Climate forcing from the transport sectors

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Although the transport sector is responsible for a large and growing share of global emissions affecting climate, its overall contribution has not been quantified. We provide a comprehensive analysis of radiative forcing from the road transport, shipping, aviation, and rail subsectors, using both past- and forward-looking perspectives. We find that, since preindustrial times, transport has contributed ≈15% and 31% of the total man-made CO_2 and O_3 forcing, respectively. A forward-looking perspective shows that the current emissions from transport are responsible for ≈16% of the integrated net forcing over 100 years from all current man-made emissions. The dominating contributor to positive forcing (warming) is CO_2, followed by tropospheric O_3. By subsector, road transport is the largest contributor to warming. The transport sector also exerts cooling through reduced methane lifetime and atmospheric aerosol effects. Shipping causes net cooling, except on future time scales of several centuries. Much of the forcing from transport comes from emissions not covered by the Kyoto Protocol.

radiative forcing | emissions | GWP | greenhouse gases | aerosols

Transport of goods and people is one of the key drivers for the growth in global greenhouse gas (GHG) emissions. Although global CO_2 emissions increased by 13% from 1990 to 2000, CO_2 emissions from road transport and aviation each grew by 25%. In Eastern Asia, the NO_x and CO_2 emissions from road transport doubled from 1990 to 2000 (1). In the European Union, most sectors decreased their GHG emissions from 1990 to 2001, but emissions from transport increased by nearly 21% (2). The accompanying emissions of NO_x, CO, volatile organic compounds (VOC), aerosols, and SO_2 are often higher than for other sectors but have increased less than CO_2 because of improved vehicle technologies and reduced fuel sulfur content. The growth in GHG emissions from transport is expected to continue throughout the world. In 2050, as much as 30–50% of total CO_2 emissions are projected to come from the transport sector (3), compared with today's 20–25%.

In light of the objectives of the United Nations Framework Convention on Climate Change, the increasing levels of emissions from transport suggest that stronger mitigation efforts may be necessary for this sector. This may be difficult to accomplish for several reasons, including issues related to globalization and development, as well as the difficulty of assigning responsibility for emissions from international transport. A crucial first step in designing an efficient mitigation policy is to quantify the extent to which emissions from transport affect the climate system.

There are four main mechanisms by which emissions from transport affect climate: (*i*) by emission of direct greenhouse gases, mainly CO_2; (*ii*) by emission of indirect greenhouse gases, i.e., precursors of tropospheric O_3 or gases affecting the oxidation capacity of the atmosphere, such as NO_x, CO, and VOC; (*iii*) by the direct effect of emission of aerosols or aerosol precursors, in particular black carbon (BC), organic carbon (OC), and sulfur compounds; and (*iv*) by the indirect effect of aerosols, which trigger changes in the distribution and properties of clouds.

Although current climate policies focus on the well mixed GHGs (WMGHGs), which have relatively well known behavior and radiative forcing (RF) of climate, there is strong evidence that the other emissions and mechanisms (*ii*–*iv* above) play an important role for the transport sector. Quantifying these effects is a complex scientific undertaking because of the broad mix of substances and physical/chemical processes involved. Adjustment times are short for many of the emissions associated with transport—months for O_3 and days for sulfate (SO_4), BC, and OC—whereas the WMGHGs have adjustment times of decades (CH_4) and centuries (N_2O and CO_2). Thus, an evaluation of the climatic impact of transport depends on how future effects are evaluated from a long-term perspective. Furthermore, emissions can cause both negative and positive RF; for example, aerosols such as OC and SO_4 reflect solar radiation and cause cooling. Comparing all of these effects on a common scale is a challenging task that involves exercising value judgments, e.g., comparing and weighting different climate effects occurring at different times and thus affecting different generations.

Approach

Whereas previous studies have provided detailed results on specific forcing agents or subsectors (4–12), we present a quantitative overview of the climate effects in terms of chemical responses and RF for all transport emissions related to fossil fuel use and for all major transport subsectors. First, we calculate the contribution since preindustrial times to the current RF, in accordance with the traditional historical perspective used by the Intergovernmental Panel on Climate Change (IPCC). Then, to evaluate the impact of current emissions from each transport sector, we compare the future integrated RF caused by present-day emissions. (We chose to focus on current emissions rather than future emissions scenarios because the latter would demand an analysis of future policies, which would be beyond the scope of this article.) In both the historical and future perspectives, we quantify (with uncertainty ranges) the RF from the individual substances and subsectors.

Emission inventories for the transport sector are compiled by using existing datasets and our own estimates. The impacts on tropospheric O_3, methane lifetime, sulfate, BC, and OC (driven by emissions of NO_x, SO_2, CO, VOC, BC, and OC) are calculated with the Oslo-CTM2 global chemical transport model (13). A radiative transfer model is then used to calculate the RF from these changes (14, 15). For the indirect effects of aerosols on cloud albedo, we use the ratio of the indirect and direct RF for land and ocean adopted from ref. 16. The ratio for land (1.5) is applied for road transport and rail, whereas the ratio for RF over ocean (2.1) is used for shipping. In this way, we account for the land–ocean differences in the indirect aerosol effect (9). Because of the short lifetime of ozone, aerosols, and aerosol precursors, these RF estimates can be used to calculate the contributions to both current RF and the future integrated RF

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of current emissions [see supporting information (SI) *Methods*]. The historical development in global concentration of CO_2 from transport is calculated using a scheme based on ref. 17, and for N_2O and CH_4 we use standard box models (see *SI Methods*). To calculate impacts of transport, we use the common method of removing all emissions from one transport sector at a time and then calculating the difference from the reference simulation (8). Because nonlinear processes control some substances (e.g., O_3 and OH), the RF of ozone and methane cannot be scaled exactly to obtain the effect of marginal changes reflecting realistic short-term mitigation measures. The approach is modified for CO_2 to account for the nonlinearity in the emission–concentration–RF relationships (18).

Emissions

We use results from published studies to establish current emissions of WMGHGs and the short-lived gases and past emissions of WMGHGs for 1850–2000. We include emissions from energy consumed from tank to wheel, and we exclude emissions of halocarbons from air conditioning and road dust. Because railways may use electricity rather than fossil fuels, to enable a fair comparison with the other transport subsectors the emissions associated with the production of electricity have been included. For fossil fuels, the indirect component (well-to-tank) constitutes a smaller share of well-to-wheel emissions (19) and has not been included in the analysis. Emissions data for 2000 are taken from the EDGAR database (1), except for aviation (20), shipping, and BC and OC (21). Transport is the most important source of man-made emissions of NO_x (37%). It is also a major contributor of CO_2 (21%), VOC (19%), CO (18%), and BC (14%). For other substances, the transport sector's share of total man-made emissions is 10% or less. With respect to the subsectors, road transport is the largest contributor of emissions of all substances except SO_2, for which shipping is the most important (56% of transport emissions). For BC in particular, the contribution of off-road mobile machinery to total emissions is high, but in this article these sources are not considered part of transport. Estimates of BC and OC emissions from transport are generally more uncertain than estimates of the other substances. SI Table 1 shows the emission data for 2000 used in our calculations.

Historical CO_2 emissions were calculated from 1850 for rail, 1870 for shipping, 1900 for road transport, and 1930 for aviation. Emissions data between 1970 and 1990 are taken from ref. 22, except for shipping, where emissions for 1970–2000 were estimated from energy consumption recorded by the International Energy Agency. Because of a lack of fuel consumption statistics, time-series for all sectors were constructed by combining multiple data sources (see *SI Methods*). Fig. 1*A* shows the development in CO_2 emissions from the various subsectors. The figure shows a rapid growth in emissions from road transport and aviation and a decline in emissions from rail. Emissions from shipping decreased in the middle of the last century as a result of conversion from coal to diesel propulsion but later increased, until a decline in the 1980s. The figure also shows that the total transport CO_2 emissions as fraction of total man-made CO_2 emissions has increased since the middle of the 20th century to >20% in 2000.

Estimates of shipping fuel consumption vary considerably, ranging from ≈160 to 280 million metric tons (Mt) of fuel per year (23). We have used 577 Mt CO_2 in 2000 (corresponding to 180 Mt of fuel), which is in good agreement with ref. 24 when fishing is subtracted from the latter estimate. Other datasets would give substantially higher emissions, and the probability of higher emissions is included in our uncertainty analysis.

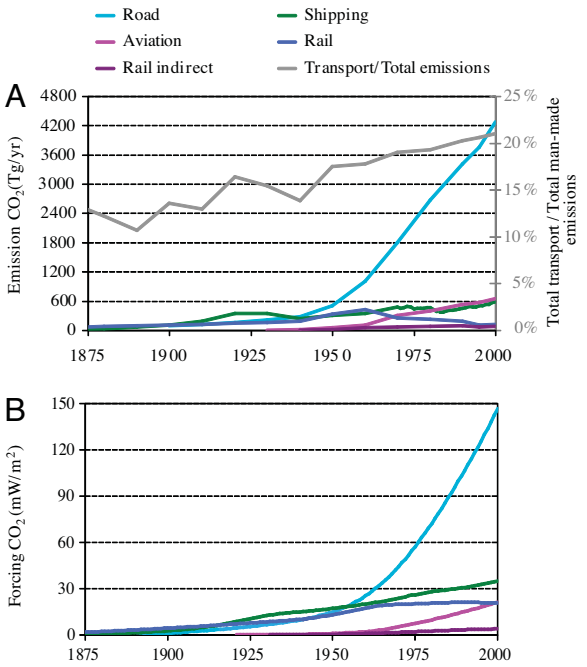

Fig. 1. Historical development in emissions and radiative forcing for CO_2 from the transport sector. (*A*) Development in CO_2 emissions from the various transport subsectors and the fraction (right axis) of total man-made CO_2 emissions (excluding land use changes). (*B*) Development in RF due to CO_2 from these sectors.

Atmospheric Burden and RF

The historical emissions of the WMGHGs are used to calculate the development in contributions to the global atmospheric concentrations and RF for the various subsectors. After 1950, the CO_2 RF from road transport increased dramatically and is currently causing the largest transport-related CO_2 forcing (Fig. 1*B*), whereas for rail the RF is constant, even though CO_2 emissions decreased after 1960.

The effects on tropospheric O_3, methane lifetime, and aerosols are calculated using the Oslo CTM2 model. Emissions of NO_x enhance the levels of OH and thus reduce CH_4 concentrations, whereas CO and VOC have the opposite effect (25–28). For aviation, we calculated the RF from the WMGHGs, as well as BC and OC; the RF from changes in ozone, methane lifetime, and sulfate, as well as water vapor, contrails, and cirrus, are taken from refs. 10 and 29.

We find that the largest change in atmospheric O_3 burden is caused by road transport (13 Tg) and shipping (13 Tg), whereas the effects of rail (direct and indirect) are an order of magnitude smaller. The O_3 burden change due to aviation is ≈40% of the changes from either road transport or shipping. The largest contributor to changes in methane lifetime is the shipping sector, as a result of the high NO_x/CO and NO_x/VOC ratios in the emissions and the generally low NO_x environment in which the emissions take place (26). The NO_x/CO and NO_x/VOC ratios are 70 and 40 times higher, respectively, for shipping than for road transport, which favors OH increases and thus loss of methane.

For O_3 and BC, road transport has higher radiative efficiency than shipping (i.e., RF/burden change). For the aerosols, the variation can be explained by land–ocean differences in surface albedo, cloud cover, and relative humidity. For instance, over oceans with low surface albedo, the radiative efficiency increases for scattering aerosols (SO_4 and OC) and decreases for absorbing aerosols (BC) (see SI Table 2). For ozone, the variation can be explained by the more effective vertical mixing over land that

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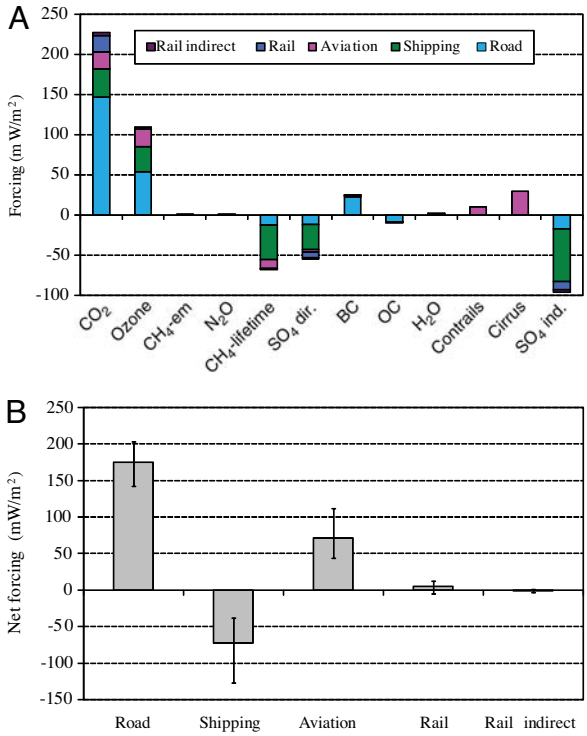

Fig. 2. Radiative forcing since preindustrial times, by substance and transport subsector. (*A*) Global mean RF (mW/m^2) for 2000 due to transport, relative to preindustrial times. (*B*) Global mean net RF (including all components in *A*) for 2000 due to transport, relative to preindustrial times, per sector. Uncertainty ranges are given for 1 SD. (BC and OC from off-road vehicles and equipment are not included but are estimated at 13 and −1.1 mW/m^2, respectively, for 1996 emissions.)

enhances the ozone change at higher altitudes where the forcing efficiency is higher.

Based on the model calculations and historical development in emissions of WMGHGs and the current emissions of short-lived species, Fig. 2 shows the transport-initiated RF (mW/m^2) in 2000 relative to preindustrial times, given by substance and transport subsector. CO_2 gives the largest RF, with a total contribution from transportation of 230 mW/m^2 or 15% of the total man-made CO_2 forcing since preindustrial times. For road transport alone, the corresponding numbers are 150 mW/m^2 and 10%. The second largest contribution to positive forcing (warming) is from tropospheric O_3. The share of the total man-made O_3 RF is as high as 31% for the whole transport sector, and road transport alone is responsible for 15% of the total man-made ozone forcing. Our O_3 RF estimate of 54 mW/m^2 for road transport is consistent with previous results for this subsector (7). In addition to the dominating effects from CO_2 and O_3, changes in sulfate and the lifetime of methane also make significant contributions. If we add up the RFs across substance and subsector, we find that the total net RF amounts to ≈11% of total net man-made RF in 2000. This fraction reflects the shorter history of the transport sectors compared with other sectors, such as agriculture and industry, as well as the role of emissions that have cooling effects. These differences in history are most important for CO_2 because of the long memory of the carbon cycle; man-made emissions originating before the transport sector became active still have an impact on atmospheric CO_2 levels. SI Table 5 gives estimated uncertainty ranges for the RF values in Fig. 2*A*. (See *SI Methods* for methods and input for the uncertainty assessment). The uncertainty analysis includes uncertainty in activity (i.e., fuel use), emission factors, modeling of atmospheric dispersal and removal, and RF. Uncertainties are given at the level of 1 standard deviation (SD).

Fig. 2*B* shows the net forcing (mW/m^2; including all RF agents considered here) in 2000 caused by historical emissions from each subsector. Road transport is the dominating sector. In contrast to the other subsectors, shipping gives a significant negative RF, mainly because of sulfate aerosols and reduced methane lifetime. The RF from shipping is of the same magnitude as the RF from aviation, although their signs are opposite. For shipping, the effect of reduced methane lifetime is larger than the direct effect of sulfate aerosols. Because the emissions causing the methane effect (NO_x) also lead to a positive RF through ozone formation, the negative net effect of the NO_x emissions on the global mean RF is small and is also smaller than the direct SO_4 effect. This balance between ozone and methane effects is different for road transport, where higher fractions of CO and VOC in the emissions lead to an ozone RF that is larger than the negative CH_4 from the same emissions. Uncertainties of 1 SD in the total net RF from the various sectors are based on data shown in SI Table 5 and are indicated by the bars in Fig. 2*B*. The road sector is the least uncertain (a 1 SD uncertainty range of −19% to +16%). Uncertainty is largest for shipping because of the contribution of several factors: uncertainties in fuel use, larger sulfur emissions with uncertain direct and indirect aerosol effects, and small net effect of NO_x, CO, and VOC emissions with significant uncertainties in the effects on ozone and methane. Uncertainty is also large for aviation, mainly because of cirrus and contrail uncertainties. At the 1 SD level, the net RF of rail may be either positive or negative, whereas the net RF for shipping is negative at the 99% confidence level.

Future Impact of Current Emissions

The current RF shown in Fig. 2 is a function of historical emissions and may be an inappropriate basis for policymaking because of the very different time histories of both the transport subsectors and the other main sectors. It also ignores the long-term perspective of future climate change. To evaluate emission-reduction policies, a forward-looking perspective is more relevant; i.e., how much do current emissions contribute to future climate change? However, forward-looking evaluations involve not only scientific issues but also value-related questions, such as how to weight future effects over time and the choice of time horizon; different methods for comparison can be applied depending on the perspective chosen (30–33).

One way to assess future climate effects of current emissions (as 1-year pulses) is by integrating the RF over a chosen time horizon (W/m^2·yr) (34), which is the approach taken when Global Warming Potentials (GWP) are used as weights for comparing emissions (35, 36). The integrated RF concept is constructed to include effects occurring between the time of the emission and the chosen time horizon, and it puts equal weight on all years along the path up to the horizon. Integrated RF is a general indicator that is useful for calculating the relative magnitudes of the different perturbations placed on the climate system (by various components, sectors, or sources). Integrated RF does not take into account the thermal inertia of the climate system (except for adjustment of stratospheric temperatures). In this study, we show the future integrated RF from year 2000 emissions for the three standard time horizons used by the IPCC.

Note that even very short-lived species like sulfate and black carbon can contribute a significant fraction of the total integrated RF, even over a 100-year time horizon. This is because the ratio between the specific forcings of sulfate or BC vs. CO_2 is of the of order 2×10^5 and 1×10^6 for sulfate and BC, respectively, which are larger than the ratios between the adjustment times of CO_2 and the lifetimes of sulfate or BC. As discussed in refs. 31 and 37, the application of integrated RF may overestimate the effect of short-lived species if the goal of climate policies is to

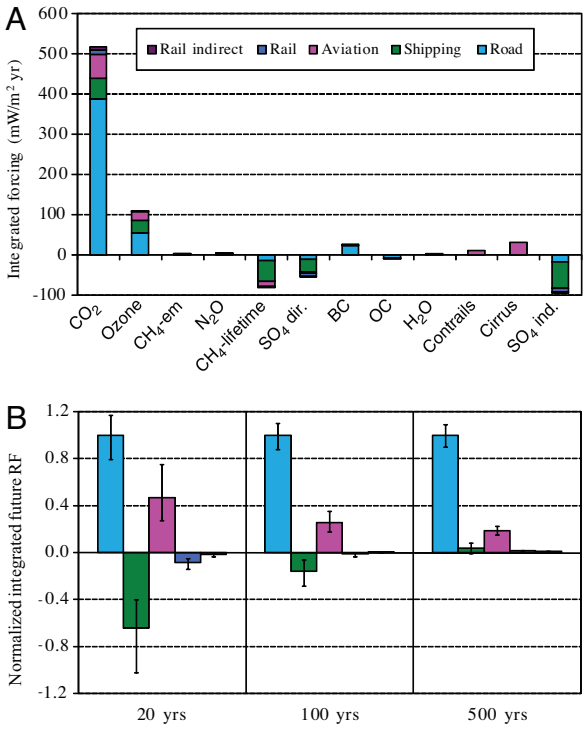

Fig. 3. Integrated radiative forcing of current emissions, by substance and transport subsector, over different time horizons. (*A*) Integrated global mean RF (mW/m^2 yr) due to 2000 transport emissions, time horizon $H = 100$ years. (*B*) Integrated global mean net RF per sector due to 2000 transport emissions, normalized to the values for road transport for various time horizons (20, 100, and 500 years). Uncertainty ranges are given as 1 SD.

limit long-term temperature increase (e.g., the European Union has stated that "the global annual mean surface temperature increase should not exceed 2°C above preindustrial levels"). Alternative approaches include choosing the change in global mean temperature for a selected year as an indicator (33, 37). This would take the thermal inertia of the system into account, and, in contrast to the integrated RF concept, would allow more short-term effects of the short-lived gases to be reduced over longer time scales. Using temperature change after 100 years for the evaluation would place less emphasis on short-lived components, but any perturbations of temperature between the time of emission and the evaluation year would not be captured.

Fig. 3*A* shows the integrated RF for the various components and sectors with a time horizon of 100 years, as adopted by the Kyoto Protocol. With this perspective, CO_2 is by far the most important substance, with the largest contribution coming from road transport. Again, the second largest positive RF is from tropospheric O_3, also with a dominating contribution from road transport. With respect to methane and sulfate, both of which cause a negative RF, the dominating contribution comes from shipping. Note that with the perspective embedded in the choice of a 100-year horizon, the contributions from the short and intermediate perturbations (ozone, aerosols, and methane) become significantly smaller compared with CO_2 than in the historical perspective (Fig. 2). Long-lived substances tend to contribute more to the total integrated RF with this forward-looking perspective than in the historical perspective used in Fig. 2*A* when recent emission growth is large. The total net RF from transport amounts to 16% of the 100-year integrated net RF of total current man-made emissions (see *SI Methods*).

Discussion

The adoption of 100 years as time horizon has implications involving value judgments, and it may be argued that other horizons should be applied (30). If the main concern is the near-term impacts of climate change, a shorter horizon is more appropriate. Fig. 3*B* shows the effect of the current emissions from the transport subsectors, relative to the effect of road transport for three time horizons. The uncertainties in the estimates of current emissions and in the RF calculations are accounted for (see *SI Methods*) and form the basis for the 1 SD uncertainty bars. Because of the critical role of sulfate, the impact of shipping switches from negative in a short and medium time perspective to positive on a scale of several centuries. The RF caused by sulfate (directly and indirectly) is strong and short-lived. Because this approach integrates the RF over the time horizon, the effect of sulfate is still significant in a 100-year perspective. For still longer time horizons, the effect of CO_2 becomes dominating. This is also the case for rail. The integrated RF from road transport and aviation, however, is positive for all three time horizons. For all three horizons, road transport dominates, with aviation as the second largest contributor to warming. Shipping switches to a positive net forcing for a time horizon of 500 years, but with an uncertainty range that still includes negative RF. In general, the longer the time horizon, the less uncertain is the net effect because of the decreasing influence of the short-lived components that have high uncertainty.

Given the forcing mechanisms included in our analysis, with their corresponding uncertainties, we find that the main results regarding dominating sectors and forcing agents are robust at the 1 SD level for all time horizons. In addition to the RF mechanisms considered in this study, other indirect processes have been proposed. These include reduction of snow and ice albedo by BC deposition (38–40), the so-called semidirect effect of BC on clouds (41), and indirect effects on cirrus clouds by particles from aviation (8). These RF mechanisms are generally given a low or very low level of scientific understanding by the IPCC (34).

The use of RF as a metric for global warming is based on the assumption that RF is proportional to global mean warming and that this relationship is independent of the forcing mechanism (i.e., equal climate efficacy for all RF mechanisms). As discussed in ref. 34, deviations from this assumption may be seen for RF mechanisms affecting high latitudes or altitudes. However, because there is no firm consensus from general circulation model studies on this issue, and because RF and integrated RF (as used in the GWPs) are still the preferred metrics for climate policy, we do not include variation in climate efficacies in our comparison of the transport sectors.

Many of the RF agents studied here are controlled by processes that are sensitive to changes in climate (e.g., water vapor, temperatures); for example, a change in OH levels affects O_3 and CH_4. We have assumed a constant background atmosphere and climate. These chemistry–climate couplings may be significant on time scales beyond those of the responses in the chemically active components.

The transport sector is characterized by many small sources with high emission factors for NO_x, CO, VOC, and aerosols. This is reflected in the ratio between change in ozone burden and CO_2 emission. Compared with the electricity production sector, where the range of this ratio is 0.8×10^{-3} to 5×10^{-3} $TgO_3/TgC \cdot yr^{-1}$ depending on geographical region (42), the corresponding global number for road transport is a factor of 2–15 times higher.

In our analysis, we have focused on changes in concentration levels initiated by emissions of a suite of gases and aerosols from the various transport sectors. Alternatively, an emission-based perspective could be used that attributes the forcings to the various individual emissions (e.g., NO_x, CO, etc.) (27, 34). This would fit well with a gas-by-gas approach in policymaking, whereas our perspective is better suited for a policy perspective

that focuses on the total RF effect of the various sectors, aimed at reducing the total activity of a sector.

Conclusions

This analysis has shown that there are large differences between the transport subsectors in terms of sign and magnitude of forcing, as well as in terms of the mix of contributions from short- and long-lived substances to the net RF and thus its temporal characteristics. Our calculations show that transport contributes significantly to man-made RF for some components. We find that, since preindustrial times, transport has contributed ≈15% and 31% of total man-made CO_2 and O_3 forcing, respectively. The current emissions from transport are responsible for ≈16% of the integrated net forcing over the next 100 years for all current man-made emissions. The dominating contributor to positive forcing (warming) is CO_2, followed by tropospheric O_3. By subsector, road transport is the largest contributor to warming. Shipping causes net cooling, except on future time scales of several centuries. As discussed above, a variety of perspectives may be used in the evaluation and comparison of climate forcing from the transport sectors. We have used the integrated RF concept, which puts equal weight on all forcings over time, up to the chosen time horizon, and does not account for the thermal inertia of the climate system. This choice of metric is in line with the adoption of GWPs in the Kyoto Protocol and IPCC 2007 (34). Other metrics may also be used (e.g., change in global annual mean surface temperature at a chosen time).

Significant uncertainties are related to our estimates of both historical and integrated RF from the transport sectors, mainly due to cirrus, contrails, and direct and indirect aerosol effects, but the conclusion that road transport is the dominating warming sector and that CO_2 and O_3 are the dominating warming agents, while shipping causes cooling, remains robust. The calculated RFs present a different picture than that shown by emissions data alone, mainly because of indirect effects, nonlinear atmospheric interactions, and dependence on geographical location of emissions (25, 28). In addition to its emission of CO_2, which is addressed by the Kyoto Protocol, the transport sector contributes to climate change by means of several forcing agents that are not covered by the Protocol, most notably tropospheric O_3 driven by NO_x, CO, and VOC. In addition, the negative forcings caused by SO_2, OC, and ozone precursors (on methane lifetime) are not included in the Kyoto "basket." Thus, a Kyoto Protocol perspective that includes only WMGHGs does not capture the full climate effects of transport, in particular for the shipping sector because of its large contribution to SO_2 and NO_x emissions.

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