An attempt to estimate the risk from weather-induced natural disasters in future Costa Rica

Teruaki Ohnishi, Gustavo Hernández Sánchez and Víctor Meza Picado

Instituto de Investigación y Servicios Forestales, Universidad Nacional, Heredia, Costa Rica

(January 2010)

ABSTRACT: A model of a sort of system dynamics was developed to estimate the frequency and the extent of unusual weather-induced natural disasters in Costa Rica under the global climate change. According to the five scenarios regarding the growth of global temperature and its variability, the extent of the disasters such as flood, landslide, sea surge and strong wind, together with the time variation of human risk originated from them were derived. The ensemble average of calculation indicates the considerable enhancement of the damage which is imagined to occur along the coast lines in Costa Rica due to the sea surge, and the substantial increase of the extent of disasters and human risk which are certainly led by the growth of the temperature fluctuation. The individual calculation also indicates that, since the extent of the climate anomaly becomes larger in future, the harmful influence on the economical activity and the social welfare must probably be increased by the disasters at the time of a large climate fluctuation. The continuous allocation of budget to the disaster measures is strongly suggested for the future Costa Rica.

KEY WORDS: weather-induced natural disaster; climate change; temperature variability; model; ensemble average; human risk; social welfare; Costa Rica

1. Introduction

Costa Rica had experienced more than 100 direct and indirect attacks of tropical cyclones and hurricanes during the last century (Lizano and Fernandez, 1996; Alvarado and Alfaro, 2003). Whenever the attack of those phenomena had occurred, various types of disasters usually broke out to result in an enhancement of human risks (Grandoso, 1979; Fernandez and Vega, 1996; Chinchilla, 2009). Although the natural disasters as flood and landslide which are directly related to abnormal meteorology are thus so frequent in Costa Rica, the protection against those disasters along with the construction of disaster measures are far from the state of completeness at present.

Hegerl *et al.* (2007) have pointed out the possibility that the frequency and the strength of unusual meteorological phenomena may grow with the increase of global temperature. Under such circumstance, the extent of natural disasters induced by the unusual meteorology will inevitably increase in almost every country in future (Milly *et al.*, 2002). There is no clear information, however, at what time in the future and with what extent of scale the disasters will take place in Costa Rica, although such an ambiguous situation is not limited solely for Costa Rica but common for all countries. It is not unreasonable, therefore, that Costa Rica has an intention to confront the difficulties from the global warming with the policy of adaptation as a long term plan (IMN, 2007).

Although the adaptation is vulnerable when unusual meteorological events suddenly occur in a large scale, it is still effective in general for the industry, the society and the human living in case of the gradual change of global climate. Even in the adoption of adaptive strategy, however, it is necessarily required the quantitative, or at least qualitative estimation on some measurements regarding the weather-induced natural disasters which may take place in future. Whether or not there exists such information must probably lead significant difference in making policies for future Costa Rica, and hence in what this country ought to be in future.

Under the condition of global warming, the probable increase of not only the average temperature but also the temperature variability has been pointed out to occur (Schar *et al.*, 2004; Christidis *et al.*, 2005; Trenberth *et al.*, 2007; Hegerl *et al.*, 2007). Namely, the fluctuation of average temperature becomes larger with time, and therefore, unusually severe and extreme meteorological events possibly breaks out when an extremely high temperature occurs due to fluctuation. Generally speaking, the relations among the meteorological variables are highly non linear and moreover the quantities seem to vary in a quite stochastic manner, being subject by various factors so that simple extrapolation is powerless in estimating future values. In this paper, a non-linear model is developed from the viewpoint of system dynamics to relate the atmospheric temperature as an index of global climate change and the unusual weather-induced natural disasters and by using it, the extent of the disasters and the human risk originated from them are estimated for the future Costa Rica.

In the next section, a model and its mathematical expression are described. Examples of numerical calculation are shown in Section 3 for the cases of ensemble average and independent, single calculation under given conditions. Concluding remarks are made in Section 4.

2. A model of the influence of climate change on Costa Rica

Climate change systematically influences not only on the direct matters related to the change itself but on the indirect subjects regarding the society, the economical activity and the daily life of the society, all of which occur in association with the climate change. The influence of the climate change on the natural disasters in Costa Rica is, therefore, not limited only to the frequency and the extent of disasters, but to all the human-related subjects such as the damage of the industrial facilities, the decrease of the productivity together with the tax income of the nation, the increase of finance required for the disaster measures, the decrease of the quality of life and the increase of the disaster risk of the public. In the case when the disbursement is made for the disaster measures from the limited amount of national budget, the social welfare must partially be reduced in order to decrease, to some degree, the human risk from the natural disasters. In modeling the influence of climate change, therefore, it is necessary to consider the circulation between the cause and effect among various factors of disasters and society. Figure 1 shows a simple schematic diagram, according to which we try to develop a model to estimate the time evolution of those factors.

Figure 1

2.1. Meteorological model

We introduce an exogenously given temperature T_t at a given time t at some imaginary point on the earth as only one parameter for the global climate change, called the *representative temperature* hereafter, which determines the conditions of weather in Costa Rica. The following five scenarios are considered for the variation of the average of representative temperature and its variability.

Scenario 1: The annually averaged representative temperature $<T>_t$ of the year t and its standard deviation σ_t from its mean value are constant throughout a reference time to 2100 and equal to those at the reference time :

$$<T>_t = <T>_o \text{ and } \sigma_t = \sigma_o, \tag{1}$$

where the suffix o indicates the reference time for which we take the year 2007.

Scenario 2: The quantity $<T>_t$ increases linearly with time to 2100, but the σ_t is held constant as the value at the reference time :

$$<T>_t=<T>_o+(t-2007)\cdot\Delta T/(2100-2007) \quad \text{and} \quad \sigma_t=\sigma_o, \tag{2}$$

where ΔT is the increment of temperature during the period.

Scenario 3: Both the quantities $<T>_t$ and σ_t increase linearly with time to 2100 :

$$<T>_t=<T>_o+(t-2007)\cdot\Delta T/(2100-2007) \quad \text{and} \tag{3.1}$$

$$\sigma_t=\sigma_o+(t-2007)\cdot\Delta\sigma/(2100-2007), \tag{3.2}$$

where $\Delta\sigma$ is the increment of the standard deviation.

Scenario 4: The quantity $<T>_t$ linearly increases with time between the reference time and 2050 and becomes constant after 2050, whereas the σ_t is held constant from the beginning :

$$<T>_t=MIN(<T>_o+(t-2007)\cdot\Delta T/(2050-2007), <T>_o+\Delta T) \quad \text{and} \quad \sigma_t=\sigma_o. \tag{4}$$

Scenario 5: Both the quantities $<T>_t$ and σ_t grow to increase up to 2050 and become constant after that, as is the case of the temperature in Scenario 4 :

$$<T>_t=MIN(<T>_o+(t-2007)\cdot\Delta T/(2050-2007), <T>_o+\Delta T) \quad \text{and} \tag{5.1}$$

$$\sigma_t=MIN(\sigma_o+(t-2007)\cdot\Delta\sigma/(2050-2007), \sigma_o+\Delta\sigma). \tag{5.2}$$

In what follows we set $<T>_o$=17°C, ΔT=3°C, $\sigma_o=\Delta\sigma$=1.4°C, simply taking the values in Schar *et al*. (2004) and Trenberth *et al*. (2007) as reference values. The value of $<T>_o$ does not influence on the final results in our model.

Various types of disasters as flood and landslide have broken out in Costa Rica by the passage of unusual meteorological events as atmospheric depression and the hurricane. The unusualness of these meteorological event is determined here by simply judging from the height of the representative temperature T_t. The temperature T_t, which is stochastically determined, follows the Gaussian distribution $f(T_t)$:

$$f(T_t)=\frac{1}{\sqrt{2\pi}\sigma_t}\exp\left\{-(T_t-\langle T\rangle_t)^2/2\sigma_t{}^2\right\}. \tag{6}$$

The more distant becomes the representative temperature from the average $<T>_t$ in the positive direction, the severer the unusualness of the event is assumed to be.

As for the meteorological variables co-varying with the temperature, we introduce the average amount of precipitation per unit time X_P, the time duration X_H, the maximum wind velocity X_V, all for the unusual weather during its attack on Costa Rica, and the extent of influence from the sea surge X_S during the unusual weather which possibly increases due to the sea level rise originated from the global temperature rise. By simply assuming the increase of these quantities with the representative temperature, we have

$$X_i \equiv X_i(T_t) = \sum_{\ell=-\infty}^{+\infty} \alpha_{i\ell} (T_t / \langle T \rangle_o)^{\ell} \approx \alpha_{i0} + \alpha_{i1}(T_t / \langle T \rangle_o) \quad (7)$$

where the suffix i indicates the species of the variables (i=P, H, V, S) and the quantity X_i is the value normalized to the reference time. The quantity $\alpha_{i\ell}$ is a constant corresponding to the expansion coefficient for which we assume

$$\alpha_{i0} = 0.5 - r_i \quad \text{and} \quad \alpha_{i1} = 0.5 + r_i . \quad (8)$$

Here the quantity r_i is a random number within a range [0,1] in the case of ensemble calculation, whereas r_i =0.5 in the case of individual, single calculation.

By using the meteorological variables we define the energy E of the unusual event as

$$E = {X_V}^3 \cdot X_H \quad (9)$$

where the factor X_V^3 represents the energy dissipation, and by integrating the factor with respect to time, we obtain the energy of the event (Emanuel, 2005).

In the numerical calculation, we introduce a discrete time span Δt which is much smaller than one year. During every time span, we assume the occurrence of one hypothetical meteorological event which attacks Costa Rica. Here the event of that sort is defined as the one which is born under the temperature condition $T_t \geqq \langle T \rangle_o$. Of those hypothetical ones, only the event born under the condition $T_t > T_e (> \langle T \rangle_o)$ (called the disaster-inducible event, hereafter) is assumed to cause the weather-induced natural disasters in Costa Rica. Although in this case the T_e is to be determined by analyzing the observational data in the past (Lizano and Fernandez, 1996; Alvarado and Alfaro, 2003), we suppose in what follows as $T_e = \langle T \rangle_o + \sigma_o$ for convenience, where σ_o is the previously defined standard deviation at a reference time. In this case the probability P_d for the disaster-inducible event to take place during Δt is given by

$$P_d = \left\{1 - erf\left(\frac{T_e - \langle T \rangle_t}{\sqrt{2}\sigma_t}\right)\right\} \Big/ \left\{1 + erf\left(\frac{\langle T \rangle_t - \langle T \rangle_o}{\sqrt{2}\sigma_t}\right)\right\} \quad \text{when } T_e \geqq \langle T \rangle_t \qquad (10.1)$$

$$= \left\{1 + erf\left(\frac{T_e - \langle T \rangle_t}{\sqrt{2}\sigma_t}\right)\right\} \Big/ \left\{1 + erf\left(\frac{\langle T \rangle_t - \langle T \rangle_o}{\sqrt{2}\sigma_t}\right)\right\} \quad \text{when } \langle T \rangle_t > T_e \qquad (10.2)$$

where erf(x) is the error function. With increasing $\langle T \rangle_t$, P_d grows large to asymptotically become 1.0. This indicates that the probability for Costa Rica to be attacked by the disaster-inducible event gradually increases with the increase of $\langle T \rangle_t$, which is not inconsistent with the observational trend (Pielke *et al.*, 2003; Webster *et al.*, 2005)

Figure 2 shows the feature of temperature variation corresponding to the hypothetical meteorological event for Scenarios 1, 2 and 5 where we take Δt=0.1 y. In this case the number of the attack of the disaster-inducible event on Costa Rica during the period from 2007 to 2100 is 146, 487 and 568, in average, for Scenarios 1, 2 and 5, respectively. The number 147 for the stationary Scenario 1 is not inconsistent with the number 158 for the hurricanes and tropical storms which influences on Costa

Rica during 1886 to1988 (Lizano and Fernandez, 1996).

Figure 2

2.2. Disaster model

The natural disasters taken into account here are (i) flood caused by the overflow of rivers and the lack of drainage, (ii) landslide originated from the excessive rainfall, (iii) the disasters of coastal region due to the sea surge and the sea level rise due to the global warming, and (iv) the destruction of houses, buildings and social infrastructures caused by strong winds (Grandoso, 1979; Poncelet and Venegas, 1987; Montero and Salazar, 1991; Estado de la Nacion, 2007; Chinchilla, 2009). We consider the extent of robustness at a time t against the disaster j for the Costa Rican territory and various facilities in Costa Rica as a whole, $p_j(Z_j, t)$, where Z_j which is defined below, is an indicator for the strength of meteorological event which induces the disaster j. The quantity $p_j(Z_j, t)$ is defined as the probability of robustness against the disasters. In this case, the complement of this quantity to 1.0, that is $1.0 - p_j(Z_j, t)$, gives the probability for the disaster j to break out in Costa Rica due to the vulnerability of disaster measures when the disaster-inducible event with Z_j attacks Costa Rica.

The time variation of the quantity $p_j \equiv p_j(Z_j, t)$ is given by

$$\frac{d}{dt}\int_0^1 (1-p_j)\,q_j s_j\,dZ_j = \beta_1(1-p_j)s_j\delta(t) - \beta_2\Xi_j + \frac{\beta_3}{\tau}\int_0^1 p_j q_j s_j\,dZ_j \qquad (11)$$

where β_1, β_2 and β_3 are constants, $q_j \equiv q_j(Z_j, t)$ is the frequency of attack of the disaster-inducible event on Costa Rica per unit time, $s_j \equiv s_j(Z_j, t)$ is the area fraction of the territory which is influenced by the event with Z_j, $\delta(t)$ is Dirack's delta and δ

(t)=1 when the disaster-inducible event attacks Costa Rica during $[t, t+\Delta t]$ whereas δ *(t)*=0 otherwise, Ξ_j is the contribution to the enhancement of robustness against the *j* by amending and maintaining the disaster measures by the nation and the local municipality, and τ is the life time for the protective facilities against the disaster. From the definitions of p_j, q_j and s_j, the left hand side of Equation (11) represents the time variation of the quantity proportional to the frequency of occurrence of the disaster *j* in Costa Rica. The first term on the right hand side, on the other hand, is the number of disasters which increases due to the destruction of protection facilities by the disaster-inducible event at the time *t*, the second one is for the enhancement of robustness, while the third term gives the increment of the disaster due to the degradation of the protection system with time.

We define the variables Z_j which relate the meteorological variables X_i to the extent of the disaster *j* as

$$Z_f \equiv (X_P - C_f) X_H \big/ Z_f^{\max} \tag{12}$$

$$Z_\ell \equiv (X_P - C_\ell) X_H \big/ Z_\ell^{\max} \tag{13}$$

$$Z_s \equiv ({X_V}^2 - C_s) X_H X_S \big/ Z_s^{\max} \tag{14}$$

$$Z_w \equiv ({X_V}^2 - C_w) X_H \big/ Z_w^{\max} \tag{15}$$

where the suffixes *f, l, s* and *w* respectively indicate the flood, the landslide, the sea surge and the strong wind, while the superscript *max* means the maximum value of the quantity. The quantity C_j is the threshold values for Z_j so that the hypothetical meteorological event results in the disaster *j* only when $X_P>C_f$, $X_P>C_l$, $X_V>C_s^{1/2}$ and $X_V>C_w^{1/2}$ are satisfied, respectively.

The functional form of Z_f and Z_l in Equations (12) and (13) comes from the fact that the extent of disaster of those types is roughly proportional to the total amount of rainfall, but that they do not take place in so far as the precipitation per unit time does not exceed a certain limited value. The factor X_V^2 in Z_s and Z_w, on the other hand, comes from the fact that the wind pressure is proportional to the square of wind velocity, and that the extent of the disaster of the types *s* and *w* is proportional to the wind pressure times the duration time of wind. The C_s and C_w represent the extent of strength of the buildings and the infrastructure against the wind storm. Since the event only with the temperature $T_t > T_e$ causes the disaster in Costa Rica, $C_f = C_l = X_P(T_e)$ and $C_s = C_w = \{X_V(T_e)\}^2$, where $X_i(T)$ is given by Equation (7).

As for the function $p_j(Z_j,t)$ in Equation (11), we assume the following mathematical formula:

$$p_j(Z_j,t) = 1.0 - \frac{1.0 + \exp(b_j - a_j)}{\exp(b_j) - \exp(b_j - a_j)} \cdot \frac{\exp(b_j) - \exp(b_j - a_j Z_j)}{1.0 + \exp(b_j - a_j Z_j)} \qquad (16)$$

where $a_j \equiv a_j(t)$ and $b_j \equiv b_j(t)$ are functions of t. The function $q_j(Z_j,t)$ in Equation (11), on the other hand, is proportional to the probabilistic distribution function of Z_j at t, $Q_j(Z_j,t)$, which can be derived by the use of the variable X_i given by Equation (7) and the definition of Z_j, Equations (12)~(15), under a given probabilistic distribution of temperature, that is Equation (6), at a given time t :

$$q_j(Z_j,t) = C\,Q(Z_j,t) \qquad (17)$$

where C is a constant whose value is determined by using the frequency of unusual meteorological events observed up to the reference time in Costa Rica (Lizano and Fernandez 1996; Alvarado and Alfaro 2003).

As for the function $s_j(Z_j,t)$ in Equation (11), the following mathematical form is introduced:

$$s_j(Z_j,t) \equiv s(Z_j) = \{1.0 + \exp(-cZ_j + d)\}^{-1} \tag{18}$$

where *c* and *d* are constants. We have assumed here for simplicity the independency of s_j from time, and also the constants *c* and *d* from the type of disaster. Such assumptions are only due to the fact that the values of *c* and *d* are difficult to determine though they must actually depend on the disaster type, because the meteorological variables X_i considerably vary from region to region in Costa Rica (Fernandez and Vega, 1996). In this paper we adopt the values c=0.2 and d=3.2 as default values so that $s_j(Z_j \to 0)$=0.05 and $s_j(Z_j \to 1)$=0.25.

To derive the values $a_j(t)$ and $b_j(t)$ in Equation (16), we discretize them with respect to time as $a_j^n \equiv a_j(t^n)$ and $b_j^n \equiv b_j(t^n)$ at $t=t^n$, and $a_j^{n+1}=a_j^n+\Delta a_j$ and $b_j^{n+1}=b_j^n+\Delta b_j$ at $t=t^{n+1}$. Assuming that $dq_j/dt << dp_j/dt$, we discretize Equation (11) as

$$\frac{1}{\Delta t}\int_0^1 (p_j^{n+1} - p_j^n)\, q_j^{n+0.5}\, s_j^{n+0.5} dZ_j = -\Phi^n \tag{19}$$

where Φ^n represents the value of the right hand side of Equation (11) at the time t^n, and the superscript $n+0.5$ denotes the average of the values at t^n and t^{n+1}. By making the Taylor expansion of p_j^{n+1} with a_j and b_j around p_j^n, and taking up to the second term, we have

$$\Delta a_j \int_0^1 \left(\frac{\partial p_j}{\partial a_j}\right)^n q_j^{n+0.5} s_j^{n+0.5} dZ_j + \Delta b_j \int_0^1 \left(\frac{\partial p_j}{\partial b_j}\right)^n q_j^{n+0.5} s_j^{n+0.5} dZ_j \equiv \Delta a_j \Psi_a^n + \Delta b_j \Psi_b^n = -\Phi^n \tag{20}$$

On the other hand, when we suppose the robustness of the protection system against disasters to be stationary in Costa Rica at the reference time t_o, that is, in a state negligible for the influence from the climate change, we have

$$\frac{d}{dt}\int_0^1 p(Z_j,t_o) dZ_j = 0\,. \tag{21}$$

Hence

$$\Delta a_j^0 \int_0^1 \left(\frac{\partial p_j}{\partial a_j} \right)^0 dZ_j + \Delta b_j^0 \int_0^1 \left(\frac{\partial p_j}{\partial b_j} \right)^0 dZ_j \equiv \Delta a_j^0 \Pi_a + \Delta b_j^0 \Pi_b = 0 . \tag{22}$$

Therefore we have

$$\Delta b_j^0 = -\Pi_a \cdot \Delta a_j^0 / \Pi_b . \tag{23}$$

Here the superscript 0 indicates the value at the reference time. Assuming the relation between Δa_j and Δb_j at the reference time held also in a later time, that is, in the case of the robustness in an almost stationary condition when there exists no fluctuation in the representative temperature, we have from Equation (20) and Equation (23) with replacing Δa_j^0 and Δb_j^0 *by* Δa_j and Δb_j respectively

$$\Delta a_j = \frac{\Phi^n \Pi_b}{\Pi_a \Psi_b^n - \Psi_a^n \Pi_b} \tag{24}$$

and

$$\Delta b_j = \frac{-\Phi^n \Pi_a}{\Pi_a \Psi_b^n - \Psi_a^n \Pi_b} . \tag{25}$$

By using the function $p_j \equiv p_j(Z_j,t) \equiv p_j(Z_j,a_j,b_j)$ thus obtained, we define the extent of economical influence or the insurance loss from the disaster *j*, Λ_j, which originates from the disaster-inducible event with Z_j as

$$\Lambda_j = (1.0 - p_j)\, s_j\, Z_j G(t)\, O(t) \tag{26}$$

where *G(t)* and *O(t)* are respectively the gross national product (GNP) and the population at the time *t* both normalized to the reference values. The factor Z_j comes from the assumption that the physical extent of the destruction is proportional to Z_j, whereas the multiplied factor $G(t)O(t)$ gives the contribution from the economic and demographic growth in Costa Rica, in proportion to which the influence from the disaster increases. The value of $G(t)$ is given in the following subsection, whereas the $O(t)$ is estimated by extending the past trend of population growth into the future.

We furthermore define the human risk R_j originated from the disaster j and the total risk R_{ttl} by using the function p_j as

$$R_j \equiv R_j(t) = \zeta_j \int_0^1 (1.0 - p_j) q_j s_j Q(Z_j, t) Z_j dZ_j \tag{27}$$

and

$$R_{ttl} \equiv R_{ttl}(t) = \sum_j R_j(t) \tag{28}$$

where ζ_j is a constant whose values are determined by using the values of human risk at the reference time, whose values are determined rather arbitrarily as $R_f = 5\times10^{-6}$, $R_\ell = 1\times10^{-5}$, $R_s = 1\times10^{-7}$ and $R_w = 2.5\times10^{-7}$, all in a unit of $(\text{year})^{-1}$ (Poncelet and Venegas, 1987; Montero and Salazar, 1991). Here the human risk is the probability of death for a person during one year by the disaster j. The quantity $Q(Z_j,t)$ is the probabilistic distribution function of Z_j which was introduced in Equation (17).

2.3. Influence on Costa Rican society

The damage to Costa Rican territory and the destruction of various facilities caused by the natural disasters is directly related to the decrease of industrial productivity. Here we assume, for simplicity, that the flood induces the damage of farmland and pastures, together with the social infrastructure such as roads, bridges, water supply systems and power lines, while the landslide induces the damage of the social infrastructure, the sea surge damages of the social infrastructure such as harbor facilities and coastal buildings, and strong winds damage the social infrastructure, and houses and buildings. The extent of the economical loss for such social facilities is proportional to the quantity Λ_j defined by Equation (26), and the industrial productivity decreases in proportion to the economical loss. We further assume, for simplicity, that the influence on the primary industry is proportional to the extent of damage on the farmland and pastures, while the secondary industry to that extent on the social infrastructure, and the tertiary industry to the extent on houses and buildings, respectively.

In this case we have

$$\frac{dF_1}{dt} = F_1 g_1 - \gamma_1 \int_0^t \Lambda_f(t') \exp\{-(t-t')/\tau_d\} dt' \tag{29}$$

$$\frac{dF_2}{dt} = F_2 g_2 - \gamma_2 \int_0^t \{\Lambda_f(t') + \Lambda_\ell(t') + \Lambda_s(t') + \Lambda_w(t')\} \exp\{-(t-t')/\tau_d\} dt' \tag{30}$$

$$\frac{dF_3}{dt} = F_3 g_3 - \gamma_3 \int_0^t \{\Lambda_s(t') + \Lambda_w(t')\} \exp\{-(t-t')/\tau_d\} dt' \tag{31}$$

where F_m (m=1, 2, 3) are the productivity of the m'th industry in a certain unit of money, g_m are the growth rate of the industry in case of no disasters, γ_m are constants, and τ_d is the time constant for the recovery of the territory and the facilities from the damage, for which we assume τ_d=1.0 year independently on the sort of damage. The GNP in Costa Rica is given by $G(t)=F_1(t)+F_2(t)+F_3(t)$, whereas the decrement caused by the disasters $\Delta G(t)$ is given by

$$\Delta G(t) = \Delta t \cdot \int_0^t \{\gamma_1 \Lambda_f + \gamma_2(\Lambda_f + \Lambda_\ell + \Lambda_s + \Lambda_w) + \gamma_3(\Lambda_s + \Lambda_w)\} \exp\{-(t-t')/\tau_d\} dt' \tag{32}$$

So that the rate of decrease of productivity due to the disasters, $L(t)$, is

$$L(t) = \Delta G(t)/G(t). \tag{33}$$

Annual amount of national budget in Costa Rica received as the tax, $B(t)$, is proportional to the GNP; $B(t)=\xi_1 G(t)$, ξ_1 being a constant. Assuming that a finite fraction ξ_2 of the $B(t)$ is allocated for the social welfare, and that the fraction ξ_3 of the budget of social welfare is cut for constructing some protective system against disasters, the factor Ξ_j in Equation (11) is given by

$$\Xi_j = \xi_1 \xi_2 (1 - \xi_3) \xi_4 \xi_j G(t) \quad (34)$$

where ξ_4 is an enhancement factor of Ξ_j by the flow of budget from the sectors other than the social welfare, and ξ_j is the fraction of the budget allocated for the measures against disaster j in the total amount of budget for the disasters. We set in the following calculation as $\xi_f = \xi_l$ =0.4 and $\xi_s = \xi_w$ =0.1 as for example. On the other hand, the amount of social welfare per capita, *W(t)*, is given by

$$W(t) = \xi_1 \xi_2 \xi_3 G(t) / O(t) . \quad (35)$$

The values of constants appeared in the above mathematical formulae are generally determined so that the calculation toward the past direction fits most satisfactorily the past trend of various statistical quantities of Costa Rica. The growth rates of some statistical quantities as the industrial productivity in the future is estimated from the data in the past. Some values at the reference time such as the human risk and the frequency of unusual meteorological events which attack Costa Rica are given by averaging those quantities during several years in the past up to the reference time. Only one parameter for every case of Scenarios 1~5 is the fraction ξ_3 of the social welfare cut for preparing the protective measures of disasters. The time step is set as Δt=0.1y and the ensemble average is taken as the average of 100 times trials with different random number series.

3. Numerical calculation

3.1. Ensemble average

In the first place, the time evolution of the energy of unusual meteorological events is shown in Figure 3 where we can see the increase of energy of only about 1.5 times the reference value in case of the temperature rise of 3°C with a constant standard deviation σ_t , whereas 1.75 times that values in case of the increase of both temperature and σ_t.

Figure 3

The quantity Λ_j defined by Equation (26) is the insurance loss which is proportional to the payment of the insurance industry. Figure 4 shows the Λ_j for the cases of flood and sea surge, as examples. The rise of temperature by 3°C leads the insurance loss of ~10^2 times the reference value in case of flood and also landslide at 2100, ~10^4 times the value in case of sea surge, and ~2×10^3 times the value with strong winds. The gradual increase of the insurance loss with time in Scenario 1 is owed to the increase of the GNP and population.

Figure 4

Figure 5 shows the time variation of the rate of decrease of GNP by the disasters, together with the variation of the amount of budget per capita for the social welfare. The increases of both the temperature and its standard deviation, as in the cases of Scenarios 3 and 5, usually bring the economical loss by several percent of the GNP in the latter half of this century, and therefore Costa Rica can scarcely make progress in the economical sense in these cases. On the other hand, in case of a constant standard deviation of temperature, only about 1/10 the rate of those cases is lost in GNP so that the economical growth is never obstructed. The time trend of the social welfare per capita is somewhat similar to the trend of GNP. The welfare realized at 2100 in case of Scenario 5 is only about 1/8 the level of the case of no global warming.

Figure 5

Figure 6 shows the time evolution of the risk due to floods for the two cases (a) with the investment of ξ_3 =0.1 to the protective facilities against disasters, and (b) without any investment for the facilities. In case of Scenario 5, the growth of the GNP becomes least in the five scenarios considered here. Hence, the monetary amount input for the disaster measures becomes least in case of Scenario 5 even if the finite fraction of GNP by ξ_3 =0.1 is invested for the measures, so that the human risk against the flood (and also against the other types of disasters) becomes maximum in Scenario 5. From the comparison of the flood risks at 2100 under the conditions of ξ_3 =0.1 and 0.0, we obtain the efficiency of the investment for the flood measures, η_f, defined by $\eta_f(scenario\ k) \equiv \Delta R_k / \Delta\xi_3$ as $\eta_f(1)=4.7\times10^{-5}$, $\eta_f(2)=3.2\times10^{-4}$, $\eta_f(3)=6.0\times10^{-4}$, $\eta_f(4)=2.9\times10^{-4}$ and $\eta_f(5)=5.1\times10^{-4}$, where ΔR_k is the decrement of the risk in Scenario k with the increment of ξ_3 by $\Delta\xi_3$.

Figure 6

Figure 7 shows the time variation of four types of risk in case of Scenario 5. The rapid increase of the risk from the sea surge is the outcome of the composite effect from the strengthening of the meteorological event and the sea level rise.

Figure 7

Figure 8 shows the time evolution of the total risk under the conditions of (a) ξ_3 =0.1, and (b) ξ_3 =0.0. From the comparison of the risks at 2100 in (a) and (b), the efficiency of the investment for reducing the total risk, η_{ttl}(Scenario *k*), is estimated as $\eta_{ttl}(1)=1.8\times10^{-4}$, $\eta_{ttl}(2)\approx\eta_{ttl}(4)\approx1.5\times10^{-3}$, and $\eta_{ttl}(3)\approx\eta_{ttl}(5)\approx3\times10^{-3}$. These values indicate that the greater is the risk for the scenario, the larger effect is brought to reduce the risk by investing a constant fraction of national budget for the disaster measures. In other words, with increasing the risk, it becomes easier to reduce the human risk to a certain point.

Figure 8

3.2. Single trial of calculation

Under the real situation of global warming, the meteorological variables and other statistical quantities regarding disasters, human activities and economics do never vary smoothly as the ensemble average shown hitherto. Since, being subject by a certain distribution function, the representative temperature randomly varies, those quantities also randomly fluctuate around an ensemble average. In such a situation, it is important to ascertain the width of the fluctuation for each quantity, which becomes useful information in making policies for the climate change.

To see the feature of fluctuation, Figure 9 (a), (b) and (c) show the examples of time evolution of the quantity Λ_j for the flood. The extent of fluctuation of this quantity is so remarkable that we can not imagine its real behavior from a simple ensemble average. At the time when a large Λ_f is realized by the fluctuation, Costa Rica suffers from a flood with an unusual extent of damage.

Figure 9

Figure 10 shows the time behavior of *L(t)*, the rate of decrease of the productivity due to disasters relative to the GNP. When the meteorological condition largely fluctuates to an extreme direction, the quantity *L(t)* increases and this greatly influences on the economics of Costa Rica to result in the prevention of its economical development. Although the time required for the recovery from such a large scale disaster is assumed one year in our mode (τ_d =1y), the possibility was pointed out that the disaster in developing countries exerts unfavorable influence on the economical activity during two to three years after it (Wilbanks *et al*., 2007).

Figure 10

Figure 11 shows the time variation of the total human risk $R_{ttl}(t)$. Also in the case of risk, its fluctuation with time is so conspicuous that the human risk certainly becomes higher every time whenever the large scale disaster occurs in the future.

Figure 11

----

4. Concluding remarks

The frequency and the extent of disasters originated from the climate change are highly stochastic, and therefore we can not make any reliable estimation for them. However as far as we investigate them by means of the ensemble average, the frequency and the extent of disasters seem to certainly increase hereafter in Costa Rica. The unusual weather-induced natural disasters lead the impediment to the economical progress, the enhancement of human risk and the decrease of the extent of social welfare. Although it seems useless at a first glance to strengthen the measures against uncertain disasters and to invest the valuable national budget in the protective measures against disasters which are far from the national strength, we should note that it is just the right way, paradoxically, for leading the state of future economics not to be obstructed and for enhancing certainly the quality of life of the public in the future.

Regarding the extent of what amount of national budget should be invested in the protective measures against disasters, we can estimate it by using the value function, $V(\xi_3, t)$, for instance, defined as

$$V(\xi_3,t) = \ln\left(W(\xi_3,t)/R_{ttl}(\xi_3,t)\right). \quad (36)$$

The value of ξ_3 which makes the function $V(\xi_3, t)$ maximum at any given time is shown in Figure 12, from which we can see that the amount corresponding to 25~30 percent of the social welfare budget should be continuously invested in the disaster measures hereafter independently on the global warming scenario. When we seriously consider the future progress of Costa Rican economy, it is necessary to make a positive anti-disaster policy, not an adaptive one, to continuously invest a certain amount of national budget in the disaster measures. Although such a policy may not return any material benefit to the public, it can lead the definite decrease of human risk from fatal disasters even if the direct effect of global warming does not attack Costa Rica in future.

Figure 12

When the sea level rise really takes place in future due to the global warming, we should note hereafter the conspicuous growth of the extent of sea surge-induced disaster on the coastal region of Costa Rica. The sea surge, whose influence has not been seriously considered in Costa Rica, leads not only the damage of the coastal infrastructure, the harbor facilities, the fishing industry, the tourist attractions and the ecological systems along the coastline, but also the backward flow of sea water towards the upstream of rivers which induces the inundation along the rivers, the intrusion of sea water into the underground water, and so on. An anti-disaster policy specified to the coastal region is urgently needed in Costa Rica.

When we speak of the estimation of weather-induced natural disasters in future Costa Rica, it is absolutely deficient the data of the frequency of occurrence and the extent of disasters in relation to the condition of unusual meteorological events. Explicitly it is needed the information which links the natural disaster and the weather in spite of the fact that the disaster to be considered is just the *weather-induced* natural disaster. It is highly desirable, therefore, to accumulate that type of data hereafter and to reanalyze the data in the past.

Although we intended to specify Costa Rica in our model, it is the so-called one-point approximation which does not take into account the expansion of the territory and the difference of the disasters and the meteorology from region to region.

Our model can only estimate the average trend of Costa Rica as a whole. To make an estimation of the disaster risk for each local region, that is, to make a hazard map in Costa Rica, therefore, it is required to collect the data for each local region and to develop a model which includes the interaction among local regions.

In our model we have simply assumed as the zero'th approximation that the meteorological conditions of the unusual event which attacks Costa Rica are determined only by the global temperature at some unspecified, representative position, and it is recognized that this may be a very simple assumption. The occurrence of inundation in Costa Rica may be subject also to the state of sea water in the north Atlantic and the eastern tropical Pacific oceans (Solano *et al*., 2002). Although it does not seem to exist a consistent relation between the rise of sea surface temperature and the hurricane intensity (Emanuel, 2005), there exists a correlation between the precipitation in Costa Rica and the sea surface temperature of the Atlantic Ocean (Aguilar *et al*., 2005). Before improving our model, it is necessary to include the sea surface temperature as another parameter, and more urgent researches are needed to clarify the relation between the indexes of the global climate change and the meteorological variables in Costa Rica.

References

Aguilar E *et al.* 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961-2003. *Journal Geophysical Research* **110**: D23107.

Alvarado LF, Alfaro EJ. 2003. Frecuencia de los cyclones tropicales que afectaton a Costa Rica durante el siglo XX. *Top.Meteor.Oceanog*, **10**:1-11.

Chinchilla MR. 2009. Arancibia landslide-debris avalanche in Costa Rica, retrieved Jan. 2009 from http://www.geo.mtu.edu/˜jahheric/Documents/Costa_Rica_ Arancibia Landslide.pdf.

Christidis N, Stott PA, Brown S, HegerlG.C, Caesar J. 2005. Detection of changes in temperature extremes during the second half of the 20th century. *Geophys.Res.Lett.* **32**: L20716.

Emanuel K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686-688.

Fernandez W, Vega N. 1996. A comparative study of hurricane Fifi (1974) and Greta (1978) and their associated rainfall distributions over Central America. *Top.Meteor.Oceanogr.* **3** : 89-106.

Grandoso H. 1979. Estudio meteorologico de las inundaciones de diciembre de 1970 en Costa Rica. *Geofisica Internacional* **18**: 129-176.

Hegerl G.C *et al.* 2007. Understanding and attributing climate change in *Climate Change 2007 The Physical Science Basis* (Solomon S *et al.* eds.). Cambridge Univ. Press: Cambridge, UK.

IMN (Instituto Meteorologico Nacional). 2007. *Adaptacion del sistema hidrico de la zona noroccidental de la gran area metropolitana de Costa Rica al cambio climatico*.

Ministerio de Ambiente y Energia: San Jose, Costa Rica.

Lizano OG., Fernandez W. 1996. Algunas caracteristicas de las tormentas tropicales y de los huracanes que atravesaron o se formaron en el Caribe adyacente a Costa Rica durante el periodo 1886-1988. *Top.Meteor.Oceanog.* **3** : 3-10.

Milly PCD, Wetherald RT, Dunne KA, Delworth TL. 2002. Increasing risk of great floods in a changing climate. *Nature* **415:** 514-517.

Montero A, Salazar SV. 1991. *Los desatres en Costa Rica*. Comision Nacional de Emergencia: San Jose, Costa Rica.

Pielke RA, Rubiera J, Landsea C, Fernandez ML, Klein R. 2003. Hurricane vulnerability in Latin America and the Caribbean : normalized damage and loss potentials. *Natural Hazards Review* **4 :** 101-114.

Poncelet LJ, Venegas OM. 1987. *Resumen historico de desastres ocurridos en Costa Rica*. Comison Nacional de Emergencia: San Jose, Costa Rica.

Estado de la Nacion. 2007. Capitulo 4; Armonia con la naturaleza in *Estado de la Nacion, 13*. Programa de Estado de la Nacion : San Jose, Costa Rica.

Schar C *et a*l. 2004. The role of increasing temperature variability in European summer heatwaves. *Nature* **427** : 332-336.

Solano J, Retana AJ, Villalobos RV. 2002. Inundaciones. *Top.Meteor.Oceanog.* **9** : 104-122.

Trenberth KE *et al*. 2007. Observations: Surface and Atmospheric Climate Change in *Climate Change 2007 The Physical Science Basis* (Solomon S *et al*. eds.). Cambridge Univ. Press : Cambridge, UK.

Webster PJ, Holland GJ, Curry JA, Chang HR. 2005. Changes in tropical cyclones number, duration, and intensity in a warming environment. *Science* **309**:

1844-1846.

Wilbanks TJ *et al*. 2007. Industry, settlement and society in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (Parry ML *et al*. eds.). Cambridge Univ. Press : Cambridge, UK.

Figure Captions

Figure 1. Schematic diagram regarding weather-induced natural disasters in Costa Rica. Two grayish boxes of the disaster risk and the social welfare are the factors used to determine the value function, Equation (36).

Figure 2. Time variation of the temperature corresponding to the hypothetical meteorological events for (a) Scenario 1, (b) Scenario 2, and (c) Scenario 5. Small closed squares are the temperature at a given time averaged over the five points of time around the one considered.

Figure 3. Time evolution of the energy of hypothetical meteorological events normalized to the reference value.

Figure 4. Time evolution of the extent of economical influence Λ_j for (a) j =flood, and (b) j =sea surge, both for the case of ξ_3=0.1.

Figure 5. Time evolution of (a) the decreasing rate of GNP by disasters, and (b) the amount of budget per capita allocated for the social welfare normalized to the reference value, both for the case of ξ_3=0.1.

Figure 6. Time evolution of the risk due to the flood for the cases of (a) ξ_3=0.1, and (b) ξ_3=0.0.

Figure 7. Time evolution of the four types of human risk in case of Scenario 5 with ξ_3=0.1.

Figure 8. Time evolution of the total risk for the cases of (a) ξ_3=0.1, and (b) ξ_3 =0.0.

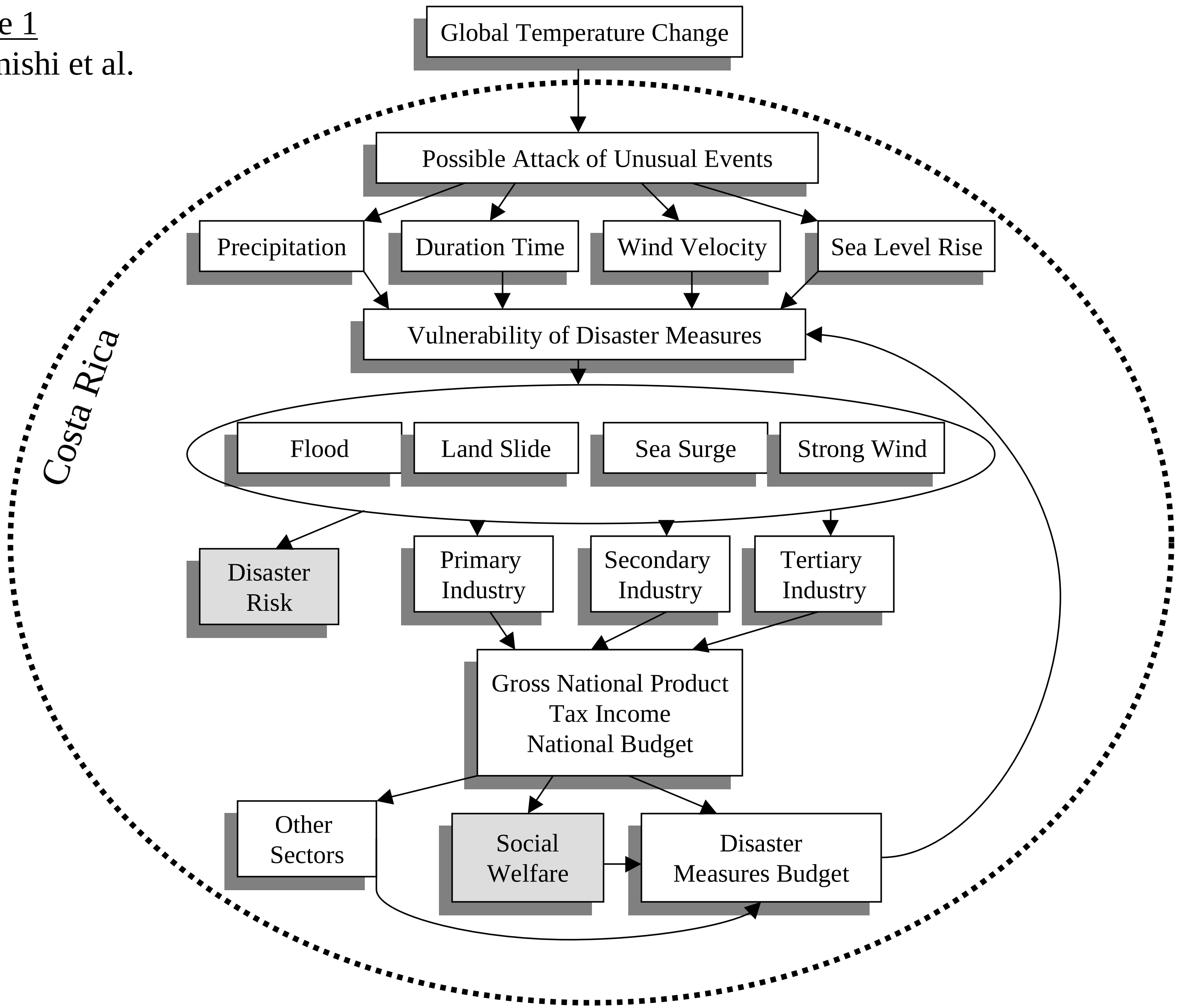
Figure 9. Time evolution of the extent of economical influence by the flood Λ_{flood} for the cases of (a) Scenario 1, (b) Scenario 2, and (c) Scenario 5. Note the difference of the unit of ordinate of these figures from each other.

Figure 10. Time evolution of the rate of decrease of productivity due to the disasters relative to GNP for (a) Scenario 2 and (b) Scenario 5. Note the difference of the unit of ordinate among these figures.

Figure 11. Time evolution of the total risk for the cases of (a) Scenario 1, (b) Scenario 2, and (c) Scenario 5, all for the case of ξ_3 =0.1. Note the difference of the unit of ordinate among these figures.

Figure 12. Time evolution of the optimum value of ξ_3 which makes the value function maximum. Five cases from Scenarios 1 to 5 are simultaneously drawn on this figure.

Figure 1
T.Ohnishi et al.



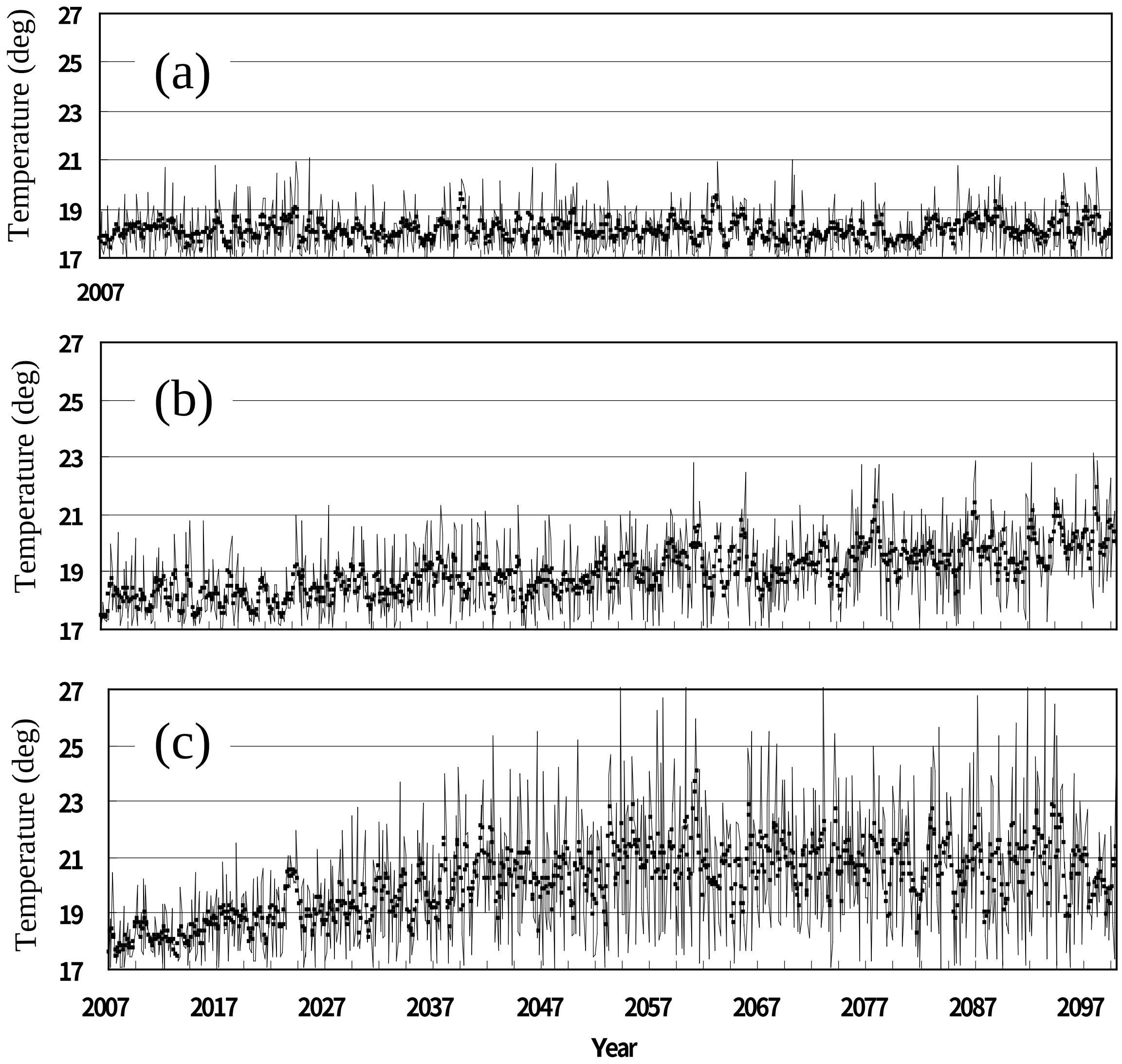


Figure 2 T.Ohnishi et al.

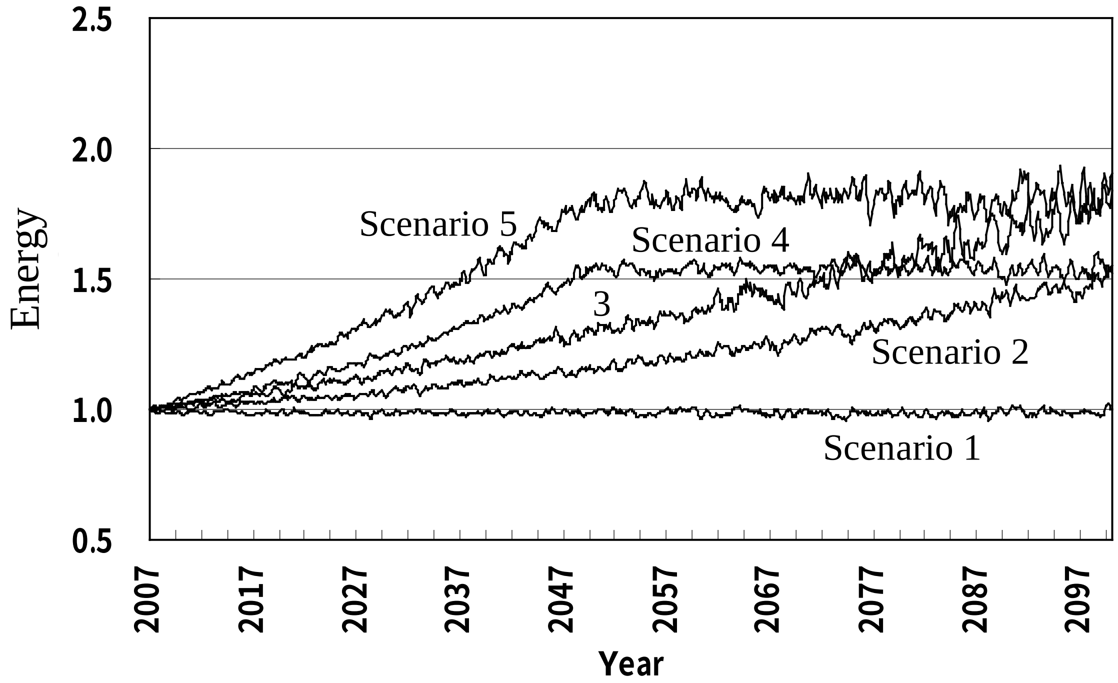


Figure 3 T.Ohnishi et al.

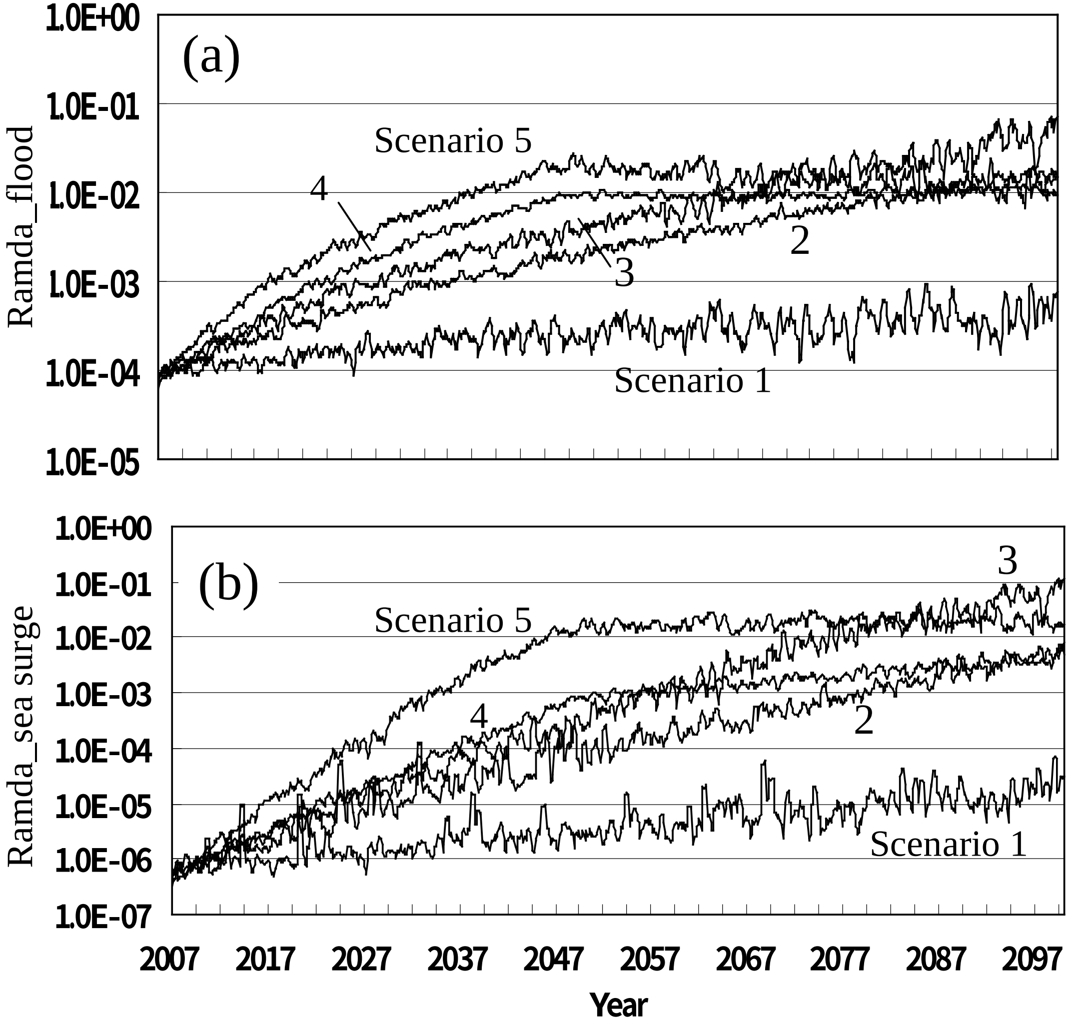


Figure 4 T.Ohnishi et al.

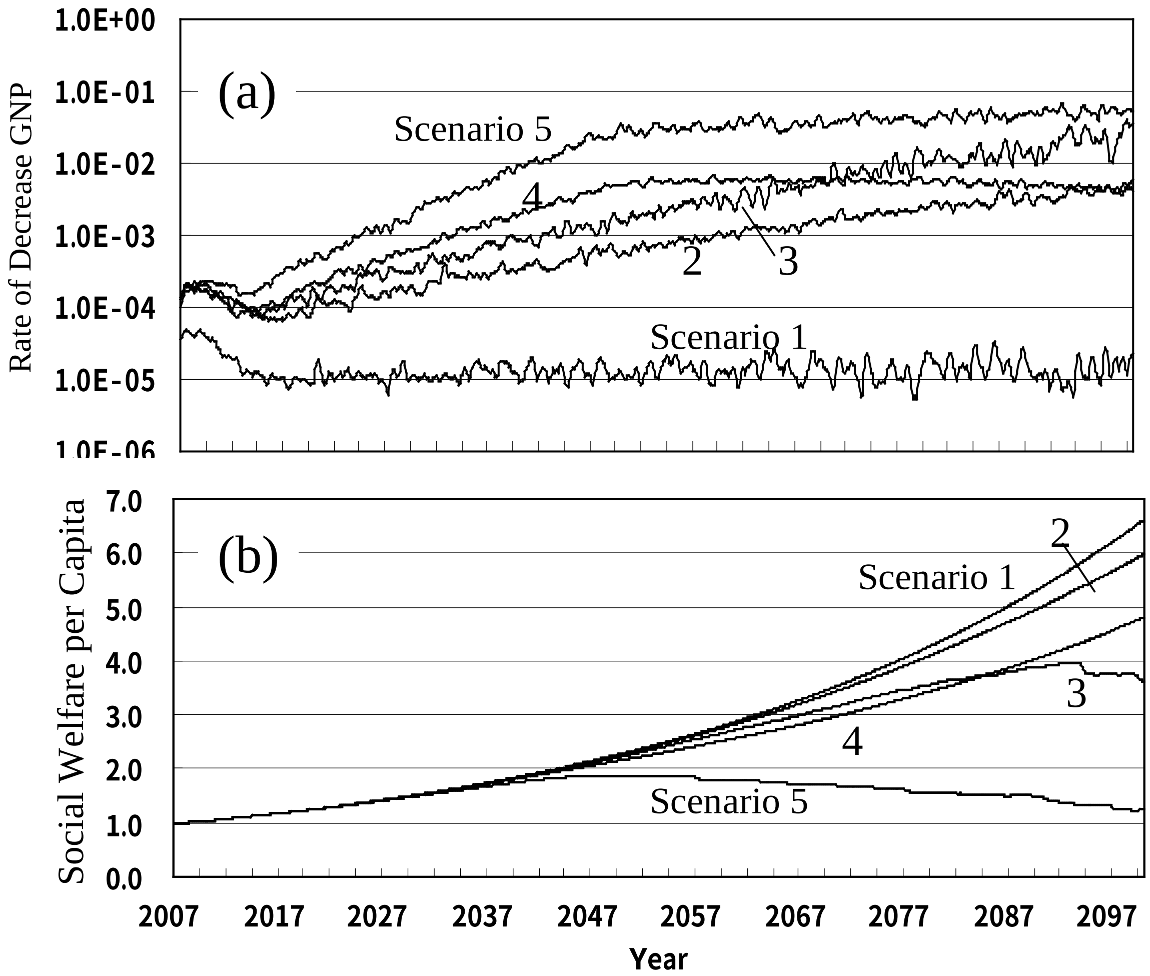


Figure 5 T.Ohnishi et al.

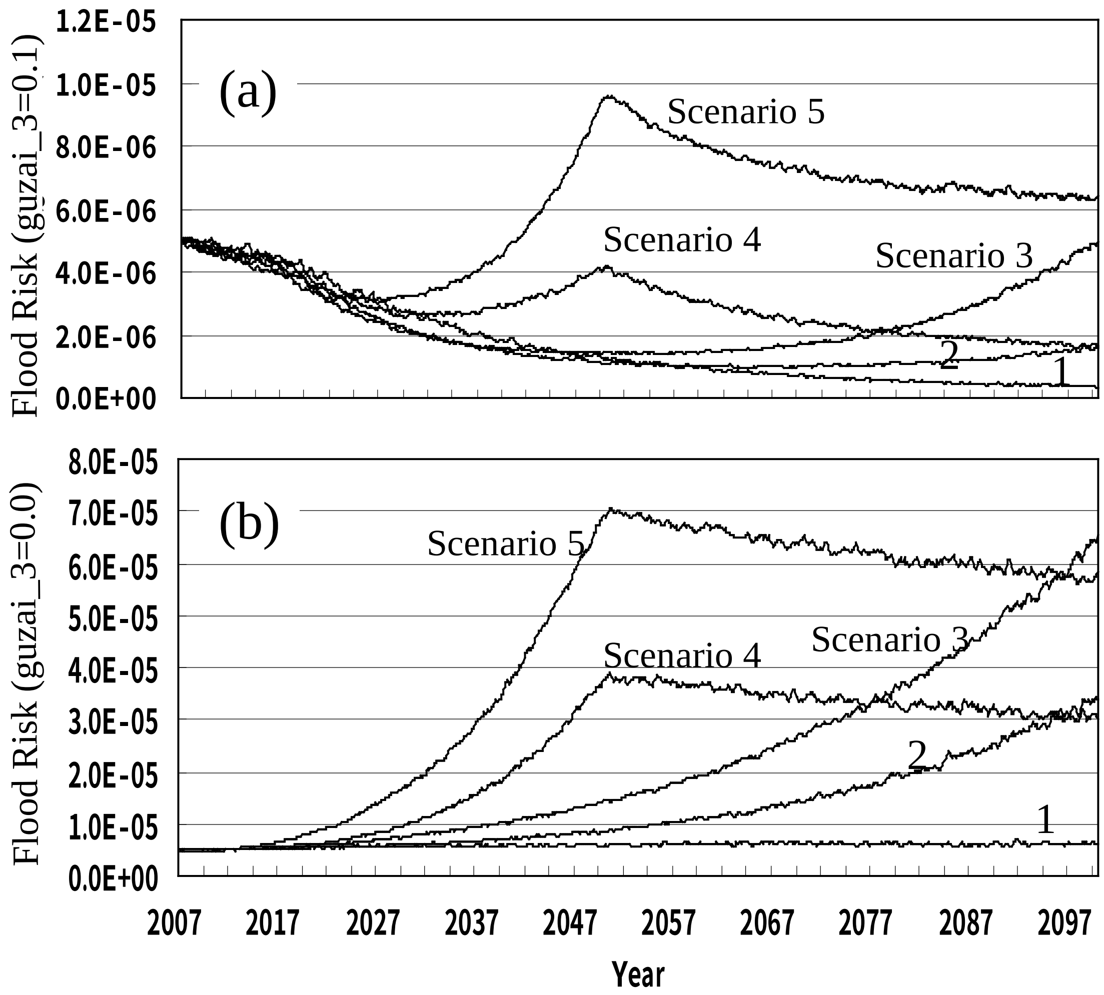


Figure 6 T.Ohnishi et al.

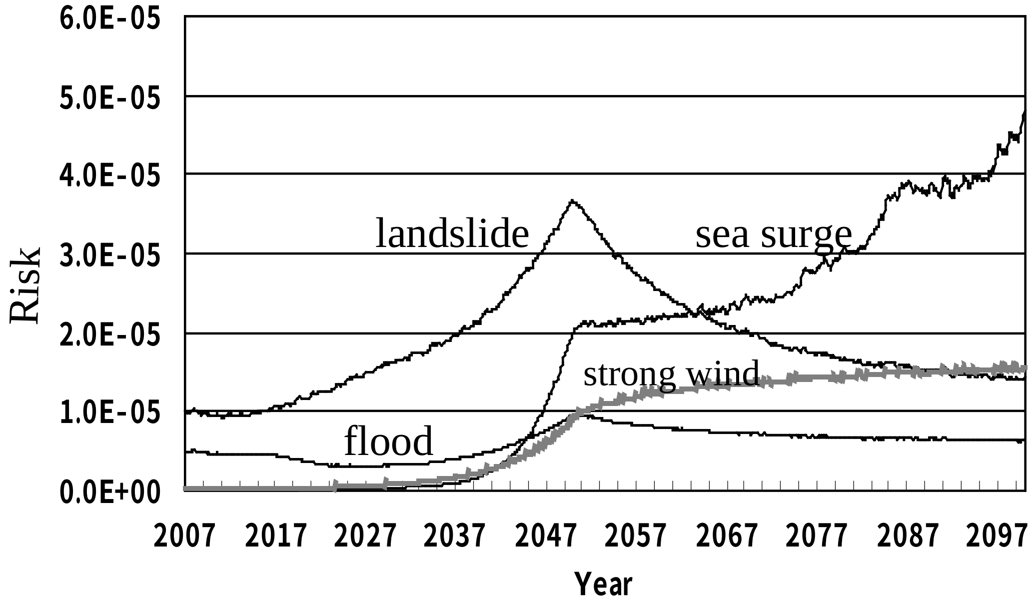


Figure 7 T.Ohnishi et al.

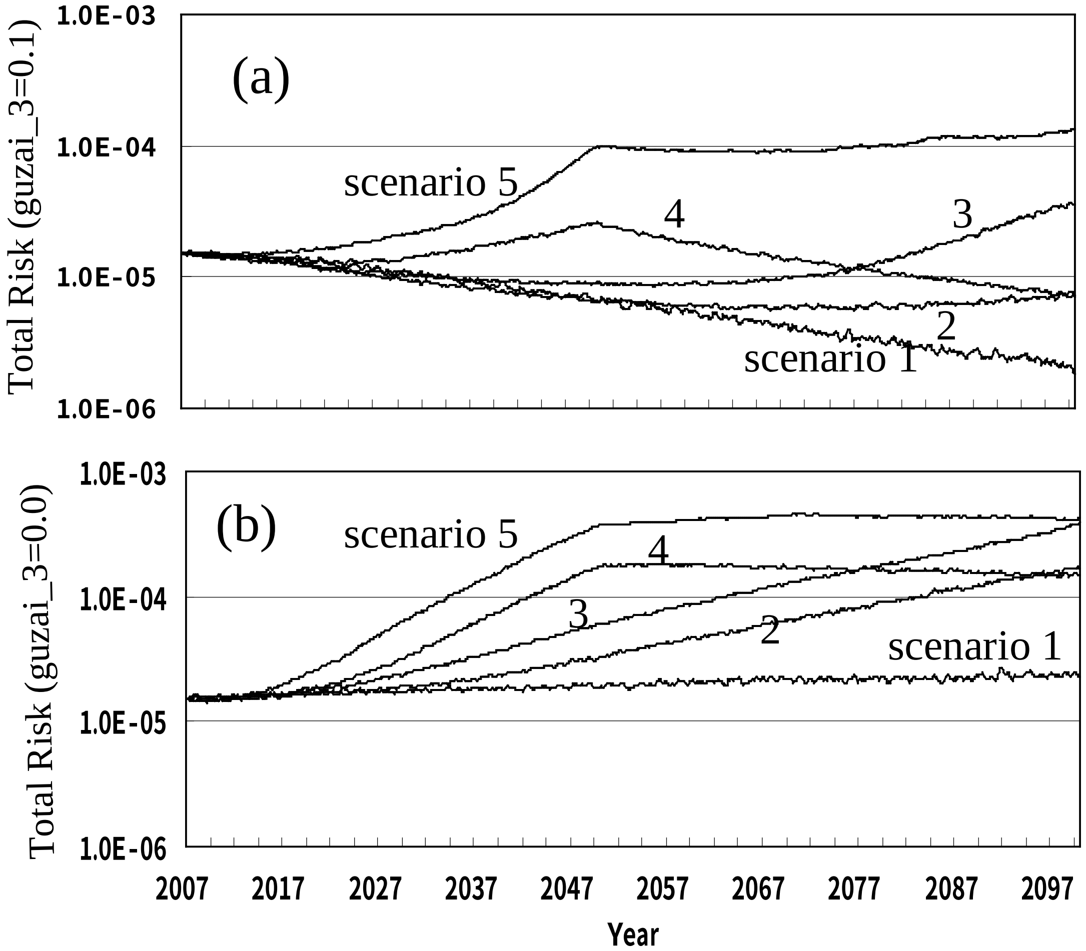
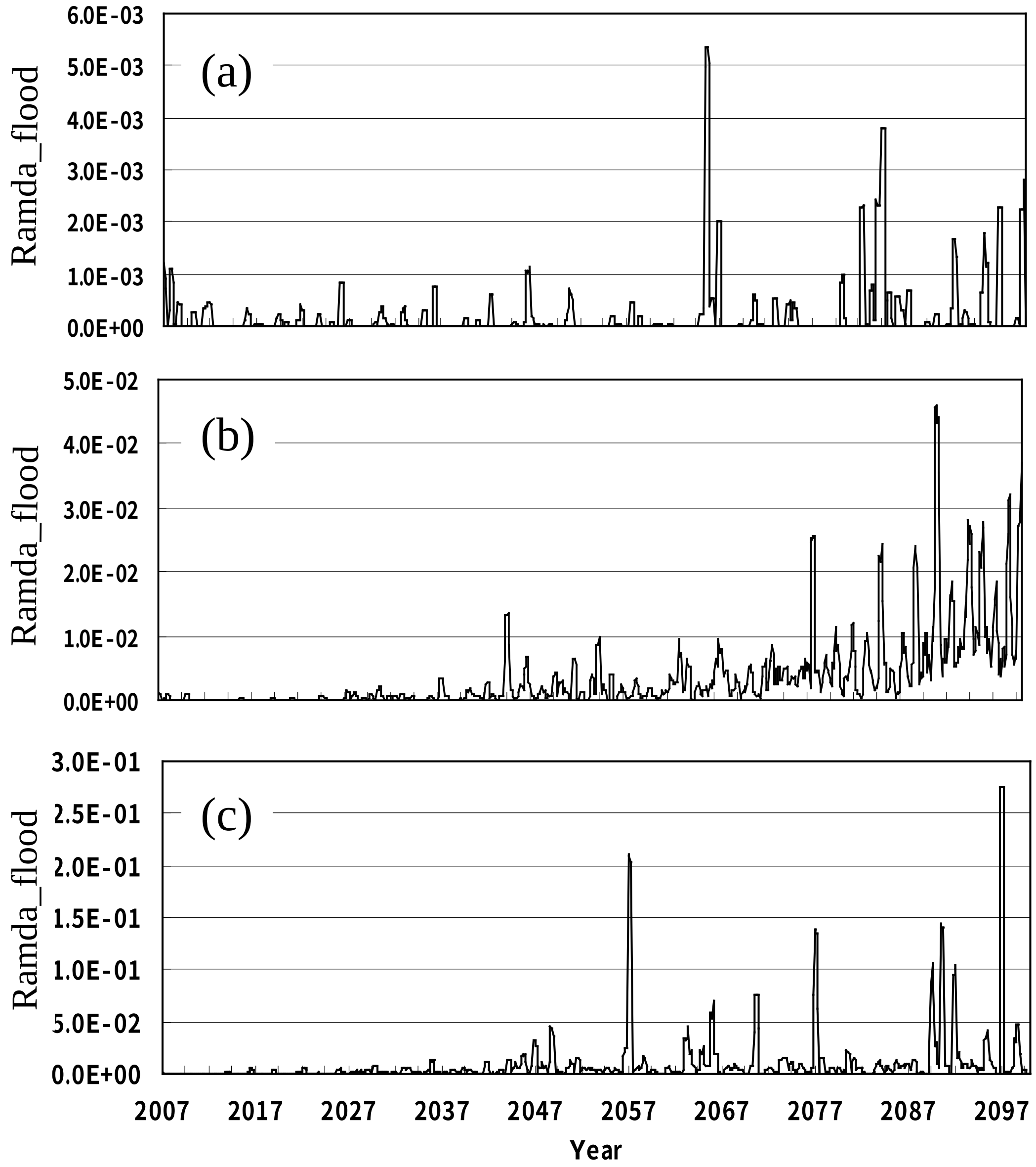


Figure 8 T.Ohnishi et al.



<u>Figure 9</u> T.Ohnishi et al.

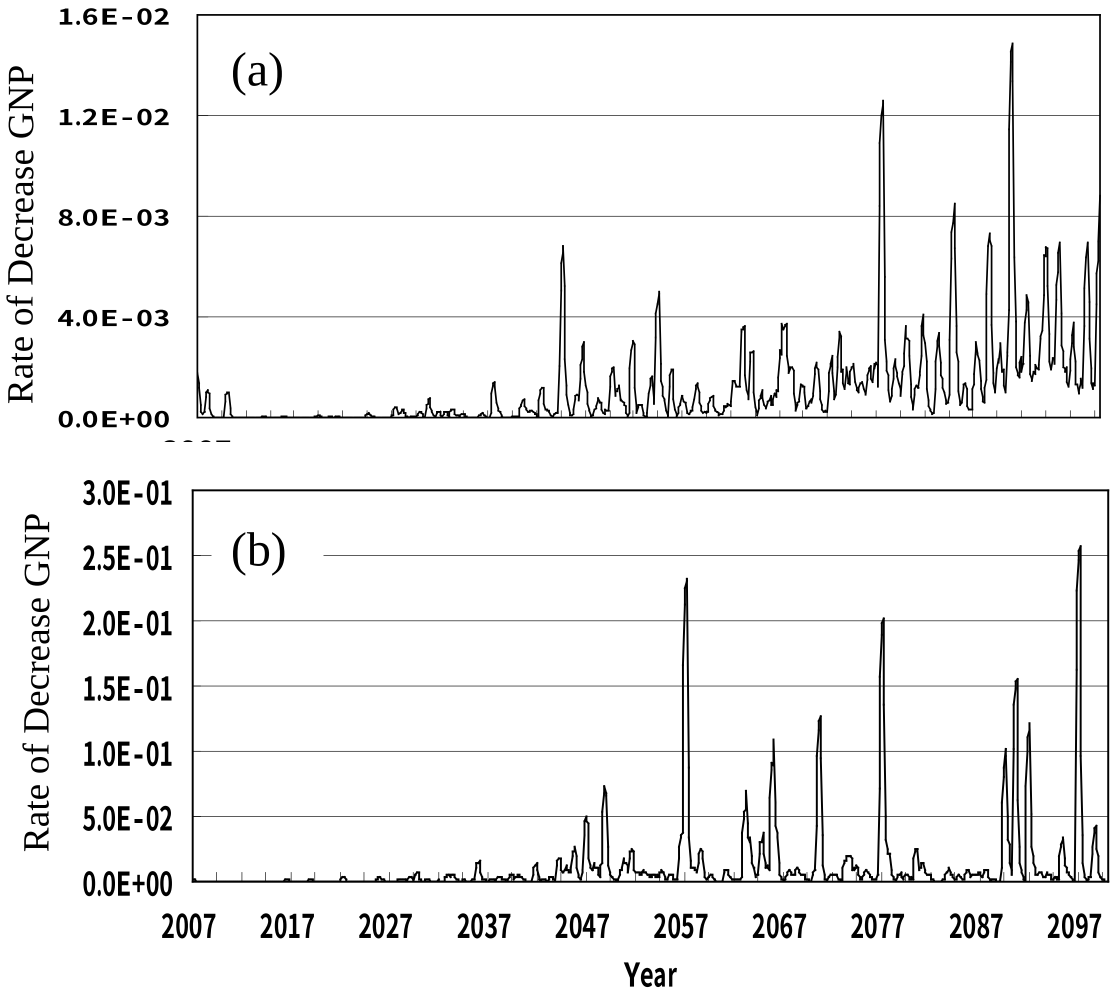


Figure 10   T.Ohnishi et al.

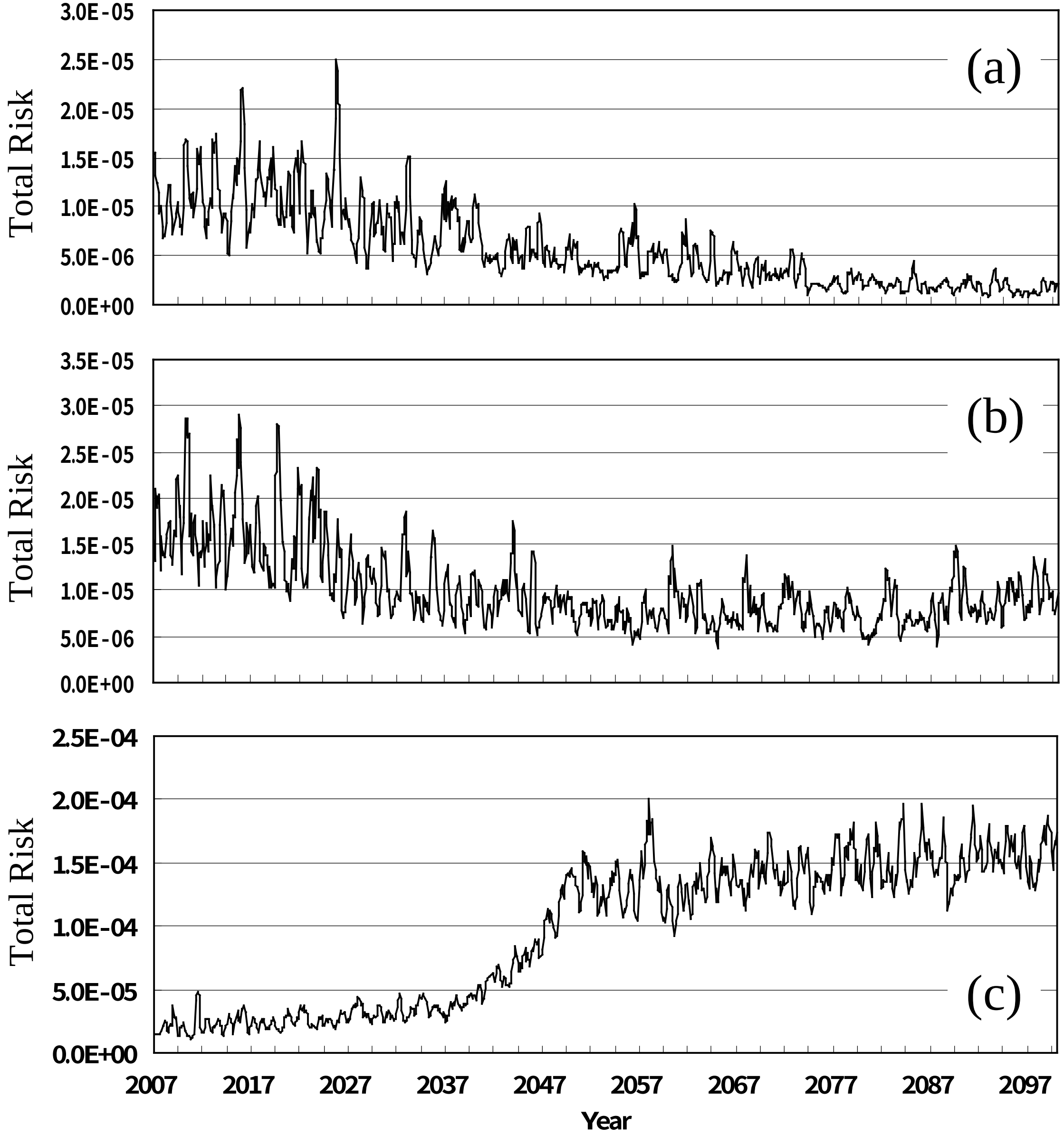


Figure 11

T.Ohnishi et al.

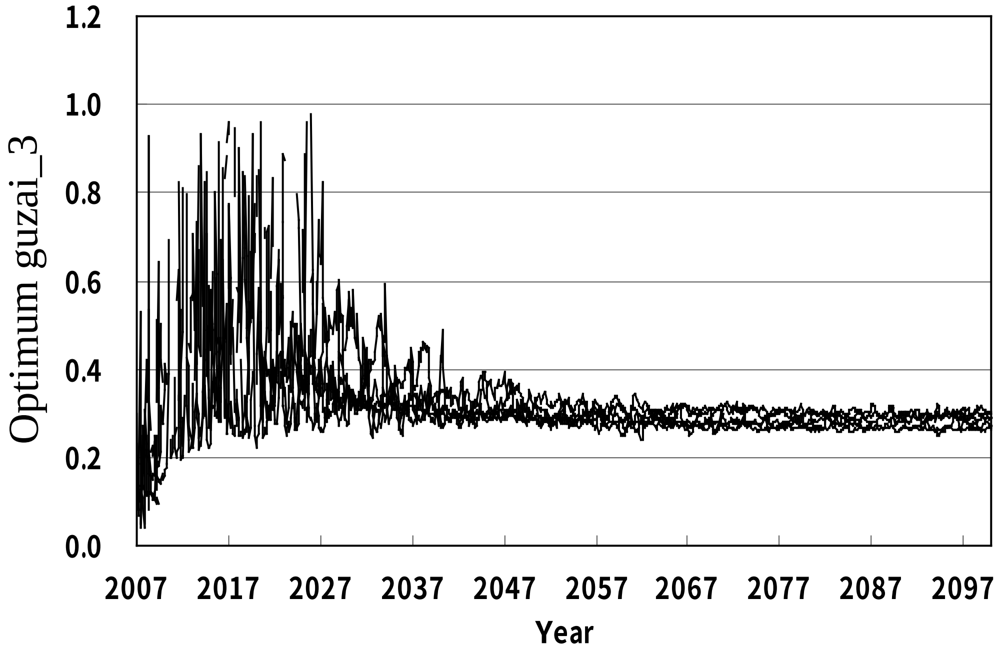


Figure 12 T.Ohnishi et al.