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# The impact of emissions from shipping, aviation and road traffic on atmospheric composition and climate

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## Introduction

Fossil fuel combustion by aviation, shipping and road traffic contributes about one fifth of the total global anthropogenic emissions of CO<sub>2</sub>. These emissions are growing more rapidly than those by other sectors such as power generation and industry. This rapid growth could make it difficult to meet the emission targets agreed upon within the EU, the Kyoto Protocol, and its possible follow-up. In addition to CO<sub>2</sub>, the transport sectors also emit nitrogen oxides (NO<sub>x</sub>=NO+NO<sub>2</sub>), carbon monoxide (CO), and hydrocarbons (HCs) that lead to further perturbations of the atmospheric concentrations of the greenhouse gases ozone and methane. The emissions of particles and particle precursors by the transport sectors change the optical depth and properties of aerosols, which affects the radiation balance of the atmosphere regionally. The total climate impact of aviation emissions (excluding the uncertain impact on natural clouds) was estimated to be a factor 2-3 higher than that of CO<sub>2</sub> from aircraft alone. While the climate impact of the aviation sector has already been assessed quite extensively, e.g. in the IPCC Special Report on Aviation and the Global Atmosphere<sup>1)</sup>, the impact of other modes of transport has received much less attention. Calculation of the individual impacts of sectors would allow an intercomparison as well as an evaluation of the efficacy of possible mitigation measures.

Shipping emissions occur in a relatively clean environment and it is not clear to what extent this affects their impact on climate. Until recently, also the impact of road traffic emissions was quite uncertain because of uncertainty about vehicle emission factors, and lack of information about road traffic intensities in developing countries.

KNMI participates in the EU Integrated Project Quantify (Quantifying the Climate Impact of Global and European Transport Systems; see <http://www.ip-quantify.eu>), which aims at reducing these uncertainties and quantifying the impact of the transport sectors on atmospheric composition and climate. The Port of Rotterdam participates in the project as an advisor for shipping. Within Quantify new emission inventories for road transport, aviation

and shipping have been constructed for the year 2000 as well as emission scenarios up to 2100. The year 2000 emissions have been used as input to atmospheric chemistry models, such as the KNMI TM4 model, to calculate the impact of the transport sectors on the global distributions of the greenhouse gases ozone and methane. Here we summarize some of the first findings.

## Emissions by transport modes

Emissions from fossil fuel combustion by aviation (~2%), shipping (~14%) and road traffic (~22%) contribute together about 38% of the total global anthropogenic emissions of NO<sub>x</sub> (excluding biomass burning). Road traffic has been estimated to contribute between about 8-15 % of the total emissions of CO. The contributions of shipping and aviation to global CO emissions are estimated to be much smaller, likely due to more efficient fuel combustion.

Road traffic emissions occur mostly over the land surfaces of the eastern US, Europe, the Far East and India. In these regions also other, non-traffic, sources are important. Ship emissions are largest over the North Atlantic and along the coastlines of the US, Europe, and East Asia. Aviation emissions peak over the east and west coasts of the US, and Western Europe. At upper levels the aircraft emissions in the North Atlantic Flight Corridor constitute an important perturbation. Overall, the east coasts of the US and Asia, and Western Europe, including the North Sea, are regions with a relatively high emission contribution by transport.

## Model simulations

In order to calculate the current impact of aviation, shipping and road traffic, five simulations were performed with the atmospheric chemistry models involved in Quantify: a) a base simulation b) three simulations with aviation, shipping and road traffic emissions respectively reduced by 5% c) a simulation with the emissions from all transport modes (aviation+shipping+road traffic) reduced by 5%. It was chosen to apply 5% perturbations, instead of 100% ones, because atmospheric ozone chemistry is non-linear for perturbations where e.g. road traffic is

completely switched off. The relative impact of the different transport sectors on ozone and methane for the present-day background composition of the atmosphere was obtained by scaling back to 100% perturbations. The fifth simulation allowed us to check the validity of the assumption of linearity and additiveness for the perturbations. This assumption was found to be satisfied almost everywhere to within 1%. As background emissions the EDGAR3.2 FT 2000 emissions described by Olivier et al.<sup>2)</sup> (see also <http://www.mnp.nl/edgar>) were used. The production of NO<sub>x</sub> by lightning in the models was scaled to 5 Tg (N)/year, which is in the range of current best estimates.

The simulations for the year 2003 were analysed but the models were run from January 2002 in order to allow for sufficient spin-up of the new emissions. The results of the base simulation were also used to evaluate the models against observations for 2003 collected in the ETHmeg observational database (<http://www.megdb.ethz.ch>). This model evaluation against ozone soundings showed that the KNMI TM4 model was performing relatively well with respect to tropospheric ozone in comparison to other European models. One of the reasons may be that a significant improvement in the description of the stratospheric influx of ozone has been implemented recently by Van Noije et al.<sup>3)</sup> TM4 was underestimating tropospheric ozone over Africa in 2003, perhaps due to an underestimate of NO<sub>x</sub> emissions in the EDGAR3.2 FT2000 biomass burning inventory which is based on the Global Fire Emissions Database (GFED) constructed by Van der Werf et al.<sup>4)</sup> The emission factor for NO<sub>x</sub> in EDGAR3.2 FT2000 was taken from a recent update by Andreae (pers. comm., 2004) yielding a 40% lower value for savannah fires than in previous inventories that used estimates made by Andreae and Merlet<sup>5)</sup>.

#### Effects on global ozone and methane

Figure 1 shows the zonal mean distribution of ozone and the perturbations caused by aviation, road traffic, shipping, and all transport modes together, as calculated by the TM4 global atmospheric chemistry model for July 2003. Although the NO<sub>x</sub> emissions from aviation are an order of magnitude smaller than those from road traffic and shipping, they cause the largest ozone perturbation. This is because the lifetime of NO<sub>x</sub> increases with height, making catalytic

ozone formation by NO<sub>x</sub> more efficient in the upper troposphere and lowermost stratosphere. The ozone perturbation due to aviation thus maximizes at cruise altitudes in the northern hemisphere. Road traffic emissions have a significant effect in the mid-latitude upper troposphere in summer because they can be rapidly transported upward by summertime convection over warm continental surfaces. In winter (not shown) their impact on the upper troposphere is much smaller. Ship emissions are transported much less efficiently upward than road traffic emissions because there is much less convection over the oceans than over land at mid-latitudes. However, there is some upward transport of ship emissions by tropical deep convection, giving a relatively more important contribution from shipping to tropical upper tropospheric ozone. As a result of the geographical distribution of all emissions, the increase of the ozone column due to transport is largest in the northern extra-tropics (north of 30°N), with a regional maximum of about 3.5 DU over the central North Atlantic in January, and of about 4.5 DU over western Europe in July.

The lifetime of methane in the base simulation with TM4 was 9.1 years. Aviation reduces this lifetime by about 0.8%, road traffic by about 1.9%, and shipping by about 4.5%. Especially, ship emissions are quite effective in reducing methane levels because they occur in the relatively clean marine environment. Hence, emissions by transport have counteracting effects on ozone and methane. Globally averaged the ozone perturbation dominates, giving a net positive radiative forcing (warming). However, it should be noted that the ozone and methane perturbations have different geographical patterns, so that even a zero net radiative forcing might still lead to significant regional climate changes.

#### Acidification

The ultimate fate of nitrogen and sulphur compounds emitted by transport modes is removal by dry deposition to the earth's surface or by wet deposition by precipitating clouds. Since sources and sinks of nitrogen and sulphur more or less balance when considering a full year, total annual deposition is almost equal to the total emissions for each sector. Road traffic annually emits about 6.8 Tg N and about 2.2 Tg S, and shipping emits about 4.4 Tg N and about 6 Tg S

## *Emissions by transport have counteracting effects on ozone and methane*

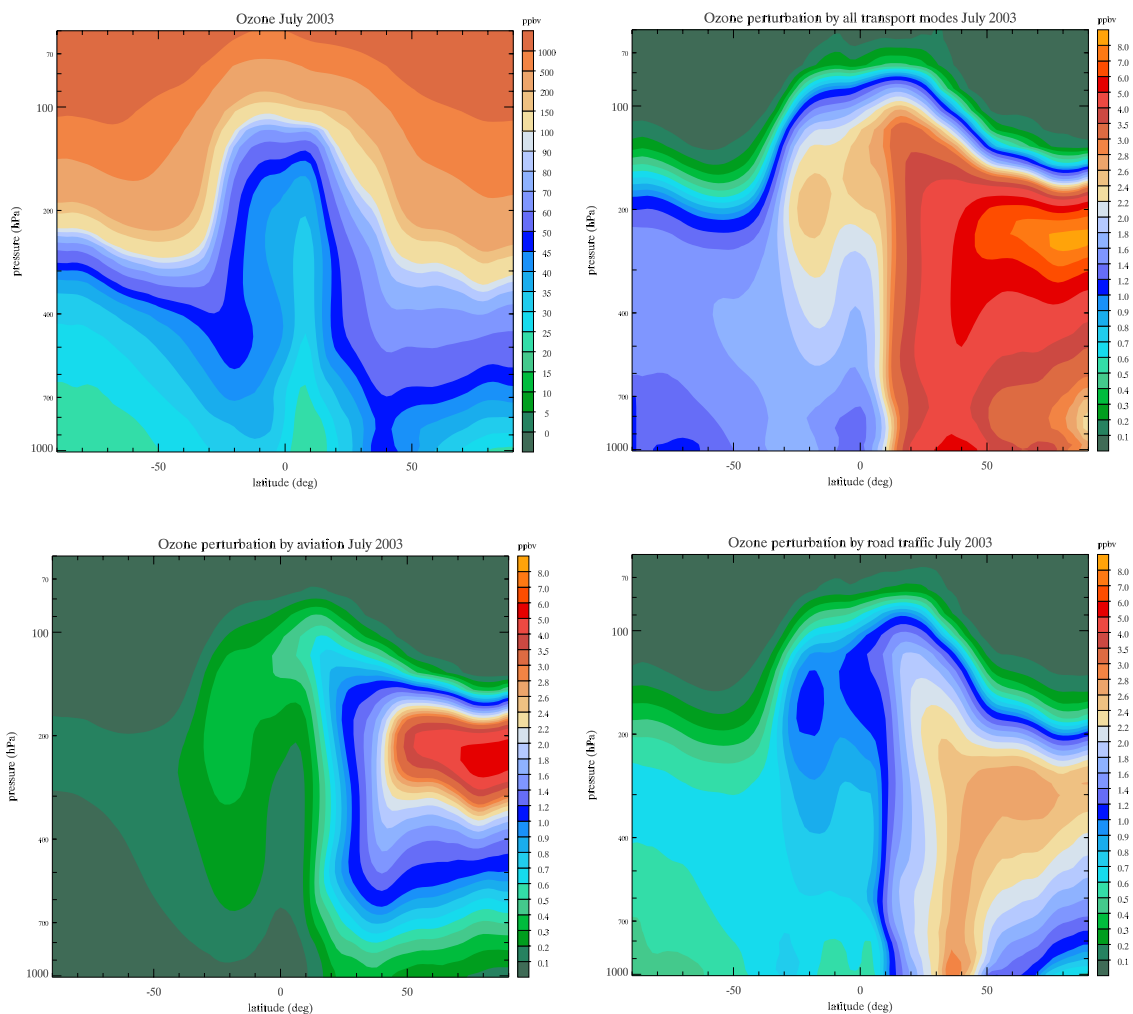


Figure 1. Zonal mean background distribution of ozone, and the perturbations caused by aviation, road traffic, shipping, resp. all transport modes together, for July 2003. Units are ppbv. The colour scales of the perturbation plots are identical, but different from the plot of the background distribution.

compounds. In view of its total emission of about 0.76 Tg N and 0.07 Tg S, aviation is much less relevant for acidification than road traffic and shipping. The calculated deposition maps in Figure 2 show that the deposition of nitrogen compounds from transport is concentrated in a few specific geographical regions. The same is true for sulphur compounds emitted by the transport modes (not shown). Most nitrogen deposition occurs over Western Europe and the east coasts of the US and Asia, close to the major emission sources from shipping and road traffic. Due to emissions from transport in total about 12 Tg N and about 8 Tg S is deposited globally. This is about one tenth of the total global sulphur deposition and about a quarter of the total global nitrogen deposition.

### Conclusions and outlook

Emissions by the transport sector (aviation, road traffic and shipping) are of concern because they grow more rapidly than those from other sectors. The emissions of  $\text{NO}_x$  by transport lead to an increase in ozone in the northern extratropical troposphere and a global decrease in methane. The effect of  $\text{NO}_x$  emissions by shipping on methane was larger than expected, probably because they occur in a relatively clean environment. In summer, road traffic emissions have an appreciable impact on ozone up to the tropopause due to upward transport by convective clouds over land. The acidifying effects of emissions by transport are mostly concentrated in a few regions, including Western Europe and the east coast of the US and Asia.

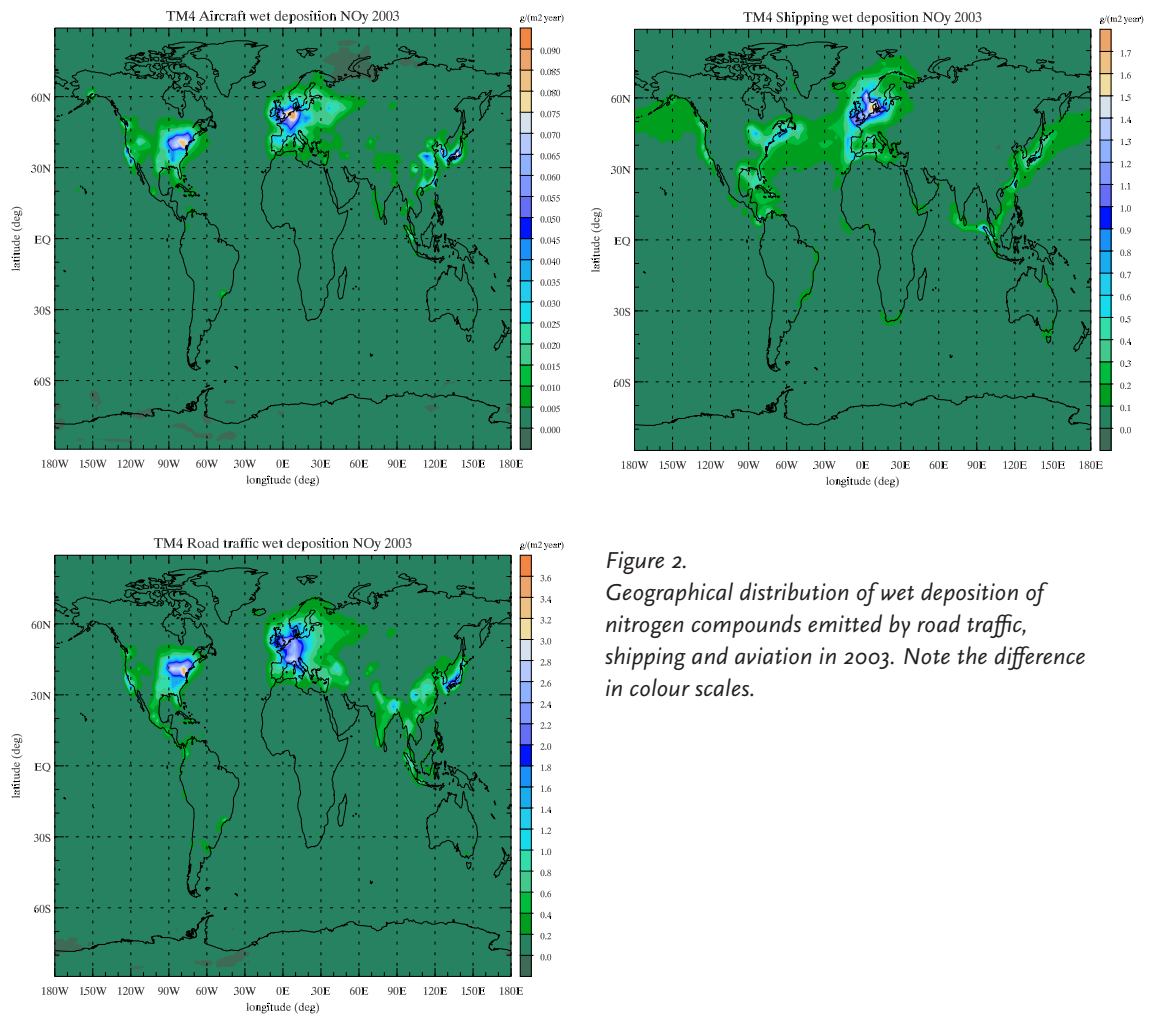


Figure 2. Geographical distribution of wet deposition of nitrogen compounds emitted by road traffic, shipping and aviation in 2003. Note the difference in colour scales.

## The deposition of nitrogen (and sulphur) compounds from transport is concentrated in a few specific geographical regions

The 5 year EU project Quantify is now almost halfway. Following the calculation of the current impact also the future impact will be calculated based on scenarios linked to the IPCC SRES scenarios, but with timelines adapted to the technical, economic and geographic development of the transport sectors. Also the influence of climate change on the calculated impacts will be assessed, and the effect of a few mitigation options will be quantified. For shipping it will be especially important to quantify the effect

of the expected increase in Arctic routes, especially during fall, winter and spring when ozone and other pollutants have relatively long lifetimes, and thus could cause an appreciable acceleration of Arctic climate warming<sup>6</sup>). Presently, ozone values in the Arctic are still a factor 2-3 smaller than at northern mid-latitudes.

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