0.5 Sv (500 mSv), and becomes much higher than the deterministic dose limit (100 mSv).

We also do not have to consider the exposure risk determined as occupational exposure, as long as flying under the normal altitude.  For these reasons, consideration should be focused only on the exposure for the general public, as 1 mSv per event. Under normal (or quiet) sun with smaller sunspot area (Aspot = 0.0005) no scenario reaches the maximum dose up to 1 mSv at normal flight altitude (12 km) except PMF scenario, whereas under active sun with larger sunspot area (Aspot = 0.003) flares occurs once every 10 years may cause the dose exceed to 1 mSv.

For each of the two cases, the estimated dose may become larger than this limit when flying at the normal flight altitude (12 km), under the Spot Maximum Flare and decadal maximum flare scenarios. In these cases, flying at 9.5 km and 7 km, may provide more safety, while flying at 7 km would be the safest.

Figure 5 introduces the estimated dose in different aviation altitudes by normalized flares. Note that in Figure 3 and 4, PMF is the scale of $10^{36}$ ergs, the normalized value reaches a similar value. It should be noted that since this scale of superflares may never occur on our current Sun (Maehara *et al*. 2012, Notsu *et al*. 2019), this is only considered as a theoretical maximum, we do not need to worry about such a radiation dose. However, even with such a dose, the expected dose does not exceed the fatal dose, set at 10 Sv. Superflares in the scale of $10^{34}$ ergs induce a dose larger than 1 mSv, but not 20 mSv at normal aviation altitude. For a flare with $10^{35}$ ergs the estimated dose becomes larger than 20 mSv, which may be a critical value for the effective dose limit for occupational exposure (20 mSv). In such case, flying at the alternative aviation altitude (1) and (2) gives lower doses than the limit for occupational exposure (20 mSv), but not lower than the limit for the general public (1 mSv). If such a superflare occurs, it might be better to cancel the flight. However, it is generally understood that a superflare larger than $10^{34}$ ergs may not be common (it has never been observed in human history) so these extreme conditions are not important for operational levels.

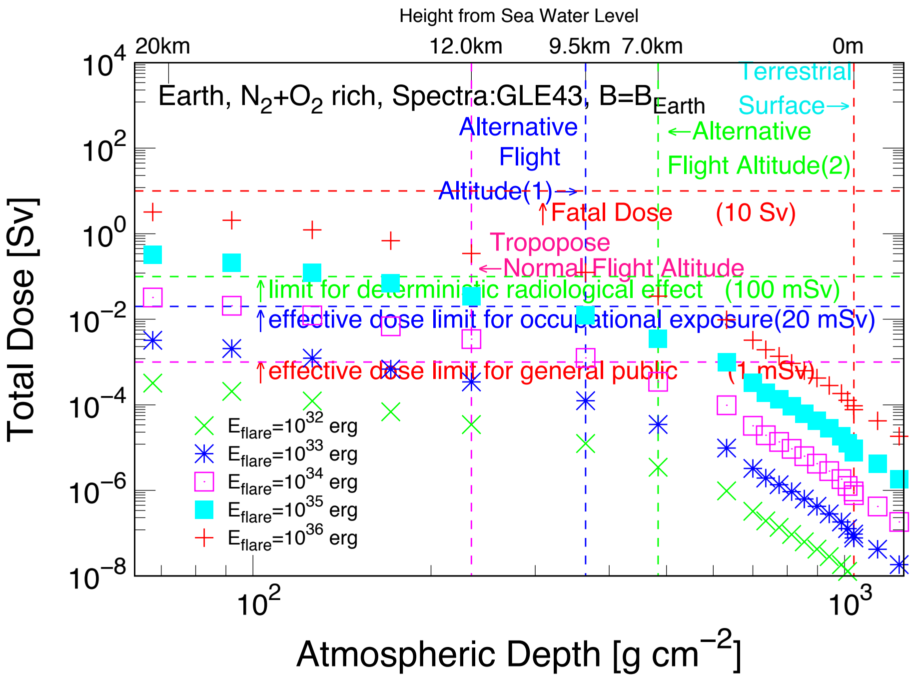



Figure 5. Vertical profile of radiation dose on Earth aviation altitudes for normalized flares

Figure 5 Vertical profile of radiation dose on Earth at different aviation altitudes for normalized flares, caused by hard proton spectrum (imitating GLE 43) penetrating N2+O2 rich (terrestrial type) atmosphere for Earth with $10^{32}$ erg (green cross), $10^{33}$ erg (blue star), $10^{34}$ erg (pink square), $10^{35}$ erg (blue square) and $10^{36}$ erg (red cross) in Sievert (Sv). The vertical legend shows the three-typical aviation altitude reference layers: Normal Flight Altitude equivalent to 243 g/cm$^2$, Alternative Flight Altitude equivalent to 365 g/cm$^2$ , and Alternative Flight Altitude equivalent to 484 g/cm$^2$, and Terrestrial Surface equivalent to 1037 g/cm2. Note that the value is not identical to the real observation data but at the nearest value employed in the Monte-Carlo numerical simulation using PHITS included in ExoKyoto.

In Chapter 2, the risk of solar flares was evaluated by the X Scale measured by the GOES satellite. In other words, it relies on the data above the sky, not on the ground, and assumes an average for the entire earth. In addition, this chapter uses a simple one-dimensional model in which the probability of a solar flare is expressed as a power of 10, and the flight path is relatively short.
On the other hand, in the next chapter, we estimated, calculated, and evaluated the probability of radiation exposure based on the database of GLE, which monitors the neutrons delivered to the ground called Oulu database.

Table 4. Comparison between Chp3 and 4

| | Chp3 | Chp4 |
|---|---|---|
| SEP Evaluation Method | X Scale | Oulu station |
| Flight Routes | Not Considered | Considered |
| Cost Estimation | Fixed | Multiple conditions |

### 3.4. Conclusion

We evaluated the estimated radiation dose under several SPE scenarios, which may occur either annually or decadally. The estimated dose under the ICRP's expected SPE events did not reach the effective dose limit for occupational exposure (20 mSv) per event. Accordingly, for these possible scenarios we consider the ICRP's expected SPE events did not reach the effective dose limit for the general public (1 mSv), estimating the cost of legal restriction of an airline. According to the scenario, we concluded that an alternative flight altitude would provide the most cost-effective alternative solution in such a case, reducing the total exposure of radiation and minimizing the total loss associated with flight changes. Moreover, flying at a lower altitude provides more safety as flying at 7 km will reduce radiation exposure up to ~ 10% when compared with flying at 12 km.

In this study, We only employ simple a case for this evaluation, since in our calculations we only averaged out a global scale estimated radiation dose, without distinguishing the different radiation exposures for different regions of the earth. Accordingly, in this simulation we could not evaluate how much of a risk may be expected if we fly a polar route, which is normally used for aviation on the Pacific Ocean.

In the next phase of our study, we plan to employ calculations that may provide different doses for different flight paths. The estimated cost for each radiation exposure scenario in our calculations has not been considered, as the estimated dose is too low to calculate (most of them are below 1 mSv). At the same time, we may conduct these calculations, assuming the same linear relationship can be applied for radiation exposure below 100 mSv in a future study.

We have not validated individual events and doses observed on airplanes regarding the possibility of the occurrence of superflares in this study. Moreover we should have statistically validated the probability of the occurrence of high SPE and determined the return period for such events. At the same time, it should be noted that we have records of SPEs and Ground Level Enhancement, but we do not have historical records of doses in each SPE. Converting the possibility of flare occurrences into the dose estimation might be the best solution at this stage. For this reason, we consider that our model may provide one of the most effective solutions for aviation exposure event. In a future study, we will be trying to utilize more realistic dose records in each flight record in order to improve our model.

Summarry of Chapter 3

In this Chapter, potential risk-cost caused by exposure to Solar Particle Events (SPEs) from solar flares for the airline industry was estimated by one-dimensional model. In Chapter3, the model was expanded to four-dimentional model.

## 4. Probabilistic Risk Assessment of Solar Particle Events Considering the Cost of Counter Measures for Reduction of the Aviation Radiation Dose

In this chapter, four-dimentional model based on WASAVIES and ExoKyoto was employed to assess the risks associated with the countermeasure costs to reduce SEP doses and dose rates for eight flight routes during five ground level enhancements (GLE).

In this Chapter, Cosmic-ray exposure to flight crews and passengers, which is called aviation radiation exposure, is an important topic in radiological protection, particularly for solar energetic particles (SEP). We therefore assessed the risks associated with the countermeasure costs to reduce SEP doses and dose rates for eight flight routes during five ground level enhancements (GLE). A four-dimensional dose-rate database developed by the Warning System for Aviation Exposure to Solar Energetic Particles, WASAVIES, was employed in the SEP dose evaluation. As for the cost estimation, we considered two countermeasures; one is the cancellation of the flight, and the other is the reduction of flight altitudes. Then, we estimated the annual occurrence frequency of significant GLE events that would bring the maximum flight route dose and dose rate over 1.0 mSv and 80 μSv/h, respectively, based on past records of GLE as well as historically large events observed by the cosmogenic nuclide concentrations in tree rings and ice cores. Our calculations suggest that GLE events of a magnitude sufficient to exceed the above dose and dose rate thresholds, requiring a change in flight conditions, occur once every 47 and 17 years, respectively, and their conservatively-estimated annual risks associated with the countermeasure costs are up to around 1.5 thousand USD in the cases of daily-operated long-distance flights.

### 4.1. Introduction

Cosmic-ray exposure is an important topic for aviation workers, such as cabin attendants and pilots in most flight companies. In principle, the higher the altitude and latitude of the plane, the higher the dose rate of radiation when flying. Therefore, the International Committee on Radiological Protection (ICRP) recognizes the cosmic-ray exposure to aircrews as an occupational hazard (ICRP, 1991). In addition, ICRP provided an updated guidance on radiological protection from aircrew exposure, considering the current ICRP system of radiological protection (ICRP, 2016). In response to these publications, the International Civil Aviation Organization (ICAO) has recently decided to use radiation dose as mandatory information requested from space weather information providers (ICAO, 2018).

Two primary cosmic-ray sources can contribute to aviation radiation exposure: galactic cosmic rays (GCR) and solar energetic particles (SEP). Galactic Cosmic Rays (GCR) are the slowly varying, highly energetic background source of energetic particles that constantly bombard Earth. GCR originate outside the solar system and are likely formed by explosive events such as supernova (NOAA).

Solar energetic particles (SEPs), which form an essential component of the radiation environment near Earth (Vainio *et al*. 2009; Schwadron *et al*. 2017), appear as sporadic fluxes of energetic protons and a small fraction of heavier particles associated with powerful solar flares and/or coronal mass ejections (Poluianov, 2018).
The GCR fluxes are relatively stable and predictable compared to of SEP, and their dose rates are always low – below 10 μSv/h at the conventional flight altitude of 12 km (Sato, 2015). By contrast, SEP fluxes suddenly increase when a large solar particle event (SPE) occurs, and their dose rates occasionally become very high – more than 2 mSv/h (Matthiä *et al*, 2015), though the duration of such high dose rate events are generally short. Considering that ICRP recommends suppressing the dose to an embryo/fetus below that of about 1 mSv[2], it is desirable to take adequate actions such as reduction of the flight altitude during such large SPEs.

There are two major methods for detecting a SPE: one is based on high-energy proton detectors mounted on Geostationary Operational Environmental Satellites (GOES), and the other is based on neutron monitors on the Earth's surface. The former can detect SEPs directly by measuring proton fluxes above 1 MeV, while the latter detects SEPs indirectly by measuring secondary neutrons generated through nuclear interactions induced by SEPs in the atmosphere. SPEs with a significant increase in neutron monitor count rates are rarely observed in comparison to those with an increase in the GOES proton fluxes, because most SPEs do not emit high-energy protons ($E$ > 450 MeV) that can create neutrons reaching the Earth's surface. These events are called ground-level enhancement (GLE), and only 72 of them have been recorded over eight decades of observation. Using the GOES and/or neutron monitor data, several systems have been developed to issue an alert to SEP exposure or provide the information on SEP doses at flight altitudes (Latocha *et al*, 2009), (Mertens *et al*, 2010), (Lantos *et al*, 2003), (Kataoka *et al*, 2018), (Sato *et al*, 2018), (Copeland, 2016).

If an airline company takes actions to reduce aviation doses in response to an alert issued by these systems, it is necessary to estimate its costs. A potential mitigation procedure is a reduction of flight altitude, and Matthiä *et al* discussed its economic impact（Matthiä *et al*, 2015）. However, the discussion was based on calculated aviation dose for a certain flight condition, which was a transatlantic flight on December 13th, 2006 from Seattle to Cologne, during which GLE 70 occurred (Yamashiki *et al*, 2020), also made a cost estimation of aviation radiation exposure for a short flight distance (US domestic flight) using X-ray flux ($W/m^2$) based on GOES satellite measurements as the index of the magnitude of an SPE, but the spatial variation of the SEP dose rates were not considered in their estimation. In order to generalize the cost and develop insurance for aviation radiation exposure, estimations of aviation doses for various flight conditions are indispensable. The frequency of the occurrence of SPEs that require a mitigation procedure must also be evaluated.

With these situations in mind, we calculated the maximum doses and dose rates due to SEP exposure for eight flight routes with two cruise altitudes during five GLE events, by integrating the four-dimensional aviation doses calculated by WASAVIES Compared to the previous chapter, this chapter utilizes four-dimentional model. Based on the results, the annual occurrence frequency that the total doses exceed 1 mSv or the dose rates exceed 80 μSv/h were estimated by scaling the magnitude of the GLE using the event-integrated intensity (EII) proposed by Asvestari (2017) or peak-event intensity (PEI) proposed in this study. Note that 80 μSv/h is the threshold dose rate that is classified as "severe" exposure in the Space Weather D-index (Meier *et al*, 2018), (Matthiä *et al*, 2014) and the ICAO space weather advisory information (ICAO, 2018). Then, the cancellation and extra fuel costs were estimated in order to help to design an insurance system for airline companies to protect against elevated aviation radiation dose.

## 4.2. MATERIALS AND METHOD

### 4.2.1. Estimation of flight route doses during GLE events

Four-dimensional (Three spatial dimensions and one temporal dimension) dose rate data for 5 different GLE events (GLE60, 69-72) were prepared using WASAVIES: WArning System for AVIation Exposure to Solar energetic particles. WASAVIES can determine event profiles by using real-time data of the count rates of several neutron monitors (NMs) at the ground level and high-energy proton fluxes observed by Geostationary Operational Environmental Satellites (GOES) satellites.

This can determine the aviation dose during a GLE anywhere in the atmosphere in five-minute intervals using databases based on SEP transport simulations from the Sun to the ground level of the Earth. In WASAVIES, it is assumed that the SEP fluence and its temporal variation generated around the Sun can be simply expressed by a power function of energy and the inverse Gaussian distribution of time, respectively. Then, the database of the SEP fluences at 1 astronomical unit (AU) was prepared by solving the one-dimensional focused transport equation for 6 power indexes and 3 shape parameters (Kubo *et al*, 2015). In addition to the power index and shape parameter, the total fluence and tilt angle of the SEP incident to the Earth must be determined in order to characterize GLE, and their numerical values are evaluated in real time using the GOES proton fluxes and the count rates of several neutron monitors on the ground. Note that the evaluated parameters vary with time, and thus, the temporal variations of the GLE characteristics such as hard and soft spectra of SEP at the increasing and decreasing phases of GLE, respectively, can be considered in WASAVIES. For spatial resolution, the atmosphere was divided into 28 altitude layers, and the data for each altitude was an average value at intervals of 15 degrees for longitude and 10 degrees for latitude. The intricated latitude, longitude, and altitude dependences of the dose rates were reproduced by developing the databases of SEP trajectories in the magnetosphere using the empirical geomagnetic field model T89 (Tsyganenko, 1989) and the airshower simulation performed by the PHITS code (Sato *et al*, 2018). PHITS code is a Monte Carlo calculation code that simulates the behavior of various radiations in an arbitrary system using a nuclear reaction model and nuclear data (Sato, 2019).

The aviation doses due to GCR exposure can also be calculated in the system, using the PARMA model[4]. The PARMA model can be used to quickly calculate cosmic ray doses with the same accuracy as Monte Carlo simulations. This requires much less computation time. These properties allow PARMA to improve the accuracy and efficiency of cosmic ray exposure dose estimation for crew members as well as civilians on the ground (Sato, 2008).

Table 5. Information on 8 selected flight routes and their fuel and cancellation costs

| Flight ID | Departure | Arrival | Distance | | Time | Cost (1,000 USD) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | (Mile) | (km) | (h) | Fuel@12km | Fuel@9km | Fuel increase (@9km-@12km) | Cancellation |
| LAX_LHR | Los Angeles | London | 5,488 | 8,832 | 10.6 | 51 | 63 | 12 | 97 |
| SYD_EZE | Sydney | Buenos Aires | 7,368 | 11,858 | 13.9 | 68 | 84 | 16 | 67 |
| SFO_LHR | San Francisco | London | 5,399 | 8,689 | 10.4 | 50 | 62 | 12 | 98 |
| NRT_LHR | Narita | London | 6,009 | 9,671 | 12.9 | 62 | 77 | 15 | 78 |
| SYD_GIG | Sydney | Rio De Janeiro | 8,463 | 13,620 | 15.9 | 77 | 95 | 18 | 52 |
| SYD_LIM | Sydney | Lima | 8,006 | 12,884 | 15.1 | 73 | 90 | 17 | 59 |
| SYD_CPT | Sydney | Cape-town | 6,882 | 11,075 | 14.6 | 71 | 87 | 16 | 62 |
| NRT_JFK | Narita | New York | 6,784 | 10,918 | 12.9 | 63 | 77 | 13 | 76 |

Eight long-distance and high-latitude flight routes were selected in this study for investigating aviation doses, and they are summarized in Table 1. The information on each flight route and time are taken from the Japanese Internet System for Calculation of Aviation Route Doses, JISCARD (Yasuda *et al*, 2011), which assumes that the aircraft flies on the great circle routes at a constant cruise altitude (9 km or 12 km). The average speeds for each route are between 531 miles/h (855 km/h) and 467 miles/h (752 km/h), which was calculated considering the drag force during ascent and descent as well as cruising with a stable speed at the altitude of 12 km. For the alternative cruise altitude of 9 km, we simply applied the same flight path and speed with 12 km in order to unify and simplify the discussion along the flare time. This should be improved in further studies. Then, we calculated the dose rates on each flight path at 5-minute intervals based on the four-dimensional (latitude, longitude, altitude, and time) dose rate data evaluated by WASAVIES. The total doses obtained for each flight were estimated by simply integrating the calculated dose rates with respect to the entire flight duration. In this estimation, we made a series of hypothetical timelines for the departure of each flight, setting before, during, and after the onset of each GLE event in order to find the flight schedule to give the maximum total dose.

The fuel costs were estimated for a B747-400 with weight of 500,000 lbs (226,796 kg) at the altitudes of 9 and 12 km with the respective fuel consumption rate of 21,000 lbs (9,525 kg)/hour and 17,000 lbs (7,711 kg)/hour, respectively found in literature (Hagiwara *et al*, 1994). They are shown in Table 1. Note that the price of fuel was set to 0.284 USD/lb (0.626 USD/kg) in this estimation. Cancellation costs were estimated based on the methodology and cost parameter introduced by Marks (2014) based on statistics of airlines in the USA. The cancellation costs consist of three major components. One is the base incremental cost which includes costs for crew, maintenance, and airport related costs. Second is the net offset cost which become unnecessary, such as fuel that would have been burnt, landing fees, and overflight fees. These are negative costs. Third is the commercial cost which is caused by ticket refunds and displacement of revenue associated with rebooking of passengers. Accommodation cost for passengers were not considered, because the SPE can be considered as an uncontrollable event for which airlines are not responsible. The total cancellation costs are the sum of the cancellation costs of the particular flight and its subsequent flight which will also be cancelled. We used the parameters shown by Marks (2014) for a long-haul international flight with two-cabin-class configuration. The ticket prices are assumed to be on average the same for all the routes. The fuel related parameters were replaced by those used for the fuel costs calculation at 9 and 12 km. The results are shown in Table 1. It should be noted that the cost may be different for airlines operating in different regions.

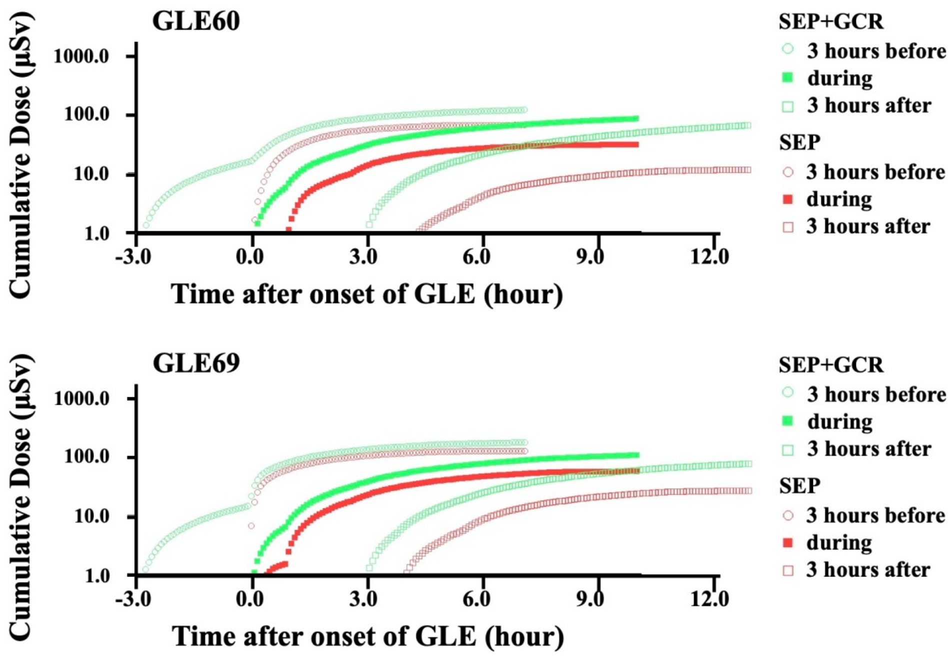



Figure 6. Calculated cumulative dose for flights from Los Angeles to London departing 3 hours before, during, and 3 hours after the onset of GLE 60 and 69, respectively. The cruise altitude was set to 12 km in this calculation.

Figure 6 shows the temporal changes in cumulative dose for the flight route of Los Angeles to London (LAX-LHR) departing 3 hours before, during, and 3 hours after the onset of GLE 60 and 69, respectively. For the numerical simulation, we evaluated in 5 minutes sequences for the duration of 24 hours. Note that all doses calculated in this study are the effective dose based on the definition of the 2007 recommendations of ICRP (2007). The green and red dots represent the cumulative dose in $\mu$Sv for a single flight path with different departure times, including and excluding the GCR dose component, respectively. In this case, a flight departing approximately 3 hours before the onset of GLE gives the maximum dose for both GLEs. This calculation has been accomplished for all flight routes, with different GLEs under different flight altitudes.

3.2.2. Calculation of the annual frequency of GLE

For representing GLE magnitude, Asvestari *et al* (2017) proposed using EII, which is defined as the integral of the excess above the GCR background over the entire duration of the event. It corresponds to the total fluence of SEPs with energy sufficient to cause an atmospheric cascade (several hundred MeV). The EII in the unit of %*h for 48 GLEs in the past 70 years was evaluated by Asvestari *et al* (2017), using GLE records of polar sea-level neutron monitors. Although the count rates of the neutron monitors located only at the polar region were used in the determination of EII, it can be used as an index for representing the global increase of aviation dose level for the entire GLE period because the SEP doses barely increase at lower latitude regions.

I calculated this EII by downloading data from all stations at Oulu and multiplying %INC. (how the percentage increased from the normal neutron fluxes) by time (minutes) and calculated the average number in the same way of EII by Asvestari.

On the other hand, the index for representing the highest SEP dose at a certain location in the world can be also useful for considering aviation exposure insurance.

I therefore calculated and introduced the Peak Event Integrated Intensity (PEII), which is the highest EII recorded among all neutron monitors collected at the International GLE database.

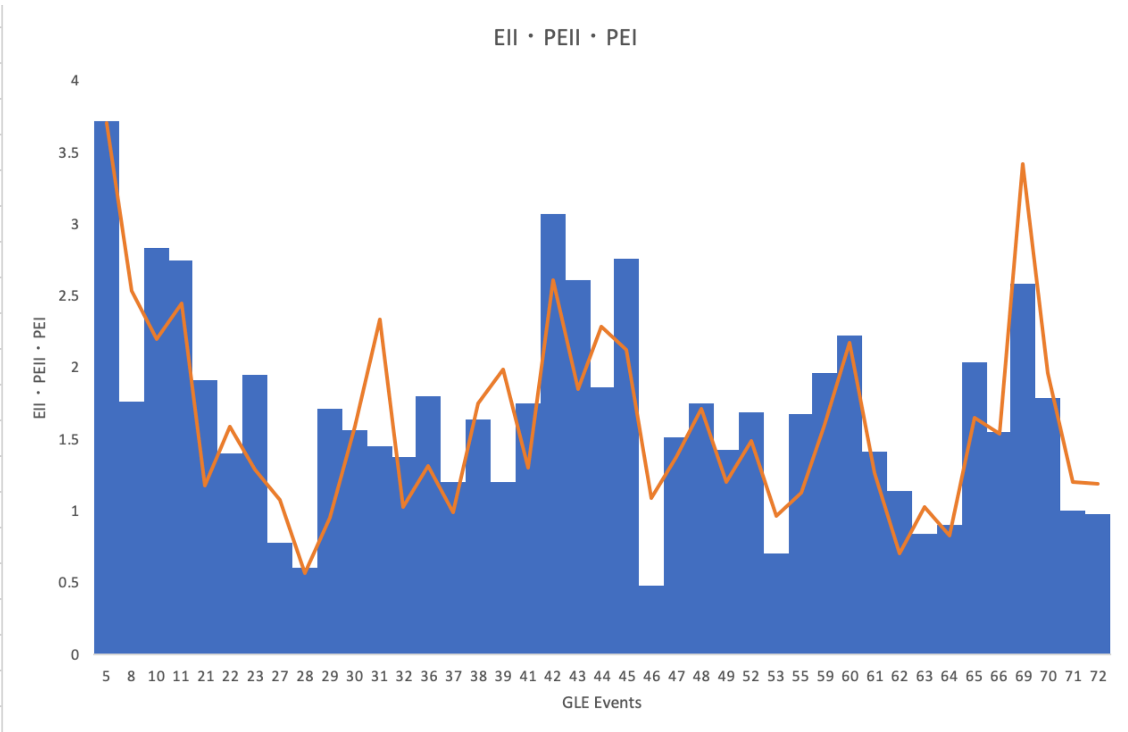



Figure7. EII and PEII for all GLE events from Oulu database.

However, in order to utilize Dose rate, it is better to introduce the data of the highest% of the highest points as PEI (Peak Event Intensity) instead of PEII. Since PEII calculates the sum of all the values of Peak's EII, if there is a variation between high and low values, it is necessary to use

the ratio index because the bias is not reflected by the value alone.
That is, I utilize EII for the 1mSv limit and PEI for the 80uSv / h limit.

Moreover, the index for representing the highest SEP dose rate at a certain location in the world can also be useful in considering insurance for aviation radiation exposure. We therefore introduced PEI, which is the highest count rate (counts per minute) increase above GCR background count rate seen among all neutron monitors except for the South Pole station. The reason for excluding the data from the South Pole is that the altitude and latitude of the station are so high that the count rates cannot be directly compared with the data for other stations. The numerical values of PEI for each GLE were obtained from the count rates of all available neutron monitors provided on the Oulu station website (http://cosmicrays.oulu.fi/).

Then, we calculated the annual frequencies of the occurrence of GLE with EII or PEI above a certain threshold value $s$, $F_{\mathrm{EII}}(s)$ or $F_{\mathrm{PEI}}(s)$, by counting the number of corresponding GLEs divided by 70. For example, 10 GLEs with EII above 92 %*h were observed in the past 70 years, $F_{\mathrm{EII}}(92)$ can be determined to be 0.143, i.e. 10/70. The calculated frequencies are shown in Figure 2 as a function of the threshold EII or PEI. In the plots, we excluded GLEs with EII or PEI values less than 10 %*h or 10% because SPEs with such low EII or PEI might not be detected as a GLE. In addition, recent investigations on the cosmogenic nuclide concentrations in tree rings and ice cores have revealed that extremely large SPEs with hard SEP spectra occurred in AD 774/5 and AD 993/4 (Miyake *et al*, 2012), (Miyake *et al*, 2014). The total SEP fluences during these events were estimated to be 119–141 and 51–68 times higher than those during GLE 69 (Mekhaldi, 2015). We therefore assumed that the SPE having EII 59.5 and 130 times higher than that of GLE 69, 385 %*h, could occur twice and once per 2000 years respectively, and added the frequencies of $F_{\mathrm{EII}}(22908) = 0.001$ and $F_{\mathrm{EII}}(50050) = 0.0005$ in Figure 2. On the other hand, PEI of those historical events has not been investigated, and they are not included in Figure 2. It should be mentioned that those historical events might consist of multiple SPEs. However, this fact does not result in the large uncertainties of the fitting described below because the magnitude and frequency of each SPE become smaller and higher, respectively. For example, if 10 SPEs with an equal magnitude would have occurred during those historical events, the corresponding frequencies would be $F_{\mathrm{EII}}(2290.8) = 0.01$ and $F_{\mathrm{EII}}(5005) = 0.005$, which are still consistent with the fitting results shown in Figure 8.
In this study, $F_{\mathrm{EII}}(s_{\mathrm{EII}})$ is assumed to follow the power-law function of $s_{\mathrm{EII}}$, as written by:

$$F_{\mathrm{EII}}(s_{\mathrm{EII}}) = 10^{\{A_{\mathrm{EII}}\log_{10}(s_{\mathrm{EII}})+B_{\mathrm{EII}}\}}\,, \tag{1}$$

where $A_{\mathrm{EII}}$ and $B_{\mathrm{EII}}$ are the fitting parameters obtained from the scatter plot shown in Figure 2 and their numerical values are -0.706 and 0.591, respectively. In a similar manner, $F_{\mathrm{PEI}}(s_{\mathrm{PEI}})$ can be calculated by

$$F_{\mathrm{PEI}}(s_{\mathrm{PEI}}) = 10^{\{A_{\mathrm{PEI}}\log_{10}(s_{\mathrm{PEI}})+B_{\mathrm{PEI}}\}}. \quad (2)$$

The numerical values of $A_{\mathrm{PEI}}$ and $B_{\mathrm{PEI}}$ are evaluated to be -0.604 and 0.425, respectively. Then, the annual frequency that the maximum flight route dose exceeds the threshold dose, $D_{\mathrm{thre}}$, for a certain flight route $i$ estimated from the $j^{\mathrm{th}}$ GLE event can be calculated from Eq. (1) by substituting $s_{\mathrm{EII},j}D_{\mathrm{thre}}/D_{i,j}$ into $s_{\mathrm{EII}}$, i.e. $F_{\mathrm{EII}}(s_{\mathrm{EII},j}D_{\mathrm{thre}}/D_{i,j})$, where $s_{\mathrm{EII},j}$ is the EII value for the $j^{\mathrm{th}}$ GLE event and $D_{i,j}$ is the maximum SEP dose for a flight route $i$ during the $j^{\mathrm{th}}$ GLE event. For example, if the maximum SEP dose for a certain flight route $i$ during the $j^{\mathrm{th}}$ GLE event with EII = 1000 %*h is 0.1 mSv, $F_{\mathrm{EII}}$ for $D_{\mathrm{thre}}$ = 1.0 mSv is estimated to be $10^{(-0.706*\log10(1000(1.0/0.1))+0.591)}$ = 0.00584. In a similar manner, the annual frequency that the maximum flight route dose rate exceeds the threshold dose rate, $\dot{D}_{\mathrm{thre}}$ can be calculated from Eq. (2) by substituting $s_{\mathrm{PEI},j}\dot{D}_{\mathrm{thre}}/\dot{D}_{i,j}$ into $s_{\mathrm{PEI}}$, i.e. $F_{\mathrm{PEI}}(s_{\mathrm{PEI},j}\dot{D}_{\mathrm{thre}}/\dot{D}_{i,j})$, where $\dot{D}_{i,j}$ is the maximum SEP dose rate for flight route $i$ during the $j^{\mathrm{th}}$ GLE event. Note that these threshold dose and dose rate do not include the contribution from GCR.

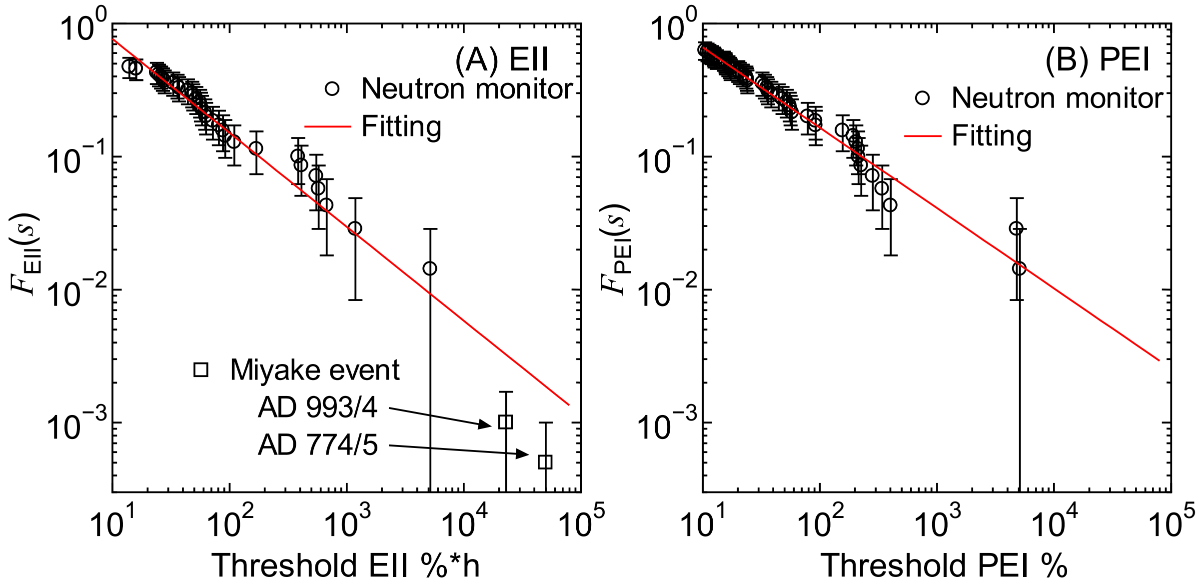



Figure 8. Annual frequency of the occurrence of GLE with (A) EII or (B) PEI above certain threshold value $s$. The error bars were simply estimated from $F_{\mathrm{EII}}(s)/\sqrt{N_{\mathrm{GLE}}}$ and $F_{\mathrm{PEI}}(s)/\sqrt{N_{\mathrm{GLE}}}$, where $N_{\mathrm{GLE}}$ is the overall number of GLE contributing to the data.

### 3.3. Probabilistic risk estimation

In the risk estimation associated with aviation exposure due to SEPs, we assumed two simple and fundamental solutions as countermeasures to reduce the SEP dose; one is the cancellation of the flight when the maximum dose or dose rate exceeds $D_{\mathrm{thre}}$ or $\dot{D}_{\mathrm{thre}}$ at the flight altitude of 9 km, and the other is to lower the cruise altitudes from 12 km to 9 km when the maximum dose or dose rate exceeds the threshold level at 12 km but does not at 9 km. Here, we simply assume that cruising at altitudes lower than 9 km would not be practical, because the aircraft may suffer from turbulence induced by upwelling flow more frequently and from increased air drag due to exponentially increasing air density than flying at a higher altitude. A more practical solution should be addressed in a future study, together with the potential countermeasures for en route flights, such as routing to lower latitudes, temporarily lowering flight altitude, and emergency landing, which should be assessed with a more realistic aircraft performance model and considerations from the viewpoint of air traffic management (Mattiä *et al*, 2015), (Saito *et al*, 2021).

Based on this strategy, the annual risk associated with avoiding the maximum dose of $D_{\rm thre}$ for flight routes $i$ estimated from the $j^{\rm th}$ GLE event, $R_{i,j}(D_{\rm thre})$, was calculated as follows:

$$R_{i,j}(D_{\rm thre}) = \left[F_{\rm EII}\left(s_{{\rm EII},j}D_{\rm thre}/D_{i@12{\rm km},j}\right) - F_{\rm EII}\left(s_{{\rm EII},j}D_{\rm thre}/D_{i@9{\rm km},j}\right)\right]\left(C_{i@9{\rm km}} - C_{i@12{\rm km}}\right) + F_{\rm EII}\left(s_{{\rm EII},j}D_{\rm thre}/D_{i@9{\rm km},j}\right)C_{i{\rm Cancel}}, \quad (3)$$

where $D_{i@9{\rm km},j}$ and $D_{i@12{\rm km},j}$ are the maximum SEP doses for flight route $i$ at the cruise altitudes of 9 km and 12 km, respectively, $C_{i@9{\rm km}}$ and $C_{i@12{\rm km}}$ are the fuel costs of flight route $i$ at the cruise altitudes of 9 km and 12 km, respectively, and $C_{i{\rm Cancel}}$ is the cancellation cost given in Table 1. The first term represents the risk associated with the extra fuel cost when a flight can be operated at an altitude of 9 km but not at 12 km, and the second term represents the risk associated with the cancellation cost when a flight cannot be operated even at an altitude of 9 km. In the same manner, the annual risk associated with avoiding the maximum dose rate of $\dot{D}_{\rm thre}$ for flight routes $i$ estimated from the $j^{\rm th}$ GLE event, $R_{i,j}(\dot{D}_{\rm thre})$, was calculated as follows:

$$R_{i,j}(\dot{D}_{\rm thre}) = \left[F_{\rm PEI}\left(s_{{\rm PEI},j}\dot{D}_{\rm thre}/\dot{D}_{i@12{\rm km},j}\right) - F_{\rm PEI}\left(s_{{\rm PEI},j}\dot{D}_{\rm thre}/\dot{D}_{i@9{\rm km},j}\right)\right]\left(C_{i@9{\rm km}} - C_{i@12{\rm km}}\right) + F_{\rm PEI}\left(s_{{\rm PEI},j}\dot{D}_{\rm thre}/\dot{D}_{i@9{\rm km},j}\right)C_{i{\rm Cancel}}, \quad (4)$$

where $\dot{D}_{i@9{\rm km},j}$ and $\dot{D}_{i@12{\rm km},j}$ are the maximum SEP dose rates for flight route $i$ at the cruise altitudes of 9 km and 12 km, respectively. We calculated the risk for $D_{\rm thre}$ = 1 mSv and $\dot{D}_{\rm thre}$ = 80 μSv, which are the annual dose limitation of public exposure in planned exposure situations recommended by ICRP and the threshold dose rate that is classified as "severe" exposure in the Space Weather D-index, respectively.

It should be noted that Eqs. (3) and (4) give conservative estimates of the risks based on the maximum dose or dose rates for each flight route, i.e., they intrinsically assume that the worst-case-scenario flight is always scheduled when a GLE occurs. To reduce the conservativeness, we introduced the scaling factor for considering the probability of scheduling the worst (or equivalent) scenario flight, which should complicatedly depend on the flight route and frequency, as well as the temporal and spatial variations of the SEP dose rates. For simplicity, we presume that the worst scenario always occurs when the GLE onset is during the cruise time of a flight in this study, and approximate the scaling factor by the product of the number of annual scheduled flights per route and cruise time per flight divided by the total time per year. For example, the scaling factor is determined from the cruise time in hours divided by 24 in the case of daily-operated flight. Further analysis for more precisely evaluating the scaling factor must be performed in the future.

### 4.4. RESULTS AND DISCUSSION

Table 6 shows the maximum doses and dose rates due to SEP exposure for eight selected flight routes at a 12 km altitude during five GLE events, $D_{i@12\mathrm{km},j}$ and $\dot{D}_{i@12\mathrm{km},j}$, respectively, estimated from the four-dimensional dose rate data, which are characterized by the spectral power index, temporal shape parameter, total fluence, and tilt angle of SEP incident to the Earth evaluated by WASAVIES. In general, the SEP dose and dose rates during GLE 69 are the largest among the five selected GLE events, particularly for the dose rate. This is because GLE 69 was one of the largest and the most impulsive events that have occurred since they have been reliably recorded by neutron monitors.

Table 6. Maximum doses (μSv) and dose rates (μSv/h) due to SEP exposure for eight selected flight routes at 12 km and 9 km altitude during five GLE events estimated from the four-dimensional dose rate data calculated by WASAVIES

| Flight ID | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
|---|---|---|---|---|---|---|---|---|
| GLE60 | EII = 170 (%*h), PEI = 149%, *Duration = 34 hours | | | | | | | |
| Dose @ 12km (μSv) | 67.7 | 42.2 | 68.3 | 48.6 | 56.1 | 12.5 | 43.2 | 45.6 |
| Dose @ 9km (μSv) | 25.5 | 16.1 | 25.6 | 18.4 | 21.1 | 4.81 | 16.4 | 17.6 |
| Dose Rate @ 12km (μSv/h) | 36.7 | 21.2 | 36.7 | 33.1 | 31.7 | 8.22 | 24.7 | 27.6 |
| Dose Rate @ 9km (μSv/h) | 14.2 | 7.91 | 14.2 | 12.7 | 11.9 | 3.12 | 9.34 | 10.9 |
| GLE69 | EII = 385 (%*h), PEI =2650%, *Duration = 36 hours | | | | | | | |
| Dose @ 12km (μSv) | 117 | 96.3 | 104 | 121 | 125 | 41.5 | 124 | 120 |
| Dose @ 9km (μSv) | 41.9 | 35.4 | 37.6 | 44.6 | 45.8 | 16.0 | 45.3 | 43.9 |
| Dose Rate @ 12km (μSv/h) | 200 | 241 | 200 | 273 | 241 | 54.6 | 127 | 148 |
| Dose Rate @ 9km (μSv/h) | 73.5 | 91.4 | 73.5 | 101 | 91.4 | 20.0 | 49.8 | 54.1 |
| GLE70 | EII = 62 (%*h), PEI =92%, *Duration = 31 hours | | | | | | | |
| Dose @ 12km (μSv) | 21.2 | 33.6 | 21.8 | 31.1 | 35.3 | 10.6 | 39.0 | 32.6 |
| Dose @ 9km (μSv) | 7.64 | 12.8 | 7.86 | 11.9 | 13.0 | 4.58 | 14.6 | 11.9 |
| Dose Rate @ 12km (μSv/h) | 8.40 | 26.1 | 7.51 | 18.1 | 26.1 | 9.65 | 27.2 | 21.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dose Rate @ 9km (μSv/h) | 3.29 | 10.8 | 3.10 | 7.79 | 10.8 | 4.43 | 11.2 | 8.46 |
| GLE71 | EII = 10 (%*h), PEI =16%, *Duration = 14 hours | | | | | | | |
| Dose @ 12km (μSv) | 3.75 | 5.77 | 4.41 | 5.00 | 5.63 | 2.04 | 6.76 | 5.74 |
| Dose @ 9km (μSv) | 1.34 | 2.11 | 1.56 | 1.85 | 2.07 | 0.84 | 2.46 | 2.10 |
| Dose Rate @ 12km (μSv/h) | 1.90 | 5.03 | 3.67 | 4.24 | 5.03 | 2.08 | 5.03 | 4.78 |
| Dose Rate @ 9km (μSv/h) | 0.78 | 1.90 | 1.38 | 1.62 | 1.90 | 0.87 | 1.90 | 1.81 |
| GLE72 | EII = 9.5 (%*h), PEI =16%, *Duration = 54 hours | | | | | | | |
| Dose @ 12km (μSv) | 10.9 | 9.60 | 12.1 | 10.7 | 13.0 | 1.54 | 12.9 | 12.5 |
| Dose @ 9km (μSv) | 3.62 | 3.17 | 3.96 | 3.28 | 4.12 | 0.57 | 3.98 | 3.92 |
| Dose Rate @ 12km (μSv/h) | 3.27 | 2.80 | 3.43 | 2.42 | 2.94 | 1.06 | 2.40 | 3.46 |
| Dose Rate @ 9km (μSv/h) | 1.18 | 0.96 | 1.20 | 0.65 | 1.01 | 0.39 | 0.69 | 1.20 |

*Approximate duration with GOES proton (E > 100 MeV) flux over 1 (/$cm^2$/sr/sec)

Table 7. Annual occurrence frequencies of the maximum SEP dose exceeding 1 mSv at the cruise altitudes of 12 km and 9 km for eight selected flight routes.
The mean values and the standard deviation (Std) of the frequencies obtained from the five selected GLE events are also summarized.

| 12 km | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
|---|---|---|---|---|---|---|---|---|
| GLE60 | 0.0155 | 0.0111 | 0.0156 | 0.0123 | 0.0136 | 0.0047 | 0.0113 | 0.0117 |
| GLE69 | 0.0128 | 0.0112 | 0.0118 | 0.0131 | 0.0134 | 0.0062 | 0.0134 | 0.0130 |
| GLE70 | 0.0139 | 0.0193 | 0.0142 | 0.0183 | 0.0200 | 0.0085 | 0.0214 | 0.0189 |
| GLE71 | 0.0149 | 0.0202 | 0.0167 | 0.0182 | 0.0198 | 0.0097 | 0.0225 | 0.0201 |
| GLE72 | 0.0327 | 0.0299 | 0.0353 | 0.0323 | 0.0371 | 0.0082 | 0.0369 | 0.0361 |
| Mean | 0.0180 | 0.0183 | 0.0187 | 0.0188 | 0.0208 | 0.0075 | 0.0211 | 0.0200 |
| Std | 0.0083 | 0.0078 | 0.0094 | 0.0080 | 0.0097 | 0.0020 | 0.0101 | 0.0097 |
| 9 km | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
| GLE60 | 0.0078 | 0.0056 | 0.0078 | 0.0062 | 0.0068 | 0.0024 | 0.0057 | 0.0060 |
| GLE69 | 0.0062 | 0.0055 | 0.0058 | 0.0065 | 0.0066 | 0.0031 | 0.0066 | 0.0064 |
| GLE70 | 0.0068 | 0.0098 | 0.0069 | 0.0093 | 0.0099 | 0.0047 | 0.0107 | 0.0093 |
| GLE71 | 0.0072 | 0.0099 | 0.0080 | 0.0090 | 0.0098 | 0.0052 | 0.0110 | 0.0099 |
| GLE72 | 0.0150 | 0.0137 | 0.0160 | 0.0140 | 0.0165 | 0.0041 | 0.0161 | 0.0159 |
| Mean | 0.0086 | 0.0089 | 0.0089 | 0.0090 | 0.0099 | 0.0039 | 0.0100 | 0.0095 |
| Std | 0.0036 | 0.0034 | 0.0041 | 0.0031 | 0.0040 | 0.0011 | 0.0041 | 0.0040 |

Table 8. Annual occurrence frequencies of the maximum SEP dose rate exceeding 80 μSv/h at the cruise altitudes of 12 km and 9 km for eight selected flight routes. The mean values and the standard deviation of the frequencies obtained from the five selected GLE events are also summarized.

| 12 km | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
|---|---|---|---|---|---|---|---|---|
| GLE60 | 0.0408 | 0.0293 | 0.0408 | 0.0384 | 0.0374 | 0.0165 | 0.0322 | 0.0344 |
| GLE69 | 0.0440 | 0.0493 | 0.0440 | 0.0531 | 0.0493 | 0.0201 | 0.0335 | 0.0367 |
| GLE70 | 0.0403 | 0.0800 | 0.0377 | 0.0641 | 0.0800 | 0.0439 | 0.0820 | 0.0703 |
| GLE71 | 0.0521 | 0.0938 | 0.0775 | 0.0846 | 0.0938 | 0.0550 | 0.0938 | 0.0909 |
| GLE72 | 0.0289 | 0.0263 | 0.0297 | 0.0241 | 0.0271 | 0.0146 | 0.0240 | 0.0299 |
| Mean | 0.0412 | 0.0557 | 0.0460 | 0.0529 | 0.0575 | 0.0300 | 0.0531 | 0.0524 |
| Std | 0.0083 | 0.0302 | 0.0184 | 0.0233 | 0.0284 | 0.0182 | 0.0323 | 0.0268 |
| 9 km | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
| GLE60 | 0.0230 | 0.0162 | 0.0230 | 0.0215 | 0.0207 | 0.0092 | 0.0179 | 0.0196 |
| GLE69 | 0.0240 | 0.0274 | 0.0240 | 0.0291 | 0.0274 | 0.0110 | 0.0190 | 0.0200 |
| GLE70 | 0.0229 | 0.0469 | 0.0221 | 0.0385 | 0.0469 | 0.0274 | 0.0480 | 0.0405 |
| GLE71 | 0.0304 | 0.0521 | 0.0429 | 0.0473 | 0.0521 | 0.0325 | 0.0521 | 0.0506 |
| GLE72 | 0.0156 | 0.0138 | 0.0158 | 0.0109 | 0.0142 | 0.0080 | 0.0113 | 0.0158 |
| Mean | 0.0232 | 0.0313 | 0.0256 | 0.0295 | 0.0323 | 0.0176 | 0.0296 | 0.0293 |
| Std | 0.0053 | 0.0175 | 0.0102 | 0.0142 | 0.0165 | 0.0114 | 0.0189 | 0.0153 |

Table 7 shows the annual occurrence frequencies of the maximum SEP dose exceeding 1 mSv at the cruise altitudes of 12 km and 9 km, i.e. $F_{\mathrm{EII}}\left(s_{\mathrm{EII},j}D_{\mathrm{thre}}/D_{i@12\mathrm{km},j}\right)$ and $F_{\mathrm{EII}}\left(s_{\mathrm{EII},j}D_{\mathrm{thre}}/D_{i@9\mathrm{km},j}\right)$ for $D_{\mathrm{thre}}$ = 1 mSv, estimated from the calculated SEP doses given in Table 2 in combination with the regression line obtained from EII as shown in Figure 1. For example, the calculated maximum SEP dose for LAX_LHR at 12 km during GLE 60 (EII = 170 %*h) is 0.0677 mSv, indicating that GLE with EII = 170/0.0677 = 2511 %*h can give the SEP dose of 1 mSv for the flight route. Then, the frequency of the occurrence of a GLE event with EII above 2511 %*h is estimated to be $10^{(-0.706*\log10(2511)+0.591)}$ = 0.0155 per year. The annual occurrence frequencies of the maximum SEP dose rate exceeding 80 μSv/h at the cruise altitudes of 12 and 9 km, i.e. $F_{\mathrm{PEI}}\left(s_{\mathrm{PEI},j}\dot{D}_{\mathrm{thre}}/\dot{D}_{i@12\mathrm{km},j}\right)$ and $F_{\mathrm{PEI}}\left(s_{\mathrm{PEI},j}\dot{D}_{\mathrm{thre}}/\dot{D}_{i@12\mathrm{km},j}\right)$ for $\dot{D}_{\mathrm{thre}}$ = 80 μSv, are given in Table 8.

The tables showed that the frequencies deduced from the analysis of GLE69 are generally smaller than the others because SPE with hard spectra such as GLE69 tend to give lower aviation radiation doses compared to those with soft spectra at the same EII. However, the standard deviations of the frequencies are less than half of the corresponding mean values, indicating that the GLE dependences of the calculated frequencies are not too significant. This tendency suggests that the maximum SEP doses and dose rates for certain flight conditions can be roughly represented by EII and PEI, respectively, instead of the large uncertainties between the count rates of the polar neutron monitors and the spectral index of SEP as discussed in Asvestari *et al*[14]. Among the eight selected flight routes, the largest mean frequencies are observed in the cases of SYD-CPT and SYD-GIG, which are 0.0211 and 0.0575 at 12 km for the dose and dose rate regulations, respectively. These results suggest that a GLE event that is strong enough to request a change in flight conditions occurs once per 47 and 17 years, respectively.

Evaluating all individual results shown in Tables 3 and 4, the frequency of exceeding the threshold value becomes higher when applied to the dose-rate criteria rather than the total dose criteria in most cases. Dose-rate regulation limits the maximum dose rate even for a short duration aviation route, which increases the sensitivity for risk, accordingly. Considering the fact that it is almost impractical to predict the total SEP dose during a GLE event, regulation based on dose-rate may give us a chance of avoiding significant exposure, as no aviation path reaches the threshold dose (1 mSv) among the five selected GLE cases and eight selected flight-routes.

Table 9. Annual risks in the units of 1000 USD/year to avoid the maximum SEP dose exceeding 1 mSv for eight selected flight routes calculated from Eq. (3) multiplied with the worst-case-scenario scaling factor for daily-operated flight. The mean values and the standard deviation of the frequencies obtained from the five selected GLE cases are also summarized.

| | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
|---|---|---|---|---|---|---|---|---|
| GLE60 | 0.37 | 0.25 | 0.36 | 0.29 | 0.29 | 0.11 | 0.25 | 0.27 |
| GLE69 | 0.30 | 0.25 | 0.27 | 0.31 | 0.28 | 0.14 | 0.29 | 0.30 |
| GLE70 | 0.33 | 0.44 | 0.32 | 0.44 | 0.42 | 0.20 | 0.47 | 0.43 |
| GLE71 | 0.35 | 0.45 | 0.37 | 0.43 | 0.41 | 0.22 | 0.49 | 0.46 |
| GLE72 | 0.74 | 0.63 | 0.75 | 0.69 | 0.73 | 0.18 | 0.74 | 0.75 |
| Mean | 0.42 | 0.40 | 0.41 | 0.43 | 0.43 | 0.17 | 0.45 | 0.44 |
| Std | 0.18 | 0.16 | 0.19 | 0.16 | 0.18 | 0.05 | 0.20 | 0.19 |

Table 10. Annual risks in the units of 1000 USD/year to avoid the maximum SEP dose rate exceeding 80 μSv/h for eight selected flight routes calculated from Eq. (4) multiplied with the worst-case-scenario scaling factor for daily-operated flight. The mean values and the standard

deviation of the frequencies obtained from the five selected GLE cases are also summarized.

| | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
|---|---|---|---|---|---|---|---|---|
| GLE60 | 1.08 | 0.75 | 1.07 | 1.04 | 0.91 | 0.42 | 0.81 | 0.91 |
| GLE69 | 1.14 | 1.27 | 1.12 | 1.41 | 1.21 | 0.50 | 0.86 | 0.94 |
| GLE70 | 1.07 | 2.13 | 1.02 | 1.82 | 2.01 | 1.19 | 2.14 | 1.88 |
| GLE71 | 1.42 | 2.41 | 2.00 | 2.28 | 2.29 | 1.45 | 2.37 | 2.37 |
| GLE72 | 0.74 | 0.65 | 0.74 | 0.56 | 0.64 | 0.37 | 0.55 | 0.75 |
| Mean | 1.09 | 1.44 | 1.19 | 1.42 | 1.41 | 0.79 | 1.35 | 1.37 |
| Std | 0.24 | 0.80 | 0.48 | 0.67 | 0.71 | 0.50 | 0.84 | 0.71 |

Tables 9 and 10 show the annual risks calculated from Eqs. (3) and (4) multiplied with the worst-case-scenario scaling factor for daily-operated flight. The costs given in Table 1 and the frequencies shown in Tables 3 and 4 were used in the calculation. The mean values and the standard deviation of the risks obtained from the five selected GLE cases are also summarized in the tables. It is found from these tables that the mean annual risks estimated based on the dose and dose-rate regulations are less than 0.5 and 1.5 thousand USD, respectively, for all flight routes. These risks are not significantly large in comparison to the other aviation risks such as a volcanic eruption (Mazzocchi *et al*, 2010). For example, many flights were cancelled when Eyjafjallajökull in Iceland erupted in 2010. During this eruption, the economic impact on aviation was estimated to be 1.7 billion USD (IATA, 2010). Since the frequency of Icelandic volcanic eruptions was estimated to be 44 ± 7 years (Watson *et al*, 2017), the annual risk of the Icelandic volcano eruption on aviation was calculated to be 38.6 million USD. This value is 10,000 times higher than the annual GLE risk for daily-operated long-distance flight obtained from this study.

## 4.5. Conclusion

The risk assessment for the cost of countermeasures to reduce the radiation doses and dose rates due to SEP aviation exposure was performed in order to design an insurance product. In the assessment, the maximum SEP doses and dose rates for eight flight routes with two cruise altitudes during five GLE cases were evaluated by integrating the four-dimensional aviation dose rate data calculated by WASAVIES. Based on the results, the frequency that the total doses exceed 1 mSv or the dose rates exceed 80 μSv/h were estimated by scaling the magnitude of the GLE event using EII or PEI, respectively. Our calculations suggest that a GLE event of sufficient magnitude to request a change in flight conditions occurs once per 47 and 17 years in the case of following the dose and dose-rate regulations, respectively, and their conservatively-estimated annual risks associated with countermeasure costs are up to around 1.5 thousand USD for daily-operated long-distance flights. However, these results were derived from many simplifications such as constant flight speed and altitude during the cruise flight. Thus, more comprehensive risk assessments considering realistic flight schedules and detailed cost estimations must be conducted before an insurance system for aviation SEP exposure can be created.

Summary of Chapter 4

This chapter assesses the risks associated with the cost of measures to reduce SEP doses and dose rates on eight flight routes during five ground-level enhancements (GLEs) in aeronautical radiation exposure.

## 5. Policy Recommendation

In this chapter, the series of risk assessments conducted in this paper as LPHC risk countermeasures for the aerospace industry was made into a framework, the possibility of parametric insurance was discussed, and policy recommendations were made. First, based on the quantitative risk assessment process proposed by previous studies, I organized and constructed a framework for quantifying LPHC risks in the aerospace industry. Next, I defined parametric insurance, as well as its mechanisms, advantages and disadvantages, and discussed the possibility of designing parametric insurance using the index proposed in Chapter 3. Finally, I proposed a system of public-private-academic collaboration, laws and regulations, and databases that are necessary to design such parametric insurance.

### 5.1. Theories and a New Framework of Risk Assessment for Natural Disasters and Low-Probability, High- Consequence Events

Even though the breadth, depth, and application areas of quantitative risk assessment are very broad and diverse, all risk assessments can be conducted according to the same basic procedures. The process of quantitative risk assessment is as follows (Garrick, 2021).

Step1: Establish a reference point that will serve as a baseline for risk assessment. That is, the system is defined by the elements constituting the normal operation of the system to be analyzed.

Step2: Identify the cause of the dangerous situation and clarify its characteristics. This is called a hazard. For example, dangerous goods and terrorism deserve this.

Step3: Formulate a scenario of "what kind of bad things will happen?" And quantify the degree of damage / damage and the result / impact. At the same time, identify system vulnerabilities.

Step4: Quantify the likelihood of various scenarios and the degree of damage / damage associated with those scenarios.

Step5: Classify and organize scenarios according to the degree of damage / damage. The results will be expressed as an appropriate risk curve and reflected in the priority evaluation from the perspective of risk.

Step6: Interpret the risk assessment results to guide the risk management process.
In this paper, by calculating the risk (economic loss amount) in changing / canceling the operation plans of the aircraft when a solar flare occurs, it was possible to perform up to Step 5 in the above framework. Based on this, we will build and propose an index insurance design framework specializing in LPHC risk in the aerospace industry as shown below.

Step1：In the context of this paper, I will cover eight flight routes, such as between Tokyo and London and between Sydney and Cape Town.

Step2：In this paper, solar flares, GLE, etc. deserve this.

Step3：In this paper, we will quantify the exposure dose to aviation industry workers and passengers due to the occurrence of GLE. It corresponds to quantifying the amount of economic loss (risk) associated with changing / canceling the flight plan (altitude) as well as showing the protocol to change / cancel the flight plan (altitude) by this amount.

Step4：In this paper, it corresponds to calculating the frequency and probability of how many years a GLE of a scale that should correspond to a change in the flight plan occurs.

Step5：In this paper, I derive a risk formula that expresses the risk (economic loss amount) associated with the above-mentioned flight plan change / cancellation.

Step6：The frequency and risk identified in this paper should be assessed, which is discussed in Chapter 6 of this paper. In order to make concrete proposals, more accurate risk assessment based on detailed operation plans is indispensable, so we plan to continue conducting such research in cooperation with related organizations in the future. I believe that it is possible to design index-type insurance and provide it to society.

Based on this, we will build and propose an index insurance design framework specializing in LPHC risk in the aerospace industry as shown below.

Step1：Define the reference points and systems that serve as the baseline for risk assessment of eight flight routes.

Step2：Clarify the hazards of solar flares and GLE.

Step3：

・Data of Phenomenon

It is assumed that there is data about natural phenomena. It is assumed that data is accumulated about when and how large an event occurred.

Step4：

・Logarithmic, Annual Rate, Scatter Plot, Fitting

First, the data is scaled by arranging the units such as common logarithm, natural logarithm, and in some cases lognormal distribution. Then, the annual frequency is calculated by dividing by the number of years in consideration of the total occurrence period of the phenomenon. Also, by plotting it in a scatter plot, we can visualize the relationship between the two variables. Finally, we fit this into a simple regression equation as much as possible.

Step5：

・Lowering the altitude or Cancellation, Risk Equation

In order to quantify the amount of economic loss that accompanies the assumed protocol, we derive a risk formula that expresses the cost in each scenario. The risk formula is mainly expressed by multiplying the frequency of occurrence of scenario events with the cost at that time, and is expressed by adding them as a total.

If the flight plan / cancellation cost of the aircraft in this paper is applied to rockets, the normal flight altitude / flight altitude at the time of GLE occurrence, fuel cost, and cost at the time of cancellation can be estimated and substituted into this risk assessment formula. We believe that the risk (economic loss amount) can be calculated in the same way.

Step6：

As a future outlook, I would like to carry out a more accurate risk assessment based on detailed operation plans, and we plan to continue conducting such research in cooperation with related organizations in the future.

However, we propose an index-type insurance design based on the data and analysis results that have been clarified at this time. As shown in the examples of weather derivatives and weather index type insurance, which will be described later as case studies in Chapter 4, target indexes are set for events and risks, the correlation with sales and damages is clarified, and when the correlation is strong, this designs index insurance to cover statistically determined damages. Then, when introducing the insurance, I propose to improve the system, laws and regulations, and DB.

### 5.2. Parametric Insurance and Flight Cancellation Compensation

In this section, I define parametric insurance, as well as its mechanisms, advantages and disadvantages, and discuss the possibility of designing parametric insurance using the index proposed in Chapter 3.

First of all, Parametric insurance is also called index insurance or index-based insurance, and parametric insurance is a predetermined fixed amount of insurance when the indicators (parameters) that have a causal relationship with damage meet the conditions set at the time of contract. Insurance that pays money（Hamada, 2019）.

Parametric insurance does not require an on-site investigation (damage assessment) to confirm the amount of damage, and the period required for insurance payment can be significantly shortened. It is also thought to contribute to solving problems related to ordinary insurance such as moral hazard, information asymmetry, and adverse selection. In insurance payments, concerns about non-payment issues are greatly reduced, and it is not necessary to confirm the amount of damage, so it is said that transparency between contracting parties can be increased. Furthermore, it is beginning to be suggested that the insurance money may be used for pre-disaster prevention and prevention of damage spread depending on the trigger, a feature of this insurance that conventional insurance does not have. However, since parametric insurance pays based on indicators such as rainfall and seismic intensity, there might be a discrepancy between the actual damage amount and the payment amount. This divergence is called basis risk, and there can be cases where the insurance money is too small and cases where it is too large. Therefore, it is necessary to verify the correlation between indicators and damages through empirical experiments and design better insurance that reduces the basis risk. Since this is an important issue from the viewpoint of contractor protection, it is necessary to fully explain the basis risk to the contractor and gain their understanding. In particular, it will be important to propose risk mitigation and business continuity methods and encourage policyholders to make efforts in preparation for the possibility of underpayment of insurance claims（AIG, 2018）. Very similar to derivatives, a comparison with traditional insurance is below（AIG, 2018）.

Source：Translated from ”Society 5.0" and parametric insurance* will open the way to "risk transfer" for huge disasters”

Table 11: Comparison of traditional and parametric insurance.

| | Traditional Insurance | Parametric Insurance |
|---|---|---|
| Security Risk | Combined enumerated hazards such as hail and wind storms (but with exclusionary hazards) | Contractually agreed-upon risks only |
| Risk Underwriting Criteria | Past crop damage, location, and cropped area | Historical weather data/crop damage/yields, data stations |
| Insurance Payment Criteria | Actual damages | Weather data |
| Adverse Selection | High | Low |
| Moral Hazard | High | Low |
| Basis Risk | No Basis Risk or Low | Middle or High |
| Transparency of risks from the perspective of shareholders and other investors | Need to understand the risks that insurance companies are taking on | Easier understanding of risk through greater transparency and objectivity |

In addition, the benefits of parametric insurance are as follows（Hamada, 2019）.

Source：Translated from ”Current Status and Issues of Parametric Insurance”

Table 12: Benefits of parametric insurance for the insured and property/casualty insurers.

| Benefits to the insured | Benefits for property and casualty insurance companies |
|---|---|
| ・Claims are paid quickly, as they are processed upon the occurrence of a covered event (or subsequent notification by the insured), meeting the needs of the insured who need funds for recovery immediately after the disaster.<br>・Some products offer flexibility in insurance product design, such as the ability to adjust thresholds and policy amounts to meet the needs of the insured.<br>・In combination with conventional insurance, as a supplement to the conventional insurance, | ・Since payment is automatically determined based on indicators, there is no need for accident investigation and no need for appraisal costs<br>・Since the insurance money is paid out in advance regardless of whether the damage is large or small, there is an incentive for the insured to reduce the actual amount of damage, and the problem of moral hazard is less likely to occur than with conventional insurance<br>・It is easier for major international insurance companies to be allowed to enter |

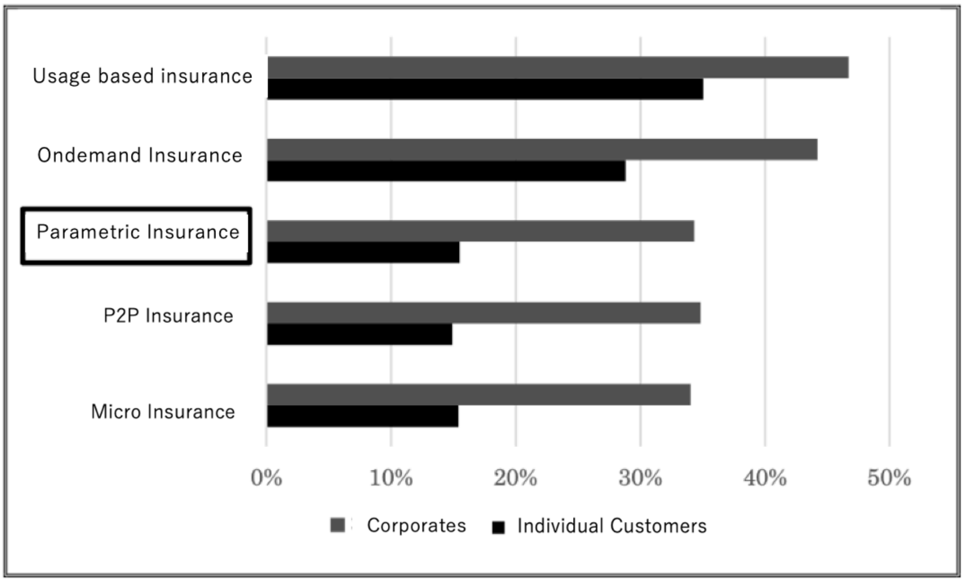
| | |
|---|---|
| it is possible to compensate for the deductible (amount) portion of the policy<br>・The use of the insurance money paid is not limited and can be used at the discretion of the insured | developing markets. While regulators in developing countries are generally interested in competing with domestic insurers, parametric insurance is easier to gain access to because it is not offered by local insurers or it is difficult to offer. |
| ・No complicated terms and conditions or exclusion clauses, making it easy for the insured to understand and making the contract more transparent for both the insurer and the insured<br>・Eliminates the need for negotiations associated with minimum insurance payments<br>・If the risks are contingent and can be modeled, risks that cannot be underwritten by conventional insurance can be underwritten<br>・Insurance premiums can be lowered by reducing the operating costs of insurance companies, such as insurance enrollment and underwriting procedures, and the design of low insurance amounts allows for smaller premiums, making it easier to apply for micro insurance | |

・ Market conditions

Regarding parametric insurance, there are no official statistics and data such as the size of insurance premiums and the rate of increase in the market as a whole are unknown, but in recent years the interest of customers and insurance market participants have increased. The number of cases of efforts by market participants such as insurance companies and brokers that can be confirmed from public information such as websites is increasing, and the number of insurance products and the types of target risks are also increasing.

Table 12 shows the results of a survey conducted by Capgemini, a consulting firm, on the level of interest in new insurance models among more than 8,000 companies and individuals in 20 countries from January to February 2019. The survey found that 34.3% of corporate customers and 15.5% of individual customers are "interested" in parametric insurance as one of the new insurance models.

The parametric insurance efforts of major European and American non-life insurance companies may not be clearly understood by the companies from public information alone, but AXA, Swiss Re, and Lloyd's Insurance Association are likely to be proactive. AXA saw parametric insurance as a future growth area in 2017, launched a specialized subsidiary, AXA Global Parametrics, renamed it AXA Climate in 2019, and he is already active in 40 countries. We are developing our business in Japan. In particular, we are aiming to expand products for SMEs and individuals. Swiss Re already offers a wide range of parametric insurance products. Lloyds has also traditionally underwritten his parametric insurance.




Source：Translated from "Current Status and Issues of Parametric Insurance"

Figure 9: Interest in new insurance models among corporate and individual customers.

Although parametric insurance has such merits and is of interest to major non-life insurance companies, there are issues that must be overcome. According to (Hamada, 2019), the following issues are important:

・ Preparation of statistical data

Parametric insurance is still in the growth stage, and that there are not enough players (insurance companies, etc.) to compete for each jurisdiction and target risk compared to conventional insurance. There is a possibility that insurance premiums will be further reduced due to competition in the future. Therefore, in order for the market to mature in the future, it will be necessary to prepare statistics such as premiums, insurance claims, and loss ratios for parametric insurance.

・ Development of laws and regulations

According to Clyde & Co's analysis, parametric insurance has legal and regulatory uncertainties, as it is a new type of insurance, often without legal provisions, and without a structured regulatory framework.

・ Approval as non-life insurance

Regarding parametric insurance, there is a problem with approval as non-life insurance. The details of each jurisdiction are unknown, but it seems that there are still cases where parametric insurance is not approved as insurance, and in countries where it is not approved, there is no choice but to replace it with other solutions such as derivatives. However, there are also differences such as insurance regulations not working for derivatives. Business development is possible in countries in Asia and Africa, where laws and regulations are relatively loose, and in some countries that have already established the active promotion of parametric insurance.

Some companies, such as Moonshot, Swiss Re, and ANA fully digitally compensate for flight cancellations by parametric insurance.

Moonshot offers a full digital type of flight cancellation compensation. The system pays the cancellation fee even if there is no flight cancellation receipt.

Swiss Re offers real-time flight delay insurance. The app automatically calculates the probability of delay and payment, making it a simple and transparent product. Pricing factors are Date and Time, Airport, Operator, Route etc.

ANA also offers flight cancellation insurance "Soramoyo". This insurance covers cancellation and refund fees for reservations cancelled or refunded due to the threat of flight cancellation because of bad weather, as well as additional expenses if the scheduled flight is cancelled or significantly delayed due to bad weather.

From these cases, I believe that it is possible to provide flight cancellation/delay insurance/compensation if a clear index and delay/cancellation probability is known.

I propose flight cancellation insurance with PEII or PEI as parameters.
This is because the correlation between PEII or PEI and the amount of economic loss is high, so it can be used as an index for parametric insurance.
Specifically, although it may be a small amount, when PEII or PEI exceeds a certain threshold, 100% of the cost amount will be paid (referring to Moonshot).
I calculated the costs associated with the risk in Chapter 3 for lowering altitudes of the airplane or cancellation the flight, which are up to around 1.5 thousand USD based on the statistical data and calculations.

Based on the example of earthquake insurance from the company Jumpstart, the amount of the claim paid will be “Based on statistical data, the amount of money that many people will need when an earthquake of a certain size or larger occurs.” (Yoshizawa, 2020).

Based on the above, a simple design example is shown below.

・Index：PEI/PEII or Sv

・Threshold： 17,000/1,200 or 1.0mSv or 80μSv/h

・Claim Paid：Around 500～1500 thousand dollar for each route

The relationships between SEP dose/dose rate and PEI / PEII of 8 flight routes during 5 ground level enhancements (GLE) which are above 1m Sv or 80μ Sv/h are summarized in the table. Based on this correspondence table, the insurance payment will be determined when a similar GLE occurs.

Table13. Relationship between PEI/PEII and SEP dose/dose rate

| Flight ID | LAX_LHR | SYD_EZE | SFO_LHR | NRT_LHR | SYD_GIG | SYD_LIM | SYD_CPT | JFK_NRT |
|---|---|---|---|---|---|---|---|---|
| GLE60 | PEII = 461 (%*h), PEI = 149%, *Duration = 34 hours | | | | | | | |
| Dose @ 12km (μSv) | 6,809 | 10,924 | 6,750 | 9,486 | 8,217 | 36,880 | 10,671 | 10,110 |
| Dose @ 9km (μSv) | 18,078 | 28,634 | 18,008 | 25,054 | 21,848 | 95,842 | 28,110 | 26,193 |
| Dose Rate @ 12km (μSv/h) | 325 | 562 | 325 | 360 | 376 | 1,450 | 483 | 432 |
| Dose Rate @ 9km (μSv/h) | 839 | 1,507 | 839 | 939 | 1,002 | 3,821 | 1,276 | 1,094 |
| GLE69 | PEII = 2225 (%*h), PEI =2650%, *Duration = 36 hours | | | | | | | |
| Dose @ 12km (μSv) | 19,017 | 23,105 | 21,394 | 18,388 | 17,800 | 53,614 | 17,944 | 18,542 |
| Dose @ 9km (μSv) | 53,103 | 62,853 | 59,176 | 49,888 | 48,581 | 139,063 | 49,117 | 50,683 |
| Dose Rate @ 12km (μSv/h) | 1,060 | 880 | 1,060 | 777 | 880 | 3,883 | 1,669 | 1,432 |
| Dose Rate @ 9km (μSv/h) | 2,884 | 2,319 | 2,884 | 2,099 | 2,319 | 10,600 | 4,257 | 3,919 |
| GLE70 | PEII = 101 (%*h), PEI =92%, *Duration = 31 hours | | | | | | | |
| Dose @ 12km (μSv) | 4,811 | 3,036 | 4,679 | 3,280 | 2,890 | 9,623 | 2,615 | 3,129 |
| Dose @ 9km (μSv) | 13,351 | 7,969 | 12,977 | 8,571 | 7,846 | 22,271 | 6,986 | 8,571 |
| Dose Rate @ 12km (μSv/h) | 876 | 282 | 980 | 407 | 282 | 763 | 271 | 349 |
| Dose Rate @ 9km (μSv/h) | 2,237 | 681 | 2,374 | 945 | 681 | 1,661 | 657 | 870 |
| GLE71 | PEII = 16 (%*h), PEI =16%, *Duration = 14 hours | | | | | | | |
| Dose @ 12km (μSv) | 4,267 | 2,773 | 3,628 | 3,200 | 2,842 | 7,843 | 2,367 | 2,787 |
| Dose @ 9km (μSv) | 11,940 | 7,583 | 10,256 | 8,649 | 7,729 | 19,048 | 6,504 | 7,619 |
| Dose Rate @ 12km (μSv/h) | 674 | 254 | 349 | 302 | 254 | 615 | 254 | 268 |
| Dose Rate @ 9km (μSv/h) | 1,641 | 674 | 928 | 790 | 674 | 1,471 | 674 | 707 |
| GLE72 | PEII = 16 (%*h), PEI =16%, *Duration = 54 hours | | | | | | | |
| Dose @ 12km (μSv) | 1,468 | 1,667 | 1,322 | 1,495 | 1,231 | 10,390 | 1,240 | 1,280 |
| Dose @ 9km (μSv) | 4,420 | 5,047 | 4,040 | 4,878 | 3,883 | 28,070 | 4,020 | 4,082 |
| Dose Rate @ 12km (μSv/h) | 391 | 457 | 373 | 529 | 435 | 1,208 | 533 | 370 |
| Dose Rate @ 9km (μSv/h) | 1,085 | 1,333 | 1,067 | 1,969 | 1,267 | 3,282 | 1,855 | 1,067 |

With reference to the above PEI/PEII thresholds, if a GLE of a magnitude exceeding 1 mSv or 80 μSv/h occurs, the estimated damage (the estimated risk of economic loss incurred by the passenger) shall be paid, also referring to Table 9 and 10 in Chp4. In the future, it will be

possible to propose rocket-launch cancellation insurance for future space travel by changing the size, number of flights, and cost of the aircraft for rockets.
In addition, the next section proposes a system of industry-government-academia collaboration that overcomes the above-mentioned issues (preparation of statistical data, preparation of laws and regulations, and approval as non-life insurance).

In addition, as a case study, I will provide a design example of derivatives (especially weather derivatives) that are sometimes used as an alternative to index insurance, and a summary of Myanmar's cases regarding the points to be considered when introducing actual index insurance.

**Case Study. Feasibility Study of Agricultural Insurance and WIBI in Myanmar**


**Abstract**

Due to the influence of the military and socialist regime that lasted from 1962 to 1988, the insurance market in Myanmar has long been a monopoly system by the National Insurance Company. However, since 2012, the market has been opened to private insurance companies, and the market liberalization is still being considered. In recent years, many foreign insurers have established a representative office in anticipation of the high potential because the market size at this stage is expected to grow rapidly. The possibility of liberalization of this market has been announced by the Government of Myanmar to allow 100% foreign capital in the life insurance market more than once in 2018. As the market is released and competition is encouraged, the insurance products that meet the needs of the people will be introduced, and the effectiveness of the public's insurance awareness will be expected to increase. In order to do this, however, modern internal management and risk management and appropriate insurance regulations and supervision are necessary to support them. In addition, it is necessary to improve the system of the law of the Government and authorities, the ability construction of the supervisor, and the raising of the industry by referring to other ASEAN countries. In this report, first and foremost, an overview of the current status of the insurance market is provided, including the weather index insurance. Then, the usefulness of the data, sales network, players and regulations in the insurance market in Myanmar are organized. These are the basis for the specific proposal for industry-government-academia collaboration system in the next section.


**Overall Insurance Market Situation**

The current state of the insurance market in Myanmar is that, compared with the ASEAN countries, the rate of insurance penetration is only less than 1% which is lower than that of Cambodia and Laos, and is still in its infancy. The size of the insurance market is about US $50 to 100 million, and it is estimated that casualty insurance accounts for 80 to 90 % and that it is life insurance accounts for the rest (Saito, 2017).

In addition, Myanmar has been promoting democratization and economic reforms from the military and socialist regimes, but the insurance market has remained undeveloped since the economic sanctions of the West and the decline in foreign investment due to the long-lasting. The national monopoly has been lagging significantly behind other ASEAN countries in terms of market size, product variation, compensation, insurance sales service (sales network) and insurance payment services (JICA, 2017).

The market opening has been announced multiple times until 2018, if this is achieved, there will be a promotion of competition among insurance companies that are currently hampered by a number of constraints, and various management efforts will be introduced to provide insurance products that meet the needs of the people, the results can be expected to improve the public's insurance awareness (Saito, 2017).

**1. Agricultural Insurance**

The agricultural insurance is not sold at present. As for foreign capital, the domestic private insurance company expect the foreign insurance company to give a guidance about the insurance technology of the agricultural insurance. They hope that the product, authorization and system of insurance will be disseminated by the technical support and establishment of the system in cooperation with the public and private sectors (JICA, 2017).

**2. Weather Index Insurance**

PwC, Sumitomo Mitsui and JICA developed weather index insurance based on rainfall for rice farmers in the delta region suffering from excessive rainfall. They selected the partners, collected the data necessary for development, developed an insurance product as a prototype, and confirmed that there was a certain degree of acceptability of local farmers on this product by interviews conducted by the anticipated customer. On the other hand, it was difficult to obtain the approval for the sale of the insurance product through the consultation with the insurance authorities several times. (as of 2015) It is difficult to commercialize the business immediately after the end of the survey, but the plan is set to discuss with the insurance authorities aiming at commercialization in the long-term and obtaining approval. Another possibility was to consider the possibility of commercialization of insurance products for partners in parallel (JICA, 2015).

The basis of judgment of the feasibility of this investigation are the following 8.

① Acquiring business partner with sales network to farmers
② Acquiring rainfall data at a level that can be insured product design
③ Acquiring agricultural production data of target crops
④ Confirming the correlation between agricultural productivity and rainfall data
⑤ Detailed design of insurance products

⑥ Securing identification and business integrity with target customers
⑦ Acquisition of approval for sales of insurance products
⑧ Securing feasibility of sales, insurance premium storage and insurance payment practice.

To implement this project, they need to do ⑦ and ⑧.

With regard to ⑧, they will resume consultation on the detailed design of the practice after obtaining authorization. After the investigation, it is expected that the insurance authorities will continue to work to obtain the approval and, in the prospect of obtaining approval, they will conclude an agreement on a business partnership with a partner company. They plan to provide a detailed design of the business process for insurance product sales, insurance premiums, and insurance payments, and implement an insurance product sales pilot business for the flood risk of rice-rainy season. Thereafter, in the delta region, they plan to carry out product design and pilot implementation for the other regional expansion of the product and the excessive rainfall of the dry season crops in the delta region, and the pilot implementation for the drought risk in the central impression zone. In addition, the second step is to expand the sales range to a lower income tier than the original existing customers, and to expand the sales range through cooperation with the microfinance institutions. These are expected to take at least 3 years after obtaining approval (JICA, 2015).

In the design of the weather index insurance, they confirmed that the necessary sample data is at the level of the insurance product design, and that the data measurement method at the weather station has not a fatal problem in the business examination. It has been found that the rainfall data held by DMH can be used to design insurance products to some extent. The components to be determined are ①insurance payment per unit area, ②insurance premium rate, and ③payment terms. However, it is not easy to obtain the agricultural production data of the past in Myanmar. It is necessary to request the Ministry of Agriculture and Irrigation (MOAI) to data by specifying the type of farm products, data types (acreage and productivity, etc.), geographical aggregation units, and the acquisition year. It takes several weeks to get. Therefore, they requested the data after they arranged the crop planting area data, selection of target crops by the State, provisional selection of crops by the region, and the target crop by the region (JICA, 2015).

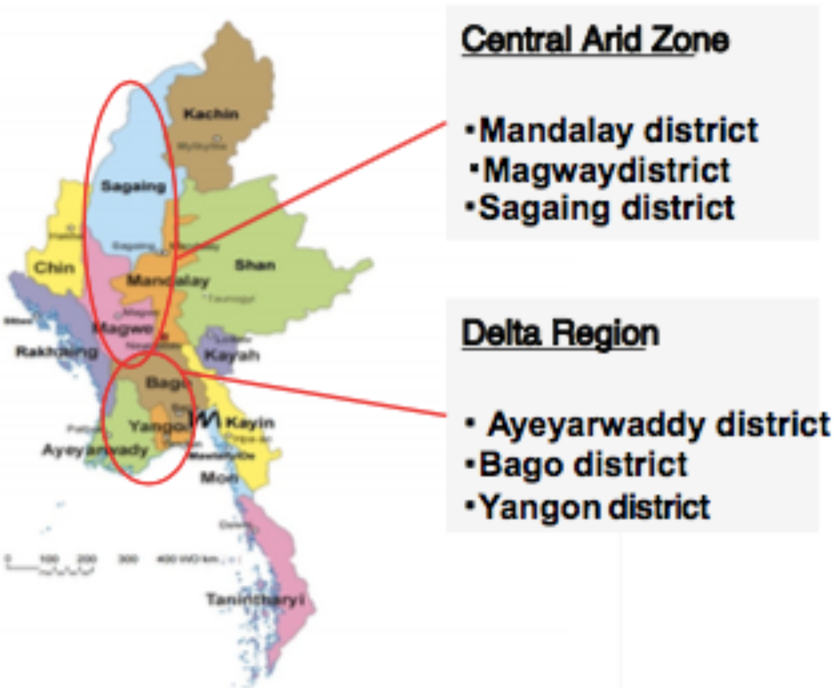
In this project, a questionnaire was conducted for 148 households in the delta region as target customers. These are almost all self-employed farmers, and that more than 60% of the surveyed farmers fall under the BOP (JICA, 2015).

More than 80% of the surveyed farmers have experience in borrowing loans from banks, MFIs, and agricultural affiliates. For weather information, 71% of the farmers have obtained information by some means, and their sources are mainly television and radio. On the other hand, about 12% of farmers have the means to reduce the impacts of weather risk for agriculture. They have voluntarily avoided the risk by changing arable land, securing waterways and dams. In the delta region where the weather risk is high, the demand for the insurance is considered to be high, but the farmer does not have much experience in buying insurance at present. Also they confirmed the purchase intention of the prototype insurance, about 85% showed the intention to purchase (JICA, 2015).

Insurance product sales are subject to the overlap of three types of examination areas: areas within a radius of 35 km of the Meteorological Observatory, the unit area of agricultural production data, and the coverage range of partner dealers selling insurance products. The number of customers expected for prototype insurance products is 63,461 million, and sales units are approximately 180,000 (JICA, 2015).

### 3. Data for Insurance Design and Sales, Sales Network, Player, and Legal Regulations

Although there are parts overlapping with Chapter 3 with reference to both PwC's pilot project and Myanmar's insurance market report, again organized the data, sales network, players, legal system for insurance design and sales.




Source：”Republic of the Union of Myanmar Preparatory Survey on BOP business on Weather Index Insurance in Myanmar”

Figure 10: Assumed Business Areas

#### 3.1. Data

The outline of the data is as follows.

(1) Ensured the level of rainfall data that can be designed for insurance products and confirmed the meteorological observatory that holds the rainfall data of more than 25 years necessary for the insurance product design exists at a certain degree. Then, obtained the data.
(Ayeyarwaddy District: Pathein, Maubin, Hinthada, nagathaing, Zalun, Myaungmya,
Mandalay District: Mandalay, Meiktila, Lun Kyaw, Yamethin, Myingyan, Hlaing-Tat)
・ The accuracy of rainfall data (percentage of missing areas, data correlation, measurement method, quality control) and the time of publication of data were confirmed that there are no critical issues in business examination.
(2) Acquiring agricultural production data for target crops
・Selected crops and risks for each of the delta and central arid areas.
Township-level agricultural production data and damage data were obtained from MOAI.
・Since the credibility of the agricultural production data of Paddy rice is low, they decided to use the damage data as an alternative.
They confirmed the usefulness of rainfall data and crop data (JICA, 2015).

(1) Rainfall data Review step
The historical rainfall data required for product design of weather index insurance can be purchased from DMH (data purchase cost is 8US $ by the data, observation field, and day for a year). As a study on rainfall data, ①Sample data acquisition and accuracy confirmation, ②Validation of data collection methods at the Meteorological Observatory, ③Identification of the target Meteorological Observatory and the acquisition of additional data, they went through three steps.

The confirmation of the usefulness of the data was arranged in the following each step.
Step ①: Sample data acquisition and accuracy confirmation
To confirm that the rainfall data available in Myanmar has the accuracy to withstand the product design of insurance, they acquire rainfall data of three points (Pathein, Hinthada, Pyapon) of the Ayeyawarddy district. Data loss and data correlation of each point were confirmed. As a result, they confirmed at an early level that the rainfall data in Myanmar can be used for insurance design (JICA, 2015).


Source："Republic of the Union of Myanmar Preparatory Survey on BOP business on Weather Index Insurance in Myanmar"

Figure 11: acquisition point of Rainfall Sample Data

・Data loss: Pyapon only holds 12 years of data, but Hinthada and Pathein have 25 years of data. However, some data loss was observed in Hinthada and Pathein at the level that did not interfere. (The data deficit of one month sentence for Hinthada on 1999 August, Pathein on 1990, March.)

・Data correlation of each point: the validity and the consistent correlation of three points were observed (JICA, 2015).

Step ②: Validation of data measurement methods at meteorological stations

They conducted a visit or telephone interview to DMH office of Hinthada and Pathein to confirm how the daily rainfall data was measured and how was it converted into data. As a result, it is confirmed that there is no fatal problem in the business examination at the time of 2015 (JICA, 2015).

・Data Disclosure timing: One month of data is available after the second week on the following month.

・Measurement method: The accuracy of the measurement is less than the automatic measurements due to manual measurement by gauges, but it is considered to be acceptable level.

・Quality control: When reporting to the NPT (Naypyidaw), certain quality controls such as data comparisons of each point and trend checking of each point are carried out.

| Survey Items | DOMH Interview Result |
|---|---|
| **Data Retention Period** | ✓ Regarding how many years the Meteorological Agency holds the data, it was decided by each Meteorological Agency (Refer to Step 3). |
| **Timing of data release** | ✓ Weather data is provided from DOMH to television, radio, etc., and is publicly released as public weather information.<br>✓ Can purchase in the form of data after one week of the following month. |
| **Measurement method** | ✓ Rainfall amount data is measured by visual observation of rain gauge's eye line (Currently, the introduction of automatic observation equipment is scheduled to be introduced led by the government, but the current situation is manual observation).<br>✓ Basically the measurement method has not changed during the data measurement period (Ultimately need to check with individual observation stations) |
| **Data measurement~ Aggregate** | ✓ The type of collected data differs depending on the attributes of the weather stations.<br>✓ It is measured 5 times a day, every 3 hours starting 9:30 as the beginning of the day. Data after 18:30 will be measured at 6:30 collectively. (9:30 - 12:30 - 15:30 - 18:30 - 6:30 – 9:30 )<br>✓ Measurement data is reported by telephone to NPT's DOMH at each measurement timing.<br>✓ In cases of emergency abnormalities such as cyclones and when government request is invoked, data measurement may be performed every hour. |
| **Quality control** | ✓Data collected in NPT is compared with data of each location and trend check by location. If abnormality is suspected, reconfirmation will be made on each station by phone. (As for technical approaches, need to confirm) |
| **Missing data** | ✓ "Trace": Data whose total rainfall per day was less than 2 mm although rainfall was observed by 3 hour measurement.<br>✓ "*": Hinthada August 1999→Additional data acquired, Pathein March 1990 <Checking> |

Source : Translated from "Republic of the Union of Myanmar Preparatory Survey on BOP business on Weather Index Insurance in Myanmar"

Table 14: Validation of data measurement method etc.

Step ③: Identify and obtain additional data for the Meteorological observatory

By step ① ②, it was confirmed that the rainfall data held by DMH in Myanmar can be used for the insurance product design to some extent. Among the 118 meteorological stations that exist as of August 2014, it is necessary to identify which weather stations have more than 25 years of rainfall data and obtain additional data in the future (JICA, 2015).

(2) Approach to acquire agricultural production data and regional target crop determination step

In Myanmar, it is not easy to get past agricultural production data necessary for designing the weather index insurance products. In the acquisition of the data, MOAI need to specify the data type (acreage and productivity, etc.), geographical counting units and year, etc. to request the acquisition of data. It takes several weeks to acquire.

The data used at this time is "Central Statistics Organization, Myanmar Data on CD-ROM 2011" obtained from the Ministry of Agriculture and Irrigation.

Based on this, in order to organize the crop acreage data of Myanmar in 2010-2011 by state, in the three provinces of the Delta region and the central arid region, the crops were arranged for the six States of three States, and the target crop was selected and decided.

Based on the consideration in the preceding paragraph, they requested MOAI to the provision of necessary data on the target crops in each region. The request data, five kinds of data, "acreage", "crop area", "productivity", "production" and "damage", related to the target crop, the period of the past 25 years, and the geographical counting unit was township level. They obtained the list of data from MOAI is as follows. All data is provided in the local language and needs to be translated. Moreover, different types of data and periods can be obtained by state (JICA, 2015).

| # | State | Retrieved Data | Data (# of pages)* | Paper (# of pages)* | Status | |
|---|---|---|---|---|---|---|
| | | | | | Translate | Data Confirmation |
| 1 | Ayeyarwaddy | ✓ Rice Paddy, Summer Paddy, Black gram Green gram (1994-2014)<br>✓ Damage by weather (2005-14), | N/A | Received (About 250) | Finished | Finished |
| 2 | Yangon | ✓ Rain Paddy, Summer Paddy, Black Gram, Green Gram (1994-2014),<br>✓ Damage by weather (2009-2014) | Received (27) | Received (27) | Finished | Not Implemented |
| 3 | Bago | ✓ Paddy Yield (1988-13),<br>✓ Black Gram Green Gram Yield (1994-13),<br>✓ Damage by weather (2007-08, Aug 2008, 2009, 2012, 2013-14) | Received (100) | Received (100) | Finished | Not Implemented |
| 4 | Mandalay | ✓ Paddy (1995-2014),<br>✓ Seasamum, peanut, green gram, pigeon pea and gram pea (2001-14)<br>✓ Damage by weather (2007-13) | N/A | Received (About 200) | Finished | Finished |
| 5 | Sagaing | ✓ Paddy Yield (1993-2014),<br>✓ Sesamum, Peanut (2001-14),<br>✓ Green Gram Yield (93-2014),<br>✓ Damage by weather (1994-2014) | Received (250) | Received (About 250) | Finished | Not Implemented |
| 6 | Magway | ✓ Rain paddy, summer paddy, seasamum, peanut, green gram, pigeon pea and gram pea. (94-2014)<br>* Include data related to damage above | Received (160) | Received (160) | Finished | Not Implemented |

Source：Translated from ”Republic of the Union of Myanmar Preparatory Survey on BOP business on Weather Index Insurance in Myanmar”

Table 15: List of acquired agricultural data

### 3.2. Sales Network

The list of sales networks in the insurance market in Myanmar is shown below (JICA, 2017).

| No. | Name of Domestic Insuarance company | Sales Network (feature) |
|---|---|---|
| 1 | Aung Thitsar Oo Insurance Co,Ltd. | Direct sales from military-related group companies are mainly |
| 2 | Aung Myint Momin Insurance Co,Ltd. | Direct sales from military-related group companies are mainly |
| 3 | AYA Myanmar Insurance Co,Ltd. | Sales from group banks, direct sales of employees, and sales of distributors |
| 4 | Capital Life Insurance Co,Ltd. | Direct sales, counter sales and bundle sale with the product of group company |
| 5 | Citizen Business Insurance Co,Ltd. | Direct sales and contact sales only |
| 6 | Excellent Fortune Insurance Co,Ltd. | Direct sales of 50 employees only |
| 7 | First National Insurance Co,Ltd. | Group banks, direct sales of employees, sales of distributors, mainly sales of banks |
| 8 | Global World Insurance Co.Ltd. | 86% mainly in direct sales, 14% of sales via affiliated banks |
| 9 | Grand Guardian Insurance Public Co,Ltd. | 400 individual agencies, direct sales and contact sales, and sales via partner banks |
| 10 | I.K.B.Z. Insurance Co,Ltd. | Individual distributors are not registered, and direct sales of group banks and employees are carried out. |
| 11 | Myanma Insurance | Direct sales, referral contracts from foreign brokers and foreign insurance companies, only reinsurance transactions and fronting transactions with foreign capital are possible. |
| 12 | Young Insurance Global Co,Ltd. | Direct sales. It is permitted to sell the set with the group's microfinance institution, and it plans to sell it. |

Source：Translated from ”Final Report of Investigation of Collecting Information and Review Survey in the Private Insurance Sector of Republic of the Union of Myanmar”

Table 16: List of major sales networks of domestic insurance companies

As of 2017, the main sales channels are personal agencies that have registered and qualified for about 2000 (about 1,000 in sales operations), direct sales, referrals from bank. However, half of the registered insurance applicants are said not running. The broker has not yet been approved for sale, and the company is the primary reinsurance agent for the Myanma Insurance, and there are no corporate agents. Insurance companies and bank employees who are involved in insurance recruitment are not required by law to obtain an insurance recruitment qualification, although they are mainly conducted through referrals from individuals, insurance companies, and banks. From the perspective of customer protection, regardless of the sales channel, it is important to have sufficient knowledge of the insurance products and to provide products that meet the needs of the customer after gaining a good understanding of the product content. Insurance recruitment by insurance company staff and bank staff should also be regulated. In addition, the authorities are currently conducting a training program about recruiting people, and what kind of cooperation is possible with the Myanmar Insurance Association (MIA), which was formally enacted in October 2017. Moreover, it is thought that it is necessary to examine the point how to enrich the recruiting training, and to make the registration examination system effective. As for reinsurance, only national insurance company is permitted to move the risk to the outside by reinsurance. For private insurance companies, the company is supposed to make joint insurance with other companies if it exceeds a certain amount of payment. Officials are also said to be gearing up for the lifting of the ban on access to the reinsurance market for private insurers in 2018.

**3.3. Player**

The trend of the insurance market in Myanmar is the following. MI, which has dominated the market for many years, has the largest scale. The company currently has 1,300 employees and 38 branches nationwide, and has been commissioned to sell to about 700 individual distributors.

Myanma Insurance is Composite Insurers dealing with both types of life insurance and property insurance. After market opening to the private sector, 12 companies in Myanmar have been approved and opened, but no insurance market statistics have been announced in the country, and the market size cannot be accurately grasped.

The insurance category that private insurance companies can operate at the time of 2015 is limited to six types of ①Life insurance, ②Fire Insurance, ③Automobile Insurance, ④ Cash-in-transit Insurance, and ⑥Fidelity Credit Insurance, and 12 private insurance companies that have started operating with authorization.

In the breakdown, 9 companies are Composite Insurers, 3 companies are life insurance companies, the total of 12 companies are 100% domestic capital. In Myanmar, the state and private insurance companies operating in the above 12 companies, the organization form and form of investment are as follows (JICA, 2017).

| NO. | Name of insurance company in the Federal Republic of Myanmar | Form of organization | Group company/Jurisdiction/related organization |
|---|---|---|---|
| 1 | Myanma Insurance | National Insurance Company | Ministry of Planning and Finance |
| 2 | Aung Thistar Oo Insurance | Composite Insurers | Myanmar Economic Corporation |
| 3 | AYA Myanmar Insurance | Composite Insurers | Max Myanmar Group |
| 4 | Excellent Fortune Insurance | Composite Insurers | Excellent Fortune Development Group |
| 5 | First National Insurance | Composite Insurers | Htoo Group |
| 6 | Global World Insurance | Composite Insurers | Asia World Group |
| 7 | Grand Guardian Insurance | Composite Insurers | Shwe Taung Group |
| 8 | IKBZ Insurance | Composite Insurers | KBZ Group |
| 9 | Young Insurance | Composite Insurers | Young Investment Group (Include Micro Finance) |
| 10 | Aung Myint Moe Min Insurance | Life insurance | Myanmar Economic Corporation |
| 11 | Capital Life Insurance | Life insurance | Capital Diamond Star Group |
| 12 | Citizen Business Insurance | Life insurance | CB Bank Group: Co-operative Bank |

Source：Translated ”Final Report of Investigation of Collecting Information and Review Survey in the Private Insurance Sector of Republic of the Union of Myanmar”” 

Table 17: Insurance companies and investment organizations in Myanmar

These insurance companies are capitalized by the funders of major conglomerates, government or military companies that are successful in their business in Myanmar. They also have financial companies in the group, including banks and microfinance institutions (JICA, 2017).

| NO. | Name of Insurance Company | Group or Affiliated Banks/Financial institutions | Capital (Kyat) | Number of employee (person) |
|---|---|---|---|---|
| 1 | Myanma Insurance | – | 567 Hundled million Kyat | 1,393 |
| 2 | Aung Thistar Oo Insurance | Myawaddy Bank / Inwa Bank | 46 Billion Kyat | 137 |
| 3 | AYA Myanmar Insurance | Ayeyarwady Bank (AYA Bank) | 46 Billion Kyat | 300 |
| 4 | Excellent Fortune Insurance | – | 46 Billion Kyat | 50 |
| 5 | First National Insurance | Asia Green Development Bank | 46 Billion Kyat | 237 |
| 6 | Global World Insurance | – | 46 Billion Kyat | 108 |
| 7 | Grand Guardian Insurance | No bank in the group but affiliated with 10 banks | 46 Billion Kyat | 406 |
| 8 | IKBZ Insurance | Kanbawza Bank | 46 Billion Kyat | 600 |
| 9 | Young Insurance | Myanmar Industrial Development Bank | 46 Billion Kyat | 25 |
| 10 | Aung Myint Moe Min Insurance | Inwa Bank | 6 Billion Kyat | 200 |
| 11 | Capital Life Insurance | Partnering with Myanmar Citizens Bank | 6 Billion Kyat | 60 |
| 12 | Citizen Business Insurance | Co-operative Bank | 6 Billion Kyat | 135 |

Source：Translated ”Final Report of Investigation of Collecting Information and Review Survey in the Private Insurance Sector of Republic of the Union of Myanmar”

Table 18: Financial institutions, capital and number of employees of domestic insurance companies in Myanmar

In the PwC project, Myanmar Awba Group Co., Ltd. (Awba) was selected as a candidate for negotiation by investigating the organization and the company which provides microfinance. It will be business execution partner securing the sales network to the farmer. Upon selection, they emphasized two points: ①There are many customers of micro finance targeting farmers, ②Efficient operation and easy tie-up negotiation (JICA, 2015).

PwC and others cooperate with Awba and MI as a business model to assume that a series of processes of product sales, premium collect, payment delivery. At present, it is assumed that insurance premiums and insurance payments are paid by manual. However, since it is assumed that the mobile payment system that Awba is currently implementing is in the process of penetration, it is necessary to reexamine the business process according to the situation of the commercialization timing (JICA, 2015).


Source：Translated "Republic of the Union of Myanmar Preparatory Survey on BOP business on Weather Index Insurance in Myanmar"

Figure 12: Partner Roles

Partners will be responsible for collecting premiums and delivering payments, and will conduct desktop surveys and interviews for microfinance providers as listed below. In the end, they decided to Myanma AWBA Group, a company ①that has many microfinance customers, and ②is an organization that is easy to operate and negotiate effectively (JICA, 2015).

| # | Category | Organization (Excerpt) | Detail | # |
|---|---|---|---|---|
| 1 | RSC (*1) | ✓ MAPCO (*3)<br>✓ Gold Delta<br>✓ Ayeyar Hinthar | A private company that is engaged in contract cultivation of rice with farmers in a particular area, and has a loan in the kind of seed or fertilizer, or a small cash. | 9 |
| 2 | Agri-specialized Companies (Seed & Fertilizer) | ✓ Myanma Awba group<br>✓ Shan Maw Myae<br>✓ Capital Diamond Star | A private company that carries out the sale of seed/fertilizer/ agricultural machinery to farmers and provides loans in the physical and small cash. | 15 |
| 3 | MFI (*2) | ✓ Acleda<br>✓ LOLC<br>✓ Aeon | Private Microfinance institutions. The number is limited just after the opening of the microfinance market. | 3 |
| 4 | NGO | ✓ PACT<br>✓ GRET<br>✓ Proximity Design<br>✓ World vision | NGO that operates nationwide as a target area of agriculture . There are Local NGOs working only in Myanmar and International NGOs that are also active in Myanmar while setting the whole world as the activity area. The leading microfinance providers in Myanmar. | 13 |
| 5 | Others | ✓ Central Cooperative Society<br>✓ MRF (*4)<br>✓ MFA | Organizations such as agriculture-related association and cooperative . Like NGOs, there are organizations that are active nationwide and have a strong network of farmers. | 5 |
| 6 | Government | ✓ Ministry of Cooperatives<br>✓ MADB | A government-based microfinance provider. Widely reach farmers across the country. (but out of scope for this time) | 2 |

Source：Translated "Republic of the Union of Myanmar Preparatory Survey on BOP business on Weather Index Insurance in Myanmar"

Table 19: Partner List (summary)

### 3.4. Legal Regulations

The following is an overview of the conditions and approval procedures for the insurance market in Myanmar. The insurance policies and rates are pre-sanctioned, but private insurers use the same tariff rates and conditions as the state insurance companies.

It is a topic as the Myanmar insurance industry that there is a need to revise all insurance products as a new insurance product for the insurance product by an old contract because it references the agreement about 60 years ago of the India country. The approval procedure for insurance products such as insurance conditions and insurance rates is required for the the Insurance Business Regulatory Board (IBRB) to be approved by the Insurance Business Rules 29 (a) and (b). The insurance company apply to IBRB for the contents of the insurance product (explanatory materials on insurance terms, insurance rates, insurance sales methods, etc.), and it is approved by the deliberation in about one month in case of early, and it is said that it becomes authorization in about five months depending on the situation. Currently, MI sells about 29 kinds of insurance products, and a private insurance company sells 9 kinds of insurance products. At the beginning of 2013, they started with 6 types, but then there were 3 additional types of medical insurance.

Private insurance companies are not allowed to use their own terms and their own insurance rates, and all company is using the same insurance policy and insurance premium for products as the Myanmar Insurance Corporation. Recently, in December 2016, the application for approval of new products has been started, and 28 new products have been applied to each insurance company. In January-March, 11 different insurance products were scheduled to be approved on April 1, but there was no announcement as of June, when they were consulted in IBRB and private insurance companies. In addition, private insurance companies are expected to start handling reinsurance that had not been accepted so far within 2017. Approval from both sides is expected to be announced soon (JICA, 2017). The detail will be following.

(1) Legal system and regulations

The laws and regulations of the current insurance business are following. ① In June 1996, the Insurance Business Law (IBL) is Promulgated, and a private insurance company and Myanmar Insurance Supervisory Board is established. ② In June 1997, the Insurance Business Rules (Enforcement Regulations of the Insurance Business Law) is being operated with the rule promulgated to keep the Myanmar Insurance Business Law promulgated in 1996. In the previous The Myanmar Insurance Law (MIL) (until 1993), MI was defined as the only state-owned insurance company, and the sales of other private insurance companies were banned. The new IBL, which was promulgated in 1996, shows the policy of introducing private insurance companies, and it is stipulated that a sales license need to be obtained when running the insurance business in Myanmar. However, until May 2012, no new sales licenses were issued.

These laws, except for compulsory insurance for car owners and for businesses approved by the foreign Investment law, have no provision to indicate the obligation of retention to the Myanma Insurance in relation to properties and risks located in Myanmar. However, these laws are constructed to prohibit foreign insurers from undertaking domestic risks without obtaining a license, as the insurance companies in Myanmar stipulate procedures for obtaining business licenses. In Myanmar Foreign Investment Law (MFIL), which is promulgated in November 2012, all foreign companies and investors have been stipulated to conclude insurance contracts with domestic insurance companies.

The Insurance Business Act (IBA) stipulates the establishment and authority of IBRB (supervised by insurance companies etc.) (revised since 1996), the business license of insurance companies / insurance underwriting agents, insurance intermediaries (brokers) The obligation of the business operator, the obligation concerning auditing by the business operator, etc. In addition, under the Insurance Business Act Enforcement Regulation, applications such as insurance companies' business licenses, the amount of paid-up capital, etc. are stipulated. The main objectives and outline of the law and regulations are as shown in the table below. According to Mr. Maung Maung · Ting, former director of MPF, who was the chairman of the IBRB Executive Board,

when creating the insurance business law, Myanmar has been referring to the insurance industry law and enforcement regulations in 17 countries (not only the United States and the UK but also Japan, China, Korea, Taiwan, Czech Republic, Singapore, Australia, Portland and other countries) (JICA, 2017).

| No. | Insurance laws and regulations | Date of publication | Purpose and summary |
|---|---|---|---|
| 1 | Insurance Business Law | June 24, 1996 | <Purpose><br>① Contribute to the development of the national market economic system.<br>② To develop foreign investment and domestic investment.<br>③ Private sector insurance business, underwriting agency or insurance broker pave the way for the line.<br>④ To ensure the trust and credibility of the people in the insurance system by providing various types of insurance that may be necessary for the overall development of the nation.<br>⑤ To make the insurance business and business successful and excellent. |
| 2 | The Insurance Business Rules | June 26, 1997 | <Summary><br>① Amount of paid-up capital<br>② Provisions on a reserves fund<br>③ Application procedure for business license<br>④ Obligation to use the application, article, and rate of insurance that has been approved by the IBRB<br>⑤ Obligation to maintain contracts, accidents and accounting documents<br>⑥ Duties of insurance companies , insurance agents , and insurance broker , etc. |

Source：Translated "Final Report of Investigation of Collecting Information and Review Survey in the Private Insurance Sector of Republic of the Union of Myanmar"

Table 20: National Insurance Law and the purpose or summary of the rules

(2) Business License System

Currently, the establishment of an insurance company requires a license and authorization by IBRB. The minimum capital in the case of begins of domestic private insurance companies is 46 billion kyat (approximately $ 4 million) and high requirements are specified. 11 companies of Myanmar's domestic private insurers have started an insurance business that meets the requirements of single-price minimum capital at the start of business in 2013. The insurance company which intends to do the insurance business is specified in article 8 of the Insurance Business Act that it is necessary to approve the enterprise and the insurance product by IBRB for each handling event (JICA, 2017).

(3) Solvency Regulation (solvency)

As an insurance policy, it is stipulated in article 11 of the Ordinance for Enforcement of that it should possess the highest amount of 2 million kyat (approx. $ 20K), 50% of the net income insurance premiums for the most recent fiscal year and 50% of the kyat (JICA, 2017).

(4) Approval process flow for Clause and Products

According to IBRB, in order for a new insurance product to be approved, a private insurance company will provide detailed discussion in terms of the characteristics and effects of the product, the premiums and rate levels, the sales method, the prospect of the insurance policy, and the benefits of the policyholder. IBRB will approve the application form and the report that the private insurance company has applied for, and make an offer of the decision of the authorization approval. Then, with the permission of the domestic Economic Committee and the domestic cabinet, the insurance company is notified of the approval of the insurance product by submitting it to MPF. According to MPF, the period until the approval of the insurance product was about one month, but in the interview of the private insurance company, it was recognition of about one month to six months until approval. A private insurance company will have the right to sell it only after it has authorized and approved each insurance product from the point of view of the product characteristics, insurance premiums and insurance rate level, and the benefit of the contractor, IBRB. On the other hand, if insurance products are judged to exceed the protection of policyholders, MPF explain that insurance products may be denied approval (JICA, 2017).

Although the status of a PwC project has been approved for sale of insurance products, it is considered that it is difficult to obtain the immediate approval of the Weather index insurance product sales in multiple consultations with the insurance authorities. It was considered realistic to resume negotiations for implementation after the second half of the 2015 elections (JICA, 2015).

(5) Status of Authorization

According to the Director of FRD of MPF, the private insurance company has approved 28 types of insurance products in December 2016, and IBRB will approve 11 types of insurance products. It was announced in March 2017, it will be available for sale in 2017, but was not disclosed as of June 2017. In addition, private insurance companies seemed to expect to sell the products now monopolized by MI such as agricultural insurance, agricultural weather Index insurance, machinery insurance, Erection All Risks Insurance (EAR), construction insurance and revision of medical insurance. In addition, MPF have explained that the IBRB is in the direction of re-insurance transactions, but as with insurance products, it is not disclosed at the time of 2017 (JICA, 2017).

## 5.3. Proposal of an industry-government-academia collaboration system

In this section, I propose a system of public-private-academic collaboration, laws and regulations, and databases that are necessary to design parametric insurance based on the case study of Myanmar.

As a background, unlike an HPLC, there are no positives to being prepared before a real LPHC disaster. This is because it is low frequency and does not benefit the company. However, the amount of damage and the scale are enormous.

Therefore, in governmental and space-science sectors, such as NASA-JPL, there is a need to communicate the threats and dangers to the public and prepare for these LPHC by creating incentive for the company. The climate change issue is now driven by international organizations such as the IPCC for preparatory means. However, from the authors' point of view, they are not yet ready for other types of emerging risks. Finding mechanisms to compensate for those potential risks are essential to increase preparedness for LPHC.

As for the Macro Framework, I consider an international donor fund for these massive risks as "Prioritization Assessment" (To be explained in a later). We did a literature survey and propose new funds which allows us to prepare for these massive risks from many international organizations and governments. First, we should establish the new treaty through an International Conference based on the objective target and domain, then we should decide the amount or ratio of a grant from each institution or government. After this, we will have a pilot project to materialize this concept.

As for the micro framework, first we need to decide project objectives, outcomes and each output supporting these outcomes. Since the projects launch, we have cooperated with international organizations, academia, and private companies to develop insurance tools or new social regimes to support this idea. Also, we will monitor the results and investigate the issues to resolve any problems.

It is argued that a comprehensive approach based on the Sendai Framework for Disaster Risk Reduction 2015-2020 is necessary in the United Nations Framework Convention on Climate Change. The United Nations has also set out to quantify the damage caused by climate change (UN, 2018).

According to JICA (2018), There are methods of risk control (avoidance / prevention, reduction) and risk financing (relocation, possession), but among them, this time, LPHC is a low-frequency

but large-scale risk, so for the method of reducing the risk itself, it is desirable to use risk financing, which is a method of diversifying risks, instead of risk control.
Non-life insurance, which is a typical mechanism for sharing and distributing all or part of the risk to external parties, is preferable. In risk financing, the loss of society as a whole remains the same, but by dispersing it throughout society, financial risks that an organization cannot tolerate can be avoided.
Based on the characteristics of LPHC in this paper, I propose a new risk financial scheme for large scale disaster risks by referring to Mexico's Natural Disaster Fund (FONDEN) and the Philippine Catastrophe Insurance Facility (PCIF).
FONDEN could be used for rehabilitation and reconstruction. It consists of two complementary budget accounts, the FONDEN program for reconstruction and FOPREDEN program for prevention, and their respective financial accounts (World Bank).
The Philippine Catastrophe Insurance Facility (PCIF) is billed to be the first private sector-focused catastrophe risk financing initiative of its scale that will allow all insurers to pool their catastrophe risks and benefit from efficiencies (ARTEMIS). It aims to allow insurers to manage their catastrophe exposures more efficiently by providing them with part of a more diversified pool instead of a more concentrated risk portfolio (ARTEMIS).

As for funding, it has two sources: Disaster Fund with Trust Funds as Resources from Contributions from Other Countries and Issuing Multiple CAT Bonds to raise money from market investors. Utilizing these funds, people can work on risk assessment, disaster research, product development, and sales through public-private-sector collaboration.
CAT bonds are bonds with an event-triggered principal loss mechanism in the event of a large-scale disaster, such as a major earthquake, hurricane, or pandemic, under specific conditions. As a response to the risk of loss of principal, a high coupon is set (Nomura Securities, 2011). This means that in the event of a disaster that meets certain conditions, such as a typhoon, earthquake, or tsunami, the issuer is exempted from some or all of the principal to be redeemed. In other words, it is a financial derivative (derivative) to receive disaster compensation (Sumitomo Mitsui DS Asset Management).

If the damage exceeds a certain level, which will be set later, we are considering a mechanism to gain access to these funds (as a "Prioritization Assessment").
The government has established frameworks and laws as facilitators to provide a safety net against more than a certain risk. Private companies sell financial products and insurance based on a huge amount of data and skills, and provide advice to academia. Academia conducts research on

disaster risk financing and develops necessary systems and models with the aim of assessing risks and quantifying damage. This is drawn in Figure 13.

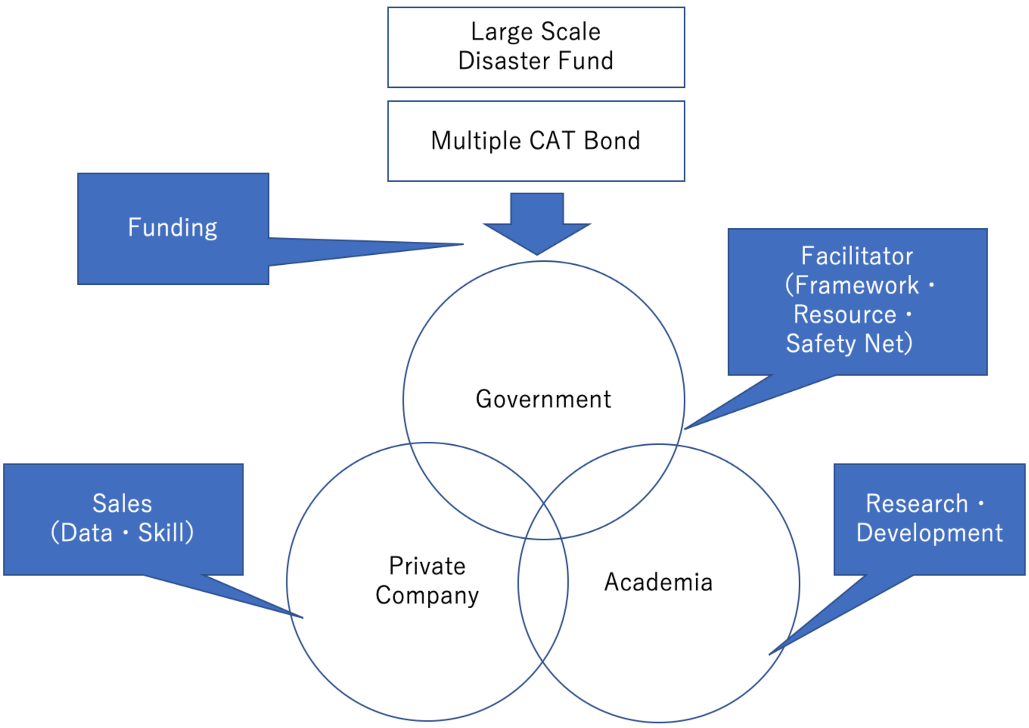



Figure 13. International Schemes for funds and CAT bonds include a government, private companies, and academia

The development and implementation of these disaster risk financing schemes for funding and public-private studies is realized separately, and there are several outputs (Micros) that support the realization of the outcome (Macro), which is the purpose for each project. As a result, it aims to achieve the objective in both macro and micro directions as in Figure 14.

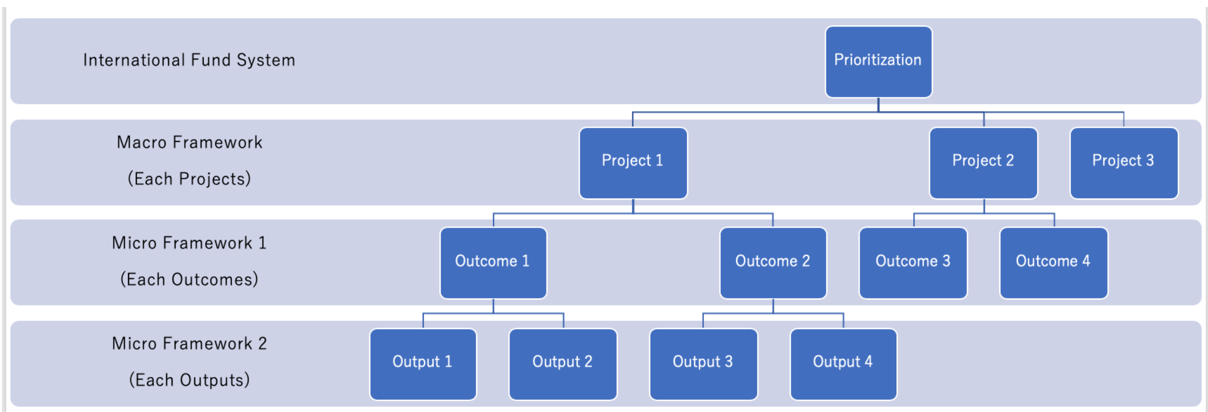


Figure 14. Macro and Micro Concepts

I propose a Prioritization Assessment for preparing these LPHC.

Conceptual Figures for classifying Risk Management Tools were recompiled based on the Frequency (X-Axis) and Severity (Y-Axis) by reviewing Clarke and Mahul (2011). LPHC is categorized as the left most position on the graph and it is needed to recognize and assess the risk by preparing a "Prioritization Assessment". Due to the uncertainty of the occurrence of severe and catastrophic damage induced by such risks, and due to the extreme potential cost caused by such a disaster, it is very difficult to establish an international donor assistance proposed by Clarke and Mahul (2011). However, it is necessary to prepare research funds, recognize risks, identify them, and evaluate them because they have a large impact and a large amount of damage can occur when considered in the long term.

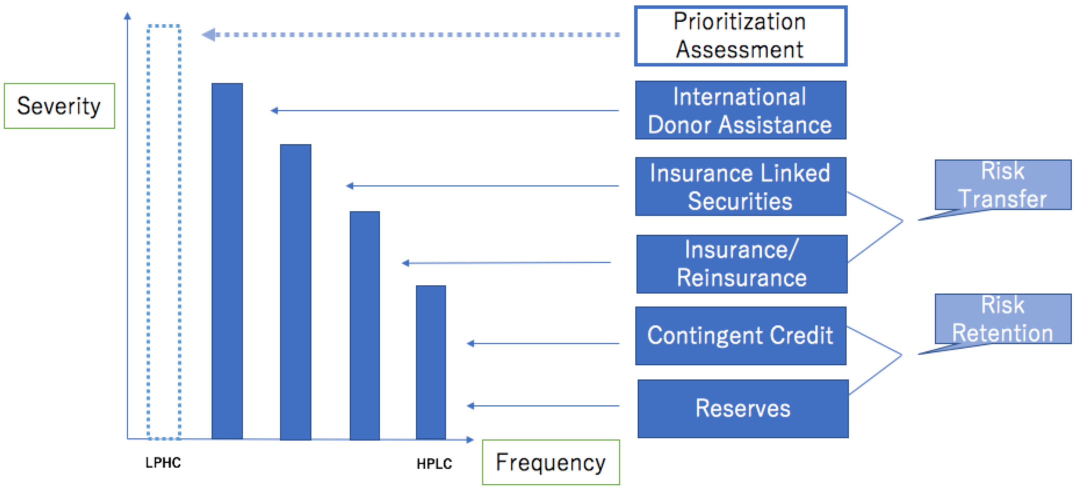



Figure 15. Risk layering and disaster risk financing strategy for considering LPHC risk (reconstructed figure compiled by Clarke and Mahul 2011)

HPLC is categorized as the right-end position in this x-axis. The larger the potential damage is, the larger framework should be prepared for risk evaluation. At the same time we should realize that at a certain level of the potential disaster under a lower probability event, the threat itself will be excluded from consideration. In such a case we propose to include "Prioritization Assessment" in order to compensate such potential hazards.

Basically, HPLC is usually covered by private insurance companies, but for LPHC, the scale and impact is so great that governments and international organizations should cooperate to compensate the three entities for the parts that cannot be covered by the private sector.

It is also important to achieve the following two things. First, the establishment of Risk

assessment Data Base. Under the cooperation with each institution, it is better to create a unified database for the entire international community to refer to cases and countermeasures.
It is important to develop the data statistically.
Second, each country needs to clearly sets insurance certification standards. As insurance is a regulated industry, there are many cases where innovative new products are planned but cannot be sold or realized due to regulations. In order to avoid such a situation, it is necessary to establish a system for smooth and speedy approval of insurance.

The public and private sectors will work together internationally to develop a database internationally and collect statistical data. Furthermore, thresholds and insurance standards are set for each country and situation, and thresholds are set for each event like index insurance. In addition, the collected data will be used for insurance and development.
In the event of an actual LPHC or emerging risk, payment shall be made from the pooled reserve and compensation shall be made. Then, when some kind of LPHC actually occurs like index insurance, if the threshold value set in advance is exceeded, payment and compensation shall be provided. In addition, we will develop new types of parametric insurance by utilizing the advanced cases and knowledge of each country.
Then, we will accumulate knowledge from case studies and prepare for risk reduction / prevention. We summarized most of those potential risk management tools (Prioritization Assessment, International Donor Assistance, Insurance Linked Securities, Insurance/Reinsurance, Contingent Credit and Reserves) depending on the severity and frequency of the risks. As for Prioritization Assessment, it is important to pool the funds in case of unprecedented low frequency and super-massive disasters in the international community, as a whole rather than the private sector and each nation, and to establish guidelines.

The entire process can be summarized in the following diagram.

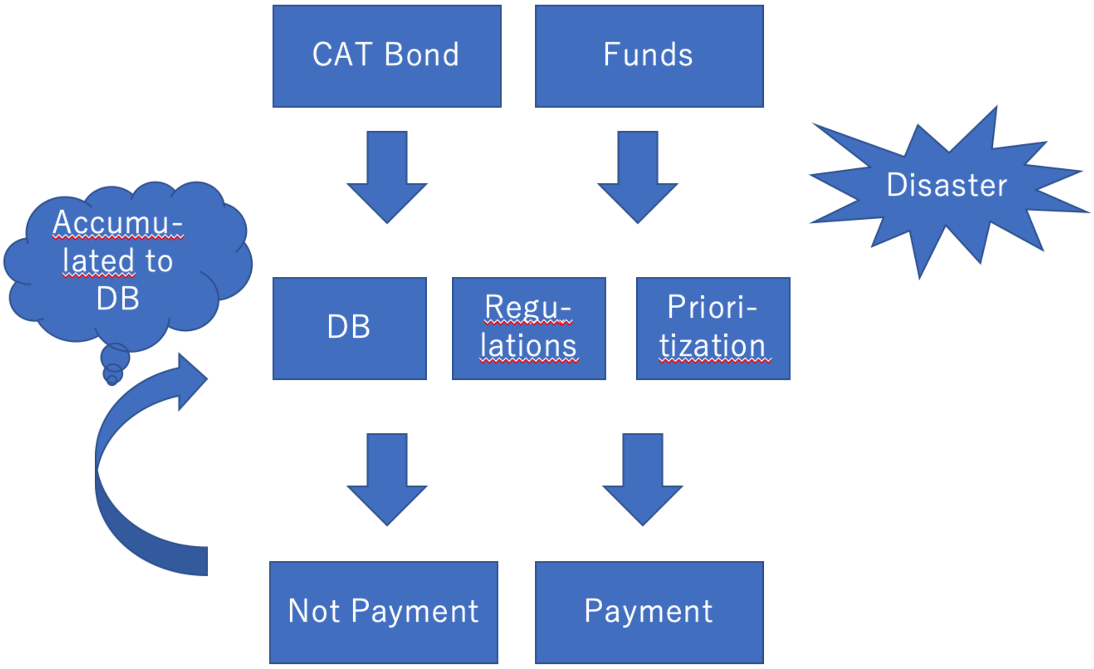



Figure 16.　Industry-government-academia collaboration system as a whole

First, in preparation for a catastrophic event, funds from investors through CAT Bonds and contributions from governments, private companies, and international organizations will be pooled. Then, in the event of a major catastrophe, the catastrophe database is used to deliberate on regulatory approvals, and risk assessment is conducted in light of the prioritization mechanism. Finally, if the size of the payout and the approval are met, the insurance will be paid out. In the event that claims are not paid, they are stored in the database and used as new knowledge to facilitate future disaster prevention, risk assessment and payment.

### 5.4. New Space

This research quantified the risk of economic loss due to solar radiation exposure for the first time, and made it possible to determine the optimal aircraft operation countermeasure guidelines during solar flares and to examine the risk countermeasures.
In addition, the space travel plan promoted by Space X, Virgin Galactic, Blue Origin and others is expected to increase the risk of solar radiation exposure, so the risk quantification using the method constructed in this study and its proposals for exposure dose reduction measures based on the results will become even more important.

・ Background of the space industry
In addition to the conventional market, it has been booming in recent years.
The intersection of trends inside and outside the space industry has created a new trend in the world space industry called "New Space." In addition to the conventional space-related companies, venture companies and companies from different industries such as IT, electronics, and robotics are entering the market one after another, and there are signs that they will develop into a major industry where people, goods, and money gather (Ishida, 2017)
It is said that there are currently more than 1,000 venture companies in Europe and the United States (confirmation required), capital has increased due to self-investment by entrepreneurs themselves, and the ecosystem of the space industry has changed significantly. In addition to the traditional pyramid structure of government agencies, large companies, and SMEs, venture companies, companies from different industries, professionals, and third parties are entering the market, and the number of players is increasing. Furthermore, flexible collaboration is taking place across business boundaries, and a new ecosystem is being created. In this way, the world space industry is in the midst of a major transformation that can be called "New Space" (Ishida, 2017).

・ Overview of the market
According to the "State of the satellite industry report" released annually by the US industry group SIA (Satellite Industry Association), the market size in 2016 is estimated to be $ 339.1 billion (confirmation required). About 25% of the total space industry in 2015 is public demand. If only the equipment industry is taken out, about 70% is government demand (Ishida, 2017).

・ Legal development / policy

It is fresh in my memory that the enactment of the Space Activity Law, which is an institutional collateral for private companies to conduct space business in Japan, became a big topic in 2016. On the other hand, in Europe and the United States, legislation regarding commercial space activities has been gradually established for decades. In addition to legislation, various policy support is also provided. Commercial space activities have been set as the top agenda in the United States, Germany, France, the United Kingdom, Luxembourg, etc., and various policies to support private companies have been put into practice (Ishida, 2017).

・Player

Ambitious and enthusiastic entrepreneurs like Elon Musk, Jeff Bezos and Mark Zuckerberg stand out. It is a fact that not only such ventures and companies in different industries, but also major European and American aerospace companies that have traditionally led the industry are actively participating in new space businesses. Airbus, one of Europe's leading aerospace companies, is a good example. In the past, it has grown through acquisitions and mergers mainly in the European region, but in recent years it has been aggressively offensive, such as partnering with OneWeb, a venture company aiming for a satellite Internet construction network, and launching an investment fund in Silicon Valley. Is attracting attention (Ishida, 2017)

・ Industry-government-academia

Industrial platform In terms of "industrial platform", cross-industry efforts are conspicuous. For example, a non-profit industry group hosts a large-scale business conference to create a place for stakeholders to interact with each other, raising awareness of the industry as a whole and providing an opportunity for business to be born. Many of these organizations make positive policy recommendations to government agencies. The media also plays a major role, and there are not only media for the general public but also professional media that provide information for investors (Ishida, 2017).

・ Private sector: Inflow of risk money

As risk money, the inflow of private capital is accelerating. According to the report "STARTUP SPACE" by the US Tauri Group, a research institute, a cumulative total of more than 1 trillion yen has been inflowed over the past 10 years. Furthermore, in the United States, well-known venture capital firms are increasingly incorporating space-related ventures into their investment portfolios. Regarding the government budget, a wide variety of measures have begun to be taken beyond mere subsidies for new players such as seeds investment for industrial development, technology development investment, and service purchase (Ishida, 2017).

・Technology

A fusion of traditional space development technology and know-how cultivated mainly by government-affiliated space agencies and major aerospace companies and new technology and know-how that has been flowing in from the IT industry centered on Silicon Valley in recent years has occurred. There is. The former has technologies for dealing with various extreme environments such as radiation, thermal vacuum, and vibration. The latter includes various cheap technologies, advanced processing capabilities, and development / manufacturing methods such as agile development and utilization of 3D printers. Furthermore, the movement to utilize artificial intelligence and machine learning for satellite data analysis is accelerating, and various application developments are progressing (Ishida, 2017).

The fusion of IT and big data is also progressing. It is desirable to enter the space industry during such a prosperous period.

Although the space industry is booming in this way, in order to conduct the risk assessment in this paper, it is necessary to develop a protocol for the occurrence of GLE and estimate the amount of economic loss (risk) as in the case of aircrafts. In doing so, it is important to accurately estimate the cost of fuel increase and the cost of flight cancellation when changing altitude or route. A single rocket launch is estimated to cost several billion to ten billion yen. If we can calculate these costs, it will be possible to apply them to rockets.

Summary of Chapter 5

In Chapter 4, the series of risk assessments conducted in this paper as LPHC risk countermeasures for the aerospace industry was made into a framework, the possibility of parametric insurance was discussed, and policy recommendations were made. First, based on the quantitative risk assessment process proposed by previous studies, I organized and constructed a framework for quantifying LPHC risks in the aerospace industry. Next, I defined parametric insurance, as well as its mechanisms, advantages and disadvantages, and discussed the possibility of designing parametric insurance using the index proposed in Chapter 3. Next, as a case study, I presented a design example of weather derivatives and discussed the possibility of introducing weather index insurance in Myanmar. Finally, I proposed a system of public-private-academic collaboration, laws and regulations, and databases that are necessary to design such parametric insurance.

## 6. Conclusion

This thesis develops a framework for the quantification of LPHC risk in the aerospace industry to enhance and improve social resilience, and also discusses and proposes the necessary framework.

In Chapter 2, various types of natural disasters in human and global history are classified according to their frequency and damage scale. Disasters that caused extinction events in Earth's history include (1) volcanic disasters, (2) asteroid impacts, and (3) climatic disasters, which are classified as low- probability, high-consequence (LPHC) events. On shorter timescales, however, humans are subject to more frequent disasters such as (i) major floods, (ii) epidemics, (iii) earthquakes, (iv) tsunamis, and (v) medium-sized volcanic eruptions, which are known as high-probability, low-consequence (HPLC) events. Above all, I focused on the risks in the operation planning of modern man-made artificial objects such as aircrafts. LPHC events have a very low probability of occurring, but they would have catastrophic consequences. HPLCs occur more frequently, with most of them having decadal frequency. They cause local fatalities, but they are never global in scale. In this study, these events were classified and evaluated based on the potential risk for human civilization. I also discussed how to incorporate different considerations related to prioritizing different disasters, focusing on whether insurance mechanisms can be applied or not. In this chapter, I reviewed in detail the historical facts of various disasters including MEE, LPHC, and HPLC, and explained the background of this paper. In the next chapter, I quantified the flight risk of GLE based on a one-dimensional model.

Chapter 3 presents a systematic approach to effectively assess the potential risk costs of exposure to solar particle events (SPEs) resulting from solar flares for the aviation industry. In addition, based on a previous study (Yamashiki *et al*. 2019 ApJ), ExoKyoto was used to assess the associated health risks of radiation and provided relevant alternatives to minimize economic losses and opportunities. In this chapter, the potential risk costs caused by the aviation industry's exposure to solar particle events (SPEs) from solar flares were estimated by a simple one-dimensional model. In the next chapter, the model is extended to a four-dimensional model for quantification. In this calculation we set a hypothetical airline shutdown scenario at 1 mSv for a single flight per passenger, due to legal restrictions under the potential radiation dose. In such a scenario, I calculated the potential loss in direct and opportunity cost under the cancellation of the flight. As a result, lower altitude flights provide more safety for the potential risk of radiation doses induced by severe SPEs. At the same time, since there is total loss caused by flight cancellation, we propose that considering lower flight altitude is the best protection against solar flares.

In Chapter 4, the risk assessment of cosmic ray exposure performed in Chapter 3 was quantified in consideration with the location and temporal changes of the earth, and quantified based on actual aircraft operation routes. Cosmic ray exposure to flight attendants and passengers is called aeronautical radiation exposure and is an important topic, especially for protection aginst solar high energy particles (SEPs). Therefore, I evaluated the risks associated with the cost of measures to reduce SEP doses and dose rates for eight flight routes during five ground-based level rise events (GLEs). A four-dimensional dose rate database developed by WASAVIES, which is a warning system for aviation exposure to solar energetic particles, was employed for SEP dose assessment. For the cost estimation, two measures were considered. One is the cancellation of flights and the other is the reduction of flight altitude. Next, I estimated the annual frequency of significant GLE events with maximum flight path doses and dose rates exceeding 1.0 mSv and 80 μSv/ h, respectively, based on historical GLE records and historically significant events observed by cosmic-ray neutron and radiocarbon analysis results. Calculations indicate that a GLE event of sufficient magnitude exceeding the above dose and dose rate thresholds to require a change in flight conditions would occur once every 47 and 17 years, respectively, and that the conservatively estimated annual risk associated with the cost of countermeasures would be up to about US$1.5 thousand for daily long-haul flights.

In Chapter 5, the series of risk assessments conducted in this paper as LPHC risk countermeasures for the aerospace industry was made into a framework, the possibility of parametric insurance was discussed, and policy recommendations were made. First, based on the quantitative risk assessment process proposed by previous studies, I organized and constructed a framework for quantifying LPHC risks in the aerospace industry. Next, I defined parametric insurance, as well as its mechanisms, advantages and disadvantages, and discussed the possibility of designing parametric insurance using the index proposed in Chapter 3. Next, as a case study, I discussed the possibility of introducing weather index-based insurance in Myanmar. Then, I proposed a system of public-private-academic collaboration, laws and regulations, and databases that are necessary to design such parametric insurance. Finally, based on the recent trends, the quantification of risk using the method developed in this study and the proposal of measures to reduce exposure dose based on the results will become more and more important in the space industry, such as the application to spacecrafts.

To answer the first research question presented in this paper, a systematic approach to effectively assess the potential risk costs of exposure to solar particle events (SPEs) due to solar flares in the aviation industry was first introduced in Chapter 3, and a simple one-dimensional model to calculate the potential direct and opportunity cost losses that would result if flights were cancelled. Furthermore, in Chapter 4, the model in Chapter 3 was extended to a four-dimensional model and quantified. The risk assessment of cosmic ray exposure presented in Chapter 3 was quantified based on actual aircraft flight routes, taking into account the position of the earth and temporal changes. Eight flight routes during five ground level elevation events (GLEs) were used to reduce the SEP dose by applying EII and proposing PEII and PEI. The cost of the countermeasures and the risk associated with the dose rate were evaluated.

Finally, in Chapter 5, a series of risk assessments conducted in this paper are framed as a countermeasure against LPHC risk in the aerospace industry for implementation in society, the possibility of parametric insurance is discussed, policy recommendations are made, and the necessary systems and elements to be considered for implementation in society are presented.

Overall, the contributions made in this paper and the points that still need to be addressed in the future are summarized below.

The main contribution in Chapter 2 was the proposal of risk maps and the discussion of the possibility of insurance design. Since there is still room for further organization, it is desirable to organize the discussion in an easy-to-understand manner in the future.

The main contribution in Chapter 3 is the calculation of costs, but since this is a simple model, the model is extended in the next chapter.

The main contribution of Chapter 4 is the calculation of I for PEI and the estimation of the probability of GLEs that have occurred so far, and since the impact of future events is unknown, it is necessary to apply the research in the future.

The main contribution of Chapter 5 was to propose a framework, discuss the possibility of parametric insurance design, and make policy recommendations, but it did not lead to actual insurance design. Based on these findings, it would be desirable to propose realistic policies based on more elaborate research in the future.

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