



Damage factors of stratospheric ozone depletion on human health impact with the addition of nitrous oxide as the largest contributor in the 2000s

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Abstract

Purpose Stratospheric ozone (O₃) depletion caused by O₃-depleting substances (ODSs) remains an unsolved issue. The leakage of older ODSs in the atmosphere continue to affect stratospheric O₃, and nitrous oxide (N₂O) remains the largest contributor to stratospheric O₃ depletion. The purpose of this study was to update the damage factors of stratospheric O₃ depletion on human health impacts, particularly skin cancers and eye cataracts, for the years 2010 and 2015 by adding N₂O.

Methods The framework to derive damage factors followed that of our previous study; the marginal increase in total incidence per unit ODS emission was estimated using the following terms: ground surface emission, tropospheric chlorine loading, equivalent effective stratospheric chlorine (EESC), total O₃ in the air column, ultraviolet-B (UV-B) at the ground surface, incidence due to erythemal UV-B exposure, standardized age structure, population, and ODS atmospheric lifetime. By multiplying the disability-adjusted life years (DALYs) per incidence by the marginal increase in total incidence per unit emission, the damage factor was obtained as the DALY per unit emission. The following update was made in this study: the addition of N₂O and revisions of the relationship between EESC and total O₃, ODS lifetime, population, and DALY per incidence.

Results and discussion Damage factors of all ODSs regulated by the Montreal Protocol and of N₂O were calculated for melanoma, non-melanoma skin cancers, and eye cataracts. The total damage factors of N₂O were 2.1×10^{-5} and 2.2×10^{-5} DALY per kg nitrogen (N) in 2010 and 2015, respectively. These values were smaller than those of chlorofluorocarbons and halons; however, the global effect of N₂O on stratospheric O₃ depletion was approximately 170,000 DALYs or 3.9 billion USD in 2010, accounting for 48% of the total damage. The damage factor of N₂O on climate change was estimated, based on existing literature, to be 27 times higher than that for stratospheric O₃ depletion estimated in this study.

Conclusions N₂O is currently the largest contributor to stratospheric O₃ depletion, which accounted for approximately 50% of the total health impact induced by all ODSs in 2010. Although another important impact of N₂O, i.e., climate change, was demonstrated to be 27 times more damaging than stratospheric O₃ depletion, this means that N₂O emissions contribute to two global environmental issues simultaneously. Thus, efforts to reduce N₂O emissions should be increased.

Keywords Life cycle impact assessment · Ozone depleting substance · Stratospheric ozone layer · Ultraviolet-B · Melanoma · Skin cancer · Eye cataract · Disability-adjusted life year

1 Introduction

Stratospheric ozone (O₃) depletion is a serious global environmental issue caused by the anthropogenic emissions of O₃-depleting substances (ODSs), which increases ultraviolet

intensity at the ground surface (ultraviolet-B [UV-B] in particular) and has harmful impacts on human health. Skin cancer, especially in fair-skinned individuals, and eye cataracts are important human health problems attributed to long-term UV-B exposure (WMO 2018). Major ODSs are artificial substances such as chlorofluorocarbons (CFCs) and halons. They are stable in the troposphere but release halogens in the stratosphere through their decomposition by strong ultraviolet in solar radiation, which causes catalytic and chain destruction of stratospheric O₃ (WMO 2018). The Montreal Protocol adopted in 1987 tackled the phase-down of ODS

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production and consumption in a stepwise manner (UNEP 2022) and was effective in reducing the use of strong ODSs, such as CFCs and halons. Consequently, total ODS emissions equivalent to the O₃-depletion potential (ODP), i.e., a relative index of O₃ destruction using CFC-11 as a reference substance (ODP of CFC-11 = 1.0), peaked at the end of the 1980s and has decreased since then (Ravishankara et al. 2009; WMO 2018). This represents a success story in addressing global environmental issues; however, once created and stored after the phase-out, stable ODSs continue to leak into the atmosphere, and once emitted into the atmosphere, have a long atmospheric lifetime, causing O₃ destruction (WMO 2018).

Nitrous oxide (N₂O) is a potent greenhouse gas (IPCC 2013, 2021) and an ODS (Ravishankara et al. 2009; WMO 2018). The ODP-equivalent emission of N₂O has increased its relative contribution alongside the phase-out of strong ODSs, and N₂O has been the highest contributing ODS since 2005 (Ravishankara et al. 2009). N₂O is not a target substance under the Montreal Protocol because it does not contain halogens. The ODP of N₂O is small, 0.017 as estimated by Ravishankara et al. (2009), and it was revised to 0.015 as of 2000 (WMO 2018). However, the global anthropogenic N₂O emission in 2010, which was approximately 13 Tg year⁻¹ (Tian et al. 2020), was 200 times that of CFC-11 emission (65 Gg year⁻¹) (WMO 2018). Global N₂O emissions have continued to increase in the twenty-first century, primarily owing to the ongoing increases in agricultural emissions (Tian et al. 2020). Thus, stratospheric O₃ depletion by N₂O is a future concern. Notably, the O₃-destruction ability of CFC-11 and ODP of N₂O are subject to greenhouse gas concentrations and global warming. Higher carbon dioxide (CO₂) levels induce cooling of the stratosphere, which increases the chemical destruction of nitrogen oxides (NO_x) and reduces the efficiency of O₃ destruction by N₂O (Stolarski et al. 2015). High methane (CH₄) levels result not only in slowing down of NO_x-driven O₃ loss but also in increasing a value of N₂O ODP. This is because increased CH₄ reduces the efficiency of CFC-11 at destroying O₃, and CFC-11 is used as a reference gas in the ODP concept (Revell et al. 2015, 2017). Accordingly, the ODP of N₂O (0.015 in 2000) will change in future corresponding to the Representative Concentration Pathways (RCPs; IPCC 2013, 2021) as follows: 0.015 in RCP2.6, 0.017 in RCP4.5, 0.0174 in RCP6.0, and 3.0 in RCP8.5 (WMO 2018).

The authors developed the damage factors of stratospheric O₃ depletion for ODS, except N₂O, utilizing around the year 2000 as their base (Hayashi et al. 2000; 2006), which consisted of the life cycle impact assessment (LCIA) method based on endpoint modeling (LIME) (Inaba and Itsubo 2018; Murakami et al. 2022). Struijs et al. (2010) estimated the global human health toll due to ODS emissions in 2007 to be 500,000 disability-adjusted life years (DALYs); however,

N₂O was not involved in their estimation. Brink et al. (2011) estimated the effects of N₂O on human health due to stratospheric O₃ depletion, around 2010, to be 24.2 DALY per Gg of N₂O based on the results of Struijs et al. (2010). Therefore, the global health loss in this case corresponds to approximately 112,000 DALYs using the mean global anthropogenic N₂O emissions during 2007–2016, i.e., 7.3 Tg N year⁻¹ (Tian et al. 2020). Then, we have the following questions: What were the damage factors of stratospheric O₃ depletion for all ODSs, including N₂O, in 2010 and 2015? What were the global damages to human health in 2010 and 2015 due to N₂O emissions when calculated using our LCIA method?

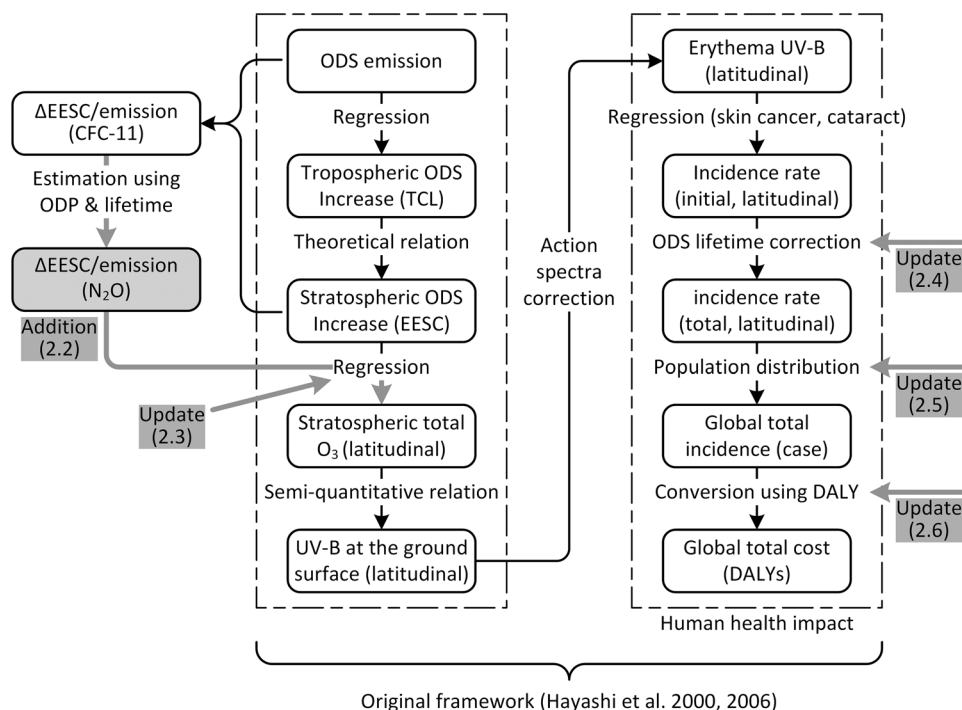
The purpose of this study was to update the damage factors of stratospheric O₃ depletion for the years 2010 and 2015, by adding N₂O that was not included in previous studies (Hayashi et al. 2000; 2006). Although stratospheric O₃ depletion has various impacts on human health, social assets, and terrestrial and aquatic ecosystems (Hayashi et al. 2006), this study prioritized human health impact on skin cancer and eye cataracts, because the skin and eyes are the organs exposed to UV-B; these impacts have been the biggest concern of stratospheric O₃ depletion, particularly for fair-skinned populations (Lucas et al. 2015). The years 2010 and 2015 were selected considering the data availability to calculate damage factors. The updated damage factors were used to compare the health impacts between 2000 and 2010 or 2015, as well as to the damages induced by N₂O as an ODS and greenhouse gas. Finally, the potential improvements and solutions to the damaging effects that could be achieved in future research were discussed.

2 Methods

2.1 General descriptions

The target ODSs in the present study were N₂O and all ODSs regulated by the Montreal Protocol. The procedure to derive the damage factors followed that of previous studies (Hayashi et al. 2000; 2006), except for N₂O which was not considered in the previous studies. The damage factors of the following 13 ODSs were calculated directly using the scheme shown in Fig. 1: chlorofluorocarbon (CFC)-11, CFC-12, CFC-113, Halon-1211, Halon-1301, carbon tetrachloride (CCl₄), methyl chloroform (1,1,1-trichloroethane), hydrochlorofluorocarbon (HCFC)-22, HCFC-123, HCFC-124, HCFC-141b, HCFC-142b, and methyl bromide. The damage factors of the other ODSs (except N₂O) were obtained by converting the directly calculated damage factor of the chemically representative ODS into that of the target ODS using the ratio of their ODP values (correspondences are shown in Table S1 Supplementary file1). Damage factors for N₂O were derived using the scheme shown in Fig. 1. The relationship between the N₂O

Fig. 1 Schematic framework to estimate the damage factors of stratospheric ozone depletion. Original framework in Hayashi et al. (2000, 2006) which was updated in this study. ODS, ozone depleting substance; UV-B, ultraviolet-B; TCL, tropospheric chlorine loading; EESC, equivalent effective stratospheric chlorine; and DALYs, disability-adjusted life years



emission at the ground surface and a marginal increase in stratospheric N₂O as the equivalent effective stratospheric chlorine (EESC) was estimated by converting that of CFC-11 using the ODPs and lifetimes of N₂O and CFC-11, as explained in Sect. 2.2.

For each step shown in Fig. 1, the following describes the steps used in a previous study (Hayashi et al. 2006; Supplementary file2 for details) that were updated in this study.

- The relationship between ground surface emission and an increase in tropospheric chlorine loading (TCL) for the 13 ODSs.
- The relationship between an increase in TCL and an increase in EESC for the 13 ODSs.
- The relationship between ground surface emission and an increase in EESC for N₂O was calculated in this study using the ODPs and atmospheric lifetimes of N₂O and CFC-11 (Sect. 2.2).
- The relationship between the total EESC and total O₃ was revised in this study (Sect. 2.3).
- The relationship between total O₃ and UV-B at the ground surface.
- The correction of the ground-level UV-B into erythemal UV-B.
- The correction of the atmospheric lifetimes of ODSs, updated in this study (Sect. 2.4).
- The incidence rates of skin cancer and eye cataracts tied to erythemal UV-B exposure, which denote the rate to unit emission per 100,000 individuals. The skin cancer types

were divided into malignant melanoma and non-melanoma skin cancer for fair, medium, and dark skin colors.

- The global latitudinal population was updated in this study for 2010 and 2015. The population distinguishing the three skin colors (fair, medium, and dark) was estimated for each 10° latitudinal belt (Sect. 2.5).
- An increase in the total incidence of each disease per unit emission of ODSs was calculated using the abovementioned relationships.
- DALYs per incidence of melanoma, non-melanoma skin cancer, and eye cataracts were updated in this study for 2010 and 2015 (Sect. 2.6).

It should be noted that the damage factor does not necessarily represent the real damage in the future; instead, it expresses an indicative impact owing to an additional emission of the target ODS in the base year. This concept agrees to the description in the Eco-indicator 99: “it is an indicator aimed at showing the approximately correct direction for designers who want to analyze and minimize the environmental load of product systems” (Goedkoop and Spriensma 2001). The incidence rates of diseases, population, and DALY per incidence values were fixed to those of the base year (2010 or 2015) in this study. The baseline EESC has been decreasing since the phase-out of strong ODSs (WMO 2018), whereas the global population has been increasing steadily (UN 2019). The DALY value can change depending on the medical condition.

2.2 Relationship between surface N₂O emission and EESC

The ODP of N₂O was estimated to be 0.017 (Ravishankara et al. 2009) and re-assessed as 0.015 (WMO 2018) and that of CFC-11 as the reference substance is 1.0 (UNEP 2022). This study applied the N₂O-ODP of 0.015, corresponding to the RCP2.6 scenario, the lowest forcing level (IPCC 2013; WMO 2018). The ODP of an ODS is a function of its O₃ destruction rate and stratospheric lifetime. Therefore, the relationship between the unit emission at the ground surface and the increasing rate of EESC for CFC-11 [*dEESC*(CFC-11)], i.e., 0.048 pptv Gg⁻¹ (Hayashi et al. 2006), was converted to that for N₂O [*dEESC*(N₂O)] using the following equation:

$$\frac{ODP(N_2O)}{ODP(CFC-11)} = \frac{F_{LT}(N_2O) \cdot dEESC(N_2O)}{F_{LT}(CFC-11) \cdot dEESC(CFC-11)} \quad (1)$$

where $F_{LT}(X)$ denotes the lifetime term for the ODS species X . This term was modified considering that it takes an average of 3 years for ODS to be transported from the troposphere to the stratosphere (WMO 1995; Hayashi et al. 2006). Therefore, $F_{LT}(X)$ is expressed as:

$$F_{LT}(X) = \int_3^{\infty} C(X, t) dt = \int_3^{\infty} e^{-t/LT(X)} dt = LT(X) e^{-3/LT(X)} \quad (2)$$

where LT is the lifetime of the ODS species X (year). $F_{LT}(N_2O)$ and $F_{LT}(CFC-11)$ were determined to be 106 and 49.1 years, respectively, using the N₂O lifetime of 109 years (Forster et al. 2021), and the CFC-11 lifetime of 52 years (SPARC 2013; WMO 2018). Finally, the *dEESC*(N₂O) value was obtained using Eq. (1) as 0.000333 pptv Gg⁻¹ N₂O and further converted to 0.000524 pptv Gg⁻¹ N using the weight ratio of nitrogen (N) per N₂O molecule (i.e., 28/44). We used the value per N rather than that per molecular N₂O because N forms not only on N₂O but also on other various compounds environmentally important. Therefore, a damage factor per unit N emission is more advantageous than that per N₂O for consistency with other accounting systems, such as national N budgets (e.g., Hayashi et al. 2021) because they express the weight of N compounds as the weight of N to comprehensively handle various commodities containing N, such as food, goods, and materials.

Although EESC expression is not suitable for N₂O as a halogen-free molecule, a value corresponding to EESC was used in this study for convenience. The O₃ destruction by N₂O affects the total O₃ observed at the ground surface. Therefore, a regression equation with the total O₃ as the objective variable and EESC baseline as the explanatory variable as shown below contains the effect of N₂O on O₃ destruction. The EESC baseline in the Southern Hemisphere

is approximately 3000 pptv (NASA 2022), whereas the marginal increase in EESC due to unit emission of N₂O is relatively very small, 0.0005 pptv Gg⁻¹ N as calculated above. Thus, we judged that the method for calculating the effect of N₂O on O₃ destruction using the EESC equivalent value might not be the best way but an acceptable method to estimate the marginal impact due to an additional emission.

2.3 Update of relationship between EESC and total O₃

The regression equation of the total O₃ as the objective variable and EESC baseline as the explanatory variable for each 10° latitudinal belt (18 zones between the north and south poles) and each season (December–February, March–May, June–August, September–November) was obtained using available data. The slope (regression coefficient) was used as a factor that indicates the marginal decrease in total O₃ due to a marginal increase in EESC. The EESC baseline was obtained from NASA (2022) as an estimation in the Southern Hemisphere. The previous studies (Hayashi et al. 2000; 2006) used the total O₃ observational dataset provided by McPeters and Beach (1996) that contains data from 1978 to 1993. In this revision, another dataset covering a period from 1970 to 2021 provided by GSFC (2022) was also used. As the latter dataset has no data for latitudes higher than 80°, the two datasets were combined to create the regression equations (Supplementary file2).

2.4 Update of atmospheric lifetime of ODSs

A previous study (Hayashi et al. 2006) referred to WMO (1999) to obtain the lifetimes of 13 ODSs. These values were then updated in WMO (2018) (Table 1). Using Eq. (2), the original lifetime was converted to the F_{LT} value for each ODS species, and an ODS with a lifetime less than 3 years can partly flow into the stratosphere, as shown for HCFC-123 and methyl bromide (Table 1).

2.5 Update of global latitudinal population

The population of each country and region in 2010 and 2015 was obtained from the World Population Prospects (UN 2019). The world was divided into latitudinal belts with a width of 10°. The population of each country was allocated to the corresponding latitudinal belts, principally using the area in the latitudinal belt as the weight. The population ratio of skin colors (fair, medium, and dark) in each country was estimated using information on ethnic groups (CIA 2021), assuming a common ratio regardless of the latitudinal belts within the country. The total population and population of each skin color in each latitudinal belt were estimated (Supplementary file2).

Table 1 Ozone depleting substances (ODSs), their atmospheric lifetimes, and the corrected atmospheric lifetime in the stratosphere (F_{LT}) for direct calculation of the damage factors of stratospheric ozone depletion

ODS species		Lifetime in literature (year)	F_{LT} from Eq. 2 (year)	Reference: lifetime used in the previous study ^c (year)
CFSs	CFC-11	52 ^a	49.1	45 ^d
	CFC-12	102 ^a	99.0	100 ^d
	CFC-113	93 ^a	90.0	85 ^d
Halons	Halon-1211	16 ^a	13.3	11 ^d
	Halon-1301	72 ^a	69.1	65 ^d
Carbon tetrachloride (CCl ₄)		32 ^a	29.1	35 ^d
Methyl chloroform (CH ₃ CCl ₃)		5.0 ^a	2.74	4.8 ^d
HCFCs	HCFC-22	11.9 ^a	9.2	11.8 ^d
	HCFC-123	1.3 ^a	0.129	1.4 ^d
	HCFC-124	5.9 ^a	3.55	6.1 ^d
	HCFC-141b	9.4 ^a	6.83	9.2 ^d
	HCFC-142b	18.0 ^a	15.2	18.5 ^d
Methyl bromide (CH ₃ Br)		0.8 ^a	0.019	0.7 ^d
Nitrous oxide (N ₂ O)		109 ^b	106	Not subject

References: ^aWMO (2018); ^bForster et al. (2021); ^cHayashi et al. (2006); ^dWMO (1999)

2.6 Update of DALYs for skin cancer and eye cataract

The years of life lost due to premature mortality (YLLs) and years of healthy life lost due to disability (YLDs) of malignant melanoma and non-melanoma skin cancers in 2010 and 2015 were obtained from the Global Burden of Disease Study 2019 (IHME 2020). For each cancer type, the summation of YLL and YLD as the world total loss in the year was divided by the number of incidences in the same year to estimate the DALY per incidence.

Eye cataract is treated as a non-fatal disease in IHME (2019), which provides only the total YLDs in a target year and does not specify the number of incidences in the year (IHME 2020). Therefore, the YLDs per incidence of eye cataracts for eight world regions (i.e., established market economies, formerly socialist economies of Europe, India, China, other Asia and islands, Sub-Saharan Africa, Latin America and the Caribbean, and Middle Eastern Crescent including North Africa) estimated by Struijs et al. (2010) were used. The population of each of the eight regions in 2010 and 2015 was obtained using the World Population Prospects (UN 2019), and the global mean (weighted-mean) YLD per incidence of eye cataracts was calculated using the population in each region as the weight.

Table 2 summarizes the estimated DALYs per incidence, including those in a previous study (Hayashi et al. 2006). We suggest that each user decides the monetary cost per DALY according to one's purpose of use. As a reference, the monetary cost of 23,000 USD per DALY was provided in this study as the weighted-mean of G20 countries using population as the weight (Murakami et al. 2022). A European study provided a value of 40,000 euro per DALY (Brink et al. 2011).

3 Results and discussion

3.1 Estimated damage for major ODSs

The increases in the total incidence per unit emission of each of the 13 ODSs and N₂O are shown in Table 3. The estimated values denoted that 1-Gg emission of halons and CFCs causes approximately one dozen to several hundred cases of melanoma, one to twelve thousand cases of non-melanoma skin cancers and eye cataracts, respectively. CCl₄ has similar effects to CFCs. The impact of unit emission of N₂O was less than 3% of CFC-11; however, it was less than 2% when using the same denominator, i.e., Gg of the compound instead of Gg N.

The pattern of latitudinal impacts due to a unit emission of an ODS is similar regardless of the ODS species, because the regression equation expressing the variation in total O₃ in each latitudinal belt to a marginal increase in EESC is common regardless of the ODS species. Here, the latitudinal pattern is shown using the impact of 1-Gg N emission of N₂O as an example (Fig. 2). The global population is

Table 2 Estimated disability-adjusted life years (DALYs) per incidence of skin cancer and eye cataract

Disease	DALY per incidence (DALY case ⁻¹)		
	2010	2015	Ca. 2000 ^a
Malignant melanoma	6.31	6.02	5.9
Non-melanoma skin cancer	0.196	0.193	0.34
Eye cataract	1.05	1.07	1.2

Reference: ^aHayashi et al. (2006)

Table 3 Increase in total cases per unit emission of 13 ozone depleting substances (ODSs) and N₂O

ODS species	Increase in total cases per unit emission (case Gg ⁻¹ for 13 ODSs, case Gg ⁻¹ N for N ₂ O)						
	2010			2015			
	Melanoma	Non-melanoma	Eye cataract	Melanoma	Non-melanoma	Eye cataract	
CFSs	CFC-11	15.0	876	577	15.5	897	612
	CFC-12	13.8	803	529	14.2	823	561
	CFC-113	15.2	883	582	15.6	905	617
Halons	Halon-1211	51.0	2972	1950	52.4	3040	2070
	Halon-1301	209	12200	8010	215	12500	8500
Carbon tetrachloride (CCl ₄)		11.3	656	432	11.6	672	459
Methyl chloroform (CH ₃ CCl ₃)		0.94	54.5	35.9	0.96	55.8	38.1
HCFCs	HCFC-22	0.53	30.6	20.1	0.54	31.3	21.4
	HCFC-123	0.03	1.53	1.01	0.03	1.57	1.07
	HCFC-124	0.19	11.0	7.27	0.19	11.3	7.72
	HCFC-141b	1.18	68.7	45.3	1.21	70.4	48.0
	HCFC-142b	0.77	44.6	29.4	0.79	45.7	31.2
Methyl bromide (CH ₃ Br)		0.12	7.06	4.64	0.12	7.23	4.92
Nitrous oxide (N ₂ O) (ODP: 0.015)		0.36	20.7	13.7	0.37	21.2	14.5

concentrated in the mid-latitudes of the Northern Hemisphere, where populations with fair skin covers are concentrated at higher latitudes. The health impact consists mostly of skin cancer for fair skin populations and eye cataracts regardless of skin color, which has the highest peak in the mid-latitude of the Northern Hemisphere, similar to the population distribution. However, the health impact tends to increase at high latitudes in both hemispheres because stratospheric O₃ depletion is more likely to occur at high latitudes, as is typical of the O₃ hole.

Damage factors, i.e., the loss of DALY per unit emission (kg N for N₂O and kg for other ODSs), are summarized in Table 4 for the 13 ODSs and N₂O. The full list, including other ODSs regulated by the Montreal Protocol, is compiled in Table S1 (Supplementary file1). For example, multiplying by 23,000 USD per DALY, the damage factor of N₂O

emissions was estimated to be approximately 0.5 USD kg⁻¹ N. The damage factors of N₂O correspond to the RCP2.6 scenario (ODP = 0.015). The user should multiply the following ODP ratios according to the RCP scenario for one’s purpose; 1.13, 1.16, and 2.0 for the RCP4.5, RCP6.0, and RCP8.5 scenarios, respectively.

3.2 Sources of uncertainty

Many processes are involved in the impact of stratospheric O₃ depletion from ODS emissions on human health. Struijs et al. (2010) discussed the uncertainty in LCIA of stratospheric O₃ depletion. We aimed to add information of the possible uncertainties to determine the damage factors for stratospheric O₃ depletion.

Fig. 2 **a** Latitudinal population in 2010 estimated using UN (2019) and CIA (2021). **b** Estimated latitudinal damage factors on human health for stratospheric ozone depletion per unit emission of N₂O (disability-adjusted life year [DALY] Gg⁻¹ N)

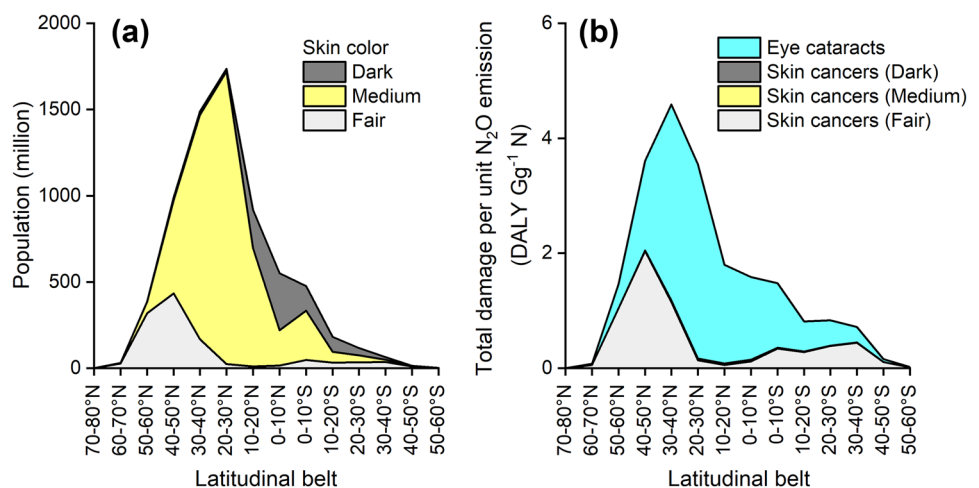


Table 4 Damage factors of stratospheric ozone depletion per unit emission of 13 ozone depleting substances (ODSs) and N₂O

ODS species		Damage function (DALYs) per unit emission (DALY kg ⁻¹ for 13 ODSs, DALY kg ⁻¹ N for N ₂ O)							
		2010				2015			
		Melanoma	Non-melanoma	Eye cataract	Total	Melanoma	Non-melanoma	Eye cataract	Total
CFSs	CFC-11	9.49E-5	1.72E-4	6.07E-4	8.74E-4	9.31E-5	1.73E-4	6.56E-4	9.22E-4
	CFC-12	8.70E-5	1.58E-4	5.56E-4	8.01E-4	8.53E-5	1.58E-4	6.02E-4	8.46E-4
	CFC-113	9.57E-5	1.74E-4	6.12E-4	8.81E-4	9.38E-5	1.74E-4	6.62E-4	9.30E-4
Halons	Halon-1211	3.22E-4	5.84E-4	2.06E-3	2.96E-3	3.16E-4	5.86E-4	2.22E-3	3.13E-3
	Halon-1301	1.32E-3	2.39E-3	8.43E-3	1.21E-2	1.29E-3	2.40E-3	9.12E-3	1.28E-2
Carbon tetrachloride (CCl ₄)		7.11E-5	1.29E-4	4.55E-4	6.55E-4	6.97E-5	1.29E-4	4.92E-4	6.91E-4
Methyl chloroform (CH ₃ CCl ₃)		5.90E-6	1.07E-5	3.77E-5	5.43E-5	5.79E-6	1.07E-5	4.08E-5	5.73E-5
HCFCs	HCFC-22	3.31E-6	6.01E-6	2.12E-5	3.05E-5	3.25E-6	6.03E-6	2.29E-5	3.22E-5
	HCFC-123	1.66E-7	3.01E-7	1.06E-6	1.53E-6	1.63E-7	3.03E-7	1.15E-6	1.62E-6
	HCFC-124	1.20E-6	2.17E-6	7.65E-6	1.10E-5	1.17E-6	2.18E-6	8.28E-6	1.16E-5
	HCFC-141b	7.44E-6	1.35E-5	4.76E-5	6.86E-5	7.30E-6	1.36E-5	5.15E-5	7.24E-5
	HCFC-142b	4.83E-6	8.76E-6	3.09E-5	4.45E-5	4.74E-6	8.79E-6	3.34E-5	4.69E-5
Methyl bromide (CH ₃ Br)		7.28E-7	1.39E-6	4.88E-6	7.00E-6	7.12E-7	1.39E-6	5.28E-6	7.38E-6
Nitrous oxide (N ₂ O) (ODP: 0.015)		2.25E-6	4.07E-6	1.44E-5	2.07E-5	2.20E-6	4.09E-6	1.55E-5	2.18E-5

“E-X” denotes “ $\times 10^{-X}$.” The damage factors of N₂O correspond to the RCP2.6 scenario. For the scenarios of RCP4.5, RCP6.0, and RCP8.5, multiply the factors of 1.13, 1.16, and 2.0, respectively

On ODS emissions, the total ODP-weighted emissions for all CFCs in 2016 was estimated to be 110 Gg year⁻¹ CFC-11-equivalent, with a possible uncertainty of ± 30 Gg year⁻¹ CFC-11-equivalent (WMO 2018). The global N₂O budgets based on a wide variety of top-down and bottom-up methods have various sources of uncertainty such as the inversion of atmospheric N₂O measurements into its emissions in top-down approaches and the differences in model configuration and parameterization of each N₂O emission process in bottom-up approaches (Tian et al. 2020). Transportation of atmospheric constituents from the troposphere to the stratosphere and O₃ destruction in the stratosphere fluctuate spatially and seasonally (WMO 2018). The pace of O₃ destruction in the stratosphere is affected by the greenhouse gas levels and climate change as explained in the Introduction (Stolarski et al. 2015; Revell et al. 2015; 2017; WMO 2018). The atmospheric lifetime of ODSs is subject to changes in atmospheric chemistry and therefore has a certain degree of uncertainty (WMO 2018; IPCC 2021). EESC also changes greatly depending on the setting of the attenuation curve (Newman et al. 2007). Only the optical depth of total O₃ was considered in this study to calculate the UV-B intensity at the ground surface. Nonetheless, clouds also attenuate UV-B (Estupiñán et al. 1996), whereas snow and ice cover increase UV-B exposure via their surface reflection (Moehrlé 2008).

UV-B intensity at the ground surface does not always equal the UV-B exposure of individuals. For example, there are lifestyles that reduce UV-B exposure, such as not going out during the mid-day, and those that increase UV-B

exposure, such as utilizing tanning salons (Lucas et al. 2015). Estimating the proportion of skin color in the population was difficult because changes in skin color are continuous, not discrete, and pigmentation of skin, i.e., change in color, can happen as a result of stresses such as UV-B exposure (Costin and Hearing 2007). There are also individual differences in damage caused by UV-B exposure (Heenen et al. 2001). Although the DALYs of skin cancer and eye cataracts in this study were calculated as the world mean values, and the suggested monetary value of DALY corresponded to the G20-weighted mean value, DALYs and their monetary values are subject to medical and economic conditions as well. Additionally, human health impacts of UV-B exposure are not limited to skin cancer and eye cataracts, but also involve solar keratoses, sunburn, photoaging, and photoimmunosuppression (Struijs et al. 2010; Lucas et al. 2015).

3.3 Sensitivity analysis

To identify the contribution of each parameter to the damage factor of stratospheric O₃ depletion, the damage factor response to a 10%-increase in each parameter was investigated. This sensitivity analysis was performed for the damage factor of N₂O for skin cancer in 2010. As explained in Sect. 2.2, the marginal EESC increase in CFC-11 per unit emission was converted to that of N₂O using the ODPs and lifetimes of CFC-11 and N₂O to calculate the damage factor of N₂O. Certain parameters related to CFC-11 were also used for this sensitivity analysis.

Table 5 Sensitivity analysis of the parameters to calculate the damage factor of stratospheric ozone depletion for N₂O (skin cancer, the base year of 2010). Response of the damage factor to a 10% increase in each parameter

Parameter	Response of damage factor to a 10% increase in parameter
Slope of EESC–total O ₃ (latitudinal belt, season)	11.4%
Atmospheric lifetime (CFC-11)	10.6%
ODP (N ₂ O)	10.0%
UV-B irradiance (top of the atmosphere)	10.0%
Total population	10.0%
Population ratio (latitudinal belt, fair skin)	9.7%
$dEESC(CFC-11)$	9.5%
Erythema correction factor (300–310 nm)	6.9%
DALY (non-melanoma)	6.4%
Incidence rate factor (non-melanoma, fair skin)	6.4%
DALY (melanoma)	3.6%
Incidence rate factor (melanoma, fair skin)	3.4%
Erythema correction factor (310–320 nm)	1.7%
Total EESC in base year	1.3%
Incidence rate factor (melanoma, medium skin)	0.1%
Incidence rate factor (melanoma, dark skin)	0.1%
Incidence rate factor (non-melanoma, medium skin)	0.1%
Incidence rate factor (non-melanoma, dark skin)	0.0%
Atmospheric lifetime (N ₂ O)	0.0%

Some parameters related to CFC-11 were also subject to this sensitivity analysis since they were used to calculate the damage factor of N₂O (see the main text for details)

As shown in Table 5, the most effective parameter was the slope (regression coefficient) of total O₃ to EESC that showed an effect of more than 10% to its increase in 10%. The second was the lifetime of CFC-11. The lifetime of N₂O showed no effect because an increase in N₂O lifetime reduced the parameter of $dEESC(N_2O)$ (Eq. 1), but this effect was canceled by multiplying the $F_{LT}(N_2O)$ by the initial impact to estimate the total damage. The ODP, UV-B irradiance at the top of the atmosphere, and total population showed a 1:1 effect on the damage factor. The relatively high effect of the ratio of fair-skinned populations is ascribed to their high risks of skin cancer. Notably, an increase in fair-skinned populations by the 10%-increase in its ratio in a latitudinal belt was compensated for by reducing the medium and dark-skinned populations using their population ratios as the weight not to change the total population. $dEESC(CFC-11)$ showed a near 1:1 effect on the damage factor. In addition, $dEESC(N_2O)$ is the objective variable being estimated using $dEESC(CFC-11)$ and ODPs and lifetimes of CFC-11 and N₂O (Eq. 1), and therefore, it was excluded from the sensitivity analysis. The correction factor of erythema UV-B (300–310 nm) was effective; however, that of the shortest wavelength of UV-B (290–300 nm) was fixed at 1.0 in definition (CIE 1987), and therefore was left unchanged in this analysis. The effectiveness of DALY and incidence rate factor (fair-skinned populations) for non-melanoma skin cancer is attributable to the increase in non-melanoma skin cancer per unit emission, approximately 60 times larger than that of melanoma (Table 3). The parameters described here will be the subject of future improvement.

3.4 Global impacts

The main purpose of using damage factors in LCIA is to assess the impacts of additional emissions of ODSs due to an industrial process; however, it is also interesting to investigate the degree of the total impact of global emissions. Global emissions of major ODSs and N₂O in 2010 were obtained from WMO (2018) and Tian et al. (2020), respectively, as the average of the top-down and bottom-up estimations of global emissions. Given the global phase-out of the production of CFCs and halons for dispersive uses under the Montreal Protocol, their emissions to the atmosphere are expected to be due only to leakage from banks (WMO 2018). Thus, even phased-out ODSs continue to threaten stratospheric O₃. Global emissions were obtained for 11 ODS, i.e., all in Table 1 except HCFC-123 and HCFC-124. Figure 3 shows that the global emissions of CFCs and halons ranged from several Gg year⁻¹ to several dozen Gg year⁻¹, that of HCFC-22 was approximately 360 Gg year⁻¹, and that of N₂O was orders of magnitude higher than other ODSs, i.e., approximately 13 Tg year⁻¹ as N₂O (i.e., 8 Tg N year⁻¹), owing to large emissions from agriculture, fossil fuel consumption, and industry (Tian et al. 2020; Canadell et al. 2021).

The global impacts of these emissions were calculated by multiplying global emissions by the total damage factor for each substance. Although the difference in global impacts between N₂O and other ODSs narrowed in comparison with that of global emissions (because of the smaller damage factor of N₂O per unit emission; Table 4), the impact of N₂O emissions accounted for 48% of the total impact (Fig. 3).

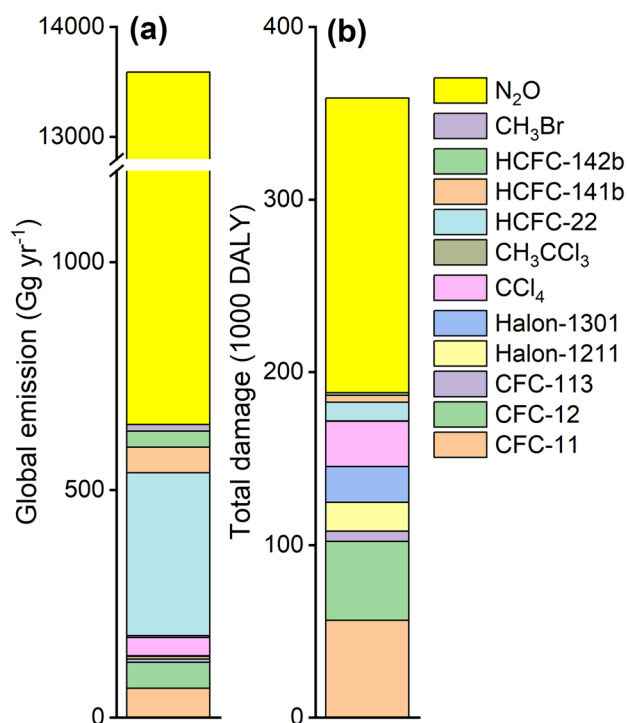


Fig. 3 **a** Global emissions of major ozone depleting substances and N_2O in 2010 estimated using WMO (2018) and Tian et al. (2020). **b** Estimated global damage on human health by stratospheric ozone depletion, shown as the total impact induced by emissions in 2010. DALY, disability-adjusted life year

However, this estimation does not cover all ODSs regulated by the Montreal Protocol. The impact of N_2O emissions in 2010 was estimated to be approximately 170,000 DALYs, corresponding to approximately 3.9 billion USD, using a value of 23,000 USD DALY⁻¹ (Murakami et al. 2022).

3.5 Comparison with previous studies

The damage factors of stratospheric O_3 depletion estimated by Hayashi et al. (2006) around the year 2000 were compared with those estimated in this study for the years 2010 and 2015. The difference between the two studies mainly originated from the revision of regression coefficients between EESC and total O_3 , ODS lifetimes, DALYs, and population. The 13 ODSs shown in Table 1, except N_2O , were the targets of this comparison because N_2O was not treated in the previous study. Figure 4 compares the damage factors (DALY per kg emission) in approximately the year 2000 to those in 2010 and 2015 for melanoma, non-melanoma skin cancers, eye cataracts, and the total. As a general trend, the damage factors obtained in this study decreased compared to those in the previous study. The damage factors of melanoma were 68% on average compared to the previous study (range: 47–115%). The damage factors of non-melanoma skin cancer and eye

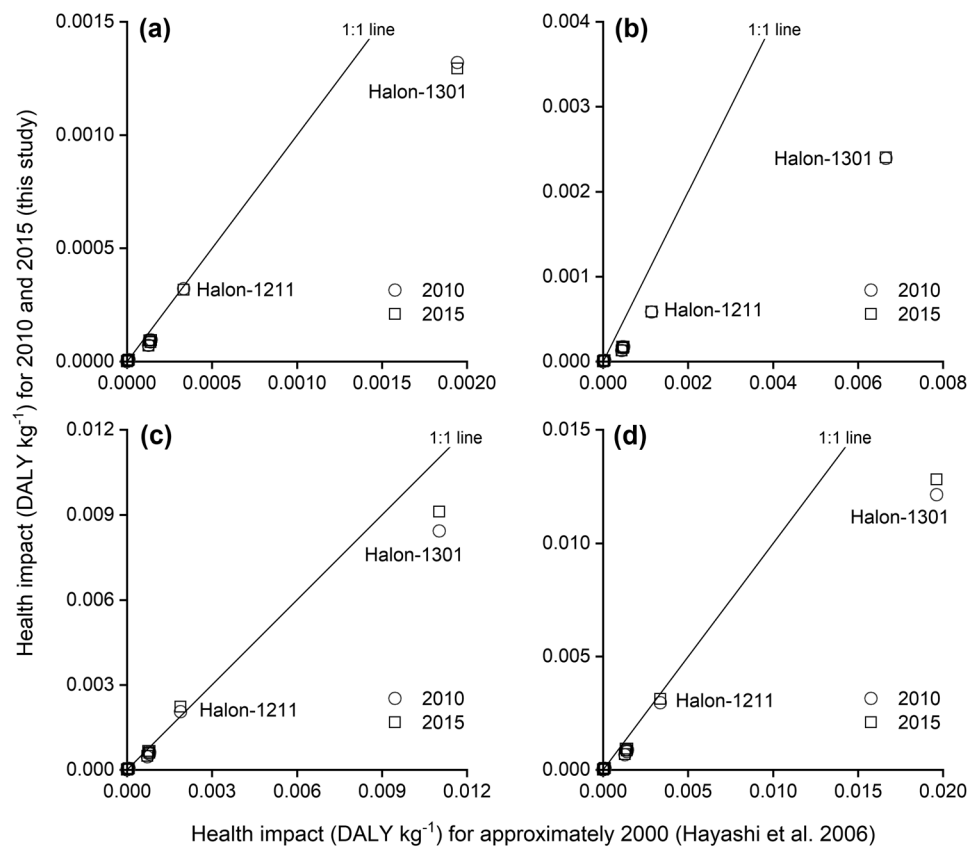
cataracts, and the total damage were 37% (26–63%) and 81% (54–144%), and 65% (44–113%), respectively. The general decrease of the damage factors is ascribed to the revision of the regression coefficients between EESC and total O_3 , i.e., the strongest parameter on the damage factor (Table 5), where their absolute values decreased compared to the previous study. Atmospheric lifetime is also an effective parameter to the damage factor (Table 5). The reason for the difference in decreasing trends among the ODSs is ascribed to the difference in the revision of ODS lifetimes (Table 1). For example, F_{LT} (Eq. 2) of HCFC-123 decreased to 79% but that of CH_3Br increased to 195% between the two studies. The DALY of melanoma increased to 104% on average between the two studies, whereas that of non-melanoma skin cancer and eye cataracts reduced to 57% and 88%, respectively. This is why the decrease in damage factors was particularly remarkable in non-melanoma skin cancer. The world population, which had the effect of increasing the overall damage factors by 1:1, increased from 6.14 billion in 2000 to 6.96 billion (113%) in 2010 and 7.38 billion (120%) in 2015; however, the decreasing effect of the regression coefficients between EESC and total O_3 seems to cancel the increasing effect of population.

As mentioned previously, Brink et al. (2011) estimated the damage factor of N_2O emissions on health impacts (skin cancer and eye cataracts) through stratospheric O_3 depletion in approximately 2010, utilizing the results of Struijs et al. (2010). Their value of 24.2 DALY per Gg of N_2O corresponds to 38.0 DALY per Gg $N = 3.8 \times 10^{-5}$ DALY kg⁻¹ N. Our results, i.e., 2.1×10^{-5} and 2.2×10^{-5} DALY kg⁻¹ N in 2010 and 2015, respectively (Table 4), corresponded to 55%–58% of their estimation.

3.6 Comparison of N_2O impacts on climate change and stratospheric O_3 depletion

Anthropogenic N_2O emissions cause both climate change and stratospheric O_3 depletion. In this study, the impacts of N_2O emissions on human health through climate change and stratospheric O_3 depletion were compared. Tang et al. (2018) estimated the effects of carbon dioxide (CO_2) emissions on human health based on the Special Report on Emission Scenarios (SRESs) of the IPCC (Nakicenovic and Swart 2000): 6.2×10^{-7} (A2 scenario), 4.2×10^{-7} (B2 scenario), 2.1×10^{-7} (B1 scenario), and 2.0×10^{-7} (A1B scenario) DALY kg⁻¹ CO_2 . These scenarios, A1, A2, B1, B2, are called story lines, i.e., narrative scenarios, on the development of future human society. These values were converted to those of N_2O using the global warming potential of N_2O for 100 years of 273 (Forster et al. 2021), and a conversion factor from kg N_2O to kg N (i.e., 44/28): 2.7×10^{-4} , 1.8×10^{-4} , 9.0×10^{-5} , and 8.6×10^{-5} DALY kg⁻¹ N for the respective scenarios. Tang et al. (2019)

Fig. 4 Comparison of damage factors between a previous study (Hayashi et al. 2006) and the present study of the following: **a** melanoma, **b** non-melanoma skin cancers, **c** eye cataracts, and **d** the total (i.e., the sum of impacts on melanoma, non-melanoma skin cancers, and eye cataracts). DALY, disability-adjusted life year



updated this estimation for the Shared Socioeconomic Pathways (SSPs) for the scenarios SSP1, SSP2, and SSP3 (e.g., Hasegawa et al. 2015): 1.3×10^{-6} (SSP1), 1.5×10^{-6} (SSP2), and 2.0×10^{-6} (SSP3) DALY kg⁻¹ CO₂, respectively. SSPs are also narrative scenarios but consider the socioeconomic challenges for adaptation and mitigation against climate change, where SSP1, SSP2, and SSP3 correspond to “Sustainability – Taking the Green Road,” “Middle of the Road,” and “Regional Rivalry – A Rocky Road” scenarios, respectively (O’Neill et al. 2017). These values, converted to those of N₂O in the same manner, were 5.6×10^{-4} (SSP1), 6.4×10^{-4} (SSP2), and 8.6×10^{-4} (SSP3) DALY kg⁻¹ N. The damage factors obtained for the SSPs were 3–5 times higher than those obtained for the SRESs. Tang et al. (2019) interpreted that this was mainly because the relative risk per temperature increase used in a later study (WHO 2014) was higher than that used in a previous study (McMichael et al. 2004). SSP1 is the scenario with the most successful mitigation and adaptation against climate change. In addition, it is the scenario closest to achieving RCP2.6, which is the lowest radiative forcing among the RCPs. Therefore, to examine the effects of N₂O emissions, the impact of climate change in SSP1 calculated using the results of Tang et al. (2019) and that of stratospheric O₃ depletion in RCP estimated in this study were compared. The former, 5.6×10^{-4} DALY kg⁻¹ N, was 27 times higher than the latter, $2.1\text{--}2.2 \times 10^{-5}$ DALY kg⁻¹ N (Table 4).

3.7 Further development needed

Stratospheric O₃ depletion may be a solved problem owing to the phase-out of major ODSs; however, the contribution of N₂O to stratospheric O₃ depletion has increased since the 1990s, with N₂O becoming the largest contributor in the mid-2000s (Ravishankara et al. 2009; WMO 2018) and anthropogenic N₂O emissions continuing to increase (Tian et al. 2020; Canadell et al. 2021). WMO (2018) also pointed out that strengthening the greenhouse effect enhances stratospheric O₃ depletion as shown in the increasing ODPs of N₂O according to the RCP scenarios from RCP2.6 to RCP8.5. Accordingly, stratospheric O₃ depletion is not a solved problem.

The health impacts of N₂O emissions were evaluated to be 27 times greater due to climate change compared to stratospheric O₃ depletion (Sect. 3.6). Even though the total damage (i.e., the total amount of impact after emissions) due to stratospheric O₃ depletion caused by N₂O emissions in 2010 amounted to 170,000 DALY, the equivalent to 3.9 billion USD (Sect. 3.4), stratospheric O₃ depletion remains an unsolved issue. In particular, refinement of the calculation scheme for N₂O from its emission to impact is required. The method used to obtain the damage factors in this study aimed to estimate the slight increases in impacts due to the additional emissions of various ODSs as simply and

quantitatively as possible. According to the sensitivity analysis (Sect. 3.3), the following parameters were particularly effective on the damage factors: the relationship between EESC and total O₃, i.e., actual state of O₃ destruction in the stratosphere, atmospheric lifetimes of ODSs, ODPs, UV-B irradiance perturbed with solar activity, population distribution with the ratio of skin colors, and DALYs. As the impact of N₂O is currently larger than that of other ODSs, a methodological development is recommended to incorporate the following schemes on stratospheric O₃ depletion into the existing Earth system models to simulate the effects of N₂O behavior on climate change: changes in UV-B irradiance at the ground surface due to N₂O emissions; estimation of human UV exposure considering actual lifestyle; elaborating estimation of the global population; and elaborating dose–response relationships of major diseases due to UV exposure. It is expected that a common method will enable consistent evaluation of the impacts of both climate change and stratospheric O₃ depletion due to N₂O emissions based on common future scenarios such as SSPs.

This study focused on some of the various impacts induced by stratospheric O₃ depletion, i.e., skin cancers and eye cataracts. There are other possible impacts on human health, such as photoimmunosuppression; social assets, such as crop and timber production and material degradation; biodiversity loss in terrestrial and aquatic ecosystems; and net primary productivity of terrestrial and aquatic ecosystems (Hayashi et al. 2006). In a previous study (Hayashi et al. 2006), we attempted to estimate the damage factors of crop, timber, terrestrial, and aquatic production, in addition to those of skin cancers and eye cataracts. For re-evaluation, it is necessary to determine the precise dose–response relationships to UV-B exposure of major biological species as well as their production rates and biomass with information on spatial distribution.

4 Conclusions

CFCs and halons, which are artificial substances, once brought great benefits to industries and human life as useful materials; however, they have had the unexpected impact of depleting stratospheric O₃ and subsequently increasing UV-B exposure at the ground surface. These major ODSs have been gradually phased out, representing a success story in addressing global environmental issues. However, the effects of historically-created ODSs remain due to their leaking and/or their lingering in the atmosphere, and N₂O has emerged as the largest contributor to stratospheric O₃ depletion in addition to its effects on climate change. In this study, we evaluated the damage factors of N₂O and re-evaluated those of all ODSs regulated by the Montreal Protocol for 2010 and 2015

on human health impacts (skin cancers and eye cataracts). The damage factors of many ODSs did not change remarkably compared to a previous study, which targeted around the year 2000. The steady increase in the global population has increased the damage factor, most of which was counterbalanced by the downward trend of the DALY per incidence in non-melanoma skin cancers and eye cataracts. The damage factors of N₂O were estimated to be 2.1×10^{-5} and 2.2×10^{-5} DALY kg⁻¹ N in 2010 and 2015, respectively. They correspond to approximately 0.5 USD kg⁻¹ N using the coefficient of 23,000 USD DALY⁻¹. Although N₂O had much smaller damage factors than CFCs and halons, which were comparable to those of other ODSs, the health impact induced by N₂O emissions was the largest among all ODSs because it has the largest global emissions by several orders of magnitude. The total impact due to N₂O emissions in 2010 was estimated to be 170,000 DALY, or 3.9 billion USD. Another important impact of N₂O, i.e., climate change in the SSP1 scenario, demonstrated a damage factor 27 times larger than that of stratospheric O₃ depletion in the RCP2.6 scenario. However, N₂O emissions affect both stratospheric O₃ depletion and climate change. Thus, efforts to reduce N₂O emissions are efficient in simultaneously addressing both these issues.

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Data availability The authors declare that the datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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