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QUANTIFY
Quantifying the Climate Impact of
Global and European Transport Systems

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Global Change and Ecosystems

Final activity report

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1. Scientific objectives of the QUANTIFY Integrated Project

1.1 Motivation and background

The transport sector contributes about one third of the total global anthropogenic CO₂ emissions. The annual growth rate of transport related greenhouse gas emissions is larger than for other mature industrial sectors. In the light of the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and possible follow-up Protocols, this rate of increase creates a severe problem when trying to achieve emission reduction targets. Additionally, the impact of the transport sector on climate is complex and is mediated through more than just the list of gases in the Kyoto Protocol.

Nonetheless, the global and European economic systems are largely dependent on an efficient transport system. This dependency has grown during recent decades. Life style and the availability of cheaper transport in developed countries are also enhancing demand. In addition, strong growth of the transport sector is expected in developing countries. In the long term, a sustainable transport system is needed that satisfies in an optimal way the demands of economy and population whilst following the constraints of climate change control. In order to meet these constraints clear information on the climatic impact of different transport emissions is needed.

Transport can impact on climate in several ways:

- (1) by direct emissions of greenhouse gases, mainly CO₂, but also N₂O and others;
- (2) by emissions of indirect greenhouse gases, e.g., precursors of ozone, such as NO_x, CO or VOCs;
- (3) by emissions of aerosols or their precursors, in particular black carbon and SO₂, which are directly and indirectly (via cloud formation and cloud modification) radiatively and chemically active;
- (4) by directly triggering additional clouds (e.g., contrails, contrail cirrus¹).

The climate effects and further effects of transport emissions can best be visualized with the chain of impacts of emissions (Figure 1). The chain starts with the emission of substances that get then mixed with the ambient atmosphere, whereby they undergo chemical reactions (processing) and spatial dilution. As a consequence, the chemical composition of the atmosphere changes. Particulate emissions lead to additional clouds and may modify natural cloud properties. All these effects lead to changes in the flow of radiative energy in the atmosphere, that is, the balance between radiative energy received from the sun and radiative energy leaving the Earth-atmosphere system is perturbed, which is termed radiative forcing. Ultimately, the Earth and its atmosphere have to react in order to restore the energy balance. This manifests itself as the climate change which can appear in many forms, e.g., as higher temperatures, risen sea-level, changed precipitation patterns, etc., so that a multitude of climate impacts on health and economy are possible. Unfortunately, while it is relatively straightforward to compute the transport emissions, the predictions become more and more uncertain when going down the cause-effect chain, because the complexity of the problem grows from stage to stage and the uncertainties from one stage are transferred down the chain. The QUANTIFY Integrated Project was initiated with this cause-and-effect chain in mind.

¹ A contrail cirrus is a cirrus cloud that developed from a contrail. A contrail cirrus is similar to a natural cirrus cloud but would not have developed without the formation of the contrail.

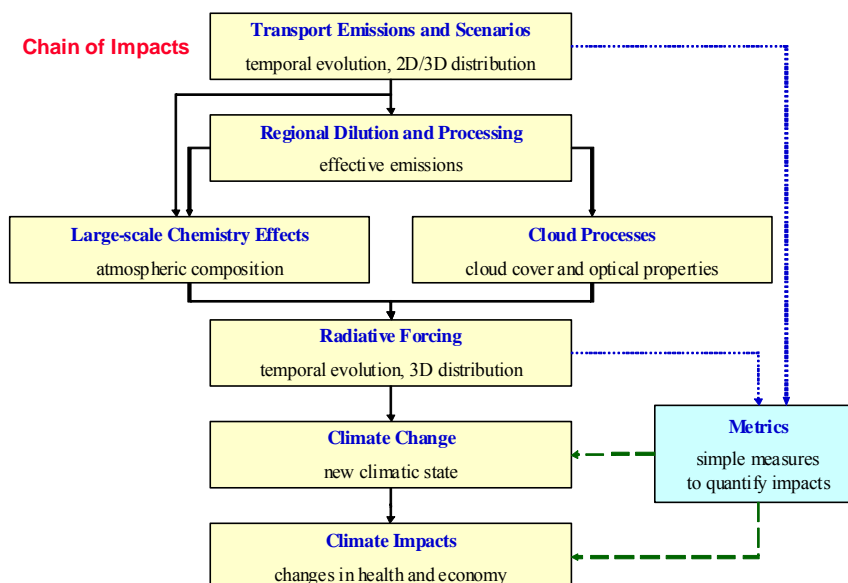


Figure 1: Schematic of chain of impacts from emissions to climate change and climate impacts. Only the main fluxes of information are indicated by arrows. QUANTIFY science tasks are printed in blue, output is in black.

Currently only the six gases or groups of gases from the Kyoto basket² are regulated or can be included in emission trading, using the 100-year Global Warming Potential as an exchange rate. No suitable metric had been agreed that would allow for a scientifically credible inclusion of other effects, e.g., contrails, ozone precursors or particles. For these components, the climate effect strongly depends on the location and time of the emission and on the current state of the background atmosphere. Metrics, once developed and agreed on, can be used as a short-cut to conclude from emissions on the potential climate change and impact.

Before QUANTIFY, the global climate impacts of other modes of transport than aviation have not yet been assessed in a consistent way. Such an assessment would enable a comparison of individual contributions and therefore a fair judgement of the impact of changes in the mode of transport or the value of mitigation strategies.

1.2 Objectives

In the light of the development time and long lifetime of land, sea and air vehicles, together with transport infrastructure (several decades up to 100 years), the long residence time of some of the emitted species and the thermal inertia of the climate system, it was clear that potential mitigation procedures needs to be assessed to provide policymakers and industry with adequate guidance for decisions. It was our aim to provide such guidance through the QUANTIFY Integrated Project based around new focussed field measurements, further exploitation of existing observations, and a range of chemical, radiative and coupled climate models.

The main **project goal** of QUANTIFY was

- *to quantify the climate impact of the global and European transport systems for the present and for different scenarios of future development.*

² CO₂, CH₄, N₂O, PFCs, HFCs, SF₆.

This overall goal was approached via the following more detailed objectives:

1. To establish consistent inventories of emissions (greenhouse gases, particles, precursors of greenhouse gases and aerosols) from present day and past transport, separately for the different modes of transport.
2. To generate inventories of transport emissions for scenarios of future development, which are consistent with the IPCC SRES scenarios.
3. To determine the fate of emissions from shipping during the dilution to regions of the size of global scale models, i.e., to scale in the range 100 to 500 km.
4. To develop parameterisations for "effective emission indices" linking local emissions (at the exhaust) to scales of global models for all modes of transport (aviation, shipping, land surface transport).
5. To consistently calculate the global chemical impact of the different modes of transport, for present day conditions and several future scenarios.
6. To determine regional structures in transport-induced perturbations of the chemical composition of the atmosphere, e.g., North-South contrast, tropics versus extra-tropics, in particular in the UTLS region.
7. To provide quantitative estimates of the impact of the different modes of transport on aerosols and clouds, in particular on cirrus (contrails and contrail-cirrus) and low marine clouds (ship track) in terms of, e.g., clouds cover and cloud optical properties.
8. To verify the hypothesis that anthropogenic aerosol causes the formation of additional clouds (indirect aerosol effect of the 1sr kind).
9. To consistently determine the radiative forcing from transport-induced changes in atmospheric (and surface) parameters, including the separation of the contributions from different modes of transport, for present day transport and for several future scenarios.
10. To determine the spatial and temporal pattern of transport-induced climate change and to search for specific fingerprints distinct from other causes of climate change.
11. To develop and evaluate policy relevant metrics that allow the inclusion of all import impact on climate and that take the particular aspects of transport into account.
12. To estimate the impact of potential mitigation options on atmospheric composition and climate.

The rest of this report describes in more detail how these objectives have been met, i.e., what kind of methods have been applied, which results have been obtained, and which conclusions may be drawn.

2. QUANTIFY methods

It is obvious that the cause-effect chain of Figure 1 cannot be treated with a single tool or a single method. Instead, a whole bunch of methods is needed, starting from scenario building, over laboratory experiments, field campaigns, satellite data retrieval and analysis, up to a hierarchy of numerical models for the simulation of atmospheric chemistry, atmospheric radiation transfer, clouds and contrails, and the general atmospheric dynamics. Therefore, QUANTIFY was organised in 7 Science Activities that followed the logical structure of the cause-effect chain.

In Activity 1 (*Transport Emissions and Scenarios*), emission scenarios for all motorised modes of transport were developed and/or adapted (in a top-down approach) such that they fitted to selected IPCC SRES scenarios for the overall development. Space and time resolving inventories of transport emissions were generated for these scenarios, for present and past emissions as well as several potential futures. The related transport volumes were also estimated.

The further fate of the emissions in the plume up to the scale of a global model's grid boxes was studied in Activity 2 (*Regional Dilution and Processing*). The emitted species not only undergo dilution and mixing with the ambient air but also chemical reactions with other emitted species and species present in the background air. Methods used here were field measurements (ship campaign) and numerical models of regional scale. A major product of this Activity are the "effective emissions" parameterisations, whereby sub-grid scale conversions are accounted for.

The large-scale impact of the transport emissions on the chemical composition of the atmosphere was studied in Activity 3 (*Large-Scale Chemistry Effects*), using global Chemistry Transport Models (CTMs) and global Climate-Chemistry Models (CCMs). Such models needed to be validated against measurements from satellites, campaigns, programs like CARIBIC and MOZAIC. For this purpose we collected, processed and archived such data within Activity 4 (*Long-term Measurements of UTLS Compounds*).

Activity 5 (*Aviation, Shipping and Clouds*) concentrated on the investigation of the generation of new clouds and the modification (cloud cover, optical properties) of natural clouds due to land, sea and air traffic, with emphasis on aviation and shipping. For that purpose the following methods were applied: development of new satellite data retrieval algorithms, cloud resolving numerical models for ship tracks and contrails, general-circulation models (GCMs) with focus on aerosol and clouds, statistical methods in order to find the anthropogenic footprint in cloud and aerosol changes, and last but not least even laboratory experiments on the ice nucleating ability of exhaust soot.

Both the changed chemical composition of the atmosphere and the changed cloudiness have an impact on the radiative transfer. The resulting radiative forcings were calculated in Activity 6 (*Radiative Forcing and Climate Change*). In this Activity, General Circulation Models (GCMs) and radiation transfer models were applied.

Activity 7 (*Metrics*) used and calibrated simple climate models with the aim to improve metrics of climate change, in particular with respect to non-homogeneously distributed climate change agents, which are an important feature of the transport sector. These metrics allow a better comparison of emissions from transport and other sectors with respect to climate effects and with respect to impacts on health and economy.

Two non-scientific Activities contributed to the dissemination of the results obtained by organizing annual project meetings, the TAC and TAC-2 conferences, and a post-QUANTIFY stakeholder workshop, a summer-school, and e-learning materials. QUANTIFY runs a web site, which contains an overview of the project: <http://www.ip-quantify.eu>.

3. QUANTIFY results

3.1 Emissions

QUANTIFY established consistent global 3D/4D transport inventories of (direct) emissions (greenhouse gases, particles, precursors of greenhouse gases and aerosols) for past and present, and for different transport modes. Additionally we developed scenarios of emissions for future transport (for the various modes of transport), which are consistent with IPCC SRES scenarios (A1B, A2, B1, B2), and generated associated emission inventories. There are new aviation, shipping emission and land transport inventories for the present day (year 2000) and for several future years, 2020, 2050 and 2100.

The QUANTIFY roads inventory is probably the first global 'bottom-up' inventory developed for the scope of pollutants produced, technological differentiation (5 vehicle classes with 4 fuel types each) and globally at the country level. The inventory was evaluated by cross-checking of the calculated fuel consumption with fuel sold in each region. This resulted in a good agreement between the factors for independently determined traffic volumes, consumption and emission factors, and the independent data on total fuel consumption. More than half of the global mileage of

mopeds and motorcycles is driven in the Asian regions. Likewise, three quarters of bus mileage is driven in non-OECD countries. At an occupancy rate of 20 or (many) more passengers per kilometre, busses are by far the most important means for road passenger travel in these countries. On the contrary, and not as a surprise, cars are the most important passenger transport means in OECD countries. More than 80% of global mileage is driven there, with almost half in North America and Western Europe, each. Heavy duty trucks are in all regions the backbone of road freight transportation; their global transport volume is distributed about 60% to 40% between OECD and non-OECD countries. Light duty trucks are most prominent in North America but are popular in non-OECD regions as well. As an example the spatial distribution of road transport's NO_x emissions in the year 2000 is shown in Figure 2.

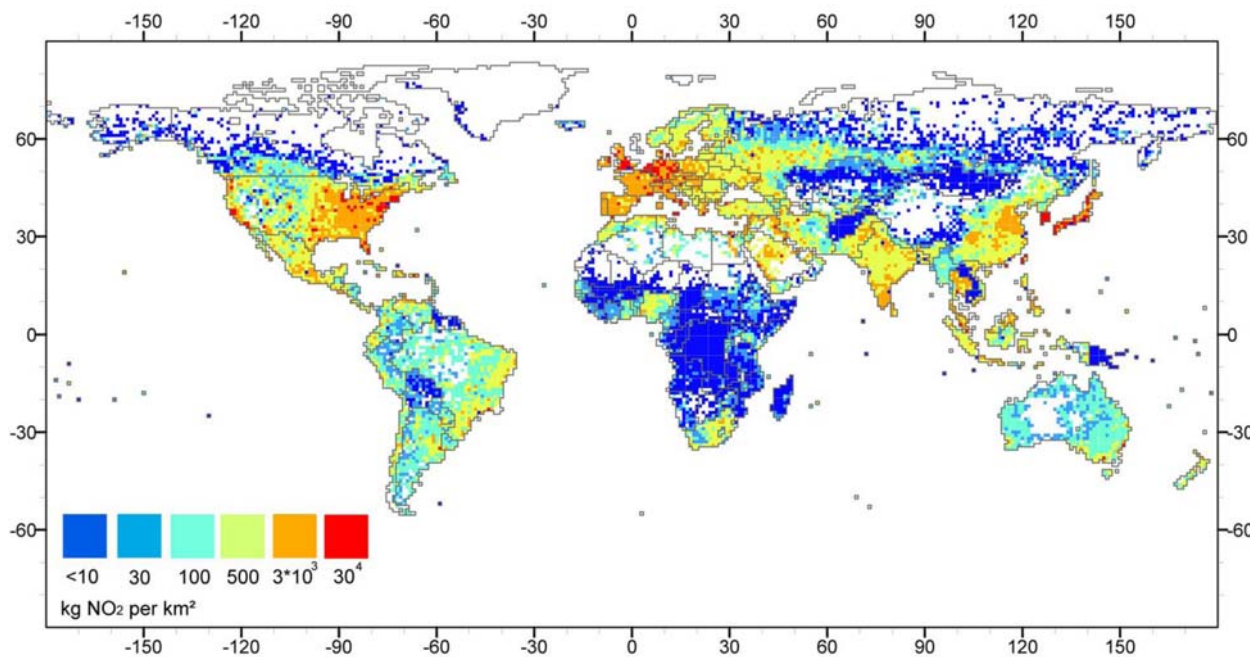


Figure 2: Gridded road emissions of NO_x as NO_2 in 2000.

A substantial effort was made in quantifying the indirect emissions from fuel provision for the present day which will enable a comparison of emissions from the different transport modes. This is particularly important for rail which relies on electricity. This scheme is extended for future emissions taking into account bio energy and synthetic fuels as well as traditional fossil fuels and electricity. Consistent draft historical global emissions back to 1900 for all transport modes have been compiled and compared to global total emissions (CO_2) showing an increasing share of transport emissions.

The Quantify emissions scenarios are available after registration and signing of a data protocol via the website (<http://www.pa.op.dlr.de/quantify/emissions/>). There has been significant uptake of the usage of these data by the external international community. QUANTIFY data are now being used by an international consortium of modellers undertaking simulations for the IPCC AR5. This gives a prominent position to QUANTIFY in the AR5.

3.2 Plume processes

Emissions from vehicles into the atmosphere occur rather locally, namely on a spatial scale characterised by the diameter of the exhaust pipe, that is, typically a few centimetre up to a few metres. These localised emissions initially form plumes with pollutant concentrations that are much higher than in the atmospheric background. In the course of time the plumes are diluted by mixing

with the ambient air, and during this dilution process the emitted species are chemically transformed. Secondary species (e.g., ozone) are formed, particles are modified by coagulation and condensation processes, and part of the emitted compounds are removed from the atmosphere by wet and dry deposition. These processes depend non-linearly on the concentrations of the primary emissions, on the atmospheric background concentrations and on the actual meteorological state of the atmosphere.

Numerical models of the atmosphere (e.g. GCMs or CTMs) divide the atmosphere in so-called grid boxes that are much larger than a plume, typical resolutions are many tens of kilometres in the horizontal directions and several hundred metres in the vertical. The problem to be solved is therefore how to distribute the initially localised emissions over such large grid boxes without losing information on the chemical and physical transformation processes that take place in the plumes. What is needed are the amounts of the emissions after undergoing all these plume processes; these are the so-called effective emissions. QUANTIFY studied the small-scale chemistry processes in plumes from ships, aircraft and road traffic to derive effective emissions. A particular focus was laid on the role of heterogeneous reactions in plumes.

Processes in ship plumes were investigated during two measurement campaigns where ship plumes were probed with the DLR research aircraft Falcon in a series of plume transects at plume ages between 100s and 1h. During the second campaign, simultaneous measurements onboard the ship were performed. The transformation of exhaust products during plume evolution from stack emission into a polluted shipping corridor was also studied in the 2007 field campaign. Transects of the highly frequented shipping corridor in the Gulf of Biscay were analysed. Effective emission indices for soot particle number, soot mass, NO₂ and various organic species were determined.

Numerical simulations of plumes were performed for ship and aircraft exhausts in order to complement the measurements. It could be shown, that a ship plume initially disperses due to the additional heat in it which leads to buoyant motions, but only for a short period. Thereafter, the plume disperses due to convection in the ambient atmosphere. The latter is therefore the more important process for the parameterization of effective emissions for ship plumes.

A new parameterization that accounts for the transformation of emissions and their chemical reactions has been proposed for the plume NO_x chemistry in large-scale models (Cariolle et al., 2009). This is based on the representation of the plume effects via a fuel tracer and a characteristic lifetime during which the nonlinear interactions between species are important and operates via conversion rates for the NO_x species and an effective reaction rate for O₃. This parameterization, applied on aircraft emissions, was then integrated into a GCM (note that at the scale of a global model, the concentration of NO_x is low enough to produce O₃, as opposed to what happens in the plume where NO_x is much higher and leads to O₃ destruction). The results showed that accounting for plume chemical transformation leads to significantly lower global ozone production by the aircraft NO_x emissions, within regions of dense air traffic like the North Atlantic Flight Corridor and over parts of Asia by 15 to 25%, see Figure 3.

3.3 QUANTIFY ship measurement campaign

Regional impacts of transport emissions have been investigated experimentally during ship corridor measurement flights over the English Channel. Numerical modelling of the plume expansion and chemistry was employed to aid the interpretation of the measurement results.

The main measurement campaign on ship emissions was rather successfully performed in June 2007. Trace gas and particle measurements were carried out from the DLR research aircraft Falcon, which was based in Brest, France, and onboard the container ship Atlantic Conveyor. On board of the Falcon the following species were measured in situ: CO₂, CO, O₃, NO, NO₂, NO_y, SO₂, HC, aerosol size distribution, aerosol volatility, black carbon, and meteorological parameters. Corresponding measurements were also performed onboard the Atlantic Conveyor in the fresh exhaust. 8 flights were performed including: (a) three flights across the ship corridor from Brest to Cornwall during conditions of easterly wind with impact of ship emissions and continental

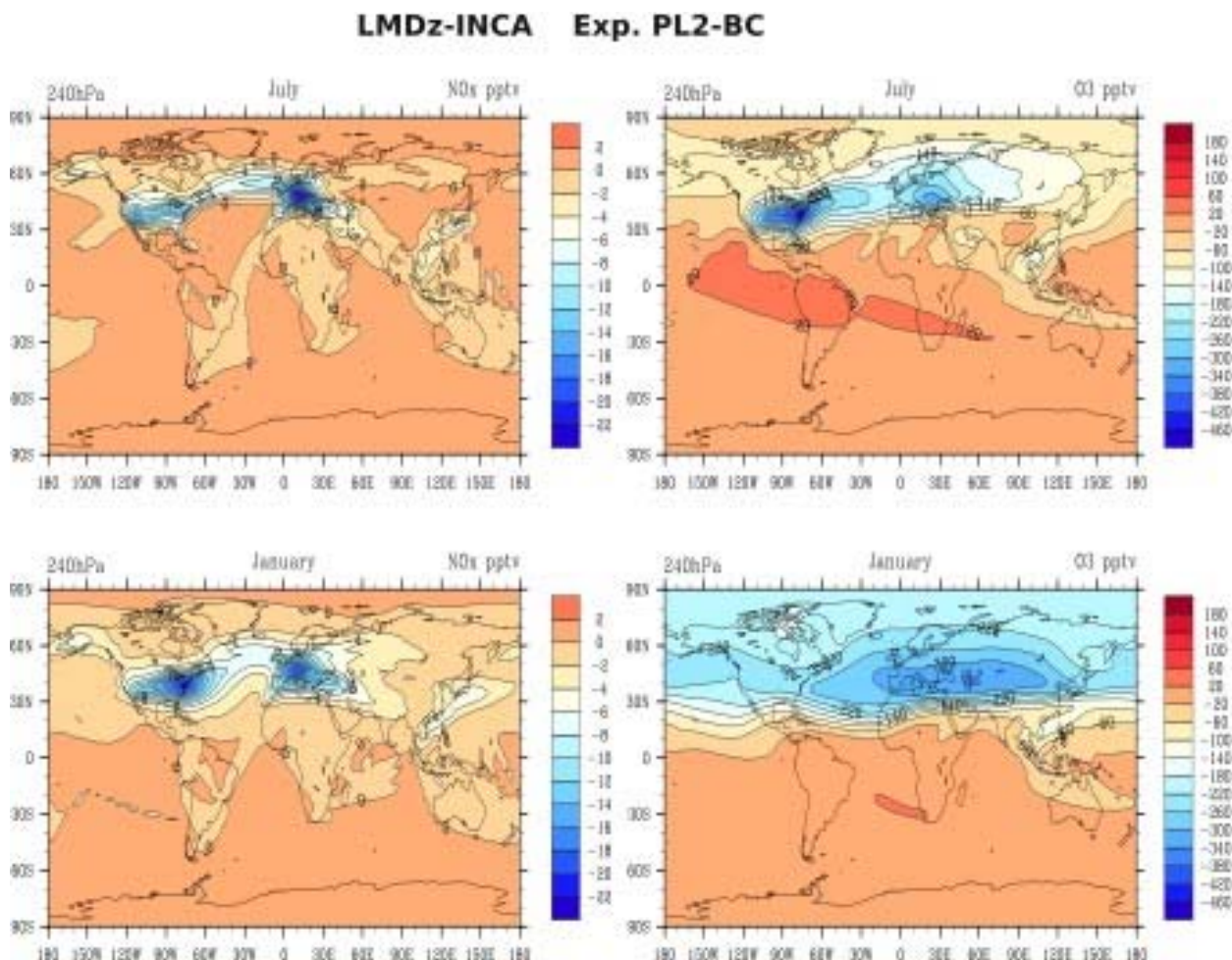


Figure 3: Effect of plume sub-grid chemistry on the perturbation of NO_x (left) and ozone (right) over the globe.

European ground-based emissions, (b) two flights across the ship corridor between Brest and Cornwall/Brest and Spain during westerly wind with strong contrast of pristine marine boundary layer air and ship emissions, (c) one flight along the entire English Channel, and (d) two flights in the exhaust trail of the Atlantic Conveyor during different meteorological conditions.

For the same source ship, the composition of the exhaust from the diesel engine using heavy fuel oil was investigated onboard. Mass, size distribution, chemical composition and microphysical structure of the particulate matter (PM) were investigated. The emission index for PM was 5.3 g/(kg fuel). The PM composition was dominated by organic carbon, ash and sulphate while the elemental carbon composed only a few percent of the total PM. Laser analysis of the cooled exhaust showed presence of a rich mixture of polycyclic aromatic hydrocarbon (PAH) species while PM collected in the hot exhaust showed only four PAH species. Microstructure and elemental analysis of ship combustion residuals indicate three distinct morphological structures with different chemical composition: soot aggregates, significantly metal polluted; char particles, clean or containing minerals; mineral and/or ash particles. Additionally, organic carbon particles of unburned fuel or/and lubricating oil origin were observed. Hazardous constituents from the combustion of heavy fuel oil such as transitional and alkali earth metals (V, Ni, Ca, Fe) were observed in the PM samples.

Emission indices of gaseous compounds (NO_x , SO_2), non-volatile particles, and black carbon particles were determined from engine test rig measurements, airborne measurements in exhaust

trails of two container ships, and from data sampled in a heavily travelled shipping corridor. Table 1 includes a summary of the measured emission from the different investigations.

Table 1: Compilation of measured emission indices for ship engine exhaust

Compound	Study	EI	Reference
Nitrogen oxides (NO _x)	Clifford MAERSK	112 ± 10 g (NO ₂)/kg fuel	Schlager et al. 2007
	Atlantic Conveyor	69 ± 5 g (NO ₂)/kg fuel	Schlager et al. 2010
	Ship Corridor	82 ± 10 g (NO ₂)/kg fuel	Schlager et al. 2010
	Test rig	72 ± 5 g (NO ₂)/kg fuel	Petzold et al. 2010
Sulphur dioxide (SO ₂)	Clifford MAERSK	20 ± 5 g (SO ₂)/kg fuel	Schlager et al. 2007
	Atlantic Conveyor	42 ± 12 g (SO ₂)/kg fuel	Schlager et al. 2010
	Ship Corridor	33 ± 4 g (SO ₂)/kg fuel	Schlager et al. 2010
Non-volatile particles	Clifford MAERSK	0.9±0.1 x 10 ¹⁶ /kg fuel	Petzold et al. 2008
	Atlantic Conveyor	2.3±0.5 x 10 ¹⁶ /kg fuel	Petzold et al. 2010
	Ship Corridor	2.0±0.5 x 10 ¹⁶ /kg fuel	Pfaffenberger et al. 09
	Test rig	1.3±0.2 x 10 ¹⁶ /kg fuel	Petzold et al. 2008
Black carbon (BC)	Clifford MAERSK	174±43 mg/kg fuel	Petzold et al. 2008
	Ship Corridor	130 mg/kg fuel	Pfaffenberger et al. 09
	Test rig	179±18 mg/kg fuel	Petzold et al. 2008

3.4 Impact on global chemistry

The present and future (2025, 2050) impacts of emissions from aviation, shipping and road traffic have been evaluated using an ensemble of global atmospheric chemistry models in order to obtain not only a quantification of the impact of the transport sectors on global atmospheric composition but also an estimate of the associated model uncertainties. The assessment included chemistry-transport models from the University of Cambridge (p-TOMCAT), KNMI (TM4), University of Oslo (OsloCTM2), University of California in Irvine (UCI-CTM) and Meteo France (MOCAGE), and chemistry-climate models from LSCE (LMDz-INCA), DLR-IPA (E39/C) and MPI für Chemie (ECHAM5-MESSy). In the simulations the EDGAR32FT2000 inventory was used for anthropogenic emissions, with the transport emissions replaced by improved estimates for present and for the SRES A1 and B1 scenarios (2025, 2050) from the QUANTIFY inventory. The A1 scenario represents a world of very rapid economic growth, and rapid introduction of new and more efficient technologies. The B1 scenario assumes rapid introduction of clean and resource-efficient technologies, and is considered to be far more optimistic than the A1 scenario. The results from the scenario calculations for the impact of shipping on ozone in the lower troposphere (surface to 800 hPa) are shown in Figure 4: The impact on ozone from the shipping sector will increase significantly if emissions evolve according to the A1 scenario, while the B1 scenario leads to a much smaller increase.

The results obtained for shipping are particularly interesting in the sense that the impacts on hydroxyl (OH) and thus on methane (CH₄) were larger than anticipated before the start of the QUANTIFY Integrated Project. The reduction of the global atmospheric lifetime of methane due to ship emissions was about a factor of 2-3 larger than that due to road emissions, and about a factor of 4 larger than that due air traffic emissions (Hoor et al., 2009). This is due to the more pristine chemical conditions over the oceans and the slightly different mix of emissions from ships. As a result, the net impact on radiative forcing of ozone and methane perturbations from shipping is negative, corresponding to a more or less globally uniform cooling. This adds up to the cooling via widespread cloud modifications caused by ship emissions of sulphate aerosols (Myhre et al, 2010).

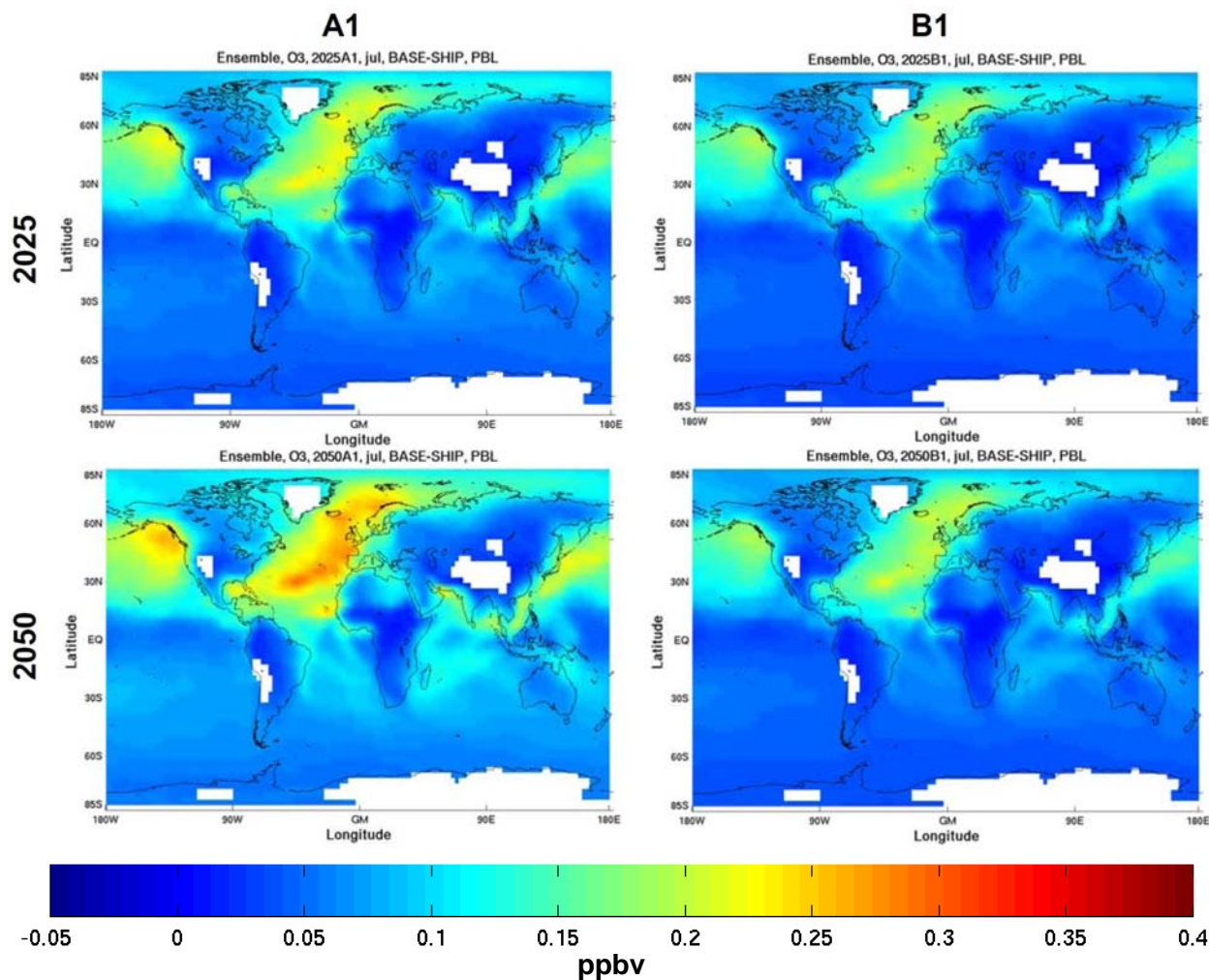


Figure 3: Ensemble mean perturbations of ozone (ppbv) for ship traffic in the lower troposphere (surface-800 hPa) during July, when applying a 5% emission reduction (BASE minus REDUCED SHIPPING).

It was also interesting to see the strong seasonal variation in the model-simulated impact of road traffic related to the much stronger vertical mixing over land by deep convection in summer. The sensitivity of ozone formation per NO_x molecule emitted is highest for aircraft emissions because the lifetime of NO_x is larger in the upper troposphere than near the surface. Estimated aircraft impacts are largely in line with previous assessments.

A few mitigation options were evaluated, e.g., the B1-ACARE scenario with reductions of the aircraft emissions due to projected improvements in technology. In the QUANTIFY B1-ACARE scenario the emissions of NO_x by aviation in 2050 were estimated to be 0.7 Tg(N)/year while in the B1 scenario they are 1.05 Tg(N)/year. The impact of aviation on ozone in 2050 was found to be reduced more or less proportionally to the total NO_x aviation emissions (Hodnebrog et al., 2011). Also for road traffic a mitigation and non-mitigation scenario were assessed.

In the above model simulations the effect of changes on climate was not taken into account. When this is taken into account for scenario A1, a decrease of the tropospheric ozone burden in 2050 due to climate change of slightly more than 1% is simulated, although locally in the upper troposphere in the inter-tropical zone an increase of ozone of up to 2% is calculated due to the enhanced lightning activity in a changed climate (Koffi et al., 2010). A reduction due to climate change of similar magnitude was found for the transport-induced ozone burden perturbation (1.6%).

We would also like to note that, for interpretation of the simulations, the performance of the global models were evaluated through comparison to the ETH Model Evaluation Global (ETHMEG) database (Schnadt et al., 2009). The model outputs were compared to measurements from aircraft (e.g. SPURT and MOZAIC), ozone soundings and surface observations, focussing on the year 2003 since meteorology for that year was used to evaluate the impacts of current emissions by the transport sectors. In particular, it was found to be difficult to simulate carbon monoxide (CO) correctly in both the lower and upper troposphere. This could be attributed to several causes: First of all, 2003 was characterized by exceptionally strong biomass burning events in the northern hemisphere. Secondly, the amount of CO emissions from road traffic and the production by oxidation of non-methane hydrocarbons were found to be quite uncertain. Upper tropospheric CO is also quite sensitive to transport by deep convection and mixing across the tropopause, both of which are notoriously difficult to simulate in global models. This indicates a direction for future model improvements.

3.5 Impact on aerosol

Particulate emissions of traffic have a multitude of potential impacts on climate. First, they scatter radiation, leading to a negative radiative forcing. Soot absorbs radiation and thus leads to a positive forcing. These are direct effects and they are minor compared to the so-called indirect effects. The latter come about via the involvement of particles in cloud microphysical processes, that is, condensation and ice formation. Without particles, i.e., aerosol, in the air, water droplets and ice crystals would not form until the relative humidity reaches enormous values of several hundred percent. The fact that water clouds form readily at water saturation (in fact, a tiny supersaturation of a few per mille is needed) shows that aerosol particles are always present in sufficient amount to serve as condensation nuclei. In order to form ice crystals a substantial ice supersaturation is needed, the amount of which depends on the process at work: Freezing of liquid solution droplets, which are of natural origin (homogeneous nucleation) needs supersaturation exceeding 45%, while freezing with the aid of appropriate solid particles, which are partly of anthropogenic origin, (heterogeneous nucleation) starts at lower supersaturation (say 20-30%). The effect of the addition of particles from traffic emissions on water and ice cloud formation depends on the predominant pathway of cloud formation in the absence of traffic emissions.

If aerosol is added in an air mass, where water clouds form, we get the so-called Twomey effect. An important example is ship tracks. As droplet formation is not very selective of the nature of the aerosol particles (i.e., every particle leads to a droplet), the addition of particles leads to more droplets. The amount of condensable water vapour does not change much, so that on average the droplets will be smaller than without additional aerosol. More but smaller cloud droplets (the same amount of liquid water) lead to an increase in cloud reflectivity, that is, such clouds appear brighter when viewed from space. This means, more solar radiation is reflected away from the Earth; hence this is a cooling effect. Ship tracks are one example of minor climatic importance, but the widespread effect of ship emissions (in particular sulphates) on low maritime clouds was shown to potentially have the largest cooling effect of all traffic emissions.

To predict the effect of additional aerosol on ice clouds is difficult; even the sign, i.e., cooling or heating, is uncertain. The difficulties arise from the presence of various pathways to ice formation and from a lack of knowledge of which process dominates in the atmosphere. In clean unpolluted air ice clouds form by homogeneous nucleation, while in polluted air, perhaps like in air traffic corridors, heterogeneous nucleation might be predominant. Now, there are always very many solution droplets (order 10^8 m^{-3}), such that ice cloud forming homogeneously have large number concentrations of ice crystals. In contrast, heterogeneous ice formation is a very selective process: Only 1 out of a million particles are an appropriate ice forming nucleus (IN). Thus, ice clouds forming predominantly by heterogeneous nucleation have small number concentrations of ice crystals. The addition of IN into a clean environment leads to heterogeneous ice formation *before* homogeneous freezing can occur. Thus the resulting ice cloud has less but bigger crystals than a cloud that would have formed purely homogeneously. This effect has been termed “negative

Twomey effect". When, however, heterogeneous ice formation is already dominant like in a polluted air mass, then the addition of IN can lead to more but smaller ice crystals than in the case without additional IN.

There are a number of complications to this picture which currently hinder the formulation of firm results: first, whether heterogeneous or homogeneous freezing dominates depends not only on the relative number of the respective aerosol particles but also on the vertical wind speeds (giving rise to different adiabatic cooling rates). Second, IN from various sources may have a spectrum of threshold supersaturation for nucleation instead of a single value. These thresholds seem to depend furthermore on temperature and on the nature of particle coating. They are not well known. Third, representation of ice formation in supersaturated air is difficult to represent in large-scale models because a supersaturated state is not uniquely related with a cloudiness state. This can mean: (1) a cloud is not yet formed (cloud free); (2) heterogeneous cloud is formed, (3) heterogeneous and homogeneous cloud are formed. Simulations performed in the QUANTIFY project (e.g., Penner et al. 2009) have therefore rather the value of highlighting the problems we currently have than yielding firm results.

3.6 Impact on clouds

There are two principle kinds of impacts of traffic particulate emissions on clouds. (1) These emissions may cause the formation of clouds that would not form naturally. A prominent example of this mechanism is the formation of jet exhaust contrails. Examples that are more difficult to observe are certain ship tracks and aircraft aerodynamic contrails. (2) The second kind of cloud impact is indeed a multitude of effects: The emitted particles first get mixed with the background aerosol and later – when the background aerosol becomes involved in natural cloud formation processes – the emitted particles can affect cloud formation, cloud evolution, and cloud properties. Most ship tracks belong to this category, but also the hypothetical so-called soot cirrus, which labels a type of ice clouds that are strongly affected by aviation soot particles. Natural cirrus clouds can also be affected by contrails formed within them or in their vicinity, in particular when these contrails spread and eventually form the so-called contrail cirrus, because these two cloud types then compete for the same space and for the same condensable water vapour.

An algorithm for the automatic detection of ship tracks in data from the second Along-Track Scanning Radiometer (ATSR-2) was described by Campmany et al. (2009) and applied to two years (1999-2000) of ATSR-2 data. The geographical and temporal patterns of detected tracks display most tracks in the northern Atlantic and Pacific oceans during the local summer. The detection algorithm was combined with another one for the retrieval of cloud properties like optical thickness, particles effective radius, cloud-top temperature, phase (water or ice), cloud water path, and others. These data were used to examine the extent of cloud modification by ship-stack effluents and estimate the radiative forcing of tracks. Compared to background low water clouds, tracks show enhanced optical depth (60%), liquid water content (40%), and height (5%), and a diminished effective radius (20%). This is consistent with modification of cloud properties by aerosol through the cloud albedo effect, the cloud lifetime effect, and the cloud height effect. The global annual mean radiative forcing due to ships in the vicinity of tracks has also been estimated as -8.9 mWm^{-2} with 60% uncertainty. This figure is, however, anyway small compared to the overall radiative forcing of ships, with estimates from -38 to -600 mWm^{-2} (Eyring et al., 2010).

Man-made changes in cirrus cloud cover were detected by comparing cirrus trends over adjacent regions with dense and sporadic air traffic. Some exemplary long-term trends are shown in Figure 5. It is evident that cirrus cloud coverage increases more or decreases less in regions with dense air traffic compared to regions with little air traffic. This could be considered a signature of increasing miles travelled by aviation in the past 20 years. Preliminary estimates from the differences in cirrus cloud cover suggest a minor effect the order of 6 mW/m^2 for an assumed optical thickness of 0.4.

Much better information on the statistics of optical thicknesses of single contrails, including the variation over their life cycle, can be obtained now from a contrail tracking algorithm that has been developed during QUANTIFY (Vazquez-Navarro, 2010). The combination of such a tracking

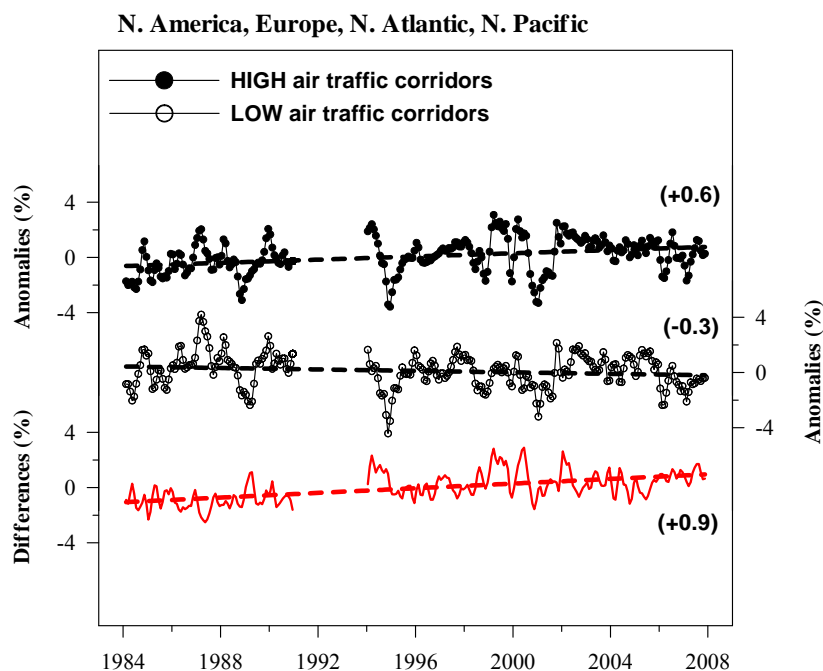


Figure 5: Averaged cirrus cloud trends over high and low air traffic regions in North America, Europe, North Atlantic, and North Pacific.

algorithm, based on satellite data, with a numerical contrail plume model for which first developments have been made in the project, allow to extend the observable fraction of a contrail life cycle in both directions, that is, from formation up to its end.

3.7 Radiative forcing

In the absence of any natural or anthropogenic driven climate change, and averaged over the whole globe and periods of a few years, there must be an approximate balance between the absorption of the sun's radiation by the Earth and its atmosphere, and infrared radiation emitted into space by the Earth and its atmosphere. Most climate change is initiated by some mechanism (for example a change in the concentration of greenhouse gases or aerosols) that perturbs this balance. Radiative forcing is a measure of the size of the imbalance and is usually reported in Wm^{-2} . The climate system responds to this imbalance by either cooling down (in the case of a negative radiative forcing) or warming up (in the case of a positive radiative forcing) in an attempt to re-establish the planetary energy balance. There is an approximately linear relationship between the size of the radiative forcing and the global-mean surface temperature change, and this is what has motivated the use of radiative forcing as an indicator of the strength of different climate change mechanisms. However, in order to understand the spatial (horizontal and vertical) distribution of temperature change and other climate change parameters (rainfall, cloudiness etc), more sophisticated models are required.

QUANTIFY has focused on several aspects of radiative forcing due to different modes of transport. The calculation of the radiative forcing due to emissions of CO_2 is relatively easy, and is essentially independent from the source of the emissions, as the atmospheric circulation spreads the change in CO_2 over the whole planet over time periods of around 1 year. By contrast, other transport-induced radiative forcing mechanisms are much more difficult to calculate, because most of them are, by contrast to CO_2 , very short lived in the atmosphere. For example, the transport-sector is a major source of emissions of oxides of nitrogen (NO_x). A significant complication is that the impact of NO_x emissions depends on the location of the emission; emissions from relatively polluted cities (which characterise the location of most road transport emissions) are distinct from the generally clean marine environment into which shipping emissions take place which are distinct

again from conditions in the upper troposphere where the majority of aviation emissions occur. The aerosol particles impact on radiative forcing in two ways – they *directly* influence the scattering and absorption of the sun’s energy, and they also influence the properties of clouds, so *indirectly* influencing the energy absorbed, scattered and emitted by the Earth and atmosphere.

QUANTIFY focused its effort on a number of radiative forcing mechanisms due to the transport sectors, some of which are highlighted here (Myhre et al. 2010; Balkanski et al. 2010; Marcowicz et al. 2010). The forcings represent the effect of the transport sectors in the year 2000, relative to the mid-19th century.

The radiative forcing due to emissions of NO_x and other short-lived reactive gases, by the transport sectors, shows broad agreement between the participating models in that the road and air sectors lead to a net positive forcing, while the shipping sector leads to a negative forcing, because the effect of the loss of methane is greater than the increase in ozone. There is roughly a factor of two difference in the forcing amongst the models, as a result of the different methodologies adopted.

The radiative forcing for the three sectors as a result of the direct effect of aerosols on the scattering and absorption of radiation was calculated by three different QUANTIFY groups. The aerosols from aviation have very little direct impact (although they may have a strong impact via changes in cloudiness). The emissions of black carbon (“soot”) by road transport lead to a strong positive net direct aerosol forcing for this sector; for shipping, the sulphur emissions lead to a strong negative forcing. Model results for the road black carbon forcing differ due to assumptions about how the black carbon aerosols are mixed together with other aerosol components.

Contrails influence the emitted thermal infrared radiation (causing a positive forcing) and scatter and absorb solar radiation (causing a negative forcing); both these forcings are impacted by assumptions about crystal shape (which is not well established and likely varies significantly between contrails and also changes as contrails evolve), and the net forcing can vary by about a factor of 2 between different assumptions.

The results from QUANTIFY, and from other recent literature, have been combined to come up with an overall assessment of the impact of the different transport sectors on radiative forcing. Table 2 shows these forcings together with assessments of the uncertainties. Note that the impact of aerosol resulting from the transport sectors is particularly uncertain and is the subject of ongoing studies. Our current best estimate forcing for the road sector is strongly positive; CO₂, ozone, HFCs/CFCs and black carbon aerosols are the main contributors. For shipping, the relatively strong positive forcing from CO₂ and ozone is more than offset by the negative forcings from methane change, the direct sulphate forcing and the indirect aerosol forcing, resulting in a net negative forcing. For aviation, CO₂, ozone and the aviation-induced contrails are the dominant positive forcings. For rail, the net forcing is dominated by the CO₂ forcing.

3.8 Impact on climate

It is desirable to know the climate impact of total transport and of each individual transport system in terms of physical parameters like temperature change, precipitation change, or sea level rise, rather than just in terms of their radiative forcing. The same holds for the various components contributing to the net effect of each transport system, in order to assess mitigation measures quantitatively when they involve tradeoffs between the component forcings. However, these effects are generally much too small to be distinguished from the background natural variability, either for the simulated or for the observed climate system. It is for this reason that radiative forcing is so commonly used to quantify individual impact contributions, as it can be calculated even for the smallest component effects and allows a first order estimate of the global mean surface temperature change.

In QUANTIFY we investigated whether the radiative forcings and climate impacts from different sources are simply additive and whether and how far there are linear relations between the amount of emissions, the strength of the forcing, and the resulting climate change. For the radiative

Table 2: Year 2000 radiative forcing (in mWm^{-2}) for each transport sector and each forcing mechanism relative to pre-industrial times, together with uncertainties. SWV is stratospheric water vapour.

	ROAD	SHIP	AIR	RAIL
CO ₂	131 ± 15	34 ± 6	20 ± 3	23 ± 7
Ozone	32 ± 9	24 ± 6	18 ± 3	2 ± 0.4
CH ₄ lifetime	-7 ± 4	-19 ± 2	-5 ± 1	-1 ± 0.4
CH ₄ - ozone	-3 ± 2	-8 ± 1	-2 ± 0.5	-0.3 ± 0.2
SWV methane	-1 ± 0.7	-3 ± 0.7	-1 ± 0.3	-0.1 ± 0.1
SWV direct			1 ± 0.2	
CFCs/HFCs	28 ± 3			
Stratospheric Ozone	-2 ± 4			
Sulphate aerosol	-9 ± 4	-26 ± 11	-1 ± 0.4	-1 ± 0.3
Black carbon aerosol	44 ± 17	2 ± 1	0.3 ± 0.1	1 ± 0.3
Organic carbon aerosol	-2 ± 1	-1 ± 0.5		-0.5 ± 0.3
Indirect aerosol effect	6 ± 111	-49 ± 209	-127 ± 128	0.5 ± 10
Contrails			7 (-4,+6)	
Aviation induced cirrus			21 (-9,+17)	

forcing of ozone, aerosol, and water vapour, substantial deviations from linearity only occur for scaling factors beyond 100 (that is, the actual forcing is artificially enhanced by a factor of 100). The scalability of contrails is limited with respect to its coverage, which on a local scale is constrained to be less or equal the coverage of co-existing natural clouds. Adding radiative forcings of different perturbations to yield the radiative forcing of a combined perturbation is hardly affected by non-linearities. The deviations from linearity are more severe for the expected change of near-surface temperatures. For a special effect of absorbing aerosols, in particular soot (the semi-direct effect where a positive radiative forcing leads to a decrease of the near-surface temperature) the whole concept becomes questionable.

Using an Atmosphere-Ocean General Circulation Model we have studied climate change due to transport taking into account 6 different forcings: CO₂, CH₄, O₃ and aerosols for all sectors, CFCs and HCFCs for road traffic, and contrail formation for aircraft (Olivié et al., 2010). For this we used the A1B scenario of the IPCC which assumes a rapid economic growth with a global population increase until 2050 and a decline thereafter. This scenario results in an intermediate increase in anthropogenic forcing.

Figure 6 shows the time series of the impact of 3 different transport modes on the evolution of the global mean surface temperature. In 2100 the warming from all sectors due to the CO₂ increase is about 0.5 K with a major contribution from road traffic (0.3 K). The non-CO₂ impact peaks at 0.05 K in 2050 for the road traffic, whereas the non-CO₂ impact from shipping is negative ranging from -0.05 to -0.1 K over the period 2000-2100 due to aerosol effects on clouds as reported above. The non-CO₂ impact from aircraft is larger than the CO₂ impact, it reaches 0.15 K at 2100. It is caused by an enhanced O₃ production (compared to road and ship traffic) due to the altitude of the NO_x emissions, and by the direct radiative positive forcing from linear and contrail-induced cirrus. The total anthropogenic global temperature increase is about 3K in 2100 with a contribution of about 0.65 K from transport, with 0.5 K due to CO₂ impact and 0.15 K due to a non-CO₂ impact dominated by aircraft traffic. Impacts are in general more pronounced at high latitudes, but the signal there is strongly influenced by the timing of the Arctic sea-ice melting, which is quite uncertain.

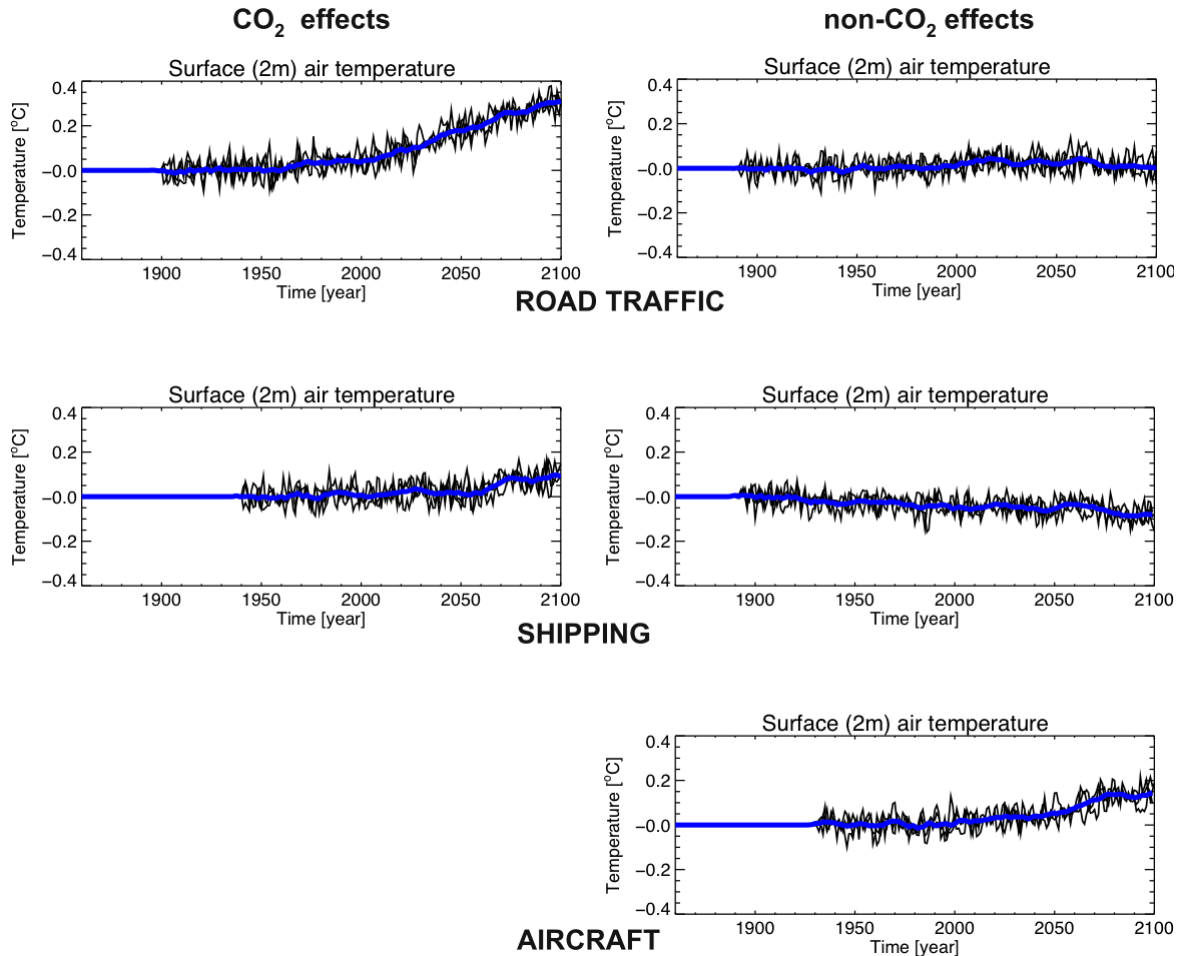


Figure 6: Time series of annual global mean surface temperature impact for the different transport modes, due to CO₂ only (left) and non-CO₂ (right) effects.

3.9 Putting emissions on a common scale

The transport sector emits a wide variety of gases and aerosols, with distinctly different characteristics, which influence climate directly and indirectly via chemical and physical processes. Tools that allow these emissions to be placed on some kind of common scale in terms of their impact on climate have a number of possible uses such as: in agreements and emission trading schemes; when considering potential trade-offs between changes in emissions resulting from technological or operational developments; and/or for comparing the impact of different environmental impacts of transport activities. Usually, CO₂ is used as reference, and thus the use of metrics transforms the effects of non-CO₂ emission onto a "CO₂-equivalent" scale. Ideally, the same equivalent CO₂ emissions should produce the same climate effect regardless of their composition, but in practice this is not possible.

Many of the non-CO₂ emissions from the transport sector are short-lived substances, not covered by the Kyoto Protocol. There are challenges in developing metrics and these are particularly acute for short-lived species. One difficulty concerns the choice of an appropriate structure for the metric (which may depend on, for example, the design of any climate policy it is intended to serve) and the associated value judgments on the appropriate time periods to consider; these choices affect the perception of the relative importance of short- and long-lived species. A second difficulty is the quantification of input parameters (due to underlying uncertainty in atmospheric processes). In addition, for some transport-related emissions, the values of metrics (unlike the gases included in

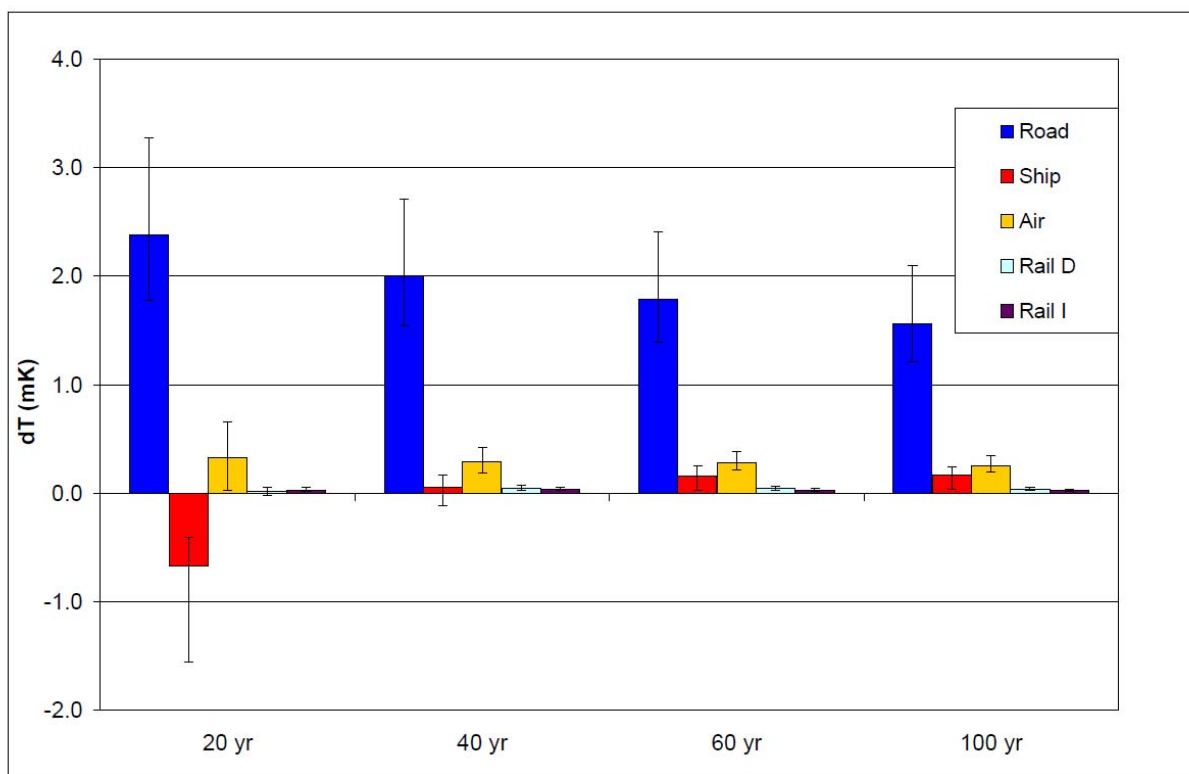


Figure 7: Contribution from a 1-year pulse of current (year 2000) emissions to net future temperature change (mK) for each transport mode for 4 future times (20, 40, 60, and 100 years), including uncertainties at the 1-sigma level.

the Kyoto Protocol) depend on where and when the emissions are introduced into the atmosphere – both the regional distribution and, for aircraft, the distribution as a function of altitude, are important.

In QUANTIFY we evaluated existing metric concepts and also new concepts. These are, together with various simple climate models, applied in evaluations of emissions from transport and of the net temperature effect of the various transport modes. Several approaches are possible in quantification and evaluation of climate impacts of transport. We used both backward looking perspectives (e.g., current forcing relative to pre-industrial times, and development of temperature effect over time), and forward looking perspectives; both for pulses, sustained emissions and for more sophisticated emission scenarios. These approaches have been used in quantifications and comparisons of contributions from components and sectors; as well as comparing technologies and fuel types.

Figure 7 shows a comparison of the transport modes in terms of net warming or cooling (temperature change) for 4 chosen time horizons after 1 year's (i.e., year 2000) emissions. Road transport is clearly the dominating sector, with aviation as the second largest contributor. For time horizons of 20 and 100 years, the net warming from road transport is 7 and 6 times larger, respectively, than the net warming from aviation. This is approximately the same ratio as the ratio between the CO₂ emissions from these sectors; thus, in these cases, it is mainly CO₂ that controls the climate response on timescales beyond 10 years. The net warming of shipping changes sign from negative for a time horizon of 20 years to positive for the other horizons used here. The 2 rail sectors seem small, but added together they become on the order of 15–30% of the effect of the aviation sector for time horizons between 20 and 100 years. The results in Figure 7 show how the relative importance of the different transport sectors changes depending on the time perspective.

3.10 Comparing transport impact weighted by transport volume

The different transport modes serve passenger and freight transport differently and they vary strongly in the total transport work performed. Therefore, we compare in this section the climate impact with the total transport work for each mode; this provides an intensity measure which mode has a bigger impact, the so-called specific climate impact (Borken-Kleefeld et al. 2010). The global average values derived here provide a first order indication of the undesired outcome – the climate impact – per underlying unit of activity.

Here the transport specific climate impact is defined as the ratio of the CO₂ equivalent climate impact divided by the transport work of the mode. This transport specific climate impact is for each mode a function of the time horizon or the target year chosen in the climate metric to calculate the CO₂ equivalent climate impact and of the measure for transport work.

Transport work is usually expressed as the product of the number of passengers travelling times their average travel distance in the case of passenger transport and of the tons of cargo transported times their average transport distance in the case of freight transport, called passenger-kilometres (Pkm) and ton-kilometres (tkm), respectively.

Figure 8 presents the specific climate impact in terms of temperature change for the different passenger and freight transport modes and for short (5 years), intermediate (20 years) and long (50 years) time horizons. For freight transport the ranking by specific climate impact is robust on these time scales: The specific climate impact of air transport is 7 to 36 times higher, for a light truck it is 4 to 12 times higher per ton-kilometre than the transport with an average heavy truck. On global average rail transport had a 4 to 8 times lower specific climate impact than trucking. Ship transport has by far the lowest climate impact. It exerts 25 times less warming per transport work than trucking, and is even cooling on shorter time scales. Including short-lived climate forcing into the assessment strongly increases the specific impact from aircraft on shorter time scales. However, the ranking remains valid, when only CO₂ emissions were considered. While the specific climate impact from aircraft is by far the highest, delivery vans come close.

The specific climate impact of passenger travel is lowest for rail and coach: Per passenger-kilometre they have resulted in 2 to 5 times lower impact. On shorter time scales high emissions of short-lived climate forcers from powered two- and three-wheelers means that their impact per passenger-kilometre can be comparable to the impact from cars. Only on long-time scales, i.e., when only CO₂ is the relevant forcing, they appear to be more efficient. The specific climate impact from car travel is at the same level as air travel for longer time-horizons (and given the uncertainties). On short-time horizons however the very high contributions from short-lived climate forcings lead finally to a much higher specific climate impact from air travel.

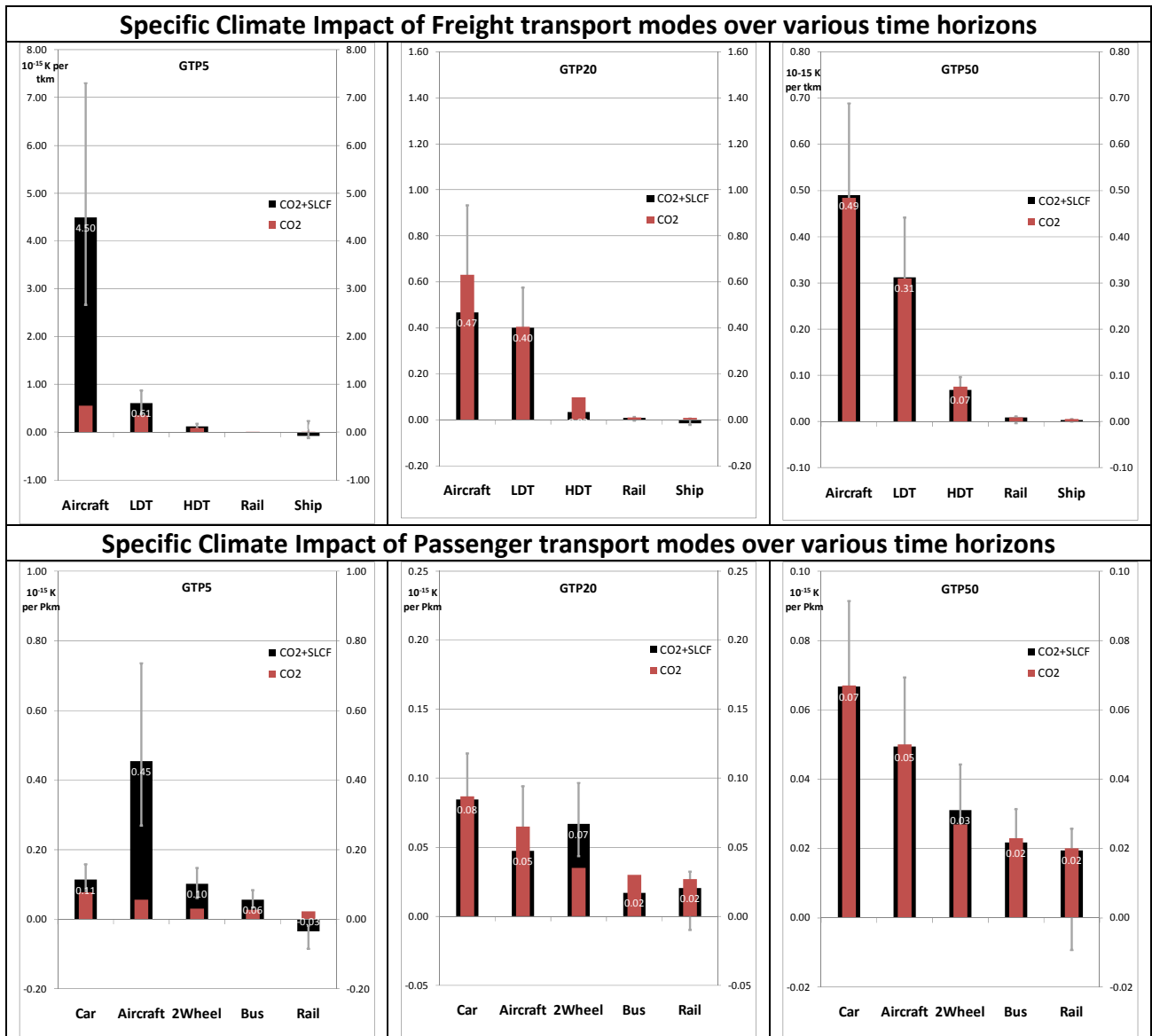


Figure 8: Temperature change from emissions in the year 2000 after 5, 20 and 50 years: For passenger transport modes (upper panels) per passenger-kilometre, for freight transport modes (lower panels) per ton-kilometre performed. The columns differentiate the impact when all short- and long-lived climate forcings (in black) are considered and when only CO₂ (in red) are considered.

4. Final remarks

4.1 QUANTIFY and its objectives

QUANTIFY achieved its objective. In a broad effort the impact of all major modes of transport on the composition of the atmosphere, on radiative forcing have been quantified, allowing a fair comparison of the impacts. In particular:

- QUANTIFY created consistent inventories of emissions (greenhouse gases, particles, precursors of greenhouse gases and aerosols) from present day and past transport, separately for the different modes of transport.
- QUANTIFY generated inventories of transport emissions for scenarios of future development, which are consistent with the IPCC SRES scenarios.
- QUANTIFY determined the fate of emissions from shipping during the dilution to regions of the size of global scale models.
- QUANTIFY developed and tested for "effective emission indices" linking local emissions (at the exhaust) to scales of global models for the relevant modes of transport (aviation and shipping).
- QUANTIFY consistently calculated the global chemical impacts of the different modes of transport, for present day conditions and several future scenarios.
- QUANTIFY determined regional structures in transport-induced perturbations of the chemical composition of the atmosphere.
- QUANTIFY provided quantitative estimates of the impact of the different modes of transport on aerosols and clouds, in particular on cirrus (contrails and contrail-cirrus) and low marine clouds (ship track) in terms of, e.g., clouds cover and cloud optical properties.
- QUANTIFY consistently determined the radiative forcing from transport-induced changes in atmospheric (and surface) parameters, including the separation of the contributions from different modes of transport, for present day transport and for several future scenarios.
- QUANTIFY determined the spatial and temporal pattern of transport-induced climate change, which potentially might allow for the search for specific fingerprints distinct from other causes of climate change.
- QUANTIFY developed and tested policy relevant metrics that allow the inclusion of all import impact on climate and that take the particular aspects of transport into account.
- QUANTIFY estimated the impact of some potential mitigation options on atmospheric composition and climate.

Unfortunately, QUANTIFY was not able to verify the hypothesis that anthropogenic aerosol causes the formation of additional clouds (indirect aerosol effect of the 1st kind), despite several measurement attempts. However, the probability to find suitable atmospheric conditions in the few possible attempts was low.

4.2 Main findings of QUANTIFY

Selected results of QUANTIFY have been presented in Section 3. The results of QUANTIFY formed the core for the ATTICA assessment reports that were produced in parallel (Lee et al., 2010; Eyring et al., 2010; Uherek et al., 2010; Fuglestedt et al, 2010), which have been published in a special issue of Atmospheric Environment (Sausen, 2010). Here we only summarise the main findings:

- The impact of transport, in particular of aviation and shipping, on climate grows faster than the impact from other sectors of human activity.
- The non-CO₂ effects of aviation and shipping (e.g., NO_x, induced clouds) are particularly large in comparison to other modes of transport.
- A NO_x molecule from aviation produces five times as much ozone than a molecule from road transport.
- A NO_x molecule from shipping is four times more efficient in reducing methane than a molecule from aviation.
- Aircraft-induced clouds warm the atmosphere. The associated radiative forcing (RF) is of similar magnitude than RF from aviation CO₂.
- Ship-induced clouds cool the atmosphere. The associated radiative forcing (RF) may be as large as one third of the total anthropogenic RF.
- The total RF from road transport and aviation are positive, the RF from shipping is negative.
- The relative weights of the non-CO₂ effects of transport depend on the metric and time horizon selected. A temperature based climate metric produces a very different picture than GWP based metrics.
- Specific climate impact of passenger transport is much lower for railways compared to road transport and aviation.
- Specific climate impact of passenger air travel approaches that of cars on the time scale of decades.

4.3 Some caveats and a perspective for the future

Despite all the progress achieved some caveats need to be stated and a lot of open questions remain.

Most of the quantifications achieved in QUANTIFY are associated with substantial uncertainty, sometimes even effecting the sign of an effect, in particular: The climate impact of indirect aerosol effects on clouds is still very uncertain, even the sign of aircraft aerosol effects on clouds is not firmly known. We still do not know whether soot cirrus really exists. Potentially the net effect of aircraft NO_x emission might cause a net negative radiative forcing if a recently stated additional chemical reaction is confirmed.

Many of the transport related atmospheric and climate effects are still understood relatively poorly, and they have only been quantified with large uncertainty. In some cases, e.g. soot clouds or the replacement of fossil fuels by bio fuels, it is still not determined whether they eventually result in a warming or a cooling. Therefore, it is presently not yet possible to include all non-CO₂ effects in climate policies or to develop suitable mitigation strategies for all non-CO₂ effects. Furthermore, many of the emitted species responsible for the non-CO₂ effects also impact air quality, e.g., sulphur emissions.

By applying a hierarchy of models (from process models, cloud resolving models to CTMs, GCMs and CCMs) and analysing measurements from e.g. satellites and dedicated field campaigns, the main uncertainties with respect to short-lived non-CO₂ effects on the atmospheric composition and on climate should be reduced: (1) The importance and magnitude of trade-offs in the NO_x effect (short-term increase in ozone versus longer-term decrease in methane and the associated ozone decrease) should be explicitly simulated by comprehensive models covering the long response time of methane. (2) The climate impact of direct effects on clouds (in particular contrail cirrus) should be simulated by climate models including parameterizations of contrail cirrus and evaluated by recently available tracking algorithms of these clouds in satellite data. (3) The climate impact of indirect effects on clouds (e.g. soot cirrus, aerosol-induced effects on low level clouds from transport, industry and agriculture) should be simulated by now available CCMs including aerosol-cloud interactions; the necessary parameters should be obtained by dedicated airborne measurement campaigns. (4) The regional response pattern in atmospheric composition and climate resulting from heterogeneous transport emissions need to be determined consistently in a multi-model approach.

The effects arising while replacing fossil fuel by bio-fuels should be considered. Finally, tradeoffs between climate and air quality effects of emissions from different sectors should be examined for robust policy formulation.

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