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Development of Damage Function of Ozone Depletion for Life Cycle Impact Assessment

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The ozone depletion problem is one of the serious global environmental problems because of the wide impact on human health, ecosystem and so forth. The problem has been evaluated using the ozone depletion potential (ODP) in previous life cycle assessment (LCA). However, it is insufficient for impact assessment, because the concept of ODP is lack in cause-effect aspects. The purpose of this study is to estimate the damage function of ozone depletion, namely the quantitative relationship of ODSs emission to the harmful impacts on human health, especially on skin cancer and cataract. We produced the damage function connecting with the main processes of the ozone depletion. Consequently, we could produce the damage function of ozone depletion, that is the change of incidence of skin cancer, c.f. melanoma and non-melanoma, for every ten degrees of latitude band and for the each type of skin color, white, yellow and black.
Key words: LCA, ozone depletion, damage function, skin cancer and cataract

1. INTRODUCTION

Artificially emitted halocarbons, such as chlorofluorocarbons, are called “ozone depleting substances (ODSs)” in the cause of destroying the stratospheric ozone. Stratospheric ozone depletion is not only to affect the climatic system in the stratosphere, but to cause increasing ultraviolet radiation at the surface, significantly B region, and lead various environmental impacts on human health, ecosystems and materials along with it (1).

The ozone depletion problem is also an important subject in the field of life cycle impact assessment (LCIA). Previous LCIA studies has evaluated the problem using ozone depletion potentials (ODPs). The ODPs are determined as relative values, the ozone depleting ability of one ODS over that of CFC-11. The ODPs are broadly used to grasp the ODS emission inventory of each member country in the Montreal protocol.

The concept of ODP means the potential ozone depletion amount, however, that does not have a mean of the impacts on receptors as result of ozone depletion. Therefore, the ODP concept is seemed to be insufficient to evaluate the impacts of ozone depletion in LCIA.

To improve such circumstances, the Working Group of Impact Assessment allocated a research program to develop damage functions for ozone depletion, namely the functions to evaluate the quantitative impacts of ozone depletion on the receptors. The Working Group is a part of the LCA Project that New Energy and Industrial Technology Development Organization (NEDO) has been promoting. This study forms a part of the research program.

Although the impacts of ozone depletion include many receptors, we focused our aim on the human health impacts as first step of the research program. The purpose of our study was to develop the damage functions of ozone depletion on human health impacts, especially skin cancer and cataract.

2. METHODOLOGY

The human health impacts of ozone depletion arise with several processes. They are, 1: emission of ODSs at the surface, 2: increase of ODSs in the troposphere, 3: increase of ODSs in the stratosphere, 4: ozone depletion in the stratosphere, 5: increase of ultraviolet B radiation at the surface, and 6: increase of risk on human health. There are many previous studies concerning each process, however, there is few comprehensive study to clear the quantitative relationship of the impacts to the causes (2,3).

In this study, we collected the existing information and data of concerns on the ozone depletion processes and related each process with linear approximation and so forth, then calculated the damage function of ozone depletion on human health impacts. The calculation flow is shown in Fig.1.

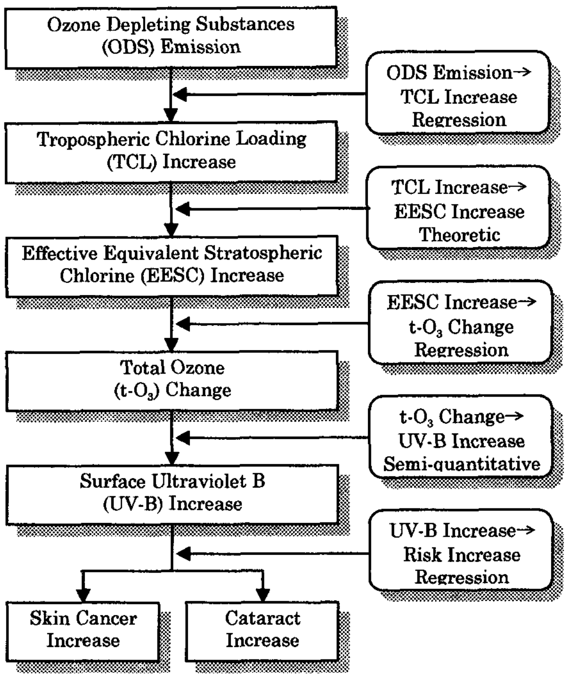

Fig.1 Damage function calculation flow

3. CALCULATION OF DAMAGE FUNCTION

3.1 ODS emission and tropospheric ODS increase

We estimated linear regression coefficients of tropospheric Cl and Br concentration increase due to ODSs emission.

Cl and Br concentration in the troposphere are represented as Tropospheric Chlorine Loading (TCL) defined by Daniel et. al. (4).

$$TCL = \Sigma \{ nCl(X) + nBr(X)\,\alpha \}\, C(X)_{trop} \qquad \text{(eq.1)}$$

X means one ODS, nCl and nBr are number of Cl and Br in a molecular of X respectively, α is Br/Cl ratio on ozone destroying ability, and $C(X)_{trop}$ is concentration of X in the troposphere [pptv]. α = 40 based on the existing references (4,5).

Using global emission amount of CFC-11 (6) and tropospheric level of CFC-11 (7), a linear regression coefficient of TCL increasing to CFC-11 emission was estimated. Based on the relation, the regression coefficient of each ODS, cf. dTCL(X)/dt, was estimated with compensations by the molecular weight and number of Cl and/or Br atoms in X.

3.2 Tropospheric ODS and Stratospheric ODS

ODSs emitted into the troposphere reach the stratosphere with general circulation process in the atmosphere. Only free Cl and Br separated from ODSs destroys ozone, however, separating tendency depends on ODS species. Therefore, Cl equivalent concentration in the stratosphere should be estimated as that of contributing ozone depletion.

Stratospheric concentration of Cl and Br that contribute to destroy ozone is defined as Effective Equivalent Stratospheric Chlorine (EESC) (4).

$$EESC_t = \Sigma\, TCL(X)_{t-3}\, FC(X) \qquad \text{(eq.2)}$$

It approximately takes three years that the air in the troposphere flows into the stratosphere (5), so that the year of TCL is three years earlier than that of EESC. FC(X) indicates the degree of separating Cl and/or Br from X in the stratosphere, and is determined as follows (4);

$$FC(X) = \{ \mu_{entry}(X) - \mu_{\Phi,z}(X) \} / \mu_{entry}(X) \qquad \text{(eq.3)}$$

$\mu_{entry}(X)$ is concentration of X that flows into the stratosphere, $\mu_{\Phi,z}(X)$ is concentration of X at latitude Φ and altitude z. FC of each ODS was determined using FC(CFC-11), calculated by a concentration vertical profile (8), and the relative values of FC(X) to FC(CFC-11) (4).

Based on the eq.2, the value, a part of dTCL(X)/dt, that contributes to increase EESC was determined. Sum of EESC increase for all target ODSs, namely ΣdEESC(X)/dt, was calculated and added to the EESC of the base year 1995. This new EESC was assumed the EESC after emitting ODSs at one year. There is time lag for three years that the tropospheric air is transported into the stratosphere, the TCL in 1995 corresponds to the EESC in 1998. Hence, ΣdEESC(X)/dt was added to the EESC in 1998.

3.3 Stratospheric ODS and total ozone

Approximately 90% of atmospheric ozone exist in the stratosphere (5). It was assumed that the change of total ozone indicated the change of the stratospheric ozone. However, it is known that total ozone amount and degree of ozone depletion have much spatially and seasonally fluctuations. Additionally, concerning the ozone destroy processes, more complex system, such as heterogeneous reaction system between solid-liquid phase in the polar stratospheric clouds, has large contribution to drastic ozone depletion.

The correlation between the past EESC trend (5) and total ozone trend (9) was estimated. The trend of total ozone was derived from the observation for Nov.1978-Apr.1993 by a total ozone mapping spectrometer (TOMS) with the artificial satellite, Nimbus-7. Using monthly and 5 degrees of latitude band data, weighted averages for 10 degrees of latitude band were calculated, the weight was the area of each latitude band, then seasonal averages were estimated, seasonal divisions were Dec.-Feb., Mar.-May, Jun.-Aug. and Sep.-Nov.

It was assumed that the EESC in one season in one year had same value and not changing spatially among latitude bands. On the assumption, the correlation between the EESC and the total ozone amount of each latitude band was estimated, and a group of regression equations was derived, that determine the total ozone amount in each latitude band with EESC as an explanatory variable. Target latitude bands were set between lat.60N and lat.60S., because of the lack of the satellite data in the region that has the polar nights.

3.4 Total ozone and UV-B at the surface

The relationship of B region ultraviolet radiation (UV-B) at the surface to total ozone amount was regressed with observation data of total ozone (9) and UV-B (10). Based on the relationship, UV-B changes were estimated due to total ozone changes.

Averaged absorption cross-sections for molecule of ozone was calculated for 290-300nm, 300-310nm and 310-320nm band with each wavelength cross-sections data (11). Then, using the total ozone data, optical thickness of ozone for UV-B, τ_{O3} was calculated. The wavelength band 280-290nm is also in UV-B range, though the band was excluded because of hardly reaching at the surface (10).

τ_{O3} corresponds to the ability for reducing direct solar radiation. As a matter of fact, UV-B is also scattered by other gas and scattered /absorbed by aerosols. Furthermore, UV-B radiation at the surface consists of direct and scattered radiation. Therefore, it is impossible to estimate the incidence of UV-B at the surface correctly only based on the $\tau_{O3.}$ The incidence of UV-B can be calculated according to the radiation theory, but it is quite difficult to solve a radiation transfer equation rigidly. Even if an analytic solution is adopted, it is required to develop an approximation method not only collect much data. That is why, a more simple regression method was examined and used to lead the relationship of UV-B changes at the surface to the change of total ozone.

Firstly, data of total ozone in daytime at fine weather, UV-B radiation intensity at the surface on same time that of total ozone, and solar zenith angle ZA were extracted from existing observations (10).

Next, UV-B intensity at the upper end of the atmosphere was theoretically calculated for each wavelength band with solar constant (11) and correction by the distance between the sun and the earth in the day of a year (12).

With theoretical UV-B intensity at the top of the atmosphere and observed UV-B intensity at the surface, and it was assumed that reduction of UV-B was represented by the attenuation equation of direct radiation, then apparent optical thickness, τ was. Finally, the correlation between theoretical τ_{O3} and empirical τ was grasped and linear models were introduced for each wavelength band.

UV-B intensity at the surface due to any total ozone amount and solar zenith angle could be calculated by these equations, and annual UV-B amount at the surface for each latitude band was calculated.

The reason why τ was leaded, instead of the direct correlation between τ_{O3} and UV-B intensity at the surface, was to avoid the effect of the distance in the atmosphere, = 1/cosZA.

3.5 UV-B at the surface and human health

Using incidence rate of skin cancer (13) and patient ratio of cataract (14), the relationship between these data and annual UV-B amount at the surface was found. These epidemiological data were as of respective countries or regions in the world, and latitude at the center of each country or region was obtained from geographical maps.

Annual surface UV-B radiation in the base year was represented as a function of latitude based on the estimated UV-B amount at the surface for each latitude band.

Using the function, annual surface UV-B radiation at the center of each country or region, where epidemiological data available, was calculated. And the relationship between annual surface UV-B amount and the incidence rate was found with plotting the estimated surface UV-B and the incidence rate for each country or region, then regression models were obtained with UV-B amount as the explanation variable and incidence rate as the objective variable.

Concerning skin cancer, changed incidence rate after ODS emitting was firstly calculated with substituting the surface UV-B amount after ODS emitting to the regression model. Next, the increase of incidence rate, namely the difference between that of the base year and after ODS emitting, was obtained. Then, the number of incidence of skin cancer increased while the emitted ODS remains in the atmosphere was estimated with the atmospheric life times of one ODS. The estimation was done for each latitude band, each human skin color: white, yellow and black, and each type of skin cancer: melanoma and non-melanoma. The result was located as a damage function of ozone depletion for skin cancer by emitting ODSs.

Meanwhile, incidence rate of cataract could not be clear in our study. That is why, a damage function for cataract could not be obtained. Only, strong positive relationship was found between annual surface UV-B amount and patient ratio of cataract.

4. RESULTS OF DAMAGE FUNCTION

Target ODSs were 13 species, CFCs, Halons, HCFCs and so forth. Table 1 shows a part of the estimated damage function of ozone depletion, namely, regression coefficients of increased skin cancer incident in the period of one ODS life times [person/100000person] to its emission [kt/yr].

Table 1 Damage Function of Ozone Depletion for Melanoma Skin Cancer (part) [person/100000person]

ODS	Lat. Band	Skin Color		
		White	Yellow	Black
CFC-11	50-60N	3.56E-5	–	–
	40-50N	5.52E-5	–	2.50E-7
	30-40N	6.32E-5	5.03E-6	2.86E-7
	20-30N	4.41E-5	3.51E-6	1.99E-7
	10-20N	–	2.10E-6	1.19E-7
	0-10N	–	4.17E-7	–
	30-40S	8.70E-5	–	–
	40-50S	9.28E-5	–	–
HCFC-22	50-60N	1.76E-6	–	–
	40-50N	2.72E-6	–	1.23E-8
	30-40N	3.11E-6	2.48E-7	1.41E-8
	20-30N	2.17E-6	1.73E-7	9.83E-9
	10-20N	–	1.04E-7	5.89E-9
	0-10N	–	2.06E-8	–
	30-40S	4.29E-6	–	–
	40-50S	4.57E-6	–	–
HCFC-141b	50-60N	3.87E-6	–	–
	40-50N	5.85E-6	–	2.65E-8
	30-40N	6.69E-6	5.33E-7	3.03E-8
	20-30N	4.67E-6	3.72E-7	2.11E-8
	10-20N	–	2.23E-7	1.27E-8
	0-10N	–	4.42E-8	–
	30-40S	9.22E-6	–	–
	40-50S	9.83E-6	–	–
HCFC-142b	50-60N	2.28E-6	–	–
	40-50N	3.53E-6	–	1.60E-8
	30-40N	4.04E-6	3.21E-7	1.83E-8
	20-30N	2.82E-6	2.24E-7	1.28E-8
	10-20N	–	1.34E-7	7.64E-9
	0-10N	–	2.67E-8	–
	30-40S	5.56E-6	–	–
	40-50S	5.93E-6	–	–

* The damage function provides total increase of skin cancer incident [person/100,000person] while the emitted ODS in a year remains in the atmosphere by multiplying with emission amount of one ODS [kt/yr].
* Excluded latitude band and "-" in the table means that out of the area where epidemiological data obtained or no data available on concerned skin color.

5. CONCLUSION

Problems to be solved regarding our study are, 1: evaluation of confidence intervals and uncertainties, 2: more quantitative estimation of damage function, 3: development of a damage function for cataract, 4: consideration of other impacts, and 5: examination of usage methodology in LCIA.

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REFERENCES

(1) EAJ (eds.), Ozone Depletion – Impact of Ultraviolet on Human Health, Plant and Ecosystem (Jpn), Chuo-hoki Press, Tokyo (1995), 216p.
(2) UNEP, Environmental Effects of Ozone Depletion: 1994 Assessment (1994).
(3) UNEP, Environmental Effects of Ozone Depletion: 1998 Assessment (1998).
(4) J. S. Daniel, S. Solomon and D. L. Albritton, On the Evaluation of Halocarbon Radiative Forcing and Global Warming Potentials, Journal of Geophysical Research, Vol.100, No.D1, pp.1271-1285 (1995).
(5) WMO, Scientific Assessment of Ozone Depletion: 1994, WMO Global Ozone Research and Monitoring Project, Report No.37 (1994).
(6) J. A. Kaye S. A. Penkett and F. M. Ormond (eds.), Report on Concentrations, Lifetimes, and Trends of CFCs, Halons, and Related Species, NASA References Publication 1339, NASA Office of Mission to Planet Earth, 247p. (1994).
(7) NOAH/CMDL/NOAA, Halo Compounds Data Set through its ftp site, "ftp://ftp.cmdl.noaa.gov/noah/"
(8) EAJ, Annual Report on Monitoring the Ozone Layer (Jpn), 87p. (1998).
(9) GSFC/NASA, Version 7 Ozone Gridded Data: 1978-1993.
(10) Japan Meteorological Agency, Annual Report on Monitoring the Ozone Layer (CD-ROM), (1998).
(11) J. T. Houghton, The Physics of Atmospheres second edition, Cambridge University Press, Cambridge (1986), 271p.
(12) M. Aida, Promenade to Meteorology 8: Atmosphere and Radiation Process (Jpn), Tokyo-do Press, Tokyo (1982), 280p.
(13) J. Ferlay, R. J. Black, S. L. Whelan and D. M. Parkin, CI5VII: Electronic Database of Cancer Incidence in Five Continents Vol.7, IARC CancerBase No.2, International Agency for Research on Cancer (IARC)/WHO, CD-ROM with Booklet (1997).
(14) EAJ, A-4.3 International Cooperative Studies on the Relationship between Cataract Appearance and UVR Exposure, Global Environment Research, pp.127-130 (1998).

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