Results from GRAPE model (phase 1,revised)

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The integrated assessment model GRAPE (Global Relationship to Protect the Environment) consists of five modules dealing with issues on energy, climate, land use, macroeconomics and environmental impacts. The results for the assessment of contributions to climate change (phase 1) are summarized as follows.

[1] Assessment framework and input data

Emissions or radiative forcing data, shown in the table below, are given to obtain global average surface atmospheric temperature change. IPCC WGI TAR A2 scenario data and own assumptions are used to supplement information specified by the project.

Table.1 Input Data

	Emissions		Concentration		Radiative Forcing
	Past	Future	Pre-ind.	Current	Future
CO2			(*2)	(*2)	Endogenous
Fossil Fuel	(*1)	(*1)			
LULUCF	(*1)	(*1)			
CH4	(*1)	(*1)	(*2)	(*2)	Endogenous
N2O	(*3)	(*1)	(*2)	(*2)	Endogenous
Other GHGs (#)					(*2)
Aerosol					(*2)
SOx（direct, indirect）					(*2)
others（BC,OC）					(*2)

(#) PFC,SF6,HFC,Montreal Gases(CFC,etc.) ,Ozone, etc.

(*1) Data specified by the project

(*2) IPCC WGI TAR

(*3) Own assumptions

[2] Reporting parameters

(1)Historical anthropogenic emissions

Historical emissions after industrial revolution period is important data to verify present GHGs concentration level and climate model benchmarks. The assumption of anthropogenic emissions of CO2, CH4 and N2O after 1760 is summarized in Table 2. CO2 and CH4 data are from CDIAC (ORNL). N2O emissions are obtained by own assumption climate model in the Appendix.

Table 2 Historical anthropogenic emissions

	1760	1770	1780	1790	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990
CO2 (GtonC)	0.22	0.24	0.26	0.29	0.31	0.32	0.33	0.35	0.37	0.40	0.45	0.51	0.65	0.85	1.02	1.38	1.27	1.36	1.51	1.88	3.12	4.84	5.99	7.10
CH4 (Mton-CH4)	25	30	35	40	45	50	55	60	65	70	79	85	92	103	114	130	137	149	162	178	221	276	319	310
N2O (Mton-N)	2.00	2.00	2.00	2.10	2.11	2.12	2.13	2.14	2.15	2.16	2.17	2.18	2.19	2.20	2.30	2.40	2.50	2.60	2.80	3.00	3.30	3.80	5.00	6.70

(2) Cumulative emissions after 1990

Cumulative Emissions after 1990 are shown in Table 3. Since IPCC SRES A2 is specified as future GHG emission data, marker results from ASF model are used. Assumed cumulative emission up to 2100 for CO2, CH4 and N2O are 276Gton-C, 8590Mton-CH4 and 161Mton-N, respectively.

Table 3 Cumulative emissions after 1990

Cumulative Emissions after 1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
CO2 (GtonC)	75	163	272	407	561	729	912	1112	1332	1579	1855
CH4 (Mton-CH4)	3163	6629	10602	15152	20288	25983	32243	39073	46479	54473	63064
N2O (Mton-N)	68	144	232	333	443	559	684	818	962	1114	1275

(3) Atmospheric GHG concentrations

The gas in the atmosphere is balanced with emissions (sum of anthropogenic and natural) and gas decay. Historical atmospheric concentration of CO2, CH4 and N2O are approximately consistent with IPCC WGI TAR. Atmospheric concentration of CO2, CH4 and N2O in 2100 are calculated 971(ppm), 3325(ppb) and 449(ppb), respectively.

Table 4 Atmospheric concentration

	1760	1770	1780	1790	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
CO2 (ppm)	282	282	282	283	283	284	284	285	285	286	286	287	288	290	292	295	298	300	303	306	313	324	339
CH4 (ppb)	707	718	732	746	760	774	788	803	817	832	850	869	888	912	942	983	1027	1072	1125	1190	1274	1403	1551
N2O (ppb)	271	273	274	275	276	278	279	280	281	281	282	283	284	284	285	286	287	288	290	291	293	296	300

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
CO2 (ppm)	352	367	419	461	511	565	622	681	744	812	887	971
CH4 (ppb)	1700	1760	1839	1962	2116	2283	2453	2623	2795	2969	3146	3325
N2O (ppb)	308	316	325	335	348	361	374	388	402	417	433	449

(4) Radiative forcing

Radiative forcing of CO2, CH4 and N2O is endogenously assessed by the atmospheric concentration above. On the other hand, radiative forcing by Kyoto Protocol gases such as PFCs, HFCs and SF6, Montreal Protocol gases, Ozone, sulfate and other aerosol are followed by IPCC WGI TAR A2 scenario. Radiative forcing relative to pre-industrial level is as follows.

Table 5 Radiative forcing relative to pre-industrial level

Radiative Forcing	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
(W/m2)	1.14	1.79	2.58	3.18	3.81	4.44	5.19	5.92	6.66	7.43	8.22

(5) Temperature rise (global mean surface air temperature)

Simple atmosphere-ocean model in the Appendix provides global mean atmospheric temperature in the Table 6. Temperature rise in 2100 relative to 1990 is approximately 3.4 deg C.

Table 6 Global mean surface air temperature rise relative to 1990

	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
deg C	0.16	0.30	0.55	0.84	1.15	1.48	1.84	2.22	2.61	3.01	3.43

[3] Works for Phase 2

We have noticed that the results above are relatively high in terms of CO2 concentration compared to the IPCC TAR WGI reference run by ISAM and BERN model. In phase 2, we are planning to estimate future CO2 concentration assessment using simple BERN model prepared by the project web site for the assessment of contributions to climate change, which will provide different concentration, radiative forcing and temperature level. Sea level rise by thermal expansion will be assessed also.

Appendix: Model Structure

Climate module structure of GRAPE depends on the previous modeling framework such as Mori [1], IPCC WGI TAR [3] and RITE/NEDO [3].

(1)Emission - concentration

Emission - concentration relationship of CO2, CH4 and N2O are summarized as follows.

a. CO2 [1]

Atmospheric concentration of CO2 is given by the sum of the ones from previous periods with different time constants and emissions remaining in the atmosphere.

$$C_{CO2,t} = \sum_{i=1}^{5} C\_TLAG_{i,t} \tag{1}$$

$$C\_TLAG_{i,t+1} = C\_TLAG_{i,t} \bullet e^{-BSHRi \bullet \Delta T} + \int_{0}^{\Delta T} ASHR_i \bullet E_{CO2} dt \tag{2}$$

where

$C_{co2,t}$	atmospheric CO2 at t(GtonC)、
$C\_TLAG_{i,t}$	atmospheric CO2 at t with ith time constant (GtonC)
$BSHR_i$	decay parameter
$ASHR_i$	distribution fraction of ith composition(---)
$E_{CO2,t}$	CO2 Emission at time t (GtonC)
ΔT	time step

Future CO2 concentration can be assumed by the initial concentration composition. Time step ΔT=10(years) in the simulation. Parameter ASHR and BSHR are from Enting et.al. [4]

	ASHR	BSHR(1/yr)	C_TLAG_{1990}
i=1	0.130164	0.0	642.9
i=2	0.333279	0.024127	11.245
i=3	0.260540	0.0116449	28.689
i=4	0.165742	0.0017107	34.3652
i=5	0.110275	0.00024156	36.8351

Historical CO2 concentration is estimated by BERN model parameter specified in the project web page. BSHR is the reciprocal number of time constant of ith fraction.

	ASHR	BSHR(1/yr)
i=1	0.152	0.0
i=2	0.253	0.0058480
i=3	0.279	0.0555556
i=4	0.316	0.3891051

Difference equation of (2) is given by the following.

$$C\_TLAG_{i,t} = C\_TLAG_{i,t-1} \bullet e^{-BSHRi} + ASHR_i \bullet \Delta T \bullet \frac{E_{CO2,t} + E_{CO2,t}}{2} \qquad (3)$$

The concentration is obtained by applying the conversion factor 0.471(ppm/GtonC) after each period atmospheric CO2 concentration from (3).

b. CH4 and N2O [2]

It is assumed that CH4 and N2O behaviors follow the one-box model in the equation (4).

$$\frac{dC_i}{dt} = \alpha_i E_i - \frac{C_i}{\tau_i} \qquad (4)$$

$$i = CH_4, N_2O$$

where C:concentration(ppb)、E:emission（Mton-CH4 or Mton-N）、

α:emission - concentration conversion factor,

τ:time constant of decay (years)

In the simulation, time constant of CH4 and N2O are from IPCC WGI TAR (e.g. τ_{CH4}=12.0(years), τ_{N2O}=114.0(years)). Difference equation from 1990 and 2000 data provides α for10-year time step. They are α_{CH4}=0.253(ppb/Mton-CH4), α_{N2O}=0.210(ppb/Mton-N2O).

Difference form of (4) is given by the following (index i is omitted).

$$\frac{C_{t+1} - C_t}{\Delta T} = \alpha \frac{E_{t+1} + E_t}{2} - \frac{1}{\tau} \frac{C_{t+1} + C_t}{2} \qquad (5)$$

(2)Concentration – radiative forcing [2]

Concentration – radiative forcing formula follows by the simplified expressions in IPCC WGI TAR.

$$\begin{aligned}
\Delta F_{\mathrm{CO2}} &= \beta_{CO2} \bullet \ln(C_{co2} / C_{CO2,0}) \\
\Delta F_{\mathrm{CH4}} &= \beta_{CH4} \bullet (\sqrt{C_{CH4}} - \sqrt{C_{CH4,0}}) - (f(C_{CH4}, C_{N2O,0}) - f(C_{CH4,0}, C_{N2O,0})) \quad (6) \\
\Delta F_{\mathrm{N2O}} &= \beta_{N2O} \bullet (\sqrt{C_{CH4}} - \sqrt{C_{CH4,0}}) - (f(C_{CH4}, C_{N2O,0}) - f(C_{CH4,0}, C_{N2O,0}))
\end{aligned}$$

where ΔF：radiative forcing increase relative to pre-industrial level（W/m2）、

β: conversion factor to the radiative forcing

$$f(X,Y) = 0.47 \ln\left[1 + 2.01 \times 10^{-5} (XY)^{0.75} + 5.31 \times 10^{-15} X (XY)^{1.52}\right]$$

0 is the subscript representing pre-industrial period.

Parameter β and concentrations in the pre-industrial level is as follows.

	β	C_o
CO2	5.35	278(ppm)
CH4	0.036	700(ppb)
N2O	0.12	270(ppb)

(3) Radiative forcing - temperature [1]

Temperature behavior is modeled by the energy exchange between ocean and atmosphere in the global scale. The formulas of temperature change are given by the following.

$$\frac{dT_E}{dt} = C_1\left(\Delta F - \lambda T_E - C_2\left(T_E - T_L\right)\right) \tag{7}$$

$$\frac{dT_L}{dt} = C_3\left(T_E - T_L\right) \tag{8}$$

where T_E :atmospheric temperature rise relative to the pre-industrial level(degC)
$T_{L:}$ lower ocean temperature rise relative to the pre-industrial level(degC)
λ: climate feedback factor
ΔF:increse of radiative forcing relative to the pre-industrial level（W/m2）
$C_{1:}$conversion factor
$C_{2:}$atmosphere-upper ocean heat transfer coefficient
$C_{3:}$lower ocean-upper ocean heat transfer coefficient

The parameters in the 10-year step simulation are λ=1.41,C_1=0.226, C_2=0.440 and C_3=0.02 respectively.

Reference

[1] S.Mori, “Effects of Carbon Emission Mitigation Options Under Carbon Concentration Stabilization Scenarios”, Environment and Economics Policy Studies, Vol.3, No.2, PP.125/142, 2000

[2] Climate Change 2001 The Scientific Basis, IPCC, 2001

[3] Report of New Earth Program, RITE/NEDO, NEDO-GET-9907, March 2000 (in Japanese)

[4] Enting, et.al., Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/ Atmosphere/ Land Analyses, CSIRO Division of Atmospheric Research Technical Paper no. 31, 1994