Supporting information for

Global-mean temperature change from shipping towards 2050: Improved representation of the indirect aerosol effect in simple climate models

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Section SI 1 Shipping emissions

Historical and present-day emissions

Emissions from shipping are taken from the Second IMO greenhouse gas study[1], where present-day (2007) and historical emissions back to 1850 are estimated. The estimated CO_2 emissions in 2007 from this study are 1050 Tg(CO_2) yr^{-1}. Present-day emissions of other greenhouse gases (GHGs) and pollutants have been estimated by applying fuel-based emission factors for each of the relevant compounds and a fuel consumption inventory. The emissions are subsequently calculated by multiplying the fuel consumption by the emission factors. Emissions of non-CO_2 species are extended back in time by scaling with the historical CO_2 time series.

Future scenarios

We use the recent emission scenarios from the Second IMO GHG study to estimate the future global mean temperature change due to emissions from total shipping. The methodology for generating emission data is described in detail in Buhaug et al.[1]. The scenarios are consistent with the IPCC SRES storylines and key driving variables affecting the shipping emissions are *shipping transport demand*, *transport efficiency* and *fuel use* (e.g. future fuel mix, availability and cost). Energy consumption and emissions of CO_2 are modeled based on key assumptions about growth in seaborne transport, transport efficiency, fleet composition and developments in marine fuels within each scenario. For non-CO_2 species, the emissions are assumed to develop according to the regulations of MARPOL Annex VI, which means SO_2, NO_x and particulate matter (PM) emissions will be reduced following regulations.

We also use shipping emissions from the Representative Concentration Pathways 4.5 and 8.5 (RCP 4.5 and RCP 8.5, respectively).[2-5] The RCP scenarios[6] give trajectories for emissions of GHGs and other climate forcers to reach target radiative forcing levels in 2100 and are available at www.iiasa.ac.at/web-apps/tnt/RcpDb. These new scenarios differ from the previous IPCC SRES scenarios on which the IMO scenarios are based. The corresponding historical emission inventory is described in Lamarque et al.[7] Future RCP CO_2 emissions from shipping are not given explicitly on the RCP website, but were provided by the RCP4.5 and 8.5 development teams. We did not obtain such estimates for the remaining two RCPs (RCP2.6 and RCP6.0) and these are thus not considered in our calculations. The models used for calculating RCP4.5 and RCP8.5 emissions are calibrated to energy data from the

International Energy Agency (IEA), which are then used to estimate CO_2 emissions. The IEA data significantly underestimate the shipping fuel use (Shilpa Rao (IIASA) and Steve Smith (PNNL), pers. Comm., 2011 and Smith et al.[8]), which leads to a discrepancy between the RCP year 2000 CO_2 emission estimate and the value given by Lamarque et al.[7], where fuel consumption and CO_2 are based on the IMO study.[1] In order to obtain a consistent CO_2 emission trajectory we scale emissions from 2000 to 2050 with the year 2000 estimate from Lamarque et al.[7] divided by that from the RCP scenarios for the same year.

Section SI 2 Model description

The simple climate model (SCM) used in our study calculates global mean concentrations from emissions of 24 species and the radiative forcing for 30 components based on detailed input. Historical CO_2 emissions from land-use change are from Houghton et al.[9], while global CO_2 emissions from fossil fuel burning, cement manufacture and gas flaring are from the Carbon Dioxide Information Analysis Center (CDIAC).[10] Global historical emissions of non-CO_2 species are from the EDGAR database,[11, 12] except for black and organic carbon emissions which are taken from Bond et al.[13] Future emissions are the International Panel on Climate Change (IPCC) SRES scenarios.[14] The model also uses the representative concentration pathways (RCPs), with corresponding historical emissions, available at www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about#intro. For more details see also supporting information of Skeie et al.[15]

The global mean temperature change is calculated by an energy-balance climate/up-welling diffusion ocean model developed by Schlesinger et al.[16] The SCM assumes additivity of all forcing mechanisms and the energy balance model uses total net radiative forcing as input. In the SCM the atmosphere is represented by a single layer separated into a Northern and Southern hemisphere, while the ocean under the surface layer is split into 40 vertical layers in addition to the north/south separation. The climate response is governed by the prescribed climate sensitivity, which encompasses the processes, including feedbacks, involved in the response of the climate system to a radiative forcing, and by parameters which control the uptake of heat by the oceans.[17] The input parameters are based on output from more detailed general circulation model (GCM) experiments. In this work we have used a climate sensitivity of 0.8 K $(Wm^{-2})^{-1}$.

The historical development in global concentration of CO_2 is calculated using a scheme based on Joos et al.[18] The CO_2 module uses an ocean mixed-layer pulse response function that characterizes the surface to deep ocean mixing in combination with a separate equation describing the air-sea exchange.[19] It also includes changes in CO_2 uptake by terrestrial vegetation due to CO_2 fertilization. A feedback between atmospheric CO_2 levels and CO_2 uptake via changes in oceanic pH is included, while the feedback via ocean temperatures is not. For the other gases, standard values for lifetime/adjustment time are used. Indirect effects of CH_4 on tropospheric O_3 and stratospheric H_2O as well as effects on its own adjustment time are taken into account. Radiative forcings for the well-mixed gases are parameterized using updated concentration-forcing relations from IPCC Fourth Assessment Report,[20] while for short-lived components we use radiative forcing results based on detailed global 3D chemistry transport models (CTMs) and forcing calculations (see below).

To calculate the climate impact of shipping, we use the common method of removing all emissions from this sector and then calculating the difference between this perturbed case and the reference simulation with all anthropogenic emissions.[21-24] The difference in the climate response is then a measure of the impact. For long-lived greenhouse gases (CO_2, CH_4, N_2O) we subtract the emission trajectories for shipping. For short-lived components we subtract pre-calculated radiative forcing (RF) over time. Shipping emissions have a spatial distribution that differs from that of the total global anthropogenic emissions. This distribution must be accounted for when atmospheric burden and RF of short-lived components from the transport sectors are calculated. To establish the global mean RF evolution in time, *RF(t)*, for short-lived components from shipping, reference radiative forcings ($RF_{ref,2000}$) and emissions ($EM_{ref,2000}$) for the year 2000 from Fuglestvedt et al., Balkanski et al. and Myhre et al.[22, 25, 26] are used. These studies use global 3D CTMs and detailed radiative transfer models to calculate the RF. The reference RF and emissions are scaled with emission trajectories (*EM(t)*) for the shipping sector:

$$RF(t) = \frac{RF_{ref,2000}}{EM_{ref,2000}} \cdot EM(t) \qquad \text{(SI1)}$$

For SO_4 direct and indirect forcing we scale with the SO_2 emission trajectories and for black carbon (BC) and organic carbon (OC) we scale with BC and OC emissions, respectively. For

the short-term ozone forcing due to NO_x, CO and VOC changes, we scale with NO_x emissions.

NO_x emissions reduce the lifetime of CH_4 (and thus the concentration), which gives a negative RF.[27-29] Since the $RF_{ref,2000}$ for the CH_4 lifetime effect from more detailed studies is due to all NO_x emissions up to 2000, the RF development can not be calculated by using Eq. SI1. Instead Eq. SI2, which takes into account the effect of NO_x on CH_4 over time, is used:

$$RF(t) = \sum_{t'=0}^{t'=t} \frac{NOx(t')}{NOx_{ref,2000}} \cdot RF_{ref,2000} \cdot (-\exp(-1/\tau)) \cdot \exp(-(t-t')/\tau) \quad \text{(SI2)}$$

where τ is the methane adjustment time (12 years), $NOx_{ref,2000}$ is the reference NO_x emission in 2000 and $RF_{ref,2000}$ is the RF-CH_4 at steady state corresponding to $NOx_{ref,2000}$. The term $RF_{ref,2000} \cdot (1-\exp(-1/\tau))$ gives the RF after one year and the term $\exp(-(t-t')/\tau)$ accounts for the decaying effect over time. By summing up these contributions we capture the effect of historical and future emissions of NOx on CH_4. This implicitly assumes that CO and VOC changes are parallel to NOx.

The O_3 perturbation consists of two components. In addition to the short-term forcing mentioned above, there is also a longer-term perturbation, called primary mode O_3 forcing (O_3PM), which results from changes in CH_4 due to NO_x emissions.[27, 29] The development for RF-O_3PM is calculated in a similar way as for the CH_4 effect and the $RF_{ref,2000}$ is calculated as in Berntsen et al.[27]. The changes in CH_4 lifetime are from Myhre et al.[26] For the sensitivity of O_3 to changes in methane we use results from Ehhalt et al.[30]

Although we for simplicity scale only with NOx emissions when calculating RF(t) from changes in O_3 and CH_4, the underlying RF_{ref} calculated using more complex models also accounts for effects of CO and VOC. Figure SI1 shows a schematic illustration of the general model setup and framework, including the structure of the SCM and input of emissions and results from more complex studies.

Section SI 3 Improved parameterization of indirect aerosol effect

Figure SI2 shows the indirect aerosol effect (IAE) versus SO_2 emissions from simulations with the ECHAM/MESSy Atmospheric Chemistry model (EMAC) including the aerosol

module MADE.[31, 32] The results are divided into groups by the emission inventory used in the global aerosol-climate model simulations (AMVER, ICOADS and PAXIAN[33]). Also shown is the logarithmic (AMVER and ICOADS) and linear (PAXIAN) fit to the data. We use the corresponding functions to parameterize the IAE in the SCM:

AMVER: $$RF(t) = -0.181 * ln\,EM(t) - 0.1056 \quad \text{(SI3)}$$

ICOADS: $$RF(t) = -0.217 * ln\,EM(t) - 0.048 \quad \text{(SI4)}$$

PAXIAN: $$RF(t) = -0.0174 * ln\,EM(t) - 0.0897 \quad \text{(SI5)}$$

The functions replace the original linear parameterization originally used and provide an estimate for the uncertainty related to the geographical distribution of emissions. Due to the relatively few values in each group we also perform regression to look at the statistical significance of the relationship. We do this also for the fits to all ECAM-MADE results described in the manuscript. Results show statistical significance at the 0.05 level in all cases.

Section SI 4 Treatment of uncertainty

Uncertainty estimates for the global mean surface temperature change due to shipping are established using the same method as in Skeie et al.[15] where modeling uncertainty in RF for all components and uncertainty in climate sensitivity are combined using a Monte-Carlo approach.

A detailed description and values for the uncertainties in atmospheric modeling (atmospheric dispersal, removal and RF) can be found in Skeie et al.[15] In this study we use updated estimates of modeling uncertainties for aerosols, ozone and methane,[25, 26] which are mostly somewhat smaller than those used in Skeie et al.[15] The uncertainty range for the total ship-induced RF is obtained by using a Monte Carlo approach where the RF of each species is treated as a random variable following a probability density function (PDF) defined by the modeling uncertainty and mean value. In dealing with the modeling uncertainty for the indirect effect of SO_4, a log-normal distribution based on multi-model results from Forster et al.[20] is applied. We assume this same probability density function for calculations with both the original parameterization of IAE and with the new functions. The PDF for the total RF is obtained by summing the individual RF components. In the case of climate sensitivity we use the uncertainty in the transient climate response (TCR – defined as the globally averaged

surface air temperature change at the time of CO_2 doubling in the 1% yr^{-1} transient CO_2 increase experiment[34]). IPCC[34] gives a 90% confidence interval ranging from 1 to 3°C, with a best estimate of 2°C, for the TCR based on climate modelling. We use this confidence interval to calculate the standard deviation for the climate sensitivity, which is then 30% of the best estimate of the TCR, and combine the uncertainty with the uncertainty in RF.

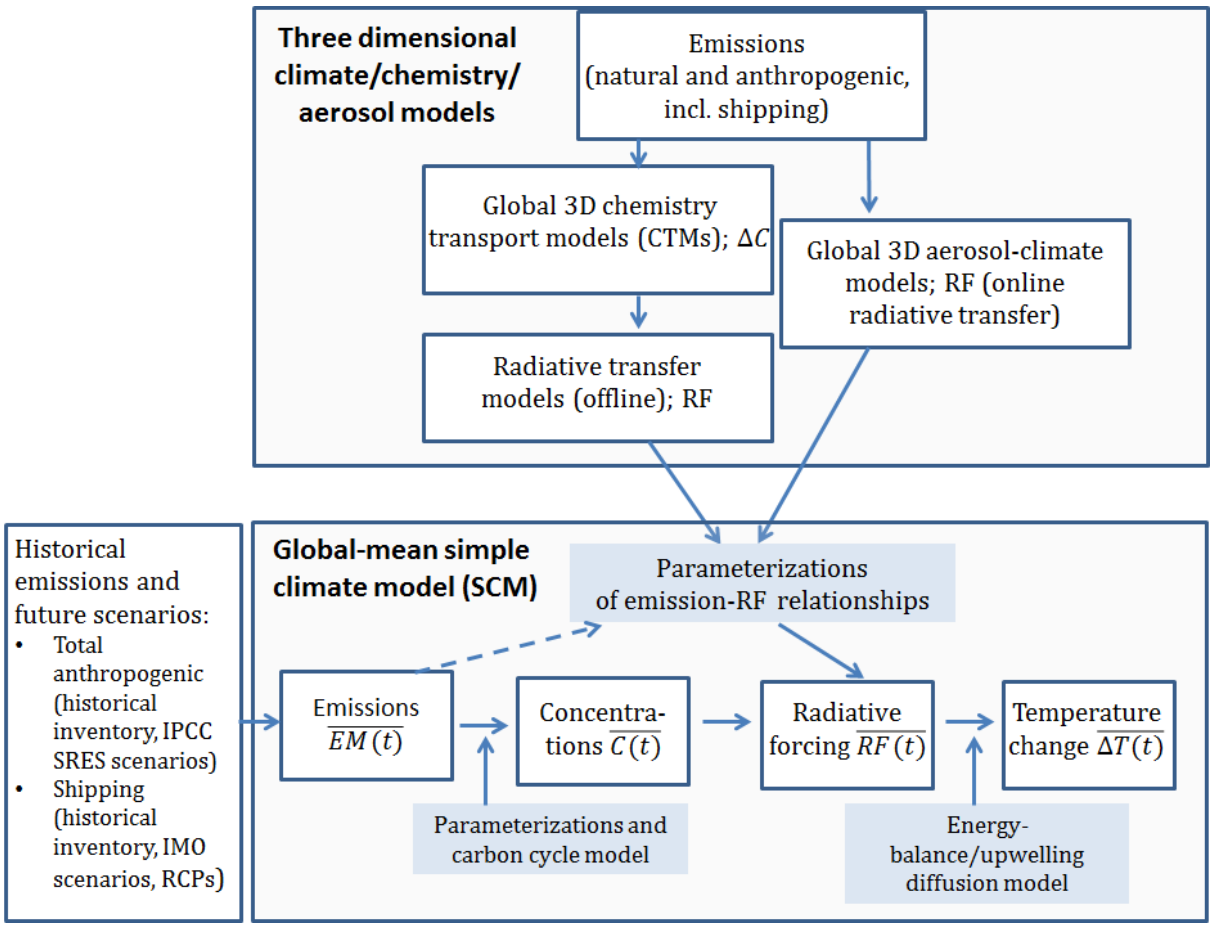

Figure SI1: General model framework and structure. Overbar indicates global-mean values, t gives temporal development and ΔC denotes changes in atmospheric concentrations. In our study the global 3D aerosol-climate model used is EMAC-MADE.

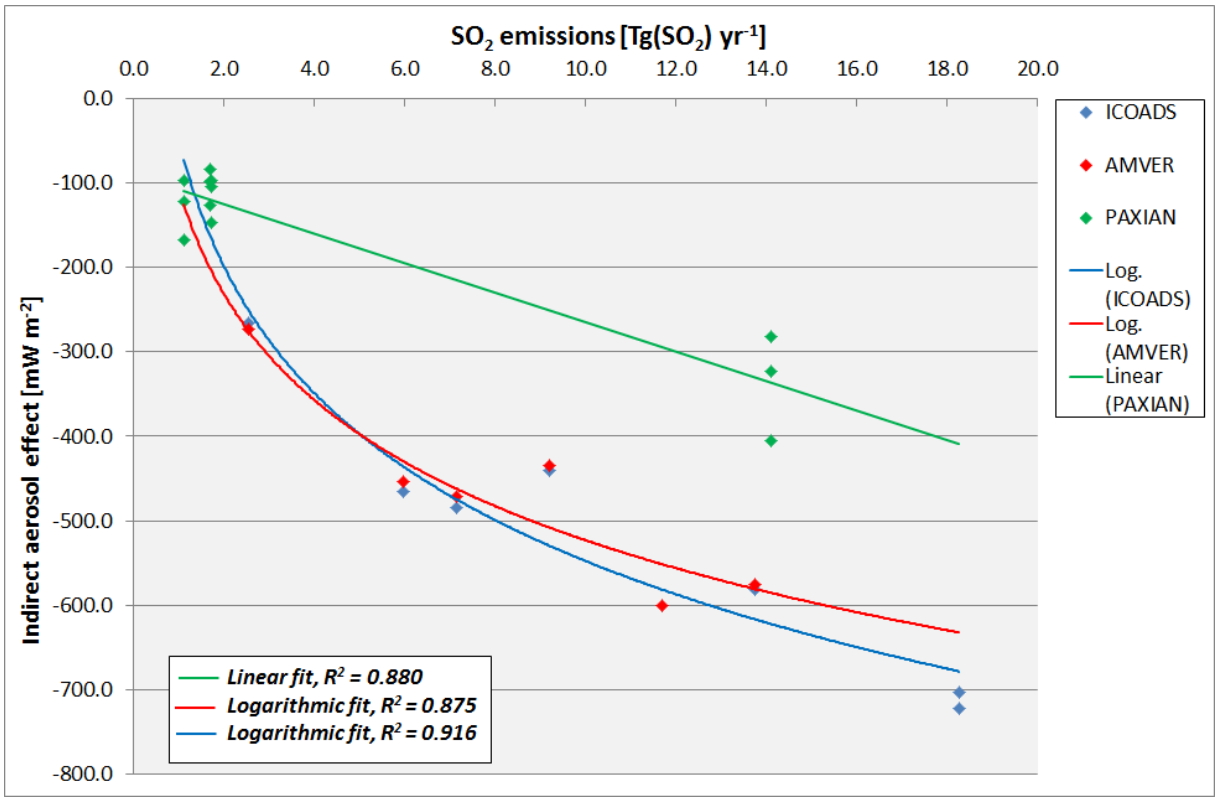

Figure SI2: Indirect aerosol effect [mWm−2] versus SO_2 emissions [Tg (SO_2) yr−1] in EMAC-MADE model runs with linear or logarithmic fit to the data. Global aerosol-climate mode data is grouped by the emission inventory used (AMVER, ICOADS or Paxian et al.[33] (PAXIAN)).

Table SI1: Full table summarizing the shipping emission inventories and geographical distributions of emissions in the EMAC-MADE model runs, and the resulting relative contribution of shipping to the tropospheric aerosol burden and change in direct and indirect aerosol forcing (simulations 1-3 from Lauer et al., 2007[32], 4-11 from Lauer et al., 2009[35], 14-25 from Righi et al.[36]).

		Geogr. Distr.	Fuel sulfur content [%]	Aerosol size dsitrbution	NO_x [Tg(NO_2) yr^{-1}]	SO_2 [Tg yr^{-1}]	Primary SO_4 [Tg yr^{-1}]	CO [Tg yr^{-1}]	BC [Tg yr^{-1}]	POM [Tg yr^{-1}]	Relative contribution of shipping to the tropospheric aerosol burdens (global annual mean) in %, values in parenthesis are absolute changes in Gg					Changes in global annual mean $SW_{clear-sky}$ radiation flux [mW m^{-2}]	Estimated direct aerosol effect (global annual mean $SW_{all-sky}$ radiation flux) [mW m^{-2}]	Global annual mean indirect aerosol effect [mW m^{-2}]	Reference
											SO_4	NH_4	NO_3	BC	POM				
1	Inventory A	AMVER	2.7	Fresh	21.3	11.7	0.77	1.28	0.05	0.13	4.69 (56.43)	3.47 (9.96)	5.92 (6.37)	0.58 (0.57)	0.21 (1.85)	-38	-12	-600	Lauer et al. (2007)
2	Inventory C	ICOADS	2.7	Fresh	16.4	9.2	0.35	1.08	0.07	0.71	2.81 (33.19)	1.92 (5.42)	6.15 (6.64)	0.93 (0.92)	1.20 (10.43)	-30	-8	-441	Lauer et al. (2007)
3	Inventory C	AMVER	2.7	Fresh	16.4	9.2	0.35	1.08	0.07	0.71	3.33 (39.45)	2.24 (6.36)	5.08 (5.41)	0.93 (0.92)	1.28 (11.12)	-30	-9	-434	Lauer et al. (2007)
4	2012 No Action	ICOADS	2.7	Fresh	24.5	13.75	0.523	1.61	0.105	1.061	4.29 (51.38)	2.80 (7.98)	8.12 (8.94)	1.34 (1.33)	1.66 (14.55)	-43	-12	-582	Lauer et al. (2009)
5	2012 Coastal 0.5	ICOADS, coastal S reduction	0.5	Fresh	24.5	7.15	0.272	1.61	0.105	0.637	1.82 (21.29)	1.15 (3.22)	9.02 (10.03)	1.49 (1.48)	1.10 (9.55)	-27	-7	-484	Lauer et al. (2009)
6	2012 Coastal 0.1	ICOADS, coastal S reduction	0.1	Fresh	24.5	5.96	0.227	1.61	0.105	0.561	1.35 (15.69)	0.82 (2.29)	9.25 (10.31)	1.53 (1.52)	0.97 (8.47)	-24	-6	-465	Lauer et al. (2009)
7	2012 Global 0.5	ICOADS, global S reduction	0.5	Fresh	24.5	2.55	0.097	1.61	0.105	0.341	0.76 (8.74)	0.47 (1.32)	9.80 (10.99)	1.50 (1.48)	0.63 (5.44)	-16	-4	-266	Lauer et al. (2009)
8	2012 No Action	AMVER	2.7	Fresh	24.5	13.75	0.523	1.61	0.105	1.061	5.05 (60.97)	3.27 (9.38)	6.71 (7.28)	1.38 (1.37)	1.81 (15.86)	-44	-14	-576	Lauer et al. (2009)
9	2012 Coastal 0.5	AMVER, coastal S reduction	0.5	Fresh	24.5	7.15	0.272	1.61	0.105	0.637	2.07 (24.19)	1.26 (3.52)	7.88 (8.65)	1.55 (1.54)	1.13 (9.81)	-26	-8	-472	Lauer et al. (2009)
10	2012 Coastal 0.1	AMVER, coastal S reduction	0.1	Fresh	24.5	5.96	0.227	1.61	0.105	0.561	1.52 (17.69)	0.87 (2.43)	8.05 (8.86)	1.64 (1.63)	1.01 (8.79)	-21	-6	-453	Lauer et al. (2009)
11	2012 Global 0.5	AMVER, global S reduction	0.5	Fresh	24.5	2.55	0.097	1.61	0.105	0.341	1.02 (11.82)	0.55 (1.53)	8.68 (9.62)	1.64 (1.63)	0.70 (6.10)	-16	-5	-273	Lauer et al. (2009)
12	New IMO 2007 Simulation (POM=0.36 Tg/yr): with SECAs	ICOADS with SECAs	2.7	Fresh	25.32	18.25	1.09	2.5	0.118	0.36	5.81 (70.77)	4.07 (11.75)	7.66 (8.40)	1.54 (1.53)	0.63 (5.49)	-50	-15	-704	Lauer et al. (2009)
13	New IMO 2007 Simulation (POM=0.36 Tg/yr): without SECAs	ICOADS without SECAs	2.7	Fresh	25.32	18.25	1.09	2.5	0.118	0.36	5.86 (71.43)	4.09 (11.82)	7.54 (8.25)	1.50 (1.49)	0.55 (4.78)	-50	-15	-723	Lauer et al. (2009)
14	BIOCLEAN REF	Paxian et al. 2010		Fresh	21.3	14.1	0.444	1.43	0.122	0.391	5.55 (67.46)	3.62 (10.43)	6.47 (7.00)	1.60 (1.59)	0.59 (5.09)	-37	-13	-405	Paxian et al. (2010)
15	BIOCLEAN REF	Paxian et al. 2010		Aged 1	21.3	14.1	0.444	1.43	0.122	0.391	5.57 (67.78)	3.76 (10.84)	6.29 (6.80)	1.72 (1.72)	0.60 (5.17)	-33	-12	-323	Paxian et al. (2010)
16	BIOCLEAN REF	Paxian et al. 2010	<0.1	Aged 2	21.3	14.1	0.444	1.43	0.122	0.391	5.46 (66.29)	3.65 (10.50)	6.29 (6.79)	1.69 (1.68)	0.56 (4.83)	-33	-12	-282	Paxian et al. (2010)
17	BIOCLEAN MGO	Paxian et al. 2010	<0.1	Fresh	21.7	1.69	3.93E-03	1.36	1.92E-02	0.193	0.70 (8.13)	0.30 (0.84)	8.98 (9.98)	0.24 (0.24)	0.37 (3.16)	-11	-4	-126	Paxian et al. (2010)
18	BIOCLEAN MGO	Paxian et al. 2010	<0.1	Aged 1	21.7	1.69	3.93E-03	1.36	1.92E-02	0.193	0.64 (7.36)	0.24 (0.66)	8.89 (9.87)	0.27 (0.26)	0.39 (3.38)	-10	-3	-99	Paxian et al. (2010)
19	BIOCLEAN MGO	Paxian et al. 2010	<0.1	Aged 2	21.7	1.69	3.93E-03	1.36	1.92E-02	0.193	0.66 (7.61)	0.24 (0.67)	8.86 (9.84)	0.22 (0.22)	0.28 (2.44)	-10	-3	-83	Paxian et al. (2010)
20	BIOCLEAN PALM	Paxian et al. 2010	<0.1	Fresh	21.5	1.12	1.51E-03	1.16	2.02E-02	0.537	0.51 (5.94)	0.12 (0.33)	9.19 (10.24)	0.25 (0.25)	1.07 (9.33)	-9	-3	-167	Paxian et al. (2010)
21	BIOCLEAN PALM	Paxian et al. 2010	<0.1	Aged 1	21.5	1.12	1.51E-03	1.16	2.02E-02	0.537	0.45 (5.18)	0.11 (0.31)	9.08 (10.11)	0.26 (0.25)	1.05 (9.10)	-8	-2	-122	Paxian et al. (2010)
22	BIOCLEAN PALM	Paxian et al. 2010	<0.1	Aged 2	21.5	1.12	1.51E-03	1.16	2.02E-02	0.537	0.47 (5.41)	0.16 (0.44)	9.15 (10.19)	0.26 (0.25)	1.01 (8.76)	-7	-2	-97	Paxian et al. (2010)
23	BIOCLEAN SOYA	Paxian et al. 2010	<0.1	Fresh	22.6	1.72	1.51E-03	1.09	4.07E-02	0.325	0.73 (8.49)	0.29 (0.81)	9.37 (10.46)	0.61 (0.60)	0.67 (5.80)	-11	-4	-147	Paxian et al. (2010)
24	BIOCLEAN SOYA	Paxian et al. 2010	<0.1	Aged 1	22.6	1.72	1.51E-03	1.09	4.07E-02	0.325	0.68 (7.90)	0.27 (0.76)	9.33 (10.41)	0.65 (0.64)	0.67 (5.84)	-9	-3	-104	Paxian et al. (2010)
25	BIOCLEAN SOYA	Paxian et al. 2010	<0.1	Aged 2	22.6	1.72	1.51E-03	1.09	4.07E-02	0.325	0.65 (7.52)	0.23 (0.63)	9.31 (10.38)	0.58 (0.57)	0.55 (4.77)	-9	-3	-97	Paxian et al. (2010)

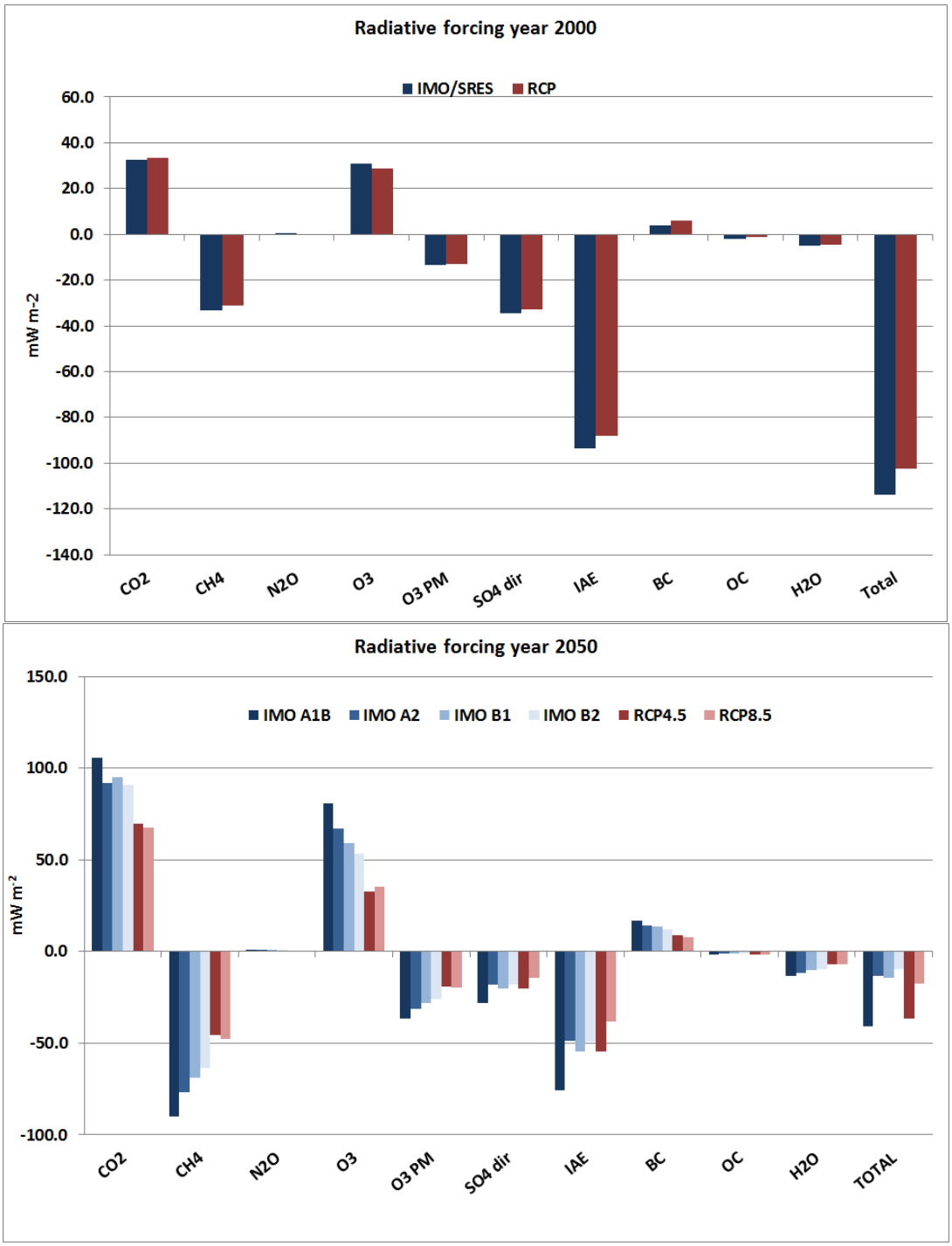

Figure SI3: Global mean radiative forcing [mW m^{-2}] (calculated by the SCM) due to shipping emissions in 2000 and 2050 from pre-industrial time by substance and scenario. The RF-CH_4 includes both the direct effect of CH_4 emissions and the indirect effect of NOx, CO and VOCs on the lifetime of CH_4. The radiative forcing in year 2000 is within the range of values reported in Eyring et al.[37] for all components. The IAE is in the lower range.

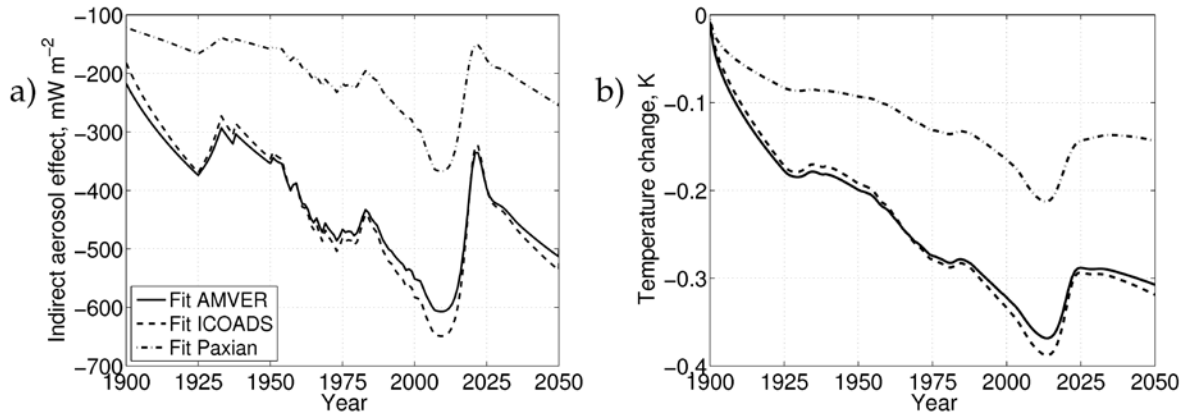

Figure SI4: a) Indirect aerosol effect [mW m^{-2}] and b) global mean total net temperature change [K] due to shipping calculated with the relationships obtained from fits to three groups of global aerosol-climate model data subsuming simulations performed with different emission inventories showing different assumptions on geographical distribution of emissions (AMVER, ICOADS and the distribution from Paxian et al.[33] (PAXIAN)). Logarithmic fits to the data are assumed for AMVER and ICOADS, while a linear fit is assumed for PAXIAN.

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