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Radiative forcing due to changes in ozone and methane caused by the transport sector

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ABSTRACT

The year 2000 radiative forcing (RF) due to changes in O3 and CH4 (and the CH4-induced stratospheric water vapour) as a result of emissions of short-lived gases (oxides of nitrogen (NOx), carbon monoxide and non-methane hydrocarbons) from three transport sectors (ROAD, maritime SHIPping and AIRcraft) are calculated using results from five global atmospheric chemistry models. Using results from these models plus other published data, we quantify the uncertainties. The RF due to short-term O3 changes (i.e. as an immediate response to the emissions without allowing for the long-term CH4 changes) is positive and highest for ROAD transport (31 mW m−2) compared to SHIP (24 mW m−2) and AIR (17 mW m−2) sectors in four of the models. All five models calculate negative RF from the CH4 perturbations, with a larger impact from the SHIP sector than for ROAD and AIR. The net RF of O3 and CH4 combined (i.e. including the impact of CH4 on ozone and stratospheric water vapour) is positive for ROAD and AIR (16±13 (one standard deviation) mW m−2) and AIR (17 mW m−2) sectors in four of the models. All five models calculate negative RF from the CH4 perturbations, with a larger impact from the SHIP sector than for ROAD and AIR. The net RF of O3 and CH4 combined (i.e. including the impact of CH4 on ozone and stratospheric water vapour) is positive for ROAD (16±13 (one standard deviation) mW m−2) and AIR (17 mW m−2) sectors in four of the models. Global Warming Potentials (GWP) and Global Temperature change Potentials (GTP) are presented for AIR NOx emissions; there is a wide spread in the results from the 5 chemistry models, and it is shown that differences in the methane response relative to the O3 response drive much of the spread.

1. Introduction

The climate impact of the transport sector occurs through emissions of CO2, aerosols (and their precursors), water vapour, and species that affect ozone and the oxidative state of the atmosphere such as NOx, CO and non-methane hydrocarbons (NHMC), with direct emissions of CH4 being negligible for these sectors. This paper examines the impact of this latter class of oxidant emissions from three transport sub-sectors – land transport (ROAD), maritime shipping (SHIP) and aviation (AIR). We calculate the radiative forcing (RF) by considering both short-term and long-term changes in atmospheric composition. The estimated RF due to all emissions is positive for ROAD and AIR, but negative for SHIP (Fuglestvedt et al., 2008). This switch for SHIP is partly due to the strong direct and indirect aerosol effect from SHIP (Balkanski et al., 2010; Fuglestvedt et al., 2008) but also a result of the high NOx emissions which reduce the CH4 lifetime. This coupling in the atmospheric
chemistry between NO\(_x\), CH\(_4\), and O\(_3\) is well established (Fuglestvedt et al., 1999; Lelieveld et al., 1998; Naik et al., 2005; Shindell et al., 2005, 2009; Wild and Prather, 2000). Emissions of the short-lived trace gas species NO\(_x\), non-methane hydrocarbons (NMHC), and CO lead to production of tropospheric O\(_3\), and we denote this as the short-term O\(_3\) RF. The reduction in CH\(_4\) also leads to additional changes in O\(_3\), but due to the long lifetime of CH\(_4\) compared to the other O\(_3\) precursors, this change in O\(_3\) occurs on a longer time-scale than the short-term O\(_3\) RF (Prather, 1994; Wild et al., 2001). We denote the change in O\(_3\) from CH\(_4\) changes as the CH\(_4\)-induced O\(_3\) change.

The RF from O\(_3\) changes since pre-industrial time is estimated to be 0.35 W m\(^{-2}\) (Forster et al., 2007; Gauss et al., 2006) and the transport sectors have been estimated to contribute as much as a third of this value (Fuglestvedt et al., 2008). In terms of RF, the reduction in the CH\(_4\) lifetime from NO\(_x\) emissions acts on a global scale in opposition to the positive RF due to O\(_3\) production from CH\(_4\), leading to a smaller net effect of NO\(_x\) (Forster et al., 2007; Shindell et al., 2005; Wild et al., 2001).

Sector-specific analyses of RF are important, particularly when mitigation measures are being considered because each sector’s impact is unique. This is especially relevant for the transport sectors where the emissions are introduced into quite different environments — road emissions are predominantly released into the polluted boundary layer, ship emissions are mostly released into the clean maritime boundary layer, and aircraft emissions are mostly released into the upper troposphere and lower stratosphere. Using several global atmospheric chemistry models and radiative transfer schemes, we quantify the RF resulting from changes in O\(_3\) and the CH\(_4\) lifetime due to emissions of NO\(_x\), CO and NMHCs from the different transport sectors. We focus on the sign of the net RF and its uncertainty for the three transport sectors. The results can be used, together with calculations of the forcing due to other emissions (e.g. CO\(_2\) and black carbon) from the transport sector, to assess and quantify the overall climate impact of each sector (e.g. Skeie et al., 2009).

This paper presents results from the European Union project QUANTIFY (Quantifying the Climate Impact of Global and European Emission Systems). Hoor et al. (2009) reported an analysis of preliminary QUANTIFY simulations, focusing on the behaviour of the different chemical models; they also included a brief discussion of the RF from the different transport sectors. The simulations reported here use the final revised QUANTIFY emission inventories, which were developed during the course of the project (Uherek et al., 2010). We concentrate on a more detailed analysis of the resulting RF and its associated uncertainty and on the computation of climate emissions metrics (Global Warming Potential (GWP) and Global Temperature change Potential (GTP)) for aviation NO\(_X\) emissions. An estimate of current climate importance of the accumulated emissions from the transport sector up to year 2000 can be made using RF. To assess the future importance of current emissions and for considerations for mitigation purposes, forward looking emission metrics such as the GWP and the GTP metrics are more useful as they account for the persistence of atmospheric perturbations and thus the integrated impacts (Fuglestvedt et al., 2010).

### 2. Methods and models

Five global chemistry models consisting of four Chemistry Transport Models (CTMs) and one Climate Chemistry Model (CCM) have been used to simulate changes in O\(_3\) and CH\(_4\) due to precursor emissions (NO\(_x\), CO, and NMHC) from the different transport sectors with year 2000 emissions (see Table 1 for model descriptions). Each model ran with fixed CH\(_4\) abundances and then adopted a spin-up period of a year in order to attain chemical steady state with respect to O\(_3\). The imbalance in the CH\(_4\) budget is diagnosed; this allows the calculation of the change in CH\(_4\) abundance that would have occurred over decades if the emissions were held constant. The QUANTIFY methodology (see Hoor et al., 2009 and Grewe et al., 2010 for details) is to include all natural and anthropogenic emissions and then to compute the impact of an individual transport sector by reducing each respective sector’s emissions by 5%, so as to ensure that perturbations act on an atmosphere close to present-day composition (Grewe et al., 2010). The 5% results are scaled by a factor 20 to represent the total change attributable to the transport sectors. The difference between a 20% 5% reduction and a complete 100% reduction are discussed in Section 3.1. Fig. 1 compares the improved emissions used in this study compared to those of Fuglestvedt et al. (2008) and Hoor et al. (2009). ROAD emissions of NO\(_x\), NMHC and CO are highest in Fuglestvedt et al. (2008), whereas the new QUANTIFY NO\(_x\) emissions for AIR are greater than those in Fuglestvedt et al. (2008) and Hoor et al. (2009). Only Fuglestvedt et al. (2008) included CO and NMHC emissions for the AIR sector, but these emissions are negligible in terms of global anthropogenic sources. Note the much higher ratio of NO\(_x\) to CO\(_2\) in SHIP and AIR emissions compared to ROAD emissions. The gridded emission data can be downloaded from [www.ip-quantify.eu](http://www.ip-quantify.eu).

The RF calculations for the O\(_3\) changes from the chemical models are performed using two sets of radiative transfer models, University of Oslo (UiO) and University of Reading (UoR). Except where stated, the simulations here use the UiO schemes, which consist of a broad-band scheme for thermal infrared radiation and a scheme using the multi-stream DISORT code for shortwave radiation (Myhre et al., 2000). UoR have performed O\(_3\) RF calculations using the O\(_3\) changes for each sector averaged over 4 of the global chemistry models (Oslo CTM2, TM4, LMDz-INCA and p-TOMCAT; the UCI results are a recent addition) using the Edwards

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**Table 1**

A short description of the CTMs and CCM used in this study. A more detailed overview of the models is given in Hoor et al. (2009).

| Model acronym | Institution | Short description | Reference |
|---------------|-------------|-------------------|-----------|
| Oslo CTM2     | University of Oslo, Norway | CMT driven by ECMWF meteorology in T42 horizontal resolution and 60 vertical layers | (Berglen et al., 2004; Gauss et al., 2006; Isaksen et al., 2005) |
| TM4           | KNMI, The Netherlands | CMT driven by ECMWF meteorology with a 2° × 3° horizontal resolution and 34 vertical layers | (van Noije et al., 2006; Williams et al., 2009; Williams et al., 2010) |
| p-TOMCAT      | University of Cambridge, UK | CMT driven by ECMWF meteorology in T21 horizontal resolution and 31 vertical layers | (O’Connor et al., 2005) |
| LMDz-INCA     | LSCE, Gif sur Yvette, France | CCM nudged to meteorological data from ECMWF with a horizontal resolution of 3.75° × 2.5° and 19 vertical layers | (Folberth et al., 2006; Hauglustaine et al., 2004) |
| UCI           | University of California, Irvine, USA | CMT driven by ECMWF meteorology in T42 horizontal resolution and 37 vertical layers | (Hsu et al., 2005; Wild et al., 2003) |
and Slingo (1996) two-stream radiation code, with 6 bands in the shortwave and 8 bands in the longwave.

The methodology for calculating the forcing due to CH4 changes follows the simple approach described by Berntsen et al. (2005) and used in Hoor et al. (2009), with two important extensions. The chemistry models do not explicitly calculate the change in CH4 concentrations and in any case the simulations are not long enough for the CH4 to come into equilibrium with the changed OH field. Instead, the change in OH is used to estimate the fractional change in CH4 lifetime. This is then multiplied by the present-day concentration of methane and a model-average feedback factor of 1.4 (Prather et al., 2001), to account for the impact of changes in CH4 concentration on its own lifetime, to yield the fractional change in CH4 concentration for steady-state conditions (Fuglestvedt et al., 1999). The QUANTIFY study did not directly calculate this feedback factor, nor the increase in tropospheric O3 per change in CH4, so we resort to the published, model-average values here.

The RF is calculated assuming a specific CH4 RF of 0.37 mW m⁻²°C⁻¹, which assumes a background concentration of 1740 ppb. The CH4-induced O3 RF is then computed, following Berntsen et al. (2005) and results from Prather et al. (2001), whereby a 10% increase in CH4 leads to a 0.64 DU increase in O3, and this O3 has a specific RF of 42 mW m⁻² DU⁻¹ (Ramaswamy et al., 2001); this RF factor is more applicable to the global-scale change in tropospheric O3 resulting from the methane change, than it is to the more regional short-term ozone change resulting from transport sector emissions.

The first extension to the Hoor et al. (2009) methodology is to account for the impact of CH4 changes on stratospheric water vapour. Based on Myhre et al. (2007), we take the stratospheric water vapour RF to be 0.15 times that of the CH4 RF. The second extension to the Hoor et al. (2009) methodology is to relax the assumption that the CH4 concentration in 2000 is in steady state with that year’s change in OH. The actual degree of imbalance depends on the history of change in OH, which is not accounted for in the chemical model calculations which used year 2000 emissions. The degree of imbalance will be greatest for AIR, for which the emissions have been growing most rapidly in recent years, and least for ROAD. The method and assumptions about the historical emissions are described in Grewe and Stenke (2008). The factor to correct this transient response in year 2000 is taken to be 0.85 for ROAD, 0.8 for SHIP and 0.65 for AIR. These factors are then applied to the CH4 RF, the CH4-induced O3 RF and the stratospheric water vapour RF from each of the CTMs. These corrections to the instantaneous year 2000 RF are a result of the historical emissions and do not apply to the calculation of GWP and GTP for AIR in Section 4.

Other consequences of the O3 precursor emissions have been identified but are not considered here. For example, changes in O3 and OH may alter the sulphate burden (e.g. Unger et al., 2006; Shindell et al., 2009) and surface O3 interaction with vegetation may impact the carbon cycle (Sitch et al., 2007). NOx emissions have a small direct RF due to the absorption of solar radiation by NO2 (Kvalevåg and Myhre, 2007) and formation of nitrate aerosols from the NOx enhances the overall aerosol negative RF (Forster et al., 2007). This paper focuses on the primary, well-established impacts of the ozone-precursor emissions on O3 and CH4 and their consequential effects.

3. Results

3.1. Short-term O3

Table 2 compares the global and annual mean total column O3 change (in DU) for the five global chemistry models and the three transport sectors for the QUANTIFY preliminary emissions (Hoor et al., 2009) and QUANTIFY final emissions used here. The largest changes in the O3 column between the simulations using the preliminary and final emissions are seen for ROAD and AIR. In addition to changes in the emissions inventories, there have also been model improvements and updates by many of the modelling groups over the two-year period in which the QUANTIFY emissions were updated. p-TOMCAT is the only model with a reduction in the O3 column change for all three transport sectors between...
preliminary and final QUANTIFY simulations in spite of increased NOx emissions.

Fig. 2 shows the global and annual mean RF for short-term O3, using the UiO radiation model, for the three transport sectors calculated by the five global chemistry models. Amongst the transport sectors, ROAD is largest, followed by SHIP and AIR sectors in four of the models. The five model average for the ROAD, SHIP and AIR sectors are 31, 24 and 17 mW m⁻², respectively. A composite, four model (without UCI) mean of the O3 change is used to compare the radiation models. For this subset the UiO RF values are 30, 21 and 16 mW m⁻² for the three sub-sectors, and the UoR calculations yield corresponding forcings of 28, 19 and 17 mW m⁻² indicating agreement to within about 10% in the RF calculations.

The relative spread in the RF among the models is within a factor of 2 for AIR, (13–21 mW m⁻²) and SHIP (17–32 mW m⁻²); by contrast for ROAD the spread in the RF is almost a factor of 3 (15–42 mW m⁻²). The model range in the sum of RF across all three sectors is less and ranges from 57 to 90 mW m⁻².

The zonal-mean RFs of short-term O3 for the three transport sectors for all five models are shown in Fig. 3. The patterns of RF are similar for the four models Oslo CTM2, TM4, LMDz-INCA, and UCI, as governed by the global distribution of emissions for each sector, with ROAD dominating in the Northern Hemisphere, ROAD and SHIP being quite comparable in the Southern Hemisphere, and AIR being very small in the Southern Hemisphere. By contrast, the p-TOMCAT RF shows AIR as dominating in the Northern Hemisphere and comparably large also in the Southern Hemisphere.

The RF results are based on radiation calculations using the 100% perturbation in O3 that is derived by multiplying the O3 change resulting from the 5% perturbation in emissions by 20 (Grewe et al., 2010; Hoor et al., 2009). Hoor et al. (2009) showed that the sum of O3 changes from 5% perturbation in the individual ROAD, AIR and SHIP emissions equals that from a single calculation of the combined emissions from all three sectors. Here, we investigate the difference between a scaled 5% reduction and a full 100% reduction of ROAD emissions with the Oslo CTM2: the 100% reduction gives column O3 changes that are 1.07 times greater than 20 × 5%; however, the non-linearity in the longwave RF reduces this to a factor of 1.03. Compared to the inter-model differences in the RF, the non-linear response to the magnitude of the perturbations is relatively small, and hence contributes little to the overall uncertainty.

Normalized radiative forcing from O3 (NRF) (RF divided by the change in the O3 column expressed in Dobson Units (DU)) is dependent on both the region and altitude of the resulting O3 change (Bernsten et al., 2000; Gauss et al., 2003). In all models, except LMDz-INCA, the AIR sector has a higher NRF than ROAD and SHIP with a mean of 36 mW m⁻² DU⁻¹ with a range from 33 to 42 mW m⁻² DU⁻¹. The values for ROAD and SHIP are 32 mW m⁻² DU⁻¹ (range from 30 to 36 mW m⁻² DU⁻¹) and 30 mW m⁻² DU⁻¹ (range from 29 to 32 mW m⁻² DU⁻¹), respectively. For the sum of RF across the three transport sectors, p-TOMCAT yields the highest NRF (34 mW m⁻² DU⁻¹) and Oslo CTM2 the lowest (31 mW m⁻² DU⁻¹). These NRF numbers show the largest spread for AIR. In some instances the agreement in the RF between models is a coincidence resulting from compensating differences in the NRF and the ozone change (as is the case for p-TOMCAT and UCI for AIR). Nevertheless, these comparisons in NRF show much less relative spread compared to the RF calculations, indicating that it is inter-model differences in the total O3 change that are mainly responsible for the differences in their RF, rather than inter-model differences in the distribution of the O3 change.

### 3.2. CH₄

The O3 precursor emissions change the atmospheric lifetime of CH₄ due to changes in OH concentrations. The percentage changes in the CH₄ lifetime due to destruction by OH (integrated between the surface and 50 hPa for each model) are given in Table 3. For most models and most transport sectors, increased emissions lead to an increase in global OH, a decrease in CH₄ lifetime and hence a decrease in CH₄ concentrations. The changes are largest for SHIP because of the different geographical pattern of emissions and background conditions as well as the mix of emitted components compared to the other sectors (Fuglestvedt et al., 2008; Hoor et al., 2009). Although AIR emissions have the largest impact on CH₄ on a per unit NOx emission basis, SHIP and ROAD each have nearly ten times larger NOx emissions. Unlike the results in Hoor et al. (2009), where all models (including p-TOMCAT) and all sectors showed a decrease in CH₄ lifetime, the current p-TOMCAT version using the final QUANTIFY emissions calculates a small increase in CH₄ lifetime for ROAD. Our analysis finds that p-TOMCAT has a much stronger response of the OH concentrations to emissions of CO and NMHC than the other models and this overwhelms the effect of the NOx emissions. This model has lower CO concentrations than the four other models, which can partly explain the different impact of the ROAD emissions.
The resulting RF for year 2000 due to CH₄ change from the transport sector (including the transient effect but not the CH₄-induced changes in O₃ and stratospheric water vapour) is shown in Fig. 4. This CH₄ RF is larger for SHIP than ROAD and AIR. The inter-model difference in the CH₄ RF is rather small for SHIP, with a spread of only 8 mW m⁻² for an average RF of 27 mW m⁻². For AIR, all models show a negative RF, with a mean of 7.3 mW m⁻² and a relatively higher spread of 4.4 mW m⁻². The ROAD RF from CH₄ varies little among four global models, −12 to −14 mW m⁻², but p-TOMCAT gives +1 mW m⁻², reducing the magnitude of the mean RF for ROAD for the CH₄ lifetime to −10 mW m⁻².

3.3. RF due to short-term O₃ and CH₄ changes combined

The net RF of short-term O₃ and long-term CH₄ combined (and now including the CH₄ impacts on O₃ and stratospheric water vapour) are shown in Fig. 5. All five models have a positive net RF for ROAD and AIR and a negative RF for SHIP. For ROAD, the net forcing varies from 9.3 to 21 mW m⁻², with a mean of 16 mW m⁻². For SHIP, the range is −12 to −25 mW m⁻² with a mean of −18 mW m⁻². Although the general agreement in Fig. 5 is quite encouraging in terms of absolute RF, the degree of agreement is less

### Table 3

| CH₄ lifetimes (yr) due to destruction by OH (between the surface and 50 hPa) for the base case and the relative changes due to year 2000 emissions from three transport sectors – the values are derived from a 5% change in emissions for each sector and then multiplied by 20. The feedback effect of changes in CH₄ on its own lifetime is not included in this Table. |
|---|---|---|---|---|
| Base (years) | Oslo CTM2 | TM4 | p-TOMCAT | LMDz-INCA | UCI |
| Road % | −1.77 | −1.62 | 0.12 | −1.54 | −1.78 |
| Ship % | −3.74 | −4.14 | −3.45 | −3.14 | −4.24 |
| Air % | −0.81 | −1.22 | −1.55 | −1.04 | −1.57 |

**Fig. 3.** Zonal and annual mean radiative forcing (mW m⁻²) from short-term O₃ for five global chemistry models. Each panel shows results for year 2000 emissions from three transport sectors.

**Fig. 4.** Global and annual mean radiative forcing for the year 2000 due to CH₄ changes (mW m⁻²) accounting for the time-history of the emissions (see text for details) for three transport sectors and five global chemistry models.
than that seen in Fig. 4 (p-TOMCAT for ROAD excepted). This is because the models show a differing amount of cancellation between the short-term O3 RFs and CH4. This uncertainty in the long-term RF (CH4 plus induced O3 changes) may be underestimated since we used a single conversion factor for the CH4 feedback on its own lifetime, and a single factor for the RF due to the CH4-induced ozone change and the stratospheric H2O change. For AIR, the spread is from 4.1 to 8.7 mW m\(^{-2}\) with a mean of 6.0 mW m\(^{-2}\). Compared to the multi-model mean, Oslo CTM2 is always more positive, by several 10's of percent, TM4 is always more negative by several tens of percent, while deviations from the mean for LMDz-INCA, UCI and p-TOMCAT are generally smaller and all are within 10% of the multi-model mean for two of the three sectors.

To derive the uncertainties in the RF, we use uncertainties in the emissions (Fuglestvedt et al., 2008), and simulations of distribution changes and radiative forcing performed in this study combined with Monte Carlo simulations (Boucher and Haywood, 2001). For O3 and the CH4 lifetime effect we use the difference in the global chemistry models as one standard deviation representative for the uncertainty in distributions for each of the transport sectors. The uncertainty in the CH4 impact on O3 takes into account uncertainty in the model change in CH4 and O3 in addition to the uncertainty in emissions. For stratospheric water vapour uncertainties in the emissions, CH4 change and the radiative transfer are considered. The latter is taken from an intercomparison study with an uncertainty of 30% (Myhre et al., 2009). The derived uncertainties (one standard deviation) are 13 mW m\(^{-2}\) (81%), 10 mW m\(^{-2}\) (55%), and 5 mW m\(^{-2}\) (81%) for ROAD, SHIP, and AIR, respectively. The dominating contributor to the uncertainty is the short-term O3.

4. Climate emission metrics for aviation NO\(_x\) emissions

Fuglestvedt et al. (2010) reported values (as well as a number of important caveats) for the GWP and GTP for NO\(_x\) emissions from aviation using available results in the literature. They found substantial differences in the derived GWPs and GTPs, which included a difference in sign for some time horizons (H). The results derived here allow a cleaner comparison of GWPs and GTPs between global chemistry models, as they are derived using the same emissions and emission perturbations, the same experimental design and use the same radiative transfer scheme to calculate the RF. Thus the spread in results gives us a measure of the uncertainty in the global chemical modelling of aviation’s impact on atmospheric chemistry. We do not present values for the other sectors, as the ozone changes for these are influenced by CO and NMHC emissions as well as NO\(_x\).

The Fuglestvedt et al. (2010) methodology is adopted here for the calculation of GWPs and GTPs, although we also include the effect of CH4 changes on stratospheric water vapour. In line with the conventional definitions of GWP and GTP, CO2 is used as the reference gas. The GTP values are somewhat sensitive to the model used to calculate the temperature change, and the assumed climate sensitivity. Appendix 2 in Fuglestvedt et al. (2010) describes the method used here, which is based on fits to coupled ocean-atmosphere general circulation model experiments, which have an equilibrium climate sensitivity to a doubling of CO2 of 3.9 K. The CH4 lifetimes given in Table 3 are multiplied by 1.4 to give the CH4 perturbation lifetimes (which accounts for the effect of a change in CH4 on its own lifetime). Time 1 for TM4 is always more positive, by several 10's of percent, TM4 is always more negative by several tens of percent, while deviations from the mean for LMDz-INCA, UCI and p-TOMCAT are generally smaller and all are within 10% of the multi-model mean for two of the three sectors. 

To derive the uncertainties in the RF, we use uncertainties in the emissions (Fuglestvedt et al., 2008), and simulations of distribution changes and radiative forcing performed in this study combined with Monte Carlo simulations (Boucher and Haywood, 2001). For O and the CH lifetime effect we use the difference in the global chemistry models as one standard deviation representative for the uncertainty in distributions for each of the transport sectors. The uncertainty in the CH impact on O takes into account uncertainty in the model change in CH4 and O in addition to the uncertainty in emissions. For stratospheric water vapour uncertainties in the emissions, CH4 change and the radiative transfer are considered. The latter is taken from an intercomparison study with an uncertainty of 30% (Myhre et al., 2009). The derived uncertainties (one standard deviation) are 13 mW m\(^{-2}\) (81%), 10 mW m\(^{-2}\) (55%), and 5 mW m\(^{-2}\) (81%) for ROAD, SHIP, and AIR, respectively. The dominating contributor to the uncertainty is the short-term O.

**Table 4**

|          | Short-lived ozone | Methane-induced ozone | Methane |
|----------|-------------------|-----------------------|--------|
| Oslo CTM2 | 1.94E-11          | −3.68E-12             | −1.01E-11 |
| TM4      | 1.86E-11          | −5.52E-12             | −1.51E-11 |
| p-TOMCAT | 2.54E-11          | −7.02E-12             | −1.92E-11 |
| LMDz-INCA| 1.62E-11          | −4.99E-12             | −1.29E-11 |
| UCI      | 2.49E-11          | −7.10E-12             | −1.94E-11 |
| Mean     | 2.09E-11          | −5.60E-12             | −1.53E-11 |
Table 5
Global Warming Potentials (GWP) and Global Temperature change Potentials (GTP) for year 2000 AIR NOx emissions (a) GWP values for one-year pulse emissions of NOx for a 20, 100 and 500 year time horizons and (b) GTP values for 20, 50 and 100 years. The first three numbers show the individual contributions from the short-lived O3, the CH4-induced O3 and the CH4 (which includes stratospheric water vapour changes), respectively; the net GWP and GTP are shown in bold. The mean values use the multi-model means of the specific forcings (Table 4) and lifetimes (Table 3). All numbers are rounded, so that the net values may not be the sum of numbers as they are presented here. All values are on a per kg N basis and are relative to CO2. The GTP values are specific to a given value of climate sensitivity – see text for details.

|                | H = 20          | H = 100         | H = 500         |
|----------------|-----------------|-----------------|-----------------|
| (a) GWP        |                 |                 |                 |
| Oslo CTM2      | 785 – 115 – 333 – 338 | 223 – 41 – 116 – 67 | 68 – 12 – 5 – 20 |
| TM4            | 753 – 170 – 490 – 92 | 214 – 61 – 174 – 21 | 65 – 19 – 53 – 63 |
| p-TOMCAT       | 1028 – 209 – 601 – 218 | 292 – 78 – 221 – 63 | 89 – 24 – 67 – 20 |
| LMDz-INCA      | 656 – 142 – 411 – 103 | 186 – 52 – 148 – 14 | 57 – 16 – 45 – 42 |
| UCI            | 1000 – 226 – 654 – 128 | 287 – 78 – 223 – 15 | 87 – 24 – 68 – 45 |
| Mean           | 846 – 173 – 496 – 177 | 241 – 62 – 176 – 2.7 | 73 – 19 – 54 – 0.8 |
| Range of net   | 92 to 338       | –21 to 67       | –6.3 to 20      |
| Fuglestvedt et al. (2010) range of net | 120 to 470 | –2.1 to 71 | –0.7 to 22 |
|                |                 |                 |                 |
| (b) GTP        |                 |                 |                 |
| Oslo CTM2      | 248 – 271 – 97 – 121 | 39 – 55 – 20 – 37 | 32 – 18 – 6.2 – 7.9 |
| TM4            | 238 – 406 – 145 – 313 | 37 – 87 – 31 – 81 | 30 – 27 – 9.4 – 5.6 |
| p-TOMCAT       | 324 – 510 – 183 – 369 | 51 – 122 – 44 – 115 | 41 – 35 – 12.3 – 5.8 |
| LMDz-INCA      | 206 – 343 – 123 – 259 | 32 – 78 – 28 – 74 | 26 – 23 – 8.1 – 4.7 |
| UCI            | 318 – 526 – 188 – 396 | 50 – 100 – 36 – 86 | 41 – 34 – 11.7 – 4.6 |
| Mean           | 267 – 412 – 147 – 292 | 42 – 88 – 32 – 79 | 34 – 27 – 9.5 – 4.1 |
| Range of net   | 396 to 121      | –115 to 37      | –5.8 to 7.9     |
| Fuglestvedt et al. (2010) range of net | –590 to –200 | –210 to –59 | –9.5 to 7.6 |

Hence, for the Oslo CTM2 model the compensating effect of the negative forcing due to CH4 and its resulting effect on stratospheric water vapour and O3 is smaller than for the other models. The differences in CH4 lifetime between the models (Table 4) have only a small influence on the range of results.

If the reason why the models differ in ratio of CH4 change to O3 change can be understood, there is hope for a marked reduction in the inter-model range in the estimated net RF from transport and in metrics such as the GWP and GTP. However, as is clear in Table 5, even when models agree in the net value of a metric, the individual components contributing to this net value can be quite different – for example, UCI and p-LMDz-INCA agree well in the net for both metrics and most time horizons, but disagree significantly for the three components; this effect is traceable to the larger change in O3 in UCI compared to LMDz-INCA (see Table 2).

5. Conclusions

We have investigated the RF for the year 2000 due to changes in O3 and CH4 caused by the transport sector, using five global chemistry models and two radiation models. We find the difference between ROAD, SHIP and AIR to be robust across all models. For the year 2000, this study reduces the CH4 and CH4-induced O3 impacts to account for the slower response of CH4 perturbations to changes in OH. It also includes the effect of CH4 changes on stratospheric water vapour. The results are also used to present values of GWP and GTP for AIR NOx emissions which are based on a range of global chemistry models adopting the same experimental design.

Fuglestvedt et al. (2008) found, based on one global chemistry transport model and one radiative transfer model, a year 2000 RF for the combined effect of O3 and CH4 amounting to 42 mW m⁻² for ROA.D, 11 mW m⁻² for SHIP and 12 mW m⁻² for AIR, based on a different set of emissions (see Fig. 1). The multi-model means obtained here are 16 mW m⁻², 18 mW m⁻² and 6.0 mW m⁻² respectively. The ROAD and AIR are significantly smaller in the present analysis than in (Fuglestvedt et al., 2008), while SHIP is significantly more negative. Various factors explain the differences. First, the emissions are different. As a consequence, a lower ozone production (at least for ROAD with lower CO and NMHC emissions) and hence less net positive radiative forcing is calculated. Second, the secondary consequences of methane changes included here (i.e. responses in O3 and stratospheric H2O) increase the negative radiative forcings. Third, the Oslo CTM2, which was used in the Fuglestvedt et al. (2008) study is seen here to produce results at the upper end of the spectrum, compared with the multi-model mean. All three factors act together to lower the calculated radiative forcing from the transport sectors compared to the values in Fuglestvedt et al. (2008). The RF for the combined effect of O3 and CH4 can be compared to the RF due to CO2 which has previously been estimated to be 150 mW m⁻², 35 mW m⁻², 21 mW m⁻² for ROAD, SHIP, and AIR, respectively (Fuglestvedt et al., 2008).

The results reported here with the QUANTIFY inventories can be compared with the previous Hoor et al. (2009) results using preliminary QUANTIFY inventories, where the multi-model means were 7.3 mW m⁻², 26 mW m⁻² and 2.9 mW m⁻² for ROA.D, SHIP and AIR, respectively. For SHIP and AIR part of the difference is due to account being taken here of the lack of steady state of the CH4 field with the changed OH field, which reduces the size of the CH4 offset to the positive short-term O3 forcing. The factor of more than two change for ROAD has a number of identified reasons (emissions, model updates, and method for CH4 RF calculations); the short-term O3 forcing is only changed by about 10% while the offset resulting from the changed OH field is now smaller. Based on the much higher emissions of CO and NMHC in Fuglestvedt et al. (2008) it is expected that the O3 RF for ROAD was higher in that study compared to Hoor et al. (2009) and this study (see Fig. 1). On robustness and uncertainties for road transport, the O3 RF is highly dependent on the background NOx emissions used in the model, including those from power generation, agriculture, lightning and biomass burning.

The inter-model absolute differences are smaller when the combined effects of O3 and CH4 RFs are calculated than they are for the short-term O3 RF alone. Nevertheless, the combined O3 and CH4 RF from individual models can deviate by many tens of percent from the multi-model mean. One significant factor in these differences, and the difference in the aviation climate emission metrics, is the ratio of the percentage change in CH4 lifetime to the column CH4 change. If the underlying reasons for this ratio could be understood, there is the possibility of markedly decreasing the inter-model differences.
The RF resulting from the effect of transport-related emissions on ozone and methane reported here must be combined with estimates of the transport-related RF from aerosols and CO2 (e.g. Balkanski et al., 2010) to improve understanding of the overall impact of the transport sector on climate.

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